THERMOGRAPHY ASSISTED CHARACTERISATION OF PRODUCTION-INDUCED DEFECTS IN CFRP AND THEIR INFLUENCE ON THE MECHANICAL BEHAVIOUR

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ABSTRACT: A novel hybrid-joint, suitable to series production, is currently developed. It overcomes the gap in stiffness by inserting a thermoplastic element between metal and carbon fiber reinforced polymer (CFRP). The main goal in terms of quality assessment is to characterise the defect-caused damage propagation (effects of defects) by means of destructive and non-destructive testing (ndt) of artificially implemented defects.
Assuming that flaws are most-likely to occur within the CFRP, close to the transition zone, first investigations are carried out on the effects of defects in pure CFRP component. Thus artificially implemented defects, i.e. missing roving, gapping, 10° misalignment, pleat and delamination, are characterised by active thermography in terms of type, size and location. A subsequent correlation of the mechanical properties under quasi-static tensile tests and fatigue experiments of a defect-free reference and the imperfect samples is carried out. In order to evaluate the damage propagation, the mechanical experiments are complemented by *in situ* passive thermography.

KEYWORDS: Effects of Defects, passive Thermography, mechanical testing

1 INTRODUCTION

To exploit the full potential of lightweight design, the application of metal to CFRP hybrid-joints increases. The main challenge that arises with these Material-compounds is located at the joining zone between the two components, as the discontinuity in mechanical properties causes structural attenuations [1] and the appearance of production induced defects may be promoted in this region.
As explained more precisely in chapter 2, a thermoplastic polymer is introduced between the metal and the CFRP component to counteract the gap in stiffness and to improve the fatigue properties.
The main objective of applying quality assessment is to detect existing flaws with subsequent evaluation of their severity, which is mainly based on the knowledge of the damage propagation processes. Although mass of investigations had been carried out on the damage mechanisms of each of the involved materials [2-4] in the past decades, less is known on the damage mechanisms of metal to CFRP hybrid-joints. This is even more the case, if one considers production induced flaws and their influence on the response of the hybrid-joint to mechanical loading.
Therefore it is necessary to investigate internal material degradation, which can be measured as mechanical property degradation as well as local temperature changes due to irreversible deformations. For the last parameter, *in situ* passive thermography has excellent capabilities investigating temperature changes with high lateral resolution [5].
Assuming, that defects occur within the CFRP adjacent to the joining zone, first investigations focus on the effects of defects in pure CFRP component by means of passive thermography damage monitoring. This is carried out under quasi-static and fatigue tensile loading on CFRP samples with different defects, which were artificially implemented within the RTM process.

2 CONCEPT OF THERMOPLASTIC INSERT

Instead of bolting or applying adhesives, the two-dimensional conjunction between the metal component and the CFRP-laminate is achieved by geometrical optimization which results in a tight fit. Thereby the metal, which is EN AW-6082 aluminum (AlSi1MgMn), is encased with Polypropylen (PP) by direct injection over-moulding. In

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the subsequent step this insert in embedded into the CFRP laminate within a Resin-transfer-moulding (RTM) –process.
The CFRP-laminate contains of four layers [0°/90°, ±45°]$_s$ of 3K plain weave with 30 vol% carbon fibre (Torayca FT300B) embedded in the epoxy matrix (Biresin CR170/CH150-3). The overall laminate thickness is 1 mm.
The benefits are a fast and cheap process chain with improved metal to PP adherence due to microscale mechanical interlocking [6] and improved corrosion resistance [7]. Moreover the thermoplastic polymer is capable of function integration, i. e. better drapery, surface structuring, and reduces the gap in stiffness, which counteracts the discontinuity in mechanical properties.
Moreover the geometrical optimization intends a homogeneous stress distribution in the whole joining zone, which contributes to structural integrity and fatigue resistance.
However by adding this thermoplastic component two interfaces are created. It is assumed that production induced defects, of which gapping, pleat, missing roving, 10° misalignment and delamination were investigated, are most-likely to occur within the CFRP adjacent to the thermoplastic polymer (PP). Thus the interface between those is of particular interest.

3 EXPERIMENTAL SETUP

In order to differentiate the effects arising from the interfaces of the hybrid-joint and the effects of defects, first investigations were carried out on the pure CFRP component containing different defects (i. e. missing roving, gapping, 10° misalignment, pleat, delamination).
The same laminate was used as for the hybrid-joint. According to [8] sample type 2, the geometrical parameters were chosen to be 120 mm length, 20 mm width and 1 mm thickness. The clamping length was chosen 25 mm on each side.
In the first step, active thermography was applied characterising size and position of the defects, which were artificially implemented into the laminate.
For this purpose a dualband infrared camera QWIP 384 by Thermo Sensorik® was used, which attains 384x288 pixels with a spectral range between 4.4-5.2µm (MWIR) and 7.8-8.8µm (LWIR).
After active thermography the samples were mounted on wedge grips on an Instron 8500 with a 100 kN load cell. Longitudinal strains were measured using an axial clip on extensometer. Tensile tests were carried out displacement controlled with 2 mm/min cross-head speed, whereas fatigue tests were driven displacement controlled with 5 Hz frequency and a displacement ratio R = 0.1.
The maximum relative displacements ranged from 40 % to 70 % of the displacement of fracture of the defect-free reference, which was found to be 1,16 mm.
The mechanical testing was complemented with an InfraTec VarioCAM® HD head bolometer camera with a resolution of 1024 x 768 pixels. The cameras interval of spectral sensitivity ranges from 7,5 to 14 µm and its temperature resolution lies beneath 0,05 K (at T = 303,15 K).

4 DEFECT CHARACTERISATION BY ACTIVE THERMOGRAPHY

Application of active thermography is based on an external excitation technique, like ultrasonic, eddy current or flash light. An infrared camera is recording the heat flow by means of the time dependent surface temperature of an excited sample. In this process defects act like heat barriers, which are depicted as bright areas in the thermography picture. In this work flash light is used as excitation source.
In Fig. 1 (left) a defect-free CFRP-sample is shown at 75 ms after excitation. It belongs to the undisturbed, upper laminate-ply. Moreover the orientation of the carbon-fibers can be extracted. Fig. 1 (middle) depicts a CFRP-sample before mechanical testing containing an artificially implemented delamination between the first and the second layer. In the middle of the sample, a bright area is evident, which can be identified as the delamination. In Fig. 1 (right) the same CFRP-sample is displayed but after mechanical testing. In contrast to the image before mechanical testing, the bright area in the middle of the sample appears brighter and broader. This indicates that the delamination became bigger and worse due to mechanical loading. However, the biggest difference is the crack on the left side in the middle of the sample. It occurs at the weakest point of the sample and lead to failure.

Fig. 1 *Left: [0/90°]-Ply of a defect-free CFRP-sample, middle: sample with delamination before - and right: after mechanical testing*

5 PASSIVE THERMOGRAPHY

Besides the possibility of external excitation, thermography can also be applied as a passive damage monitoring technique, as friction and deformation processes act as internal excitation of the sample. As Reported by Rösner and Netzelmann [9], the measured temperature change can be expressed as a superposition of the thermoelastic temperature variation ΔT_{el}, and the contributions to temperature change due to heat dissipation ΔT_{diss} and heat exchange with the environment ΔT_{loss}.

$$\begin{aligned}\Delta T(t) &= T(t) - T_0 \\ &= \Delta T_{el}(t) + \Delta T_{diss}(t) + \Delta T_{loss}(t)\end{aligned} \quad (1)$$

Where ΔT is the total temperature change and T_0 the absolute reference temperature at time $t = 0$. The elaborate review of Pitattesi [10] accounts for the classical theory of thermoelastic stress analysis under adiabatic conditions for a homogeneous orthotropic material.

The MIDA (mechanical induced dissipated heat analysis) technique is perfectly applicable to fatigue experiments, as it accounts for the incremental temperature increase per cycle. A good correlation between heat build-up measurements and accumulated residual strains and scalar damage factor, respectively, is reported by Arif [11].

The work of Roche [5] showed the successful characterisation of subcritical damages based on the analysis of the lateral temperature distribution.

6 TENSILE FAILURE

Mechanical testing was carried out on defect-free specimens, which were taken as reference, as well as specimens containing missing roving, gapping, 10° misalignment, pleat and delamination. All such defects were located in the upper [0/90°] layer. The results of the tensile tests are given in Figures 2-5. To consider scattering, five samples were tested for each of the values.

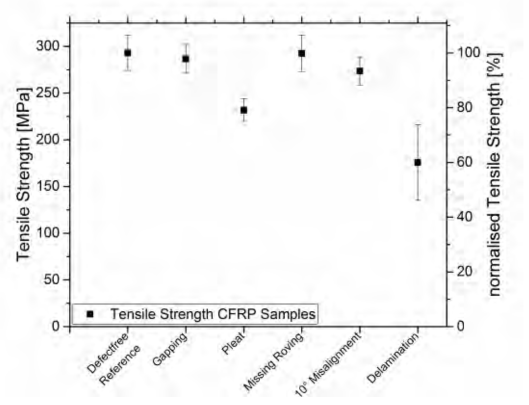

Fig. 2 *Tensile Strength of tested CFRP Samples, right scale: tensile strength normalised to the defect-free reference*

Fig. 2 reveals that gapping and missing roving have almost no effect on the tensile strength, since the deviation referring to the reference is less than the scattering. In contrast to that, the pleat and the 10° misalignment caused a drop of 20 % and 5 %, respectively. The most crucial attenuation can be found for the delamination, whose tensile strength reaches only 60 % of the reference strength. It can be further noted, that higher scattering resulted for samples containing delamination.

The similar tendency can be found for the displacement of fracture, which is shown in Fig. 3. Deviation caused by gapping and missing roving lie within the scatter of the reference. A slight decrease can be observed for 10° misalignment whereas pleat and delamination cause a drop of approximately 25 %.

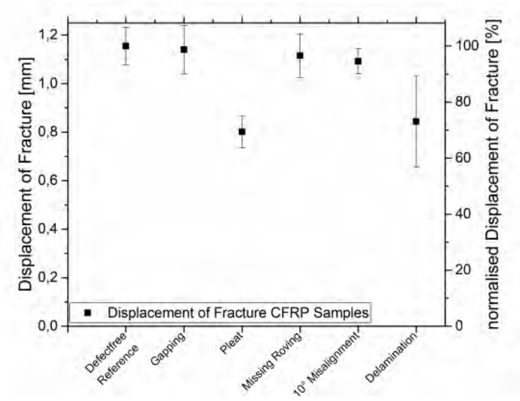

Fig. 3 *Displacement of fracture of tested CFRP, right scale: displacement of fracture normalised to the defect-free reference*

Figures 4 and 5 show the results for the breaking elongation and E-moduli, respectively. As observed for the tensile strength and the displacement of fracture, the missing roving remains effectless. In the case of gapping and 10° misalignment the breaking elongation is even higher than the reference value, which can be attributed to an equivalent drop in E-modulus.

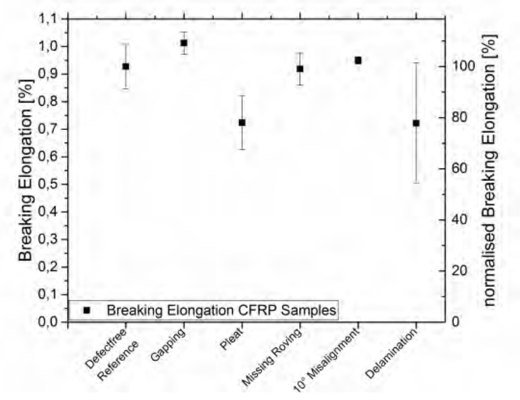

Fig. 4 *Breaking elongation of tested CFRP Samples, right scale: breaking elongation normalised to the defect-free reference*

Contrary effect is evident in the case of pleat, for which the E-modulus was found to be 113 % of the reference value, corresponding to a 20 % drop in breaking elongation. It has to be noted, that the E-modulus of the sample with pleat is only valid preliminary to the first occurrence of damage, where the pleat opens and nonlinear behaviour follows.

Serious weakening of the material by delamination is indicated by means of serious drops in both, stiffness and breaking elongation of 40 % and 21 %, respectively.

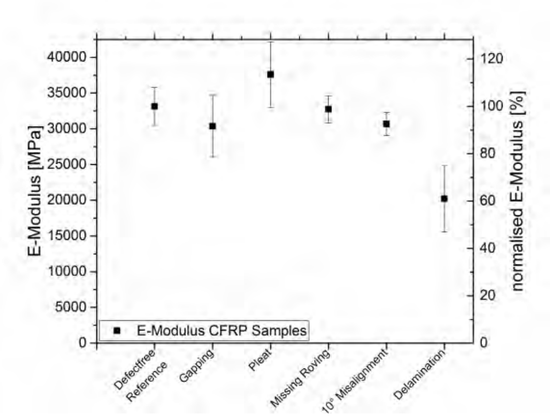

Fig. 5 *E-Modulus of tested CFRP Samples, right scale: gives the E-Moduli normalised to the defect-free reference*

As mentioned above, highest scattering comes along with artificially delaminated specimen. Assuming that the delamination sizes are not perfectly identical, this observation is a strong indicator for the mechanical properties being highly sensitive to the delamination size.

The investigations are complemented by passive thermography, which allows characterising the spontaneous heating of the fracture surface.

A representative example for a specimen with gapping is shown in Fig. 6.

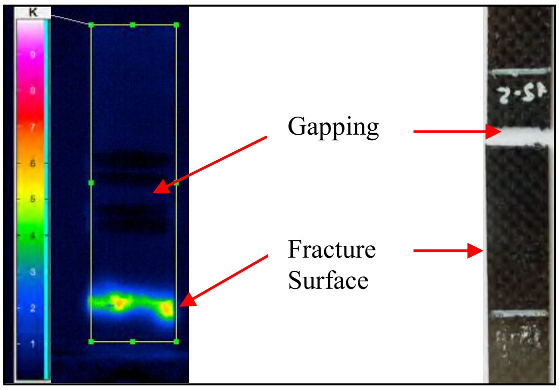

Fig. 6 *Left: differential Temperature-image, heating due to tensile fracture, right: Picture of broken sample*

It points out, that the fracture plane does not coincide with locus of the gapping. Thus, mechanical and thermographical results indicate, that the gapping has no crucial influence on the structural integrity under quasi-static tensile loading.

The thermographic images for pleat and delamination, which caused the biggest attenuations in mechanical properties, are given in Fig. 7.

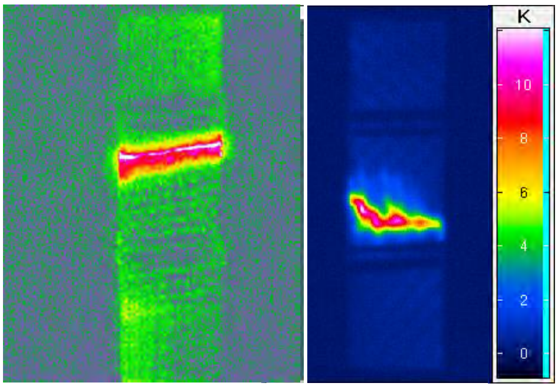

Fig. 7 *Differential Temperature-image, heating due to tensile fracture, left: fracture plane coincides with pleat, right: CFRP sample with delamination*

In Fig. 7 (left) it the tensile fracture of a sample with pleat can be seen. The contrast in differential temperature image results from the spontaneous heating due to the fracture. In contrast to randomly emerging breakage in Fig. 6, the fracture strictly coincides with the pleat. Since the fracture locus represents the weakest spot, it is clear, that the pleat is a critical defect, which causes significant attenuations of the mechanical properties of the CFRP. Fig. 7 (right) shows a broad, ziggzagging rupture zone. It can be seen from the corresponding active thermography analysis in Fig. 1 that the rupture emerges within the delaminated region. Hence the delamination represents the weakpoint and causes severe material property degradations, which was seen from the results of mechanical testing. Ultimately delamination has to be treated as a crucial defect.

7 EFFECTS OF DEFECTS IN FATIGUE

The results of fatigue experiments are summarized in Table 1. Since missing roving showed almost no effect in tensile tests, it is not further considered in fatigue experiments. Note that the relative displacement of 70 % is greater than the static displacement of fracture for samples containing pleat or delamination.

***Table 1:** Cycles to Failure for different defects and displacements*

	Relative Displace-place-ment	Cycles to failure	Standard deviation
Defect-free	70 %	729680	388833
Gapping	70 %	1,17e6	-
10° misalign -ment	70 %	53856	37818
Pleat	50 %	1075	1424
	40 %	30344	20906
Delamina-tion	50 %	51067	34337

Additionally, the representative development of the E-moduli is shown in Fig. 8.

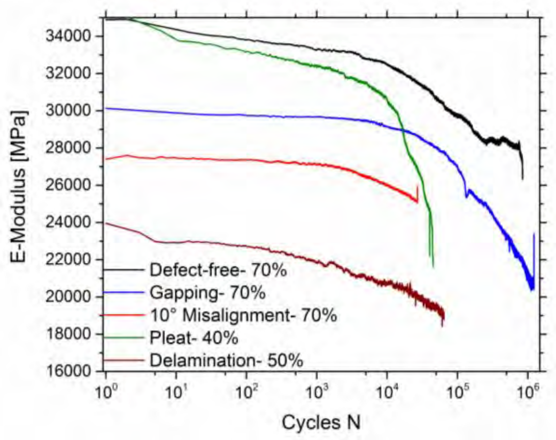

Fig. 8 *Development of E-moduli during fatigue testing, legend gives different relative displacements*

Along the defect-free samples most resisted the loading for more than 10^6 cycles, whereas some broke earlier. Therefore higher scatter could be found. The samples with gapping survived almost the same amount of cycles but with lower scatter. Though higher degradation of the E-modulus, which corresponds to the scalar damage factor [12], is evident in Fig. 8 for cycles higher than 10^4.
For specimens with 10° misalignment, subjected to a relative displacement of 70 %, the average lifetime being 54000 cycles, lowest degradation previous to fracture could be observed.
The lifetime under fatigue conditions was more sensitive to pleat and delamination, as the average lifetime showed a significant drop for those defects (see table 1). This is confirmed by Fig. 8, as the delaminated specimens suffered significant degradation within the first cycles. Moreover the highest degradation rate appeared at the gapping. A possible reason could be a change in the damage mechanisms which results in accelerated damage propagation.

However, the degree of damage at which the specimens fail seems arbitrary. Therefore passive thermography investigations are added to improve the characterisation of the damage development.
Figures 9 - 11 show the differential temperature developments for a defect-free specimen, one with pleat and one with delamination, respectively.

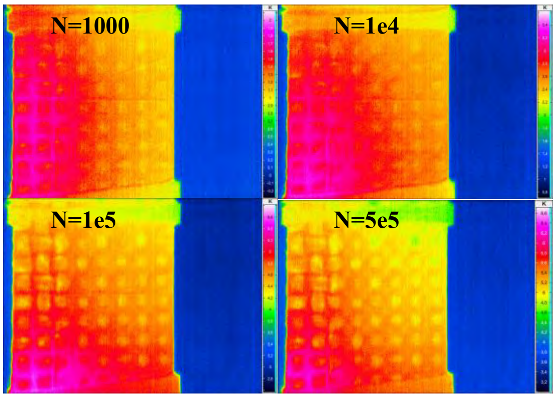

Fig. 9 *Differential temperature image of defect-free sample during fatigue, corresponding to Fig. 8 at N=10^3, 10^4, 10^5, 5•10^5*

In case of the defect-free sample, the temperature increases delocalised until approximately 1•10^4 cycles, which coincides with the regime of linear degradation in Fig. 8. For times greater than 10^4 cycles the evolution of a hot spot at the lower left corner is obvious. This can be assigned to the accelerated decrease of mechanical properties, which is in good agreement to Harris [13]. He proposed that matrix micro-cracking is the dominant damage mechanism in the initial stage until a characteristic damage state is attained. Interlaminar damage propagation follows, by means of delamination, until final failure occurs.

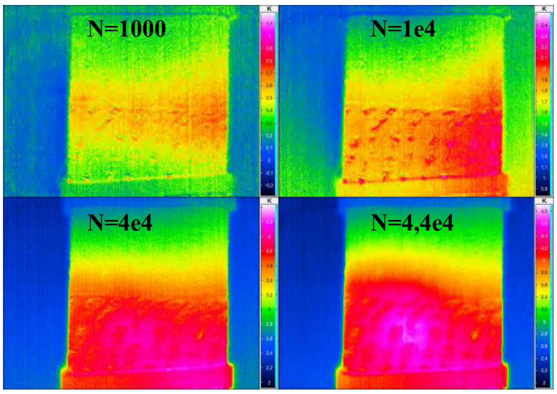

Fig. 10 *Differential temperature image of delaminated samples, corresponding to Fig. 8 at N=10^3, 10^4, 4•10^4, 4.4•10^4*

It can be seen in Fig. 10 that the pleat causes primary temperature increase surrounding the pleat at low cycles. Therefore significant deformation can be assumed in the disturbed region, which results

in the formation of a hot spot at medium cycles (<10^4). Subsequently the evolution of a dominant hot spot, ending in final failure, is observed, which fits well to the predominant rapid stiffness degradation in Fig. 8, starting at approximately 2000 cycles.
In case of the delaminated specimen (Fig. 11) a hot spot has already developed at 1000 cycles and coincides with the region, where the delamination was identified by active thermography (Fig. 1). This indicates that interlaminar damage propagation was directly activated due to the presence of the delamination. If matrix micro-cracking and intralaminar damages propagate, they have minor significance in case of the delaminated sample.

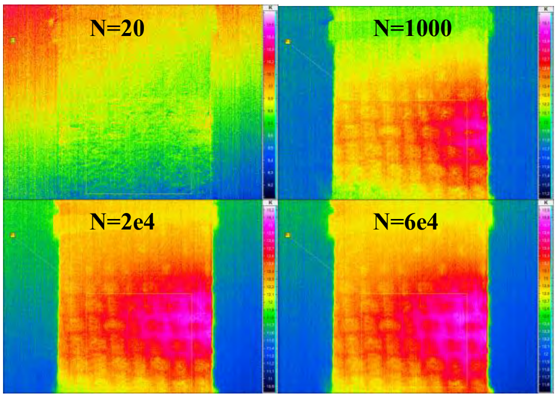

Fig. 11 *Differential temperature image of delaminated sample, corresponding to Fig. 8 at N=20,10^3, 2•10^4 and 6•10^4*

8 CONCLUSIONS

Active thermography is presented as a highly sophisticated method characterising the size and location of defects in the range of approximately 500 µm. It enabled the characterisation of damage development, introduced by mechanical loading.
Passive thermography damage monitoring during quasi-static tensile tests allowed assessing the severity of different defects.
Negligible deviations of mechanical behaviour were observed due to the defects missing roving and gapping, 10° misalignment caused slightly stronger deviations. Additional thermographic investigations depicted that the fracture plane didn't coincide with the gapping. Therefore missing roving and gapping can be treated as non-crucial disturbances of the CFRP-laminate under quasi-static tensile tests. Samples with 10° misalignment represent the borderline, since they showed no significant, but visible, effect. Massive attenuations of the tensile mechanical properties could be observed for samples containing pleat or delamination. Thermographic images of the tensile fracture confirmed the severity of both defects, as the fracture locus could be related to the region affected by the defects.
Experimental results on the degradation behaviour under fatigue condition were shown as well. Defect-free samples showed significant scattering. In the presence of gapping the samples survived as long as defect-free samples. Though, higher degradation rate was observed, which can be attributed to a slight promotion of degradation due to gapping.
Contrary was found for samples with 10° misalignment, pleat or delamination. They are seriously weakening the laminate, which resulted in crucial attenuation of the fatigue resistance and consequently in much earlier rupture.
Comparative study on the damage developments of defect-free specimens and such with pleat and delamination was supported by passive thermography. It revealed that in the presence of both, pleat and delamination, the formation of a dominant hot spot, which indicates interlaminar damage, was heavily accelerated.

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