# Non-destructive testing — Acoustic emission — Testing of fibre-reinforced polymers — Specific methodology and general evaluation criteria

ICS 19.100

British Standards

# National foreword

This British Standard is the UK implementation of EN 15857:2010.

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English Version

# Non-destructive testing - Acoustic emission - Testing of fibre-reinforced polymers - Specific methodology and general evaluation criteria

Essais non destructifs - Émission acoustique - Essai des polymères renforcés par des fibres - Méthodologie spécifique et critères d'évaluation généraux

Zerstörungsfreie Prüfung - Schallemissionsprüfung - Prüfung von faserverstärkten Polymeren - Spezifische Vorgehensweise und allgemeine Bewertungskriterien

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## Foreword

This document (EN 15857:2010) has been prepared by Technical Committee CEN/TC 138 “Non-destructive testing”, the secretariat of which is held by AFNOR.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by July 2010, and conflicting national standards shall be withdrawn at the latest by July 2010.

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# Introduction

The increasing use of fibre-reinforced polymer materials (FRP) in structural (e.g. aerospace, automotive, civil engineering) and infra structural applications (e.g. gas cylinders, storage tanks, pipelines) requires respective developments in the field of non-destructive testing.

Because of its sensitivity to the typical damage mechanisms in FRP, AE testing is uniquely suited as a test method for this class of materials.

It is already being used for load test monitoring (increasing test safety) and for proof-testing, periodic inspection and periodic or continuous, real-time monitoring (health monitoring) of pressure vessels, storage tanks and other safety-relevant FRP structures.

AE testing shows potential where established non-destructive test methods (e.g. ultrasonic or water-jacket tests) are not applicable (e.g. "thick" carbon-fibre reinforced gas cylinders used for the storage and transport of compressed natural gas (CNG), gaseous hydrogen, etc.).

The general principles outlined in EN 13554 apply (as stated) to all classes of materials but the document in fact emphasises applications to metal components (see Clause 6 "Applications of the acoustic emission method").

However, the properties of FRP relevant to AE testing are distinctly different from those of metals.

FRP structures are inherently inhomogeneous and show a certain degree of anisotropic behaviour, depending on fibre orientation and stacking sequence of plies, respectively.

Material composition and properties, and geometry affect wave propagation, e.g. mode, velocity, dispersion, and attenuation, and hence the AE signals recorded by the sensors.

Composites with a distinct viscoelastic polymer matrix (e.g. thermoplastics) possess a comparatively high acoustic wave attenuation which is dependent on wave propagation parallel or perpendicular to direction of fibre orientation, plate-wave mode, frequency and temperature dependent relaxation behaviour.

Therefore, successful AE testing of FRP materials, components and structures requires a specific methodology (e.g. storage of complete waveforms, specific sensors and sensor arrays, specific threshold settings, suitable loading patterns, improved data analysis, etc.), different from that applied to metals.

Most evaluation criteria for AE tests on FRP components and structures to date are either empirical (derived from comparative tests on a limited number of specimens) or else classified (proprietary, unpublished data banks).

The time and effort to establish qualified evaluation criteria for specific AE test applications may be too costly to make it worthwhile.

Generally applicable evaluation criteria for a class of materials – FRP – will help to pave the way for the development of new applications.

There are recent developments in AE testing, e.g. "modal AE" (wave and wave mode analysis in time and frequency domain) and "pattern recognition analysis".

In particular, feature extraction and pattern recognition techniques seem promising for achieving, among others, improved source location and damage mechanism discrimination in materials that show complex wave propagation behaviour and signals originating from multiple mechanisms acting simultaneously, such as FRP.

## 1 Scope

This European Standard describes the general principles of acoustic emission (AE) testing of materials, components and structures made of FRP with the aim of:

- materials characterisation;
- proof testing/manufacturing quality control;
- retesting/in-service inspection;
- health monitoring.

When AE testing is used to assess the integrity of FRP materials, components or structures or identify critical zones of high damage accumulation or damage growth under load this standard further describes the specific methodology (e.g. suitable instrumentation, typical sensor arrangements, location procedures, etc.).

It also describes available, generally applicable evaluation criteria for AE testing of FRP and outlines procedures for establishing such evaluation criteria in case they are lacking.

NOTE The structural significance of the AE may not in all cases definitely be assessed based on AE evaluation criteria only but may require further inspection and assessment (e.g. with other non-destructive test methods or fracture mechanics calculations).

This standard also recommends formats for the presentation of AE test data that allow the application of qualitative and quantitative evaluation criteria, both on-line during testing and by post test analysis, and that simplify comparison of AE test results obtained from different test sites and organisations.

## 2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 473, *Non-destructive testing — Qualification and certification of NDT personnel — General principles*

EN 1330-1:1998, *Non destructive testing — Terminology — Part 1: List of general terms*

EN 1330-2:1998, *Non-destructive testing — Terminology — Part 2: Terms common to the non-destructive testing methods*

EN 1330-9:2009, *Non-destructive testing — Terminology — Part 9: Terms used in acoustic emission testing*

EN 13477-1, *Non-destructive testing — Acoustic emission — Equipment characterisation — Part 1: Equipment description*

EN 13477-2, *Non-destructive testing — Acoustic emission — Equipment characterisation — Part 2: Verification of operating characteristic*

EN 13554, *Non-destructive testing — Acoustic emission — General principles*

EN 14584, *Non-destructive testing — Acoustic emission — Examination of metallic pressure equipment during proof testing — Planar location of AE sources*

EN 15495, *Non-destructive testing — Acoustic emission — Examination of metallic pressure equipment during proof testing — Zone location of AE sources*

## 3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN 1330-1:1998, EN 1330-2:1998 and EN 1330-9:2009 and the following apply.

**3.1**
**fibre**
slender and greatly elongated solid material

NOTE Typically with an aspect ratio greater than 5 and tensile modulus greater than 20 Gpa. The fibres used for continuous (filamentary) or discontinuous reinforcement are usually glass, carbon or aramide.

**3.2**
**polymer matrix**
surrounding macromolecular substance within which fibres are embedded

NOTE Polymer matrices are usually thermosets (e.g. epoxy, vinylester polyimide or polyester) or high-performance thermoplastics (e.g. poly(amide imide), poly(ether ether ketone) or polyimide). The mechanical properties of polymer matrices are significantly affected by temperature, time, ageing and environment.

**3.3**
**fibre laminate**
two-dimensionally element made up of two or more layers (plies of the same material with identical orientation) from fibre-reinforced polymers

NOTE They are compacted by sealing under heat and/or pressure. Laminates are stacked together by plane (or curved) layers of unidirectional fibres or woven fabric in a polymer matrix. Layers can be of various thicknesses and consist of identical or different fibre and polymer matrix materials. Fibre orientation can vary from layer to layer.

**3.4**
**fibre-reinforced polymer material**
**FRP**
polymer matrix composite with one or more fibre orientations with respect to some reference direction

NOTE Those are usually continuous fibre laminates. Typical as-fabricated geometries of continuous fibres include uniaxial, cross-ply and angle-ply laminates or woven fabrics. FRP are also made from discontinuous fibres such as short-fibre, long-fibre or random mat reinforcement.

**3.5**
**delamination**
intra- or inter-laminar fracture (crack propagation) in composite materials under different modes of loading

NOTE Delamination mostly occurs between the fibre layers by separation of laminate layers with the weakest bonding or the highest stresses under static or repeated cyclic stresses (fatigue), impact, etc. Delamination involves a large number of micro-fractures and secondary effects such as rubbing between fracture surfaces. It develops inside of the composite, without being noticeable on the surface and it is often connected with significant loss of mechanical stiffness and strength.

**3.6**
**micro-fracture (of composites)**
occurrence of local failure mechanisms on a microscopic level, such as matrix failure (crazing, cracking), fibre/matrix interface failure (debonding) or fibre pull-out as well as fibre failure (breakage, buckling)

NOTE It is caused by local overstress of the composite. Accumulation of micro-failures leads to macro-failure and determines ultimate strength and life-time.

# 4 Personnel qualification

It is assumed that acoustic emission testing is performed by qualified and capable personnel. In order to prove this qualification it is recommended to certify the personnel in accordance with EN 473.

# 5 AE sources and acoustic behaviour of FRP

## 5.1 AE source mechanisms

Damage of FRP as a result of micro- and macro-fracture mechanisms produces high acoustic emission activity and intensity making it particularly suitable for Acoustic Emission Testing (AT).

The common failure mechanisms in FRP detected by AT are:

a) matrix cracking;

b) fibre/matrix interface debonding;

c) fibre pull-out;

d) fibre breakage;

e) intra- or inter-laminar crack (delamination/splitting) propagation.

The resulting acoustic emission from FRP depends on many factors, such as material components, laminate lay-up, manufacturing process, defects, applied load, geometry and environmental test conditions (temperature, humidity, exposure to fluid or gaseous media or ultraviolet radiation, etc.). Therefore, interpretation of acoustic emission under given conditions requires understanding of these factors and experience with acoustic emission from the particular material and construction under known stress conditions.

Fracture of FRP produces burst type acoustic emission, high activity, however, may give the appearance of continuous emission.

For certain types of construction widely distributed AE sources from matrix or interfacial micro-failure mechanisms under given conditions commonly represent a "normal" behaviour. This particularly appears during the first loading of a newly manufactured FRP structure, where the composite strain for detection of first significant acoustic emission is in the range of 0,1 % to 0,3 %.

High stiffness optimised composites may shift the onset of first significant acoustic emission towards comparatively high stresses due to the low matrix strain in the composite.

In the case of high strength composites acoustic emission from first fibre breakage, beside of other sources, is normally observed at stress levels of about 40 % to 60 % of the ultimate composite strength.

A "normal" behaviour of FRP structures is also characterised by the occurrence of different regions with alternating higher and lower AE activity particularly at higher stress levels due to redistribution of local stress.

In the case of a serious discontinuity or other severe stress concentration, that influence the failure behaviour of FRP structures, AE activity will concentrate at the affected area, thereby providing a method of detection.

Conversely, discontinuities in areas of the component that remain unstressed as a result of the test and discontinuities that are structurally insignificant will not generate abnormal acoustic emission.

## 5.2 Wave propagation and attenuation characterisation

AE signals from waves travelling in large objects are influenced by dispersion and attenuation effects.

Polymer matrix composites are inhomogeneous and often anisotropic materials, and in many applications designed as thin plates or shells. Wave propagation in thin plates or shells is dominated by plate wave modes (e.g. Lamb waves). The anisotropy is mainly the result of volume and orientation of fibres. This affects wave propagation by introducing directionality into the velocity, attenuation and large dispersion of plate waves.

Propagation of acoustic waves in FRP results in a significant change of amplitude and frequency content with distance. The extent of these effects will depend upon direction of propagation, material properties, thickness and geometry of the test object.

Attenuation characterisation measurement on representative regions of the test objects in accordance with EN 14584 shall be performed.

The shadowing effect of nozzles and ancillary attachments shall be quantified and transmission through the test fluid shall be taken into consideration.

The attenuation shall be measured in various directions and, if known, in particular parallel and perpendicular to the principal directions of fibre orientation. In the case of a partly filled test object the attenuation shall be measured above and below the liquid level.

For FRP laminate structures losses of burst signal peak amplitudes may be in the range of 20 dB to 50 dB after wave propagation of about 500 mm. Attenuation perpendicular to the fibre direction is usually much higher than in the parallel direction.

NOTE The peak amplitude from a Hsu-Nielsen source can vary with specific viscoelastic properties of the FRP material in different regions of a structure.

## 5.3 Test temperature

The mechanical (stiffness, strength) and acoustical (wave velocity, attenuation) behaviour of FRP structures and, hence, their AE activity and AE wave characteristic (waveforms, spectra) strongly changes if the test temperature approaches transition temperature ranges of the matrix, such as the ductile-brittle transition ($\beta$-relaxation of semi-crystalline matrices) or the glass-rubber transition ($\alpha$-relaxation of amorphous matrices).

Therefore the test temperature shall be considered for data evaluation and interpretation of AE test results as well as in the loading procedure.

## 5.4 Source location procedures

Accurate source location in FRP structures is difficult. Due to the high attenuation in composite materials the AE hits only the nearest sensor in most practical monitoring situations on structures. For this reason, zone location is usually the main source of location information. The use of zone location however does not prevent linear or planar location of AE sources that has sufficient energy to hit several sensors to allow location by time arrival differences. Linear or planar location is a useful supplement, predominantly for the location of higher energy emissions. Great care shall be taken with both methods where timing information is used for location since the velocity of sound and attenuation will usually change with the direction of propagation in FRP.

An additional caution when using location methods on FRP shall be taken because of the very high emission rates (hit overlapping).

Bearing in mind the above sensor separation and positioning should be set appropriately taking into account:

a) Sensor frequency range

Lower frequencies give a greater detection range but may result in the pickup of unwanted noise sources. Practical FRP testing typically uses "high frequency" sensors (100 kHz to 300 kHz) to provide "local area" monitoring of high stress areas, and "low-frequency" sensors (30 kHz to 60 kHz) to provide "global" coverage. It is common to use two frequency ranges simultaneously.

Typical detection ranges on FRP plates are as follows: 150 kHz for 400 mm to 700 mm and 60 kHz for 600 mm to 1 200 mm and 30 kHz for 900 mm to 2 000 mm or greater depending on the material.

For research into AE source mechanisms use of wideband sensors may be preferable.

b) Directionality of propagation and attenuation

More sensors may be required in one direction as a result of higher attenuation. Application of location techniques that meet direction dependent wave velocities will achieve better location accuracy. Where the system software cannot handle directional velocities the use of "virtual" sensor positioning may improve location performance. Checking source location with Hsu-Nielsen or other simulated acoustic emission sources is recommended to achieve useful results.

c) Location performance

Where planar location of lower energy emissions is a requirement, many more sensors are necessary to obtain the required three hits.

Planar location is especially useful on small specimens or in the case where a local area of a structure is of particular interest.

## 5.5 Analysis of AE from FRP

The following types of analysis are applicable:

a) Hit, energy, and RMS based processing

For most "testing" applications, where the component under test should not be close to failure, the signal processing of acoustic emission from FRP does not differ significantly from that required for metals. The main differences are that high frequency signals are significantly shorter due to the absence of reverberation. Once damage initiates the rate of emission will be significantly higher than for metals. These factors require the monitoring system to be set so as to process appropriately, by using shorter discrimination times for example. It is possible that very significant damage may appear as a continuous signal on "hit based" analysis, for this reason supplementary processing should always be used, using for example the RMS or ASL levels, or the "absolute energy" measured as a continuous parameter.

b) Modal AE; waveform analysis; wavelets; frequency spectra

Analysis of the AE waveforms may provide useful information on the source mechanism and the propagation path, however this is a specialist task requiring experience with the materials under study and is not considered "routine" practice. Waveform analysis is usually done post test and requires the ability to store time signals, either depending on the AE activity or by a continuous streaming.

c) Real-time analysis

Real-time analysis of the detected acoustic emission and the application of defined criteria is normal practice, and essential whenever the monitoring is required to feedback for the safe progressive application of load. Real-time graphs shall provide all AE and other parameters that are necessary to make a decision about the need to stop the test, if necessary.

d) Post test analysis

Post test analysis is applied to obtain a greater insight into the acquired data, to filter known noise sources, and in production applications where real-time analysis may not have been used.

# 6 Instrumentation and monitoring guidelines

## 6.1 General

Instrumentation components (hard and software) shall conform to the requirements of EN 13477-1 and EN 13477-2.

The equipment shall be able to fulfil the data acquisition and analysis according to the written test instruction in real-time.

## 6.2 Sensors

The selection of AE sensor frequency depends on aim of AT and the factors described in 5.4.

For investigation of damage mechanisms and wave propagation wideband sensors may be more appropriate, however this also introduces the additional variable of plate waves travelling at different velocities as a function of frequency. Care should be taken when selecting wideband sensors that their characteristics are appropriate for the laminate thickness, and that their potentially lower sensitivity is taken into account.

## 6.3 Sensor location and spacing

The sensor location when not defined by an applicable code will generally be determined as follows:

a) 150 kHz sensors monitoring the high stress areas of the structure;

b) where the 150 kHz sensors do not provide the full coverage 30 kHz to 60 kHz sensors are used to monitor the remaining test areas, bearing in mind that these may be susceptible to extraneous noise;

c) distance between sensors is determined based on attenuation measurement in different directions and shall follow the guidelines for maximum allowed sensor distance "$d_{max}$" for planar location (EN 14584) or zone location (EN 15495).

The evaluation threshold is defined in 6.5.

NOTE It has to be taken into account that based on the occurrence of micro-fractures in FRP during the loading the attenuation in the material increases.

## 6.4 Sensor coupling and mounting

For good transfer of acoustic waves sensors shall be coupled using agents that do not chemically or physically react with the composite (e.g. by causing crazing, swelling, cracking or other micro-failure mechanisms). Suitable coupling agents are silicone-based high-vacuum grease or adhesives, e.g. cold hardening silicone rubber.

Composite structures shall not be machined to produce a flat and smooth surface at areas where sensors are attached. Hence, higher attenuation (e.g. factor 2) as a result of the thicker coupling film used to smooth out surface roughness or curvature must be accepted.

The choice of the coupling agent depends on test conditions (temperature, humidity, maximum surface deformation, surface roughness, etc.) as well as on necessary stability for long-term testing. It shall not produce acoustic emission itself at all possible test temperatures and maximum deformation states.

Application of adhesive tapes, fixed rings with springs, elastic rubber bands, etc. shall guarantee a stable mechanical mounting of sensors and shall prevent noise signals resulting from sensor movement at the surface of structure or by the fixtures under loading.

Prior to the test, the correct functioning of equipment operation shall be verified in accordance with EN 14584 using a Hsu-Nielsen source or automatically sensor test (AST) by electronic pulses. The average peak amplitude of a Hsu-Nielsen source should be prior to the test within ± 6 dB of the average of all sensors. Any deviation beyond ± 6 dB shall be investigated and corrected, if possible. The corresponding values shall be noted at the end of the test in consideration of possible damage induced increase in attenuation during the loading.

## 6.5 Detection and evaluation threshold

The detection threshold is set X dB above the peak background noise; this shall be less than the evaluation threshold.

The detection threshold shall be set to avoid excessive data from "normal" behaviour of certain laminate types.

High rates of micro-failure lead to a high AE activity in practice during the first loading of new (unstressed) structures. The definition of AE hits (and calculation of hit rates) from burst signals does not work under such conditions of an apparently continuous acoustic emission as a consequence of high AE activity and low detection threshold.

For this case appropriate actions should be scheduled. For example, waveform streaming, increasing threshold (makes determination of arrival times more inaccurate and decline location performance!) or using higher threshold channels in parallel or analysis of continuous signal parameters.

Extraneous noise caused by the loading process, e.g. pump noise or leakage from servo-hydraulic test machine or pressure equipment, rubbing between grips and test specimen etc. shall be suppressed prior to the test. If this is not possible, correctly identified noise signals may be removed from data during post analysis using data filter or location procedures.

## 6.6 Application of load

The application of load depends on the aim of the test, the test object, the pressurisation fluid when applicable and operation safety requirements.

The loading profile shall define the maximum test load, loading rate, level and duration of load holds and if necessary unloading/reloading steps to determine the Felicity ratio.

In cases where the test load is not sufficiently higher than the previous maximum in-service load, a longer period off-load prior to the test may be required.

The application of load shall specify the load level for starting the AE data acquisition.

Loading rate shall consider the inherent high AE activity of FRP and potential for hit overlapping leading to continuous emission.

The loading rate and times for hold periods shall be adapted for each application. Care shall be taken with very low strain rates and very long hold periods which can lead to creep (relaxation) effects.

## 6.7 Graphs for real-time monitoring

Real-time monitoring should comprise the following steps:

a) evaluating AE activity, e.g. the rate or cumulative number of selected AE hits or located events and noting their correlation with time or applied load;

b) evaluating AE intensity, e.g. the burst signal peak amplitude, burst signal energy, continuous signal parameters and their behaviour with load; and

c) AE source location.

Graphs for real-time observation and analysis of the AE behaviour depend on the type of application.

During real-time monitoring the number of graphs shall be minimised. Particularly location plots need much computing time and resource. To ensure a fast data acquisition and analysis only graphs essential to recognise the stop criteria should be activated.

Types of real-time monitoring graphs which can be chosen are:

d) External parameter vs. Time;

e) AE burst signal parameters vs. time or external parameter for each channel:

   1) hit rate;

   2) burst signal peak amplitude;

   3) burst signal energy;

   4) cumulative hits;

   5) cumulative burst energy;

f) Event location based AE parameter:

   1) location graph (zone, linear or planar location);

   2) located events (first hit) or energy analysis of AE events or clusters;

   3) cumulative first hits vs. channels;

   4) cumulative located events vs. time or external parameter for each channel;

g) Time based AE parameter (RMS, ASL or time driven cumulative AE energy); monitoring of time driven AE parameter can prevent a loss of information if the AE activity is too high and/or the measuring system cannot separate hits;

h) Waveform and spectral power of AE signals.

Examples of typical graphs containing test results are given in Annex A.

# 7 Specific methodology

## 7.1 General

There are differences and specific problems with testing of small specimens or large components and structures.

Account shall be taken of the dispersion and attenuation effects in FRP as described in 5.2.

## 7.2 Testing of specimens

FRP specimens are tested for materials characterisation and design optimisation of critical structural parts of composites.

The aim of AE monitoring is detection and characterisation of initial failure by inter-fibre fracture mode (fibre/matrix debonding and matrix cracking) and stages of ultimate macro-failure by fibre fracture and/or unstable delamination.

The advantages of AE testing of specimens from FRP structures are low wave attenuation due to short distances between AE sources and sensor and associated higher accuracy of AE event location.

A problem of specimens is that wave reflections from the side edges superimpose waves that directly propagate to the sensors and, hence, influence the AE signal.

Because of approximately one-dimensional wave propagation a linear location set-up is sufficient to locate AE events in longitudinal direction of the specimen.

By attachment of at least two sensors to the specimen (one to each clamp or support) and performing linear location, AE background noise (hydraulic, friction or electrical) can be removed by filtering.

Examples of AE data from testing of specimens are given in Annex A.

## 7.3 Testing of components and structures

### 7.3.1 Preliminary information

Prior to the test, the AE Test Organisation shall collect following information:

a) explicit statement of the purpose of the test and limitations, if any;

b) type and dimensions of test object;

c) material (composition and mechanical properties);

d) design load, in-service temperature;

e) conditions of use or operation;

f) history of the object (maximum in-service load, temperature, etc.), if available;

g) particular zones to be monitored (damage zones or zones with high stress level)

h) test conditions (type and sequence of loading);

i) environmental conditions at the test site and safety regulations to be observed;

j) potential sources of interference noise (mechanical, electrical, process noise, etc.);

k) if applicable, the results of previous examinations;

l) type, size and position of identified defects, if available.

Interpretation of results shall usually require reference to a relevant experimental data base. For uncommon structural materials, of which the AE response characteristics are unknown, a qualitative analysis shall be made under controlled test conditions using test specimens of the same material, fabricated in the same way and simulating, as near as possible, the original causes of the discontinuity and service stress conditions.

### 7.3.2 Test preparation

All safety requirements concerning the test location and test personal shall be met. Precautions shall be taken to provide protection against the consequences of unexpected catastrophic failure of the structure or the release of safety installations, structural parts or potentially hazardous fluids.

Usually for pressure vessels hydraulic tests are recommended. Special safety requirements shall be taken when pneumatic testing is required, e.g. if normal service loads include either a superposed gas pressure or gas pressure only.

Due to the Felicity effect, when the test load is not sufficiently higher than the previous maximum in-service load, the operating conditions for structures that have been stressed previously shall be reduced prior to AE testing. The time for conditioning at reduced load (generally between 12 h for 90 % or more and seven days for 40 % reduction of operating load) should ensure a sufficient stress relaxation and a clear determination of the Felicity ratio.

### 7.3.3 Load profiles

Loading procedure depends on application and aim of AE test. The loading shall be performed with a minimum extraneous noise. Hold periods during loading are a key aspect for evaluation of AE results.

An initial period at starting load is monitored to check the increase of the background noise based on the loading procedure.

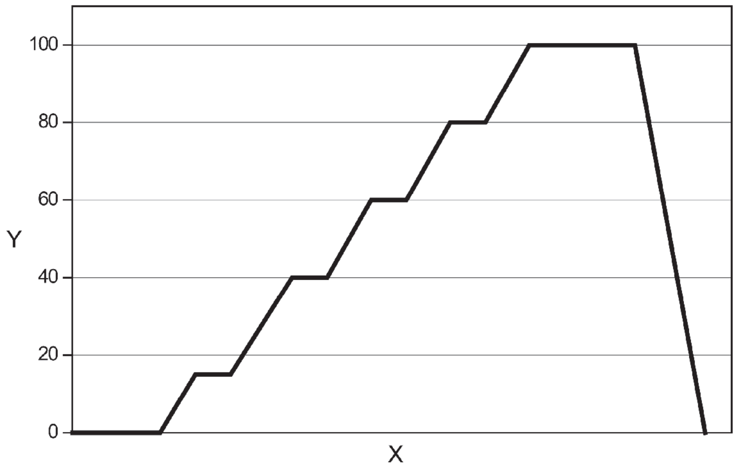
The strain rate and times for hold periods shall be adapted for each application. Care must be taken with very low strain rates and very long hold periods which can lead to creep effects.

A typical load hold time for composites is about 4 min to 10 min.

For determination of the Felicity ratio at specific load levels unload-rest-reload steps shall be designed.

The existence of damages is also indicated by friction-based AE sources during unloading.

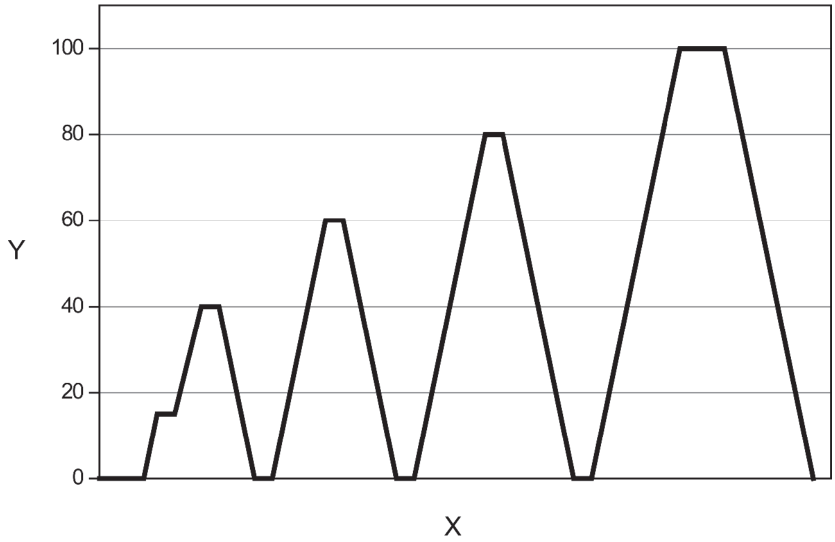
Common loading profile examples are given in Figures 1 and 2.




**Key**

X time
Y percent of test load

**Figure 1 — Load schedule with steps**



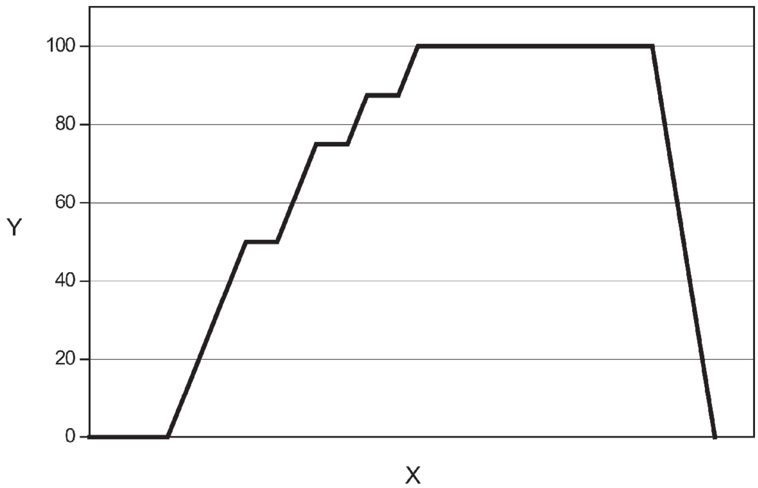

**Key**

X time
Y percent of test load

**Figure 2 — Load schedule with a loading-holding-unloading**

As examples, load schedules for fibre reinforced tanks, vacuum and pressure vessels are given in Figures 3 to 5.

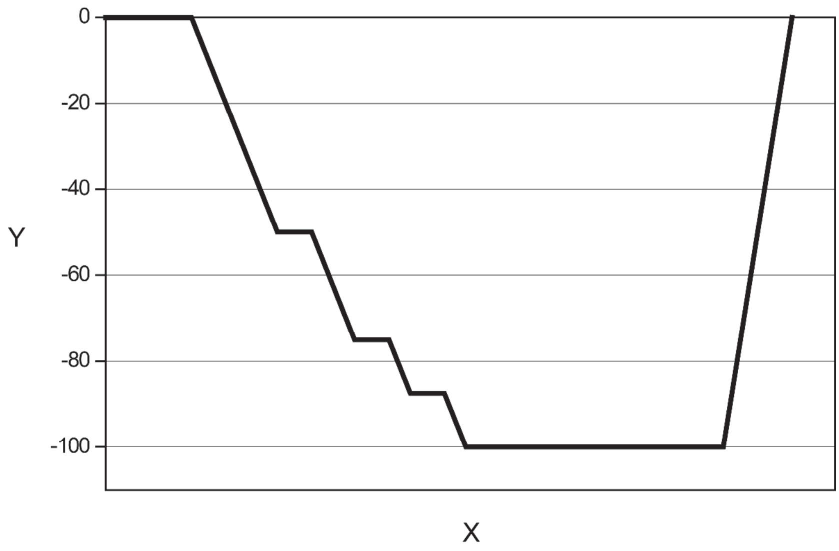
EXAMPLES Fibre reinforced tanks and vessels shall be pressurised with a maximum strain rate of 0,005 % of principal strains per minute. Intermediate load holds at specific load levels shall be 4 min and the final load hold shall be 30 min.




**Key**

X time
Y percent of test load

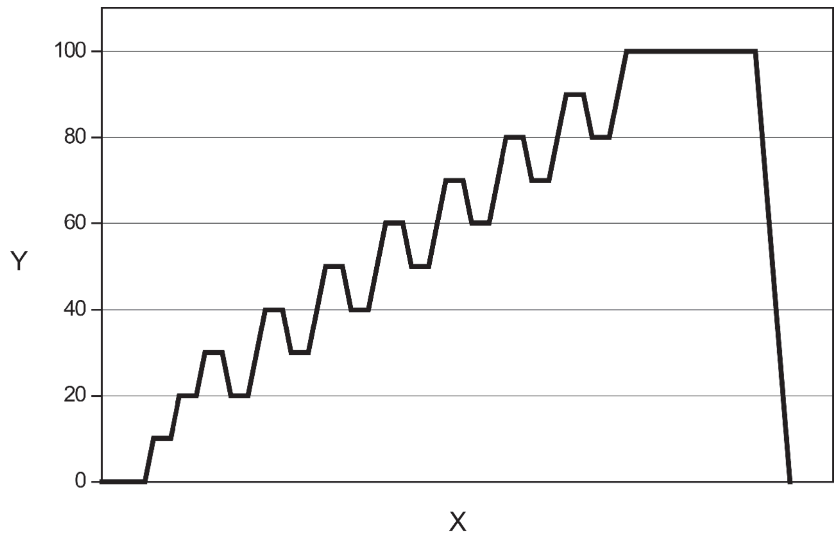
**Figure 3 — Load schedule for tanks**




**Key**

X time
Y percent of test load

**Figure 4 — Load schedule for vacuum vessels**




**Key**

X time
Y percent of test load

**Figure 5 — Load schedule for pressure vessels**

### 7.3.4 Written test instruction

The AE Test Organisation shall provide a written test instruction, which shall include appropriate parts of preliminary information and the following:

a) sensor type, frequency and manufacturer;

b) method of sensor attachment;

c) type of acoustic couplant used;

d) type of AE equipment used with the main characteristics;

e) energy measurement method to be used;

f) sensor location maps representing the structure or part of it;

g) description of equipment verification procedure;

h) description of the in-situ verification (see EN 14584);

i) type and sequence of loading, temperature range of composite;

j) waveform acquisition and analysis, if necessary;

k) recorded data and recording method;

l) available on-line presentation of data;

m) real time stop and evaluation criteria;

n) post analysis procedure with adopted filtering technique if used;

o) final report requirements;

p) qualification/certification of the personnel.

The written test instruction shall be prepared in accordance with EN 473.

### 7.3.5 Evaluation criteria

AE monitoring for structural applications frequently concentrates on assessing structural integrity using activity, intensity, Felicity ratio and/or location of AE events criteria (see Table 1).

**Table 1 — Evaluation criteria for AT of FRP**

| Evaluation criteria | AE features & information |
|---|---|
| a) Detection of significant AE | Continuous increase of both the hit rate and hit energy from onset or continuation of damage processes.<br>At low stress levels it normally indicates inter-fibre micro-failure, such as matrix cracking, fibre/matrix debonding, etc.<br>During determination of Felicity ratios from severe damage states also fibre breakage and delamination growth can be associated to AE events. |
| b) AE activity and intensity | AE activity and intensity specified by number of hits, ring down counts or signal energy as rate or cumulative function that show, e.g.:<br>– an exponential increase which can be described by a factor $\alpha$ depending on the composite, temperature and strain-rate [Brunner *et al.* (1995)]:<br>$AE_{\text{cumulative}} = k \times e^{\alpha \times \text{t}}$<br>$AE_{\text{rate}} = k \times \alpha \times e^{\alpha \times \text{t}}$<br>– an increase with a "knee" in the curve which is related to progressive damage due to inter-fibre failure and/or occurrence of new failure mechanisms, e.g. fibre breakage;<br>– values equal to or beyond statistically firmed mean values and standard deviations for "normal" AE behaviour;<br>– an increase during unloading indicating rubbing of damaged areas against each other, e.g. delaminated surfaces. |
| c) AE during load hold | Constant or increasing rate of AE activity or AE intensity parameter during hold periods<br>– indicates extensive damage and achievement of unstable damage stages;<br>– is often associated with matrix cracking. |
| d) Burst signal peak amplitude or energy | Cumulative distribution of burst signal peak amplitude or energy that:<br>– can be characterised for the amplitude distribution by its *b-value* [Pollock (1981)] in the relationship<br>$\log N = a - b \times A(dB_{\text{AE}})$<br>calculated from the slopes of the lines through the data<br>– is related to number and types of failure mechanisms;<br>– indicates the occurrence of new failure mechanisms such as breakage of fibre bundles or unstable delamination and/or critical damage stages if high amplitude or energy hits are recorded.<br>NOTE 1 If all peak amplitudes are attenuated equally, the measured slope or *b-value* of the amplitude distribution will be independent of the source-sensor distance. This is not the case for FRP structures that show a distinct anisotropic attenuation characteristic.<br>NOTE 2 Zone location of AE events from FRP does not allow a distance correction of burst signal peak amplitudes and, hence, an evaluation based on specific peak amplitude values at source location. |

(*continued*)

**Table 1** *(concluded)*

| Evaluation criteria | AE features & information |
|---|---|
| e) Felicity ratio – FR<br>$$FR = \frac{L^{\mathrm{AE}}_{\mathrm{reload}}}{L_{\max}}$$ | The Felicity ratio [Fowler (1977); Downs, Hamstad (1986, 1992, 1995, 1998); Summerscales (1986); Whittaker *et al.* (1990)]<br>– describes the ratio between the applied load at which significant AE reappears during the next application of loading ($L^{AE}_{\mathrm{reload}}$) and the previous maximum applied load ($L_{\max}$) provides a measure of the severity of previously induced damage; the lower the value the greater the severity;<br>– gives ultimate failure warning.<br>NOTE 1 FR analysis should be based upon a combination of cumulative sums of number and energy from first hits of events or most active regions determined by zone, linear or planar location mode.<br>NOTE 2 FR values are affected by several variables, e.g. temperature, loading and unloading rates, applied load relative to the ultimate strength (stress ratio), time for load holds, time delay (period for stress relaxation of the polymer matrix) between test cycles from which the values are obtained, FRP relaxation and friction properties, etc.<br>NOTE 3 Due to the different wave propagation behaviour for pneumatic pressurisation compared to hydraulic (alternative wave propagation within the liquid) the FR values obtained from hydraulic tests can be lower, overestimating the severity. |
| f) Historic Index – H(t)<br>$$H(t) = \frac{N}{N-K} \frac{\sum_{i=K+1}^{i=N} S_{0\mathrm{i}}}{\sum_{i=1}^{i=N} S_{0\mathrm{i}}}$$<br>where<br>$H(t)$ is the historic index at time *t*;<br>$N$ is the number of hits (ordered by time) up to and including time *t*;<br>$S_{0i}$ is the signal strength of the i^th hit;<br>$K$ is an empirically derived factor that varies with the number of hits. | The historic index [Fowler *et al.* (1992, 1995)] is<br>– a form of trend analysis that requires a large amount of data;<br>– a sensitive method of detecting a change in slope in the cumulative burst signal energy versus time curve characterised by the "knee" in the curve;<br>– valuable for determining the onset of new damage mechanisms;<br>– essential independent of test object size. |
| g) Severity – $S_{\mathrm{r}}$<br>$$S_{\mathrm{r}} = \frac{1}{J}\sum_{m=1}^{m=J} S_{\mathrm{om}}$$ (change into) $S_{0m}$<br>where<br>$S_{0m}$ is the signal strength of the m^th hit;<br>$J$ is an empirical derived constant that depends on the material of structure. | The severity value [Fowler *et al.* (1992, 1995)] is:<br>– the average of a specified number (*J*) of the largest burst signal strength values;<br>– a measure of structural damage.<br>An increase in severity will often correspond to new structural damage of the type detected by a Felicity ratio measurement. |
| h) Intensity diagram | The intensity diagram of log severity vs. log historic index for each channel showing different intensity zones corresponding to different degrees of damage. |
| i) AE location clusters | Criteria based on AE location cluster data.<br>High AE activity and/or intensity within a certain area indicate damage.<br>The preferred location procedure for FRP structures is zone location.<br>Analysis of the AE intensity from zone location provides information for the assessment of damage severity.<br>If applicable linear or planar location allows correction of AE signal amplitudes for attenuation between source and sensor position and the determination of size, shape and growth direction of AE areas caused by, e.g., weak areas of the structure, delamination propagation, impact damage, flaws, etc. |

### 7.3.6 Stop criteria

Stop criteria to prevent unexpected structural failure can be:

a) progressive increase of the rate of AE activity or AE intensity as a function of loading;

b) constant or increasing rate of AE activity or AE intensity parameter during hold periods;

c) Felicity ratio lower than a critical value FRC specific for the structure material.

Stop criteria shall be channel based, zone location and if possible cluster (linear or planar location) based.

If one of the stop criteria is exceeded, the loading shall be stopped and the test object shall be unloaded to a safe load level immediately.

Before the loading is continued, areas with high AE activity and AE intensity shall be investigated and appropriate NDT measurements made.

The method for calculating AE activity, AE intensity and $FR_C$ and the stop criteria shall be defined within the written test instruction by the test organisation.

The stop criteria values for specific types of loading, temperature ranges of the composite and test objects/structures will differ.

### 7.4 Health monitoring

Periodic or continuous health monitoring is applicable for detection of fatigue and environmental degradation mechanisms, sudden impact damage, etc.

The methodology and evaluation criteria are based on the above, but require correlation with process and environmental parameters for damage assessment.

## 8 Interpretation of AE results / source mechanisms

AE source identification and the separation of different damage mechanisms from extraneous noise sources is an important objective of the interpretation of AE results.

The following tools are used for AE analysis:

a) Correlation plots of waveform features [CARP Recommended Practice (1999)]

   1) Correlation of Log Burst Signal Duration (or Counts) vs. Burst Signal Peak Amplitude. Stable delamination growth in small specimens involving micro-fracture events will produce medium or high amplitude and short duration bursts. Signals from effects such as unstable splicing or major delamination produce high amplitude and long duration bursts. Low amplitude, long duration bursts may indicate sliding or rubbing. Other sources such as leaks, electromagnetic interference (EMI) and radio frequency interference (RFI) are characterised by extremely short duration burst signals.

      NOTE A characteristic of EMI and RFI is also an instantaneous arrival time for all channels.

   2) Cumulative distribution of burst signal peak amplitude: Different slopes of the peak amplitude distribution may indicate different mechanisms. The "b"-values characterise the slopes of the lines which can be drawn in specific intervals.

b) Post-test Filters

Post-test filters, e.g. for Time, Channel, Amplitude or Energy Filtering are used to remove extraneous noise data such as wind noise, mechanical sliding, impact, leak and noise from operating valves.

c) Advanced analysis methods (see Annex A)

## 9 Documentation

The documentation should include the following:

a) identification of the site and the customer;

b) identification of the component under examination;

c) reference to relevant procedural documents including the aims and objectives of the test;

d) description of the measurement test equipment, in particular the sensor frequency and sensitivity;

e) site operational conditions;

f) results of on-site verification of sensor sensitivity;

g) loading sequence;

h) type of analysis carried out;

i) examination results;

j) interpretation of results including, where appropriate, the location and relative severity of all AE sources on drawings of the component under test;

k) name, qualifications and signature of inspector;

l) place, date and time of the examination;

m) any deviation from the procedure.

The final report should be in accordance with EN ISO/IEC 17025:2005 (Section reporting).

# Annex A
(informative)

# Recommended standard formats for presentation of AE data (examples)

## A.1 AE testing of specimens

### A.1.1 Example 1: AE data from static tensile testing of UD Carbon-fibre/Epoxy composite

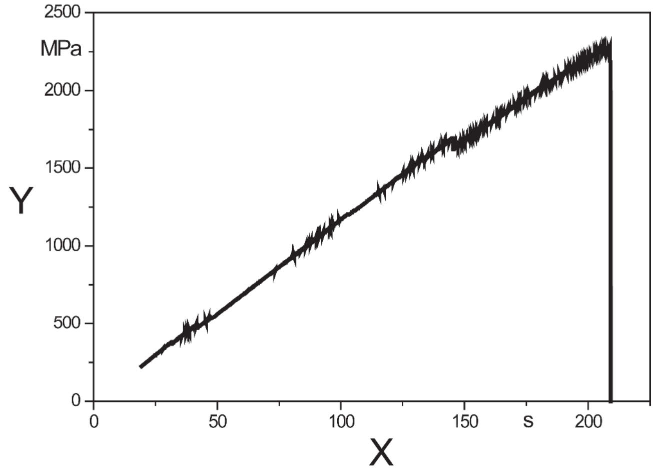
This example shows the AE behaviour of CFRP during static tensile on a unidirectional (UD) CFRP specimen up to macroscopic failure monitored with three AE sensors (each mounted 50 mm apart within the gauge length) in a linear location setup along the specimen. Sensor positions are indicated by "+" in the location graph.

Only AE features of located events are shown in the graphs. AE data were post-test filtered and features of signals with peak amplitudes A ≥ 60 $dB_{AE}$ are shown only.

Load increase is essentially linear, except for two load drops after about 40 s and 145 s. The comparison of the cumulative and rate curves of the AE activity indicates exponential behaviour, except around 40 s and 70 s.

More AE events are located closer to the clamps due to stress concentration.

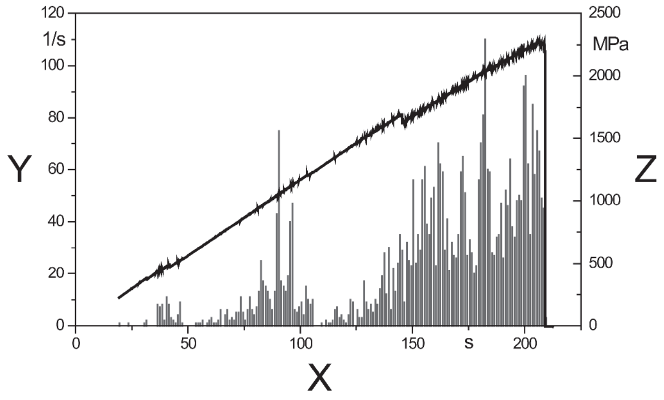
AE sources from first damage were caused by inter-fibre matrix cracks. Ultimate rupture was initiated by fast interlaminar crack growth (splicing due to fibre-matrix debonding) and breakage of fibre bundles.




**Key**

X time
Y stress

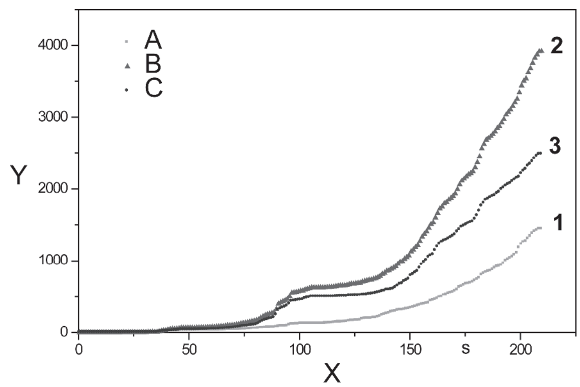
**Figure A.1 — Loading scheme**




**Key**

X time
Y event rate (channel 2)
Z stress

**a)**

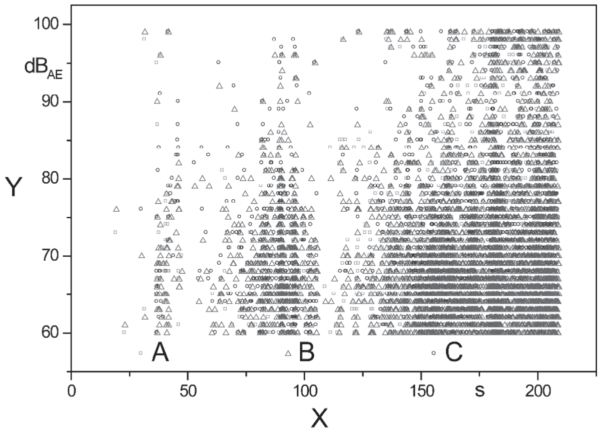



**Key**

X time
Y cumulative events
A channel 1
B channel 2
C channel 3

**b)**

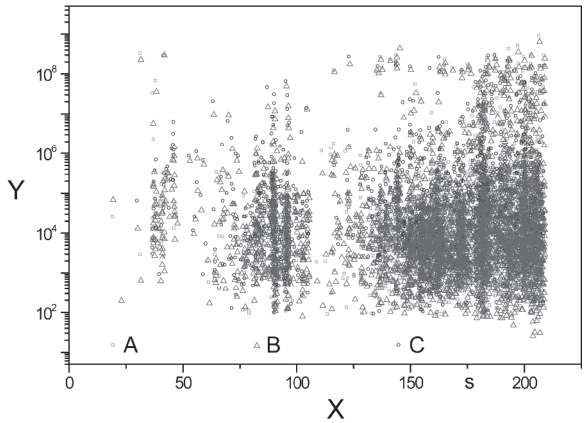
**Figure A.2 — Channel based AE activity graphs**




**Key**

X time
Y peak amplitude
A channel 1
B channel 2
C channel 3

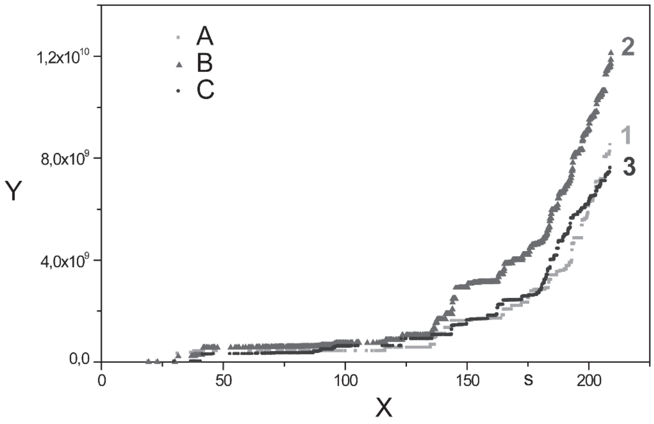
**a)**




**Key**

X time
Y AE signal energy
A channel 1
B channel 2
C channel 3

**b)**

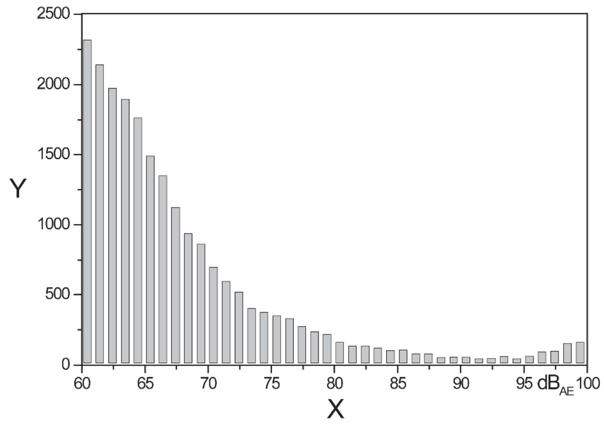



**Key**

X time
Y cumulative AE signal energy
A channel 1
B channel 2
C channel 3

**c)**

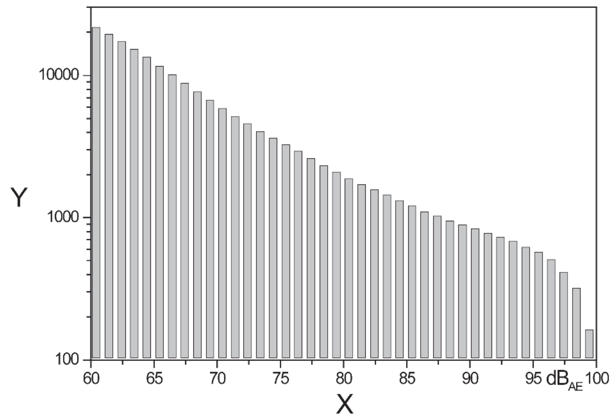
**Figure A.3 — Channel based AE intensity graphs**




**Key**

X peak amplitude
Y events

**a) differential distribution**

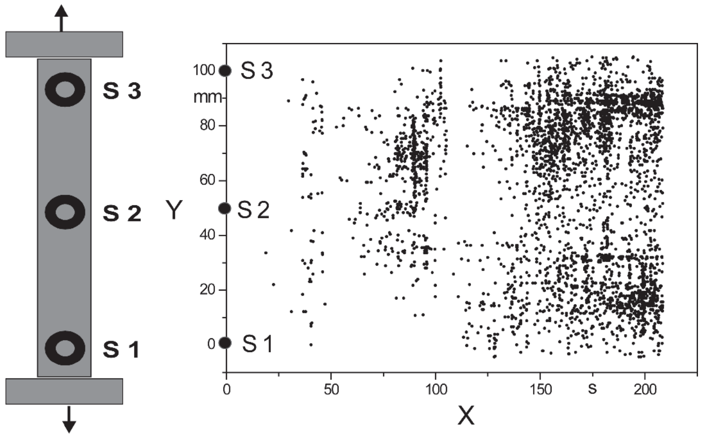



**Key**

X peak amplitude
Y cumulative events

**b) cumulative distribution**

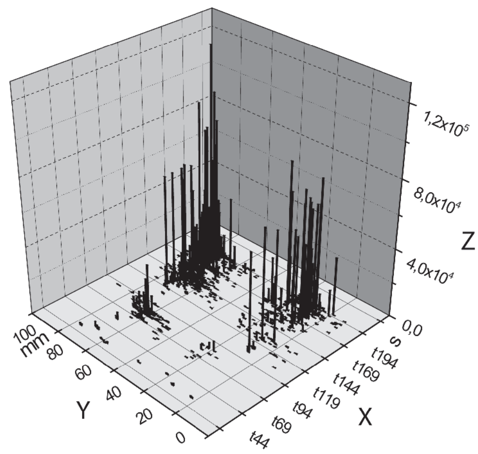
**Figure A.4 — Differential or cumulative distribution of burst signal peak amplitude**




**Key**

X time
Y X-position
S1 sensor 1
S2 sensor 2
S3 sensor 3

**a)**




**Key**

X time
Y X-position
Z AE signal energy

**b)**

**Figure A.5 — Location graph (three-channel linear location mode)**

## A.1.2 Example 2: AE data from mode I DCB delamination test of UD Glass-fibre/Epoxy composite

Fracture mechanics tests on beam-shaped FRP specimens with initial delamination crack characterize the delamination resistance of composites under different modes (tensile, shear, twist or mixed-modes) of crack opening.

By means of AE features from delamination processes different crack stages can be separated:

a) stable delamination initiation and propagation in composite materials; and

b) unstable growth of delamination. Information about the delamination rate can be derived from localised AE sources around the crack tip.

AE behaviour and stresses for inter-fibre fracture or delamination strongly depends on fibre/matrix adhesion, matrix strength, fibre orientation and volume of fibres.

As long as delamination propagation is dominated by inter-fibre failure mechanisms such as matrix cracking and fibre-matrix debonding a stable delamination propagation exist and mechanical and acoustic emission energy release are correlated.

This example shows results from an interlaminar fracture under tensile opening mode I load using the double cantilever beam (DCB) delamination test of unidirectional GF/PA-12 combined with AE monitoring.

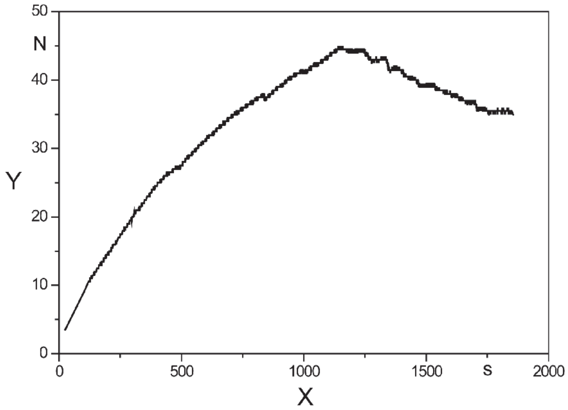
The sensor set-up allows linear location of AE sources along the delamination-direction (X); however, there is no information on the source position in the through-thickness-direction (Y) or along the width (≈ sensor diameter) of the specimen. Sensor positions are indicated by "+" in the location graph.

Only AE features of located events are shown in the graphs. AE data were post-test filtered and features of signals with peak amplitudes A ≥ 60 $dB_{AE}$ are shown only.

AE analysis characterizes initiation and propagation of the macroscopic delamination from the starter crack. From the front position of the damage zone determined by location of AE sources the initiation point (load) of macroscopic delamination after about 280 s (corresponding to delamination propagation from the starter crack tip) and the delamination rate (slope of source location band) can be derived. The sources before macroscopic delamination initiation are probably caused by sticking starter films and/or creation of a naturally sharp delamination tip without macroscopic delamination propagation.

The width of the area marked by located AE sources at specific times qualifies the size of the fracture process zone around the delamination tip along the X-direction. There is not necessarily a one-to-one correlation between this AE process zone and the fracture mechanics process zone.

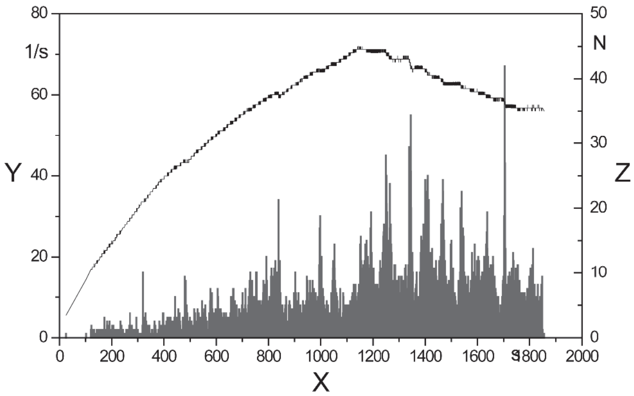
Fracture initiation is considered to be the onset of macroscopic delamination propagation, i.e. the instant in time when the microscopic delamination processes start to create new, contiguous fracture surfaces. AE analysis which is sensitive to microscopic processes can capture this transition well and hence be used to determine loads at fracture initiation.




**Key**

X time
Y load

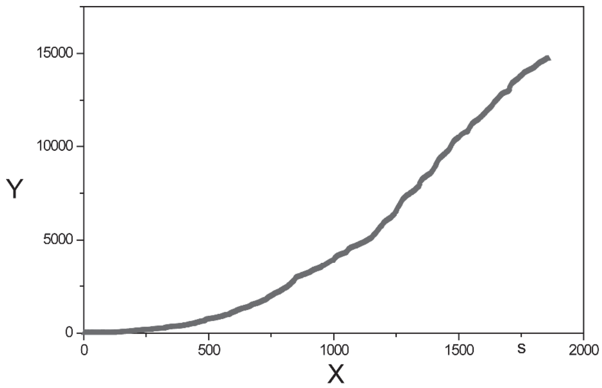
**Figure A.6 — Loading scheme**




**Key**

X time
Y event rate
Z load

**a)**

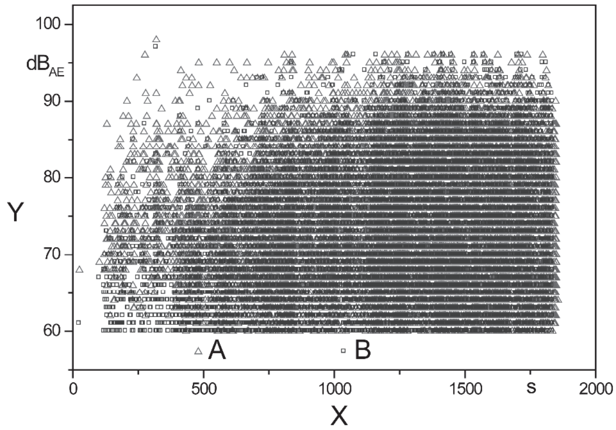



**Key**

X time
Y cumulative events

**b)**

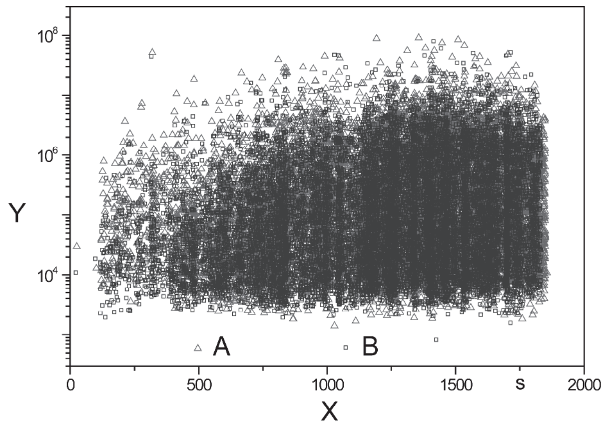
**Figure A.7 — Channel based AE activity graphs**




**Key**

X time
Y peak amplitude
A channel 1
B channel 2

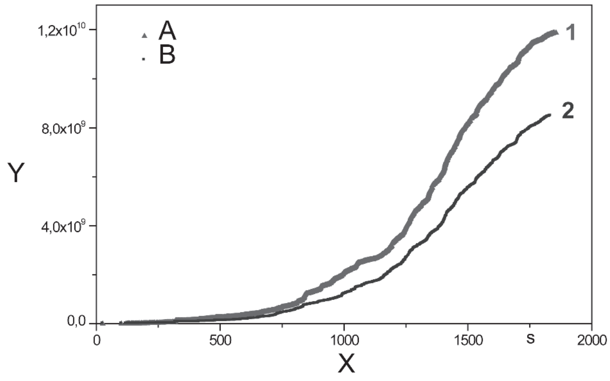
**a)**




**Key**

X time
Y AE signal energy
A channel 1
B channel 2

**b)**

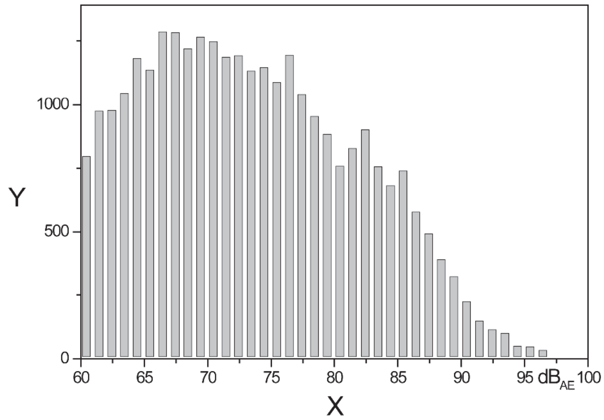



**Key**

X time
Y cumulative AE signal energy
A channel 1
B channel 2

**c)**

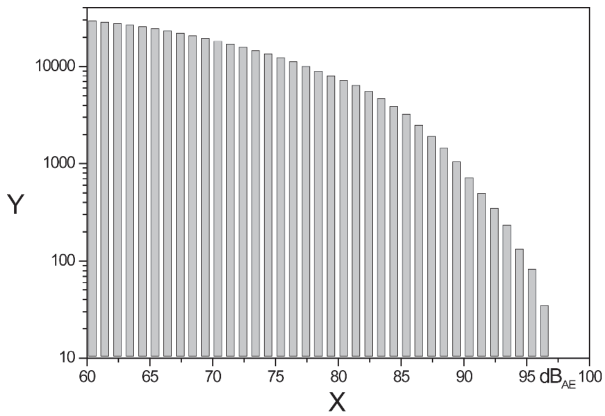
**Figure A.8 — Channel based AE intensity graphs**




**Key**

X peak amplitude
Y events

**a)**

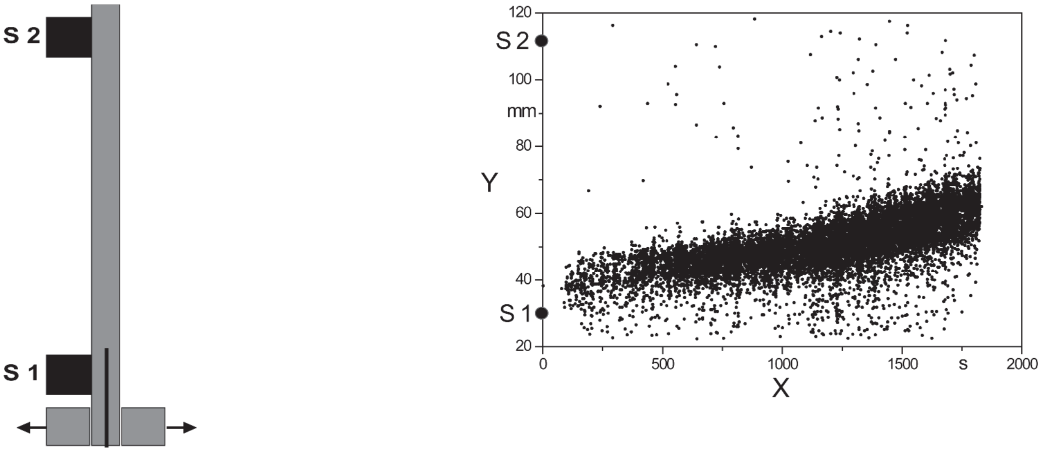



**Key**

X peak amplitude
Y cumulative events

**b)**

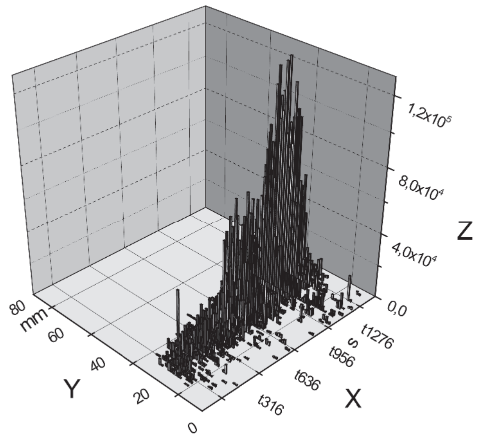
**Figure A.9 — Differential or cumulative distribution of burst signal peak amplitude**




**Key**

X time
Y X-position
S1 sensor 1
S2 sensor 2

**a)**




**Key**

X time
Y X-position
Z AE signal energy

**b)**

**Figure A.10 — Location graph (two-channel linear location mode)**

## A.2 AE testing of components and structures, example 3: AE data from pressure testing

This example shows results from pressure testing of a CF/Epoxy composite hoop wrapped pressure vessel for storage of compressed natural gas (Type II cylinder: 165 l, 200 bar) with a deep artificial fatigue crack in the steel liner.

Sensor positions are indicated by "+" in the location graph.

Only AE features of located events are shown in the graphs.

After fatigue cycling the cylinders were hoop wrapped with CF/Epoxy composite winding but no autofrettage process as in normal manufacturing could performed after wrapping. Consequently, for the subsequent AE pressure test only a model cylinder with non-typical inherent stress conditions were available.

During first pressurization ramp (≤ 200 bar) of wrapped model cylinders many AE signals were generated by failure processes due to first loading of the CF/Epoxy wrapping by pressing on the liner. Such an intense "background noise" does not exist at technical manufactured cylinders where the autofrettage process had been carried out.

Second pressurization ramp indicate the existence of a serious damage by a higher AE activity and intensity below 200 bar.

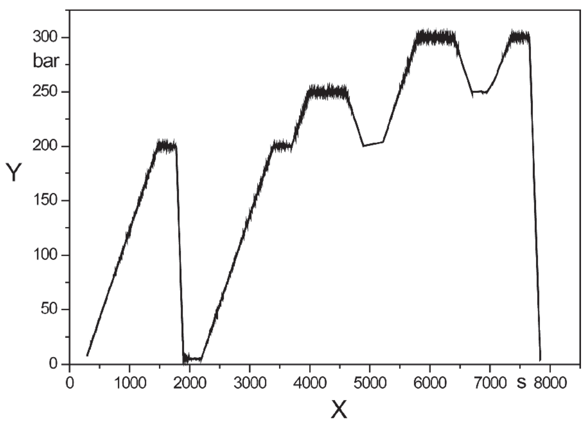
Increased AE energy below the test pressure (≤ 300 bar) is caused by shear failure of the liner/wrapping interface and a transversal failure of the CF/Epoxy winding.

From this results and information from theoretical stress and failure analysis it is deduced that acoustic emissions are generated above all by failure processes of the composite wrapping and liner/composite interface near the fatigue crack – also if the liner crack itself does not move. These sources were successful detected by linear location of AE cluster. Filtering of AE data also shows that strongest AE sources run in this area.

AE sources from the steel liner are detectable and can be located during pressure testing only if an instable crack growth occurs.

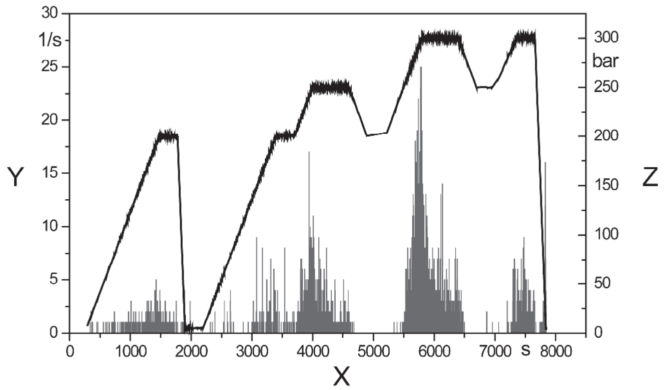
The cylinder failed by leakage after unstable break through of the liner crack at the end of test during last pressure hold period.

AE signals from liner and composite sources are not distinguishable.




**Key**
X time
Y pressure

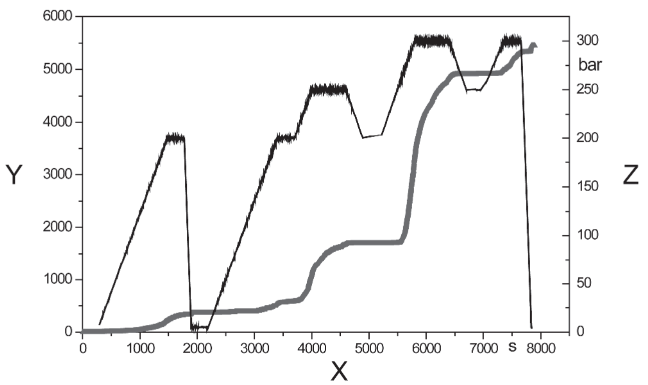
**Figure A.11 — Loading scheme**




**Key**

X time
Y event rate
Z pressure

**a)**

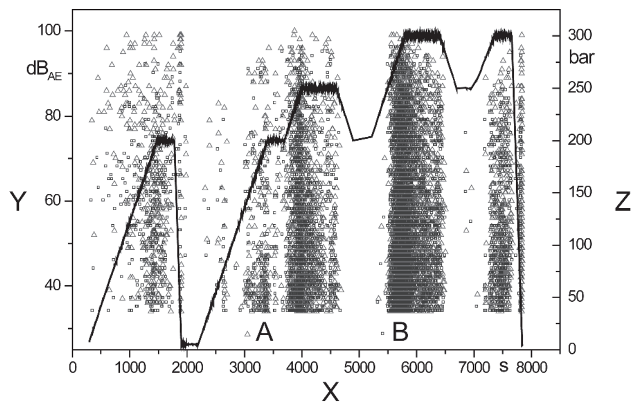



**Key**

X time
Y cumulative events
Z pressure

**b)**

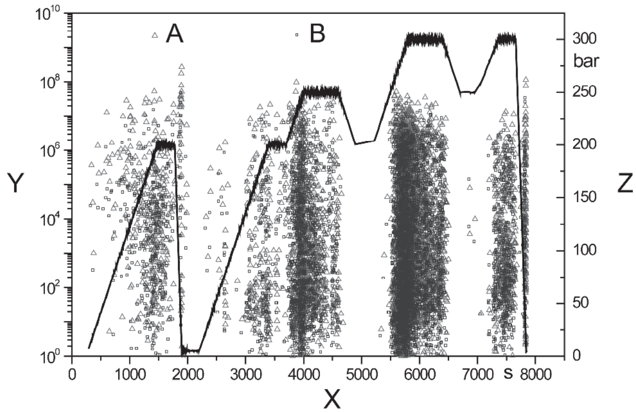
**Figure A.12 — Channel based AE activity graphs**




**Key**

X time
Y peak amplitude
Z pressure
A channel 1
B channel 2

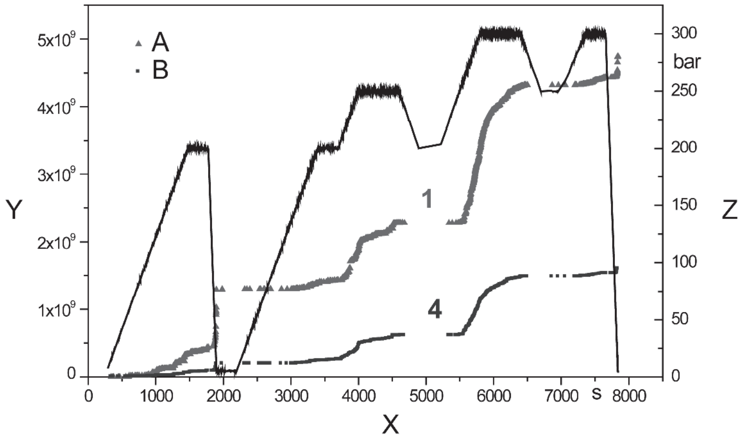
**a)**




**Key**

X time
Y AE signal energy
Z pressure
A channel 1
B channel 4

**b)**

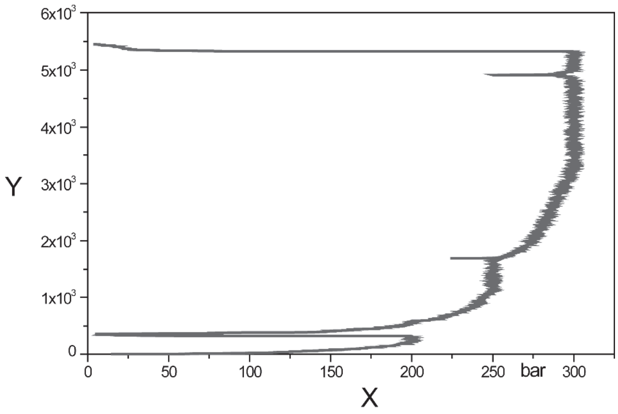



**Key**

X time
Y cumulative AE signal energy
Z pressure
A channel 1
B channel 4

**c)**

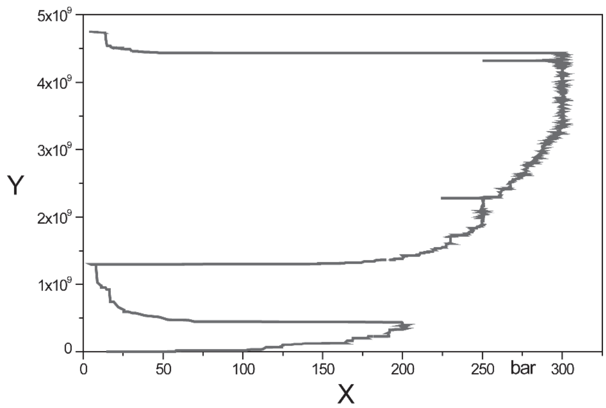
**Figure A.13 — Channel based AE intensity graphs**




**Key**

X pressure
Y Felicity - events

**a)**

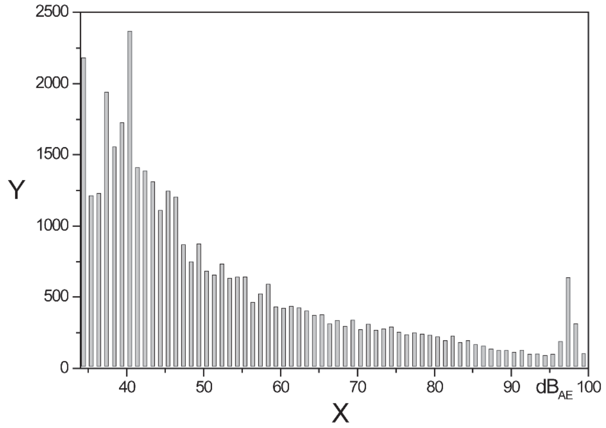



**Key**

X pressure
Y Felicity - AE signal energy (channel 1)

**b)**

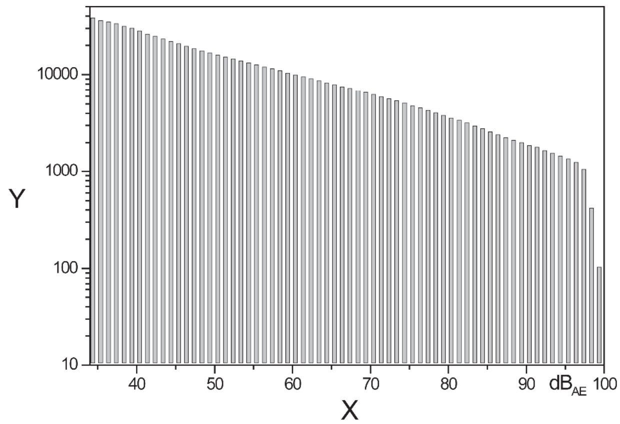
**Figure A.14 — Felicity effect (based on events or signal energy)**




**Key**

X peak amplitude
Y events

**a) Differential distribution**

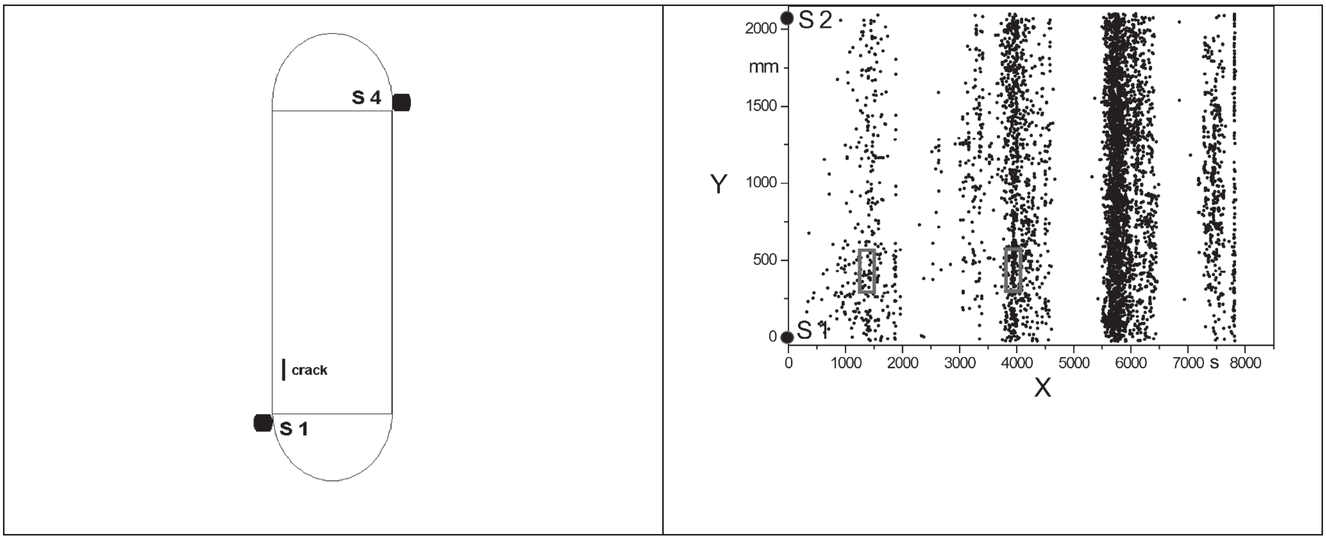



**Key**

X peak amplitude
Y cumulative events

**b) cumulative distribution**

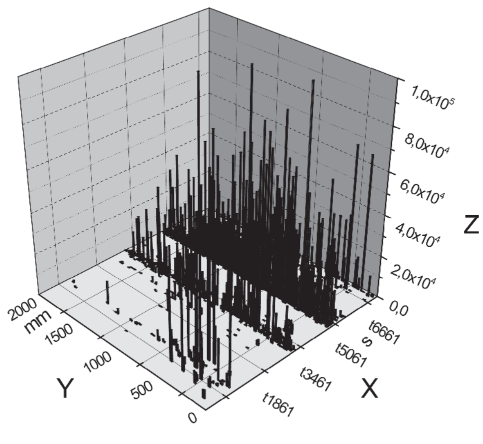
**Figure A.15 — Differential or cumulative distribution of burst signal peak amplitude**




**Key**

X time
Y X-position
S1 sensor 1
S2 sensor 2
S4 sensor 4

**a)**




**Key**

X time
Y X-position
Z AE signal energy

**b)**

**Figure A.16 — Location graph with high energy clusters found at crack position (due to wave guidance by the steel liner a two-channel linear location mode is sufficient)**

## A.3 Advanced analysis methods

### A.3.1 General

Due to the complexity of source characteristics it is very difficult to discriminate damage mechanisms in real FRP structures even using true wideband non-resonant sensors. In FRP structures multiple damage mechanisms interact simultaneously, the location will be influenced by the depth of the source and the excitation of different wave modes as well as wave propagation effects has to be obtained.

The following advanced methods might help in discriminating damage mechanism.

### A.3.2 Waveform/wave mode analysis

Provided that complete waveforms were recorded the analysis of extensional and flexural Lamb modes can be used in the evaluation of AE sources and the source location ("Modal AE") , see e.g. [Gorman *et al.* (1991, 1996); Prosser *et al.* (1995, 1996, 1999)].

Since plate waves exhibit significant dispersion, an initially sharp pulse at the origin spreads and changes shape considerably as it propagates. Source location errors occur when the threshold crossing is not on the same phase points for the wave arrivals at the sensors. In FRP structures the velocities of extensional and flexural Lamb mode proportions differs by nearly a factor of 4. A solution is to determine the arrival times based on wave modes and frequency components.

The lower frequencies in the extensional mode are non-dispersive. To determine arrival times at the sensors, the same phase point on the extensional mode must be selected. In order to perform source location on the flexural mode, the arrival time of the same frequency in the waveforms of the flexural mode to be used for the source location must be determined. This must be done since the flexural mode is dispersive in the frequency range of interest for structures testing.

The source influences the waves observed. Lead break sources create waves with large flexural modes, due to the out-of-plane nature of the source. Crack growth, due to its larger in-plane component, will create waves with larger extensional mode components. The operator shall be aware of how the source affects the wave modes to ensure accurate source location calculations based on the wave modes.

A mathematical instrument for characterisation of the velocity dispersion of Lamb modes and the energy transport by individual wave modes is the wavelet transform (time-frequency domain) of signals.

### A.3.3 Frequency spectrum (FFT) analysis

Interpretation of AE sources based on frequency spectra of signals must consider strong wave distortions from materials attenuation, frequency dependent sensitivity of AE sensors and characteristics of filters.

That means identification of AE source mechanisms using power spectra is essentially restricted to very short distances between source and sensor.

### A.3.4 Pattern recognition of AE sources

The techniques of supervised or unsupervised statistical pattern recognition and related neuronal networks can be applied for classification and identification of AE sources. A training and evaluation procedure for waveform identification based on feature extraction from waveforms and generation of distance classifier for pattern classes that are statistically characteristic for different AE sources must be carried out.

### A.3.5 Modelling of AE sources

The direct modelling of AE sources and their acoustic wave emission is restricted to very simple model sources with well defined materials properties, geometries and spatial energy radiation only, see e.g. [Suzuki *et al*. (1993); Mal (2002)].

The interpretation of AE results, however, is greatly supported by, e.g. finite element (FE) micro-mechanical modelling of local stress/strain conditions or layer-related composite stresses (laminate theory) required for initiation of failure modes in FRP laminates such as inter-fibre failure mechanisms or fibre breakage.

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