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

Essai non destructif — Essai de l'émission acoustique — Méthodologie spécifique et critères d'évaluation générale d'essai des polymères renforcés de fibre

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT), see the following URL: Foreword — Supplementary information.

The committee responsible for this document is ISO/TC 135, *Non-destructive testing*, Subcommittee SC 9, *Acoustic emission testing.*

Introduction

The increasing use of fibre-reinforced polymer (FRP) materials in structural (e.g. aerospace, automotive, civil engineering) and infrastructural 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, acoustic emission testing (AT) 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 testing and periodic or continuous, real-time monitoring (health monitoring) of pressure vessels, storage tanks, and other safety-relevant FRP structures.

Acoustic emission testing shows potential where established non-destructive test methods (e.g. ultrasonic testing 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).

The general principles outlined in EN 13554 apply to all classes of materials but this International Standard emphasizes applications to metallic components (see EN 13554:2011, Clause 6).

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

FRP structures are inherently non-homogeneous 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 AT 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 the direction of fibre orientation, plate wave mode, frequency, and temperature-dependent relaxation behaviour.

Therefore, successful AT 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), different from that applied to metals.

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

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

1 Scope

This International Standard describes the general principles of acoustic emission testing (AT) of materials, components, and structures made of fibre-reinforced polymers (FRP) with the aim of

— materials characterization,

— proof testing and manufacturing quality control,

— retesting and in-service testing, and

— health monitoring.

This International Standard has been designed to describe specific methodology to assess the integrity of fibre-reinforced polymers (FRP), components, or structures or to identify critical zones of high damage accumulation or damage growth under load (e.g. suitable instrumentation, typical sensor arrangements, and location procedures).

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

This International Standard also presents formats for the presentation of acoustic emission test data that allows the application of qualitative evaluation criteria, both online during testing and by post-test analysis, and that simplify comparison of acoustic emission test results obtained from different test sites and organizations.

NOTE The structural significance of the acoustic emission cannot in all cases definitely be assessed based on AT evaluation criteria only but can require further testing and assessment (e.g. with other non-destructive test methods or fracture mechanics calculations).

2 Normative references

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

ISO 9712:2012, *Non-destructive testing — Qualification and certification of NDT personnel*

ISO 12716:2001, *Non-destructive testing — Acoustic emission inspection — Vocabulary*

ISO/IEC 17025:2005, *General requirements for the competence of testing and calibration laboratories*

EN 13477-1:2001, *Non-destructive testing — Acoustic emission — Equipment characterisation — Part 1: Equipment description*

EN 13477-2:2010, *Non-destructive testing — Acoustic emission — Equipment characterisation — Part 2: Verification of operating characteristics*

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 ISO 12716:2001 and the following apply.

3.1
fibre
slender and greatly elongated solid material

Note 1 to entry: 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 1 to entry: 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, aging, 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 1 to entry: 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 1 to entry: Those are usually continuous fibre laminates. Typical as-fabricated geometries of continuous fibres include uniaxial, cross-ply, and angle-ply laminates or woven fabrics. FRPs 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) in composite materials under different modes of loading

Note 1 to entry: 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 1 to entry: 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 qualify the personnel in accordance with ISO 9712.

5 Acoustic emission sources and acoustic behaviour

5.1 Acoustic emission 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 following are the common failure mechanisms in FRP detected by AT:

— matrix cracking;

— fibre/matrix interface debonding;

— fibre pull-out;

— fibre breakage;

— 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, discontinuities, applied load, geometry, and environmental test conditions (temperature, humidity, exposure to fluid or gaseous media, or ultraviolet radiation). 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, might 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 optimized composites might 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, apart from 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 characterized 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 characterization

Acoustic emission 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 characterization 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 might 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 (ß-relaxation of semi-crystalline matrices) or the glass-rubber transition (α-relaxation of amorphous matrices).

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

5.4 Source location

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 have 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 has to 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 the following into account:

a) sensor frequency range:

Lower frequencies give a larger detection range but might 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, 60 kHz for 600 mm to 1200 mm, and 30 kHz for 900 mm to 2000 mm or more, depending on the material.

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

b) directionality of propagation and attenuation:

More sensors might 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 might 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, 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 acoustic emission from fibre-reinforced polymers

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 might 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) 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.

c) post-test analysis:

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

6 Instrumentation and monitoring guidelines

6.1 Instrumentation

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