THE INFLUENCE OF DELAMINATION OPENING IN CARBON FIBRE/EPOXY LAMINATES ON SIGNAL CHARACTERISTICS OF PULSE PHASE THERMOGRAPHY

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1. Introduction

Increasing use of carbon fibre reinforced polymers (CFRP) in aeronautical applications calls for non-destructive testing (NDT) methods capable to tackle the enormous amount of parts, variations of part geometry and large areas that require inspection. One of the most common damage events on aircraft structures is impact damage induced by hail, dropped tools, runway debris, ground vehicles or birds. For CFRP structures in many cases the necessity arises to use NDT methods as the formation of delaminations, inter fibre fracture and fibre fracture after impact damage may not be visible on the outside of the structure [1]. Active thermography with optical excitation shows great potential for the detection of sub-surface defects in large composite structures. Main advantage is a fast, contact free measurement of large areas, allowing in-field inspection [2].

Active thermography is based on the principle of observing the change of the surface temperature of a part during or after a modulated excitation. It has been widely investigated for its detection depth and for various evaluation and excitation techniques where pulse phase thermography (PPT) [3,4] and lock-in thermography [5,6] are the most commonly used techniques. Lock-in thermography is based on a modulated heating of the specimen creating a pulsating temperature field on the surface. The heat propagating through the part is commonly called a thermal wave allowing an evaluation not only for the amplitude, but also the phase if this wave is reflected at any discontinuity. Depending on the excitation frequency, the generated thermal wave achieves different penetration depths [5,6]. Accordingly, in order to investigate a part for all its depths numerous measurements at different frequencies are needed, which could lead to a time consuming measurement. To overcome this, a rectangular pulse can be used for excitation. Post-processing allows decomposing the signal with a Fourier transform into a multitude of sinusoidal signals of different frequencies, thus enabling an investigation of different depths with only one measurement. This thermography protocol is called PPT [3,4].

However, studies on thermography application on composite parts mostly neglect the influence of defect characteristics, which become especially noticeable for continuous fibre composites. Previous work has shown that blind holes and delaminations in the same depth yield different results for the phase contrast [7]. Delaminations which form after impact do not show a constant thickness of the enclosed air gap, but a varying thickness from the center to the sides. This delamination thickness variation has a strong influence on the results obtained from thermography, where highest contrast is achieved for the largest delamination opening. The same can be observed when specimens with delaminations are subjected to compressive loads leading to buckling of the delaminated plies. The result is an increase in the phase contrast of PPT measurements due to the increased delamination opening. In the same manner, results from inspected structures may vary depending on loads they may be subjected to during inspection or depending on the delamination’s geometric properties. In this work double cantilever
beam (DCB) and compression after impact (CAI) tests using carbon fibre reinforced plastics (CFRP) were conducted with the aim to investigate the influence of delamination opening on the phase signal of PPT.

2. Experimental method

2.1. Specimen preparation

All specimens were manufactured from a Cycom 977-2-35-24K IMS 268-T1-ALT 300 prepreg. During lay-up the laminates were subjected to a vacuum for 15 minutes every four layers, to achieve a better compaction and reduce air inclusions. Curing was conducted in an autoclave according to prepreg manufacturer specifications at 7 bar and 177°C. For each testing procedure two different types of specimens were manufactured to investigate delaminations in different depths. The DCB specimens were made from uni-directional laminates in two and four millimeter thickness, where the starter film was placed between the middle layers. For a starter film an ETFE/fluropolymer release film with a nominal thickness of 25 µm was used. It has to be noted that only the four mm thick laminates correspond to the specimen geometry recommended in the standard JIS K 7086 [8].

The formation of delaminations induced by impact occurs between adjacent layers of different orientation [1]. In order to reduce the complexity of multiple delaminations overlapping in one specimen, the lay-up suggested in the ASTM standard [9] was altered to a cross-ply laminate, where only one large delamination will form in either 0.5 or 1 mm depth. The lay-ups and geometry of the specimens can be seen in Table 1, where w is the specimen width, t the specimen thickness, t₁ the depth of the starter film and l_f the distance between the load line and the tip of the starter film.

After machining the specimens the sides were sanded with sand paper up to a grain size of 1000 to avoid edge defects. After polishing, the sides of the DCB specimens were coated with a thin layer of brittle white paint to allow a better measurement of the delamination opening and crack propagation.

Table 1: Specimen lay-ups and geometry

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Lay-up</th>
<th>w in mm</th>
<th>t in mm</th>
<th>t₁ in mm</th>
<th>l_f in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCB1-X</td>
<td>[0]₁₆</td>
<td>25</td>
<td>4</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>DCB2-X</td>
<td>[0]₁₈</td>
<td>25</td>
<td>2</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>CAI1-X</td>
<td>[0₂/90₃]₄s</td>
<td>98</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAI2-X</td>
<td>[0₄/90₄]₄s</td>
<td>98</td>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1: Schematic side view of the DCB tests with expected results for phase response
Every five millimeters from the starter film a marker was scraped into the white coating to determine the crack propagation through the travelling microscope. Aluminium loading blocks were adhered with superglue to the specimens, where the load line was 25 mm from the starter film. The CAI specimens were subjected with a 7 J impact in a drop weight tower. Anti-rebound ensured a defined energy introduction. Before testing, the introduced impact damage was determined using ultrasound c-scan.

2.2. PPT Measurements

PPT measurements were conducted with an IR NDT system from Automation Technology GmbH. A Flir® Photon 640 IR camera measuring in a spectral band of 7.5-13.5 μm at a frame rate of 8.33 Hz and with a thermal resolution of 50 mK NEdT at f/1.0 was used. A halogen spotlight with 2.5 kW power was synchronised with PC and camera via an IRX box. Measurement parameters and recording was facilitated with the Automation Technology software IrNDT 1.7 allowing an export of the measured data to Matlab. Measurements of the DCB specimens were conducted from either side, while the measurements on the CAI specimens were conducted from the side opposite the impact, to avoid a shadowing by the smaller delaminations near the impact site. Post-processing and evaluation was conducted with a self-developed Matlab program, allowing measurement of averaged values of chosen line profiles along the delamination. Investigated areas were chosen to be only in the impact damaged area (\(\phi_d\)) or in a representative non-damaged area (\(\phi_s\)). The phase angle difference between the prior to loading damaged and undamaged area \(\Delta\phi_{d,s}\) was calculated using the formula

\[
\Delta\phi_{d,s} = \phi_s - \phi_d
\]

1.

![Graph](image.png)

**Fig. 2**: Phase angle difference and delamination opening plotted over the delamination length beginning from the release film from which the delamination was initiated.
2.3. DCB Tests

DCB tests according to JIS K 7086 were conducted for both delamination depths. A Shimadzu servopulser with a 500 N load cell and servo controller 4830 was used. The specimens were loaded with a pin-fixture specified in the appendix of JIS K 7086 allowing a compensation of the orientation of the blocks if necessary. Crack propagation and delamination opening were measured with a Keyence digital microscope system VHX 500 with a VH-Z75 microscope allowing magnifications from 75 x to 750 x. The included software allowed digital measurement of delamination opening at each marker[10]. At first a regular DCB test was conducted, where the crack was propagated to approx. 50 mm length. During unloading the process was interrupted and the load held to allow a thermography measurement at constant delamination opening. After that, unloading was continued until interrupted for the next PPT measurement. During each interruption the delamination opening at each marker was measured with the microscope. Fig. 1 shows the experimental set-up and expected results for the different delamination openings.

For evaluation, the average phase value of the line profile of 2/3 of the specimen width was extracted for the frequency yielding maximum contrast. Main uncertainty of the DCB tests is whether the very simplified specimens with their limited width and open sides of the delaminations also describe the behaviour of laminates with closed delamination. To investigate this, CAI tests under compression loads were investigated.

2.4. CAI tests

CAI tests according to ASTM D 7137-05 were carried out to investigate the delamination opening caused by buckling during compressive loads and its influence on thermography results. The testing routine was altered in a way that allowed to stop the loading and to hold it at a constant level. At these points PPT measurements were carried out and the
specimen thickness along two lines perpendicular to loading direction was determined using a micrometer. For this, a cut out was machined into the clamp. However, this cut-out was machined in such a way that global buckling of the specimens was hindered. After these measurements the specimens were unloaded and removed for ultrasonic e-scans. After determination of the damage size the specimens were loaded again to the next higher load level and the procedure was repeated. Again, the averaged values along the two line profiles of the PPT measurements were extracted where the thickness was measured from which the delamination opening was calculated.

3. Results and discussion

3.1. DCB tests

During the DCB tests a stable crack growth was observed throughout the entire experiment. The load-displacement curves indicate that no further crack growth occurred during the interruption, when the PPT measurement was conducted. Furthermore, the load-displacement curves show that no excessive fibre bridging was present, which was confirmed with the microscope.

The DCB tests show that with increasing delamination opening the phase contrast between the delamination and the sound material of the specimen increases (Fig. 2). Furthermore, difference in the location of the crack tip was detected between the thermography result and actual observation by optical microscope. This is attributed to thermal blurring induced by the uni-directional fibres in the DCB specimens, which lead to anisotropic thermal properties, thus shifting the actual crack starting point as observed on the surface of the part and the possibility of a meniscus crack front which is often observed for DCB tests.

Fig. 3 shows the logarithm of the delamination opening vs. the phase contrast of two specimens, each for a delamination in one and two millimeter depth. Despite some small scatter the curves show...
the reproducibility of the experiments, as the values for the two specimens shown of each delamination depth lie in the same range. It has to be noted that further specimens were tested but omitted in this graph for more clarity. For each delamination depth a linear behavior in a logarithmic scale can be used to describe the change of phase contrast over delamination opening. This remains true until the phase contrast reaches a maximum value, after which no further increase is observed, despite a growing delamination opening. However, this is not observed until a delamination opening of at least 0.6 mm is reached. Accordingly, the practical relevant cases can all be described with this fit. Additionally, the curve of the 1 mm deep delamination starts with an offset. This is attributed to interferences of the thermal wave reflected at the backside of the specimens and the thermal wave reflected at the crack tip.

The slope of the linear fit varies depending on the thickness of the specimens and the delamination depth. This means, the closer the delamination to the surface, the more sensitive it becomes to changes of delamination opening. Furthermore, delaminations closer to the surface yield higher phase difference saturation values.

3.2 CAI tests

Ultrasound c-scans after unloading showed that no delamination growth occurred during the static loading even for loads near failure load. The results of the CAI tests complement the findings of the DCB tests. Fig. 4 shows the phase angle difference and specimen thickness over the specimen width for various compressive loads, where 0 mm denotes the point at which the impact damage was introduced. Similar saturation values for the maximum phase angle difference are observed for the loads of 20 and 42 kN when compared to the 2 mm deep delamination. The only difference between these two curves is the wider buckling of the delamination, which does not occur until high loads are reached. As seen in the experiments the maximum phase angle difference
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does not increase further despite the significant increase of specimen thickness, i.e. the delamination opening. As expected, the CAI tests showed for the specimens, where the delamination was 0.5 mm depth that the slope in the semi-logarithmic plot increased compared to the other specimens. Nevertheless, the maximum phase angle difference was in the range of 0.3 rad, as also found for the other CAI and the DCB tests. To verify whether the DCB tests are a suited method to determine the correlation between delamination opening and phase angle difference the values for each two DCB and CAI specimens are plotted in Fig. 5. Both experiments yield curves of comparable slope. However, the measurement range for different delamination openings is larger for the DCB test. Furthermore, the accuracy of determining the delamination opening is higher when using the travelling microscope compared to a micrometer. The only difference between the DCB and CAI tests seems to be that the maximum value for the phase angle difference of the CAI tests is limited to 0.3 rad, while DCB tests show changes of up to 0.4 rad. This is probably attributed to the open sides of the DCB test compared to the closed delamination of the CAI test. While the heat is retained in the closed delamination, convection in the opening of the DCB specimen allows significantly faster cooling for large openings, thus increasing the maximum change of phase contrast. However, these values are observed for large delamination openings and thus they can be regarded as non-relevant for practical applications. Additionally, the delamination opening measurement of the CAI tests is indirect, as it is calculated from the thickness measurements. Formation of further delaminations, even though not likely, could influence the results, therefore reducing the accuracy. Hence, it can be concluded that the presented DCB method to investigate the influence of delamination opening on the phase contrast yields accurate results despite some differences to closed delaminations.

4. Summary and outlook

In this work the influence of delamination opening in CFRP laminates on the phase angle difference of PPT measurements was investigated. Standardized testing methods such as DCB and CAI tests were used in combination with carefully chosen lay-ups to yield defined delamination openings for thermography measurements. The DCB method proved to be more accurate due to the measurement techniques applied and showed no significant difference when compared to CAI tests, despite the fact that the investigated delamination is open on its sides. A logarithmic-scale linear relationship was found, enabling a prediction of the phase response depending on the opening. Especially for small changes of delamination opening, high changes in the phase angle difference are observed. Delaminations closer to the surface prove to be more sensitive to changes in delamination opening and yield higher values for phase angle difference. These results allow adjusting testing procedures according to loading conditions of the inspected part, thus improving the application range of PPT. Numerical simulations allow a fast variation of parameters to fully describe the relationship of delamination opening, phase angle difference and delamination depth. These investigations are currently under development. Future efforts will be aimed at broadening the findings of these studies with modified DCB specimen, where multiple delaminations in different depths in one specimen can be propagated towards each other or on top of each other. This way the gap between the simplified experiments shown in this study and complex or realistic cases, where a multitude of delaminations form between the lamina overlapping each other in projection to the surface, can be closed.

5. Acknowledgements

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References


