Investigation of the failure development in CFRP

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Abstract

In the design of components made of fibre-reinforced plastics (FRP) the achievement of a minimum weight for a certain structure is a very common demand. Therefore the exploitation of the existing strength of FRP is of an essential interest to the designer. Because fabrics offer a good processability at reasonable costs most FRP-parts are manufactured by using carbon fibre or glass fibre fabrics. Unfortunately compared to the usual calculations based on unidirectional plies there is a significant shortage in the knowledge about the real failure development and strength of FRP when they are reinforced by fabrics. To improve or adapt the existing failure criteria the failure development in carbon fabric reinforced plastics must be well known. It is our goal to contribute to this task by monitoring the damage evolution with acoustic emission. The achievable results depend among other influences on the available acoustic emission equipment, the recording settings, but as well on the experience of the user. By giving the experience we have made up to now, we want to support those who encounter a similar task, which is to adopt acoustic emission to a new measuring task.

By analysing the recorded acoustic emission, parameters could be identified, which seem to have a direct relation to the damage development. In particular the released energy shows clearly separated stadiums in the fracture development. The verification of the interpretation of the failure development, based on the acoustic emission, is very difficult. Until now it is made by microscopy on polished samples, taken as random samples from the specimens after they were loaded to a certain point. For the future an experimental evaluation of different Non Destructive Testing techniques shall help to improve this situation.

Initial situation

Due to their favourable stiffness- and strength-to-weight ratio carbon fibre reinforced plastics are increasingly used in all engineering sectors, from aerospace structures to civil engineering. With this evolution into sectors where costs are of increasing importance the use of pre-impregnated material is not cost-effective anymore. Resin injection techniques (resin transfer moulding or vacuum assisted resin infusion) are used instead. This leads to slightly reduced mechanical performance but reduces the material and labour costs drastically. In these processes woven carbon fibre fabrics or non-crimp-fabrics are usually employed.

Opposed to this increasing use of textile products, the design engineers can still not be provided with failure criteria which allow them to create a design that efficiently takes advantage of the materials strengths, while remaining conservative. Two main questions have to be answered in order to improve this situation.

- Which types of failure occur in fabric reinforced laminates, and how are they related to the structure of the reinforcing textile?
- Which maximum stresses can be tolerated for fabric-reinforced laminates under static loading, thus can be used as design limits (represented by a failure criterion)?

At the IKV numerous experimental test series have been conducted over the past decade in order to improve and verify Puck's Action Plane Failure Criteria [Puc96; PS98; PS02] for laminates with unidirectional layers. This work significantly contributed to the acceptance of Puck's Failure Theory as the most accurate, powerful and probably the most recommended one for unidirectional laminates that currently exist.

Based on this expertise the development and evolution of failure in fabric-reinforced plies is being investigated in this work. The specimens are made of three different fabrics that differ from each other only in the weave type and are subjected to quasistatic loading. The warp direction corresponds to the x-orientation. Single tensile stress $\sigma_x^{(+)}$, compressive stress $\sigma_x^{(-)}$ or shear stress τ_{xy} are applied as well as the most relevant in-plane stress combinations. The results of these experiments shall allow us in a second step to evaluate whether existing failure criteria can be adopted for the design of fabric-reinforced laminates.

Today, some correlations between the mechanical properties of the laminate and the structure of the reinforcement can already be taken into account. Depending on the type of the binding the rowings are forced into a certain, well-defined undulation. The effect that this fibre undulation has on the stiffness of fabric reinforced plies can be predicted by using either micromechanical FE-Models or different analytical tools as for example TEXCOMP [Ver97]. Both solutions determine the stiffness tensor for one representative volume element (RVE) of the reinforced lamina. Afterwards these stiffnesses can be used to determine the deformation of a part in a structural finite element analysis where shell or volume elements are employed. These elements describe the different lamina by their orthotropic stiffness, as it is the standard today. Unfortunately, these models do only apply as long as the initial, linear elastic stiffnesses are concerned. Nonlinear stress/strain-relations, which are a consequence of the apparition of microscopic cracks and exist as well in unidirectional lamina [Sch89], cannot be determined.

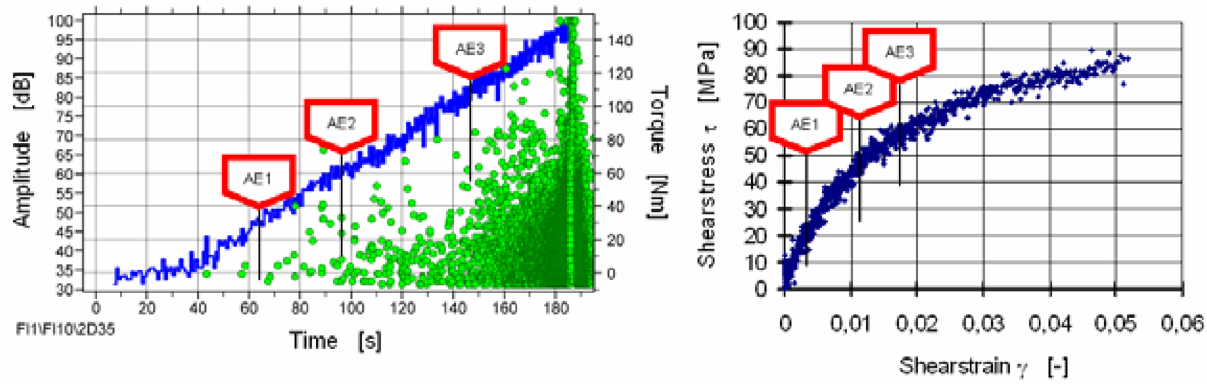

Fig.1: Hits and Shear-Stress/-Strain Diagram of a tested specimen

Unfortunately, fabric reinforced plies do exhibit a quite nonlinear stress/strain-behaviour when loaded in shear τ_{xy}, as can be seen in Fig.1. The shown nonlinear shear-stress/-strain behaviour of a fabric reinforced ply is only one example for the fact, that the maximum stress which is recommendable as a design limit lies well below the ultimate stress. However, it is not yet clear where the limit for the loading has to be set in this case. A physical evidence for an onset of some type of failure should be used for this determination in order to give an unquestionable definition for the allowable maximum stress to the designer. This would probably ensure that the failure limits and the failure theory based on them remain applicable, when the type of reinforcing fabric is changed. To define such a limit load the damage evolution must be determined experimentally first. This task is not easily accomplished, as there is no verified measuring technique to assess the state of damage in a fabric reinforced ply or even determine it online while the mechanical load is being increased.

Use of acoustic emission testing

Today the capabilities to detect and prove microscopic cracks are restricted to microscopy on specially prepared specimens. For very small cracks only the scanning electron microscopy (SEM) is applicable. Unfortunately, this restricts the examinable area to a very small part of the actual specimens, and there is no realistic solution to extend this technique to cover the whole volume of a specimen. In order to obtain the necessary "volume inspection" the use of acoustic emission (AE) is a possible solution. The reasons therefore are the high sensitivity that is offered by AE-sensors and the capability to fit this measuring technique easily into an existing test setup.

With the introduction of AE-testing a large number of uncertainties and secondary problems appear that must be taken into account. In consequence today every user must investigate and adapt the AE-system and -evaluation for every new test and application before it is capable of delivering results that support the original scientific investigation. Other authors have come to similar conclusions [Pro96, Shi85].

Nevertheless acoustic emission is the only measuring technique that seems capable to monitor the evolution of microscopic crack growth online during a test, as it is necessary to investigate the damage evolution. However, AE can definitely not deliver absolute results as many other measuring techniques do. This is because quantitative results that have an absolute value cannot be obtained by AE. The obtainable results always remain qualitative and are restricted to one exact application, test setup and even loading. Nevertheless AE-testing is a very valuable support for the evaluation of failure development, as has been proven by several very successful applications [OKKS92, LML+95].

Specifications of the used system

The AE System used for this work is the AMSY-4 from Vallen Systems [Url02] with one sensor, resonant at 150 kHz, and a usable frequency band from 100-450 kHz (Sensor type: SE150-M). The sensor signal passes by a preamplifier (Type: AEP-4) with a gain of 34 dB. The recording parameters are set to 50 μs duration discrimination time and to 80 μs rearm time. The threshold is usually set to values between 30 dB and 40 dB. The definition for the amplitude A [dB] is: $A = 20*\log(U_s/1\ \mu V)$; U_s being the excitation voltage of the sensor.

The knowledge of these settings as well as the frequency response of the sensor are crucial in order to compare the obtained results with the literature and take advantage from the experience of other authors. Unfortunately, this information is almost never given in completeness.

Calibration and Verification

The development, calibration and verification of an AE-system is a major task. The major problem in verifying results obtained with AE concerning microscopic fracture is to identify a second, trustworthy analysis (Ultrasound, FSTM, X-ray, SEM) that is actually capable to detect and prove the cracks, which caused the acoustic events. As AE leads mostly to qualitative results the proof that the AE is truly related to the investigated phenomenon must be provided for every new application [NN87]. It is especially difficult if several, different phenomena causing AE occur during a test or even concurrently to each other. In this case a discrimination of the different phenomena is very questionable and the proof of a valid relation between the AE and the different types of failure is still mostly impossible until today.

As the recording of entire waveforms has become possible, it is expected that different types of failure can be discriminated by analysing the main frequencies of each signal. This is done by decomposing the signals with Fast Fourier Transform to determine their main frequencies. Indeed the possibility to discriminate between different types of hits has much increased thanks to this evolution [GWJ95, Boh00]. But, if the number of hits is large, the hardware capacities still set considerable limits to the recording of the waveforms and only the waveforms of a small number of hits can be continuously monitored. If nevertheless a frequency analysis is to be used, it is crucial to keep in mind the many influences that change the signal before it is recorded:

- The wave velocities depend on the orientation of the fibres, they are as well a function of the wave type (compression wave, shear wave or flexural wave) and of the frequency.
- The many interfaces in a non-homogenous material cause reflections, the signal undergoes a considerable attenuation on its way to the sensor.
- The sensor reacts on each burst signal with his characteristic step response function. The overall frequency response of the sensor and finally the transmission characteristic of the used amplifier do all affect the signal before it is recorded.

Despite these numerous influences the frequency analysis is a very powerful tool because usually it is less interesting to record the signal in its most original way. Instead it is important to discriminate different signal types. As most influences listed above are more or less constant there is a high probability that signals, which are different at first, will still exhibit clear differences when they are recorded.

The frequency response of the sensor strongly influences the main frequencies of each recorded signal. Therefore a sensor that has a constant sensitivity over the whole frequency band, that is to be analysed later, should be used if the main frequencies of the signals shall be used to discriminate different AE-sources. If this is not respected, and a resonant sensor is used instead, the sensor response function must be detracted from the signal, otherwise the main frequencies will always be those where the sensor has its highest sensitivity. On the other hand resonant sensors are very useful and often used because they have the much higher sensitivity, caused by the fact that they are resonant.

The second important method to discriminate different signals is based on geometrical relations. By using several sensors, one can set up either a location algorithm in order to determine the source of one signal, or one uses the principle of guard sensors. The second method is probably the most effective to assure that the recorded signals do originate only from the area which one wants to monitor and e.g. not from the tabs of a tensile specimen. The idea is to prevent the recording at the sensors in the test area for a short time if one of the sensors being positioned on the border of the test area registers a signal first. The time for which the recording is suspended is determined from the size of the test area and the wave velocity in the part. A limitation to this principle is reached, if the tabs constantly emit AE. Then the time in which the measuring sensors are allowed to record might be completely suppressed.

A similar problem exists if location algorithms are used. In this case the system simply assumes that the signals that are recorded quasi simultaneously at each sensor originate from the same source. If little failure occurs or the failure occurs only at distinct locations this is probably applicable. But if the events are spread over the whole area, as in case of micro failure, and occur almost simultaneously this does not apply. A very successful work in using location is reported by *Prosser* [Pro98]. He found that the correlation between the location of an event and the appearing crack was as close as 3,2 mm. But to achieve this accuracy he picked the signals by hand from all the measured signals! This shows that the possibility of location is given, especially when specific, local defects exist in a material like a leakage in a tank or a notch in a specimen. But if the failure is not constrained to a few very specific locations and the overall events are numerous and occur simultaneously these techniques still do not offer a solution to the user.

Capabilities of AE and own experience

To better understand the possibilities of AE we monitored at first the damage evolution in a tensile sample, which has a thick 90° layer in its middle. Every appearing IFF in this layer can be clearly proven by the stiffness reduction occurring at once when the crack appears, and the cracks are visible, too. The correlation between the cracks and the hits of high amplitude are beyond any doubt. This shows that the appearance of IFF can easily be monitored by AE if the energy released by the crack is quite high (either the stress released is high, or the surface of the crack must be large).

Investigations trying to observe the apparition of IFF in carbon fibre reinforced plastics can be found through out the literature [Pro98; FL90]. Most of the work was focused on tensile specimens with 0° and 90° layers. These are the same orientations as in tensile specimens with fabric reinforcement (0° = x-direction = warp direction). But a careful analysis of the achieved results in the literature shows, that most authors have succeeded in detecting IFF in 90° layers only if they have a thickness of at least two or more plies of Prepreg ($t > 0,3$ mm) and the cracks extend immediately over the whole width of the specimen (≈ 20 mm). A very successful and well-documented work of this type was performed by *Ohsawa et al*. [OKKS92]. Even though they could achieve some promising results, they did not succeed in measuring the apparition of IFF when the layers had just the thickness of 1 ply (0,15 mm). In this case the energy released by the crack is too small to produce events that can be clearly distinguished by their maximum amplitude from the overall, non-reassignable AE.

The cracks in unidirectional laminates are known to extend only until they reach fibres that are oriented in another direction than the crack. They do not extend into adjacent layers. In fabrics, depending on the weave type, the maximum length a crack can reach before reaching a fibre bundle that is oriented perpendicular to it is within a few millimetres. The thickness of the area, in which such a crack can appear is even more restricted, it is that of half the layer thickness ($t < 0,1$ mm). Hence the maximum area that a matrix crack can possibly have is several times smaller than the one in a single unidirectional ply. It seems therefore impossible to distinguish appearing cracks by monitoring the maximum amplitude of the recorded hits.

This leads immediately to the main problem when monitoring failure evolution in fabric reinforced plies. By the nature of the reinforcement the crack surfaces are very small. Thus the cracks cannot be identified by the maximum amplitude of the hits. Because of this rather small size of the cracks a sensor with a high sensitivity was chosen in this work.

Experiments on carbon fabric reinforced plastics

In order to obtain acoustic emission measurements that are comparable to each other for all different kinds of stresses and stress combinations, which are to be investigated, the same type of tubular specimen is used in all experiments (Fig.2).

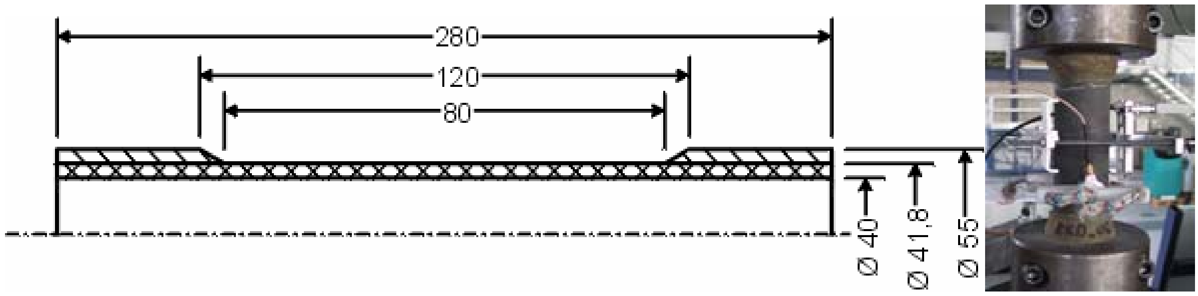

Figure 2: Test setup and tubular specimen

The laminate consists of 4 plies of carbon fabric. The fabric is wound around a mandrel to manufacture the tube. In this paper all given results are for a plain weave carbon fabric, made from HTA 5131 with an aerial weight of 200 g/mm². The Epoxy system used is Araldite LY556/HY917/D070. Both ends of the tubular specimens are reinforced with circumferential plies made from glass fibre reinforced plastic, as these have proven to effectively prevent a failure of the specimens at the grips. The specimens are subjected to a constantly increasing load in order to reach the final failure within two minutes. The strains are measured during the tests by using two global measurement systems, one to determine the average axial strain of the specimen, and one to determine the average shear strain. The use of global measurement systems is required for two reasons: strain gages deliver inaccurate results when the strain state is not homogenous over the area they are connected to; brittle glues, as they are necessary to connect the strain gages to the specimen, must never be used when AE-measurements shall be made. This is because the micro failures within the brittle glue create enormous acoustic emission, and thus prevent a reliable analysis of the gathered AE-Data.

The sensor is connected to the centre of the specimen by a self-made clamping, that allows for reproducible clamping forces. An additional shoe that fits in between the planar surface of the sensor and the curved surface of the specimen has not been used. The performed pencil-break tests have shown that the use of high-density silicone grease is sufficient to achieve a very good coupling.

To determine the onset of critical damage with increasing load the evolution of the AE-Data and the waveforms (TR-Data) gathered from all three types of single loaded tests (pure tension, compression and shear) have been analysed. The parameters that have been evaluated are: hits, counts, maximum amplitude, duration, rise time and energy. Further analyses consisted in: checking the value distribution of the different parameters, observing whether special values of the parameters were connected to certain wave types (TR-Data) and determining the main frequency of the hits by Fast Fourier Transform of the recorded waveforms. From all these analyses no results were found which would allow discriminating different types of failure in the laminate.

But the examination of this information does show several things: The scatter in the values for the hit duration as well as for the rise time is very large. Although most values lie within several µs, as they are expected to do, this proves that no recording settings could be found which would allow capturing all events as single hits. The high number of hits is a possible explanation for this finding. It might even be, that the appearance of different types of failure, occurring at different loads over the time or even simultaneously, prevent that any recording settings fit all types of signals in a test. Thus many events must be suspected to be represented by just one hit. This becomes most obvious when looking at a plot for failure under shear loading, where suddenly the number of hits with high amplitude is that high, that all events of smaller amplitude are gathered within hits of the maximum amplitude (Fig.3 sec.: 611-615).

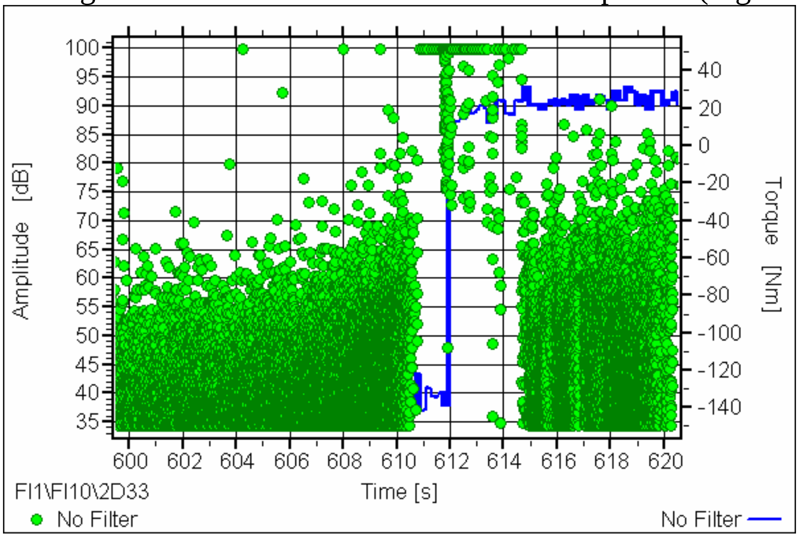

Figure 3: Hits for a final failure under shear stress, between time = 611-615 sec all Hits with small amplitudes "disappear" within a hit of the maximum amplitude.

The results of the AE-measurement, which have proven to be useful in this work, are the change of slope when characteristic data (counts, hits and cumulated energy) are plotted over time. The results of AE-measurements are well reproducible, thus the qualitative results as well as the quantitative results can be evaluated by comparison within a test series where just the load or just the weave type of the fabric has varied. Finally the good resolution of AE over time allows analysing the onset of complex failures in detail up to time differences of only a few µs.

AE of tubular specimens subjected to single loads

If the specimen is loaded by compression only very few hits of medium amplitude appear before the final failure of the specimen begins (Fig.4). During all this time there is no audible noise coming from the specimen. Most of the shown acoustic emission hits could only be recorded because the defined threshold was lowered from 40 dB to 30 dB. We interpret this AE-Data as a proof that there is only little failure occurring in the specimen and that the cracks themselves must be very small.

The damage state of the specimen was examined by normal microscopy and no cracks were found. Hence, it seems that there is no failure one needs to account for in the design of FRP-parts before the final failure of the carbon fabric reinforced plastic occurs under compression stress in the warp direction. This observation correlates well with the theory describing the failure process in unidirectional laminates. In a laminate of 0° and 90° plies one would not expect IFF to occur neither in the 90° nor in the 0° plies prior to the fibre failure in the 0° plies. This is because the transverse compressive-stress/-strain relation is very nonlinear.

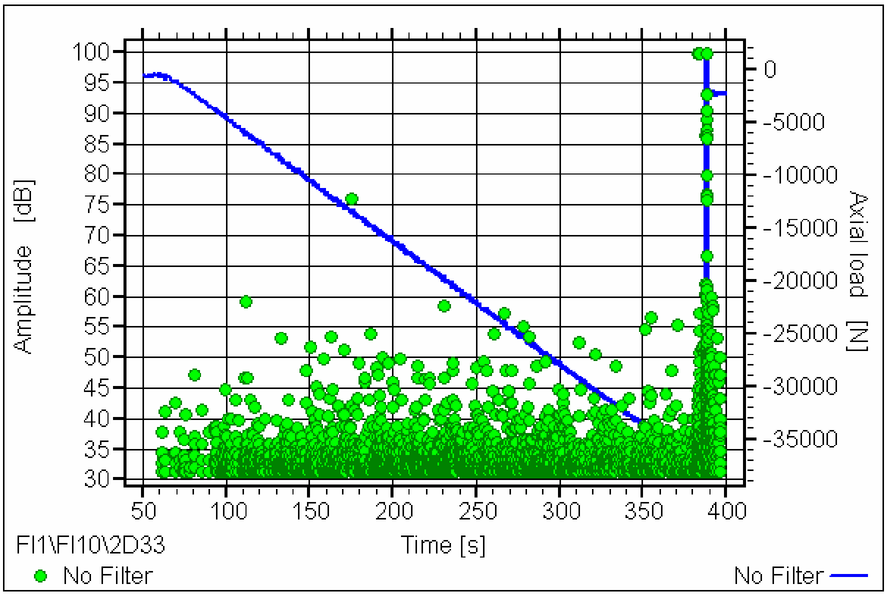

Figure 4: Acoustic emission of a tubular specimen under compressive load

The acoustic emission for shear loading of the same specimen type is shown in Figure 1 together with the corresponding shear-stress/-strain diagram. Up to about 30 % of the maximum load, almost no acoustic emission was detected. The threshold was set to 30 dB, thus it cannot be exclude that some AE exists below this amplitude. The number of hits and their maximum amplitudes increase with increasing load. Still there is a Phase I where the amplitudes do not exceed a critical level. These amplitudes have been proven to lead to no recognizable failure under compressive stress. Up to the maximum load, which is applied at the end of Phase I, no nonlinear material behaviour can be seen in the shear-stress/-strain diagram. Hence no critical damage seems to have occurred until this load. Phase II starts when the maximum amplitude of the hits clearly exceeds 40 dB, which seem not to be critical in this test. The shear-stress/-strain relation for Phase II already shows a clear nonlinear correlation. There is no clear starting point of the AE, nor does the type and amount of emissions change drastically. This behaviour is interpreted as being caused by occurring micro cracks. But a macroscopic failure is not detectable.

The first major offset in the cumulative energy determines the final Phase III. This is usually caused by the first hit that has a large maximum amplitude (A > 80 dB). In Phase III a continuously increasing number of hits occur. For the shear-stress/-strain behaviour Phase III corresponds quite well with the part of the graph where the tangent modulus has dropped almost to its final value.

In unidirectional lamina with 0° and 90° plies at a certain tensile stress macroscopic cracks start to occur. Hence, if this behaviour was similar in fabric-reinforced plies, it should be possible to record and analyse in AE. Unfortunately, no useful results could be obtained for tensile loading of the tubular specimens, because there are several types of background noise that make an evaluation of the AE-Data impossible. This background AE results from cracks that appear in the glass fibre layers of the specimens end tabs and probably there is as well AE resulting from friction caused by grip slippage. This cannot totally be prevented, as the necessary forces to reach the tensile failure are very high because of the 0° fibres in the specimens. Tubular specimens with fewer layers were considered, but even a tube with just one layer would still require forces that exceed those where the problems start to occur.

A change of the specimen’s design for tensile loading is thus necessary in order to obtain results for pure tensile stress. After benchmarking several different grip and tab combinations one combination was found that allows monitoring tensile tests of flat specimens with acoustic emission without any recognisable background noise. In fact, with the standard recording settings, which after all are sensible enough to detect fractures that cannot be detected by microscopy, tensile tests were monitored up to the failure of the specimen without any acoustic emission appearing before the final failure occurs. As there is no acoustic emission until shortly before failure, the absence of background noise is proven. Further this shows, that to detect defects, which occur under tensile stress, a very high sensitivity is necessary. To further verify and assess the failures which still can not be defined absolutely, different non destructive (FSTM) and destructive (SEM) testing techniques will be used in the future to see if they can help to determine existing micro cracks.

Conclusion

The adoption of acoustic emission techniques offers the possibility to investigate the onset of damage very closely, if some important demands can be met. The recording (even better: the appearance) of secondary acoustic emission (background noise, undesired failure mechanisms) must be prevented. For this, the use of guard sensors seems highly recommendable because the location and waveform analysis techniques, as impressive as their results sometimes seem, are not yet ready to use in standardized testing.

For carbon fabric reinforced plastics acoustic emission can help to monitor the evolution of fracture within the plies, and to assess how this evolution changes with increasing load or with different loadings. The major difficulties are to discard secondary AE when there is a lot of inevitable secondary failure occurring, and to find reliable testing methods to verify the assumptions from the AE-analysis, as most testing methods do not have the necessary resolution.

Considering the suspected dependence of the failure evolution from the weave type of the reinforcing fabric no results can be reported yet as the specimens are just being manufactured. Seeing the very good reproducibility of AE measurements we are optimistic, that if changes in the evolution of failure occur caused by different bindings they will be detectable either by increasing amplitudes if the cracks become larger, or by a decreasing number in cumulative hits if the cracks become fewer.

Acknowledgements:

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