Standard Procedure for Acoustic Emission Examination of Fiber Reinforced Plastic Structures under Controlled Loading

Boris MURAVIN *, Gregory MURAVIN *
* Integrity Diagnostics Ltd., Netanya, Israel
www.idinspections.com

Abstract. Acoustic emission technology provides many unique capabilities for inspection and diagnostics of fiber reinforced plastic structures and pressure equipment. Particularly, it allows early detection of damage accumulation, identification and assessment of failure mechanisms, identification of loading conditions contributing to flaw-development and many other. In recent decades, several international standards including ASTM and EN have been developed to provide standardized approach for examination of composite structures. Nevertheless, many aspects related to damage identification, flaw assessment and failure prediction by means of AE testing were not addressed in these documents.

In this work, we provide a generalized approach for development of new acoustic emission procedures for inspection and diagnosis of fiber reinforced plastic composite structures.

Introduction

Fiber reinforced plastics (FRP) are widely used in construction of structures such as wind turbines, airplanes and pressure/storage equipment such as reverse-osmosis pressure vessels, chemical storage tanks, aerospace composite overlapped pressure vessels (COPVs) or rocket motor cases. There are also many other structures where FRP materials are used in construction of specific parts or as reinforcement. However, despite of growing use of these materials, the theoretical knowledge related to damage initiation, accumulation and development is relatively limited. In addition, effectiveness of traditional non-destructive test (NDT) methods for damage detection and monitoring is limited. Due to these reasons, there is an increasing use of Acoustic Emission (AE) technology that provides unique capabilities and granting a significant value for those researching, designing, developing and manufacturing FRP structures and those which use and maintain them in routine.

There are several phenomenological advantages of AE technology that makes it so effective for assessment FRP materials. First, relatively high amplitudes of AE signals are produced by matrix cracking, fiber breakage and delamination growth. Second, AE sources related to damage accumulation and development in FRP materials are normally accompanied by high rate of acoustic emission. Both factors provides generally high level of detectability by the acoustic emission technology. However, the success of acoustic emission examination depend on application of the technology under right conditions, while detection of AE sources alone is not sufficient and should be followed by their correct identification and assessment of their impact on the overall integrity of the examined structure.

International standardization of AE testing for FRP materials has advanced significantly in recent years with introduction, in addition to existing standards, of several new important documents such as: ASTM E2661 / E2661M – 10 [1] and EN 15857:2010 [2]. Other standards such as ASTM WK29068 "*Standard Guide for Nondestructive Testing of Thin-Walled Metallic Liners in Filament Wound Pressure Vessels Used in Aerospace Applications"* are in preparation.

Despite significant advancement in standardization, in our opinion, many important considerations regarding preparation of AE test plan, selection of right techniques for AE examination and considerations during assessment of AE findings were not addressed extensively yet. In this document we provide considerations that can used for inspection and diagnosis of FRP structures.

1. Scope

This practice describes application of acoustic emission technology for examination of fiber reinforced plastic structures under controlled loading. Acoustic emission examination is used to detect and locate damage accumulation and development in FRP structures under stress. When suitable methods of data analysis and criteria are developed, it is also possible to identify failure mechanisms, assess flaws and in certain cases predict failure.

2. Developing AE Examination Approach

Developing examination approach and plan can be divided into the following steps:

1. Defining goal(s) of examination.
2. Learning structure, investigating material properties and flaw characteristics.
3. Selection of AE equipment and sensors positioning.
4. Defining loading profile.
5. Defining evaluation criteria.

2.1. Defining goals of examination

Development of correct AE examination approach is crucial for success of examination which is defined as a degree to which goals of examinations were achieved. Therefore, the first step prior to conducting examination is definition of the primary examination goals. The way AE technology is applied can vary with different goals. Example of primary goals are:

- Evaluate serviceability of a structure under specific load conditions.
- Characterize mechanical and fracture mechanics properties of materials and structures.
- Establish safe loads/operational conditions.
- Predict ultimate loads.

Primary examination goals can be achieved when at least one or several of the following NDT and diagnostics [3] objectives are addressed:

1. Detection of flaw-indications in the structure.
2. Location of flaw-indications.
3. Identification of flaw-indications.
4. Assessment of flaw-indications.
5. Structural integrity diagnostics and establishing structure serviceability.
6. Failure prediction.

2.2. Failure mechanisms and AE sources in FRP

Fracture development in FRP composites is always accompanied by matrix cracking and also by one or two other main failure mechanisms: fibers breakage and/or growth of delaminations. Many sub-types and combinations of these main mechanisms are possible such as fiber/matrix debonding, fibers pullout and splitting, trans-laminar cracking, fibers bundle fracture and other. Necessary condition to achieve integrity diagnostics objectives is to be able to identify main failure mechanisms in FRP composites by means of acoustic emission testing.

2.3. Learning structure, material properties and flaw characteristics

Correct interpretation of AE results for source mechanism identification, flaw-indication assessment and diagnostics depends on satisfactory knowledge of the examined structure, examination conditions (including environmental), understanding material properties of the structure, manufacturing methods and material behavior under stress. Therefore, prior to acoustic emission examination, it is necessary to obtain the following information:

1. *Structural information*:
   - 1.1. The function of the structure and its design including detailed drawings.
   - 1.2. Operational/stress/environmental conditions and other factors that may contribute to flaw origination and development.
   - 1.3. Results of previous NDT examinations, known flaws (if any).
   - 1.4. Statistics of failures of similar structures, typical flaws, possible location of flaws and expected rate of flaw propagation.
   - 1.5. Wave propagation characteristics in the structure (propagation modes, velocities, attenuation characteristics, effects of anisotropy, etc.).
2. *Material information:*
   - 2.1. Materials used, their properties and manufacturing methods processes.
   - 2.2. Failure mechanisms.
   - 2.3. Typical stages of flaws development under different loading conditions.
3. *Examination conditions:*
   - 3.1. Environmental conditions.
   - 3.2. Possible noise sources and other conditions that may affect examination.

Laboratory and/or full scale tests can provide significant part of the above required information. Tests can be conducted on specimens and/or structures with or without flaws in order to develop ability to detect, identify and assess/classify specific flaws in the structure. Normally flawless FRP specimens are examined to learn initiation and development of flaws to failure and study load bearing capabilities of materials while flawed specimens are examined to study flaw-detection capabilities by AE testing or evaluate sustainability of material with damage.

Great precaution should be taken during specimens preparation. Especially important that specimens manufacturing procedure will be identical or close as possible to manufacturing procedures of actual composite structures of interest. It is recommended that the geometry (width, thickness and length) of specimens should be representative of the bulk materials. Analysis of factors affecting the use of results of specimens testing for actual structures should be performed. This include for example, designing specimens with proper dimensions to reduce effect of a complex stress field at edges of specimens that may lead to erroneous strength data and fracture mode. Cutting and machining of specimens should be conducted with great care to avoid specimen damage and induction of stress concentrators and delaminations.

There are several considerations that should be addressed during specimens testing to minimize possible interferences and bias. Particularly, it is important to:

- Control fiber alignment in specimens. Longitudinal tensile tests are very sensitive to fibers alignment and orientation. Luck of control may lead to erroneously low mechanical properties.
- Prevent grip-induced failure by preparing suitable tabs with strong adhesion to specimens' surface.
- Avoid specimen twisting due to grip misalignment or improper sensor preparation.
- Some composite materials can be strain rate sensitive. Accurate comparison between test results is possible when test data is obtained under similar strain rates.

When small specimen laboratory tests are conducted, they should be performed according to ASTM E1932-07 standard [4]. In addition, the type and mode of specimen loading should correspond to those normally present in the structure of interest. These can be tensile (step-wise or monotonically increasing load), bending, shear or fatigue tests. There is a comprehensive set of ASTM and other international standards describing FRP composites specimens' tests that can be used a guideline for selection, preparation and correct loading of specimens.

AE characteristics acquired during the test of small specimens can be significantly affected by reflections, different geometric/size effects on flaw development and other factors. Therefore, in every test it is necessary to find invariant qualitative or quantitative AE characteristics that can be usefully applied for examination of real structures. Examples of such invariant characteristics are:

1. Stress at onset of detectable AE in flawless specimen.
2. Stress at onset of events suspected to fiber breakage and/or delamination growth.
3. Stress at onset of damage development acceleration accompanied by acceleration of AE rate.

Mechanical properties acquired during specimens tests should be documented such as ultimate strength and/or failure load. When statistically sufficient batches of specimens are tested, it is useful to:

1. Investigate statistical distribution of mechanical properties and acoustic emission parameters/characteristics of the examined specimens.
2. If several characteristic statistical groups of specimens according to their mechanical and AE characteristics will be observed, it is recommended to perform fractography examinations to identify qualitative or quantitative difference between groups of specimens. Once such differences identified, the obtained information may be used in certain cases for detection of these indications of in goal applications.

Whenever is possible, it is recommended to perform full scale tests on structures with known service developed or artificially induced flaws. Nevertheless, artificially developed flaws may have lower detectability compared with service developed flaws due to different factors.

3. Basis of application and apparatus

For an overview of basis of application including personnel training/qualification of Nondestructive Testing Agencies consult ASTM E569-13 [5]. Selection of apparatus, AE sensors and methods of their mounting can be found in ASTM E2661 / E2661M – 10 [1] with the following notes:

1. Sensor's frequency range should be selected based on investigation of wave propagation characteristics in the structure to be examined. For this purpose it is

necessary to investigate modes of AE waves that can be present, their velocity and attenuation characteristics.

2. Wideband sensors can be used whenever it is necessary to perform frequency based analysis of AE signals in order to separate different failure mechanisms by their frequency characteristics or for performing advanced AE source location and etc. Higher frequencies attenuate at shorter distances and therefore use of wideband sensors at large distances can be ineffective.

4. Sensors positioning and performance verification

Sensor positioning is defined by considering:

1. Intensity of AE waves typically emitted by flaws of interest.
2. Wave propagation characteristics along the structure of interest including attenuation.
3. Desired accuracy of source location.
4. Desired accuracy of flaw identification.
5. Position of high stress and other areas with elevated risk of flaws origination.
6. Background noise.

AE wave attenuation in FRP materials is significant and can be characterized by 30-50 dB loss along 50-70 cm. Due to anisotropy of FRP, attenuation of AE waves is different in different directions and should be addressed during selection of sensors position and in location procedure. Also, during examination of large structures significant attenuation may require performing another test with denser sensor deployment in case significant AE is detected at a large distance from AE sensors.

For system performance verification, verification of normal sensor response and system electronic noise characterization consult ASTM E2661 / E2661M – 10 [1].

5. Selecting loading profile and test load

For in-service inspections, optimal conditions for performing examination are considered those under which flaws/faults naturally originate and develop in the examined structure. In certain cases, it may be required to perform examination under higher stresses than normal operational stresses, for example, when duration of examination is short and additional stimulus is necessary to intensify flaw development or when a structure is periodically subjected to dynamic overstresses above normal operational stresses. Additional special examinations can be performed under controlled variable stress conditions to evaluate sensitivity of flaws to load/stress changes.

Selecting correct loading mode, loading profile, load magnitude and loading rate is critical for achieving primary goals of examination. Loading modes should correspond to the typical loading modes of the structure of interest. Typical loading profiles are:

1. Profile 1: Monotonic loading with or without intermediate load holds.
2. Profile 2: Felicity ratio loading with partial unloading.
3. Profile 3. Several cycles of loading-unloading to the same or higher load level with or without intermediate load holds.

Loading of FRP composite structures can be performed at once or under several cycles. Single loading cycle is normally performed when structures are loaded to failure and the goal is to monitor stages of damage accumulation and development to failure. Another example, are routine in-service inspection of structures that experienced loads equal to those applied during examination. In all other cases, at least two cycles are recommended. Additional loadings can be applied whenever significant or uncertain results are obtained.

First (virgin) loading of composites can be followed by significant acoustic emission activity due to matrix cracking and even due to fiber breakage or delamination growth. This activity may not necessary indicate present of significant flaws but be a result of disbonding of weak adhesions, fracture of misaligned and/or weak fibers, matrix micro-cracking at stress concentrators and etc. Nevertheless, areas of the structures where a localized significant acoustic emission is detected during the first cycle, must be documented even if during consecutive cycles they are not active. Such zones may have a higher probability of developing flaws in future.

Test load or the maximum magnitude of loadings during examination dictated by the examination goals. If the aim is to test serviceability of a structure then the test load should not necessary exceed the service load. The reason is that indications of critical macro damage development and structural instability in many cases are detected at 60-80% of failure load. Nevertheless, in many cases the test load is defined at 110-150% of the service load based on recommendations and approval of the manufacturer/operator. If the first or consecutive loadings are performed above service load and significant acoustic emission is detected, then it is recommended to perform another cycle of loading to 100% of service load.

*Intermediate load hold*s are conducted due to two main reasons:

1. Monitoring AE activity under constant stress which may allow to identify stress rupture conditions, reveal indications of structural instability and assess the rate of AE relaxation which normally is lower in case of significant damage development.
2. In case of difficulty to prevent or eliminate frictional and non-flaw related noises during loading.

Duration of intermediate and test load holds are defined based on the goals of examinations and can vary from few minutes to several hours. There is no general rule but the following considerations can be considered:

1. Load holds should be long enough to obtain statistically valid picture regarding damage accumulation and development state characterized by parameters and factors such as rate of acoustic emission, activity relaxation, indications of fiber breakage and other. Load holds of 3 to 30 minutes are normally applicable for most of the cases.
2. Long load holds (more than few minutes) are not recommended above service loads even if are not accompanied by significant AE. Exceptions are when stress-rupture behavior or other special cases investigated.
3. In some FRP composites, long load holds are not recommended at loads above 80% of ultimate load due to high probability of creeping and stress rupture.

Loading rate may have a direct influence on the way damage develop and consequently on AE characteristics. When defining loading rate it is recommended to consider the following factors:

1. Loading rate during examination should be close as possible to loading rates in operation.
2. Fast loading rate may result in simulations release of acoustic emission from multiple source and/or time overlap of acoustic emission waves which effectively will be accompanied by continuous AE. One may consider to reduce loading rate if differentiation between different acoustic emission mechanisms and/or location accuracy are important.
3. Fast loading may result in dynamic stresses and also affect characteristics of fracture development.

When comparison of AE examination results between different structures is one of the goals, it is essential to perform all loadings under exactly the same conditions including number of loading cycles, load holds and loading rate. This is because failure load of many FRP structures depends on the time these structures were subjected to high stresses and not only to the level of load itself. This is due to possibility of creeping and stress-rupture under high loads. In such case when loading characteristics are different, comparison of ultimate loads or failure prediction by means of acoustic emission may not be accurate or practical.

Unloading of structure should be performed in the manner similar to loading. AE monitoring during unloading can detect fracture processes and frictions caused by free boundaries closing during unloading. Normally such activity is detected at the last 1/3 of unloading. Sometime unloading can assist to detect damages which could not be detected during loading due to low maximum stresses. Nevertheless, it is important to note that not all flaw may be active during unloading. Normally it is cracks and inter-laminar discontinuities.

6. Safety Precautions

CAUTION — The energy released during failure of different FRP composites can be extremely high and can result in injury or death of personnel and/or severe damage to facilities and equipment. A possibility of unanticipated, premature failure should always be accounted. Precautions shall be taken to protect against the consequences of catastrophic failure, for example, flying debris and impact. It is recommended to conduct tests remotely with adequate personal protection and burst shielding.

7. AE examination

7.1. System Setup

Frequency range. The frequency range for conducting AE examination should be in agreement with the selection of sensors, preamplifier characteristics and noise conditions. In the case of elevated background noise, the high pass frequency range can be increased. Nevertheless, this may require shortening the distance between sensors due to increased attenuation. Any increase in the high pass frequency should be followed by analysis of attenuation and detectability of signals of target amplitude and frequency under specific background conditions and given sensor spacing. Areas of structure with reduced detectability or reliability due to elevated background noise conditions or any other reasons should be specified in the report.

Hit detection techniques. Different hit detection techniques, threshold dependent for burst AE signals or threshold independent for continuous AE signals and their combination may be used for structure examination. Among threshold dependent techniques, fixed or several float threshold methods can be used for detection of AE burst signals. In order to minimize false positive hit detection by threshold techniques, additional parametric hit filtration could be required. Continuous AE due to rapid damage accumulation and development in FRP can be monitored using RMS, ALS or energy release rate parameters measured over time intervals of 100-200 milliseconds.

7.2. Load/operational data

Load, stress, strain, displacement or other relevant test data can be measured during examination. This data is used to detect correlation between AE activity and relevant operational/stress/environmental conditions.

7.3. Documentation of Sensors Installation and of the Structure

Documentation of sensors installation and of the structure should be performed during examination and include information about exact position of the sensors, their spacing and their distance from main elements of the structure.

7.4. Visual Survey

Visual survey of the structure should be conducted before and after examination for any unusual conditions or possible deficiencies. Visual survey may provide important direct and/or indirect information about structure condition, possible overstressed zones, assist in interpretation of some of recorded AE activity, etc. All abnormal findings should be reported including cracks, changes of polymer color or newly appeared surface waviness and etc.

7.5. Preliminary Analysis

Preliminary analysis of the measured data must be performed in the field in order to reveal or rule out any severe conditions that may threaten safety of the examined structure and should be immediately addressed. Although such scenarios are rare, still they happen and therefore the role of preliminary analysis cannot be under evaluated.

8. Data analysis and interpretation

8.1. Location and Clustering

Different methods are applied for evaluation of AE source location. Commonly applied methods are time-difference locations for burst AE signals, zone location, and energy attenuation based locations.

Location clustering can be performed to identify AE source characteristics including likely AE origin, number of emissions vs. time vs. physical location, etc. AE activity locations should be compared with position of main structural elements like fitting, bores and findings of visual survey.

Statistical analysis of signals' parameters within each cluster should be performed in order to identify possible different groups of AE signals within a cluster which may indicate several physical processes occurring in the same location (for example matrix cracking and fiber breakage).

Location accuracy and reliability can be limited in cases of complex geometries and/or in cases of multiple materials used in the structure cross-section and due to anisotropy. Due to these reasons, different location artifacts including location folding and location scattering can be observed. Nevertheless, it is important to note that all AE activity regardless if it is locatable or not should be analyzed, documented and reported.

8.2. Flaw-Indication Identification and Assessment

When proper methods of data analysis and criteria are developed, AE data can be used for flaw-indication identification, assessment or classification. Flaw/fault identification and assessment is possible when unique AE characteristics characterizing different flaws/faults indications at different stages of their development in the specific material can be identified, effectively distinguished and compared with similar characteristics obtained in similar applications and/or in laboratory tests. Features used in data analysis should have an established relationship with physical phenomena being measured during AE examination in order insure correct assessment of the examined structure.

At short distances from a source, frequency separation techniques can be used to distinguish matrix cracking, fiber breakage and delamination growth. Amplitude/energy separation is another method that can be used independently or in combination with frequency separation to disti matrix cracking from fiber breakage and other fracture mechanisms. This method is based on the fact that maximum amplitude and energy of polymer matrix is limited due to limited volume of polymer confined between layers and fibers, while fiber brakeage amplitude and energy in many cases superpose those of matrix cracking.

Comparison of loading/stress/environmental conditions with AE activity and/or AE data parameters can be used to identify conditions causing flaw/fault accumulation, development, acceleration or arrest.

8.3. Evaluation criteria

Whenever a structure is suitable for continued service or whatever the applied stresses are at the critical level for the examined structure and other questions can be answered when appropriate evaluation criteria are developed. Evaluation criteria cannot be generic for all FRP structures and has to be developed explicitly for the structures of interest. Comprehensive set of parameters typically used for evaluation of composite structures is provides in Table 1 of EN 15857:2010 [2]. However, these parameters cannot be called evaluation criteria until it is clear if they are applicable/relevant for the specific application and their absolute values are provided. For example, exponentially-like increasing AE activity close to failure may not be observed in pultrusion structures when developing delaminations. Some other FRP materials will show AE activity due to matrix cracking at very low loads making simple Felicity Ratio impractical.

The following rules will assist to develop evaluation criteria:

1. Create road map of main steps of damage initiation and development in the structure of interest. For example, in pultrusion materials subjected to tension along fiber axis, it can be: initiation of matrix cracking, individual fiber breakage, fiber bundle breakage, acceleration of damage development and then failure. The same structure under bending will first develop matrix cracking and then one or several delaminations will initiate and grow in several discrete events and then prior to failure, matrix cracking will accelerate followed by a delamination macro-growth to failure.
2. Define with manufacturer/operator what damage accumulation under stress is sustainable for the specific structure. For example it may be allowed to have matrix cracking while no fiber breakage or delamination growth are acceptable. When such criteria provided and the applied method is capable of damage identification, there is no need in evaluation criteria parameters provided in Table 1 of EN 15857:2010 [2].
3. It is possible to apply evaluation criteria based on trends of AE activity during loading and load holds [2] only for the structures in which prior to failure damage accumulates in exponentially-like manner.
4. Felicity ratio (FR) can be used as an effective criterion. However critical values of FR depends on loading, loading hold duration and unloading profile and must be developed specifically for the structure of interest. Sometimes it is practical to define FR not for every type of significant AE detected but for AE activity related to fiber breakage or macro-cracks.

9. Managing Uncertainties

During data analysis a conservative approach should be taken in case of uncertain results. Flaw/fault indications that can be equally classified into two different groups by their severity level should be attributed to the group corresponding to more severe flaws/faults. Also, all AE activity distinguishable from AE background noise should be considered as flaw/fault related activity unless different is proven.

10. Report

For general content of examination report consult with ASTM E2661 / E2661M – 10 [1]. In case of in-service inspections of FRP structures provide recommendations regarding the next follow-up examination under the following considerations:

1. Re-examination of structure is performed to follow up on the condition of a structure over time. For success of monitoring it is necessary to identify quantitative and/or qualitative AE characteristics that are changing with damage accumulation and development.
2. It is important to perform monitoring at least partially under similar operational conditions as during the previous examination. If a significant change in stress/operational conditions occurs for any reason, it may require change in the monitoring policy and re-inspection interval.
3. In cases when structure is subjected to extreme dynamic event/s and trauma, it should be re-examined immediately after this event occurrence.
4. Optimal re-inspection interval is such that a risk of unexpected failure is reduced to the minimum acceptable probability, defined for the specific structure with specific operational and stress conditions, material and specific flaw mechanisms. Presence of different structural risk factors like history of uncontrolled overstresses should also be taken into consideration.

Conclusions

In this work we presented a guide for use of acoustic emission technology for examination of FRP structures under controlled loading. This guide provides a general approach that can be shared between different future standard AE applications and may improve their quality and comprehensiveness.

References

[1] ASTM E2661 / E2661M – 10, *"Standard Practice for Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Applications"*, 2010.
[2] EN 15857:2010 "*Non-destructive testing. Acoustic emission. Testing of fibre-reinforced polymers. Specific methodology and general evaluation criteria"*, 2010.
[3] B. Muravin, G. Muravin, L. Lezvinsky, "The Fundamentals of Structural Health Monitoring by the Acoustic Emission Method", *Proceedings of the 20th International Acoustic Emission Symposium*, November 17-19, 2010, Kumamoto, Japan, pp. 253-258.
[4] ASTM E1932-07 – "Standard Guide for Acoustic Emission Examination of Small Parts", *Committee E07 on Nondestructive Testing*, 2007.
[5] ASTM E569-13 "Standard Practice for Acoustic Emission Monitoring of Structures During Controlled Stimulation", *Committee E07 on Nondestructive Testing*, 2013.