Combined Acoustic Emission and Thermographic Testing of Fibre Composites

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Abstract. The digitization of NDT methods and ever increasing processing power nowadays enable the efficient combination of two or more NDT techniques in order to reach higher sensitivity and selectivity compared to a single method. Especially the combination of imaging with non-imaging methods can provide additional benefits such as improved defect localization: We combined thermography and acoustic emission for testing fibre reinforced composites. By using an excitation technique such as a tensile testing machine the parts under test are loaded to stimulate crack formation which can be detected both as an acoustic event and by looking at the heat signature. While as an imaging technique thermography simplifies the localization of events such as crack formation it does not provide easy access to a quantitative measure as the detectable events are limited to the surface. Acoustic emission provides more direct quantitative access through event density and amplitude. We present results from carbon and glass fibre reinforced composites of test samples and wind turbine components under cyclic load: for a number of events such as fibre or matrix cracks a clear correlation of thermography and acoustic could be observed showing the value of this combination of methods.

Introduction: Combined thermal stress analysis and acoustic emission analysis

The last couple of years have seen tremendous advances across all NDT methods: The ubiquity of digital data acquisition and analysis enabled the full recording of data sets to extract the maximum amount of information. Almost all of the individual methods of non-destructive testing received a boost from digitization but even more can be gained by combining data from complementing techniques.

Combined techniques are most beneficial for applications where a single NDT method cannot cover the full extent of the requirements. As materials become more complex and also the material properties need to be more controlled the demand for ever better non-destructive testing grows – especially for light weight designs both requirements coincide: The increasing usage of fibre reinforced composites on the hand go hand in hand with tight tolerances and small permissible defect sizes.

In this paper we present an example of these developments: We combined acoustic emission and thermography in a concurrent test using a cyclic load and demonstrated this combination on carbon and glass fibre reinforced composites. Acoustic emission testing and active thermography both already have profited individually from the digitization: Both methods rely heavily on processing and filtering of the measured values to provide

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meaningful test results and are therefore ideally suited for a combination. Also both techniques allow tracking the occurring damage in-situ during the loading of the material: A combination in this case simply means adding another sensor to an existing set-up which greatly simplifies the application.

Also, results from acoustic emission and thermography complement ideally: While acoustic emission specifically shows immediate failure of a part for a certain load, Thermography in the form of thermal stress analysis (TSA) also displays lower stress levels but is restricted to the surface [1]. Both methods allow a localization of the parts with high failure probability. Two set-ups have been used for experiments: In the first a carbon fibre composite sample was subjected to step-wise increased loads with cyclic hold periods in a universal testing machine. In the second set-up a cyclic bending load was applied to a glass fibre composite sandwich taken from an actual wind turbine blade material.

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Experimental set-up and results for carbon fibre reinforced composites under tensile loading

Tensile testing equipment as used in the first experiment provides a controlled environment for testing the combination of acoustic emission and TSA: The load is easily quantifiable and the systems provide easy access to the sample for both techniques. Figure 1 shows the set-up: The sample is mounted vertically into a tensile test fixture of a Zwick-Roell 1464 universal testing machine and two acoustic sensors of type WD are attached to the sample close to the grip with clamps. Medium viscosity silicone grease of type Baysilone is used as a coupling medium. The signal from the sensors is amplified by 40 dB_{AE} and are bandpass filtered between 20 kHz and 1 MHz before sampling at 10 MSP/s by an acquisition card of type PCI-2 using a threshold of 35 dB_{AE} and trigger settings of 10/80/300 for PDT/HDT/HLT. The data reduction procedure and signal classification follows the outline in [2]. For offline data analysis features are extracted from the first 100 µs after threshold crossing and are divided into several bands of 150 kHz for spectral analysis (cf. [2]). The difference in arrival time of the signals at the two sensors is used for a one-dimensional source localization along the vertical axis.

A FLIR SC7000 midwave infrared camera was used to record the surface temperature of the sample using a frame rate of 100 Hz. In order to reduce the size of the recorded data 4 consecutive images were averaged which resulted in an effective frame rate of 25 Hz and approximately half of the noise level of the unaveraged images. To enable the thermal stress analysis, the analog inputs of the camera were used to record the cross-head displacement and the force signals provided by the universal testing machine. To analyse the signal the infrared signal was correlated pixel by pixel with the force values. Because of the limited movement of the sample no compensation of movement was necessary.

In order to provide a usable signal for both techniques a cyclic load of +/- 2 kN with a cycle period of 2 s was used on top of base load which was a stepwise increased up to the destruction of the sample which occurred at the step from 10 kN to 15 kN.

For the experiments rectangular plates of carbon fibre reinforced composite with a cross section of 2.2 x 20 mm² were used. The fibre layup in the test section was chosen as $((0/90)_2)_{sym}$ with prepreg plies of the material Sigrafil CE1250-230-39 cured according to the material supplier's specification. As reinforcement, additional plies were added in ±45° direction to form a tapered contour. In order to guarantee a failure in the field of view of both methods double edge notched specimens were applied to cause a stress-concentration at the centre part of the specimen as shown in figure 1.

Fig. 1. Combination of acoustic emission testing and Thermal Stress Analysis using universal testing machine as excitation. The image on the left shows the complete set-up while the image on the right shows the positioning of the acoustic emission sensors on the back of the sample

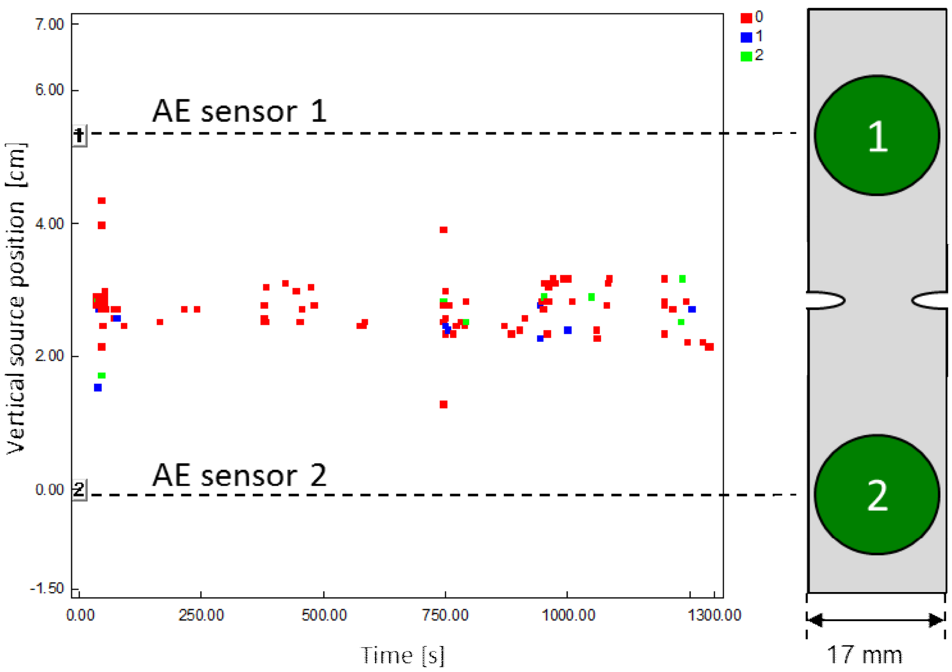

Fig. 2. Acoustic emission events from tensile testing of carbon fibre composite: The events are mainly concentrated close to the notch position of the sample. The colours classify the events according to matrix cracks (red), fibre failure (blue) and interface failure (green).

As expected the main acoustic emission events occurred around the notches in the material: Figure 2 shows a typical example of the localized acoustic emission events: The events are mainly concentrated in the notched middle plane of the sample until shortly before failure. The events were classified following the procedure in [2] as matrix cracks (red), fibre failure (blue) and interface failure (green). As only two sensors were used only a linear localization along the vertical axis is possible but the results from thermography confirm that a horizontal stress concentration occurs at the notch position.

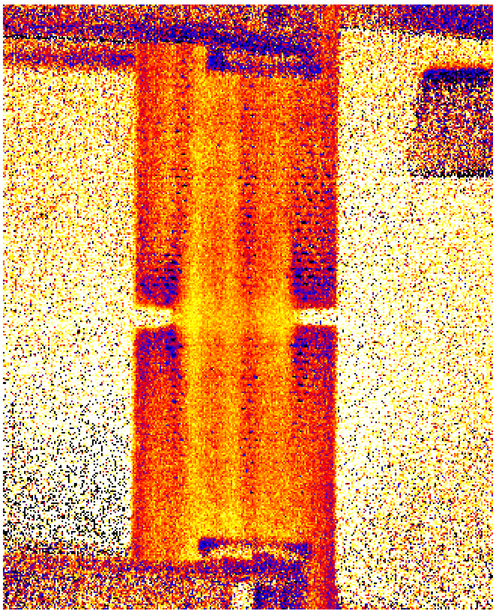

Fig. 3. Thermal Stress Analysis corresponding to figure 2: As expected the stress is concentrated at the notches but due the fibre structure the stresses show a considerable horizontal inhomogeneity.

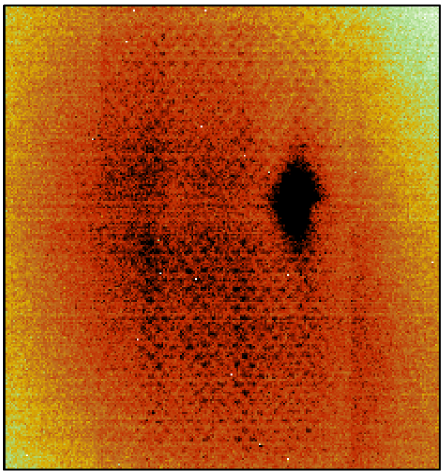

Fig. 4. The heat released by the plastic deformation due to a fibre bundle failure directly indicated the position of the event.

Figure 3 shows the result of the Thermal Stress Analysis at a base load of 9 kN (+/- 2 kN cyclic load): The main concentration of stress can be observed close to the notches and extends vertically from the remaining cross section with a distinct horizontal distribution depending on the individual fibres. For the image in figure 3 an image sequence over 3 s was taken into account when no major cracking occurred and the variations of surface temperature was driven mainly by the elastic deformation of the sample. In case of a major crack the amount of heat released from the plastic deformation completely masks the elastic component which prohibits the thermal stress analysis in the vicinity of this spot but at the same time provides a means of detecting strength and position of a crack formation or similar event. Figure 4 shows a fibre failure occurring next to the right notch. This event corresponds to one or several of the fibre failures which were also detected around at time position 1000 s with acoustic emission (figure 2).

The comparison of both methods demonstrates the value of a combination of both techniques: Acoustic emission provides a very sensitive tool which allows accurate localization and classification of the failure events. Thermal stress analysis visualizes the stresses occurring under load which easily reveals the full-field stress distribution. In the infrared images it is also easily possible to locate major failure events but the method lacks the sensitivity of acoustic emission for such events.

Application to wind turbine component: Experimental set-up and results for a wind blade segment

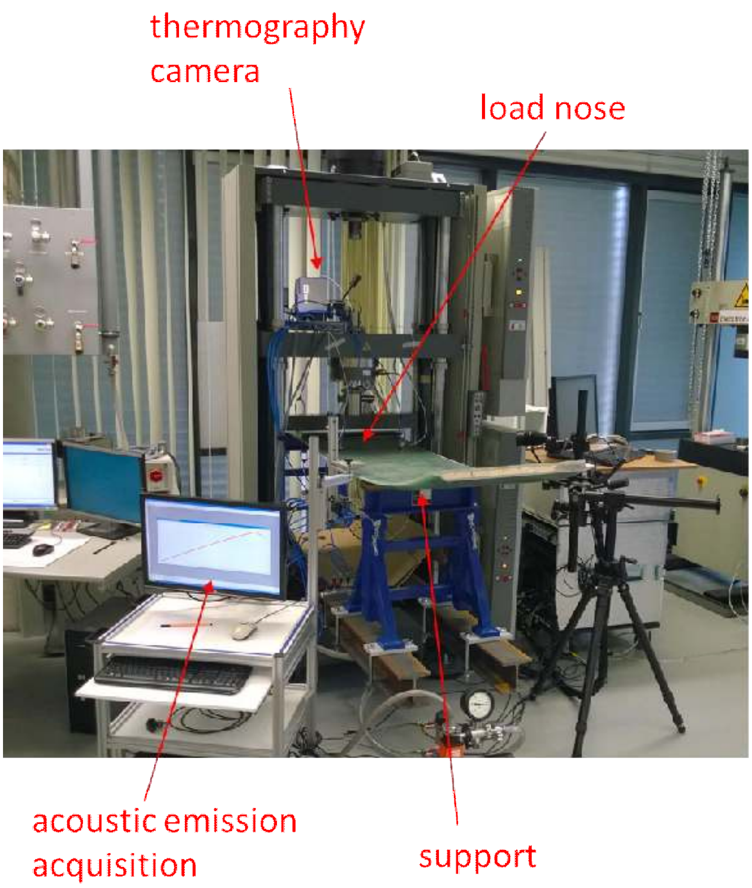

Fig. 5. Set-up for combined acoustic emission and thermography on a sample taken from a wind turbine blade. The set-up resembles a three point bending test with a support distance of approximately 1 m

As a next step towards a real world scenario the combination of methods was applied to wind turbine blade material. In order to be able to use standard excitation equipment a rectangular sample of 40 x 200 cm² was cut from a sidewall of a wind turbine blade which still fits into a universal testing machine from Zwick/Roell of type Z250. The piece was mounted in a three point bending test: The sample rested on two beams with a distance of approximately 1 m while a vertical load was applied from above through a load nose parallel to the supports, which was located centered in between the supports. Figure 5 shows a scheme and a photograph of the set-up: The thermography camera is located below the load nose in order to cover a major part of the stressed area. The acoustic emission sensors are located on the corners of a square area coinciding with the field of view of the infrared camera on top and bottom of the sample so that in total 8 sensors were mounted on the test component. The sample corresponds to the material typical for a blade of a Siemens wind turbine: The sidewall consists of a sandwich of glass fibre composite with inlays of balsa wood. Since a quasi-isotropic fibre layout is used the results are also partially representative of the bending direction and therefore can be transferred to scenarios involving bending of a whole blade.

The applied force followed the same concept as the first experiment: On top of a base load of up to 10 kN a cyclic load of +/- 400 N with a cycle period of approximately 6 s was applied. As the material is constructed to be flexible this resulted in a bending of the part and relative position of the load nose of 10-15 cm below the support beams. Again, the base load has been increased step wise: With each step above a base load of 5 kN a large number of acoustic emission events occurred until the frequency of events saturated after a couple of minutes cyclic loading.

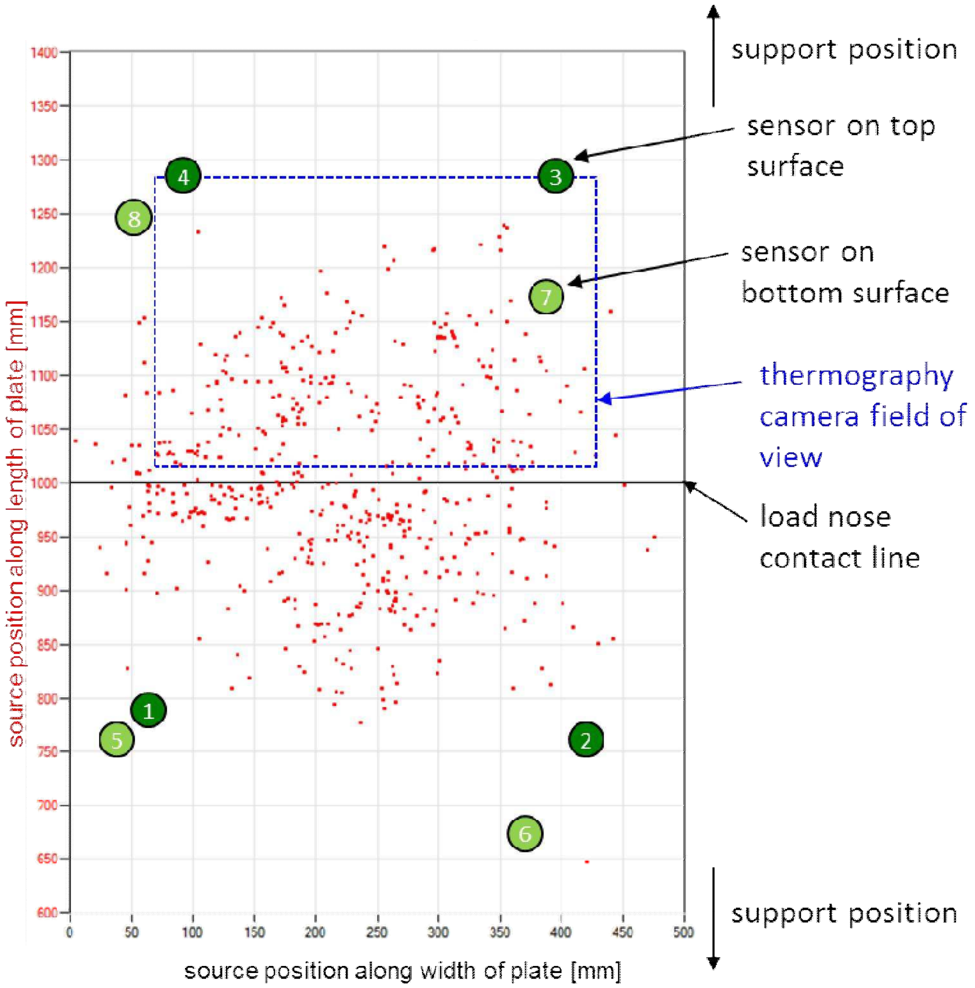

Fig. 6. Acoustic emission events for a load of 10 kN +/- 400 N recorded over several minutes after increasing the base load. All events (red) correspond to matrix cracks. The position of the sensors are marked in green (4 above, 4 below sample), the load nose position is indicated by a gray line at vertical position 1000 mm

Figure 6 shows the distribution of the localized acoustic emission sources across the surface of the part recorded for a base load of 10 kN over a time of several minutes. No distinct pattern can be found in the positions as the events are evenly distributed across the area around the load nose. Also, in this experiment only matrix cracks could be observed following the source identification procedure found in [2]. The green spots specify the location of the 8 acoustic sensors.

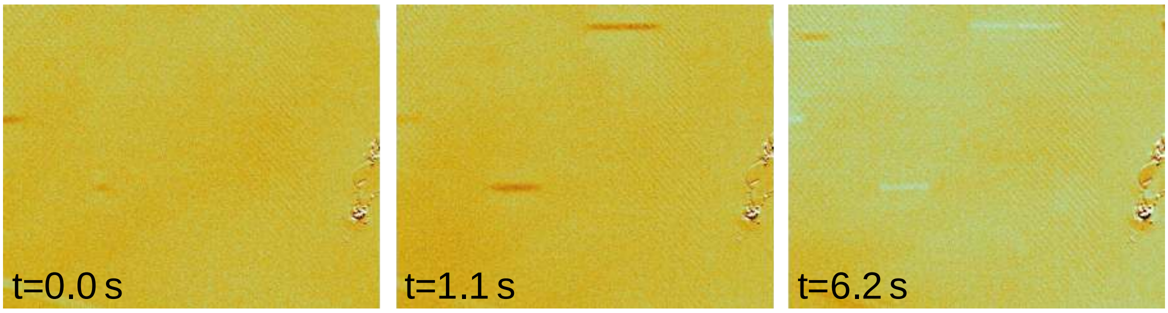

Fig. 7. Thermal signature of an emerging matrix crack (middle of images, lighter colour corresponds to higher temperature): Right after crack opens the release in stress leads to a temperature decrease due to the elastic effect. After a couple of seconds the heat generated from the plastic deformation appears on the surface leading to a temperature increase. The structure on the right originates form the fixtures of one of the acoustic emission sensors.

The results of the TSA confirm the even distribution of stress in the area close to the load nose: The stress is smoothly distributed across the part (not shown). As in the first experiment also here a small number of emerging cracks results in a temperature change. Figure 7 shows some selected images from the recorded sequence: Immediately after a crack forms the temperature decreases due to the elastic effect of the relaxation of the material. The heat released from the crack takes several seconds to reach the surface and finally leads to an overall temperature increase.

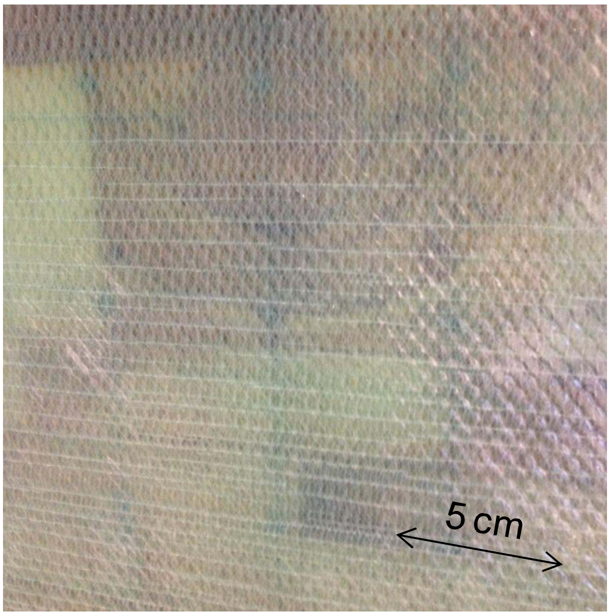

Fig. 8. A photograph of the area subject to tensile stress shows horizontal cracks (parallel to load nose direction) in the matrix confirming the signature of the acoustic emission events.

Looking at the correspondence of acoustically and thermally detected events confirms the results from the initial experiment with tensile testing: While a small number of events can be detected with both methods most events are only recorded with one of the techniques.

Conclusion

The presented results show two examples of possible applications for a combination of acoustic emission and thermography. In both cases the individual methods provided complementary information: Even though some events of cracking were visible as acoustic emission as well as thermal events in most cases the events were only detected with one of the methods which shows that more information can be retrieved from the combination.
As the measurement is done concurrently with both methods no extra time is needed compared to the individual methods. For a routine inspection with automated data analysis also the time for set-up and manual evaluation can be neglected so that the overall cost for the combination is only determined by the cost for investment and initial set-up. As both experiments immediately showed the value of the combination it can be concluded that also other applications could benefit from this approach.

Acknowledgments

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