SLOVENSKI STANDARD
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Neporušitveno preskušanje - Akustična emisija - Preskušanje z vlakni ojačenih polimerov - Metodologija in splošna ocenjevalna merila

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

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

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

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

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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of an identical text or by endorsement, at the latest by July 2010, and conflicting national standards shall be withdrawn at the latest by July 2010.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 (β-relaxation of semi-crystalline matrices) or the glass-rubber transition (α-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;