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Preface

As a student at University of Stavanger (UIS), a Master Thesis is the last mandatory & independent work as a partial fulfilment to be graduated as a Marine and Offshore engineer (MSc level). The thesis is completed during the spring of 2019 at the department Marine and offshore technology. The work is proposed by DNV GL, Stavanger.

During the work for the thesis, I have become acquainted with Acoustic Emission Technology, familiarized with NORSOK, DNV and international standards relevant to offshore structures design and inspection techniques. I also developed an understanding of how the Acoustic Emission testing can play an essential role in asset integrity management in the future for real-time monitoring for offshore structures. Moreover, I have gained experience on performing data analysis and evaluation for acoustic emission outputs during performing small-scale tests on steel specimen in DNV høvik laboratory. These learnings are very helpful for my knowledge and developed my skills in different aspects as well and hopefully they would contribute to the research of future SHM using Acoustic Emission Testing (AET).

I would like to thank my direct supervisor at DNV GL, Ole Gabrielsen for all the support, collaboration, valuable discussions and meetings which helped me during my work and giving me the opportunity to write this thesis with all the facilities he could provide. I would like to thank the whole team of engineers at the structural department for their friendly welcome and sharing their knowledge during my work in the office.

Not to forget, special thanks for the laboratory manager at høvik DNV Tor Jo Landheim for allowing me to use all the required equipment to carry out the tests and many thanks to the specialist engineer Pawel Piotrowski for assisting me in preparing and carrying out the tests in the laboratory.

At last I would like to thank my supervisors at UiS, Hirpa G. Lemu and S. A. Sudath C. Siriwardene for the close supervision and professional guidance during my work for this thesis. The department of Mechanical and Structural Engineering and Materials Science is highly appreciated for funding a critical part of the test's equipment.

Stavanger, June 2019

Khaled Dawood

Abstract

Structural health monitoring (SHM) is a critical tool to assess the structural integrity of many applications. Early detection for damage can extend the lifetime for structures through replacing damaged parts and can lower the maintenance costs and increases human safety. To evaluate the severity of damage in metallic structures, several Non-Destructive methods are used.

Therefore, the need for the acoustic emission (AE) technique, as one of the non-destructive test methods, arose that can overcome the need for specialized technician, high inspection costs and can provide many benefits for monitoring the health of the structure.

AE is a phenomenon that occurs when an elastic wave generates from rapidly released energy inside a material, for instance, at the initiation of a crack. The acoustic emissions testing has been used in condition monitoring for civil structures and aerospace fields. It can monitor the overall structural integrity continuously during real-time operation and detects any growing defects.

The aim of this thesis is to learn about the potential and limitations of AET as a monitoring tool for offshore jacket structures and assess how AET may be beneficial as an SHM tool for detection of yielding in offshore jacket structures.

The 3-point bending tests have shown significant outcomes for using AE in detecting some defects as material's yield, dislocations and crack initiation in structures made of steel. Moreover, it can be used to detect the flaw from several meters depending on attenuation and conditions effect.

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List of Abbreviations

ACFM: Alternating Current Field Measurement

AET: Acoustic Emission Testing

ALS: Accidental Limit State

ASTM: American Society of Testing Materials

CUI: Corrosion Under Insulation

CUS: Corrosion Underneath Supports

CUW: Corrosion Under Welding

CVI: Close Visual Inspection

DC: Design Class

DFT: Discrete Fourier Transformation

ECT: Eddy Current Testing

EMI: Electromagnetic Impulse

FBG: Fiber Bragg Grating

FE: Felicity Effect

FFT: Fast Fourier Transform

FLS: Fatigue Limit State

FMD: Flooded Member Detection

GVI: General Visual Inspection

HDT: Hit Definition Time

HLT: Hit Lookout Time

HSE: Health & Safety and Environmental

ISO: International Organizational for Standardization

KE: Kaiser Effect

LEFM: Linear Elastic Fracture Mechanics

LP: Liquid Penetration

MPI: Magnetic Particle Inspection

NCS: Norwegian Continental Shelf

NDT: Non-Destructive Testing

PAC: Physical Acoustic Corporation

PD: Partial Discharges

PDT: Peak Definition Time

PLB: Pencil Lead Break

PoD: Probability of Detection

PZT: Piezoelectric Transducer

ROV: Remotely operated Vehicles

RT: Radiographic Testing

SCF: Stress Concentration Factor

SHM: Structural Health Monitoring

SLS: Serviceability Limit State

STFT: Short Time Fourier Transformation

TOA: Time of Arrival

ULS: Ultimate Limit State

UT: Ultrasonic Testing

VIV: Vortex Induced Vibration

VT: Visual Testing

WSN: Wireless Sensor Network

1. Introduction

An increasing number of jacket platforms, both in North Sea and other parts of the world, are approaching or has passed their original design life. The Oil & Gas industry is constantly developing techniques to ensure safe use of these assets. Online monitoring of environmental data has improved analysis tools, development of inspection technologies, re-analysis tools and inspection planning is important in this aspect.

Ageing mechanism is a growing concern as these structures continue to operate offshore and it is an enormous challenge facing the industry to ensure that structural failure is avoided. Increasing sensor robustness, accuracy, efficiency and lower cost make it possible to collect valuable data of structural response. These data may be used primarily for two purposes:

1. Online structural monitoring to ensure safe use, prevent failures and control further degradation.
2. Assessment of the accuracy of the structural models used in design and verification.

This chapter will start with the background section (1.1) followed by the Thesis questions in section (1.2), its Aims & Objectives are explained in section (1.3). Section (1.4) mentions the scope for the Thesis work, then comes The Significance of this Work study in section (1.5) and its outcome in Section (1.6). Ending with Section (1.7) which outlines for the Thesis remaining parts.

1.1 Background

All structures including the offshore platforms, deteriorate with time due to several factors including fatigue failure caused by cyclic loads such as Environmental loads like wave, wind & current loads, besides impact loads and structural dead loads, which includes all the fixed items in the platform deck, Jacket, steel members…etc (Kharade, 2014).

Hence, the need for Structural Health Monitoring (SHM) which is referred as a tool of monitoring for structure condition on continuous basis becomes essential for structure integrity. SHM is the process of observing the structure over a period of time using some measurements techniques, analysis of some parameters to determine the current condition for the structural health (Abdo, 2014).

SHM is used to ensure the ability of the structure to continue on performing its purpose during many challenges and degradation factors as ageing, corrosion and Environment loads. Based on the current condition of the structure appropriate Maintenance, replacement of structures is decided. If SHM is implemented For Offshore Structures, then it would cut off unnecessary Inspection/ Maintenance High costs. also, data from structural monitoring can be used to ensure safe use, prevents failures and controls further degradation, to offer the potential for life extension. Therefore, a great attention has been given for SHM field last decades.

95% of offshore platforms of steel jacket structure design, which mainly are used in shallow waters with sea depth up to 300 meters (Lars-Jakob,2013). The jacket consists of steel tubes anchored to the seabed through the piles. The design time for an offshore jacket Platforms on Norwegian Continental Shelf (NCS) is 24 years average (Jacket Offshore Platform Definition, 2012), so most of the jacket platforms structures have already passed or approaching their designed life. Hence the need for extending their lifetime is in the most need nowadays and in the upcoming years.

1. Introduction

Several Non-Destructive Testing (NDT) techniques have been used in offshore structures inspection/ applications. The technique is chosen according to a lot of various factors and conditions that will be discussed later. The use of AET Technique as a NDT method for Offshore Steel Jacket structures is proposed in this work study as a monitoring tool for early warnings provider for various flaws. AET has been used as a global real-time monitoring for the assessment of the structural integrity of large structures as pressure vessels, cargo tanks. (Lee et al., 2013)

AET is one tool of SHM that can detect the flaw at early stages (Beattie, 2013). It is based on the phenomena where high frequency elastic waves are generated from release of energy inside the material of the structure, as a result from initiating flaws,yielding or growing cracks (Kaphle, 2012). It is very effective in identifying crack growth and propagation during fatigue loads.as it has been observed that acoustic emission signals intensity increases as the crack growth increases.

For a successful application of AE in an offshore sector, Signal Filtration and discrimination are critical. As the Acoustic waves are affected by Attenuation or External noises from environment.

1.2 Research Questions

- How Reliable is AET for Detecting the yield stress or defect initiation for steel material
- How mature is AET to identify Failure modes & Damage severity
- What is the Distance effect on signal attenuation for AE parameters?

1.3 Research objectives

General objectives: Doing a literature review for using AET for structural monitoring, its applications in industry considering the limitations, types of AE sensors and comparison with other NDT.

Specific objectives:

- To assess and evaluate the capability for using Acoustic emission technique for yield detection for the same material as used in jacket structure
- Whether it is possible to Identify the External noises sources, to be filtered during the diagnosis of AE Signals for offshore application.
- Could the signal attenuation be determined though steel material.

1.4 Scope

The scope is to Evaluate using AET Technique in offshore applications as a monitoring tool. Although this technique is a popular screening tool, but the effective data analysis is the challenging part.

The scope is defined by DNV-GL as follows:

- Perform a literature study on current knowledge of structural health monitoring of offshore structures with emphasis on jackets and AET.
- Describe typical failure modes and which of these can be detected by AET.
- Perform survey of various AET sensors.
- Explore signal characteristics for AET for various failure modes.
- Study how AET can be used for locating defects.
- Develop a proposal for how a system consisting of AET sensors can be used for assessing the structural integrity of a jacket, with capabilities and limitations.
- Evaluate the maturity of various sensors and measurement techniques.

1.5 Significance

This Thesis used the AE parameters (Amplitude, Absolute Energy, location, time) to determine the failure mechanisms in steel specimens under 3-point bending tests.

The results determined the level of yield damage severity with the samples. Therefore, the outcomes and results from this study can be used for successful real time monitoring for detecting yielding in steel structures.

Also, the outcome of the Experimental tests can be preliminary study for further future research in offshore and civil structures, Where Researchers with interest on AET can use it for modifying and developing more advanced Damage System for SHM.

1.6 Thesis Outcome

The outcome of this thesis is given below:

1. literature review for AET for offshore structures
2. Types of AE sensors and their maturity in the industry
3. Detecting failure modes by AE technique
4. Structural Integrity of Jacket structure using AE technique.
5. AE characteristics for different flaws of steel material.

1.7 Thesis Outlines

This thesis consists of 7 chapters. Introduction, main objectives and scope of the thesis is presented in Chapter 1. Chapter 2 is Including literature review for current SHM in offshore structures. Followed by identifying the Monitoring tools for SHM as NDT local techniques with introduction for Acoustic emission testing (AET) and its applications in industry. A proposed model of SHM using AE in monitoring offshore jacket structure with the current limitations is performed in Chapter 4. Experimental setups for small scaled steel samples monitored by AE equipment are explained in Chapter 5. Results and discussion for the experiments are taking place in Chapter 6. In Chapter 7, Conclusions for the thesis work is presented including future recommendation for further work in this field.

2. Literature Review

2.1 SHM Introduction

SHM is generally defined as the process of damage detection in a structural system. As Achenbach defines SHM as a system which provides on-demand or continuous information about the structure state, so that assessment of the structural integrity can be carried out at any time.

This process observes the structure over a period of time or continuously using periodically measurements, extracting the features from these measurements and then analyze these features, so it can determine the current condition of the health of the structural system. These features are continuously updated by the information gathered from the measurements. Basically, SHM can be considered as an evaluating tool for structural integrity and remaining lifetime for some engineering fields as aerospace, Civil structures and mechanical systems.

Implementing SHM can assess in preventing failure of the structure as it can detect some damages at early stage while the structure performance is monitored on a continuous time base. SHM has become an interesting area for research in the last few decades with the increasing need for online Real-Time monitoring of the health for large structures as bridges.

SHM observes the structure by using various sensors. During the operation phase for the structure or the system requires to be monitored, the sensors measure any dynamic changes in the characteristics of the system. Then evaluation phase takes place with the use of the post measurements/data that have been taken, resulting in an evaluation of the structural integrity.

The motivation for installing SHM system is to reduce the costs for maintenance, unnecessary inspection, A summary for Maintenance costs to North Sea steel platforms in U.K. reported in the period 1966-1986 is presented by (Tebbett,1988).

Where typical in-service inspection cost for a 100 m water depth Jacket structure in the North Sea ranges from $500,000 to $1,0000,000 per year, with half of these costs related for fatigue cracks inspection (Lotsberg,1992). Even it is very costly to carry out under water inspection in North Sea, it can cost up to $50,000 daily rate (Hennegan,1993).

Besides SHM reduces the risk related to the human factor who involves with the inspection operation as well. Many ranges of applications have used SHM for structures as Aircraft, pipelines, Bridges and Nuclear Field. (Kaphle,2012). The sensors can be mounted permanently to detect the damage occurs to the structure. Health monitoring techniques can be classified as local or global damage monitoring techniques. On the other hand, Non-Destructive Testing or Non-Destructive Evaluation should not to be confused with SHM due to the difference in concept of monitoring/sensing of the structure.

NDT is a technique used for sensing the component of the structure for specific period of time or temporary, it is known as a local damage detection technique. where it can identify the flaw only on the part being tested of the structure, where the sensor is installed.

Briefly, SHM has been used for few decades in the industry oriented to the development of monitoring techniques, which facilitate the scheduled maintenance to condition based maintenance (Semperlotti,2009), reducing risk of failure and performing the maintenance whenever necessary.

2.2 SHM phases

The Engineering SHM Concept consists of four basic stages, according to (Chang,2003).

1. Sensor allocation and measurements
2. Structural identification
3. Damage or degradation detection
4. Decision making

A successful SHM system deals with Structures should consider all the 4 phases simultaneously. Each phase is critical for SHM and can be divided into sub activities.

To identify the phases for a successful SHM System (Wilde,2009), SHM should be able to:

- Detect of the Flaw existence
- Detect Flaw location
- Identify the Flaw type
- Predict the flaw development

But with the Rapid development of technologies, extra few tasks (Uhl T.,2009) have to be considered in the requirements of SHM System:

- Ability of Self-diagnostics
- Ability of self-repair
- Ability of active control

In Figure 1, there is another arrangement for SHM method working principle, where all the phases depend on each other to perform their tasks in a proper way (Vestli, 2016).

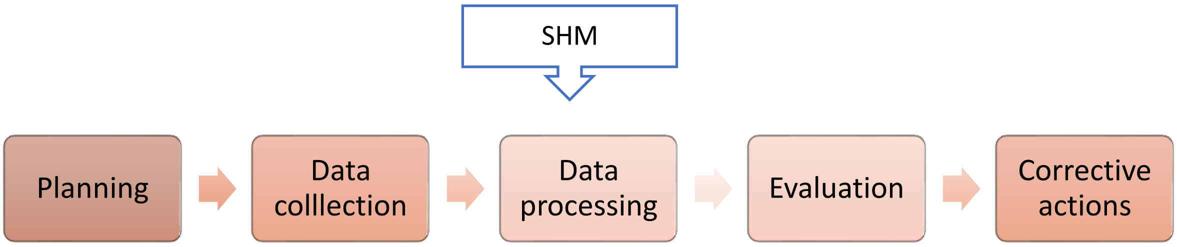

Figure 1 : SHM Phases

1. Planning phase

In this phase, it is critical to know the monitoring needs to be done. Which part of the structure is critical to be monitored; identification of the modes of failure could be expected from this part needs to be clarified.

2. Data collection phase

It is the actual monitoring part, as the measurement technique and the sensor type need to be identified in this phase. Specific Location for the expected mode of failure must be identified so that the sensor should be placed close to the flaw source. The factors that determine the storage capacity for the data are the sampling frequency and period, hence if the frequency samples are high, then the amount of data will be enormous, besides the period for monitoring if it is either continuous monitoring or periodic, that will affect the storage capacity for the data. In this phase, data acquisition facilities need to be installed. All the methods of filtration and normalization should be carried out in this phase while collecting the data to differ between the real and unnecessary information about the flaw. Environmental noises are examples for faulty data.

3. Data processing phase

This phase is the most challenging one in all phases for SHM, as it involves vast amount of the collected data, to identify between the important data and processing them is not an easy task, the challenge is to identify the important indicators for the flaw parameters and transform them into a possible understandable way, so it would be possible to evaluate the data. Some of these transformation methods are Fast Fourier Transform (FFT) as it is shown below in Figure 2 (Fast Fourier transform - Wikiwand).

FFT is the most popular technique that has been used in SHM for structures. It transforms the signal from its original time-domain to the frequency-domain and vice versa in most cases.it is widely used in engineering applications, science and mathematics.

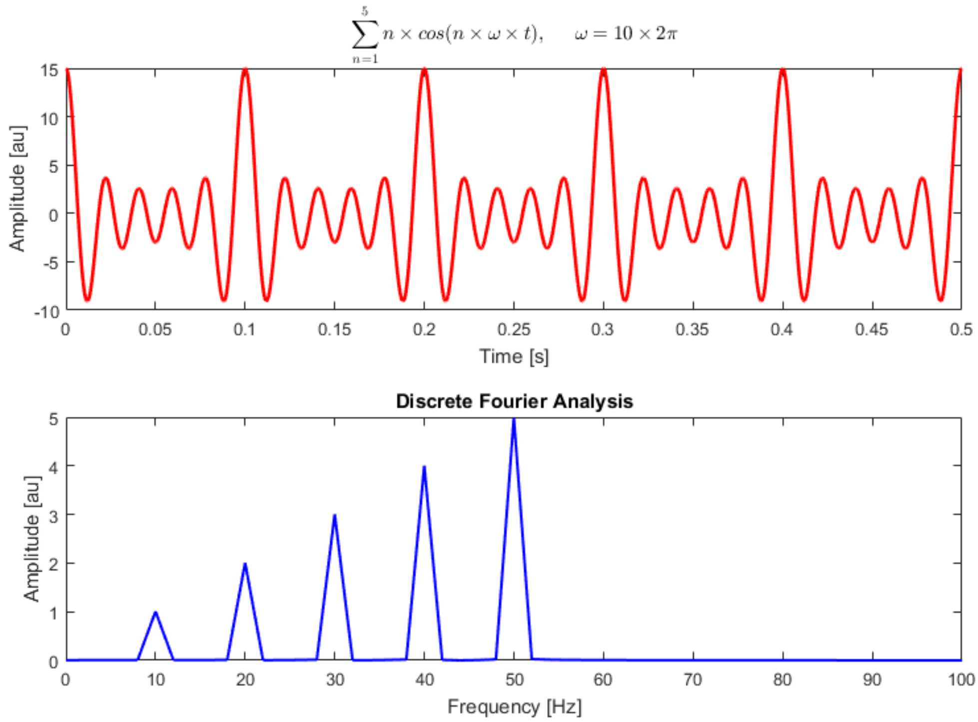

Figure 2:FFT Analysis

4. Evaluation Phase

The last phase is defining the condition of the structure. It is considered as the main purpose of the implementing the SHM for any system, based on the data collected and processed regarding the flaw, it can be divided into four levels of flaw detection according to (Rytter ,1993) and (Peeters et al,2011):

- Identifying existence of flaw
- Identifying the existence and the location of the flaw
- Identifying the existence, location and the damage severity
- Identifying the existence, location, severity of the flaw and determine the remaining lifetime for the structure (Prognosis).

5. Corrective actions and Decision making

it is not considered as a main SHM phase, in spite some modified systems have the ability to perform automatic or recommended actions in some situations (Uhl T,2009). Where the system can identify the flaw type and location and capable to maintaining the damage without human interference. While still in most SHM applications the decision for replacing or maintaining must be made by a specialist operator.

2.3 SHM Techniques

SHM methods can be categorized into two types: the global and local Damage detection Methods (Dhakal,2013). Global method refers to Monitoring the whole structure based on the global properties of the structure (Mass, Damping, Stiffness) variation, while Local method refers to only monitoring some specific area or points of damage (Carlos,2000).

SHM can be classified into two categories according to the duration of monitoring: Long-term and Short- Monitoring. Long term monitoring has been used for monitoring any deterioration for the structure for a few months or years, while the Short-term is just for assessing the current condition of the structure ranges from few hours to few weeks. short-term can be used as a design optimization for the long-term SHM methods before installation (Li, J.,2014).

1. Global Damage Technique

This method is used for assessing the integrity for the entire structure along with its deterioration and ageing, where it indicates the damage presence and can locate this damage. It depends on the variation in some values of the structure global properties (Mass, Stiffness, Damping) which cause a change in the values of the modal properties such as natural frequency and mode shapes.

Vibration based monitoring is one of the commonly used global monitoring techniques in applications. It normally involves using the accelerometers for measuring the structure vibration at some specific areas or locations, then calculating of the modal properties is followed based on the vibration values.

Global Method has some challenges in monitoring big structures as bridges, due to the large size of the structure some negligible change in the dynamic properties could be unnoticed, hence cannot identify the existence of any damage, also this method cannot accurately locate the flaw on large structures being monitored and so local techniques for monitoring were better alternatives for locating the defects on the structure.

Global technique mostly was used with vibration methods and innovative extended sensors system lately (Sadek,2001). with the development of instrumentation and more understanding of the complex structures dynamics, it leads to more successful applications for health monitoring systems and damage assessment in civil structures applications during the recent years (Stubbs,1990).

2. Local Damage Technique

The need for accurate damage localization is the reason for using local technique in monitoring the structure. With the progress ageing of the structures, the need for Monitoring methods which can detect the hidden flaws has increased, leads to the introduction of NDT methods using various sensors. Initially, NDT techniques were initiated during the 40’s in civil engineering applications (Abdo,2014).

This technique depends on detecting the defect or damage at the point the sensor is installed, it is restricted to locate the defect only on the points close by the sensor. It is applied on a periodic time base for inspection or testing some specific areas of the structure only in accessible way.

Unfortunately, this method is considered as a costly and time-consuming technique, as it must be carried out only by a specialist or an experienced technician plus the long duration would it take for implementing the testing procedures. However, it is the most common used technique in the industry for its high accuracy for Damage detection. Table 1 shows different features for local and global monitoring techniques.

Table 1: Global vs Local monitoring technique

Features	**Local Monitoring Technique**	**Global Monitoring Technique**
Common Methods	NDT Methods (Ultrasonic, acoustic emission, eddy current)	Modal-based, Response-Based methods.
Application in Industry	Accurate Location of the Flaw	Indicating a Flaw existence
Monitoring duration	Periodic	Continuous
Testing Duration	More Time-consuming	Less Time-consuming
Cost Value	More expensive on long term	Initial installments cost more
Advantages	Rapid Condition screening for the entire structure	Define the location and damage severity at specific points.

2.4 Active & Passive Sensing

Sensing technique can be classified into 2 categories; The Active technique where the external sensor excites the structure by emitting waves to inspect its condition, receives back the reflected waves and compares it to the original value to determine the material condition. While on the other hand the passive technique is receiving the waves emitted from the material itself when there is a deformation occurs without the need for any external source excitation.

An Example for an active sensing is Ultrasonic testing (UT) method, which the sensor sends ultrasonic waves to the structure and receives back the reflected wave as an echo, while in passive sensing an example of using AE which only receives the sound waves emitted from the deformed material whenever there is a crack opening or flaw initiation.

2.5 SHM Applications

Over the last 50 years , a lot of catastrophic bridge failures in US have occurred due to bridge defects in structure (MnDOT,2007).For example I-35 bridge in US failed in August 2007 without any former indication for internal structural damage, resulting in the death of 14 motorists, later it was discovered that the bridge was rated as structurally deficient after several inspections , where they found fatigue cracking in steel members and revealed some corrosion on specific areas of the bridge (MnDOT, 2007).of course this was not the only accident, afterwards the need for a structural health monitoring system , which can reveal such defects at early stage, in a cost-effective way has become critical.

SHM has been used in many industries. It has experienced rapid development in the last few years. That development in monitoring within Civil engineering and Aerospace Field were significant obvious. Currently SHM in civil engineering combines between both global damage technique as vibration damage detection with the Local NDT techniques such as (Strain measurements, acoustic emission monitoring) to receive better Monitoring outcomes for Damage detection in the structure (Aktan,2002).

2.6 SHM history in Offshore industry

Most of the offshore Platforms are jacket type, made of steel materials (Lotfollahi, 2011). SHM in offshore applications is quite similar to the civil structures monitoring system, except In these platforms periodic inspections are compulsory, as these platforms are affected by various types of damage through its lifetime as a result of environment loads, collisions with other objects as ships , impact from dropped objects on the platform decks, overload during strong storms ,overload during the maintenance or installation and operation activities, resulting mostly in fatigue and corrosion damage.

SHM application for offshore platforms are advantageous due to many reasons (Tomonori,2007):

- Cutting loss for maintenance and inspection
- Improving HSE (Health, Safety and Environmental) conditions of the platform
- Effective trace for damage identification and location

- Improving the preventive maintenance strategy plan

In the past SHM till this day in offshore applications, several Local damage detection techniques are used such as Eddy current, ultrasonic, X-ray and visual inspection and others have been developed. But the obstacle that these methods are time consuming methods and considerably expensive, as the surface of the structure needs to be exposed or accessible for testing, poor visibility and marine growth presence on the surface of the steel frames all these factors are contributing in considering the local detection technique as a slow process.

Oil industry has started using the global damage detection technique, specifically vibration-based damage detection method few decades ago (Doebling,1998). In which the frequency change was used as a damage indicator for a defect in the structure or the system being inspected. The natural frequency (f) of an offshore jacket structure is defined as follows:

$$f = \frac{1}{2\pi}\left(\frac{k}{m}\right)^{\frac{1}{2}}$$

Where the frequency value varies with the stiffness (k) and the mass (m) for the structure, which are both global properties affected by the damage occurred in the structure. Hence, the vibration-based technique is depending basically on this relation to detect any deformation in the structure. The fluctuations in the frequency can be obtained from the accelerometers placed on the surface of the structure, comparing the measured frequencies with the original values where there are no deformations on the surface, hence the change in frequency can be measured and indicates the existence of any damage and its severity. But even indicating the source of frequency changing is not a direct way. Due to the existence of some environment loads, marine growth which affects the center of gravity for the structure can lead into fake indication of damage (Doebling,1998).

So, the process for identification of real and false indicators for damage in the structure has a long research history. These methods won’t be discussed in this thesis as the focus is on using the AET, but for reviewing, there were some interesting papers published in this area of interest published by (Rubin and Coppolino), (Shahrivar and Bouwkamp), (Kim and Sttubs) for using different methods more sensitive to Structural damage than the classical way.

2.7 Jacket Platform Structure

2.7.1 Design

This section contains an overview of the platform structure main components, used in the offshore industry. Standards and recommendations for designing the offshore jacket structure are mentioned according to NORSOK, DNV-GL , API and ISO.

Using Jacket structure in transitional water regions, where depths range between 30-100 meters (Golightly,2016), was suggested rather than other structure designs for its positive effects, such as the low wave and current impact loads effect compared to other structures as Monopile, gravity, ballast foundations (Gong,2011).

Jacket substructures are designed according to (ISO-19902,2007) in some areas. The selection of the structure design and material depends on the reservoir size, type of well and water depth (Odland).

A jacket is a welded tubular space frame with 3 or more vertical tubular legs a, brace system between the legs. The jacket function is to provide support to topside of the offshore platform structure and provide attachment points for the risers, conductors and J-tubes. The piles are thick steel pipes range from 1-2 meters diameter with depth up to 100 meters into the sea bed, in which the piles are only connected to the legs at the top of the jacket, so that the axial forces are transferred to the piles at the connection, then forces are transferred to the seabed through the legs of the structure.

The steel jacket platform on a pile foundation is the most common type of offshore structure in the offshore industry (Offshore Platform frame).

These structures are designed to withstand immense vertical loading and overturning moments.

Figure 3 shows an example for steel jacket structure in a X-bracing geometry shape (Chen et al., 2016).

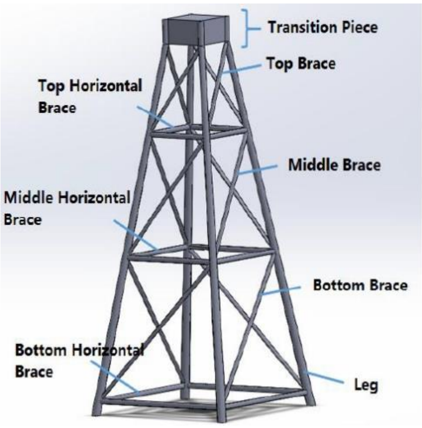

Figure 3:Structural members of a X-bracing system Jacket Structure

2.7.2 Bracing types

Jacket substructures have different types of designs including K-braces, V-braces, Z-braces and X-braces as shown in Figure 4 (Cabrera and Ávilar, 2016).

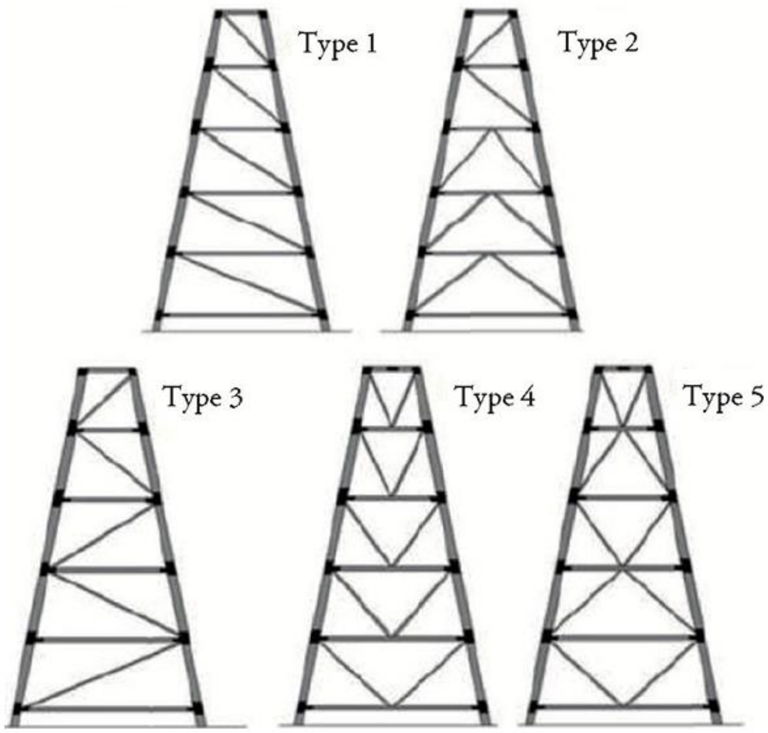

Figure 4:Bracing geometry for jacket structure

The different structure system is playing an important role in distributing the axial force in a different manner. (ISO-19902,2007)

Tubular joints are widely used for the jacket offshore structures. The tubular members have a complicated geometry at the intersection of members, but they play a very critical role in the jacket substructure's in extreme loads in the jacket structure, where the braces increase the extreme capacity to a certain extent and joints connect them to the legs.

Braces are known as one of the major causes for the structure integrity failure for an offshore jacket structure. Therefore, buckling of braces will be encountered prior to joint failure or cracking occurs (Alanjari, 2011).

2.7.3 Jacket Structure Common failures

This section will contain information about the most common failures occurs to the jacket offshore structures. Including the damage parameters and the most affected parts or points in the structure by these failures.

Before identifying the most failure modes jacket offshore structures faces, a reliability evaluation for all the significant loads and load combinations which the structure is exposed to during its operation stage must be clarified.

These loads are categorized into (Sigurdsson-DNV,1996):

1. Permanent loads:

- Weight of structure
- Weight of permanent equipment

2. Live loads:
   - Gravity loads
   - operating loads such as helicopter landing, riser forces, machinery loads
   - Any variable functional loads
3. Environment loads
   - Wind loads
   - Wave loads
   - Current loads
   - Chemical loads
   - Temperature loads
   - Ice loads
4. Motion & Deformation loads
   - Inertia loads
   - Deformation loads (Displacement and rotation of module supports)

5. Accidental loads
   - Fire
   - Explosion,
   - Dropped objects
   - collision
   - earthquake

The jacket structures capacity to withstand overload depends on the size, number of legs and bracing system for the jacket.

All the components of the jacket structure should be considered during inspection according to (NORSOK N-005,2017), where the inspection intervals should depend on:

- Fatigue life of the specific component; reference to DNVGL-RP-C210
- Inspection history for the specific component
- The strength considerations in case of corrosion
- Consequence evaluation

Some components in the Jacket structure must be considered in the inspection program as they are very critical to be measured. They are shown below in the Table 2 according to NORSOK N-005,2017

Table 2: Description for jacket components and common failure

Component	Function	Failure mode Expected
Vertical bracing/joints	Transfer environment loads to the foundation	crack
Legs	Support the deck weight,	buckling/crack
Pile sleeves/piles	Support the installation	buckling
Risers	Operational Role	Corrosion, VIV
Mechanical clamps	Supporter	Misalignment
Conductor centralizers	Restrains the conductor movement	Wear/Mechanical failure

According to NORSOK-N-005, special integrity issues for jacket structure need to be considered:

- Fatigue cracks in Braces, Steel conductor Frames, risers.
- Corrosion Protection on the surface of the structure legs
- Grouted-Pile Sleeve in the capacity of the connection.

According to (NORSOK N-005,2017) the typical damage parameters on jacket structure are listed as:

- Fatigue
- Corrosion
- Overloading
- Accidents
- Marine growth, scouring, other irregularities.

The Offshore jacket structure is designed as a redundant structure, in which the failure of a single element does not lead to the whole failure of the structure at once. For example, the jacket platform structure leg failure won't lead to the total collapse of the structure with the existence of another 3 legs that support the platform loads. The need for redundancy is for several reasons (Navilkumar,1992);

1. The risk of environmental loads that exceeds the design loads during platform lifetime
2. Welding defects, members misalignment of tubulars
3. Accidental damage such as dropped objects, collision

4. Deterioration of structure because of fatigue and corrosion due to the presence of cracks or defects.

For the safety assessment of the Jacket structure, it is necessary to relate the structural safety to some certain system limit states.

A Jacket platform is designed according to several limit states shown in Table 3 ; Ultimate limit state (ULS), Fatigue limit state (FLS), Accidental limit state (ALS) and Serviceability limit state (SLS) (DNVGL-OS-C101,2016).

Table 3: Limit states for offshore jacket

Limit state	**Definition**
ULS	Ultimate resistance to carry loads
FLS	Possible failure du to cyclic loading
ALS	Failure due to accidental event
SLS	Corresponds to the criteria applicable to normal use or durability

According to DNV-GL: Guide lines for offshore Structural Reliability for Jacket Platforms, the most important failure modes comprise;

1. Jacket members (legs and Braces) ULS:

- Buckling of members:

  Local Buckling of members

  Global buckling of members

  Buckling of members subjected to external pressure

- Total structural collapse due to environmental load

2. Tubular Joints (ULS):

   Joint failure

3. Tubular Joints & Connections (FLS):

   Fatigue in welded connections at hot spots.

Damage statistics of offshore jacket structures on NCS from 1974 until 2017 (Petroleumstilsynet, 2017) is shown in Figure 5, in which most of damages faced by the jacket offshore structures were cracks, these cracks were believed as a result of fatigue due to cyclic wave loads over time.

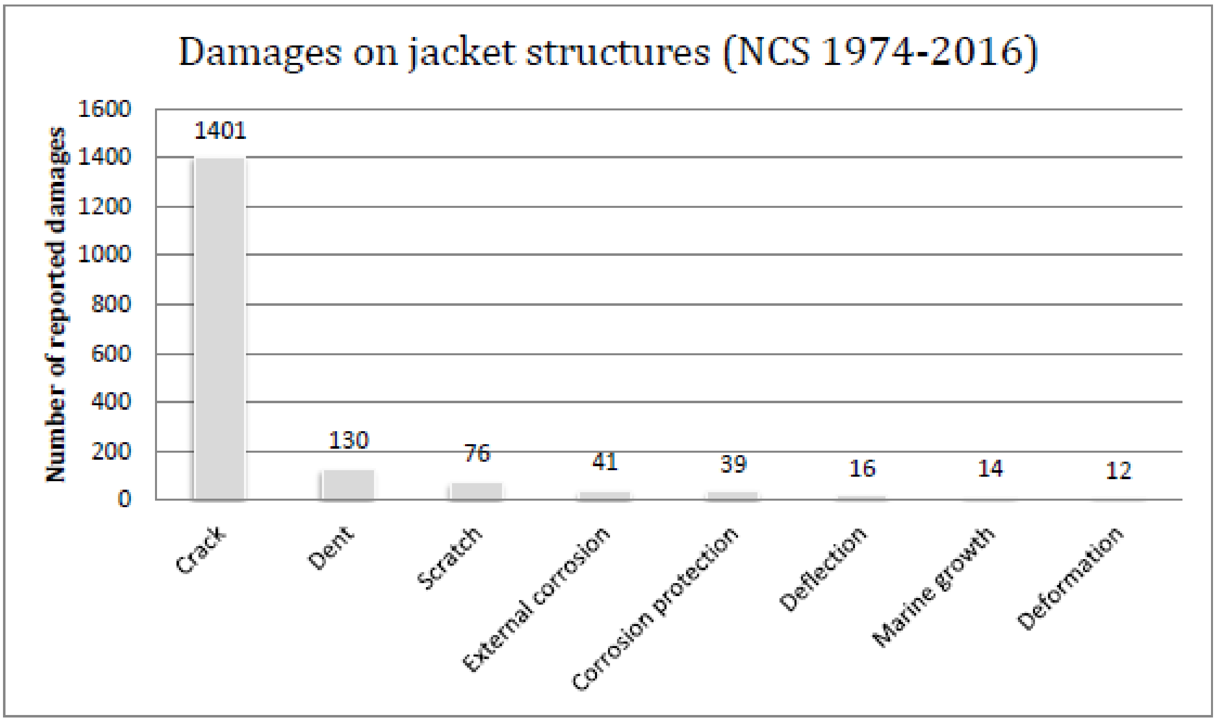

Figure 5: NCS Damages statistics for jacket structures

The majority of the reported cracks and dents were located on the bracings and jacket legs, which confirms the need for a of Reliable monitoring system for these components to detect any of the jacket offshore failure modes at an early stage while maintaining the structural integrity.

Since the tubular steel joints are formed by welding, the defects in small welding parts are usually present, because of the high stress and many waves cyclic loading act on these joints, the welds defects grow by time and the fatigue starts to form cracks along the thickness of the members and the welded intersections, eventually resulting in separation of braces from the chord members. The presence of welding residual stresses leads to increasing the risk of fracture in the structure members. Fracture failure is affected by several parameters such as the geometry shape of the joint, size and shape of the crack, weld size the material properties of the joint, the heat affected zone etc (Navilkumar, 1992).

According to NORSOK and DNV-GL guidelines, the most probable failures the jacket offshore would face are ; Fatigue cracks in the braces due to environment loads, corrosion on legs surface, fatigue in the welded connections at hot spots, Hence the need for reliable SHM for these specific areas are the utmost , where enormous losses can be avoided and improving the structural integrity would be achieved with extending the lifetime for the jacket structure than the designed life.

The objective of deploying a SHM for an offshore jacket platform, is to detect the most failure modes such as cracks and corrosion in the Jacket structure critical components; Braces, steel frames and Joints as well using NDT method as it will be discussed in the next chapter, to maintain the structural integrity for the jacket platform. Stated by (DNV-GL-RP-C210, 2015) Fatigue cracks can be more critical to failure mechanisms due to the uncertainty of the crack propagation behavior.

Stated by (Sigurdsson-Dnv-gl,1996), there have been a few total failures for the new jacket offshores but the fatigue damages have occurred in the old platforms, which means on the long term the fatigue damage will probably increase by the time offshore jacket structures get old.

2.8 Fatigue

The cyclic stress subjects on the structure, can lead to the material failing and eventually fatigue failure mechanism. The cyclic stress or loads in offshore environment are mainly caused by waves on the substructures and by wind on the topside of the platform (ISO_19902_2007).

Offshore jacket structures are deigned against failure damage, but with uncertainty in the environment conditions in the North Sea besides the material degradation through lifetime, hence the fatigue design task is challenging to estimate accurately.

However, Fatigue failure of the structure occurs after several phases of crack development, Figure 6 shows the crack development shape inside the material (Afshin et al.).

- Crack initiation
- Crack growth
- Fracture

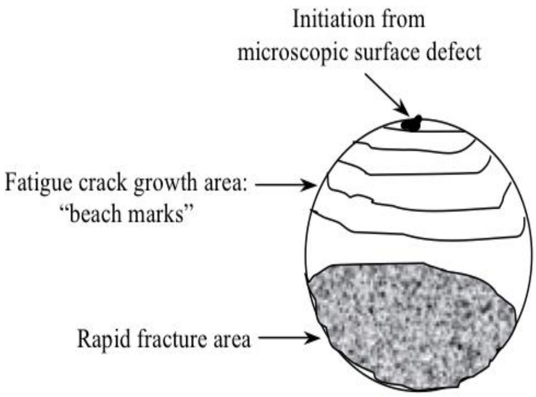

Figure 6: Crack development

The purpose of this section is to focus on the crack initiation and crack growth phases. As NDT technique will be effective only before the material reaches the fracture phase.

As outlined by Schijve, Figure 7 shows a schematic diagram of fatigue lifetime from crack initiation to final fracture phase.

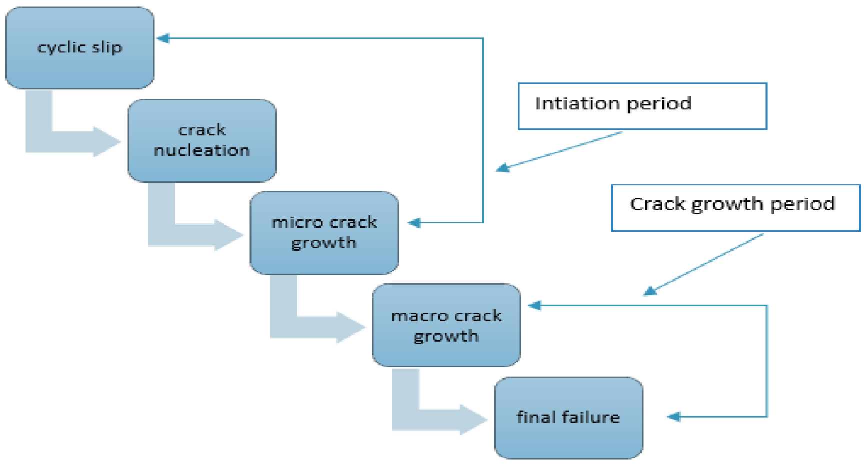

Figure 7:Schematic diagram for fatigue phases

2.8.1 Crack initiation

Typical crack initiation occurs in toe welds, existing surface scratches and heat affected zones in the material (Przybyla et al.,2010). The initial phase for the crack occurs at local discontinuities areas in the metal's crystal structure. Usually it is the longest phase and the most unpredictable one in the fatigue process.

Fatigue is a process of crack initiation and growth that depends on the microstructural properties, distribution of localized cyclic crystal deformation, loading and stress conditions. Microcracks originate normally at free surface, due to that the cyclic plastic deformation is highest near the surface, as a result of the high stress near the surface, these stresses result from bending, notches or twisting (Tu and Zhang, 2016).

2.8.2 Crack growth

Stated by (Schtz,1996) "if the crack goes outside the first-grain, then the crack growth phase starts», the crack growth is the second phase for fatigue failure .The crack continuously grows outside the first grain to hit nearby grains, for the transition between the first and the second phase ,the crack needs extra number of cycles and energy to continue growing .then the crack propagates in a different direction than the previous grain as it follows the crystal orientation of the new grain it hit (Besten, 2018).

The crack growth passes through 3 stages which are (Tudose,2017) :

Stage 1, Non-continuum Mechanisms: this mechanism depends on the material microstructure, environment conditions and the stress ratio.

Stage 2, Power growth: it is based on Paris law, and corresponds to the stable crack growth phase, this stage mainly depends on the material's constants C & n. Paris law representing a surface crack in a semi-infinite body under a constant stress cycle (Paris,1961),this method depends on using fracture mechanics to obtain the number of cycles to grow a crack from a given length to another length or fracture , it is based on this equation:

$$\frac{da}{dN} = C.\Delta K^n$$

Where:

C = the Paris law coefficient, (mm/cycle)/$((MPa.(mm)^{0.5})^n)$

n = the Paris law exponent

ΔK=K_{max}-K_{min}=β. $\Delta s.\sqrt{a}$

Δs = the stress range, MPa

B = constant depends on the geometry of the structure

Stage 3: Instability: it is considered as the unstable crack growth stage, where the crack growth accelerates the rate.

In Figure 8,The curve shown is bounded by two limits, the upper represents fracture toughness of the material K_C (or K_{IC}) and the lower represents fatigue crack threshold ΔK_{th} (Tudose,2007).

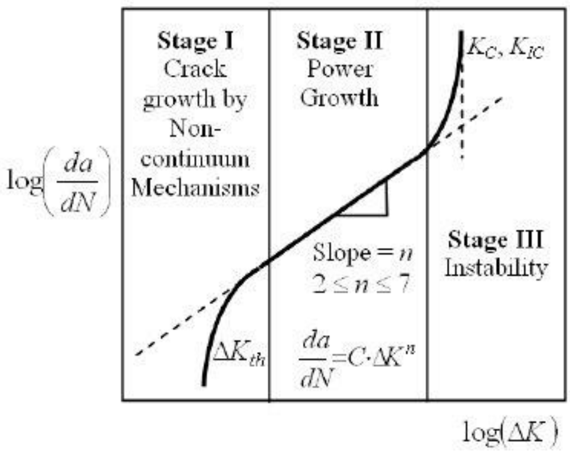

Figure 8: Fatigue Crack growth stages

In general, the application of linear elastic fracture mechanics (LEFM) for fatigue analysis is based on the analysis of stress-field equations, which show the stress field in the region of a crack opening can be described by a parameter K, which is the stress intensity factor. The crack propagation can be governed by the equation:

$$\frac{da}{dN} = f(\Delta K, R, H)$$

Where:

ΔK = the stress intensity factor range, MPa*$(mm)^{\frac{1}{2}}$

N = the number of loading cycles

da/dN = the crack growth per cycle, mm/cycle

H is the history term

a = the crack length in mm

$R = K_{min}/K_{max}$

2.8.3 S-N curves method for fatigue analysis

According to DNVGL-RP-C203, fatigue analysis is currently based on S-N data which is determined by fatigue testing or by applying fracture mechanics when the S-N data is not long enough for a specific component of the structure, where severe consequences may occur by failure.

Fatigue analysis using the S-N curves are basically derived from Miner-Palmgren approach to estimate the fatigue life, it is defined as the relation between the magnitude of the cyclic stress and the number of cycles the material can withstand before complete fatigue failure, the applied cyclic stress plotted as S versus the number of cycles as N , to give the so-called S-N curves, according to the governing equation:

$$D = \sum_{i=1}^{n} \frac{n_i}{N_i}$$

Where,

D = the damage accumulation

n = the expected number of cycles

N = the total number of cycles required to cause failure

The damage (D) is not measured or related to any physically parameter. but it is calculated by the S-N fatigue approach using Finite Element (FE)-fatigue approach (DNV-Sigurdsson et al., 1996), Figure 9 illustrates an example for S-N curve for a fatigue life assessment for evaluating the acceptance criteria for planning in-service inspection, Finite damage model is a reliable tool to evaluate the crack size and growth rate (Afshin et al.)

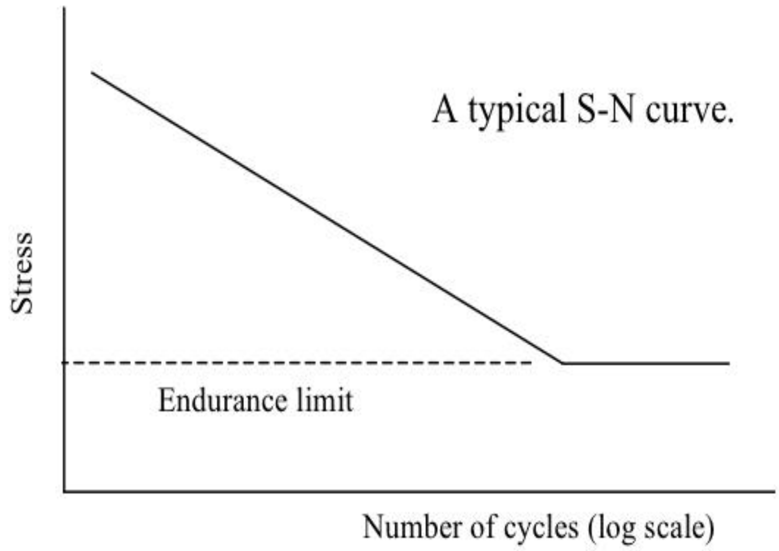

Figure 9: S-N Curve

Materials subjected to cyclic loading may fail even if the maximum stress is below their yield strengths, which accounted for at least 75% of all structure's failures (Benham,1996).

Many uncertainties are related to the fatigue analysis for offshore structures, either using the SN curves or the fracture mechanics-based model. These uncertainties due to the loading conditions, material parameters and stress intensity factor.

According to DNV-Guideline for offshore structural reliability analysis for jacket platforms-1996, the major time varying loads on jacket structures are wave induced loads. Where the long-term stress range is defined based on the sum of Rayleigh distributed stress ranges within each short-term condition, short term period is considered to be zero-mean stationary gaussian process, So, in terms of applying fatigue analysis, only the load caused by the fluctuating wave loading is considered.

2.9 Fatigue life assessment techniques

There are 2 main techniques for assessing the fatigue life for the structures which are used in industry.

1) Based on S-N curves

This method is used for assessing the fatigue life of a component or a structure.it starts by data collection, manufacture, service histories and the testing conditions, where the testing specimens are free of surface defects. The magnitudes of applied stress, material properties and manufacturing processes all must be obtained by the assessor to select the suitable S-N curve. then the fatigue life is estimated by the number of cycles to have fatigue damage.

2) Based on Crack growth rate

This method is using Paris's law to predict the crack growth rate during fatigue failure over the number of fatigue cycles da/dN. The crack growth rate can be measured as a function of the stress intensity range.

Most structures are not free from defects during manufacturing and fabrication processes, so it is more appropriate to assess fatigue life of the material based on their ability to reach critical size in the most critical regions in the structure. These critical points are called hot spots, which mostly represents the locations in the offshore jacket structure that have stress concentration factor (SCF),

SCF is defined as:

$$SCF = \frac{Hot\ Spot\ Stress}{Nominal\ Stress}$$

Where, hot spot stress is the value of the structural stress on the surface at the hot spot

Nominal stress is the stress in a component

The Figure 10 shows the hot spot stress as the red regions and the nominal stress as the yellow ones (Dnv-RP-C203). The High SCF represent the places where the cracks often initiated as in weld toes and riveted connections (May, et al. ,2009). by using FE modelling, according to DNVGL-RP-C203 to calculate the highest SCF it is possible to locate the most critical regions on the jacket structure, which the crack would probably initiates, so that the appropriate NDT sensor would be placed to monitor any defect at an early stage.

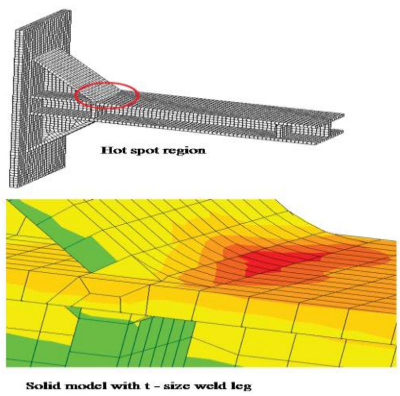

Figure 10: Hot spot stress for welded leg

3. Non-Destructive techniques

3.1 Overview

This chapter discusses the common non-destructive testing techniques for offshore structures according to the international standards in the current knowledge. Criteria for choosing the proper technique according their characteristics is presented. Introduction for Acoustic emission testing characteristics, limitations and applications are shown as well.

3.1.1 NDT Requirements

Structural Health monitoring was defined before as a monitoring tool that enables the Inspectors and surveyors to gather reliable data for the structural condition using either global or local detection methods. NDT is considered as a local detection damage technique that provides Real-time Monitoring under operational conditions (Amer, A.,2018). This method is Remote sensing, cost effective operation, safe process and reliable (Bickerstaff,2002).It is applied when a Structure is subject to periodic inspection in order to ensure its integrity, continued safe and economic operation. It uses non-invasive techniques to detect defects or structural cracks in the structure without damaging it. The Inspections are often performed by NDT methods such as Visual inspection, ultrasonic, eddy currents, magnetic particle inspection, dye penetrant inspection and radiography. It is used usually for some critical tasks such as:

Structural integrity by visual inspection, Identify the Corrosion effect through wall thickness measurement and Crack identification through various methods of NDT.

As stated in (DNV-GL CN7,2012) for testing methods requirements, The NDT techniques must be performed by certified and qualified personal with appropriate level in accordance with EN 473, ISO 9712 or another equivalent recognized standard e.g. NORDTEST.

According to ISO Standards, The Level 1 individual personal requirements to perform NDT under a Higher level of proficiency are:

- Knowledge to Set up NDT equipment
- The ability to perform the test
- Know How to record and classify the results from the testing operation
- Report the results to his supervisors
- Choosing the appropriate test methods or technique to be used but not the assessment for the test results.

3. Non-Destructive Techniques (NDT)

Procedures and Techniques shall be approved by personal certified to Level 3 in the application testing method.

NDT methods have different detection and capabilities for different degradation types.so it is very important to identify whether the testing method would be used for inspecting a specific small area of the structure or a detailed large are would be more suitable , also it is necessary to identify some factors which determine the type of NDT method should be used to implement the inspection operation (HSE-RR659,2019) such as:

- Geometry
- Materials
- Failure modes for structure
- Location and size of the defect
- Historic inspection data
- Cost of conducting the inspection

The possible defects can be inspected by NDT techniques according to Health, Safety Executive (HSE) for NDT Methods in inspection are as follows:

- Cracking in or near welds
- Cracking from welds
- Hydrogen damage
- Stress corrosion cracking
- Corrosion under supports
- Corrosion under insulation
- General corrosion
- Pitting and Erosion

NDT Types:

These are the common methods for NDT that are used for carrying out the Periodic inspections/ testing according to (DNV-RP-G103,2017).

1. Visual Testing

One of the oldest and most common NDT techniques.it is implemented by using ROV or a Camera system to detect major defects. Detailed visual inspection: it is another method for detecting any flaws by visual technique, but this method needs minimal cleaning for marine growth to detect cathodic protection condition, also this technique is used for detecting weld damage, corrosion.

This method is used by qualified surveyors, so it needs expertise, but it is the cheapest reliable technique compared to any other NDT technique. The modern type of Visual testing is Remotely visual inspection, in which the inspector uses a boro-scopes, UV lights and Micrometers to aid in the inspection process.

A boro-scope is a long, tubular optical device that allows the inspection of the narrow tubes or difficult points to reach as shown in Figure 11, a specialist holds a boroscope device to test some spots on the pipelines surface.

Figure 11: Visual testing using borescopes

2. Ultrasonic Testing

It is based on sending ultrasonic beams through the material of the structural, then receives the reflected waves to the same or different transducer. The generation of ultrasonic beams by means of piezoelectric probes which are excited by an electric pulse, the piezoelectric element vibrates and start to generate mechanical waves of broad frequency range 1 MHz-10 MHz

This method is used for corrosion monitoring by measuring the wall thickness of the specimen, fatigue crack detection and sizing as well. It also provides inspection coverage for the whole thickness of a specimen.it can be used on metals, plastics and woods.

Figure 12 shows an example for UT working principle (Structural diagnostics Inc.), in which there is the exciter and the receiver of the UV signals across the plate cross section.

3. Non-Destructive Techniques (NDT)

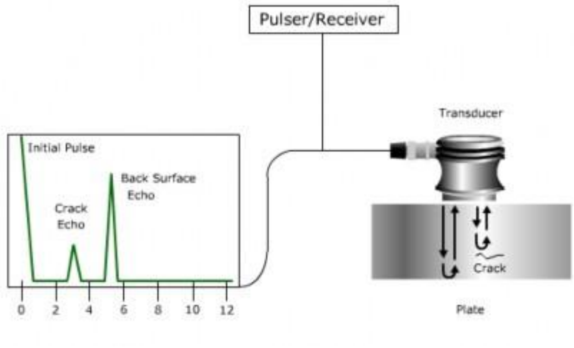

Figure 12: Ultrasonic NDT technique

3. Eddy current Testing

It is based on the principle of electromagnetism, where it induces electrical currents in the material being tested which magnetizes the specimen, so the materials demagnetize generating an eddy current, then the coil receives the interaction between the eddy currents and the material, then analyzing takes place and determines the defect existence and corrosion through the wall thickness measurement as shown in Figure 13 (Ndtt-homepage). Unfortunately, this method has limited depth penetration as the strength of the induced current decreases as the depth increases.

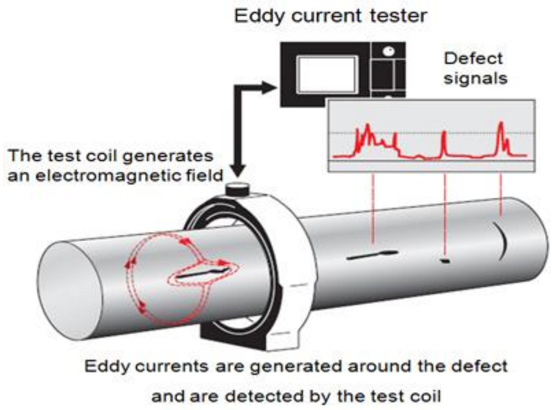

Figure 13: Eddy current testing

4. Liquid penetrant

The dye penetration is considered as a cheap method compared to the other NDT techniques, very easy to be applied. The LP method, initially the surface of the specimen needs to be cleaned, degreased and dried. The chosen penetrant is applied to the surface of the material and leaves the liquid penetrates through any discontinuities. A developer is then applied, after a period if there is any defect or discontinuity, the penetrate causes a marked local reduction in the developer contrast.

This method is considered as a slow process, but it can be used to detect very small cracks of about 1 um, surface cracks with high sensitivity. Figure 14 (LPT-homepage) shows the LP testing technique.

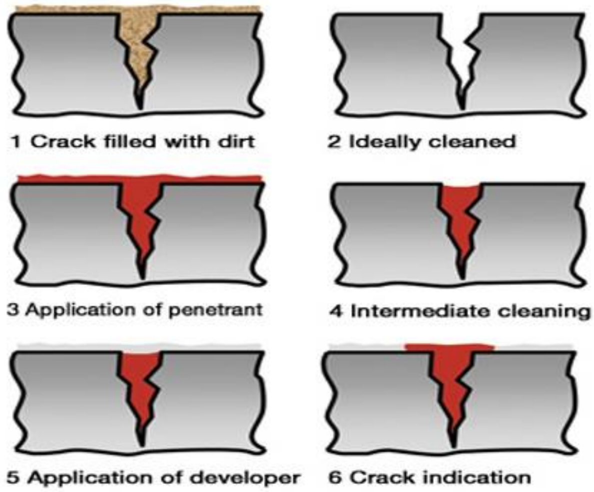

Figure 14: Liquid penetration technique

5. Magnetic particle inspection

It is based on applying a permanent magnet, electric current to have magnetization off the material either locally or overall. A magnetic field then is produced inside, if there is any defect in the material it will distort the magnetic field causing a local magnetic flux leakage. To reveal this leakage field a dry powder from ferromagnetic particles are sprayed onto the surface, which attracts the particles by the magnetic field and make the leakage visible. This method is used to detect surface and subsurface defects in ferromagnetic materials such as cracks, welds defects. It is very difficult to apply this technique in underwater structures, as it needs to be carried out in an isolated space room from water. Figure 15 (MPI-homepage) shows a simple sketch for the working principle.

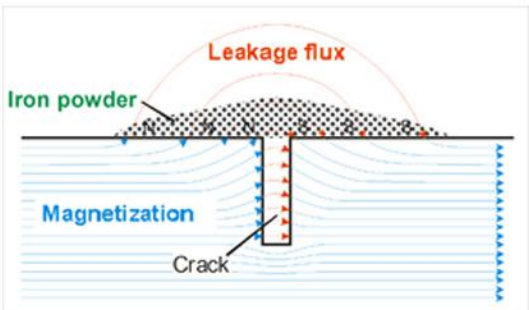

Figure 15: Magnetic particle testing

6. Magnetic flux leakage

The specimen is magnetized locally depending upon the level of induced flux density, if the specimen has any defects or deformation in its surface, the magnetic field is deviated, and the leakage flux is detected by detector coil, which indicates flaw detection. The output from the detector can be filtered, amplified and analyzed is used mostly to detect the presence of corrosion flaws. the maximum wall thickness can be tested range 10-15 mm. Figure 16 (MFL-homepage) shows the system components for testing by magnetic flux leakage.

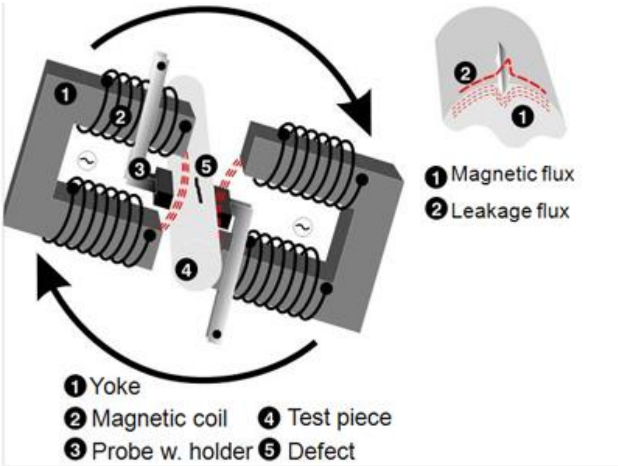

Figure 16: Magnetic flux leakage

7. Thermography Testing

It is based on measuring the temperature fluctuation due to flaw presence on the specimen surface. It is a passive method as the thermography can investigate the heat distribution of the structure with infrared camera, or it can be active method by inducing heat pulse into the structure element using an external source of heat as flash tube, which induces heat pulse into the material and by sensing the heat dissipation rate with infrared camera as shown in Figure 17 (Quality-homepage) ,it indicates the size on the flaw in the structure below the surface. This technique used only to detect flaws of several millimeters below the surface of the specimen.

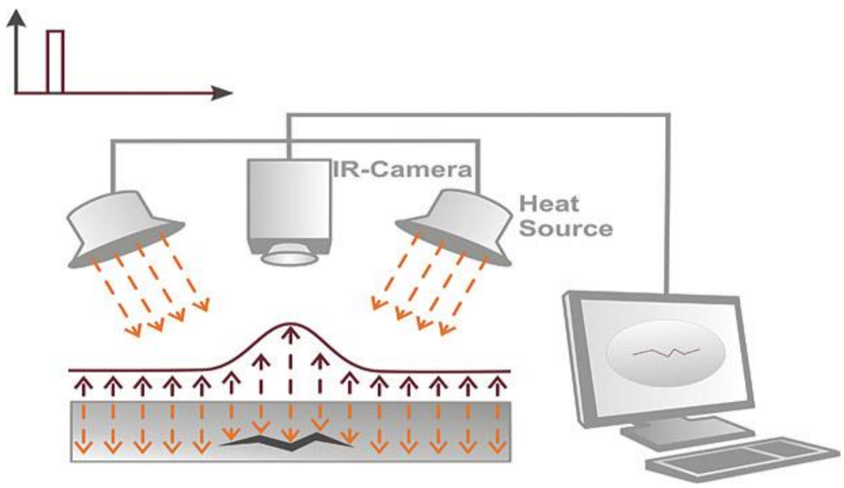

Figure 17: Thermography Testing

8. Radiography Testing

It is based on penetrating radiation phenomena, where the electromagnetic radiation such as X-rays, gamma rays are penetrating the piece of specimen, the radiation will be absorbed, and the rays will be attenuated due to the material thickness and the density of the material. The unabsorbed radiation will successfully pass through the specimen and can be recorded by a piece of film as shown in Figure 18 (Sitas-homepage). It means that thicker and more dense area of specimen will allow less radiation to pass through the testing material and vice versa.in general This method is used mostly for detecting appreciable thickness (loss of material) in a direction parallel to the radiation beam and welded joints in metallic materials.

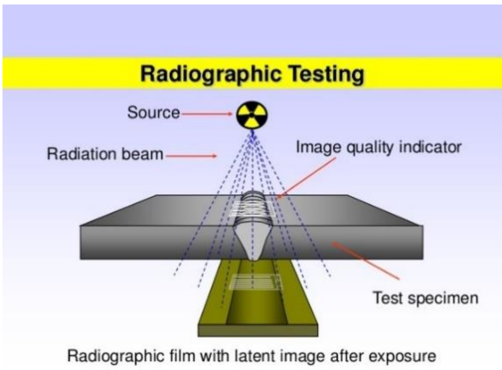

Figure 18: Radiographic Testing

9. Acoustic Emission Testing

It is based on detection high frequency elastic waves emitted from the flaw source in the material which is under deformation or stress, then converts these frequency signals into electrical signals by using piezoelectric transducers on the surface of the structure under load. The output from the transducers during structural loading is amplified through external amplifier, filtered from any external noises and eventually processed. This method has been used for detecting defects during structural operation phase, it can detect the weld defects, crack opening and growth and leakage as well. It is considered as a passive technique as it just listens to the sound waves from the flaw being under load without the need for external excitation as in Ultrasonic testing.

Figure 19 is showing the AE components to monitor the material under load or stress.as the load acts on the material, strain energy are being generated by the material and received by the sensor which is placed on the surface of the structure.

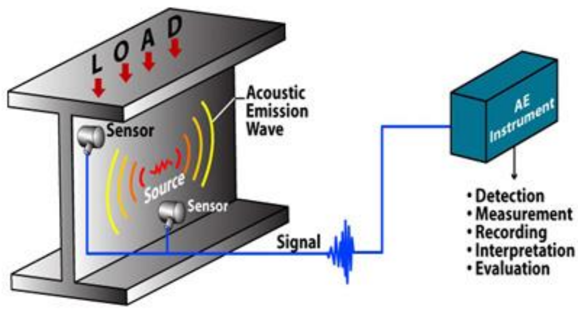

Figure 19: Acoustic Emission Testing

Several NDT techniques have been used for local structural health monitoring. most commonly are based in the use of mechanical waves such as; UT and AET, electromagnetic waves such as; Eddy current testing, radiography and magnetic particle testing.

- Appendix (A) summarizes the common NDT methods that have been used for local SHM of civil structures (Kaphle, 2012).
- Appendix (B) summarizes the NDT applications issued by Health & Safety and Environment (HSE)

3.1.2 Summary of NDT sensors applications

- Visual inspection (using ROV/Camera system): used to detect major defects such as Surface corrosion, Erosion, Pitting even weld defects.
- Ultrasonic Testing (UT): recommended for measuring structure wall thickness, detects corrosion.

- Magnetic particle Testing (MPI): used to detect surface and just below surface discontinuities in ferromagnetic materials such as cracks, welds. (very hard to apply it in subsea structures).
- Liquid penetrating Testing (PT): used to detect surface breaking flaws on the surface, but it is very slow process.
- Eddy current Testing (ECT): indicates wall thickness for evaluating corrosion as it doesn't need to remove the coating for inspection as in MPI, but the material depth for inspection is limited in this method.
- Alternating current field Measurement (ACFM): used for detecting and sizing surface defects.
- Radiographic testing (RT): detect only features which have an appreciable thickness (loss of material) in a direction parallel to the radiation beam., detect *the fusion of welded joints in metallic materials*
- Flooded member Detection (FMD)**:** used for inspection of through thickness cracks in braces in jacket structures, used for members that are air filled like braces.
- Acoustic Emission Testing (AET): based on detection high frequency elastic waves to electrical signals. When the structure start growing cracks and corrosion products, acoustic waves are generated passively by the structure itself during cracking and not induced by the sensor unlike UT technique (DNVGL-RP-G103,2017)**.**

Table 4 shows main differences between AET and other NDT methods.

Table 4 : AET vs NDT techniques comparison

Parameter	**Acoustic Emission technique**	**Other NDT techniques**
Sensitivity	More sensitive method	Less sensitive method
Access location	Requires access on sensors	Requires access to the area of inspection
Defect characteristic	Each defect has unique AE signal feature	Inspection is directly repeatable
Loading conditions	Requires loading conditions	Does not require loading condition
Parameter influences the technique output	Noise affecting the AE signals	Geometry of the structure is obstacle

Stated by (May et al., 2008) HSE for structural integrity monitoring Section 2.2, AET is used for monitoring Fatigue crack initiation, Fatigue crack growth and corrosion. Also, Acoustic Fingerprinting can be used for detecting through-thickness cracks for full-severed members in jacket structure.

NOTE: Acoustic Fingerprinting is based on the acoustic working principle, where it transmits acoustic waves to the defect structure and listen for any abnormalities in the reflection time of the acoustic signals. This method is considered as active method as it needs to send acoustic signals unlike the passive basic Acoustic emission method.

3.1.3 NDT Techniques in offshore Inspection

This section addresses the different NDT methods and techniques have been used in offshore industry. The purpose is to identify the current technology which is used for offshore structures inspection, the possible developed technologies that can be used in the future for structural monitoring.

The cost of inspections of underwater structures such as jackets can be very expensive, put a lot of strain on operational budgets, increasing the need for developing inspections programs .so the cost reduction is obtained by reducing the maintenance costs and unnecessary inspections, with ensuring cost-effective safe operation of the structure (Janbu.A.,2015.)

This can be achieved only by determining the Hot spots in the structure, which are the main critical areas expected to failure and needs continuous monitoring or periodic inspection to ensure the structural integrity as stated by (Sigurdsson,2015).

When implementing inspection on jacket offshore structures, some NDT techniques are favorably used than others, depending on the conditions for the testing process, material used, type and the location of the defect.

Failure fatigue was identified previously as the most common failure mode for jacket offshore structures and can cause significant damage to all offshore structures, therefore choosing the suitable sensor for structural health monitoring offshore jacket structures should be reliable enough for detecting the hot spots at an early stage for fatigue failure specifically.

According to DNVGL-RP-C210, using NDT technique for inspecting offshore jacket structure, EC and Alternating Current Field Measurement (ACFM) are used for detecting surface defects, Flooded Member detection (FMD) is used for detecting leakage in the Jacket leg members as a result of cracking, corrosion or weld defect. UT is used for wall thickness measurement to indicate the defect size and location precisely, General visual inspection (GVI) by using ROV can be used to detect cathodic protection condition on the surface of the structures and major defects.

But several disadvantages for these methods has limited their applications for underwater continuous monitoring in SHM systems such as:

Radiography is considered hazardous for health, MPI is only applicable for ferrous materials and very challengeable to be applied underwater as it needs removing the coating and cleaning before performing the testing then reinstalling a good quality of coating again which later leads to observing some local corrosion at the interested areas. ECT is not suitable for internal flaw detection due to their detection depth limit and UT is very expensive and needs an external exciter to send the high frequency waves to the material of the structure. Therefore, these techniques do not show suitability for all applications. On the other hand, Vibration Based detection technique provides global monitoring, therefore it maybe overlooks some defects occur in large structures (Willcox,2003).

Probability of detection (POD)

NDT is used for detecting and localizing defects in structures. The ability for detecting the defect size is defined as a function which is illustrated in POD curves (DNVGL-RP-C210,2015). These curves are provided for different methods in NDT such as:

- Flooded member detection (FMD)
- Magnetic particle inspection (MPI)
- Eddy current (EC)
- Alternating Current Field Measurement (ACFM)
- General visual inspection (GVI)

While for GVI and close visual inspection (CVI) are used for assessing the condition of the structure but cannot be used for detecting any fatigue crack before the size is large enough to be noticed along the plate thickness, after long process of cleaning and preparations for implementing the testing, which means that the existed POD for Visual inspection is based on personal judgments not test results like POD curves for other methods.

POD provides a basis on which it can compare between NDT techniques. All NDT methods must be evaluated with the same trial sample to be compared in realistic values. The POD should always be reported to the way the trial was carried out. However, the POD curves can hardly reach 100% detection probability even for deep cracks.

The governing function for POD for MPI, ACFM and EC are assumed to be similar and can be presented as the following equation (DNVGL-RP-C210,2015) :

$$PoD(a) = 1 - \left(\frac{1}{1 + \left(\frac{a}{X_0}\right)^b} \right)$$

Where,

a = Crack depth in mm

X_0 = Distribution Parameter (=50% median value for POD)

b = Distribution parameter

Table 5 shows different values for both b, X_0 in various conditions for EC,MPI,AFM techniques

Table 5 : DNV-RP-C210 PoD curves for EC, MPI, ACFM

Description	X_0	b
At ground welds, good conditions above water	0.40	1.43
Normal conditions above water	0.45	0.90
Below water, less good working conditions above water	1.16	0.90

For the 3 methods EC, ACFM and MPI as it is shown the probability for detecting a crack below water is much more difficult than above the water surface. Where 80% the Testing method can detect 1 mm crack above waterline, while with the same percentage it can only detects the crack when it reaches 5 mm in size as shown in Figure 20 below.

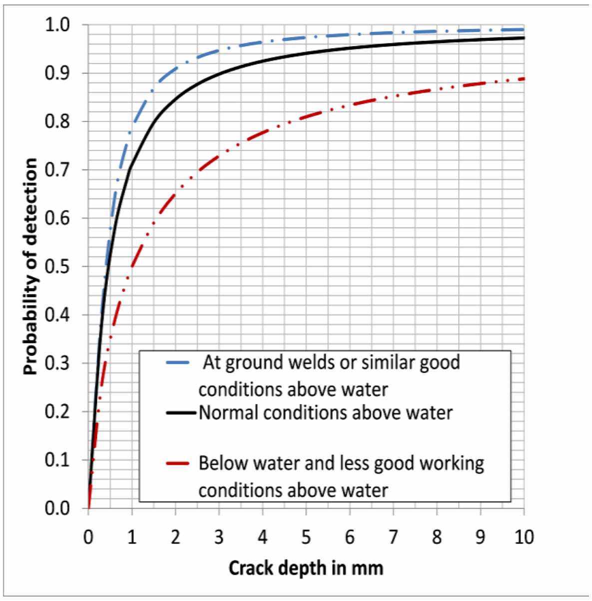

Figure 20: PoD Curves for EC, MPI and ACFM

For UT, same distribution equation will be used for POD curve, this technique is used for detecting internal cracks and sizing the defect in the material of the structure, also it is used for detecting weld defects.

Where,

a= Depth of the crack in mm

$X_0 = 0.410$

b=0.642

As it is shown in the Figure 21 below, UT can detect 4 mm crack size underwater, which shows that this technique is more reliable to detect fine cracks compared to the other technique mentioned above.

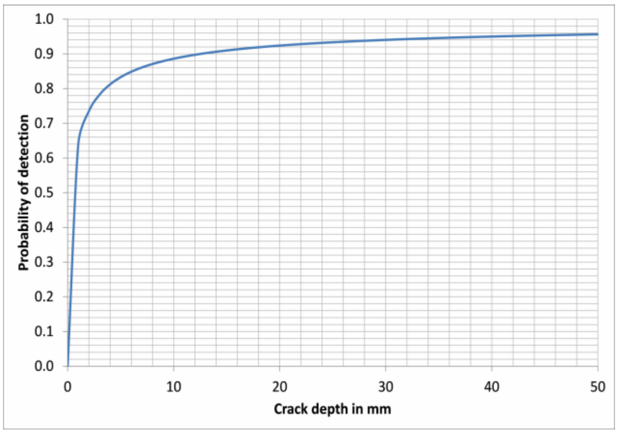

Figure 21 : PoD for ultrasonic testing

While for POD curves for Visual inspection, it is based on personal judgement assuming good cleaning for the inspected, depends on the type of the fatigue crack, if the fatigue is growing along the weld toe it will be more difficult to detect than a crack going through the plate thickness, besides assuming good light and vision conditions.

The distribution equation for visual inspection POD is as follows:

$$PoD(ax) = 1 - \left(\frac{1}{1 + \left(\frac{x}{X_0}\right)^b} \right)$$

Where,

x = crack length in mm

Table 6 shows different values for both b, X_0 in various conditions for visual inspection technique.

Table 6 : PoD for Visual inspection

Description	X_0	b
Easy access	15.78	1.079
Moderate access	37.15	0.954
Difficult access	83.03	1.079

As it is shown in the Figure 22 below, the visual inspection is much less reliable when it comes to the size of crack detection compared to the other NDT techniques, still it gives better judgements depending on the qualified person, the access to the surface being inspected of the structure.

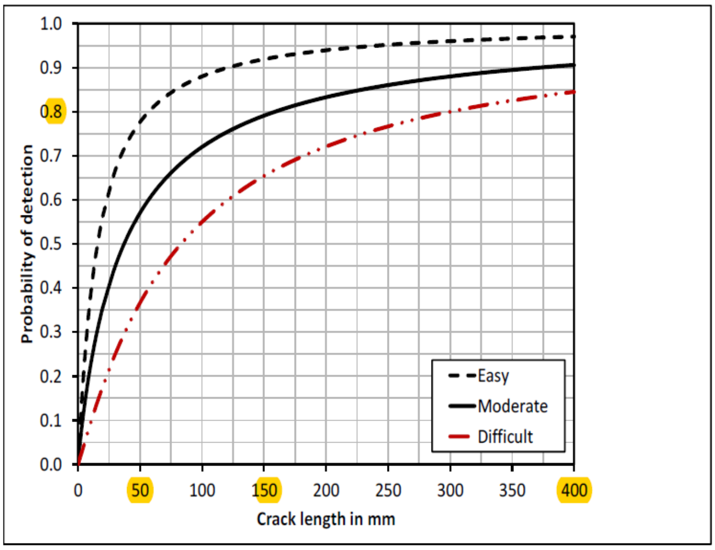

Figure 22 : PoD for Visual testing

According to DNV-RP-C210 section 11.4

Reliability of POD for other NDT techniques depends on some parameters such as:

1. Capability of the actual method
2. Degree of expertise of the operator
3. Inspection procedures used
4. Auditability

Table 7 was produced by (Vestli, H.,2016) for the most applicable sensors for local monitoring in offshore, which summarizes 5 of the most important parameters the applicable sensors for offshore inspection should have.

- Structural noise is representing any external noises produced by waves, machinery on the topside of the platform, helicopter landing.
- Electromagnetic noise immunity represents noise from lightening or any electromagnetism source around the sensor which can affect the signals gathered by the sensor.
- Mounting location is an important factor when determining the sensor type, possibility of mounting the sensor exterior or interior of the structure member needs to be tested is of importance.

- WSN compatibility is a future feature, as the Future application for SHM on offshore structures is aiming towards using WSN systems.
- Maturity is a critical factor when evaluating the sensor application history on offshore structures.

Table 7: Different techniques for testing offshore structures

Technology	Sensor Type	Structural Noise Immunity	Electrical interference immunity	Mounting Location	WSN compatibility	Maturity for Offshore Application
Electrical	Fatigue gauge	Low	Low	Surface	Yes	Low
Piezoelectric	AET	Low	High	Surface/ Embedded	Yes	Medium
Optical	FBG (Fiber Bragg grating)	High	High	Surface/ Embedded	Yes	Medium
Ultrasonic	GWT	High	Low	Surface	Yes	Low
Radiographic	FMD	High	High	Surface/ Embedded	N/A*	High

AET shows High maturity for testing on offshore structures, also High electrical interference immunity, can be mounted both on the surface or embedded (Underwater AE Sensor with Integral Preamp, physical acoustic).but it is strongly affected by any external noise due to its high sensitivity, hence various means of filtration and amplification methods are needed for proper evaluation for the gathered data.

In this study the purpose is to show the reliability for using Acoustic emission testing in detecting defects at an early stage in Steel materials, show how it can be used for SHM for Jacket structure to maintain its structure integrity besides extending the designed lifetime for jacket offshore platform.

3.2 Acoustic Emission Testing

3.2.1 Brief history

J. Kaiser in 1950 was the first scientist to research the Acoustic Emission technique extensively, but he didn't name it as acoustic emission at that time but as Acoustic phenomena, later Schofield in 1961 provided a detailed explanation and understanding of the Acoustic emissions and called it acoustic emission (Khan,2018).

AE can be defined by American Society of Testing Materials (ASTM) as the phenomena where the transient elastic stress waves are generated by the rapid release of energy from localized sources within a material. The acoustic is related to Hearing, as any structural collapse produces sound waves prior to failure (Muravin,2009)

The AE technique differs from other NDT methods in two key aspects: 1) The signal emitted from the defect source from the material itself to an external receiver or source; 2)AE detects the movements or any deformation while they occur ,unlike other NDT methods they detect existing deformations or defects in the structure (ASNT,2005) .

At the time of fracture, Huge release of stored energy occurs with the cracking phase, as a result of micro cracking, some of the elastic stress waves are released which is defined as Acoustic Emission Waves (Ohtsu, M.,1996). AE is a powerful technique for examining the behavior of materials deforming under stress.

Any form of changing pressure, temperature, load and any micro fracture inside the material releases energy in the form of AE wave, AE method is considered NDT technique, which is based on detecting high frequency elastic waves and transforming them into electrical signals. This is done by directly coupling transducers on the surface of the specimen or structure under test.

Nowadays, A lot of research and studies are conducting on AE Formation inside materials, as it is widely used in NDT of materials and structures especially in SHM for damage detection. In many of the NDT methods, the method for testing or inspecting is using an active sensing method for structures, where energy is delivered from the outside source to the testing material.in contrary to active NDT, acoustic wave does not need any external exciter to supply the testing material. The internal energy is released from the source of defect itself inside the material under stress and received by the acoustic sensor, used in Health monitoring features. Due to its high sensitivity and accuracy, acoustic emission is becoming one of the main NDT in SHM systems (Paipetis et al., 2012).

An advantage feature in using AE in monitoring the structures health, is its application ability in its loading condition. Therefore, it can provide the defect information data instantly within a very short period of time. That's the reason for using AE monitoring inspections during the operating conditions of the structure. Which prove that AE technique is a valuable monitoring tool for detecting the damage at an early stage.

Among the many attractive features of AE technique, source Location feature for the defect inside the structure, by using different algorithms methods and analyzing the AE hits, source location is defined. For example, if a single degree of source location is needed two sensors will be used to locate the defect, while if two-dimensional source is needed three sensors are used to locate the defect, and more than 3 sensors can be used to locate a defect with more than two-dimensional source (Rindorf HJ ,1981).

In addition, to the many advantages using AE for testing structural condition, the entire structural damage can be detected under the whole loading conditions by several sensors, which are placed on the surface of the structure. No replacement or prior cleaning is needed for carrying out the testing by AE technique. The only obstacle using the Acoustic emission technique is identifying the Real defect data from the noisy signals which has high influence on the data evaluation.

Therefore, AET for SHM has been widely applied in many industries such as Biomedical, Civil structures, Aerospace field as well.

3.2.2 AET Technique

AE waves are elastic stress waves that are generated from the material when it is subjected to any kind of stress. The generated waves propagate through the material's surface, AE technique is recording the elastic sound waves produced by the material under loading by means of mounted sensors on the surface of the structure being tested, analyzing these signals to identify the source of the information gathered. In AE technique, a piezoelectric transducer, is the kind of sensor used to detect any dynamic motion occurred by the elastic wave as mechanical motion and converts it into electrical signals, which then is defined as AE signal.

AE sensor is selected according to the operating frequency; hence, various types of AE sensors are commercially available based on their frequency range (Nishinoiri, S.,2004)

A simple representation of acoustic emission phenomena is showed in the Figure 23 (AE-NDT), where the structure surface is under load and elastic waves are generated from the flaw source in the material, propagate in all directions. The sensor is attached on the surface of the structure to detect any waves and the electric signals are sent to the acquisition system for evaluation. Only the growing cracks and any active deformation under the stress are recorded by the AE sensor, hence the present cracks which are not growing and in stable stage are not emitting elastic waves and so no AE signals are received.

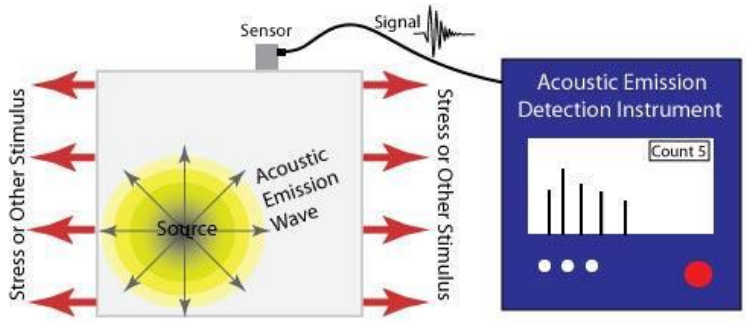

Figure 23 : AET working principle

3.2.3 AE Sources

The common sources of AE in Structural materials are generated from the initiation and growth of cracks, yielding, failure of bonds, fiber failure and pullout in composites. (Kaphle,2012).

The Materials in which AE has been used on and the source mechanisms which causes AE waves are shown in the Table 8 according to (W.H. Prosser,2002)

Table 8 : AE sources

Materials	**Metals** **Ceramics** **Polymers** **Composites** **Wood** **Concrete** **Rocks**
AE Sources	Microcracking as intergranular cracking Macrocracking as Fatigue crack growth Dislocation movement Phase transformation in metals Yielding in metals Fracture of particles Fracture of fibers Debonding of inclusions Realignment of magnetic domains

	Delamination in layered media Rock bursts Fault slip (Earthquakes)

Acoustic emission can be categorized into two types: primary and secondary emission. Primary emission is generated from internal sources of metals associated with microstructural mechanisms, on the other hand the secondary is generated from stress wave sources or external material surface with different mechanism (Holford, K.,2005).

Through literature study, Table 9 was made by (Zohora, 2016) which summarizes various examples for the primary and secondary material Acoustic Emissions

Table 9: AE emission type

Emission Type	**Examples**
Primary AE	Plastic deformation, crack growth and crack Initiation.
Secondary AE	Leakage, corrosion layer fracture, crack surface friction and fatigue from crack face closure.

Classes of AE in metals:

- **Material AE**: generated by local dynamic change in the material such as: Crack jumps, plastic deformation, phase deformation and leaks
- **Mechanical AE**: generated by a mechanical source such as: Friction and impacts

Factors that influences the AE amplitude signal in Metals (mboria, 2011) are shown in Table 10 as follows

Table 10: Material Parameters affecting AE amplitude

Increase AE amplitude	**Decrease AE amplitude**
High strength	Low strength
High strain rate	Low strain rate

Low temperature	High temperature
Brittle failure	Ductile failure
discontinuities	No discontinuities
Martensitic phase transformation	Diffusion controlled phase transformation
Mechanically induced twinning	Thermally induced twinning

- In metal structures, the AE technique preferred for detecting crack growth at early stages even for subsurface of the material down to a few hundred square µm and less (Finlayson et al.,2001), furthermore the most detectible AE signals can be recorded when a material undergoes plastic deformation under loading or close to the yielding and fracture stress. The presence of corrosion on a the surface can be as well detected, as bubble formation generates Acoustic emission signals (Beattie, 2013).

3.3 AE instrumentation

AE monitoring system basically consists of AE sensors, amplifiers, AE filtering acquisition system , software data analysis and storage PC.

The Figure 24 shows a schematic diagram of an AE monitoring system chain from the couplant to the data displaying on pc screen after processing.

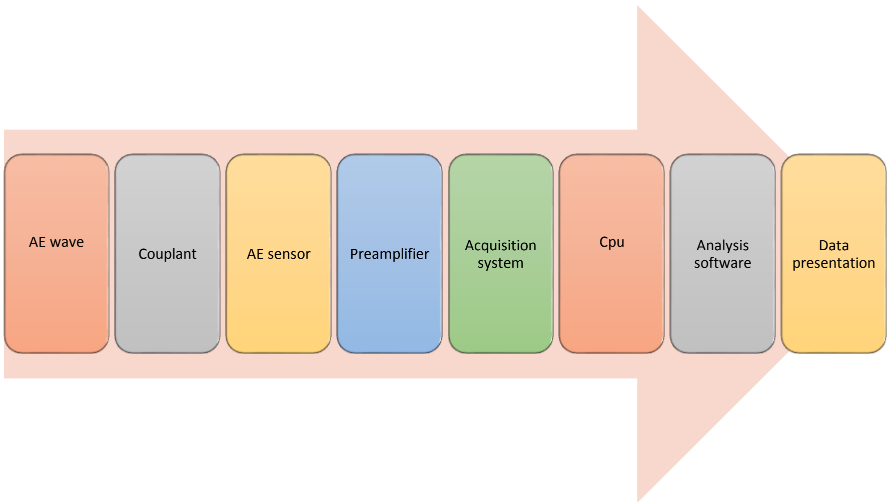

Figure 24: Schematic diagram for AE monitoring phases

AE system objective is to detect, amplify, filter, process, evaluate the signals. The ideal AE system consists of AE sensors, preamplifiers, acquisition system, CPU and an analysis software. Each item has its own role.

1. Couplant

The couplant is placed on the surface of the material under the load, the surface of the material produces weak AE signals, so the need for correct coupling between the sensor and the material is necessary to ensure good measurement of the AE signals. Various types of the couplant are used between the sensor and the surface according to the application to ensure good contact at a microscopic level. A couplant material fills any air gaps between the sensor and the surface of the material to avoid any loss in the transmission AE signals.

There are numbers of couplant types according to the application such as; gel, liquid or grease.

Before selecting the type of the couplant, the application type and how the sensor will be used should be considered, also other considerations will identify the type of couplant as listed below (Guide on Acoustic Emission Sensor Couplants, 2012):

- measurement duration
- whether the sensor is temporarily / permanently bonded
- environmental conditions i.e. temperature, humidity
- wave type to be measured

Table 11 shows different couplant types for AE applications, considering different parameters for comparison.

Table 11: AE Couplants Types

Parameters/Type of couplant	**Gel**	**Grease (most common for AE measurements)**	**Dry couplants**
Types	Ultrasonic gel, glycerin	Silicon based grease	Elastomer
Advantages	Easy to apply	Long term stability	Avoid drawbacks of wet couplants
Disadvantages	Dry out over time	Difficult cleaning after use	Poor transmission of AE
Mounting method	Vertical mounting	Vertical mounting	Elastomer adhesive

Temperature range	low	medium	Low/medium
Viscosity	medium	high	Elastic solid
applications	Rough surface,	Rough surface	Ultrasonic inspection

Surface preparation for coupling

To increase the couplant efficiency, the oxidation layers and paint should be removed for better signals transmission, the trapped air should be minimized. the smoother the surface the better the couplant will work otherwise choosing a couplant which suits the rough surfaces would be better for measurement. A layer of couplant is placed on the center of the sensor face and pushing the sensor down on the surface of the specimen, so that the couplant spreads out toward the edges of the sensor.

2. **Mounting methods**

The type of mounting method for the sensor on the surface of the structure is defined by the application conditions (mboria,2011);

- Glue is commonly used for piping testing
- Magnets are used for holding the sensors on metal structures
- Bands used for long term applications
- Waveguides (welded attachments) are used in high temperature conditions

Figure 25 below show different mounting methods for AE sensors

Figure 25: Mounting methods for AE sensors R: Magnetic holder and L:Wave guides

3. Types of AE Transducers

Acoustic emission sensor is categorized into several types according to the transducer's working principle. Most of the AE sensors are typically piezoelectric sensors with elements (PZT). which converts the mechanical displacement into electric output signal to be processed later. Other types of sensors are using capacitive transducers or laser interferometers.

3.1 Piezoelectric AE Sensor

Piezoelectric sensor is the most commonly used type among all the AE sensors in NDT testing, due to its high sensitivity and robustness (Beattie, 2013), thermal stability, balanced actuator and sensor constants (Ye et al.,2005) while the other types are limited in their applications.

The piezoelectricity is given to the coupling between the strain deformation and the electric polarization which occurs in many crystal materials (Cady,1950). the objective of the piezoelectric phenomena is to convert any dynamic surface motion into electric voltage output and vice versa.

A typical AE sensor is using (lead zicronate titanate) PZT element in most applications, which transforms elastic displacement of 1 pm (10 E-12 m) into electrical signals of 1 µV (Ohtsu,2008).

Transducers are chosen based on:

- Operating frequency
- Sensitivity
- Environmental & physical conditions

Most of AE sensors have operating frequency range of 30 kHz to 1 MHz

Wear plate is mounted on the surface of the sensor and the piezoelectric element locates inside. a schematic of AE sensor is shown in the Figure 27 (PZT).

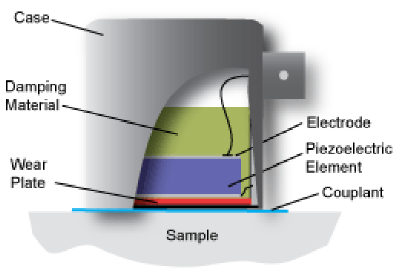

Figure 26: AE piezoelectric transeducer

The piezoelectric element thickness controls the frequency at which the sensor can be sensitive for. while the element diameter defines the area over which the sensor averages the surface motion (mboria,2011).

Also, the temperature plays an important role in the piezoelectric efficiency, the piezoelectric ceramics undergo permanent change and loose the piezoelectricity phenomena at a certain temperature called Curie temperature. Fluctuating temperature also affects the output signals from the piezoelectric material which results to spurious electric signals that are very difficult to be identified to an AE event. In this case single crystal piezoelectric (quartz) or lithium niobite are recommended for applications with fluctuating temperature

3.2 Capacitive AE Sensor

Capacitance is the property that exists between two conductive parallel surfaces within some reasonable proximity. This type can be used for both active and passive sensing. It is used mostly in lab experiments and research fields due to the highest sensitivity while consuming low power consumption (Hsu,1998) .it relies on capacitance variation when the geometry of a capacitor is changing due to any deformation in the surface of the structure being tested.

The working principle depends is considered as an electromechanical system, consists of a fixed backplate electrode, flexible diaphragm which is separated by a dielectric material as air, to form parallel capacitor. Any variation in the air gap distance due to acoustic elastic waves will provide capacitance variation, which indicates existence of surface deformation (Haque et al.,2015).

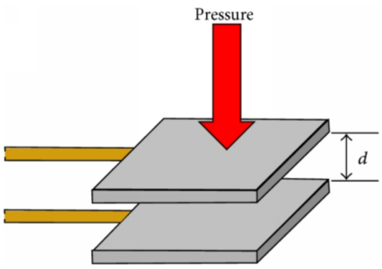

Figure 27:AE capacitive transducer

This sensor is used for flat frequency output, majority of these sensors are specialized for audio applications with uniform sensitivity for wide frequency range,20 Hz-20 kHz (Shu,2008)

3.3 Laser optical Interferometer AE Sensor

This type has been used for remote sensing applications, where there is no accessible space for sensor mounting on the surface of the structure. Acoustic signals create phase change at the optic acoustic probe and this phase changing is detected by the interferometer. Then converts into electrical signals.

it has some advantages over the other types, such as electromagnetic interference immunity, no electrical connection at the sensing point, resistant to harsh environment and light weight.

It has been used in chemical, biomedical, underwater acoustic, temperature and strain sensing (kersey, A.D.,1996).

It can be categorizing into 2 types stated by (Bilek,2015);

1) Intensity based sensors: consists of mechanical optical design, using the light intensity as the sensing parameter. When there is any vibration or deformation in the surface, acoustic signal generated will change the coupling of the light passes through from one end to another end and this will measure the deformation amplitude.

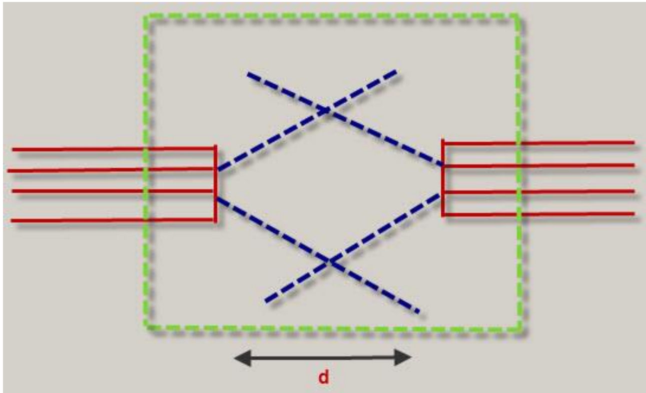

Figure 28: AE laser-intensity based sensor

2) Phase detection-based sensors: detects acoustic signals by strain generated by any pressure changing on fiber optic cable, strain changes the length of the sensing fiber and leads to changing the light optical path and phase of the light through the fiber cable. The photodetector converts optical signal to electrical output signal.

When the light source passes through the interferometer, the light separates into two beams. Where one beam is connected to the sensing environment and the other is considered as a reference which is isolated from the sensing environment. The two separate beams are recombined again and received by the detector. The most commonly used techniques are Michelson, Mach Zehnder which are shown below in Figure 29.

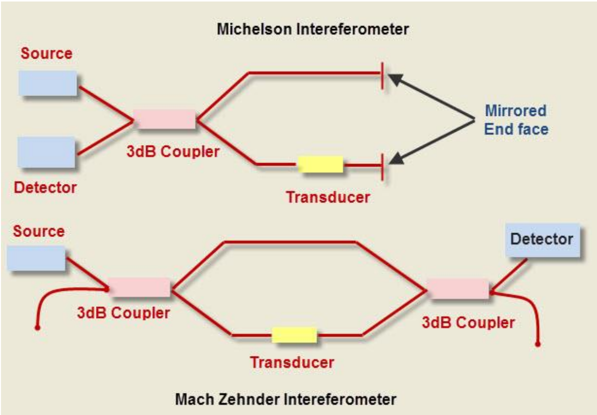

Figure 29: AE laser-phase detection-based sensor

The difference between the two techniques is that in the Michelson interferometer requires only one optical fiber coupler, as the light passes twice through the sensing and the reference fibers, so the optical phase shift per unit length is doubled. Thus, it is considered as more sensitive than the Mach Zehnder interferometer. Table 12 shows a comparison between both techniques.

Table 12: Intensity vs Phase detection-based sensor

Criteria/Type of sensor	Intensity based sensor	Phase detection-based sensor
Advantages	• Simple signal processing • Inexpensive • Simple to implement	• Can be accurately calibrated • More sensitive than intensity-based type
Disadvantages	• Susceptible to fiber bending losses • Variation in light intensity • Limited sensitivity	• Self-phase noise • More expensive equipment

This sensor has been useful in various applications such as:

- Physical properties such as (temperature, displacement, velocity, strain in any structure)
- Real time monitoring for the health of the structure
- Bridges, tunnels and dams

Limitations for using laser interferometers

- Handling or setting up the sensor is difficult
- Active sensing method unlike the piezoelectric, capacitance Acoustic sensors
- Laser source is considered as noise source which affects the performance of the sensor system

4. Pre-Amplifiers

AE signals generated from the material under test are often very small to be detected; therefore, pre-amplifiers are needed to amplify the extremely small signals recorded by the AE sensors before further filtration or processing. The typical amplification gains range from 40 to 60 db. The amplifiers are categorized into 2 types:

1) Integrated amplifiers which are built inside the AE sensor itself, this type is used where the signals are very small and need more amplification before passing through the main amplifier or when the sensor is used in inaccessible surface as in wet conditions.

2) External amplifier which is a separate item.

both types are used to amplify the signals with a possibility to set the frequency filter range, then can be fed in to the data Acquisition system to be processed and filtered.

The Figure 30 (Cheng,2002), shows a schematic diagram for AE technique, the preamplifier is used as a primary amplification method while the Main amplifier is used as a secondary one in some applications, while others only using one amplifier, which is the main amplifier only (Khan, 2018.)

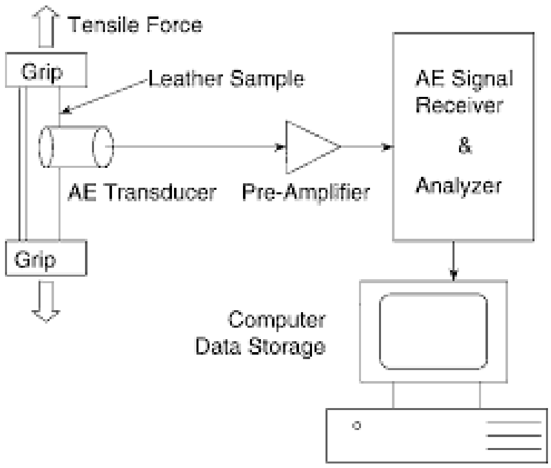

Figure 30: schematic diagram for AE monitoring system set-up

The gain (G) is the ratio of the output to the input voltage, expressed in decibels (dB). Equation … represents the relationship between the gain (G), the output voltage(V(o)) and input voltages (V(i))

$$V(o) = V(i) * G$$

The equation below represents the conversion equation from the gain factor into decibels(dB)

$$dB = 20Log_{10} * G$$

To bring the signal to an appropriate level for measurement, the gain can be either fixed feature or variable features controlled by the operator.

5. AE acquisition System

The amplified signals are transmitted to the Data acquisition system for filtration and signal processing. Nowadays, AE systems use digital processing techniques with more improved real time performance. AE acquisition systems have been developed to include time-based or continuous features, hit-based time domain features, frequency and combination-based features (mboria, 2011).

The Figure 31 shows a schematic chart for the processing functions in a simultaneous order inside the data acquisition system.

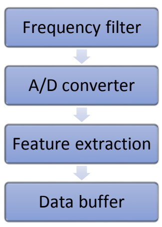

Figure 31: schematic chart for AE data acquisition system

AE data acquisition system parameters are listed as follows:

- A/D converter: Analog to digital converter
- Maximum signal amplitude in (dB) can be detected
- High pass filters for each channel (can be controlled by software):to filter the electronic noise high frequencies signals, Normal ranges (10,20,200 kHz)
- Low pass filters for each channel (can be controlled by software):to filter the low mechanical noise low frequency signals, Normal ranges (100,200,1200 kHz)

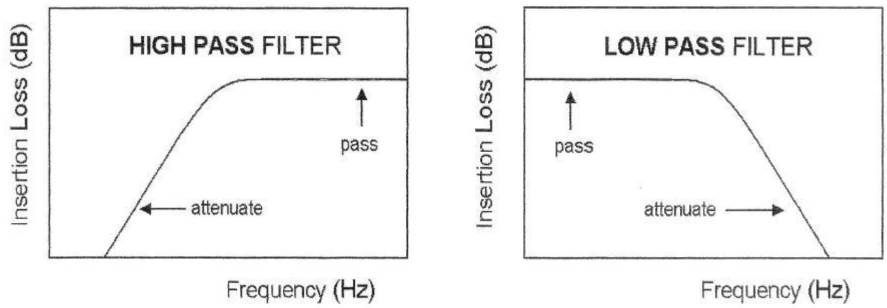

Figure 32: Frequency Filters

- Digital signal processor: microprocessor to measure, filter continuous AE signals.
- Wave form buffer: is a technique for digital synthesis of repeating waveforms, used in digital processing for the AE signals

AE monitoring is performed in the presence of external background noise, which are caused by other sources than acoustic emission (mboria, 2011).

Types of sources:

- Mechanical noise: any motion occurred by mechanical parts in contact with the structure
- Hydraulic noise: turbulent flows and cavitation
- Cyclic noise: repetitive noise from rotating machinery such as fan, motor or pump
- Electro-magnetic noise such as Radio, television transmissions and satellite

In acquisition systems the filtration technique is not only using high and low filters, but also Thresholds are used to eliminate any unnecessary signals detected by the sensor.

The threshold is the most important setting for AE measurement burst signals. Only the AE signals that have crossed the pre-defined threshold level are recorded for further anlaysis.so the threshold can be defined as the minimum amplitude for the AE signal that can be recorded.

it is controlled by the operator after identifying the background noises levels. so, it can be adjusted over the maximum background noise to eliminate as much low fake AE signals as possible, which are not emitted from the material deformation source. But care must be taken so that no critical signals are missed during recording.

Setting the threshold too high will prevent important signals from being detected, while setting it too low will cause the background noise to be detected and unwanted data will be recorded. so accurate adjustment for the threshold value is very critical for proper AE filtration.

Floating threshold /Smart threshold: is used when there is varying background noise which changes with time.so it is used to distinguish between the AE and the background noise under high fluctuations of background noise.

The Figure 33 (muravin) illustrated an example of floating threshold.

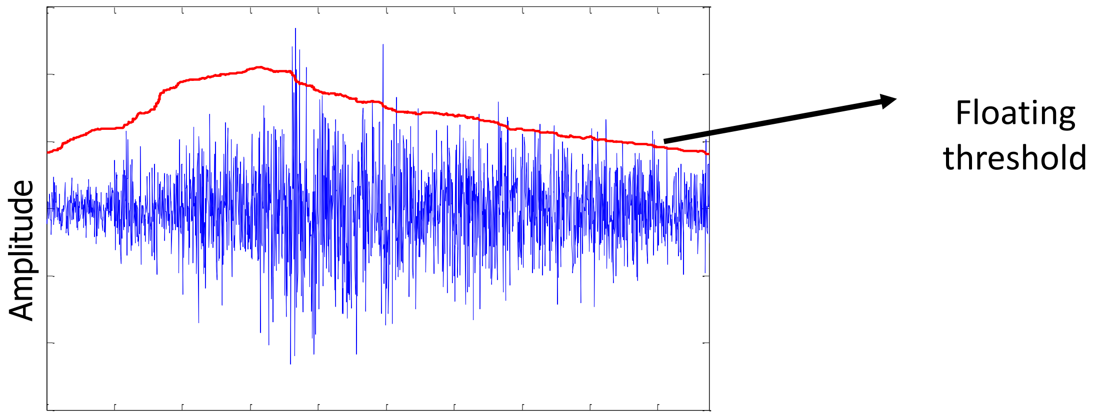

Figure 33: AE Floating threshold

Classes of AE sensors

In terms of frequency responses, AE sensor can be classified into; Broad/Wide-band or Resonant-band sensor.

The broadband is used in research applications mostly where a high-fidelity AE response is needed.it has a flat frequency response. it provides better frequency band for noise discrimination and provides more information about the AE source as it provides wider range of frequency.

On the other hand, the resonant type is more sensitive for small frequency range, as it resonant at their characteristic frequency.it gives higher amplitude response compared to the broadband type (mboria, 2011). this type is more used in the applications due to its high sensitivity, less cost to the broad and type better signal to noise ratio unlike the broadband type which has more background noise and less sensitivity (Golaski,2002). So, care is needed to choose suitable frequency range for resonant sensors according to the application.

The Sensor response is governed by these parameters:

- Piezoelectric crystal
- The way the element (PZT) is mounted inside the sensor housing/frame
- Coupling and mounting method of the sensor

Figure 34 (Labuz,2017) , shows examples of frequency response characteristics of AE sensors. Where graph a) using a resonant type sensor, R15 with a resonance frequency 150 kHz, in graph b)using broadband type sensor, UT1000 . both sensors from Physical acoustics corporation, USA.

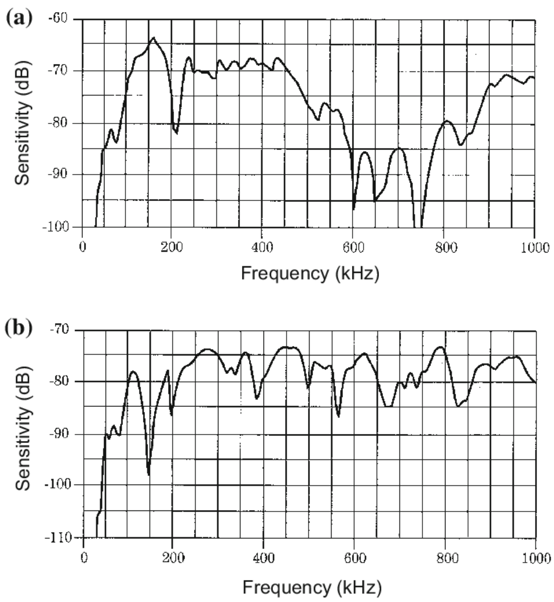

Figure 34: Resonant vs Broadband AE sensors

In graph a) it is obvious that the peak amplitude for the resonant type to detect is at its characteristic resonant frequency which is 150 kHz, while for the broadband in graph b) it is the same flat frequency response for all the frequency range.

3.3.1 Advantages of AE Technique

Many NDT techniques have been used by researchers and scientists for health monitoring of structures, the inspections are applied before or after the loading to detect any defects in the structure. Most of NDT techniques are based on sending an external exciting or energy subjected on the testing structure then by receiving back the refracted/reflected energy, the condition of the structure can be determined. This method called as active sensing, Unlike AE, is a passive sensing method, where it doesn't need to excite the testing structure, its role is only to detect any acoustic elastic waves as a result for any deformation occurs to the structure under loading.

AE is a very sensitive technique and has high accuracy to monitor any minor defects and crack growth initiated inside the material. the special feature about using AE in health monitoring application, its ability to give instant damage indication while the structure under loading. Real time analysis of the received acoustic signals can then provide information about the source of the deformation using evaluating software tools. This dynamic feature enables the AE to detect any damage in an early stage during the normal operation conditions, therefore easy and accurate measures against any damage or defects can be taken (Hamstad,2002).

Although AE is considered as a local technique for monitoring applications, it can be used for global analysis for the whole structure by using several AE sensors under loading conditions (Khan, Md.,2018). also, it can be applied for periodic and continuous monitoring applications.

Current AE techniques can locate the source of the damage inside the material, which attracts the industry to use it for SHM. source location is performed by Appling some preferable algorithms, using the Time of Arrival (TOA) method. Based on the number of sensors and dimensions of the structure. For example, if two sensors are used, a single degree of source location is applicable; if three sensors are used, two-dimensional source location is applicable; if three or more sensors are used, three-dimensional source location is applicable (Rindorf,1981). In section 3.9 location techniques is to be illustrated and explained.

3.3.2 AE Limitations

As any testing method, AE has some limitations and challenges needs to be addressed for proper analysis of AE signals.

- AE technique as mentioned before is considered as a very sensitive testing method to any crack growth, defect initiation and for any formed crack surface down to a few hundred square micrometers (Finlayson,2001).so the acoustic signals needs to be amplified, filtered from associated noise, attenuation and other factors so proper evaluation can be established.

- AE unlike other techniques cannot be used to detect existing defects in the structure.as it is only effective method for monitoring while the structure under stress or loading conditions, therefore if there is an existing flaw, AE won't be able to detect it; if the crack is not growing or in stable condition. That’s why it is recommended to mount the AE sensors at an early stage on the surface of the structure to be able to detect any initiated flaw for SHM systems.

- Each defect source produces different AE signal characteristics according to several parameters such as; material properties, shape of the specimen, type of the flaw, stage of the flaw, environment conditions and location of the flaw inside the structure, all these factors are affecting the AE signals characteristics.

- Acoustic attenuation is one of the major challenges in using AE for monitoring. Attenuation’s definition stated by (ISO-5577,2017), is the decrease of sound pressure during wave propagation through the material of the structure, as a result of absorption and scattering due to several factors. Where absorption represents any lost sound energy in the form of another type of energy as thermal energy. while scattering represents any reflected signals inside the material itself caused by the grain structure before being received by the sensor.in other sources it can be called signal dissipation. Scattering is more dominant than the absorption in the region close to the source as it represents the internal friction inside the material itself besides the dissipation of the signals intensity through passing different mediums or materials. Where the signal amplitude decreases inversely proportional as the square root of the propagation distance (Holford,2008). on the other hand the absorption is dominant further away from the flaw source, where SHM systems are made, it has an exponential relationship with the propagation distance.

Stated by (Schumacher, T.,2008) in concrete and fiber composites, the AE waves are attenuated at a rate of 45-118 dB/m, while for steels at a rate 0.1-1 dB/m, maybe that’s the main reason why most of AE applications were implemented on metals, therefore several sensors should be mounted on large structures for reliable evaluation of AE signals.

Figure 35 shows the acoustic sound wave propagation through 2 different mediums or materials, having different acoustic properties

The acoustic wave emitted from the flaw source inside the material, passes through another material or through another medium (from water to air or vice versa). Where the signal will be refracted by the medium effect or reflected with other objects in the beam passage.

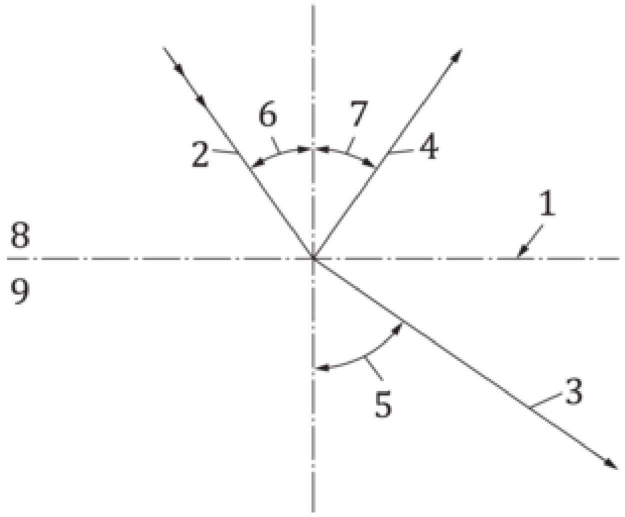

Figure 35: Sound wave across different mediums

1. Interface medium/material
2. Direction of the incident wave
3. Direction of the refracted wave
4. Direction of the reflected wave
5. Angle of the refraction: the angle between the normal to the interface and the refracted wave
6. Angle of the incidence: Angle between the normal to the interface and the incident wave
7. Angle of the reflection: Angle between the normal to the interface and the reflected wave
8. Represents the first medium/material
9. Represents the second medium/material

Most of these reflected waves are due to the presence of corners formed by two or three coincident, mutually perpendicular surfaces inside the material. They can be identified later in the evaluating process by wave mode analysis method (ISO 5577,2017). Later in section 3.7 AE wave analysis is discussed.

for better understanding to the attenuation by distance's effect on the AE parameters, this article could be a good reference (D. Polyzos,2011).

- AE is an irreversible technique, which is ruled by Kaiser effect (KE) after Joseph Kaiser (1950) , which states that a material under load emits acoustic sound waves only after a previous load level is exceeded (J.Kaiser,1953). this is showed in Figure 36, which illustrates the AE counts vs load, where a testing material subject to compression load was tested under a cyclic load. The breakdown of KE is sometimes called Felicity effect (FE). FE has been linked to crack growth, composite damage and concrete failure. which shows that AE cannot be verified by repeated measurements, as the defect can take few seconds or minutes to grow and be in stable condition and won't emits any acoustic waves. Therefore, AE monitoring has to be operated on a continuous-mode to avoid any missing data.

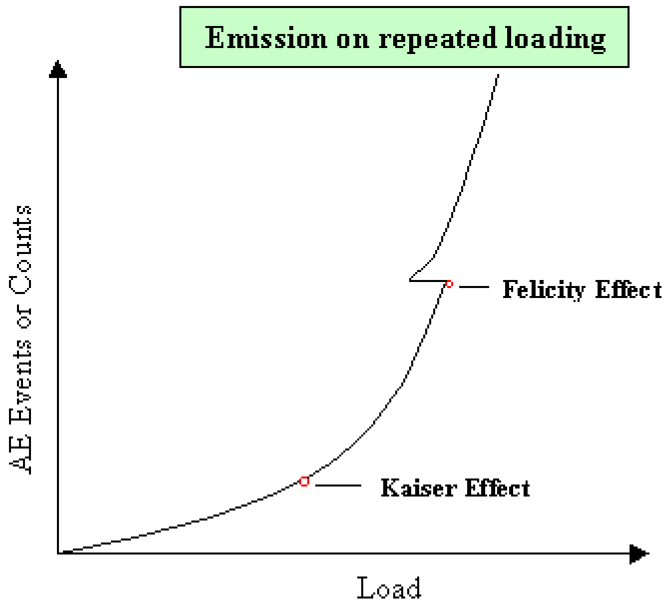

Figure 36: Kaiser effect on AE counts

- Background Noises is strongly affecting the received acoustic signals by the sensors, these noises must be filtered and identified for reliable evaluation analysis of acoustic signals. These background noise sources in offshore field are categorized into environmental and mechanical sources.

1) Environment (subsea): this represents all the sound sources acting on the top platform and the subsea structures such as; lightning strikes, earthquakes, Ambient noise and marine mammals
2) Mechanical devices: this represents in any vibration caused my mechanical devices in contact with the offshore structure that emits sound waves such as; pumps, fans, blowers, diesel engines, propellers, hydraulic noise, drilling rigs and oil & gas activities

Whether intentional or unintentional, Human activity produces noise in the offshore environment. To filter these background acoustic noises, then all the sources of noise have to be identified then by doing frequency range analysis for each source, proper filtration would be achieved.

Figure 37 according to (Underwater Noise | OSPAR Commission) ,it summarizes all the anthropogenic and naturally occurring sound sources in the offshore field. Acoustic intensity measured in decibels(dB) versus Frequency measured in Hertz (Hz).

Here are some Frequency values for some Marine surroundings according to Statistics collected by National academy of sciences (Mammals, 2003):

1) Ocean surface waves generated by the wind forces acting on the sea surface has frequency from 1 Hz to 100 kHz
2) Whales can make a noticeable contribution at certain times with peak of 100 kHz
3) Ship propellers, explosives, and sonic bombs can produce 1-10 Hz
4) Nearby ships and seismic air guns can produce from 1000-100,000 Hz
5) Sonars for seafloor mapping, depth sounders and other mine-hunting equipment have frequency up to 100 kHz
6) Thunder and lightning strokes which are 5-10 km away from the subsea can have a peal from 50-250 Hz
7) Earth quakes can extent to frequencies more than 100 Hz
8) Drilling techniques, the drill ships are considered t as the noisiest type of drilling equipment being used, with a frequency range from 10 Hz up to 10 kHz, the drill ships are the noisiest as the hull is an efficient transmitter for all noises, the ships mostly use thrusters to maintain its position, results in propeller noise.
9) Some oil activities such as; Pumping, pile driving, pipe laying, and helicopter or ship support can produce peak amplitudes around 40-100 Hz

It is obvious that the majority of marine environment noises range approximately from 1-200 kHz, therefore the threshold (frequency filter) can be determined, so it only detects any acoustic sound waves exceeds 200 kHz.

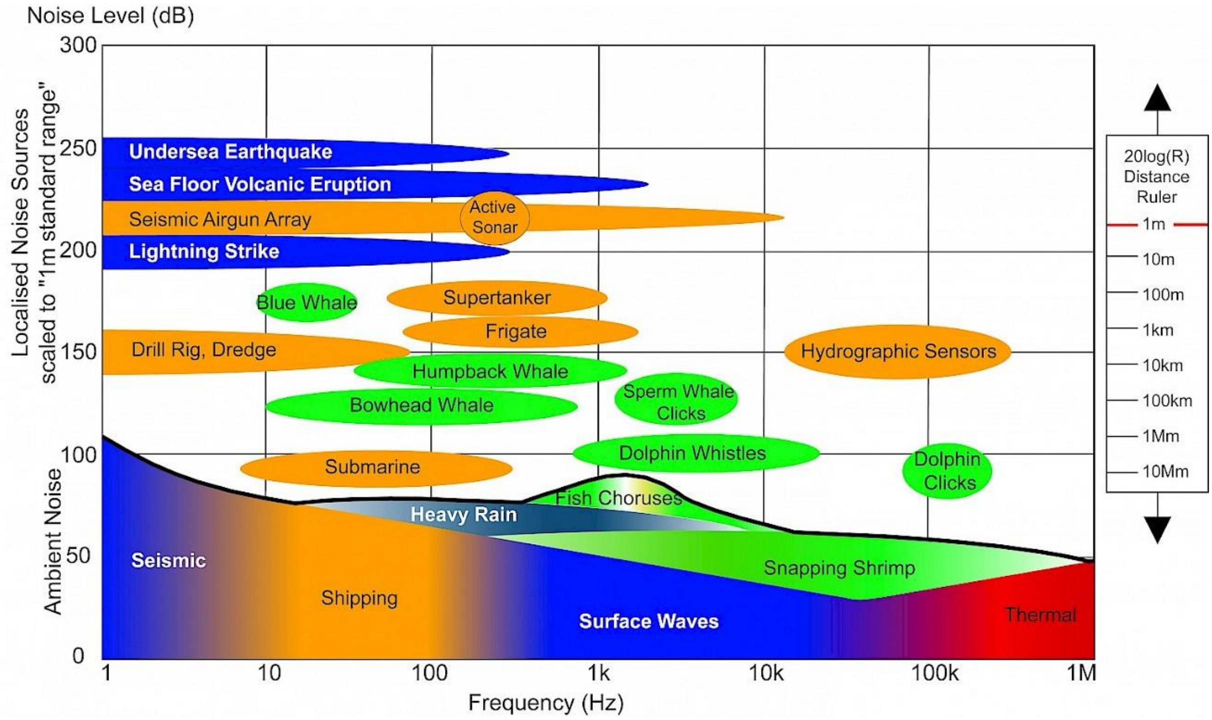

Figure 37: marine environment frequencies

for specific details for all marine environment sources of noise, describing the natural and human contributors to ocean noise are clarified in detail in this valuable reference (Mammals, 2003).

3.4 Noise controlling techniques

1) Rise time discriminator: it can be an efficient tool to differentiate between an acoustic emission signal and other noise source either from environmental or mechanical source, basically the rise time for an acoustic emission from a flaw source is short while other sources has long time duration (M. Sison, 1998)
2) Frequency discriminator (high & low pass frequency filter): the frequency from a crack normally higher than any mechanical noise source (mboria,2011).
3) Threshold: the main tool for distinguishing between the background noise and AE signals under high background noise.
4) Master-Slave technique: master sensor is the AE main sensor which is mounted on the surface of the structure under load, surrounded by slave or guard sensors .as it is shown in Figure 38 the master sensors are S2, S3 to detect the crack before the guard’s sensors which described as S1, S4. If sensors S1 and S4 detects signals before the master sensors, the signals are more likely from background noise and are filtered (M. Sison ,1998)

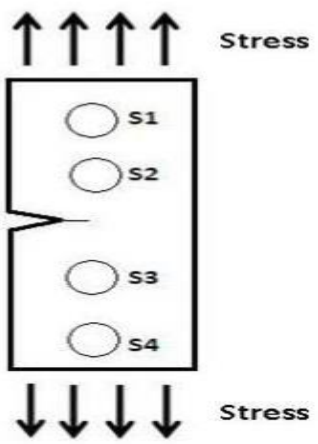

Figure 38: AE guard sensors

3.5 AE Detection Analysis techniques

Acoustic signals can be divided into three types: Burst, continuous and combined/mixed (Holroyd,2000). Burst are basically short transient signals generated by the formation of deformation, e.g. crack growth and fracture, while Continuous AE signals occur for long period of time generated by leakage, noise signals and rubbing or when multiple transient signals overlap. Mixed signals contain both bursts and continuous signals and it is the normally encountered in-service monitoring.

Figure 39 shows the difference between the burst and continuous AE signals in time domain analysis (Chacon,2015).

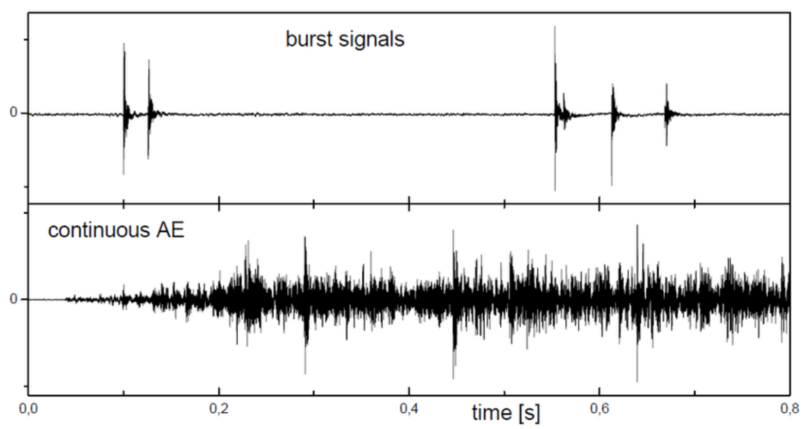

Figure 39: AE Burst vs Continuous signals

The purpose of the detection technique is to distinguish the transient AE signal from the background noise or the continuous AE. Because mainly AE are transient stress waves generated from the material under stress, so the term Hit is understood as a separated, transient from the acquired waveform. There are detection techniques to detect and determine AE hits, in this study 2 common techniques are discussed which are; Hit based and Waveform based techniques.

1) Hit/Parameter-Based analysis

The following features are collected from the AE waveform and according to (ISO-12716) are defined as follows:

- **Rise time**: Time interval between the time a signal is triggered and the time of maximum amplitude, expressed in microseconds (µsec)
- **Counts:** a number of times a signal crosses the acquisition threshold within the duration
- **Duration:** time duration between the first count to the last one, expressed in microseconds (µsec)
- **Energy envelope:** measured area under the AE signal over the duration, it is a very important feature that shows information about the strength of the AE source.
- **Absolute Energy:** is the integral of rectified voltage signal divided by the duration of the AE hit signal and can be useful for quantifying the damage.
- **Amplitude:** The peak voltage of the signal waveform is known as amplitude, expressed in decibel (dB)

  dB=20log10(Vmax/1µvolt)-preamplifier gain
- **Threshold:** Recording is triggered once the AE signal reaches the threshold value, it is a very important value to adjust the sensitivity. This value is set to remove as much noise as possible, but it should be carefully set so that weak AE signals from flaw source are not missed by setting the threshold value too high.
- **Hit:** AE signal which exceeds the threshold and causes the system to start recording
- **Average Frequency**: Determines the average frequency over the entire AE hit in kHz, it can be used for distinguishing between tensile and shear cracks signals.

$$A.F = \frac{AE\ Counts}{Duration} \quad \text{(kHz)}$$

Figure 40 shows the AE parameters in a simple plot between voltage with time (Schultz,2010).

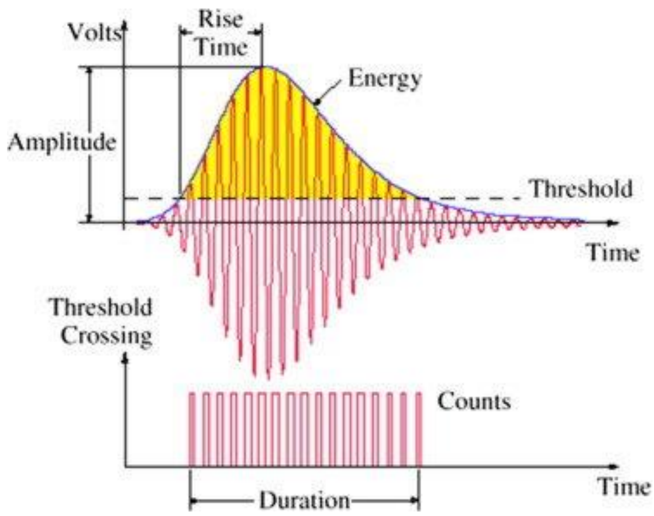

Figure 40: AE parameters

After the AE hit is detected there are three essential parameters commonly used to determine the AE hits are shown in the Figure 41 they are defined as follows (Unnþórsson, 2013):

I. Hit definition time (HDT): specifies the maximum time after the threshold crossing, i.e. if no crossing occurs during the time determined then the hit has ended , if HDT was set too high then the system consider two or more hits as one, if it was set too low then the system may not capture the AE hit or treat it as multiple ones.
II. Hit lockout time (HLT): specifies time which must pass after a hit is detected before a new one can be recorded, if it was set too high may the system cannot detect the next AE, if it was set too low then the system may capture reflections of the AE as hits.
III. Peak definition time (PDT): specifies the time allowed after the hit detection to determine the peak value. If it was set too high then false recording of the peak value could be measured, if it was too low that could lead that the true peak is not measured, it is recommended to be low value.

After the AE hit is identified, hit-based features can be measured including signal amplitude, duration, average frequency, Rise time, counts and Energy.

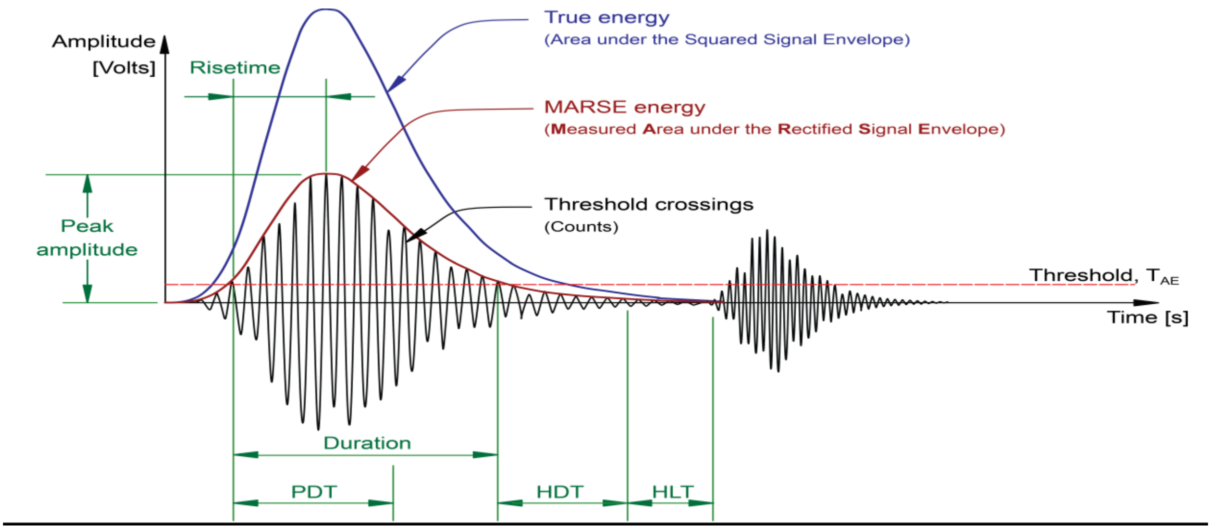

Figure 41: AE hit based features

Table 13 Made by (D.Ozevin et al,2004), Illustrates the AE parameters and their related data to the source event.

Table 13: Different domains for AE analysis

Domain	Parameter	Data about Source event
Time domain variable	Rate	Rate of damage, e.g. crack growth
	Peak amplitude	Intensity of AE event
	Relative arrival times	Defect location
	Duration	Energy of AE event
	Waveform	Structure of source event
	Energy	Damage type
Frequency domain variables	Frequency spectrum	Nature of AE event
Time-Frequency domain variables	Spectrogram	Energy distribution through time
	Time variation of each frequency component	Intensity of source frequency components

This technique uses few amounts of data compared to the Waveform based technique, also it is considered as fast data recording which extracts real-time features. still it is difficult to differentiate background noise from an AE signal using this method (Grosse, C.,2008).

2) Waveform/Signal-based analysis

In the Hit-based analysis only the parameters of the AE signal are detected, but the AE signal itself is not recorded in the store memory. Which minimizes the memory required for recording and enables fast data recording and analyzing it was mentioned before. But in this technique with the availability of better sensors and higher processing resources for acquisition, AE signals are recorded as waveform along with the parameters (Huang, M. ,1998). This technique offers better use signal processing techniques which aids in discriminating the noise from the detected AE signals based on the stored waveform. Furthermore, there is post-processing software that is used for data analysis, which provides information about the nature of the AE source event.

Frequency analysis of the recorded waveforms is the most preferred method.it is executed by means of Fourier transform or time-frequency analysis methods such as Short time Fourier transform (STFT) and Fast Fourier transform (FFT). Frequency analysis can be executed during recording in real time due to the fast-available processing tools nowadays.

Fourier function can decompose any acoustic wave function into the sum of simple functions for quantifying the noises and achieve better analysis. this decomposition of a complex function to several simple functions is the purpose of Fourier technique. The main reason for using FFT in engineering applications is to transform time-domain signal into frequency-domain signal (Bracewell, R.,1991). initially before executing FFT continuous analog to digital converting must be carried out for the recorded signals or waveform functions, in order to be analyzed accurately later.

in the Figure 42 shows the conversion from analog continuous signal to discrete digital signals in time-domain function, which are described by several bits shown in figure c).

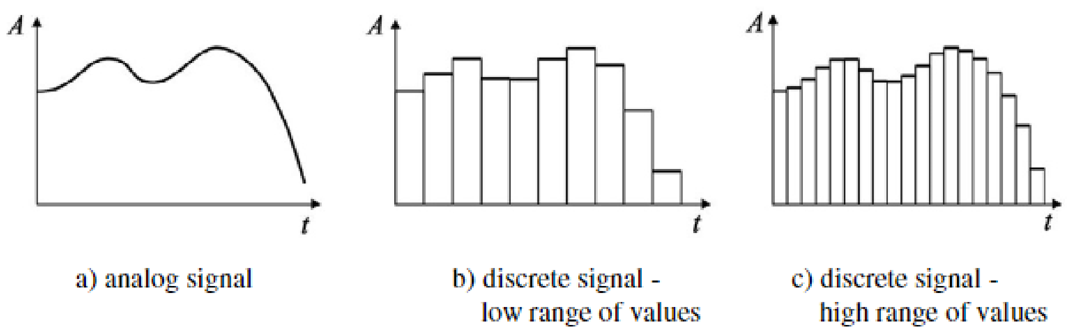

Figure 42: Conversion for signal in time domain

Assume there is a periodic function. for period $T \leq t \leq T$ this function can be written in the infinite series as follows (Harčarik T. et al.,2012):

$$x(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} \left(a_k \cos\frac{\pi k t}{T} + b_k \sin\frac{\pi k t}{T} \right)$$

Where,

x(t) = the signal in time domain

a_k & b_k = coefficients of the series to be determined

K = the integer for the frequency of the wave

By using Euler's formula and Fourier integral we get the Fourier transformation of x(t)

$$X(w) = \int_{-\infty}^{\infty} x(t) e^{-iwt}\, dt$$

Where,

w = the angular frequency

X(w) = function of amplitude spectrum of x(t)

After that FFT algorithm is used to divide each Discrete Fourier transformation (DFT) into two Fourier transforms for further analysis for the digital signals in the time-domain function

Fourier transformation x(t) is then divided into two parts which are y(t) and z(t) as shown in the Figure 43.

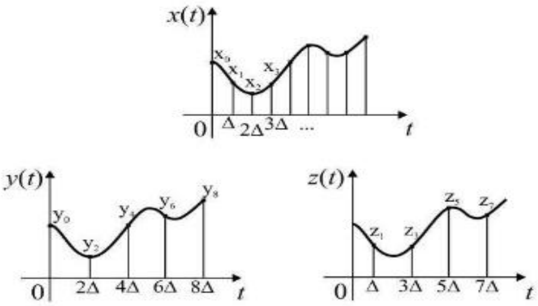

Figure 43: Fourier transformation

Which leads eventually to the following equation, most of the digital signal processing software that uses FFT are based on this equation

$$X_k = Y_k + W^k Z_k$$

The last step is to apply the transformation function from time to frequency domain in MATLAB software using FFT command, to see the frequency spectrum, as it is illustrated in Figure 44.

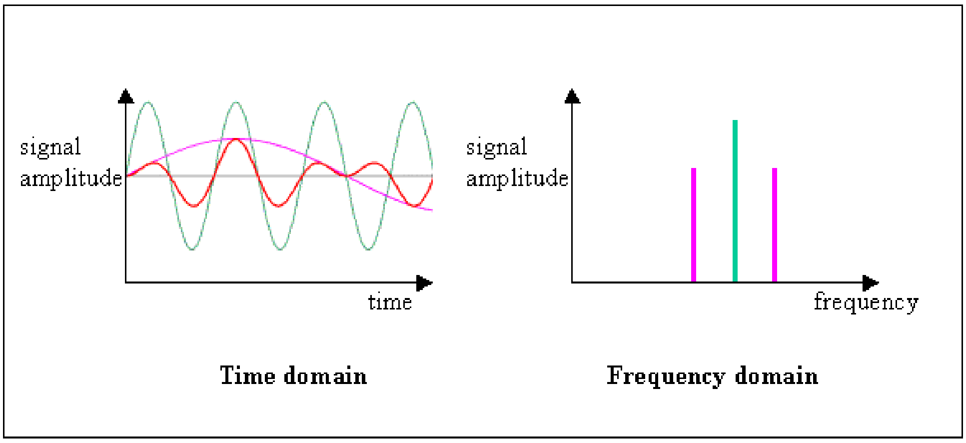

Figure 44: Time vs Frequency domain

The main disadvantage for using this technique is the need for large storage memory, so it would be able to record large volume of data, to ensure that all the AE waves are recorded which ranges from few kHz up to few MHz (Kaphle, 2012). One of the most important factors in the conversion from time to frequency domain is the sampling frequency, which must be greater than twice of the highest frequency recorded signals. For example, to record AE signals of frequencies up to 300 kHz, the sampling frequency rate should be at least 600 kHz according by Nyquist criterion.

In the next section AE waveform-based analysis will be discussed, as it is very necessary to understand the modes of travel for AE waves to have good analysis for the source of event.

3.6 AE Waves types

AE is a phenomena of elastic stress waves caused by any dynamic deformation of the material's structure. These waves generated depend on the material properties, the geometry of the sample and the frequency of the wave.AE waves in solids travel in various modes according to their types. AE waves can be classified into four main modes: Longitudinal wave (P/compression wave), Transverse wave (S/Shear wave), Surface wave (Rayleigh wave, Love wave) and Lamb/Plate wave. Reflected or

Diffracted waves are present but are not considered of the main modes as they need some conditions to occur related to physical boundary conditions (Rose J.,1999).

1) Longitudinal waves (P waves)

Both the P & S waves are called bulk waves. The longitudinal waves are also known as primary waves as they are the fastest of all waves. The particles oscillate in the same direction and parallel of the wave propagation as shown in Figure 45 (UPSeis) ,P waves are effectively propagate in solids and liquids. AE signal theoretically should be detected with a P wave, if there is high noise then either S wave or Rayleigh wave would interfere (Ohts, M.,1996)

2) Transverse (S waves)

S waves are known as secondary waves, as they arrive after the primary waves due to less speed. the oscillations occur in a perpendicular direction to the direction of the wave propagation, it is not effective in propagation through liquids or gases (Fu, 2005).

3) Surface waves

They are known as Rayleigh waves, they travel on the surface of semi-infinite solid. The interference of P and S waves on the surface produces this surface wave, the particles oscillate in rolling motion as , it travels with lower velocity than that of the S wave. Normally they have high amplitudes.

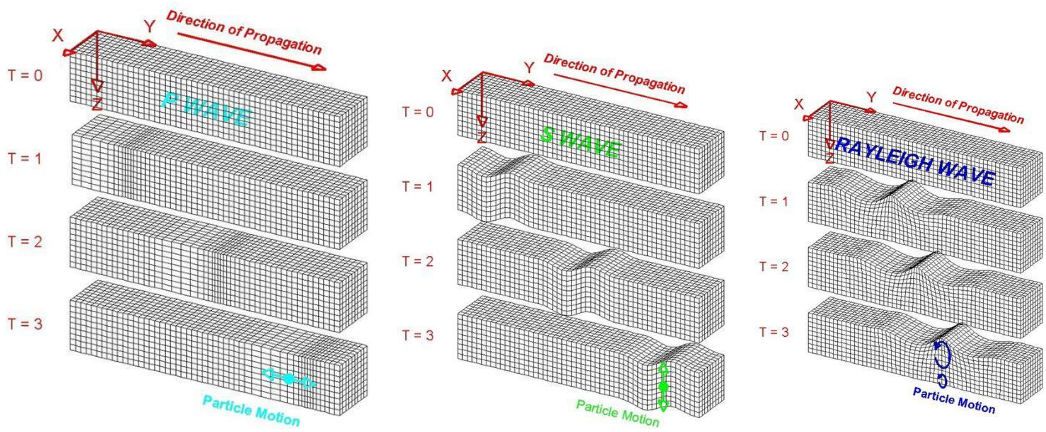

Figure 45: AE wave types (L) Longtudinal (middle) Transverse and (R) Rayleigh wave

Here is an example in Figure 46 (muravin,2011) for AE signal looks alike which consists of 3 different wave types .

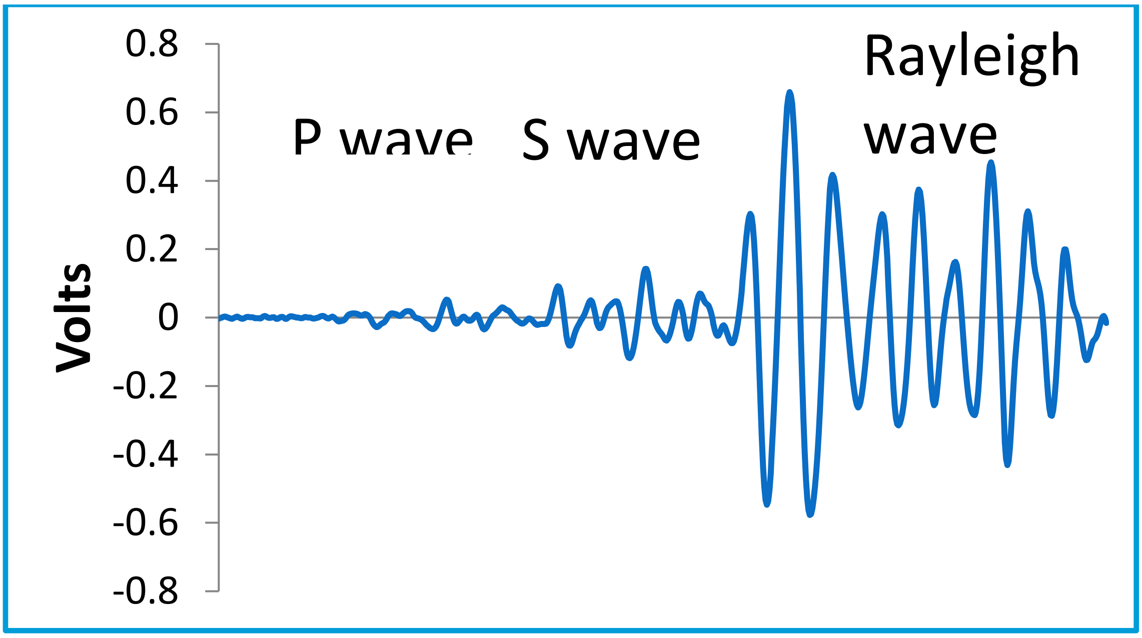

Figure 46: AE different waveforms

4) Lamb waves

AE are used for detecting flaws in structures mostly of steel material as in plates, pressure vessels, pipes and so on. therefore, good understanding and skillful using of the lamb wave theory can achieve more accurate evaluation for flaw location in the structure. Lamb waves are consisted of two modes: extensional/symmetric(S) mode that has higher velocity and lower amplitude than the second mode which is the flexural/asymmetric(A) mode, Figure 47 illustrates the difference between both modes and their arrival times versus the amplitude of the signal (Kaphle,2012).

to be noted that the lamb wave modes depend on the frequency of the wave and the thickness of the plate (Kundu,2014)

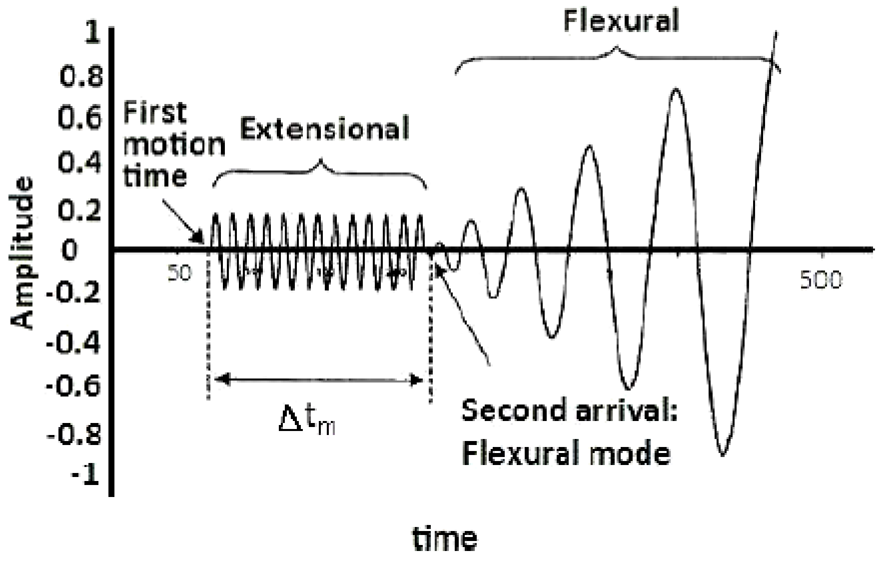

Figure 47: Lamb waves

Some researches were based on analyzing Lamb waves for AE location detection, as it was found that lamb waves carry valuable information on the type and severity of the flaw as in this research article published by Jinrui Zhang,2016 for using lamb wave analysis to detect and locate defects in switch rails, also in Kaphle M. thesis for using extensional (symmetric) and flexural lamb (asymmetric) modes to locate the defects on steel plates. lamb waves can give best indications about wave propagation from a source whose distance from the sensor is more than the material thickness (NDT-Resource Center)

In infinite media, only P & S waves are available to be detected , in semi-infinite media there are Rayleigh (Surface) waves produced besides the bulk waves, while in double bounded media as plates there are Lamb waves with the bulk and surface waves produced (Muravin et al.,2012),.The figure 48 shows various thicknesses for several plates, as it is shown in the above part of the figure it is semi-infinite plate where S & P are dominant waves, when the thickness reduces to 5mm (thin plate) in the below part of the figure, the Lamb wave arrivals become visible.

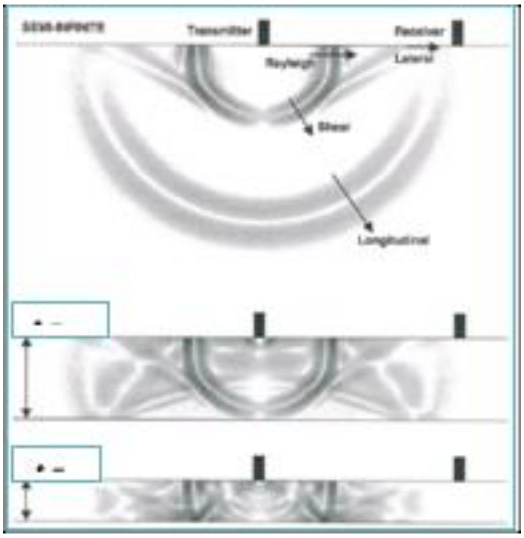

Figure 48: Several thickness plates vs AE waveforms

Wave speed in different materials:

Wave speed equation is derived originally from Hooke's Law in a theory of elasticity (Williams ,2015), they are governed by these equations (Muravin) as follows (for different wave types):

$c_1 = \sqrt{\frac{\lambda+2\mu}{\rho}}$, for longitudinal wave

$c_2 = \sqrt{\frac{\mu}{\rho}}$, for shear wave

$C_R = \frac{0.862+1.14v}{1+v} * C_2$, for Rayleigh(surface) wave

Where,

C = the wave velocity

ρ = Material density

v = Poisson's ratio

λ , μ = the elastic wave's constants indicate the strength of the coupling between atoms

Table 14 was produced by (Beattie, 2013), showing the wave velocity for different materials with respect to the wave type

Table 14: Wave velocity for different materials

Material	Longitudinal wave (C_1), Km/sec	Shear wave (C_2), Km/sec	Rayleigh (C_R), Km/sec

Aluminum	6.42	3.04	2.87
Brass	4.7	2.11	1.99
Steel	5.94	3.25	3.03
Nylon	2.62	1.07	1.01
Lucite	2.68	1.10	1.04
Water	1.50	-	-
Air	0.33	-	-

Dispersion curves are used to calculate theoretical velocities of Lamb wave (Kaphle, 2012), as mentioned before the Lamb velocity varies from one material to another depending on the plate thickness and the frequency of the wave. Therefore, for each plate thickness some experiments have been carried out to determine the dispersion curves for this material. The dispersion curve is a relation between the frequency of the wave and its group velocity.

Group velocity is defined as the group of waves that have the same frequency.

Figure 49 (muravin) shows various dispersion curves for 10mm thickness steel plate, where the two fundamental modes A_0 and S_0 and the higher order modes follows, which gives us better understanding for wave modes velocity versus the frequency.

Lamb derived the dispersion relation for different waves, where frequency-velocity pairs can be obtained from the dispersion relations (Gómez et al., 2011);

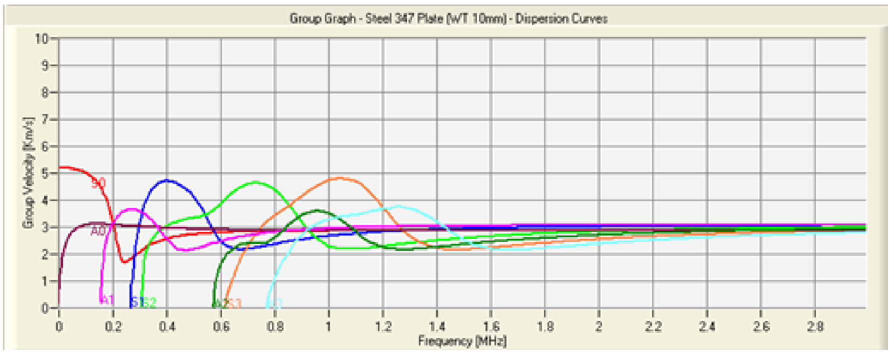

Figure 49: Dispersion curves inside Steel 347 plate

3.7 AE Signal processing

Signal processing for AE has different methods for assessment and quantification of damage , some commonly used methods for AE analyzing are spectral analysis ,wavelet analysis, time-series analysis, Fourier transform and short timed Fourier transform .FT is used to identify the frequency contents of the AE signal nut unfortunately it loses the information about time of occurrence of frequency component, while STFT can involves information for both time-frequency for the AE signal, by multiplying AE signal with a short window function and then calculating the Fourier transform.

Wavelet analysis breaks the AE signal into different levels, so further analysis for each level can be obtained (Kaphle, 2012), this method has been used in areas like fracture mode classification and detection of AE signal in low signal to noise cases (Yoon et al.,2000).

Short time Fourier transform (STFT)

Provides time-frequency information by multiplying the signal with a short window function, and calculating the Fourier transform of the multiplication. the window is then shifted, and the calculation is repeated, the governing equation (Scholey et al., 2009) for this calculation is

$$G(w,\tau) = \int_R^0 f(t)g(t-\tau)e^{-i\omega t}\text{dt}$$

Where,

$f(t)$ = the signal

$g(t-\tau)$ = the short window function

τ = specific time

Wavelet transform

Wavelet is a short effective waveform. Wavelet analysis is based on breaking up of a signal into smaller parts. Figure 50 (MATLAB) Shows some examples for MATLAB wavelet functions

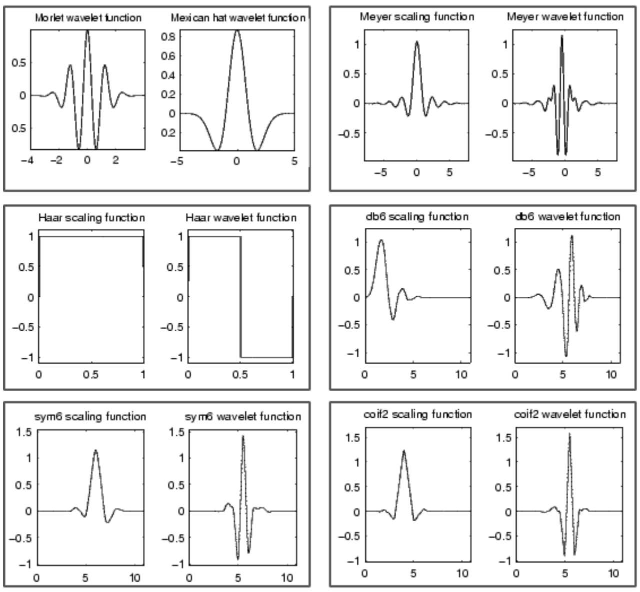

Figure 50: Wavelet functions in MATLAB

Wavelet transforms have some advantages over the Fourier transforms functions, the wavelet function is more suitable for signals with short duration of higher frequency and longer duration of lower frequency signals.

later, more advanced techniques in processing has been used for further analysis for AE signals but it takes more time and special skills to implement these techniques. Correlation plots also have been used for damage severity identification, such as: energy vs amplitude, duration vs amplitude. e.g. Application for using duration vs amplitude method is to differentiate between an acoustic source from a flaw and another noisy transient source, even if both sources have the same amplitude of the AE signals received but they would have different duration for the waveform.

Examples for AE failures waveforms

Figure 51 shows load-time curve of tensile testing for a sample of steel at a rate 10 mm/min, it shows the fracture point (brittle crack) on the specimen's surface at 155 seconds. Figure 52 shows the corresponded frequency and time plots to the fracture point at 155 seconds (Zohora,2016),Figure 53 shows the energy spikes were relevant to the yield point where new crack initiation occurred, through the AE energy over time plots there was no significant AE energy except with yield point and point of fracture , which indicates the reliability of using this technique for specific stages for crack detection.

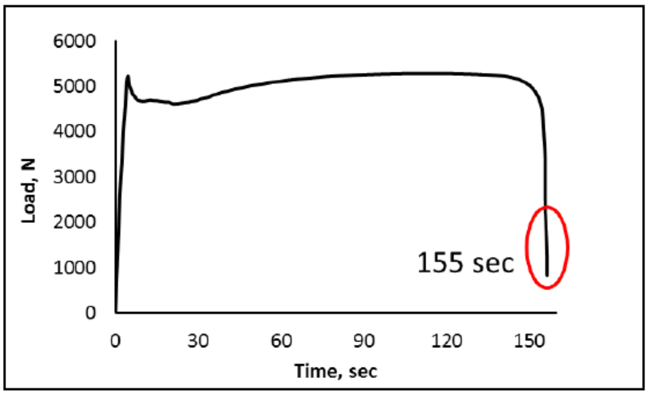

Figure 51: Load-time curve for tensile testing

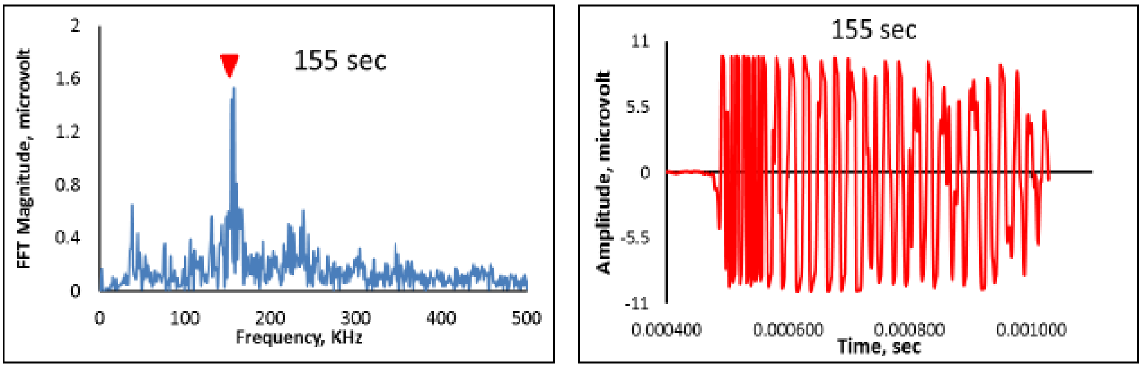

Figure 52: Frequency and AE amplitude at specific second examples

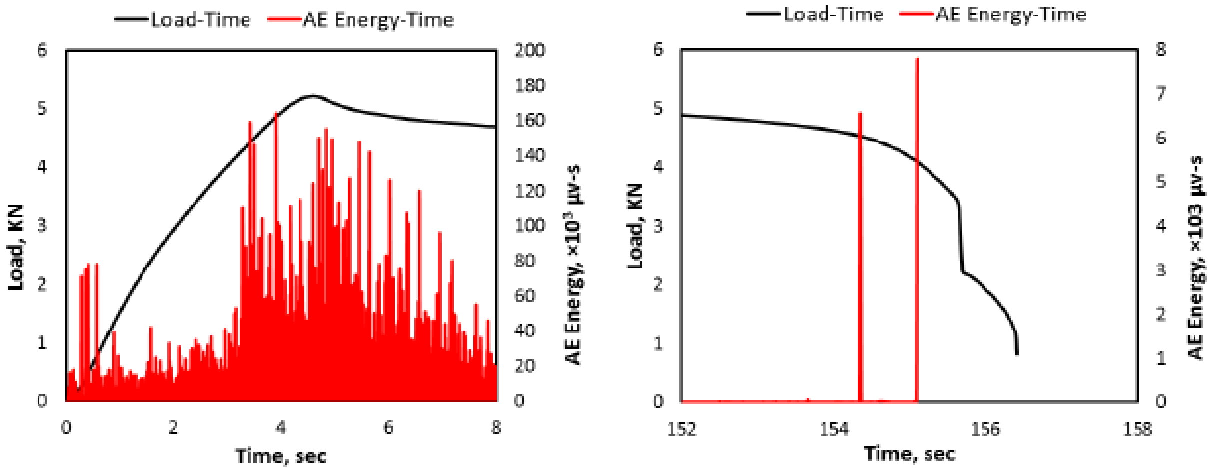

Figure 53: AE energy vs time

Figure 54 Shows an example of Hits (per channel) vs Amplitude plot of AE signal for a crack growth in a fatigue test (Beattie, 2013).

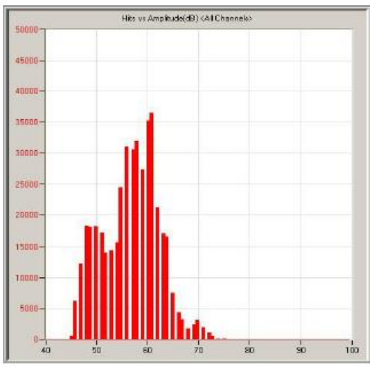

Figure 54: AE hits vs amplitude for a crack growth

Figure 55 shows laboratory results for different AE waveforms by various defects (Lee et al., n.d.),

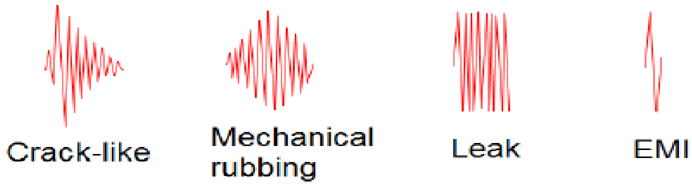

Figure 55: AE waveforms for different failures

Figure 56 below illustrates the AE amplitude correlation plot for an active corrosion during storage tank floor tests, which shows that for advance corrosion stage , AE signals give longer duration signals as shown (Duthie and Gabriels, 2014).

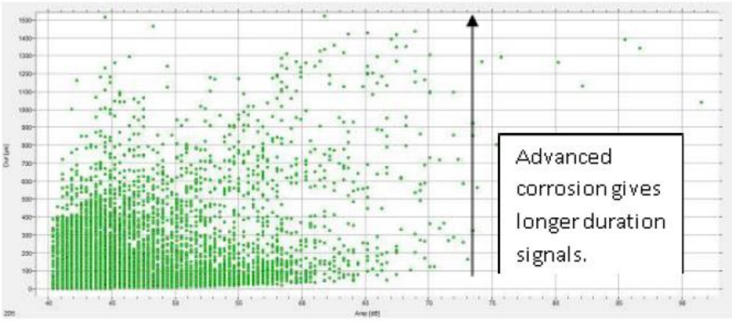

Figure 56: AE duration for Corossion

Figure 57 (Lee et al., n.d.) illustrates an example for AE correlation (Energy vs Amplitude) method for different defects.

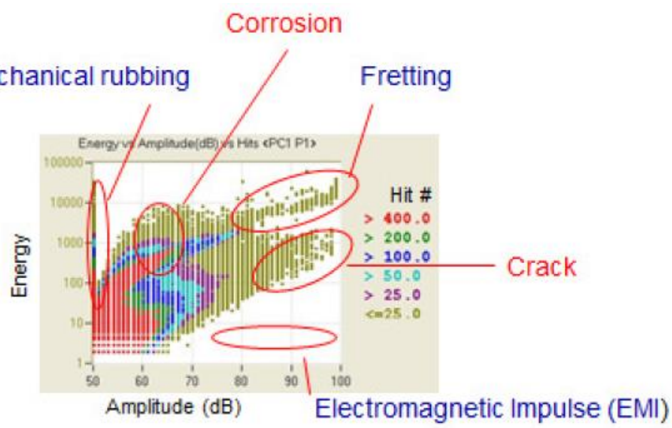

Figure 57: AE amplitude for different defects

Figure 58 shows AE waveforms for different stages of intergranular corrosion (IGC) for 316L stainless steel (Chai et al.,2015), it is shown that typical corrosion mostly emits continuous AE signals and few of burst signals.

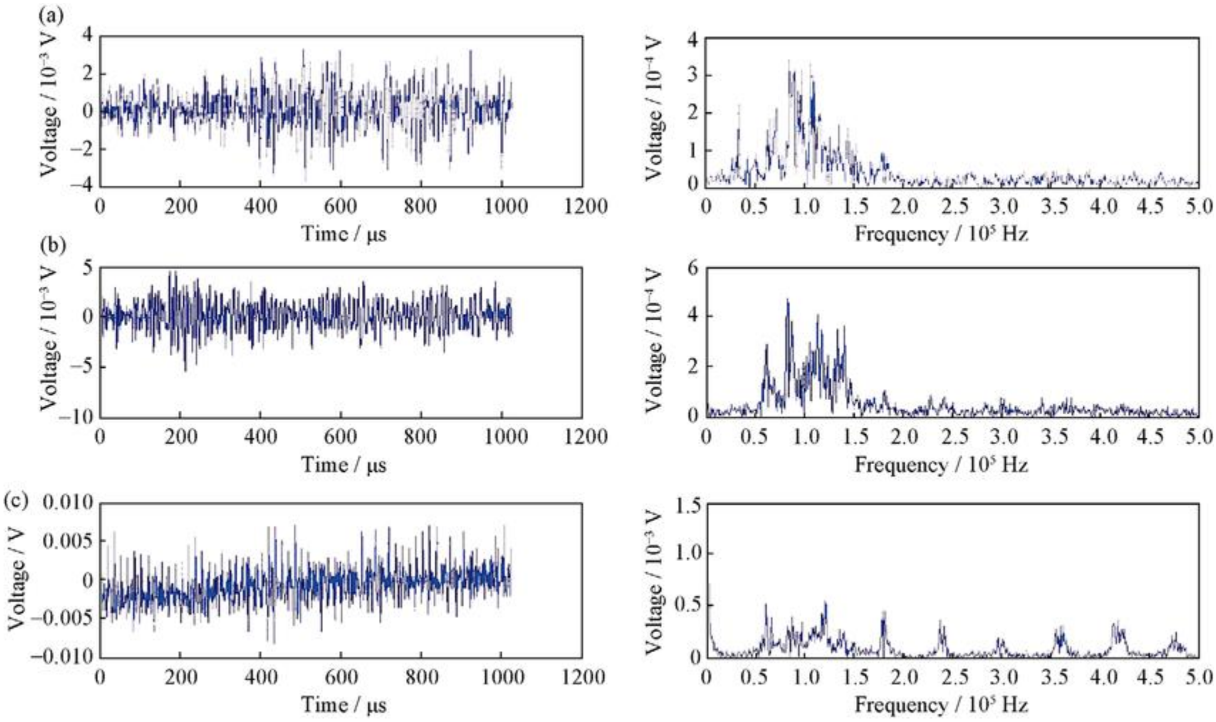

Figure 58: AE waveforms for intergranular corrosion

3.8 Source location

The AE ability to locate the defect source, is one of the main advantages in using AE monitoring system compared with many other NDTs.it can assist in source characterization and early warning of failure mechanism. Furthermore, after source location life prediction study can be effective to determine component flaw inspection periods along with the flaw shape and sizes for safety acceptance criteria.

Current source location methods:

1) Time of Arrival (TOA) method is the most commonly used way of determining the source location, other methods such as Waveform filtering methods (Miller R,2005) and Delta method can also be used (Baxter et al., 2007), recently modal location theory has been used in source location (Mohd et al., 2012).

In TOA technique several sensors are mounted on the surface of the structure, where each AE hit is recorded on individual channel in the multichannel acquisition device. When the AE sensors are placed on different distances from the source, all AE hits are recorded by the system with different arrival times, by multiplying the arrival time for each sensor by the velocity of the wave propagation thus the location can be identified, this technique is known as well by triangulation techniques (Al-Jumaili et al., 2016). The first problem within any location software is to define the AE hit. the hit arrives at the system with an arrival time value, Arrival time is defined as the instant signal crosses the pre-set threshold value.it was mentioned that the threshold values are often set to remove as much low amplitude noises as possible.

2) On the other hand Delta method is based on the same principle like TOA but the source location is derived from the structure velocity profile rather than assuming constant wave velocity as in TOA method, structure velocity profile provides variable wave velocity values related to the non-uniform geometry of the structure .these profiles are previously identified for the critical areas of the structure by mounting two sensors and measure the arrival of time delay from source locations to be used later as a calibration reference for any future measurements.so Delta method is more accurate than TOA methods as the velocity and geometry errors are minimized and it is more suitable method for SHM of structures with non-uniform geometry (Mohd et al., 2012).the main disadvantage for this method is that it is only valid if the location of the defect is within the previously calibrated regions.

3) Modal location theory is based on using Lamb waves and it is known as modal acoustic emission (MAE) (Holford,2000). this technique is more complicated for analysis and needs more skills to accurately perform the process. according to MAE for a plate, different frequency components of lamb wave modes travel at different velocities which enables this method has received considerable attention to be used as global or semi-global technique for monitoring a whole structure or larger area, as the separation of modes becomes pronounced as distance increases from the flaw source (Kaphle, 2012). In section 3.7 Lamb wave modes are defined as symmetric and asymmetric components; thus, this method determines the source location by measuring the arrival time of significant components of the Lamb waves, this method should have better location results compared to TOA due to less timing error between the first arrival hit and first arrival threshold crossing signal. However, due to using the dispersion characteristics it will lead to inaccuracy for source location due to the temporal separation measurement error (Mohd et al.,2012).
4) Zonal location technique **is** based on the principle that detecting the highest amplitude or energy received by the AE sensors will be the closest to the AE source. Zones can be areas, volumes or lengths. by Placing several sensors around the source in a pattern as shown in

Figure 59 depends on the structure dimensions and geometry, where zone location technique aims to trace the waves to specific zone around the AE sensor. This method is used in anisotropic materials or in other structures, where high attenuation presents.by increasing the number of sensors used, better source location is identified (AE Techniques)

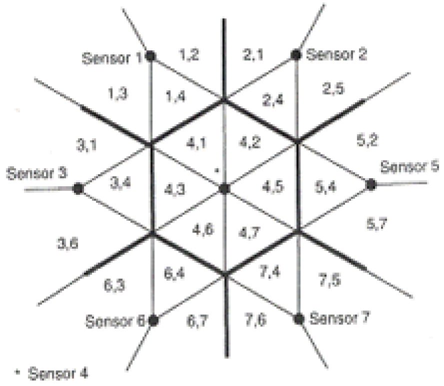

Figure 59: AE zonal location technique

- In this thesis TOA method is used in the AEwin software, as it is considered more reliable for simple experiments and has more creditability with using location software. For simplicity, it is assumed wave velocity for a specific material is constant in general AE source location technique. But for better accuracy of AE source location, some factors have to be considered like wave reflection, various wave modes (P, S mode, etc.) and precise wave propagation velocity, in Monitoring systems using several methods for locating the AE source will increase the accuracy and reliability of the measured values.

The basic idea in source location is to cover the surface of the structure with a network of AE sensors, or at least around the critical weakest points in the structure that are more likely to have a defect.

The present AE source location methods assume that AE waves propagate along straight lines (Zhou et al., 2017), because of the heterogeneity of materials, location results fail to meet accuracy requirements most of the time. Materials are classified into two categories; isotropic and anisotropic materials. Isotropic materials mean a material having same wave propagation velocity in different direction such as Metals and Glass, while anisotropic materials mean a material having different wave propagation velocity in different directions such as Wood and Composites.

The latter type of materials is more challenging in locating defects by AE, as to achieve appropriate results, it is necessary to evaluate velocity profile as a function of wave propagation direction.

Assuming that materials are isotropic may seem applicable for steel structures in offshore field. Only if the structure is made of plates with the same thickness, where assuming the wave propagation velocity is equal in all direction from the material to the sensor. the wave velocity is a function of the frequency and plate thickness. Thus, may be several frequencies can be existed in the AE waves which vary the velocity of the waves as well .as a result the waveforms recorded by separate sensors maybe quite different from each other, which leads to variations in the triggering time of each sensor from what would be expected by the model used in the analysis. Therefore, acquiring accurate results for source location is very challenging in real application.

Another major problem is that some structures have complex geometries and may consist of weld regions or other obstacles that play an important role in attenuating the AE signals, which as a result affects the source location technique, in this case it is recommended to mount the AE sensors with short distances from the defect expected locations to avoid as much of attenuation as possible.

- **TOA methods for different dimensions**

I. One-degree AE source location technique is known as linear source location, it is used for linear type of structures such as bridge and pipe. It is a very simple method to apply using only two AE sensors.

In linear source location technique, two AE sensors are mounted on the surface of the structure to an appropriate distance from the source. therefore, the time of AE signals arrivals from both sensors are collected. Based on the time delay in signal arrival time, assuming known wave propagation velocity, source location is defined. For example, if the arrival time of signals are the same this means the source of flaw is exactly in the middle point between the sensors. The schematic of one-degree source location technique is shown in Figure 60.

where,

S_0 = AE source of emission

S_1 = AE sensor 1

S_2 = AE sensor 2

t_1 = time of arrival to AE sensor 1

t_2 = time of arrival to AE sensor 2

l = distance between both sensors

l_1 = axial distance of source to AE sensor 1

l_0 = axial distance between source and the midpoint ($l/2$) of both sensors

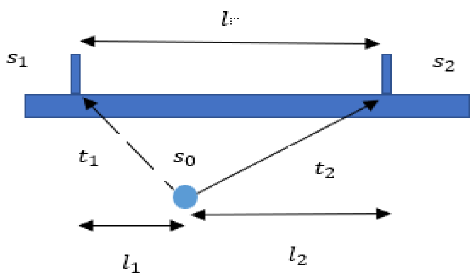

Figure 60: AE TOA method for one-dimensional location

the governing equation for the linear source location (Khan et al.,2014) is explained below, where Δt indicates the time delay between the two arrival times to AE sensors and v indicates the AE wave propagation velocity

$$l_1 = 0.5(t_1 - t_2).v = 0.5\Delta t.v$$

$$l_2 = 0.5l - l_1 = 0.5(l - \Delta t.v)$$

II. Two-dimensional source location technique

This technique is known as Planner source location technique, which requires minimum three or more AE sensors to be mounted on a plane for locating the Source for AE. Theoretically, three sensors are enough for locating AE source in two-dimensional technique, however, using more sensors increases the accuracy of the source location technique. An illustration Figure 61 shows the positions of the AE sensors around the AE source S (x, y) which is located in a uniform medium. The AE signal is generated at initial moment of T_0 , and received by any sensor (I) at moment T_i.

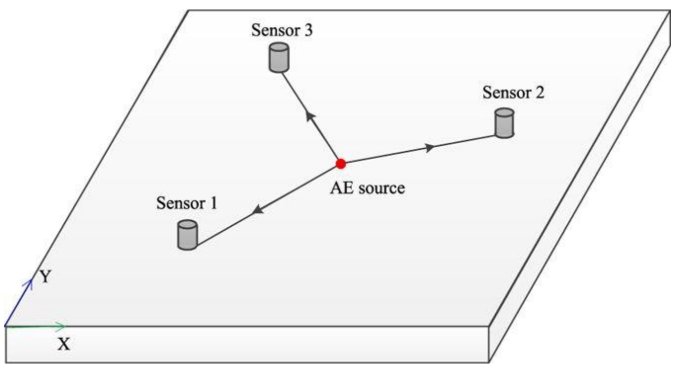

Figure 61: AE TOA method for 2-dimensional location

The distance between the AE source and any sensor I can be obtained as follows (Zhou et al., 2017):

$$L_{s-i} = \sqrt{(x_s - x_i)^2 + (y_s - y_i)^2}$$

The relation between $T_0$and T_1 can be described as follows:

$$T_i - T_0 = \frac{L_{s-i}}{v}$$

For simplification, assume initial time of the AE signal (T_o) is neglected due to difficulty in measuring it accurately, that gives

$$\Delta T_{i-j} = T_i - T_j = \frac{L_{s-i}}{v} \text{-} \frac{L_{s-j}}{v}$$

According to the above equations, it is possible to get two solutions, the correct coordinates of an AE source can be chosen from these two solutions in accordance with the real situation.

III. Three-dimensional location technique

Identification for 3D location of an AE source, so minimum four AE sensors have to be used for any volumetric shape. it is assumed that the source S (x_i, y_i, z_s) is located in a uniform medium, as shown in Figure 62 The Sensors are mounted around the source, coordinates of the AE sensor I are (x_i, y_i, z_i).The distance between the sensor I and the source S is L_{s-l} ,

where,

$$L_{s-i} = \sqrt{(x_s - x_i)^2 + (y_s - y_i)^2 + (z_s - z_i)^2}$$

For any sensor I, the time delay between the signal arrival is

$$T_i - T_0 = \frac{L_{s-i}}{v}$$

The time delay between signal arrival at two sensors (I, J) can follows this equation:

$$\Delta T_{i-j} = T_i - T_j = \frac{L_{s-i}}{v} \text{-} \frac{L_{s-j}}{v}$$

According to the above equations, it is possible to get two solutions, the correct coordinates of an AE source can be chosen from these two solutions in accordance with the real situation. This algorithm is widely used in AE monitoring systems to find 3D location (Zhou et al., 2017)

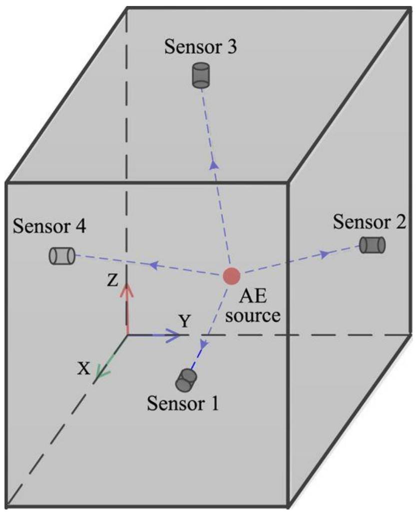

Figure 62: AE TOA method for 3-dimensional location

3.9 Applications

IN the early 70's, the first application of the AET was used on monitoring bridges. Initially this technology was developed for metals application, but then later the research interest grew stronger for concrete applications. Only recently the AE monitoring has been used in all industries for different types of structures and fields (Zohora, 2016.)

- Modern applications of AE in industry includes monitoring of pressure vessels, rotating machinery, aerospace field, wind turbine blades, bridges and even on ship's surface (Lee et al., n.d.), where it can detect the surface corrosion on the ship's hull and crack growth.

- According to (mboria,2011) application of AE into three areas as follows:

I. Structural testing
II. Process monitoring
III. Materials characterization

- It also has been applied for petrochemical, storage tanks, nuclear power, military, medical and automotive industries (Muravin,2009). It has been used as well for detecting leakage, loose particle detection and weld defects in metal structures in industrial applications

- AE technique is used for condition assessment of electric devices that have Partial discharges sources. PD are localized dielectric discharges in partial area of an electric insultation system e.g. Transformers. such that when the system releases energy, the resulting discharge manifests itself as an acoustic signals so the discharge acts as a source event for AE waves, where the intensity (dB) of the AE waves is directly proportional to the energy released from the discharge and hence the AE can be used as a tool for diagnosis for the insulation status inside an electric device (IEEE Conference Publication,2005).

4. Proposal of AE Monitoring system for offshore jacket structure

In this chapter a proposal for using AET as a monitoring tool to implement an online SHM system for offshore jacket structures underwater. Using the current knowledge and limitations for this system.

Overview

The main differences between an onshore and offshore structure is that the loads are random in offshore conditions and the it is very expensive to carry out inspections leaving the continuous monitoring systems as the proper choice to detect any growing cracks and flaws. Before installing AET sensors, some parameters and procedures must be considered for reliable SHM system.Stated by (HSE-Sharp,2009).

In order to carry out proper SHM for Structural integrity, there are critical parameters for such system:

1. Indicating Good data on the current condition
2. Using latest Techniques to determine safety margins
3. Developing an online Monitoring system
4. Understanding the degradation processes & response

Although there is no standard process exists for implementing SHM for offshore structure, a successful AET monitoring system should include prior knowledge to be obtained for the following aspects; test objectives, structural damage history, critical areas subject to failure in the structure, project crew selection, locations of AE sensors, AE sensor mounting methods and the connection between the AE sensors and the PC.

In the following Figure 63 a flowchart is proposed for using AET for offshore jacket platform structure is illustrated. This flowchart is following the same methodology for SHM procedures produced by (Lee et al., n.d.), (Vestli, 2016), (Duthie, 2014) and (Muravin et al., 2011) for SHM systems applied for Ship, Civil and offshore structures.

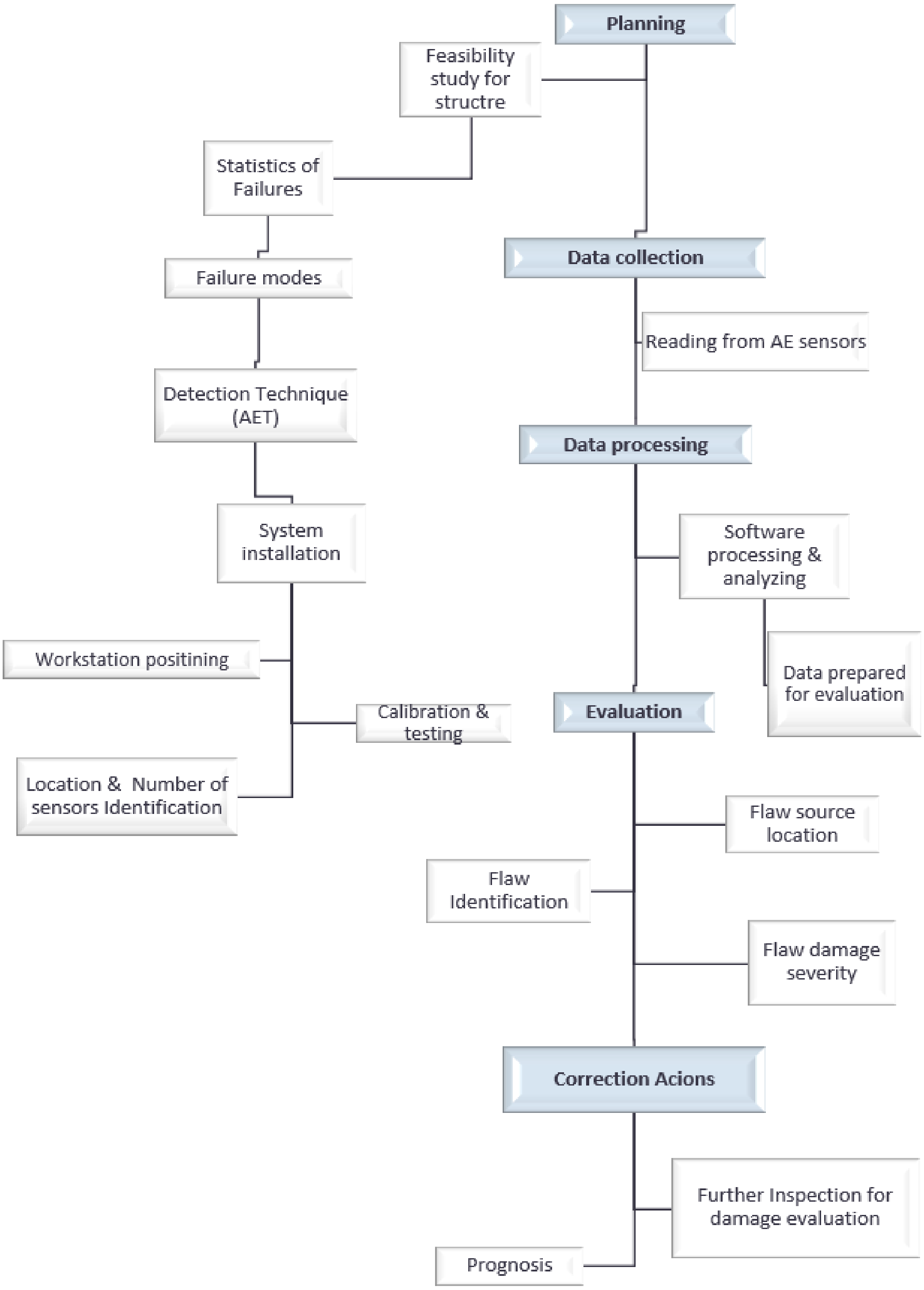

Figure 63: Flowchart for AE monitoring phases

4.1 Planning phase

- The jacket offshore structure suffers from common failure modes according to section 2.3.3 in NORSOK-N-2017.
  These failure modes mostly are Fatigue failure due to cracks or corrosion. Braces, nodes and jacket legs are the most commonly locations which are likely to have fatigue failure according to NCS damage statistics (Petroleumstilsynet,2017).
  AE sensors are chosen in this proposal for its high sensitivity in detecting early crack initiation and crack growing in various structures, especially for metals as steel.
- **Feasibility study**

According to NORSOK N-006, the following data should be collected for assessment of structural integrity for existing offshore structures:

- Drawings of the structure
- Updated information on environment data
- Functional requirements
- Design, fabrication and manufacturing specifications
- Material properties (strength, elongation and toughness)
- Weld specifications during manufacturing or modifications
- In-service inspection history for all failure modes such as: corrosion, marine growth, leakage and damage due to dents, abrasion/erosion and sulphate attacks.
- Data and forecast for seabed subsidence
- Maintenance history for the structure
- Experience from similar structures
- Information for structure response for any dynamic loads.
- Updated weight report

- After collecting the information above, a visit to the jacket platform structure is required by the AE specialist to check all the noisy external acoustic sources in the field of the jacket structure, so that the threshold value can be adjusted accurately for AE sensors to filter all background noises.

- **System Installation**

1. Type of AE sensor, choosing an appropriate sensor for a specific application is essential for successful measurement. The main selection criteria should be the frequency response which must suit the application. Some applications need sensors for high temperature, water/oil tightness,

Hazardous area applications which may be more critical criteria than the frequency range. However, choosing the right sensor frequency range according to the application considering the environment conditions is very important. If the frequency range for the application is known then it is preferred to use resonant AE-sensor than the wideband type, as the resonant is more sensitive at their resonant frequency while the wideband is used if the frequency range is unknown for the application and broad band if different frequencies in one signal should by analyzed (e.g. modal analysis for lamb wave).it has to be mentioned that the frequency range for a specific application considers some parameters such as ; specimen size ,material and the background noise.

For offshore applications, the background noise was identified previously in section 3.4.2 Ranging from 0-200 kHz, so it would be a wise selection for choosing sensors detects above 200 kHz. Table 15 is made by Vallen-section 2.2.1 for certain frequency ranges that have been proven to be best suitable for specific applications (Vallen-Guide for AE sensors, 2017).

Table 15: Frequency ranges for various failures

Application	20-100 kHz	100-400 kHz	>400 kHz
Corrosion screening of flat bottom storage tanks	X		
Leakage detection in water/oil pipelines	X		
Hot reheat pipe crack detection		X	
Integrity testing of pressure vessels		X	
Partial discharge detection	X (when noise is low)	X	
Integrity testing of metallic structures		X	
Integrity testing of composite materials		X	
Integrity testing of concrete structures	X		
Drying process monitoring of plants/wood		X	
AE-testing of small specimen			X

For subsea jacket structures, which mostly made of metallic material, would be suitable to use AE sensors with frequency range 100-400 kHz according to the table.

2. Number and Location of AE sensor relies on several parameters:
   - Jacket substructure depth in the sea: until this day the distance between the sensor to the acoustic source on the structure is variable, depending on the material type, thickness of the structure, the medium where the acoustic waves propagate and the structure design. As the depth of the structure increases the required AE sensors will increase as well. A good assumption is to use an AE sensor for local monitoring over several meters on the surface of

the structure, the closer the sensor to the source event the higher reliability the monitoring system is.

- Jacket Bracing structure: AE sensors locations depend on the number of braces, nodes and joints present in the structure as these are the critical points to monitor, so the number of AE sensors is in direct proportional relation with Bracings and joints.
- Location of AE sensors : it is advised by (May et al., 2008) HSE for structural integrity monitoring Section 4.1 , to install the Acoustic sensors externally or internally in dry hull members , but currently in the market there are Acoustic sensors for submerged conditions if AE sensors are required to be placed externally near nodes and joints, referred by the two ends of the red line in Figure 64 as suggested as well in (Vestli, 2016) thesis about using SHM for offshore jacket structure.

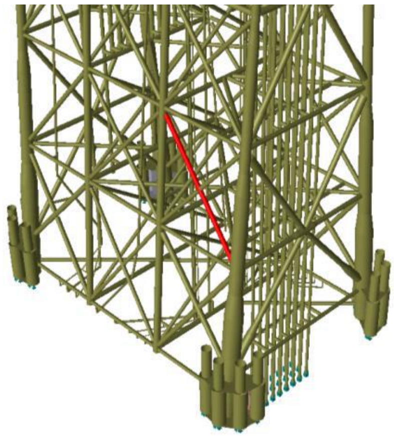

Figure 64: Severed member in jacket structure

- A proposed location for the AE sensors is shown in the Figure 65 model designed by SAP200 program in (Nguyen et al.,2015), where it shows three different types of bracing systems X-shape, V-shape and Single-shape respectively which are used in jacket offshore structures. The red circles represent the proposed locations for the AE sensors. The maximum distance between each two sensors should not exceed several meters depending on the signal attenuation in that condition. a surface attenuation of 0.01 dB/mm could have 4 meters distance between sensors, this is only a requirement not a must in order to effectively receive the acoustic signals and obtain reliable localization techniques (Beattie, 2013) for the defect.

4. Proposal of AE Monitoring system for offshore jacket structure

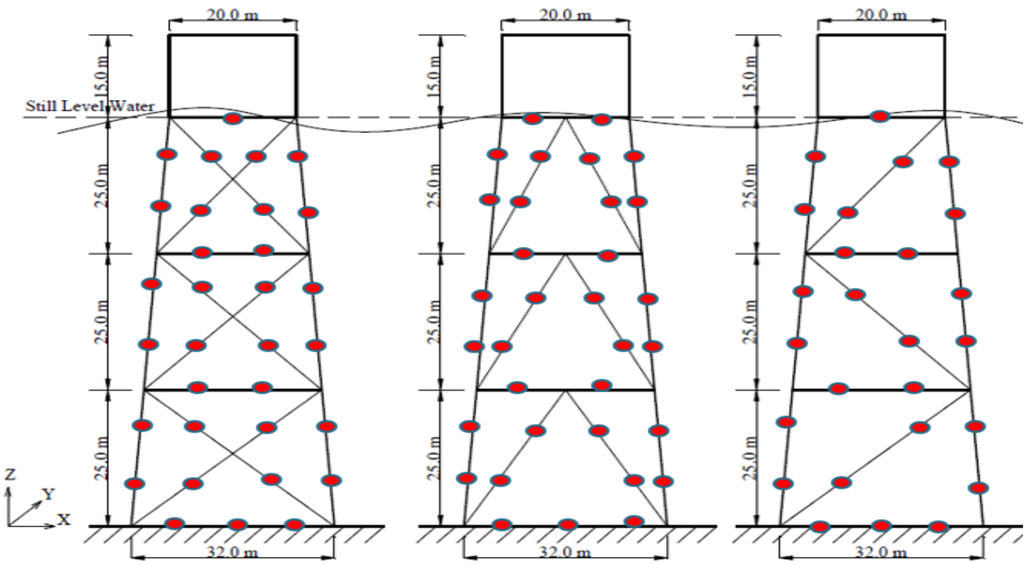

Figure 65: Proposed installment of AE sensors on Jacket structure's surface

- Figure 66 shows a simpler proposed installment for AE sensors of a J-structure model (Chen et al., 2016), where they are installed inside the legs members of the jacket structure, this one is using less number of AE sensors which decrease the regions under monitoring and affects the localization method efficiency as well, but on the other side it avoids the attenuation from refraction effect as the acoustic waves won't have to pass through water to reach the sensors, Therefore this method can have more accurate signals from the acoustic source.

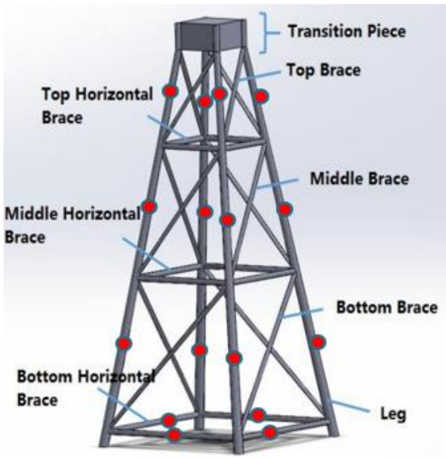

Figure 66: Proposed installment of AE sensors inside legs members of the jacket structure

- Accuracy & Reliability of Monitoring system: AS the number of AE sensors increases, it increases the accuracy of detecting any small crack, flaws at an early stage, because the sensors would cover more area of the structure under monitoring. Furthermore, increases the accuracy of detecting the source location of AE event using triangulation method.

3. The AE sensors in offshore applications are recommended to have built-in amplifiers, they are known by integrated-sensor, because the sensitivity for AE signals decreases with increasing the distance between the sensor and the amplifier and it should be maximum 1.2 meters. The integrated AE sensors are heavier than the basic AE sensors, however they are better suited for usage in the field, because measurement setup are faster, and number of connectors is reduced. especially the cables between the AE sensors and the amplifier are too thin and sensitive and must be handled with extra care.
    - Appendix C: AE sensors data sheets for Vallen, physical acoustic models.
4. The system requires special installation to adjust the sensor correctly. Either the sensors are installed during constructing phase of the structure for new jackets or are installed by divers externally on existing jacket structures.

also, all the sensors are hardwired back to the central control unit (PAC-Data acquisition device) which can be up to several hundred meters away from the amplifier, where there are inaccessible areas in subsea installations. The central control unit or PAC can be located on the top side of the platform connected by cables to the work station , which normally is positioned in a safe area inside a cabinet , where power and communications are available(Duthie, 2014).In this workstation all the processing and analysis for the received data are performed by the engineer or technician using specific software for AE diagnosis such as : Vallen, physical acoustic…etc.

Figure 67 illustrates an example for AMSY-6 system (Vallen-PAC), this control unit accommodates up to 4,12,38 or 42 channels respectively, depending on the number of sensors are used for monitoring. For each AE sensor it connects to one channel for processing, The PAC or AE system is controlled by the external PC, the data can be evaluated in offline analysis if it was previously stored. Up to eight chassis can be connected in one large system up to 254 channels. for AMSY-6 datasheet (GmbH, 2017).

Figure 67: AE AMSY-6 system

Figure 68 illustrates another example for PAC-chassis (Physical acoustic-type), this one can be used for industrial applications which can support up to 96 AE channels in a single unit. For more details it can be found in this reference (Industrial Express).

Figure 68: AE PAC-chassis (Physical acoustic)

5. During the installation safety needs to be considered-safety of personal, water tightness of cable penetrations, safety of the sensors, power supply, and any other accessories.
6. After system installations, calibration and testing should be applied to the AET system to confirm the functionality of AE sensors, amplifiers, PACs and software and the computer in the workstation. There is now a self-testing function within the VALLEN/AEwin software that allow to test all sensors in offshore/ remote areas without the need for any divers/Technicians to fly offshore to test them manually (GmbH-Vallen, 2015). this is performed by sending a pulse from each sensor to the closest three other sensors and receiving back the signals from them. The operation can take a few minutes, but it is more accurate, free and time-saving process compared to manual testing.

4.2 Data collection

During this phase it is very important to consider the current operational/environmental loads with respect to the data collected from the sensors to check its validity. If this is not the case, additional modifications should be implemented. For example: checking the connection, Recalibration the system and most critically identifying all the background noises which could affect the real data.

This phase objective is providing Real-time monitoring phase, so it is very important to improve the robustness and reliability of the equipment used in SHM.

The procedures for collecting the Data are as follows; the Acoustic signals received from the sensors, which are mounted on the surface of the critical areas being monitored are being amplified. Through internal amplifiers and external amplifiers if more amplification is needed. Then the amplified AE signals are filtered by PAC using filtration methods, which depend on the

PAC model and its specifications. Also, during processing in the PAC the Signals are transformed from Analog to digital signals to be analyzed later in the software, which deals only with discrete/continuous digital signals. After transforming the Acoustic signals into digital signals and waveforms, they are prepared to be received by the computer through cables to be processed by the software in the workstation area.

4.3 Data processing

Now the monitoring system is set up and running offshore, data already has been collected by the workstation and being processed by the software. Through this phase the processing is done by AE software as mentioned before. They have the capability to do the analysis for the data by using FFT and wavelet transformation functions or even as modern researches proved by performing modal analysis using lamb wave analysis.

In the software further filtration methods are used, such as determining the threshold value for considering the lowest hit to be recorded. The threshold value is identified by the technician who identifies the background noises present in the offshore field and their frequency range to filter all unnecessary acoustic noises.

Currently with modern algorithms, the software it can locate the defect in different planes.

This phase needs a specialized technician with software skills and acoustic background knowledge to deal carefully with the data collected.

Software's types and specifications for both suppliers can be checked on (PHYSICAL ACOUSTICS-Software) and (Vallen-Software) with different data analysis tasks. The software can be used for both zonal and linear location determination modes, it has the replay capability for saved data. Graph include 2D ,3D plots, waveforms, FFTs…etc

4.4 Evaluation

This phase where the data has already been processed and filtered and ready for being evaluated by the operator.in this stage the operator should be able to identify

- Flaw type; crack initiating, crack growth, corrosion...etc. in the previous chapter several AE characteristics for each flaw is illustrated.
- Flaw measured location considering the background noises , for example in (Lee et al., n.d.) AE has been used for SHM on ship's hull to detect flaw existence, it was a challenge to discriminate the AE signals by crack growth and water splash or raining, so the source

location has successfully differentiate as the AE resulted from the water splash was located on a wide area of the hull while the AE generated by crack growth was located on a specific area.

- Flaw severity damage; as the AE signals & Energy can be indicators for the severity of damage for a specific defect such as crack growth.
- Establishing a Warning and Alarm system can be activated in this stage, depending on the peak amplitudes/hit-counts pre-determined values in the software inputs. The warning is set to be lower than the alarm. The alarm can be based on a number of AE signals with low amplitude or even a high single AE burst amplitude signal. The best way to avoid a false alarm is to design a system to filter the background noises, an example for this a test was done by TUV Rheinland Sonovation using an electric motor to produce background noise similar to a background noise on offshore platform from rotating equipment such as pumps, compressors etc. The noise produced was semi-continuous in nature and have peak amplitudes of 50 dB. The threshold value was determined 40dB in this test to allow the AE noise burst signals to be shown with the crack growth signals initiated by pencil lead breaks on the weld, that demonstrates that a higher threshold can be used in local monitoring to reject any background noise (Duthie,2014)

4.5 Corrective Actions

After the evaluation phase, where there are AE signals indicate flaw existence, therefore some correction actions must be made such as:

- If further inspection is needed for confirming the defect existence, for example by applying another NDT technique, e.g. applying UT for the defected part of the structure to check the crack condition by measuring wall thickness or applying FMD for detecting any leakage due to crack, corrosion. Then appropriate decision can be made for scheduled maintenance or replacement. also, it could be in a good/stable condition and doesn’t require any human interference at this time.

- Prognosis: it is the forecast/prediction of the likely outcome of the situation or case, e.g. it can be estimated for lifetime prediction for a defected member in the offshore jacket structure based on diagnostic and monitoring results considering all information about the structure and its maintenance history.

Limitations and Assumptions

SHM using AE method as any other concept is based on a set of fundamental assumptions. These assumptions are based on the thesis's knowledge about AE method from physics and other researches. Therefore, it cannot be claimed whether these assumptions are complete or not. So further modifications and corrections could be needed.

1) Optimal SHM system ensures maximum PoD for the flaw.
2) AE can detect the most failures jacket structure experiences due to cyclic loading, overload or other factors. such as crack initiation, crack growth and corrosion.
3) AE sensors should be installed very close to the expected flaw source, to receive reliable AE signals from the source avoiding attenuation phenomena.
4) Background noises are identified and filtered.
5) AE can only detect active flaws for existing jacket platforms, or in other case it has to be installed on the structure's surface during the installation phase for the jacket structure to detect early stage of any flaw.
6) Real-time Monitoring can be reliable only if there are no changes in the operational/environmental loads.
7) Isotropic material should be assumed for the application, so that there is only one wave propagation velocity, which is a function of the plate thickness and frequency. Therefore, triangulation method can be applied successfully to locate the flaw source.
8) Resonance should be identified carefully, resonance or reflected waves present when a material is inside another martial e.g. jacket offshore structure in water, the acoustic waves will reflect at each interface as shown in the Figure 69, the number of reflections will depend on both the acoustic impedances of the material and water, and the attenuation in the material. In this report prepared by (Beattie, 2013) in section 2.9, he discusses the resonance phenomena for acoustic waves inside a plate immersed in water.

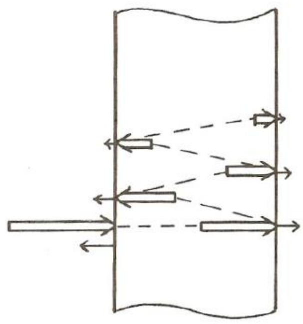

Figure 69: Reflected waves inside a submerged plate

9) Refraction waves inside two different mediums should be considered. when the AE sensor and the source are in two different mediums, the AE signal will be refracted at the interface. Therefore, the AE source localization method won't be accurate unless it considers the refraction effect as shown in Figure 70.
   There is an experiment study was done by (Zhou et al., 2017) explains this case and proposed an algorithm equation to be used for more accurate localization of the acoustic source considering the refraction.

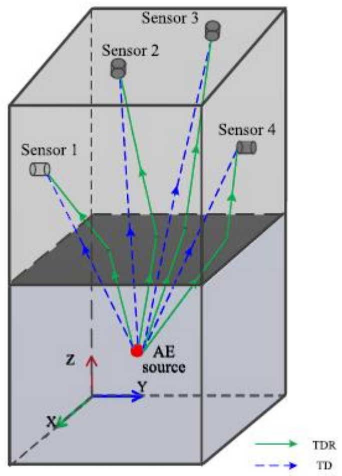

Figure 70: Propagation paths for waves inside 2 different mediums

Where,

- Red circular dot represents the acoustic source
- Blue dotted lines represent the traditional location method assuming the waves travel in straight lines through the two mediums until being received by the AE sensors.
- Green dotted lines represent the modified location method assuming the waves travel will refract at the interface between the two mediums.

10) Using the same type of sensor, as the characteristics of waveforms differ according to the sensor type. Even with detecting the same flaw from same distance from the source (Kaphle, 2012).

5. Experimental SET-UPS

5.1 Overview

The chapter describes the details of the experiments proposed by this research to achieve the objectives identified in first chapter. In Section 5.2, it illustrates the experiments conducted and their setup. Section 5.3 shows the samples dimensions and calculation of the theoretical bending stresses to apply for the tests, in order to estimate the Force to be applied by the 3-point bending machine on the samples so the samples starts to yield. Section 5.4, it presents the AE equipment that were used in the tests, Analysis software that was used for evaluation the data, the samples specifications and the 3-point bending tests as well that were performed by the Shimatzu instrument. Section 5.5 shows the calibration method used by the researcher to adjust the AE sensors location and calibrate them using Pencil Lead Break (PLB) tests.

5.2 Experimentation

The Main concern of the experiments is to evaluate the reliability in using AET in detecting pre-stage of any major cracks in the structure, in other words, detecting the signals emitted from the material during yielding stage, specially before ultimate tensile stress.

- Several experiments are performed to study different behavior for using AET for steel structures. The first type of the experiments is considered the basic one to evaluate the AE signals while material deforms.

that is achieved by applying a Normal Force to the top of the specimen at different positions, where the specimen is placed horizontally over two fixed contact supports, which is the case of 3-point bending test ass shown in Figure 71. The force acts on the specimen until it leads it to slight bending and the bending stress exceeds the yielding stress of the specimen. The specimen will bend in a slight V shape. The AE attachments are installed on the specimen and connected to the external PC to analyze the data at the same time the loading conditions of the testing machine (SHIMATZU) are controlled and displayed on another PC as a stress-strain curve, where it displays data for the load (N) vs displacement for the specimen deflection (mm).

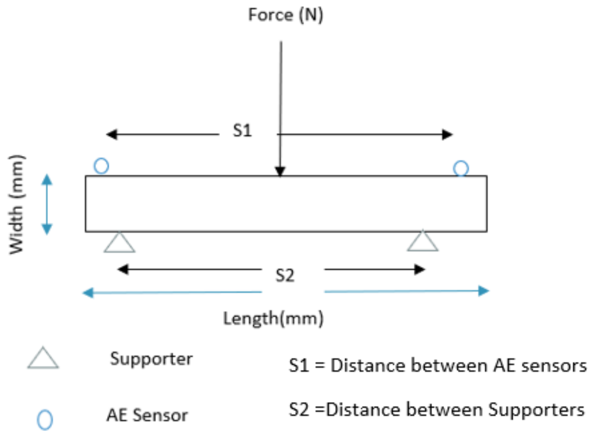

Figure 71: Schematic figure for the Experiment set-up for short specimen

- The second experiment is to show the effect of changing the thickness of the sample on the strength and behavior of the AE output signals by repeating experiment one on a thicker sample.
- The third experiment's aim is to show the distance effect on the strength of the AE signals emitted from the source to the AE sensor. By applying the force close to one end of the specimen and far from the other one, where the sensors are placed close to the two ends of the specimen as shown in the Figure 72.

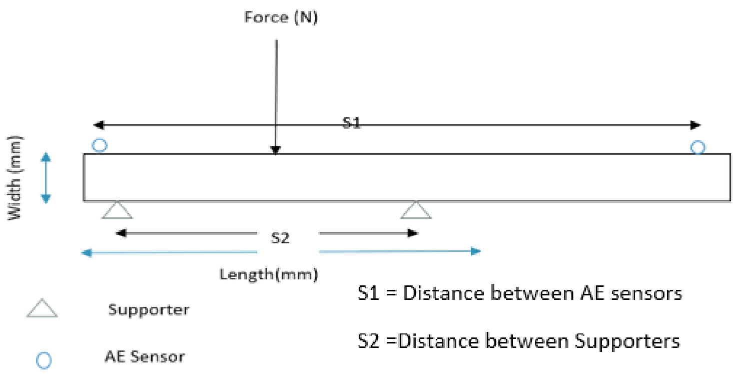

Figure 72: Schematic figure for Experiment set-up for long specimen

- The Fourth experiment is applying the 3-point bending load on the specimen with using an external source of noise (pump, compressor, any kind of noise in offshore environment), to differentiate between the AE signals received from the deformation source and the external source.

The Experiments were carried out in DNV-GL Høvik's Laboratory. The samples were brought from an external supplier, then the samples were cut and prepared in the University's Laboratory to fit the experiments required dimensions.

5.3 Specimen samples

The material selection was based on the structural steel that are used in offshore structures, according to NORSOK N-004 table 5-1, the structural joints can be classified according to the design class, joint complexity and consequences of failure.as it is shown in the table, joints and members in jacket structure from design classes DC3 and DC4 would have a failure without substantial consequences which is recommended. Table 16 shows different design classes and their consequences failure according to N-004.

Table 16:Design class for offshore materials

Design class	Joint complexity	Consequences of failure
DC1	High	Applicable for joints and members where failure will have substantial consequences and the structure possess limited residual strength
DC2	Low	
DC3	High	Applicable for joints and members where failure will be without substantial consequences due to residual strength.
DC4	Low	
DC5	Any	Applicable for joints and members where failure will be without substantial consequences.

There is a relation between the design class of steel and its quality level for a structural component, it is recommended to have quality III or more for the steel material found in NORSOK N-005 table 5-2.the Quality of steel determines the most stringent DC of joints involving the component. Through thickness stresses shall be assessed.

Table 17 illustrates the steel quality level for each corresponding design class.

Table 17:Steel quality vs design class

Design Class	Steel Quality Level			
	I.	II.	III.	IV.
DC1	X			
DC2	(X)	X		
DC3	(X)	X		
DC4	(X)		X	
DC5				X

Where (X) =selection where the joint strength is based on transference of tensile stresses in the through thickness direction of the plate.

The Material data sheet for the structural steel plates used in this research follows NORSOK MDS-Yo5 in NORSOK M-120, which has the following specification shown in Table 18:

Table 18: Sample specifications for the test

MDS NO.	Rev. no.	Standard	Steel grade	Product Type	Steel Quality Level	Design Class
Yo5	**3**	**EN 10025**	**S355J2**	**Plates**	**III**	**DC4**

The Samples Dimensions:

These experiments include 3 different dimensions samples as shown in table 19.

Table 19: Testing Samples dimensions

Thickness (mm)	Width (mm)	Length (mm)
15	30	500
20	30	500
15	30	1000

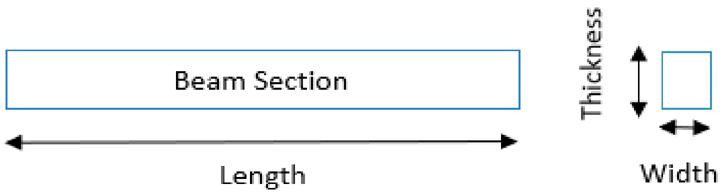

Figure 73: Three different dimensions specimens

5.4 Instrumentation

1. The 3-point bending test was applied using SHIMATZU instrument as shown in Figure 74, it is an electric type which can apply force up to 100 kN with variable loading rate.

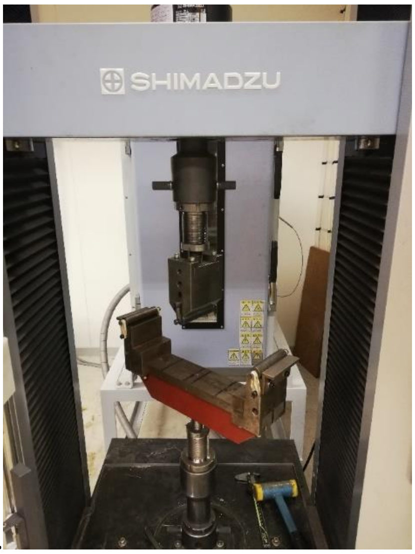

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Figure 74: SHIMATZU-Bending instrument

The Speed rate is controlled via external PC which is connected to the Machine using the software. The input parameters for the software are the dimensions for the sample, distance between the supporters which is maximum (345 mm) in this case the and speed rate (mm/sec) for increasing the Load acting on the sample. There are 2 sensors which considered as data output to the software;

Load cell (N), Stroke of the sample (mm). The software can monitor the material loading condition during the tests as shown in the Figure 75 below.

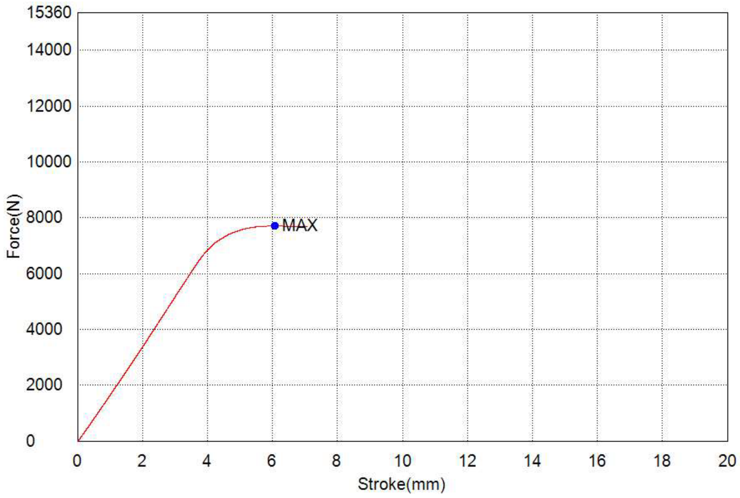

Figure 75: Example for Shimatzu software output (loading force (N) vs Stroke (mm)

2. AE Accessories

AE sensors: two resonant R15a (Physical acoustic) sensors were used in this experiment with resonant frequency at 150 kHz , Table 20 shows the AE sensor specification.

Table 20: AE sensor specifications

Resonant frequency	**150 kHz**
Operating frequency	50-400 kHz
Dimensions	19 mm Outer Diameter * 22.4 mm Height
Case material	Stainless steel
Face material	Ceramic
Operating temperature	-65 – 175 ºC
Weight	34 grams

I. Amplifiers: The 2/4/6 is a voltage preamplifier with switch-selectable gain ranges of 20, 40, and 60 decibels.it is used for laboratory tests specially when the band frequency is unknown, it can be used with all AE systems.

II. Metal Holders: They are used to hold the sensors on the steel samples, to resist any kind of motion due to vibration or any external load.

Figure 76: Photographic illustration of (L) AE sensor (Middle) AE 20-40-60 Preamplifier and (R) AE magnetic holders

III. Couplant: Grease was used between the sample surface and the adjusted sensors to fill any air gaps in between the layers, acts as connector as well and increase the sensitivity of the sensor.

IV. Cables: Physical acoustic signal cables have been used to connect the AE sensors with the Amplifiers, Power cables have been used for connecting the amplifiers with the AE instrument.

Figure 77: AE cables

6. PAC (Acquisition Device): The Micro-II Express is an industrial chassis built to enable powerful AE testing capabilities in a compact form factor. Its 4 PCI Express slots allow it to hold up to 32 AE channels, using Physical Acoustics' Express-8 AE boards as shown in Figure 78. It is a very high-speed processor and it can be controlled be locally keyboard and mouse through wired connection or by Remote system controlled by a notebook computer.

Figure 78: AE PAC-Acquisition device

7. Software: AEwin software was used for AE signal analysis and displaying. It is a windows-based program for real-time monitoring, used for wave processing, storing data, displaying online and replaying at later time as well.it has all the acquisition, graphs and capabilities needed by the customer. in this research the software was using the hit method for signal analysis.

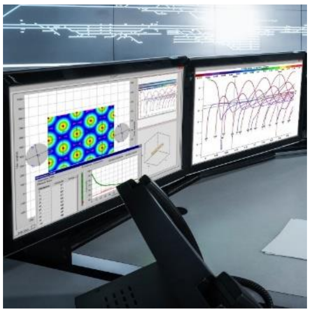

Figure 79: AEwin Software

5.5 AE Testing SET-UP

Specimen sizing for 3-point bending test

To calculate the Bending stress on the beam structure, it involves calculating the reaction forces at the supports (A, B) because of the forces acting on the beam considering the distance between the supporters as illustrated by simple sketching in Figure 80.

So initially the beam is assumed to be static state, which means that the sum for all forces in the vertical direction equals Zero. Also, the sum of the moments about any given point equals zero in the steady state.

The governing equation for the moment at a specific point (e.g. support A) on the beam is:

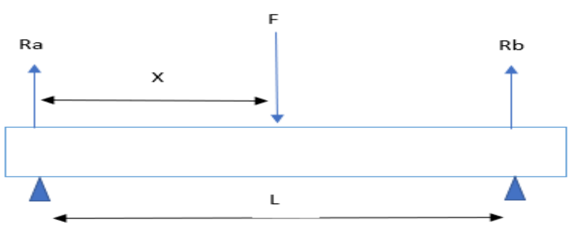

Figure 80: Forces distribution along the specimen

$$\sum M_A = 0 = FX - R_B L$$

$$R_B = FX/L$$

Where,

X = the horizontal distance between the testing load and the support point A.

L = the horizontal length between support B and A

R_B= is the reaction force on support B / A

F = the testing load

X, L are known dimensions of the specimen, the load Force can be assumed so (R_B) can be calculated but still another equation is needed to solve the unknown Reaction force on support (A).

As it is mentioned, for a beam structure at steady state, the Sum For vertical forces along the beam element equals zero, where the sum of the upwards forces are equal to the sum of the downwards forces, so R_a now can be calculated.

$$\sum F = 0 = F - R_a - R_b$$

Where,

R_a = the reaction force on support A

After identifying the Load and the Reaction forces values, The Bending stress formula will be applied to estimate the Maximum Bending stress value needed to bend the Beam structure.

Section modulus(Z) for rectangular shape is $Z = \frac{bh^2}{6}$

where,

b = the width of the beam structure

h = the thickness of the beam structure

Cross section area(A)= b.h in m^2

Bending moment (M)= F.x in Nm, where x = the distance from the load point to the support position

Maximum bending stress is (σ_{max}) = M/Z in Mpa

Table 1: Specimens accurate Dimensions

- Measurements were taken by accurate thickness gauge in the laboratory are shown in Table 21.

Table 21: Testing specimens measured dimensions

Specimen samples	Thickness (mm)	Width (mm)	Length (mm)
A1	14,74	30,1	500
A2	14,77	30,16	500
A3	14,72	29,82	500
B1	19,76	29,61	500
B2	19,74	29,4	500
B2R (Reversed)	29,4	19,74	500
C1	14,66	29,82	1000
C2R	14,67	29,79	1000

- For samples: A1, B1, C1 and C2 the Normal force acts on the width surface.
- For samples: A2 and B2 the Normal force acts on the thickness face surface, while the width represents the thickness of the sample.
- For samples: A3 the Normal force acts on the width face surface plus using an external fan, which acts an external noise in the experiment with specific frequency.
- B2R : is the same B2 sample but with reversed dimensions , means the force acts on the width surface (29.4 mm) and thickness (19.74 mm) , the reason for repeating the experiment on the same specimen is that it would be deformed after the first test, so in the second experiment the specimen will be in the plasticity stage so different AE results will be recorded and analyzed for this condition.

Figure 81 shows the external noise (dryer fan) generator used in the experiments

Figure 81:External noise source used in the experiment (Dryer)

- So according to these experiments the theoretical force (N) needed to exceed the yield stress of the material were calculated. The span length between the supporters is maintained through all tests at 345 mm.

Table 22 illustrates the yield and ultimate stresses for the samples according to the material certificates.

Table 22: Material certificate yield and ultimate stresses for the specimens

Sample (mm)	Yield stress (MPa)	Ultimate stress (MPa)
(15*30) Steel sample	439	542
(20*30) Steel sample	390	502

- See Appendix D for the two sample's material certificates.

<u>Flexural vs tensile strength</u>

Before proceeding with the calculations, it must be noted that these yield stresses values are collected from tensile tests on the samples not from bending tests or flexural tests. When a material is under bending, the fibers on the upper surface of the beam are under compression stress (point B) and those on the lower surface experiences tension stress (point A) while in the fibers in the core are experiencing the minimum stresses as illustrated in Figure 82, therefore the flexural strength is controlled by the strength of those surface fibers. However, if the same material is exposed to tensile loads all the fibers have the same stresses through the cross section of the beam and the failure will initiate at the weakest fiber.

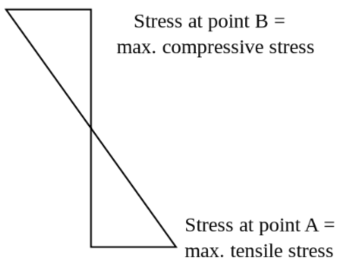

Figure 82 : Beam stresses under bending load

Therefore, it is common that the bending strengths is higher in most cases than tensile strengths of the same material. The flexural or bending strength would have equal to tensile strength if the material were homogenous. So, in these experiments higher values of load were needed for bending the specimens than the calculated values of loads in table 23.

Table 23: Beam calculations for the experiment

No.	Width	Thickness	Cross Section Area	Section modulus	Distance between Force and support	Yield Bending moment	Yield Bending stress	yield stress (material certificate)	Load should be applied (Theoretically)
	W(mm)	h(mm)	A(mm^2)	Z(m^3)	d(mm)	M(Nm)	σ(N/m^2)	y (MPa)	F (N)
A1	30.10	14.74	443.67	1,08996 E-06	17.25	478,68	439,17	439	5500
A2	14.77	30.16	445.46	2,2392E-06	17.25	983,25	439,10	439	11400
A3	29.82	14.72	438.95	1,07689 E-06	17.25	474,37	440,50	439	5500
B1	29.61	19.76	585.09	1,92691 E-06	17.25	759,00	393,89	390	8800
B2	19.74	29.40	580.35	2,84374 E-06	17.25	1116,98	392,77	390	12950
B2R	29.40	19.74	580.35	1,90937 E-06	17.25	750,37	392,99	390	8700
C1	29.82	14.66	437.16	1,06813 E-06	17.25	470,06	440,07	439	5450
C2	29.40	19.74	580.35	1,90937 E-06	17.25	750,37	392,99	390	8700
C2R	19.74	29.40	437.16	1,06813 E-06	17.25	470,06	440,07	439	5450

5.6 Pencil Lead Break test

It is performed initially as a calibration tool for using the AE sensors, as it was discovered that breaking pencil leads on the surface of the specimen generates crack like signals, therefore, they are used as source of AE signals in tests, location adjustments and sensor calibration. PLB tests are used initially before applying load on any sample. The PLB test was performed at the center point of the sample as shown in Figure 83, which is the same point the load acts on. It was noticed that some reflections occur in some trials, maybe due to lamb's waves that were mentioned before or reflections inside the material structure.

Figure 83: PLB calibration test

Before carrying out the experiments on the steel samples, AE data acquisition system Physical acoustic Corporation (PAC) is used with 4 active channels, which are two R15a AE sensors, the load (N) acts on the sample and the position (x) represents the linear distance between the sensors.

Preamplifiers with gain is set at 40 and the frequency filter range is 20-200 kHz. a layer of grease is applied between the sensor surface and the sample for better sensitivity. Magnetic holding device is used for holding the sensors on the steel samples. The threshold value is adjusted at 40 dB for all the tests. The length of the pre-trigger signal is set to 256 µsec for all tests.

The speed rate of the load for the bending machine is set 0.017mm/sec (approximately 1 mm/min) for all tests. The distance between the supporters (span length) is kept constant at 345 mm.

The distance between the sensors is 400 mm for the short samples (length = 500 mm), while 900 mm for the long ones (length = 1000 mm).

All steel samples were marked accurately as shown in the Figure 84 from the center of the sample (0 marked position), measurements were taken as well from the point where the load acts on.

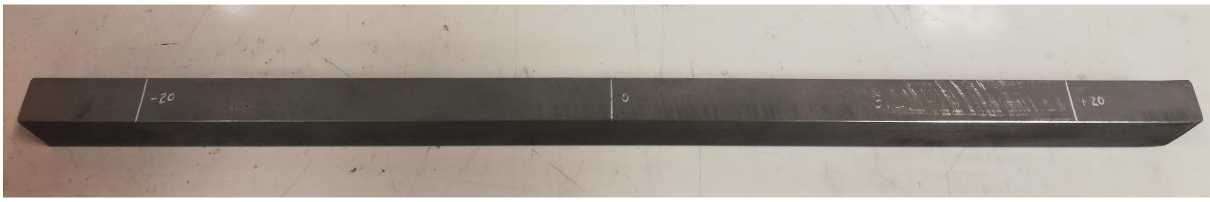

Figure 84: Marked steel sample with length 500 mm

As the tests were performed on linear plates, simple TOA method can be used for two sensors for locating the source of the AE event. When the distance between the two sensors is known and time of arrivals for the two sensors are known as well, then by simple calculation or algorithm, distance can be measured accurately by the software.

5.7 Background Noise

1) Shimatzu instrument self-Noise

Before starting the tests on the steel samples, the background noise and the bending instrument self-noise must be checked and identified. The load cell was controlled to move in vertical motion above the AE sensors which are placed on the steel sample as shown in the Figure 85. The threshold value was adjusted at (0) dB, so it can detect all the background noise, thereafter changed above this value to filter all unnecessary AE signals not from the source event.

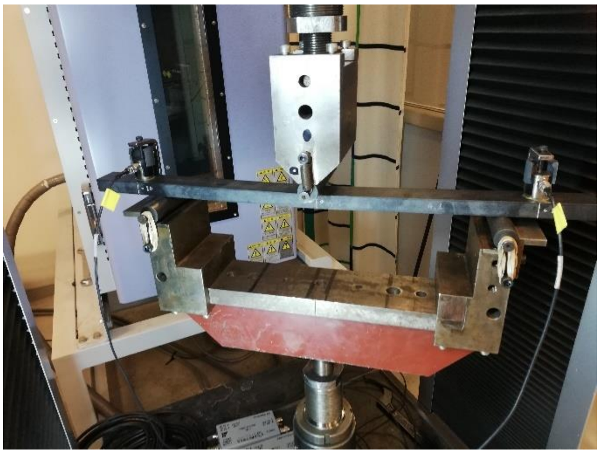

Figure 85: AE installment on the steel sample under 3-point bending test

Figure 86 graph (a) shows the number of Hits vs the AE signal's amplitude in dB, this relation shows that the instrument has self-noise was detected around 30 dB with very few hits in corresponding for these signals, as the test duration was 53 seconds.

both sensors detected same number of hits, which was so important to identify before starting the tests.as it is shown below in Figure 86 Both Sensors are detecting the same number of hits with the same magnitude in graph (c), while graph (a) shows the signal amplitude (dB) against number of hits and graph b shows the continuous wave energy resulted from the instrument. Graph (b) is showing output Energy aJ vs time (sec).

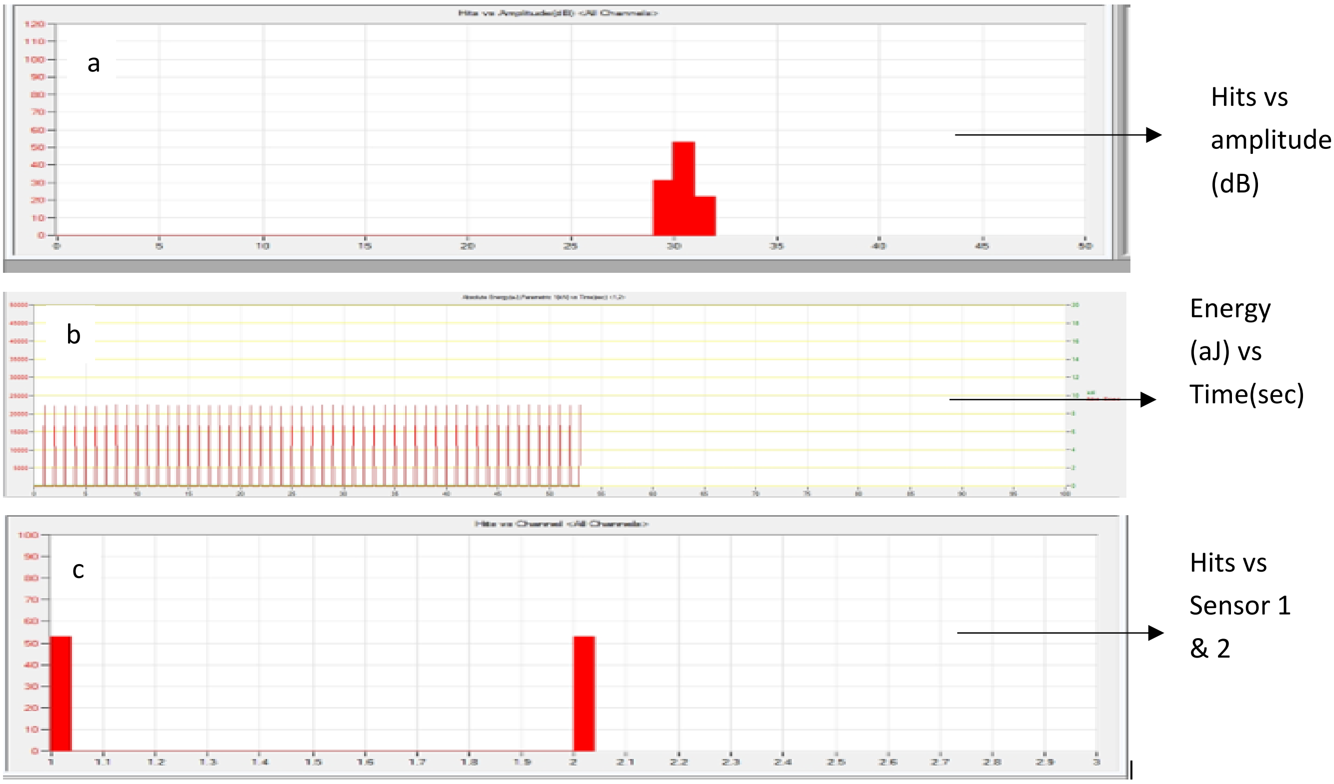

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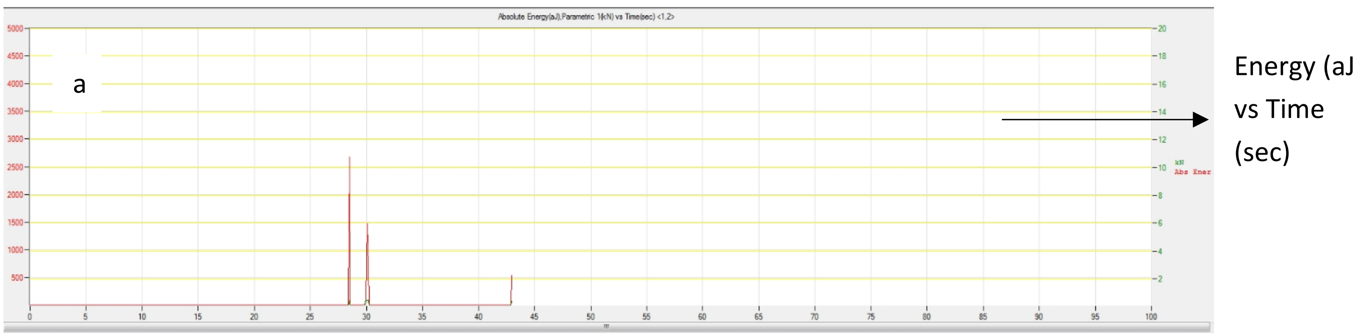
Figure 86: AE outputs for Background noise

2) Dryer fan Noise

Normal air flow was produced by the fan which was directed at a very close distance to the sample (few mm from the sample). The Figure 87 is showing the absolute energy produced from the dryer fan, it is estimated to be 2700 aJ which is too low with amplitude ranges from 44-54 dB, so it can be easily differentiated from deformation source event which normally exceeds (70 dB) according to the thickness off the material and its type. Moreover, external noise normally has continuous signals while real acoustic events have Burst signals. Figure a is the Abs energy vs time, Figure b number of Hits for the 2 sensors and Figure c shows the signal amplitude (dB) vs number of hits.



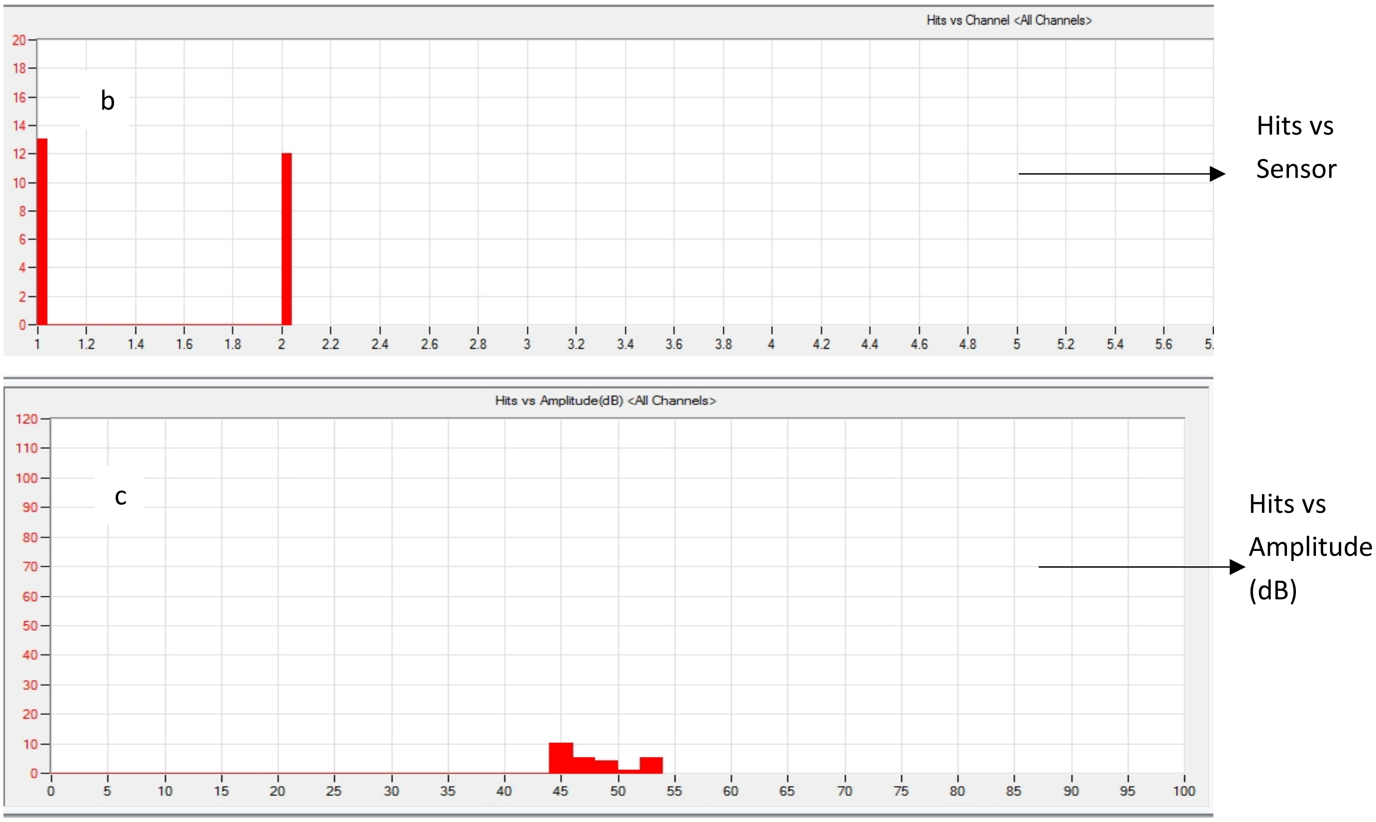


Figure 87: AE outputs for Dryer Fan

Table 24 shows the AE parameters for the background noises have been recorded in this experiment and also an example for a source event referred as (Material defect).to compare the difference in AE parameters.

Table 24: AE param

Source of Noise	Number of Hits (S1, S2)	Energy (aJ)	Signal amplitude (dB) range
Shimatzu Instrument	52,52	23000	29-32
Dryer fan	12,13	2700	44-54
Material defect	300	500000	70-85

- According to these values, the threshold value can be raised up to 60 dB, so it only detects the AE signals from the material deformation. Through this study it shows the possibility of identifying the external noises by either from the AE Absolute energy, Signal amplitude and the type of hit signal whether burst or continuous signals.

6 Results and discussion

This chapter shows the results obtained the experiments that were carried out in the previous chapter, discusses the AE characteristics for different defects received from the deformed material, in addition to identifying the critical AE parameters to analyze the data. All the test plotting and tables that include the information and data gathered from the plotting after the analysis and evaluation are given in Appendix E.

6.1 Signal Amplitude vs load

Acoustic emission amplitude indicates the level of the damage as referred in Table 13. it is in directly proportional with the deformation occurs inside the structure. AE amplitude is described in decibels (dB) and is plotted against time (sec) and load scale (kN).

An example for detecting the lower yielding point during the experiments for both samples B2, C1 using the amplitude vs Loading rate are given in Figures 88 & 90, where at load 15300 and 15800 N the AE amplitude has increased to 73 and 75 dB, these signals represent the starting of yielding phase for the specimen according to the calculated value and the Shimatzu software which shows the material stress/strain curve. while for C1 sample at load 5750-5800 N the AE amplitude increased to 84 dB noting that the two examples have different thicknesses which could be affecting the AE signal amplitude. Location graphs were used to assist the results, as the position for the defect confirms the source of the AE.

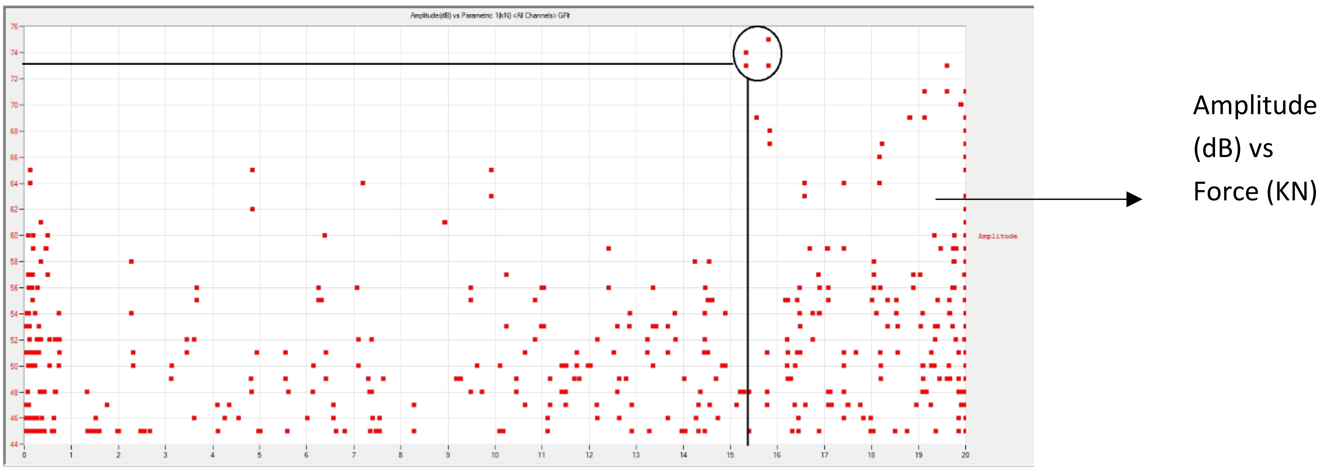


Figure 88: AE signal amplitude for B2 at yield point

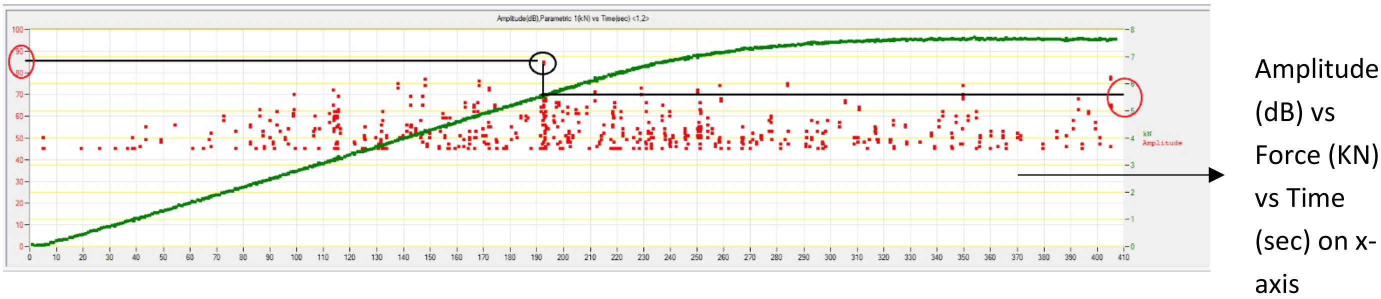


Figure 89: AE Signal amplitude for C1 at yield point

Another case for sample C2, the material has reached the yielding stage in the first experiment. Then after a while another experiment was carried out on the same sample with gradual increasing of the load on the sample, a recorded amplitude signal value at 4900 N load was 84 dB as shown in Figure 90 which indicated that the specimen was in the plasticity stage. It was interesting that at the same load value 4900 N in the first experiment, the amplitude of AE signal was only 77 pre-yielding stage.

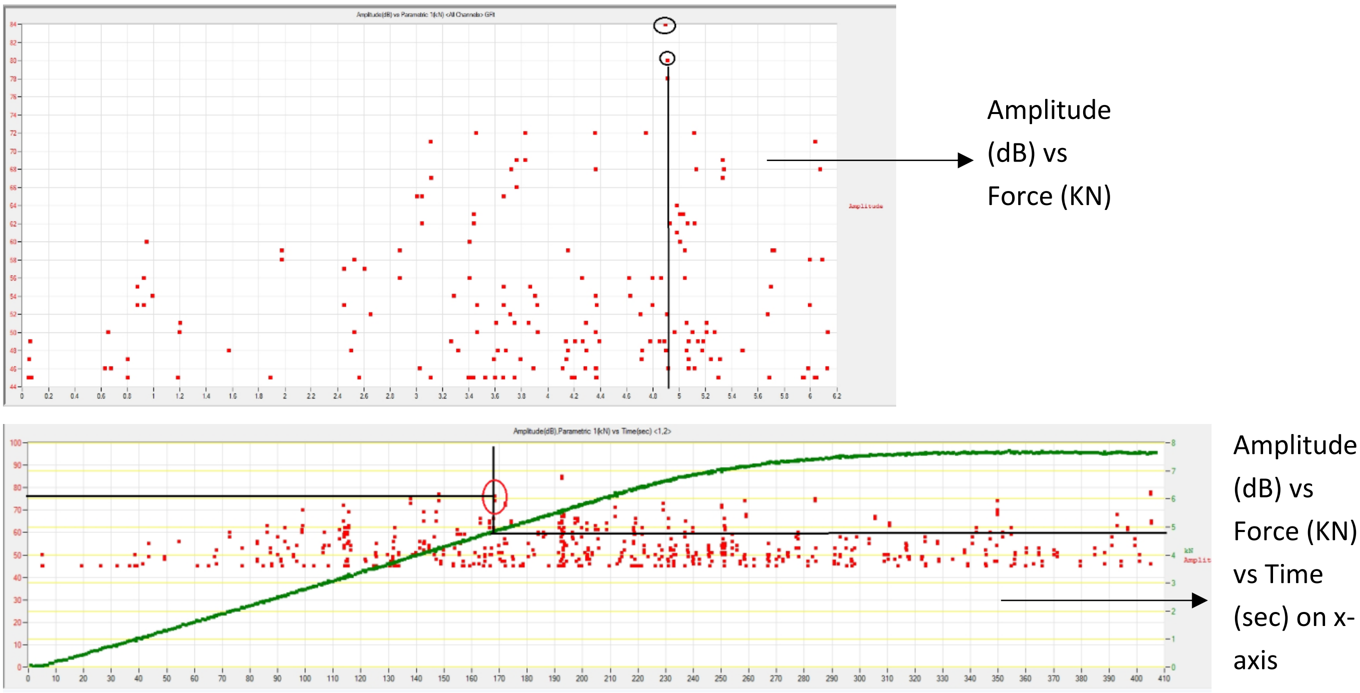


Figure 90: AE signal amplitude for C2R at higher yield stress

Probably the reason is that the material in the second test was already in a deformed condition, so it was emitting higher signal’s amplitude to indicate the plasticity stage, where it could be higher discontinues or dislocations were taking place that started to emit high energy which was noticed in the Figure 91. As normally the lower yield stress point from previous tests was noticed to be lower than 2.0E+005 aJ, while in this graph it shows higher absolute energy equals to 2.00E+006 aJ at 4900 N, it was noted before in Table 13 that AE energy describes the damage type. As in this case, higher energy could represent slip bands formation (Slip are considered as dislocations along crystallographic planes within individual grains due to shear deformation of the material

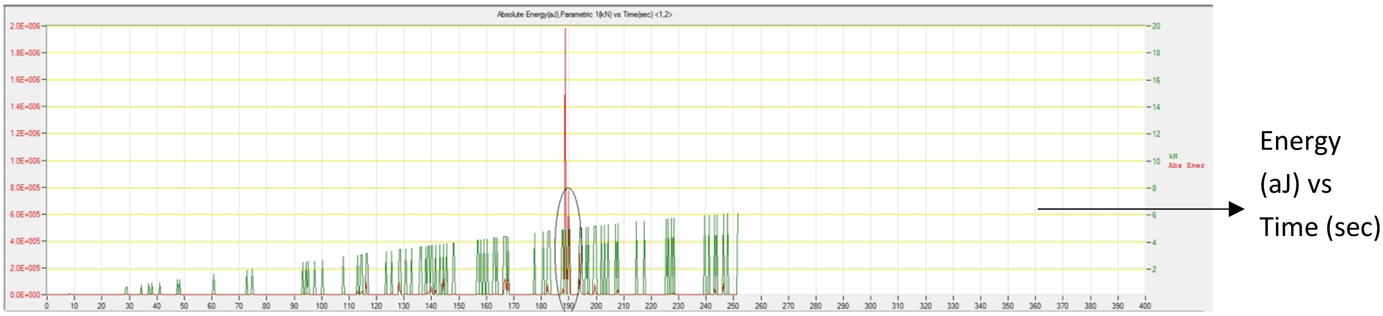


Figure 91: AE energy for C2R at higher yield stress/ Slip band formation

6.2 Location vs signal amplitude

Locating the defect is an important tool in analyzing the data, as it is not only used to locate the defect in the structure, it is also considered as a critical assessment tool for confirming the outcomes from the signal amplitude and AE energy data. It can differ between the AE received from the source event or from another source like external noises.

In this research, AEwin software was able to locate the defects accurately for one dimensional plate using 2 sensors using TOA method.

There was no need for triangulation method as all the tests have one dimensional plate shape. so only 2 sensors were needed to locate any defect. Some input parameters and values have to be entered in the software for proper functioning such as number of AE sensors, their positions on the plate and the distance between the sensors.

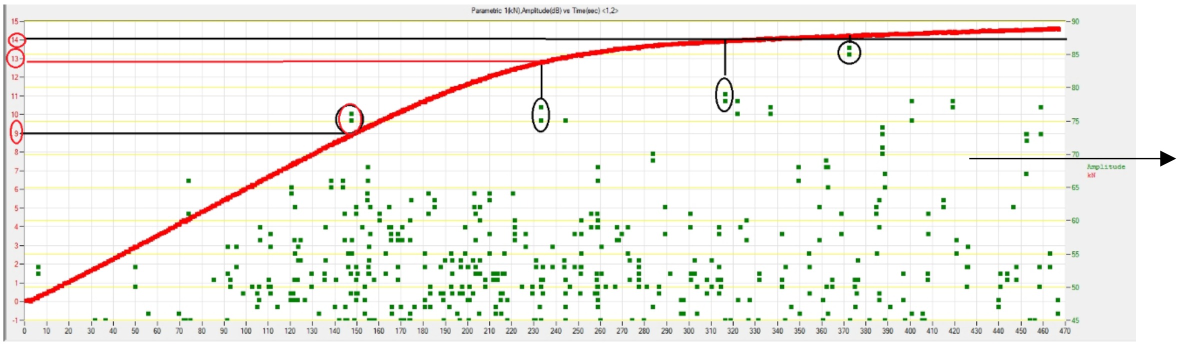
6.3 AE absolute energy vs time

AE absolute energy could be an indication key for the damage quantification. during the tests, different values for AE energy were obtained in different conditions for the material. In PLB test the crack energy was about 4.3E+007 aJ which is higher than the yielding energy that ranges from 0.4E+005 to 8.0E+005 aJ According to the results.

An example for severity damage, deformed sample B2 (second trial) which was already deformed before but has not reached the ultimate stress yet in the first experiment. The second experiment has shown higher energy values and AE signal's amplitudes for plasticity condition of the material when the load has increased, which lead to more cyclic deformation or higher degree of slip.

An example for different AE energy values and what it describes as shown in Figure 92 and table 25. The first point indicated the Lower yielding point for the material with 2.5E+005 aJ, the second and third points indicated more deformation inside the material through yielding stage with Absolute energy up to 7.7E+005.

The fourth point had a sharp increase for both absolute energy and signal amplitude (4.5E+006, 86 dB), which can be assumed as ultimate yield stress point at 14100 N>11200 N (Calculated value for upper yield force according to manufacturing tests). It produced high AE absolute energy 4.5E+006, which is the closest value to the PLB crack Absolute energy value (4.3E+07) among other values.



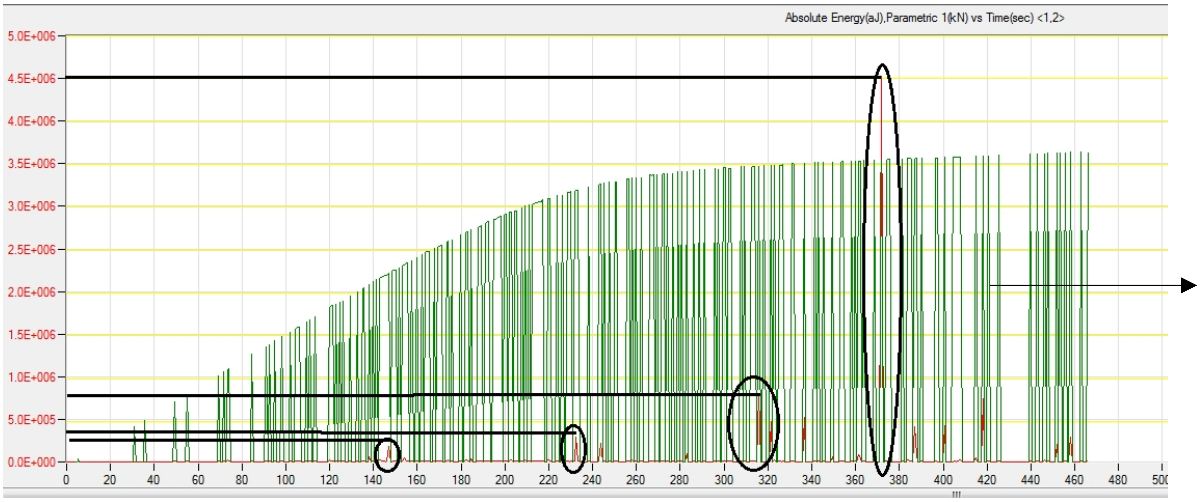


Figure 92: AE Signal amplitude and Energy for ultimate yield stress

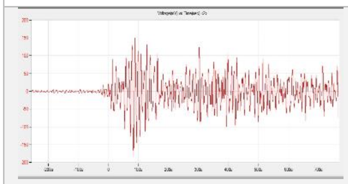
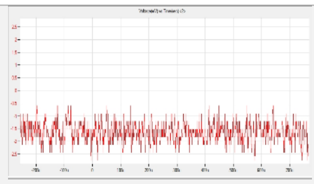
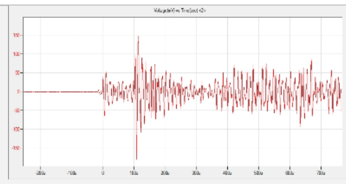
Table 25: AE parameters for yield/plasticity stage

Point	Time (Sec)	Energy (aJ)	Force (N)	Signal amplitude (dB)
1	148	2.5E+005	8800	76
2	232	3.5E+005	12800	77.5
3	317	7.7E+005	14000	79
4	372	4.5E+006	14100	86

6.4 Voltage vs Time

In these experiments 3 different waveforms were obtained for 3 different sources of AE. The 3 waveforms can be used for noise filtration in industrial applications for structural monitoring to identify the source of AE waveforms as shown in Table 26. They are giving the same waveforms as shown before in section 3.8 by (Lee,n.d) research.

Table 26: AE waveforms for 3 different sources

Mechanical rubbing (Supports contact with the sample)	Dryer fan (External noise)	PLB (crack signal)
		

6.5 Signal attenuation

- The aim is to study the signal attenuation from the source event along the structure material. Signal attenuation occurs because of several factors discussed previously in this thesis.
- To determine the signal attenuation, PLB test was carried out on C1 long Specimen, it acts as a crack signal which would be very noticeable from its signal amplitude (95-99 dB). Moreover, the location for the test was known, so further analysis could be taken to measure the TOA for each sensor and the signal amplitude that was recorded by each one

Figure 93: Experiment set-up for C1 sample

- The Pencil was held (200 mm) from S1 and (700 mm) from S2 as illustrated in the Figure 95.

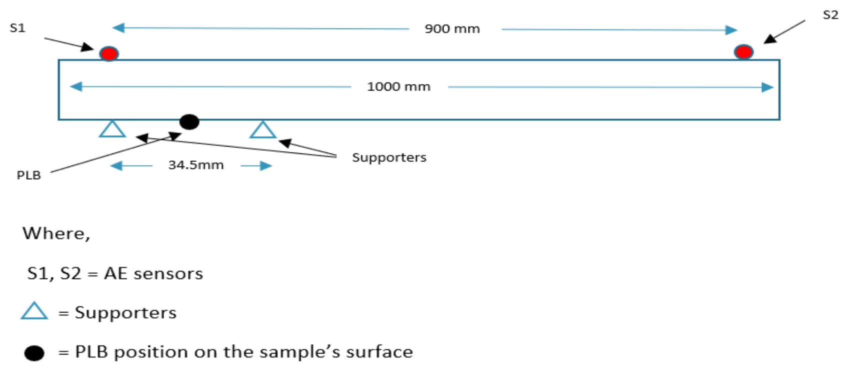


Figure 94: schematic sketch for PLB test on C1 sample

<u>Specimen Specifications:</u>

Table 27 shows C1 sample dimensions which was used for PLB testing to determine the signal attenuation, Table 28 illustrates the received AE data of both AE sensors.

Table 27: C1 sample dimensions

Sample	Length (mm)	Width (mm)	Thickness (mm)	Distance between Sensors (mm)
C1	1000	29.82	14.66	900

Table 28: AE Signal attenuation through C1 sample

AE Parameter	S1	S2
Signal amplitude	99 dB	98.5 dB
PLB Real position from S1	200 mm	700 mm
PLB Recorded position from S1	290 mm	610 mm
TOA	7400 msec	7450 msec

- The Error in Signal location could be because of several factors:

A. unproficiency in applying PLB test

B. angle of Lead breaking to the surface

C. shifting the PLB few centimeters during the test.

D. distance between sensors not exactly equals 900 mm

E. distance between the PLB point and S1 was not adjusted accurately

F. sensing point in the AE sensor is not exactly centered on the surface point

$\Delta TOA = 7450 - 7400 = 50\, msec$

$\Delta Distance = 610 - 290 = 320\, mm$

$\Delta AE\ signal\ amplitude = 99 - 98.5 = 0.5\, dB$

$$Signal\ attenuation = \frac{\Delta AE\ signal\ amplitude}{\Delta Distance} = \frac{0.5}{320} = 0.00156\, dB/mm$$

Wave velocity = $\frac{\Delta\ Distance}{\Delta TOA} = \frac{320}{50} = 6.4\ m/sec$

- Which means AE signal is attenuated by **0.00156 dB for each mm.** assuming using the same material and thickness (15 mm) as in sample C1 and same lab temperature (Room temperature) and pressure (atmospheric pressure) and the wave velocity of AE signal through steel was measured to be **6.4 m/sec**.

6.6 Coating effect on AE parameters

The coating has shown interesting results. As the Load of the cell starts to bend the specimen, it has been noticed much more receiving hits, higher Absolute Energy values as well. for coated samples A1, A2 the number of hits recorded were 10 times the normal number of hits for similar uncoated samples. The high number of hits are indicating that when the sample started to bend or yield, the collision between the coating particles started to break and initiate high strain energy due to the contact stress applied on the coating surface. Figure 95 below shows the coating surface breakage after the bending load.

Figure 95: Coating surface breakage on specimen's surface

it can't be claimed that with coated specimen it emits higher values of signal's amplitude, maybe it is giving higher signal's amplitude (82-85 dB) due to the probability of summing signals from both source event and coating particles at the same time. But it certainly gives an indication for yielding by AE monitoring.

As shown in Figure 96, the huge difference between the coated and uncoated samples for AE output hits, where the red dots represent the AE number of signals during loading represented on (y-axis) and time represented on (x-axis).

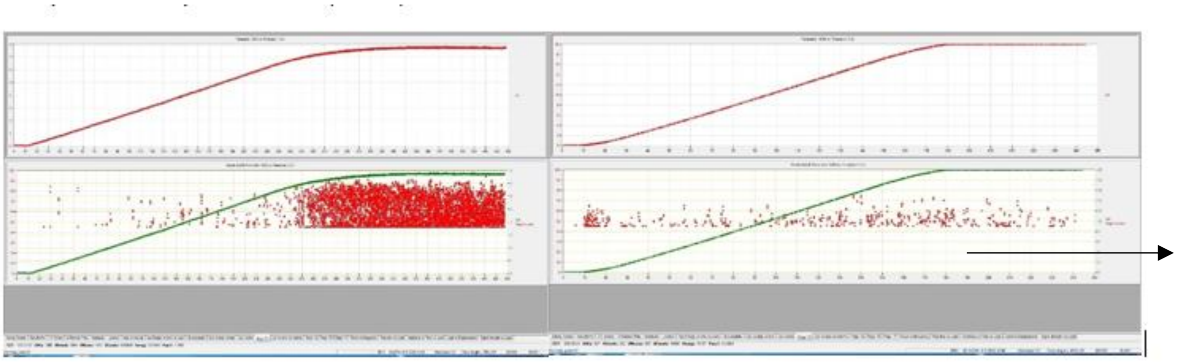


Figure 96:AE parameters Difference between Coated (L) and uncoated sample (R)

Table 29 shows the comparison between similar samples with the same dimensions but with coating and Non-coating surfaces. Which shows the difference in number of hits with coating presence.

Table 29: AE signal amplitude for coated and uncoated specimen

Sample (same Thickness)	**Coating surface (Y/N)**	**No. of AE Hits (S1, S2)**	**Signal magnitude (dB)**
A1	Y	3900-4000	83
A2	Y	3500-3550	80
A3	N	410-420	78

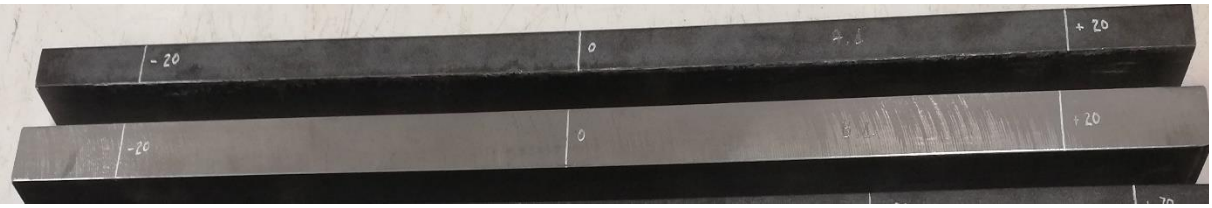


Figure 97: Coated(dark) & Uncoated sample(bright)

6.7 Thickness effect on AE Parameters

Thickness is one of the factors that affect the AE parameters as discussed before that velocity for AE waves depend on the thickness of the plate and frequencies.

In this research, 15,20 mm thicknesses for steel samples were used. There was no significant difference in the results obtained for both thicknesses. It could be because of the small difference in thickness which is only 5mm in this case or because the experiments were stopped before the material reached the fracture point where high significant AE amplitude and energy would have been generated, which I believe would give different results for both materials.

- Table 30 summarizes the collected AE parameters for the experiments that were carried out by 3-point bending on various steel samples after evaluation.

  Where,

  $\sigma_b = calculated\ yield\ stress$/force (F_b) , values depending on the material certificate values for the samples.

  $\sigma_{Sh} = Shimatzu\ yield\ stress$/force (F_{SH}) , Estimated values from the graph.

  $\sigma_{AE} = Acoustic\ emission\ yield\ stress/\text{force}\ \ (F_{AE})$, Notices/estimated values from AEwin software.

Table 30: bending stresses at yield point for all samples

Sample	F_b (N)	σ_b (Mpa)	F_{SH} (N)	σ_{Sh} (Mpa)	F_{AE} (N)	σ_{AE} (Mpa)	σ_{AE}/σ_{SH}
A1	5500	439	6700	530,18	6700	530,18	100 %
A2	11400	439	14000	539,25	11700	450,66	83,57 %
A3	5500	439	6700	536,61	6100	488,55	91,04 %
B1	8800	390	12500	559,51	9800	438,65	78,39 %
B2	12950	390	18000	545,93	15500	470,11	86,11 %
B2R	8700	390	10000	451,71	8800	397,51	88,00 %
C1	5400	439	6000	484,49	4000	322,99	66,66 %
C2	5400	439	5700	460,10	4900	395,52	85,69 %

- Table 31 and 32 respectively show different AE parameters for various samples at expected yield point and higher yield stress point.

Table 31: AE parameters at yield point for different samples

Sample	Amplitude (dB)	Energy (aJ)	Hits (S1, S2)	Time (sec)
A1	83	6.5E+005	3900,4000	244
A2	80	4.0E+005	3500,3550	123
A3	78	4.2E+005	410,420	218
B1	73	2.3E+005	105,138	157
B2	74	1.8E+005	295,330	136
B2R	76	2.5E+005	245,225	147
C1	75	3.0E+005	260,330	138

Table 32: AE parameters at higher yield stage for some samples

Sample	Amplitude (dB)	Energy (aJ)	Time (sec)
PLB	95-99	4.3E+007	5.95
A1	95	3.6E+006	412
A2	90	5.0E+005	195
B1	83	9.7E+005	222
B2R	86	4.5E+006	372
C1	85	8.8E+005	192
C2R	84	1.98E+006	188

7 Conclusions with Future recommendations

This chapter summarizes all the observed conclusions through the thesis work, identifying the remarks and future recommendations for further work to have a reliable efficient NDT monitoring tool for offshore structures.

- Piezoelectric transducers are the preferred type to be used in AE sensors due to its high sensitivity and balanced actuator for temperature and pressure fluctuations.
- AET has proved during the tests to be a Real-time monitoring tool for detecting minor defects in the steel material such as yielding or crack signals, so that early signs of failures can be identified, and corrective actions can be taken before fatal failures would occur.
- Acoustic emissions parameters differ according to the fault stage such as yielding, crack growth and major cracks. This is valid, for both ductile and brittle material properties.
- Prognosis analysis can be estimated using the monitored AE signals corresponding to the yielding force, therefore, by estimating the load amplitude the yield occurs at and the number of events are counted to be used in calculating the accumulated fatigue damage.
- AE can be used for continuous monitoring of the steel structures in which the AE sensors could be installed in the installation phase of the foundation structure at yard for best results
- it was noticed that during the experiments that the actual yield stress occurred was closer to the AE results than the calculated yield stresses. This proves that AE can be a reliable monitoring tool for detecting yielding inside steel structure.
- Coating was found to have enormous effect on the number of AE hits received by the sensors, during bending the specimen, the coating particles under contact stress generated considerable strain energy which was translated as acoustic emissions. It has proved that coating can generate 10 times the number of hits when the material deforms more than the uncoated material.so my opinion that coating can be used in some cases as a better indication for initial deformation of the structure.
- PLB tests were carried out to calibrate the AE sensors and to estimate the AE signal attenuation through the material with specific characteristics. It has shown that the signal is attenuated by 0.0015 dB/mm for steel material in room temperature and pressure conditions
- Wave velocity for the AE was calculated from the signal attenuation test, the test has shown that the AE travels through steel material at a speed 6.4 m/sec.
- AE signal's amplitude is an essential tool for detecting the yielding in steel structure as it was proven through the experiments that for yielding the AE amplitude has a value over 70 dB, this value can be used later in setting the alarm for defect initiation in real-monitoring system.
- AE Energy has proved to be a reliable tool for identifying the defect type in the steel structures, as for each defect the material emits specific amount of energy per hit which was recorded and identified through the experiments.

- During data evaluation AE signal amplitude, Absolute energy and localization AE parameters have proved to be critical tools for identifying the real acoustic emission signals from the noisy or external sources.
- TOA method has been used by AEwin software to locate the defect initiation, the results have shown its accuracy to identify the location based on the number of sensors.

Recommendation for Future Research

- The tests were carried out in laboratory conditions and were applied on specific material and dimensions. For more reliable results for using AE in online monitoring for offshore structures, it is recommended to apply the tests in more realistic conditions, as environment conditions and real time noise would probably bring some challenges for AE testing.
- Further loading cases should be carried out, as in this research only bending tests have been applied on the specimens.
- More experiments and research should be carried out for identifying the AE characteristics result from initiating a crack inside the material till the final fracture point.
- Using AE testing on specimens with different dimensions, material properties and different geometry shapes can give more assessment in analyzing the AE applications in monitoring.
- Due to time constraints, some tests were planned but couldn’t be carried out, such as using AE testing for butt welded specimens with some complexity in shapes and study how they would behave under different loading conditions.

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9. Appendices

Appendices

Appendix A: Summary of NDT techniques

Table 33: Pros & Cons for NDT techniques

Technique	Working principle	Pros	Cons
Visual Inspection (VT)	➢ Visual inspection carried out by qualified personnel in regular intervals to check any defects to recommend if any appropriate retrofitting Is needed.	➢ Simple ➢ Use of dye to facilitate the testing process	➢ Hard to detect small defects, hidden parts by lust or paint ➢ Cracks due to corrosion or fatigue may go undetected
Fiber optics	➢ Able to sense strain and temperature. ➢ It is based on intensity, wavelength and interference of light wave.	➢ No electric interference ➢ Geometric conformity	➢ Expensive ➢ Need qualified personal to perform the testing
Magnetic Particle inspection (MPI)	➢ Using flux leakage field principle ion detecting the defects and cracks by running a magnetic current which cause the magnetism to spread out from the defects	➢ Cheap method ➢ Fast ➢ easy	➢ Applicable only for ferrous materials

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Eddy current testing (ECT)	➢ Eddy-current pattern changes if there is any defect in the material	➢ Crack detection through paint ➢ Detection for cracks in welded joints	➢ Expensive ➢ Can be used only for metallic materials ➢ Only can be used by qualified personal for adjusting the sensor
Radiographic testing (RT)	➢ Depends on sending and receiving the radiation through the specimen	➢ Inspecting hidden areas within the material ➢ small preparations for pretesting.	➢ Expensive ➢ Hazardous method ➢ Large size of equipment
Ultrasonic testing (UT)	➢ Transducers sends high frequency waves into the specimen and receives the reflected pulses.	➢ Small Defects can be detected ➢ Location of the defects can be identified accurately ➢ Rel time detection	➢ Expensive ➢ Requires sending and receiver transducers to reform the testing ➢ Adjusting the sensor needs a qualified personal

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Acoustic emission (AE)	➢ Ae waves are emitted from the material that undergoes any deformation such as crack initiation.	➢ Very sensitive ➢ Location of the defects can be identified accurately ➢ Passive technique, no energy needs to be supplied.	➢ Background noises can affect monitoring large structures ➢ Large volumes of data for continuous monitoring ➢ Attenuation effect on the Acoustic signals

9. Appendices

Appendix B: HSE NDT techniques applications

Table 34: HSE NDT techniques applications

Technique	Applicable to:											Service available?	Qualified? (NOTE 1)
	Vessels	Pipes	Ferritic steel	Duplex steel	Austenitic steel	General corrosion	Pitting corrosion	Erosion	CUI	CUS	CUW		
1. Guided waves	✗	✓	✓	✓	☑	✓	☒	✓	☑	☑	☑	✓	✓
2. CHIME	✓	✓	✓	✓	☑	✓	☑	✓	✗	✓	☑	✓	✓
3. LORUS	✓	✓	✓	✓	☑	✓	☑	✗	✗	✓	☑	✓	?
4. EMAT	✗	✓	✓	✓	☑	✓	☑	✓	✗	✓	☑	✓	?
5. Verkade	✗	✓	✓	✓	☑	✓	☑	✓	☑	✓	☑	☑	?
6. TOFD FS	✓	✓	✓	✓	☑	✓	☑	✓	✗	✗	✗	☑	☑
7. M-skip	✓	✓	✓	✓	☑	✓	☑	✓	✗	✗	✗	☑	☑
8. Rapidscan	✓	✓	✓	✓	☑	✓	✓	✓	✗	✗	✗	☑	☑
9. AE	✓	✓	✓	✓	✓	✗	✗	✗	✓	✓	✓	✓	✓
10. QAE	✓	✓	✓	✓	✓	✓	☑	?	✓	✓	✓	✓	☑
11. Lixi	✗	✓	✓	✓	✓	✓	☒	✓	✓	✗	✓	✓	☑
12. SCAR	✗	☑	✓	✓	✓	✓	✓	✓	✗	✗	✗	✓	☑
13. ThruVu	✗	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	☑	?
14. Neutron backscatter	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✓	?
15. SLOFEC	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗	☑	✓	☑
16. PEC	✓	✓	✓	?	?	✓	✗	✓	✓	✗	✓	✓	☑
17. MFL	✓	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗	✓	☑
18. MW	☑	☑	✗	✗	✗	✗	✗	✗	✗	✗	✗	☑	☑
19. Thermography	☑	☑	☑	☑	☑	✗	✗	✗	✗	✗	✗	✓	✓
20. Laser shearography	☑	☑	☑	☑	☑	✗	✗	✗	✗	✗	☑	☑	☑

Key : ✗ No; ✓ Yes; ? Unknown; ☑ Yes, but only within the limitations explained elsewhere; ☒ No, not normally unless special focussing is applied.

NOTE 1 – N.B. that for those techniques that are ticked the extent to which they are qualified for a given application is potentially limited

HSE Recommendations for using NDT Techniques (HSE-RR659,2009)

CUS: Corrosion underneath supports CUW: Corrosion under Welding CUI: Corrosion under insulation

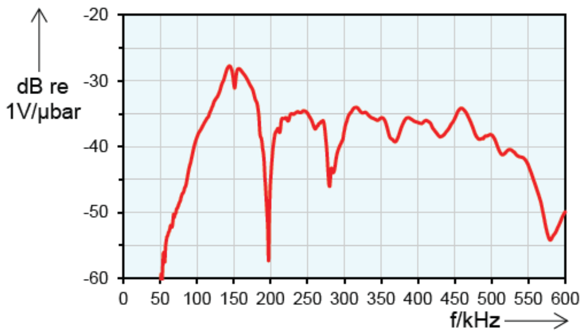
Appendix C: AE sensors data sheet

1. Vallen sensor datasheet

The datasheet below shows a water-tight integrated-AE sensor VALLEN-model, it is suitable for detecting frequency range (100-450 Hz with peak resonance at 150 Hz), this sensor can be used for online-monitoring for subsea structures up to 60 bar of water pressure.

VS150-WIC-V01

The VS150-WIC is a piezoelectric AE-sensor with integrated preamplifier. Its frequency response is characterized by a peak at 150 kHz where it exhibits a resonance. The VS150-WIC is rated watertight up to 60 bar of water pressure. It is suitable for almost all AE application and especially suited for wet environments or for on-site monitoring of underwater installations.
The integrated preamplifier has 34 dB gain and supports pulse through for automatic sensor testing.



Technical Specification			
Frequency Range (f_{Peak}) [kHz]	100 to 450 (150)	**Size (D x H) [mm]**	32.0 x 48.0
Power Supply [v_{DC}]	28 ± 2	**Weight [g]**	184
Typ. Power [W]	0.56 / 2.5 @ Signal 0% / 100%	**Case Material**	Stainless Steel (1.4571/ 1.4404)
Integrated Preamplifier	Yes	**Wear Plate**	Ceramics
Preamplifier Gain [dB]	34	**Connector**	LEMO 03 Series
Pulse Through	Yes	**Shield Cross-Talk [dB]**	< -80
Operating Temperature [°C]	-40 to +85	**Typ. Noise (max. 1/s) [$dB_{AE\ Peak}$]**	25.2 @ 95 - 300 kHz
Vibration – Sinus Sweep	2 Oct/Min, 5 to 50 Hz, 20 g	**Typ. Noise [μV_{RMS}]**	5.0 @ 95 - 300 kHz
Ingress Protection Rating	IP68, max. 60 bar (with connected cable)		

Accessories			
Mounting Holder	MAG4W-V1	**Sensor Cable**	CBL-1-xM-V11

9. Appendices

The datasheet below shows a water-tight integrated-AE sensor (Physical acoustic-model), it is suitable for detecting frequency range (200-400 Hz with peak resonance at 225 Hz), this sensor can be used for online-monitoring for subsea structures up to 69 bar of water pressure.

2. Physical acoustic sensor datasheet

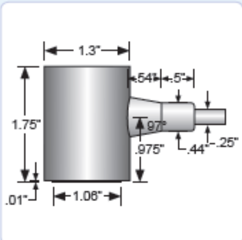
MISTRAS

PHYSICAL ACOUSTICS

PRODUCT DATA SHEET

R30-UC Sensor

Underwater Sensor

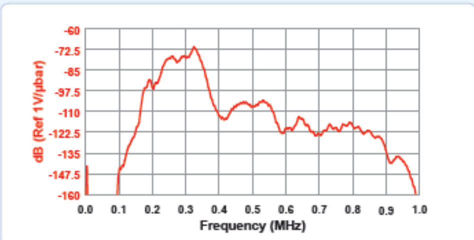


DESCRIPTION AND FEATURES

R30-UC is an underwater sensor with integrated preamplifier. The sensors feature special polymer coatings making it 100% insulated and non conductive with an integral waterproof cable for underwater use. The sensor is tested to depths of 2,200 ft (1,000 psi).

APPLICATIONS

The sensor can be used for the structural health monitoring of submerged structures like offshore oil and gas platforms, ships etc. They can be used inside any liquid filled platforms like pipelines, chemical tanks or any other submerged structures.



OPERATING SPECIFICATIONS

Dynamic	
Peak Sensitivity, Ref 1V/(m/s)	58 dB
Peak Sensitivity, Ref 1V/µbar	-64 dB
Operating Frequency Range	200-400 kHz
Resonant Frequency, Ref 1V/(m/s)	225 kHz
Resonant Frequency, Ref 1V/µbar	350 kHz
Directionality	+/- 1.5 dB
Environmental	
Temperature Range	-65 to 177ºC
Shock Limit	500 g
Immersion Depth Limit	1000 ft
Physical	
Dimensions*	1.3"OD X 1.75"H
	33 mm OD X 45 mm H
Weight	180 grams
Case Material	Epoxy coated stainless steel
Face Material	Ceramic
Connector	BNC on integral cable
Cable Locations	Side
Electrical	
Shielding for EMI	Fully shielded

ORDERING INFORMATION AND ACCESSORIES

R30-UC	R30-UC
Amplifier Subsystems	0/2/4, 2/4/6, IL-LP-30S
Sensors include	
Characterization Certificate & Warranty	

* Due to variances in coating process, the height of coated sensors may vary within a tolerance of +/- 0.015 inches (.381 mm)

CE

Appendix D: Material certificate for the test samples

1. Material certificate for Steel samples (15*30)

Duferco Danish Steel
Duferco GROUP
DK-3300 Frederiksværk - Telefon +45 47767600

BESCHEINIGUNG / CERTIFICATE
Stabstahl/Bars

Seite / Page: 1/1 Nr./No.: 104938
Type: EN 10204 / 3.1
Ihrer Auftrag/Your ord P03007372
Unser Auftrag/Our ord 63789
Datum/Date: 24-01-2019

NORSK STÅL AS LAGER
Postboks 123
NO-1378 - Nesbru
NORWAY

Lieferstelle/Delivery address:
Norsk Stål AS, avd Horten
Nedre Vei 8
NO-3187 - Horten
NORWAY

Lieferbedingung / Specification:
EN 10025-2 S355J2+AR

Toleranz Tolerance: EN10058

	Pos.	Product Type	Abmessungen/Dimensions				Stk/Pcs	Gewicht/Weight	Schmelze/Heat
1	5	Flad	6000		35.0	5.0	1	2301	40163
2	8	Flad	6000		150.0	6.0	2	4146	39715
3	7	Flad	6000		70.0	8.0	1	1975	39910
4	1	Flad	6000		60.0	8.0	2	3998	39986
5	2	Flad	6000		100.0	8.0	3	6299	40313
6	3	Flad	6000		130.0	10.0	2	4278	39720
7	6	Flad	6000		60.0	12.0	2	4116	39984
8	4	Flad	6000		30.0	15.0	1	2121	40131
9									
10									

Lieferzustand/Condition of delivery
Walzzustand / As rolled
Kennzeichnung/Marking CE
Sachverständigen/Quality inspector:
Schmelze/Heatno.
10.000-29.000 Konverter-verfahren/Oxygen converter
30.000-99.999 Elektro-Ofen/El-arc-furnace Im Pfanne raffiniert/Ladle

Total weight: 29234

	C	Mn	Si	P	S	Cr	Cu	Ni	Mo	Sn	Al	Nb	Ti	V	B	N	Ceq = Carbon-Equivalent (IIW - formula)
1	13	134	20	25	19	7	32	15	4		1	2	15	38		100	42
2	13	135	20	13	9	7	20	12	3		0	1	10	40		90	40
3	12	135	22	16	18	9	26	12	3		2	1	1	41		90	40
4	14	133	18	19	9	9	23	10	2		2	1	19	39		90	41
5	12	138	21	16	22	9	28	11	3		3	2	1	40		110	40
6	14	137	21	18	9	8	23	12	3		0	2	20	34		80	42
7	13	135	21	16	9	9	24	10	2		2	1	16	35		80	41
8	12	139	23	18	21	12	25	13	3		3	1	2	35		100	42
9																	
10																	
	% x 100			% x 1000		% x 100				% x 1000					% x 10 000		% x 100

	Zugversuch/Tensile test			Kerbschlagbiegeversuch/Impact test/ISO - V					Hardness
	ReH	Rm	A5	1	2	3	Mittel/Average	Temp	
1	430	543	29	73	87	70	77	-20	
2	405	521	32	74	67	92	78	-20	
3	395	551	27	32	30	33	32	-20	
4	403	525	34	98	115	103	105	-20	
5	400	529	31	126	116	39	94	-20	
6	386	518	27	140	139	133	137	-20	
7	388	514	33	122	93	133	116	-20	
8	439	542	32	109	89	61	86	-20	
9									
10									
	MPa		%	Joule				°C	HB

DDS requires, that all billet suppliers make statement in writing to the effect, that the billets delivered have not been exposed to and / or contaminated with radiation.

Bei Material mit einer Dicke unter 10 mm, werden die Kerbschlagproben zu einer Breite von entweder 7.5 mm oder 5.0 mm bearbeitet.

For material with thickness less than 10 mm, the impact testpieces are machined to a width of either 7.5 mm or 5.0 mm.

Wir bestätigen, dass die Lieferung den Forderungen der obengenannten Lieferbedingungen und des Auftrages entspricht.
We hereby certify, that the material has been

2. Material certificate for Steel samples (20*30)

27436.pdf - Adobe Acrobat Reader DC

File Edit View Window Help

Home Tools M-120 edition 5 n... 27436.pdf ×

1 / 2 146%

LAMINÉS MARCHANDS EUROPÉENS A04

AFV BELTRAME GROUP

Z04 CE 0398

complete CE Marking on next page

A06 NORSK STAAL A/S

POSTBOKS 123.

N 1378 NESBRU

Pag. 1/ 2

A03
INSPECTION DOCUMENT N.: 976402
OFFICIAL REGULATION: EN 10025-2/2004

C70 Steel from electric arc furnace

A10 Environmental product declaration : ICQM - 14011EPD

AGENT ORDER N. 61/2050243
CUSTOMER CODE 821
A07 CUSTOMER ORDER N. P03006594
CONSIGNEE NORSK STAAL A/S
B02 B04 GRADE S355J2+AR

A02
INSPECTION CERTIFICATE 3.1 - EN10204
ENCLOSE CERTIFICATION CE

LOADING NUMBER: 383928 LOADING DATE: 17/10/2018 A08 INTERNAL ORDER: E 870483

IT.	B07 CAST	B01 SECTION	B09 - B10 - B11 DIMENSIONS mm	CE	LENGTH mt	C71->C92 C	Si	Mn	P	S	Cu	Cr	Ni	V	Mo	Ti	Nb	N	Ceq	Al
1	LM 27436	FLAT	40X20	0398	6,00	0,11	0,23	1,10	0,024	0,021	0,33	0,12	0,14	0,057	0,03	0,0020	0,0019	0,0049	0,366	0,0019
3	LM 27852	FLAT	200X15	0398	6,00	0,10	0,21	1,09	0,025	0,020	0,41	0,18	0,18	0,063	0,03	0,0021	0,0022	0,0097	0,378	0,0027
6	LM 27802	FLAT	200X20	0398	6,00	0,10	0,25	1,08	0,020	0,024	0,33	0,16	0,16	0,059	0,03	0,0019	0,0017	0,0099	0,365	0,0029

IT.	B07 CAST	A01 ORIGIN	PRODUCT REGULATION	C00 TEST NUM	B08 Bdls n.	B13 WEIGHT Kg	TENSILE TEST C11 ReH/MPa	C12 Rm/MPa	C13 A5%	Z%	IMPACT TEST C42 Kv 300/10 J	C42	C42	C03 °C	RATIO REDUC.	BEND <	TEST D	GRAIN	HARDNESS	INSPECTION SUP. INSIDE	ANTI MIX.
1	LM 27436	TRITH	EN 10058	6008014	1	2.401	390	502	22,0		35	160	60	-20							
3	LM 27852	TRITH	DIN 59200	6008081	4	9.582	455	590	24,7		48	66	46	-20							
6	LM 27802	TRITH	DIN 59200	6008078	5	11.220	390	495	24,6		169	163	60	-20							

INSPECTOR	FACTORY	Z02 DATE	A05 QUALITY CONTROL DEPT	Document validated by electronic sign	Z02 QUALITY ASSURANCE DEPT
	TRITH ST LEGER	17/10/18	Amelie Boury		Sebastien Crom

This document is electronically reproduced and is identical to the original.

#	CO #	Item #	Del #	Heat	Lot	Your art #	Qty	Description
1	UH1921161	200	RP5431 37	27436			1	FLAT BAR S355J2 40 X 20 MM X 6 M

9. Appendices

Appendix E: Experiment plots

PLB Testing

Figure 98 below illustrates the PLB signal amplitude for steel specimen (A1)

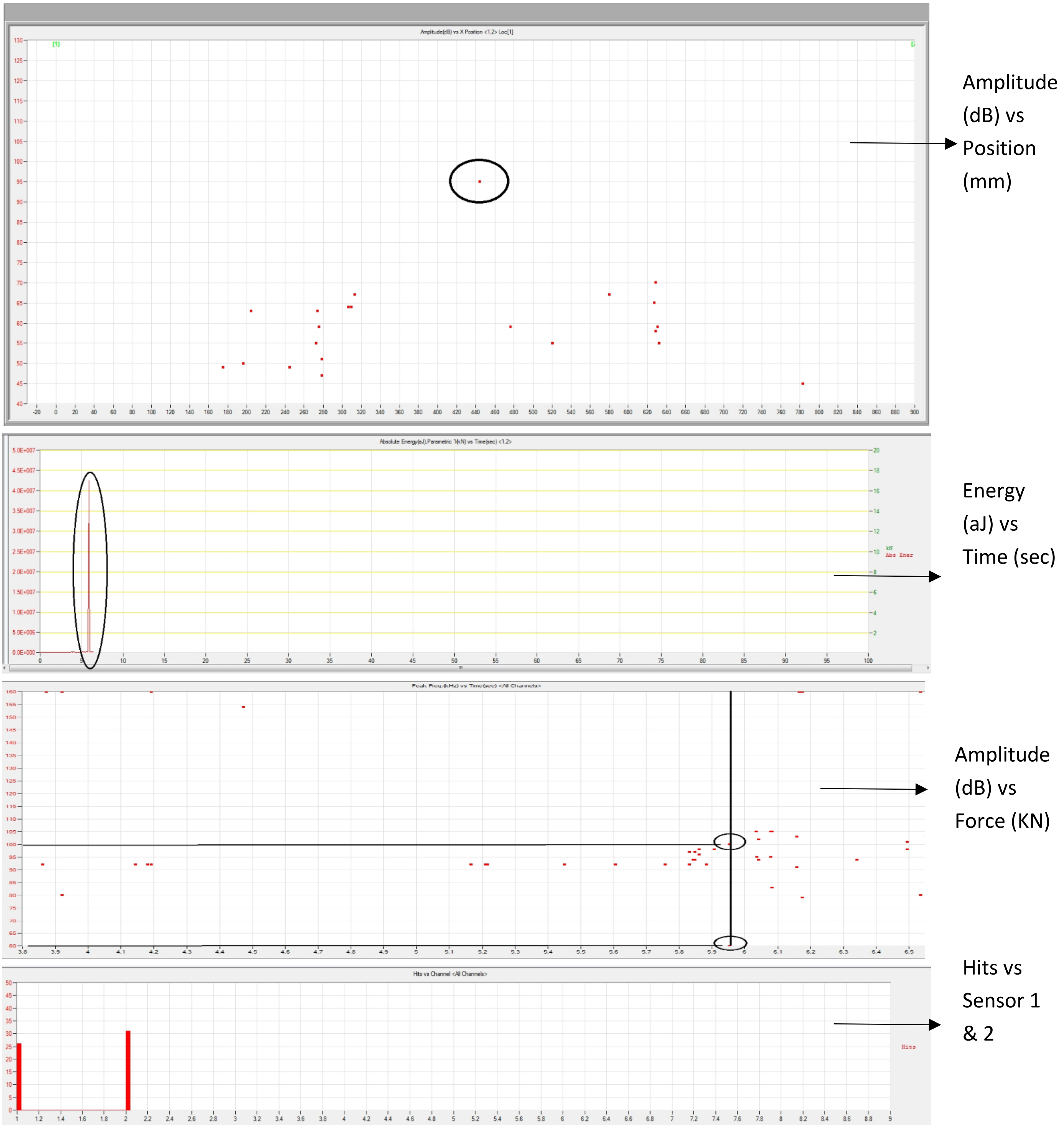


Figure 98: AE outputs for PLB test

9. Appendices

Table 35 : AE parameters for PLB test

AE Parameter	Crack signal characteristics
Amplitude (dB)	95
Time (sec)	5.95
Energy (aJ)	4.3E+07
Number of Hits (S1, S2)	26-31

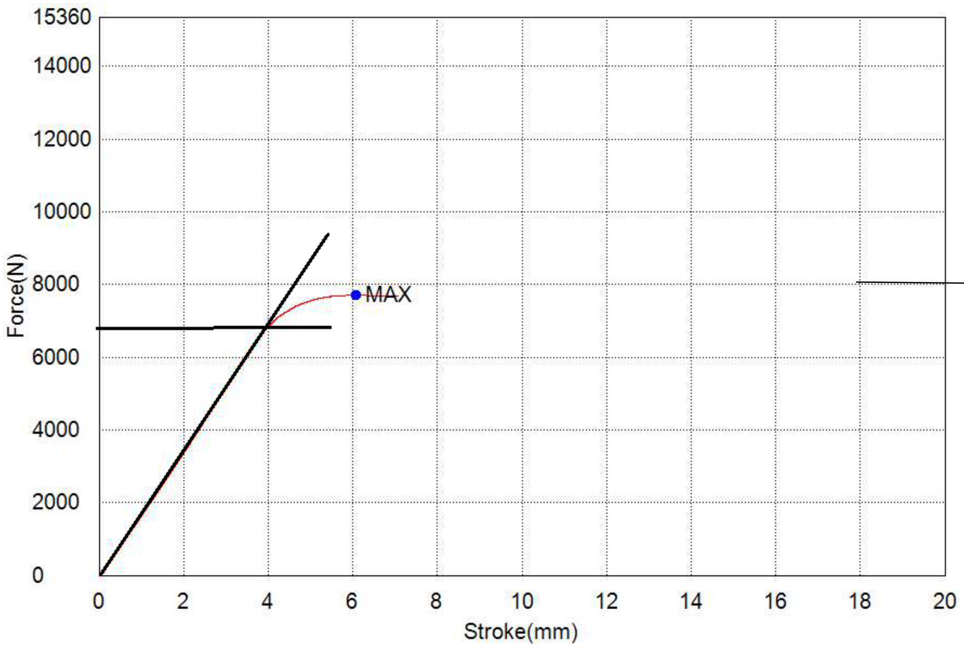
It is shown in the Figure 98 the amplitude for the lead breakage is equal to 95 dB marked by black circle, where there were some reflections with weaker amplitude as well. as it was mentioned before the pencil breaking signal gives the same crack signals amplitude characteristics, which means it should be expecting less amplitude for yielding signal's characteristics. pencil test was carried out in the mid-point between the sensors, so it seems there is slight error for the source location detection.it was expected to locate the source for equal distances from both sensors, but as it is shown it is shifted 1 mm from the center point along the sample. Later in this research it proves that the crack signals have higher amplitude than yielding.

Sample Test (A1)

Table 36: Sample A1 dimensions

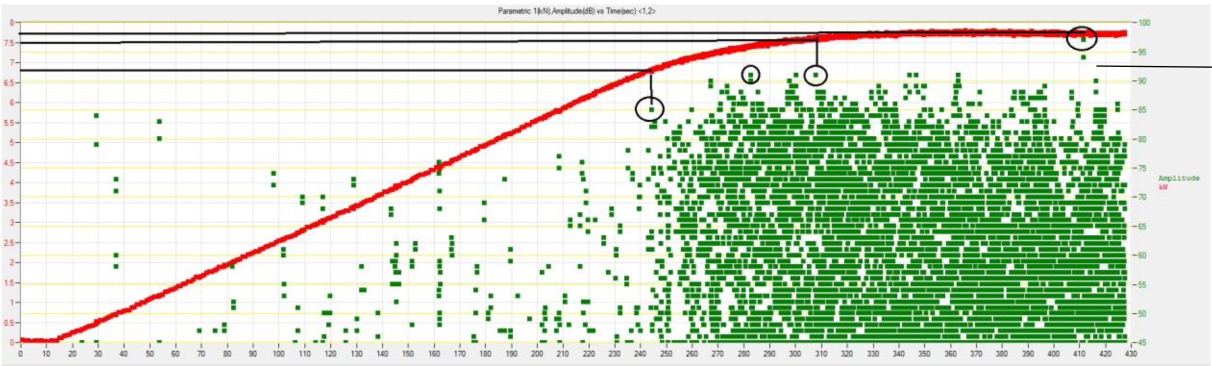
Length (mm)	Width (mm)	Thickness (mm)	Yield stress (MPa)	F_b (N)	Distance between Sensors (mm)
500	30.1	14.74	439	5500	400

9. Appendices

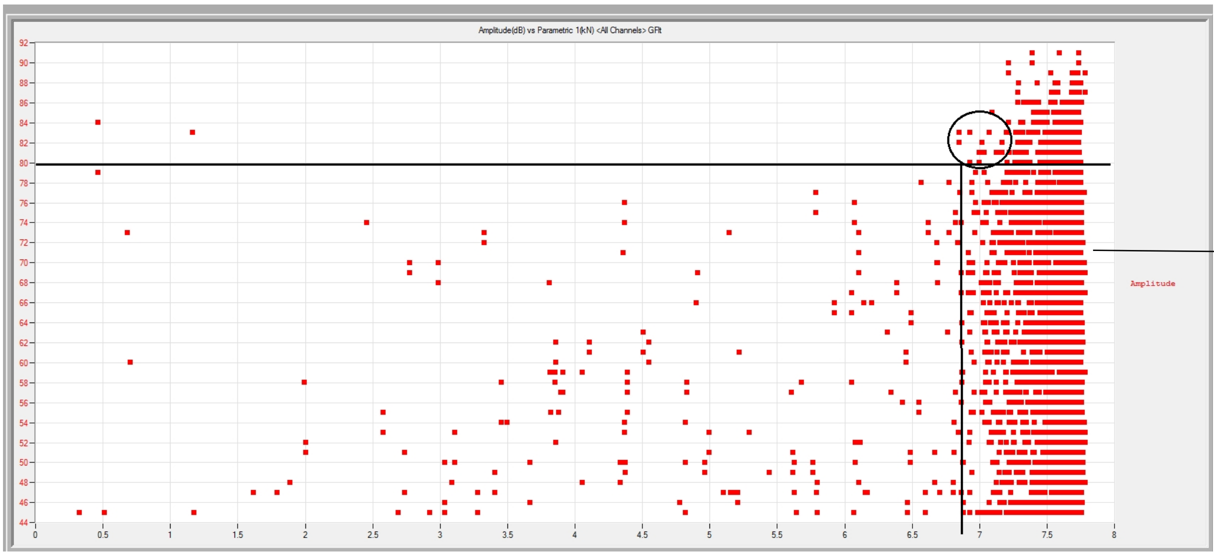


Loading Force (N) vs Stroke (mm)

Figure 99: Shimatzu-A1 force vs stroke

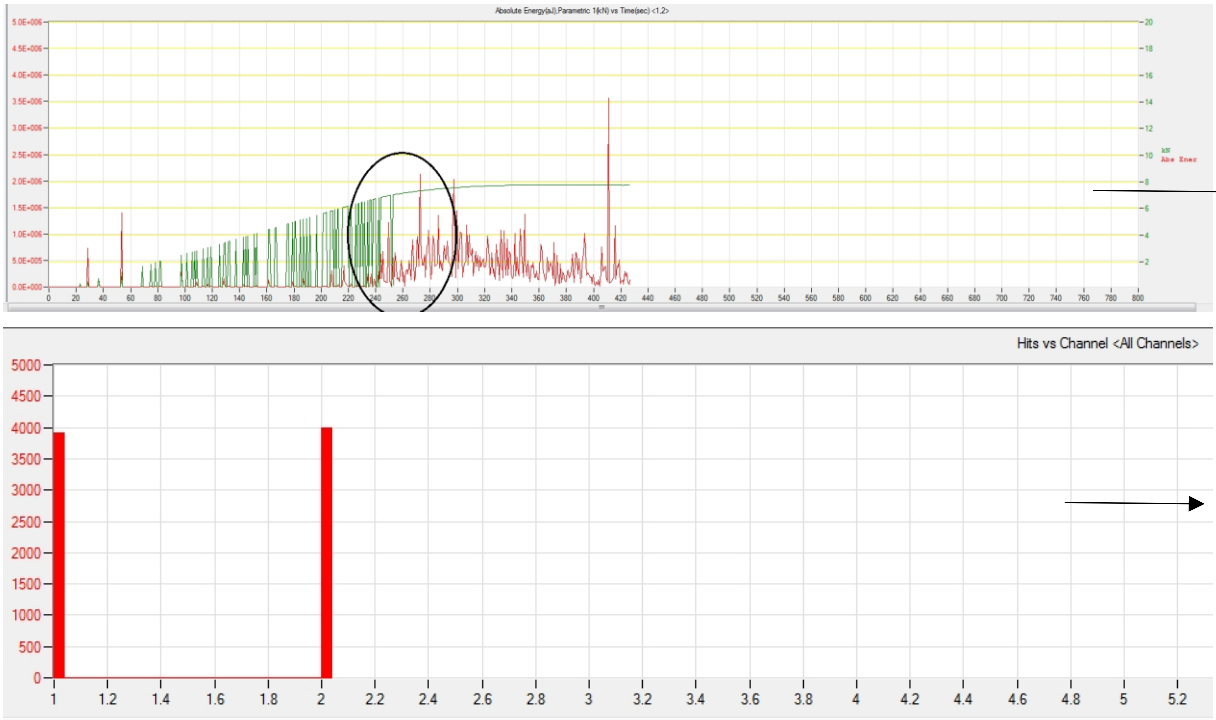


Amplitude (dB) & Force (KN) vs Time (sec)



Amplitude (dB) vs Force (KN)

9. Appendices



Energy (aJ) vs Time (sec)

Hits vs Sensor 1 & 2

Figure 100: AE outputs for A1 coated sample

Table 37:Yield point force for A1

F_b (N)	F_{SH} (N)	F_{AE} (N)
5500	6700	6700

Table 38: AE parameters for A1 sample

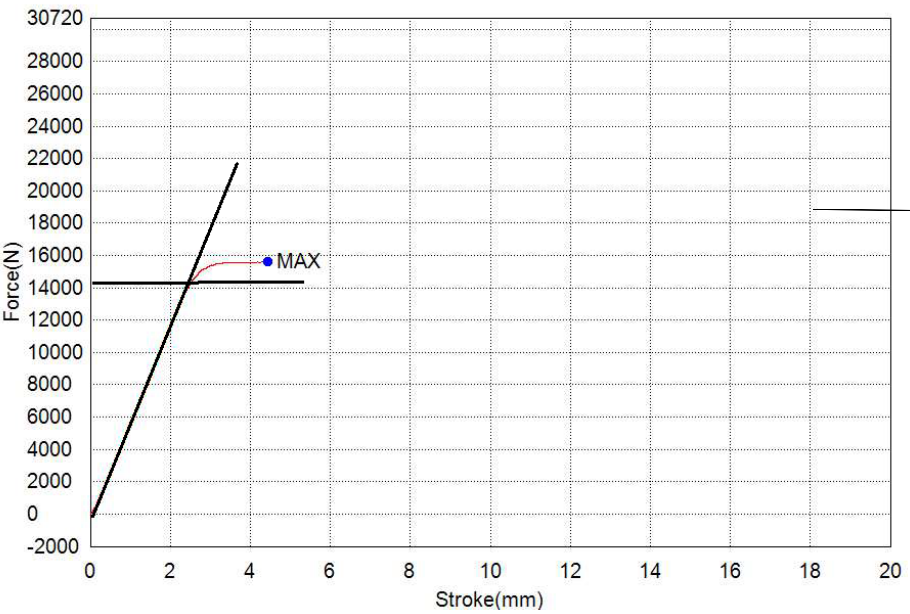
AE parameter	Yield stress point	Higher yield stress point
Load (N)	6700	7500
Signal Magnitude (dB)	82-83	95
Time (sec)	244	412
Number of Hits (S1, S2)	3900,4000	
Energy (aJ)	6.5E+005	3.6E+006

9. Appendices

Sample Test (A2)

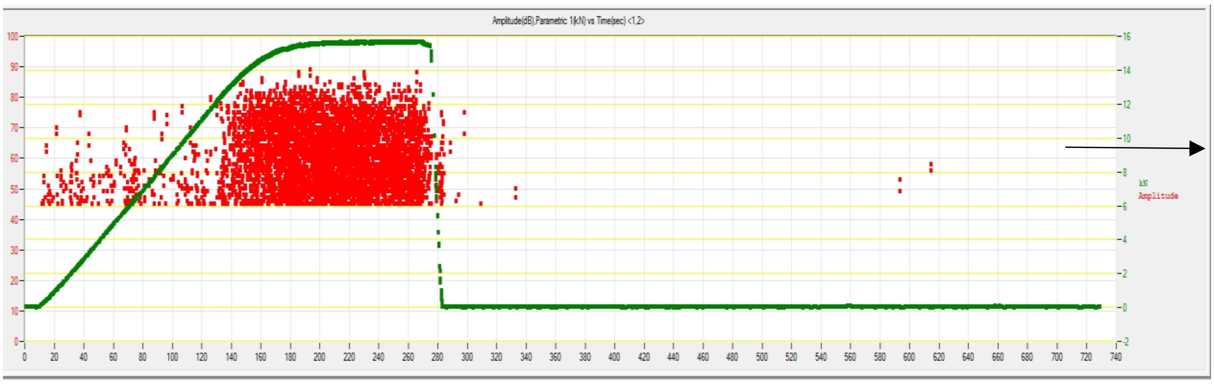
Table 39: Sample A2 dimensions

Length (mm)	Width (mm)	Thickness (mm)	Yield stress (MPa)	F_b (N)	Distance between Sensors (mm)
500	14.77	30.16	439	11400	400



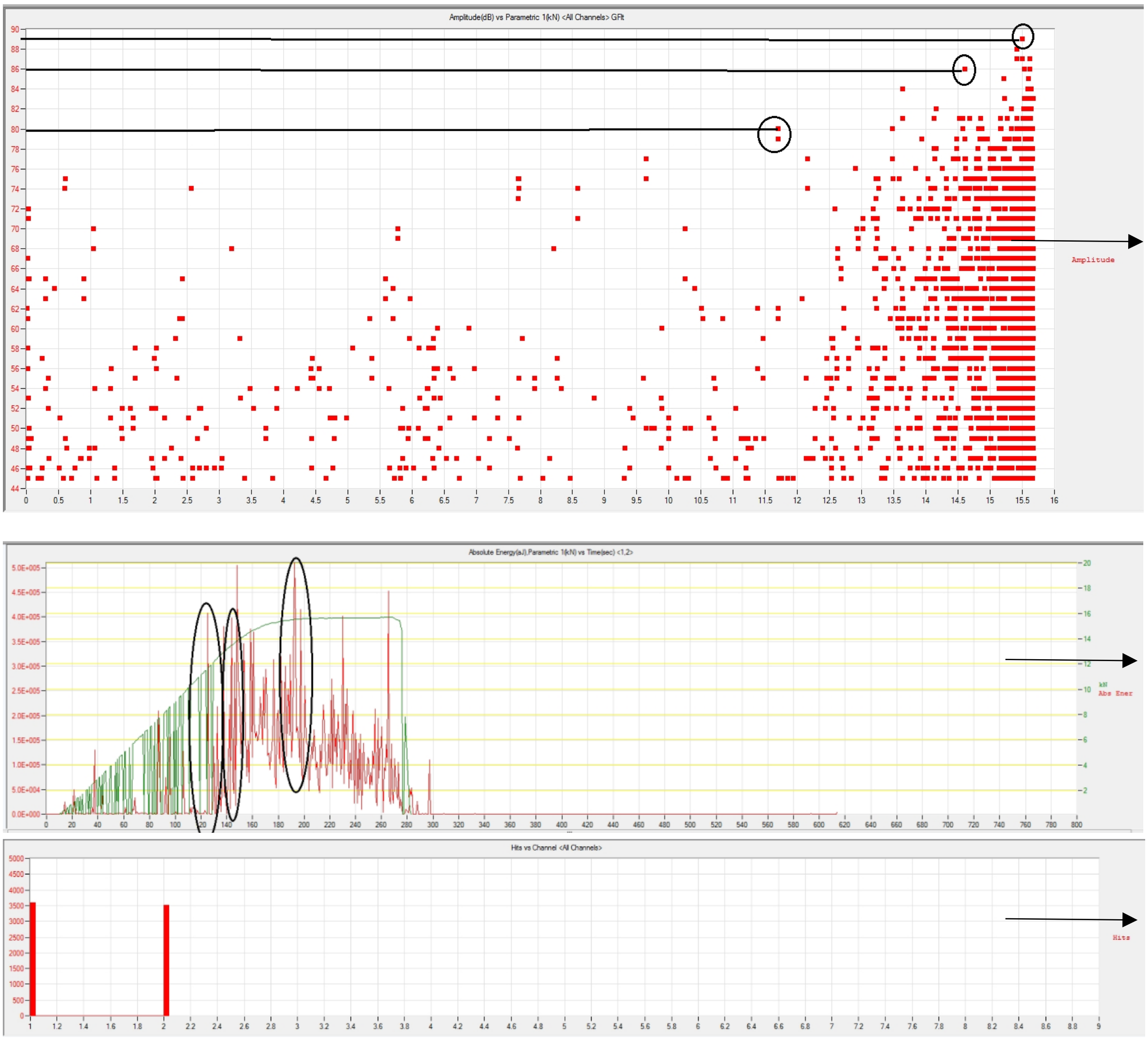
Loading Force (N) vs Stroke (mm)

Figure 101: Shimatzu-A2 force vs stroke



Amplitude (dB) & Force (KN) vs Time (sec)

9. Appendices



Amplitude (dB) vs Force (KN)

Energy (aJ) vs Time (sec)

Hits vs Sensor 1 & 2

Figure 102: AE outputs for A2 coated sample

Table 40:yield point for A2 sample

F_b (N)	F_{SH} (N)	F_{AE} (N)
11400	14000	11700

Table 41: AE parameters for A2 sample

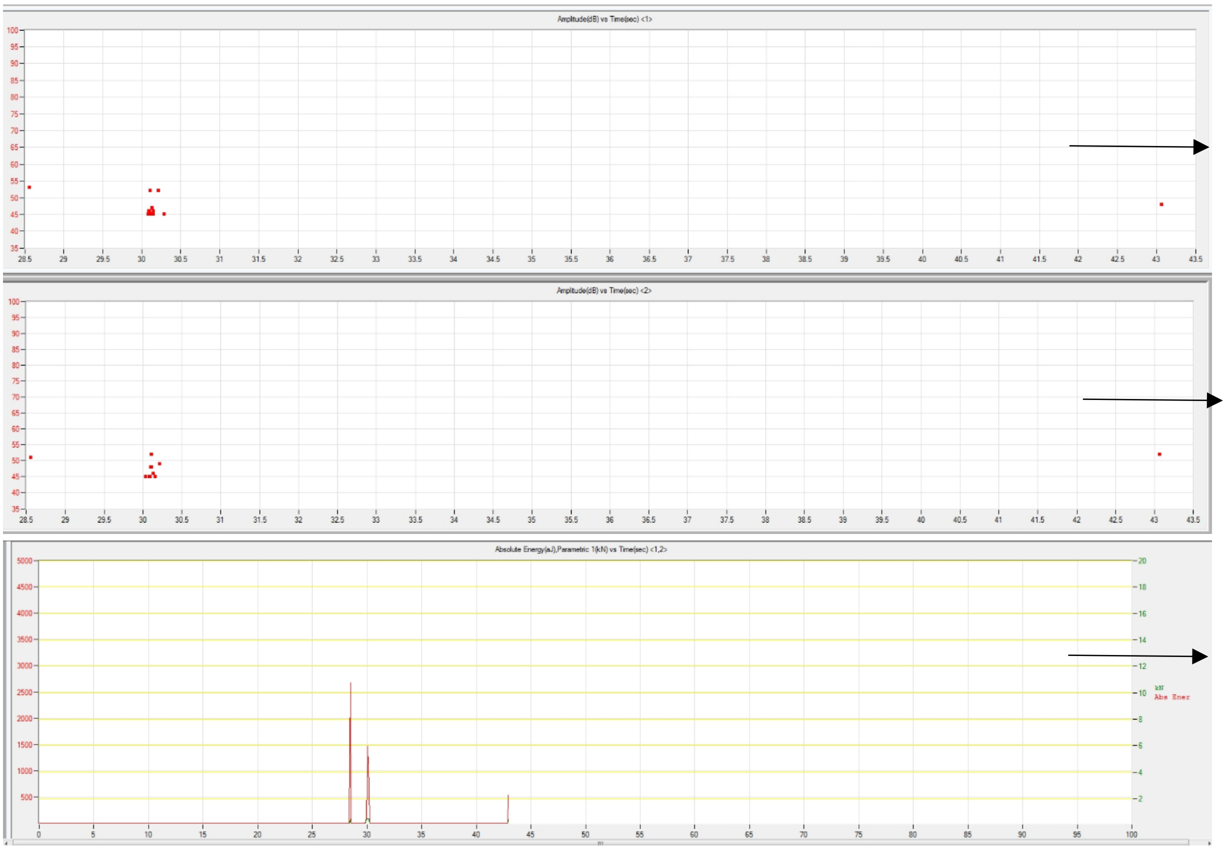
AE parameter	Yield stress point	Higher yield stress point
Load (N)	11700	13600
Signal Magnitude (dB)	80	90
Time (sec)	123	195
Number of Hits	3500-3550	
Energy (aJ)	4.0E+005	5.0E+005

9. Appendices

Sample Test (A3) Fryer Fan noise (No-load)

Table 42: sampel A3 dimensions

Length (mm)	Width (mm)	Thickness (mm)	Yield stress (MPa)	F_b (N)	Distance between Sensors (mm)
500	29.82	14.72	432	5500	400



Amplitude (dB) vs Time (sec) for S1

Amplitude (dB) vs Time (sec) for S2

Energy (aJ) vs Time (sec)

9. Appendices

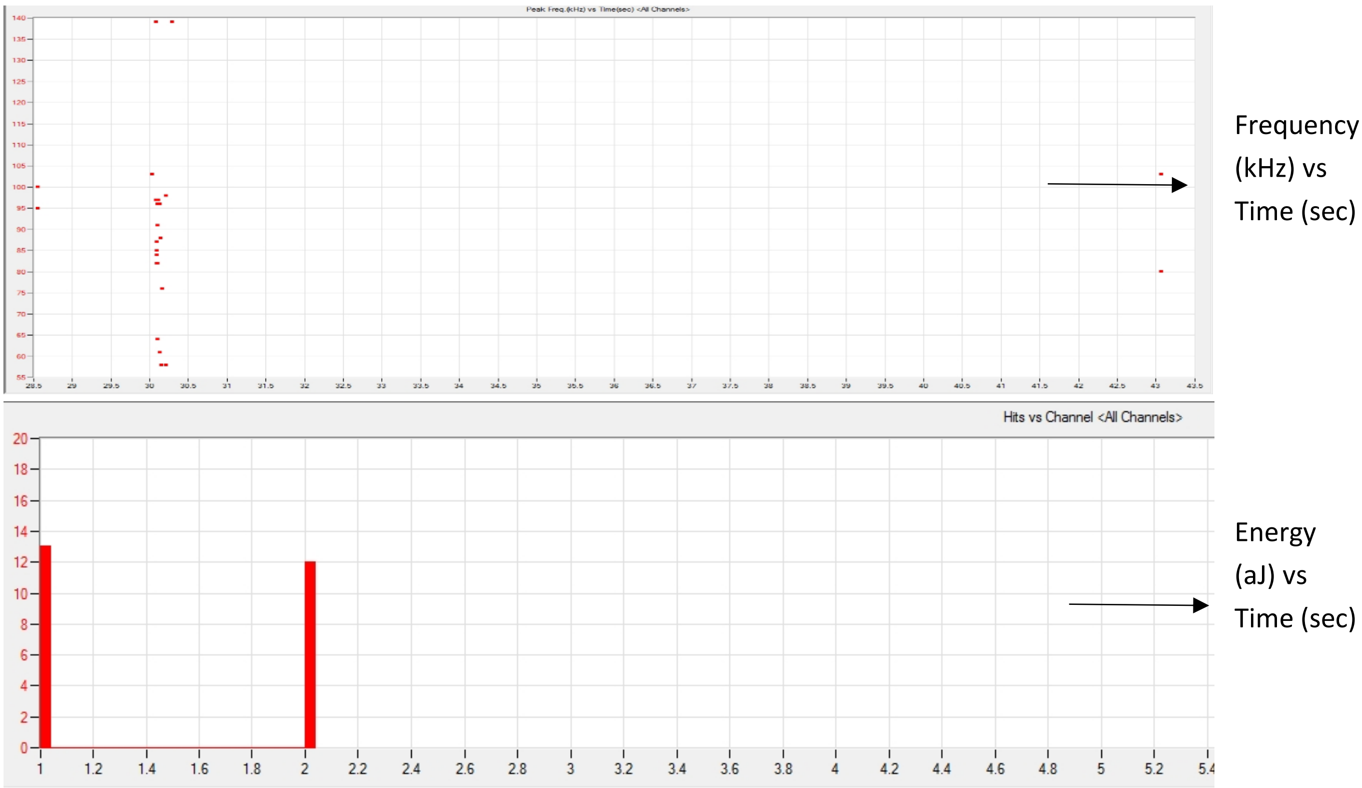


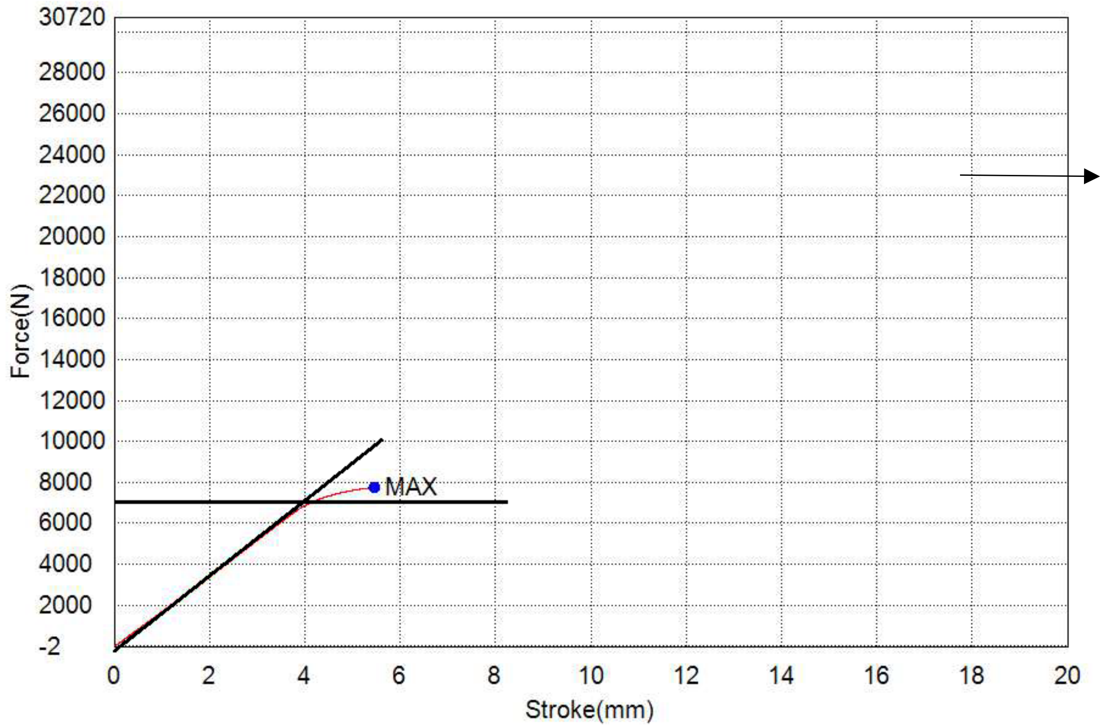
Figure 103: AE External noise for A3 sample-test

Table 43: AE parameters for external dryer without load

AE parameter	Value
Signal Magnitude (dB)	45-54
Number of Hits (S1, S2)	12,13
Energy (aJ)	2700
Frequency (kHz)	55-138

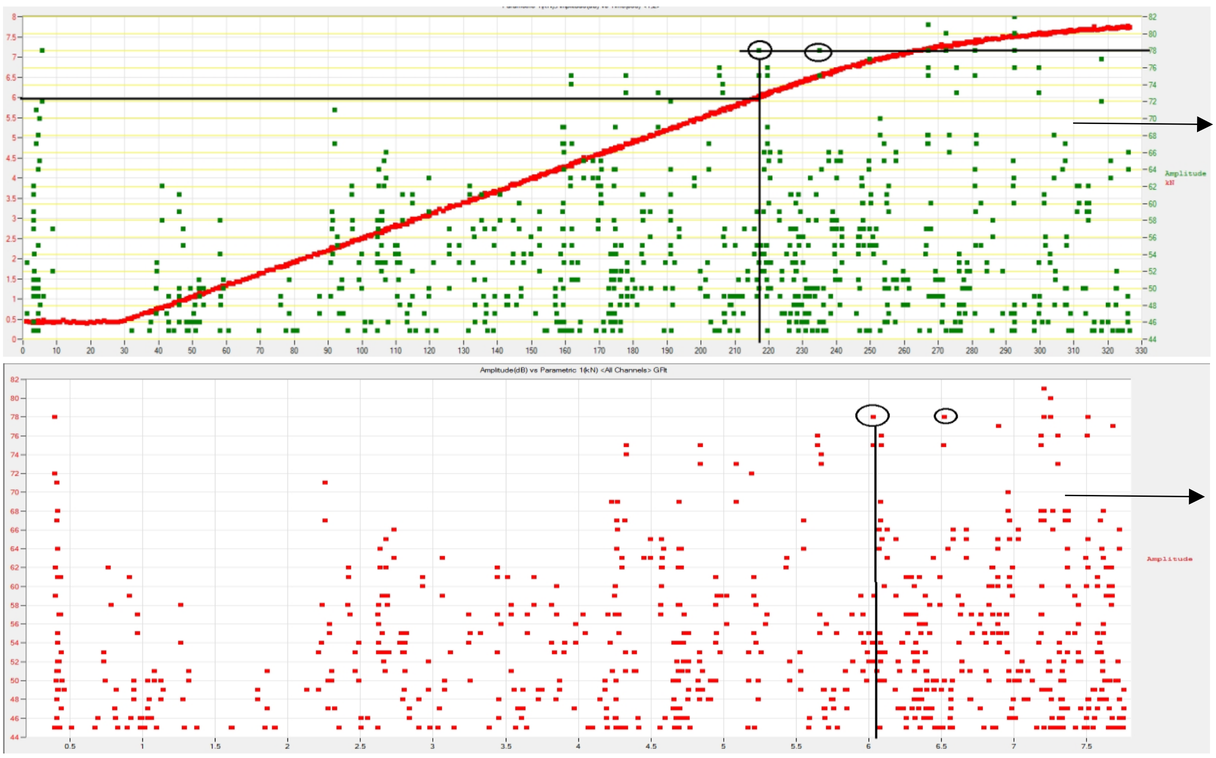
9. Appendices

Sample Test (A3) with external Dryer noise



Loading Force (N) vs Stroke (mm)

Figure 104: Shiamtzu-A3 force (N) vs stroke (mm)



Amplitude (dB) & Force (KN) vs Time (sec)

Amplitude (dB) vs Force (KN)

9. Appendices

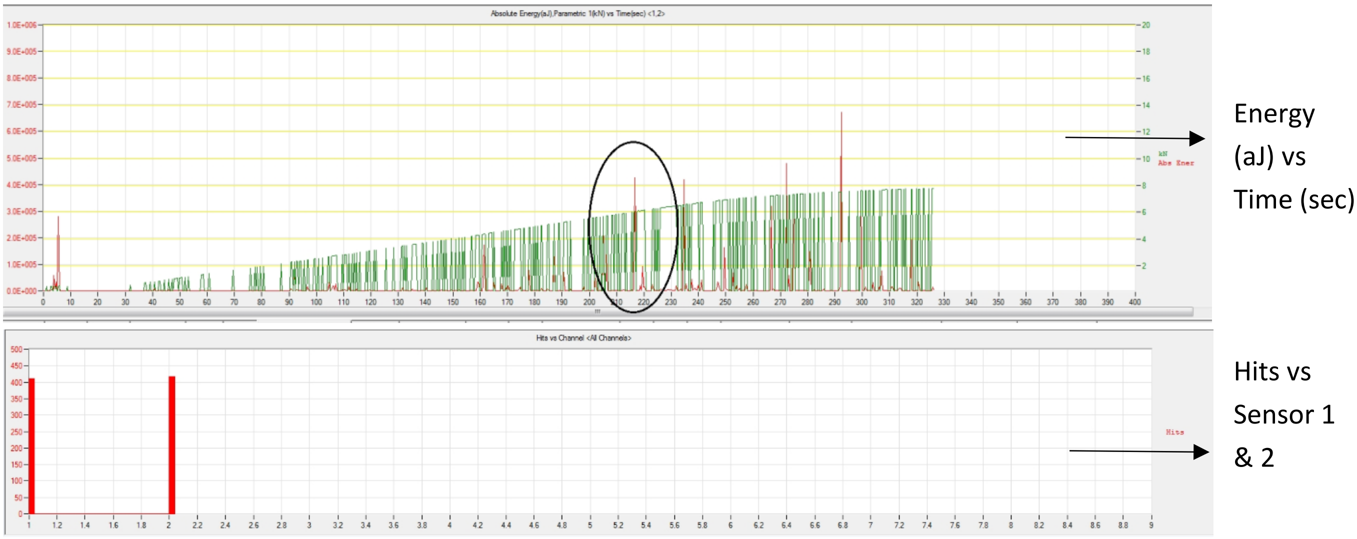


Figure 105: AE outputs for A3 sample

Table 44: yield point for A3 sample

F_b (N)	F_{SH} (N)	F_{AE} (N)
5500	6700	6100

Table 45: AE parameters for A3 sample

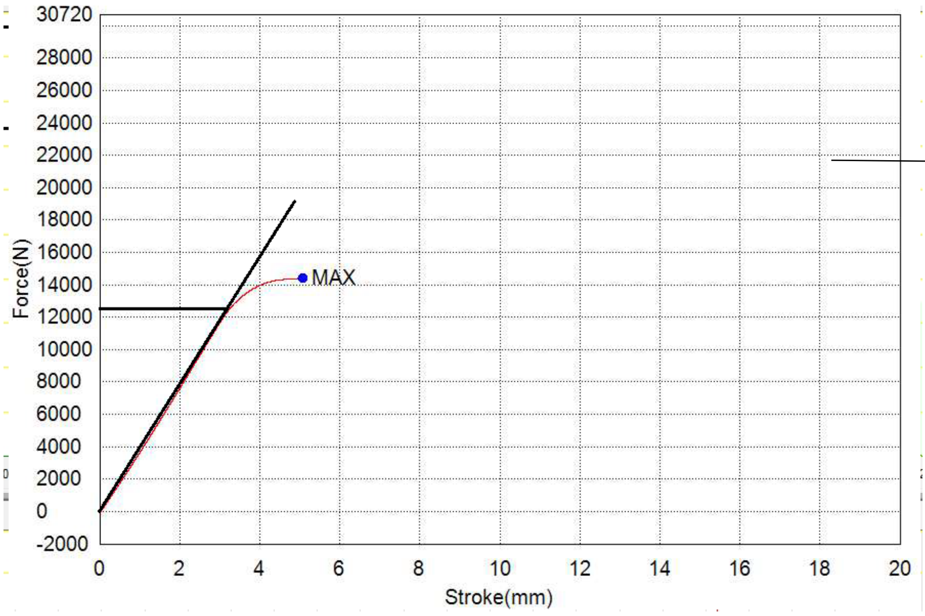
AE parameter	Yield stress point
Load (N)	6100
Signal Magnitude (dB)	78
Time (sec)	218
Number of Hits (S1, S2)	410,420
Energy (aJ)	4.2E+005

9. Appendices

Sample Test (B1)

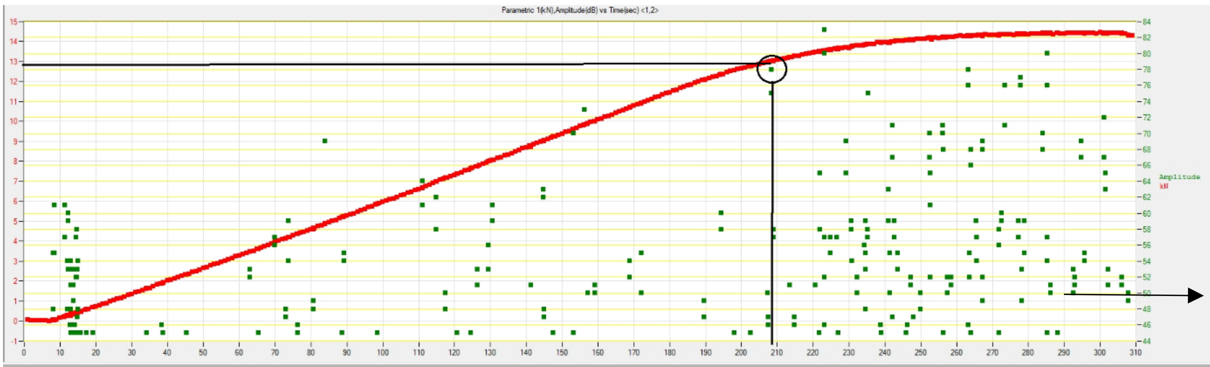
Table 46: dimensions for B1 sample

Length (mm)	Width (mm)	Thickness (mm)	Yield stress (MPa)	F_b (N)	Distance between Sensors (mm)
500	29.61	19.76	390	8800	400



Loading Force (N) vs Stroke (mm)

Figure 106: Shimatzu-B1 force (N) vs stroke (mm)



Amplitude (dB) & Force (KN) vs Time (sec)

9. Appendices

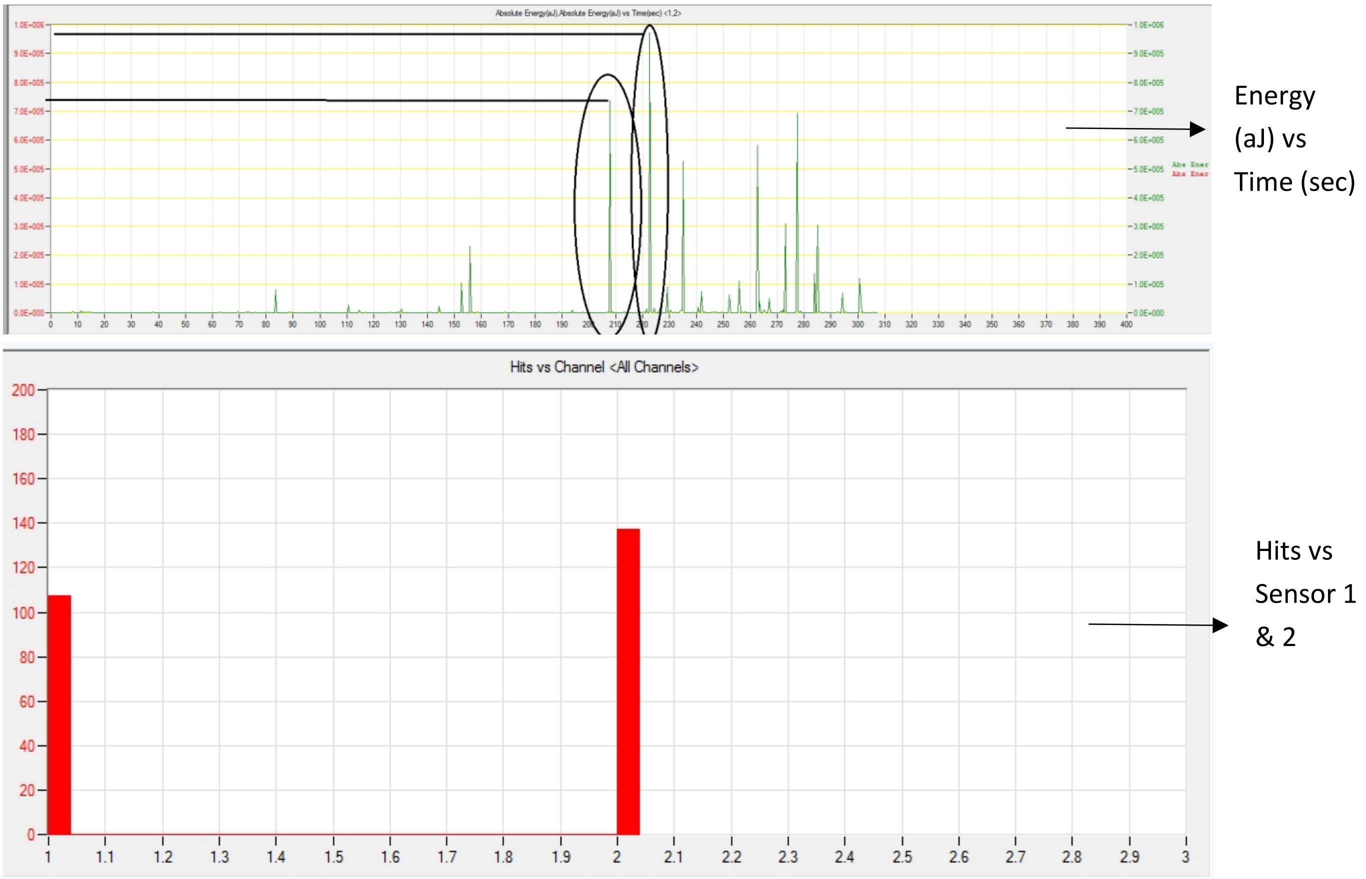


Figure 107: AE outputs for B1 sample

Table 47: yield point for B1 sample

F_b (N)	F_{SH} (N)	F_{AE} (N)
8800	12500	9800

Table 48: AE parameters for B1 sample

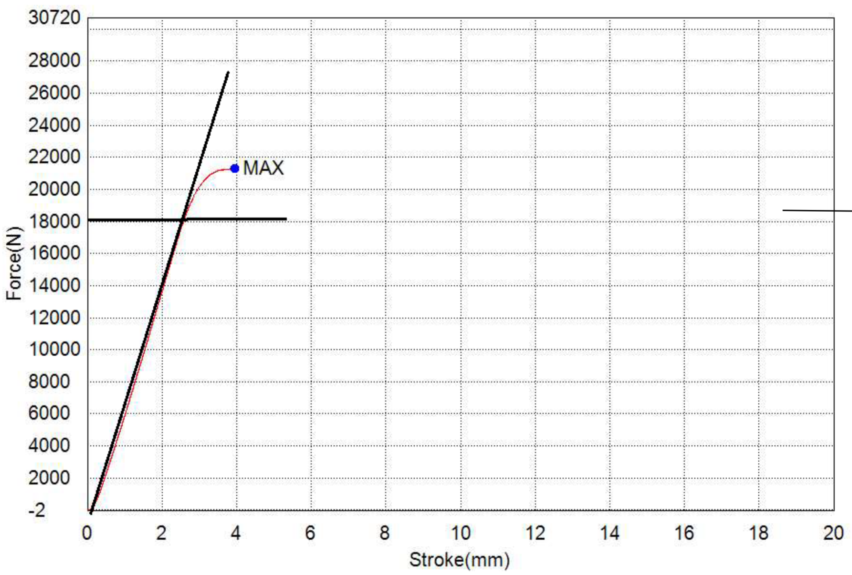
AE parameter	Yield stress point	Strain Hardening stage	Higher yield stress point
Load (N)	9800	12800	13400
Signal Magnitude (dB)	73	78	83
Time (sec)	157	208	222
Number of Hits (S1, S2)	105,138		
Energy (aJ)	2.3E+005	7.3E+005	9.7E+005

9. Appendices

Sample Test (B2)

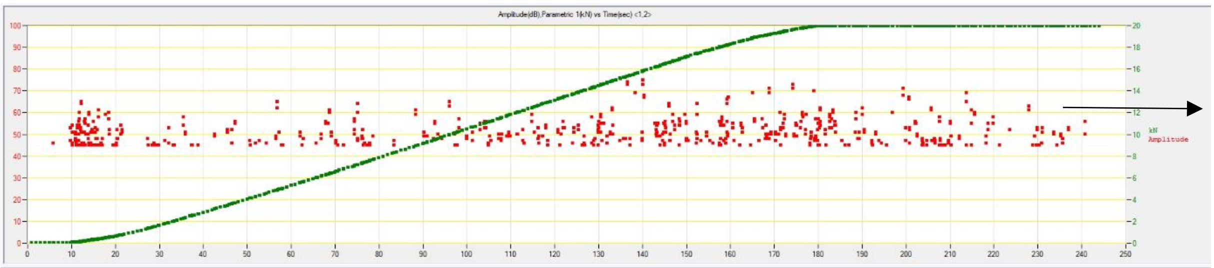
Table 49: Dimensions for B2 sample

Length (mm)	Width (mm)	Thickness (mm)	Yield stress (MPa)	F_b (N)	Distance between Sensors (mm)
500	19.74	29.4	390	12950	400

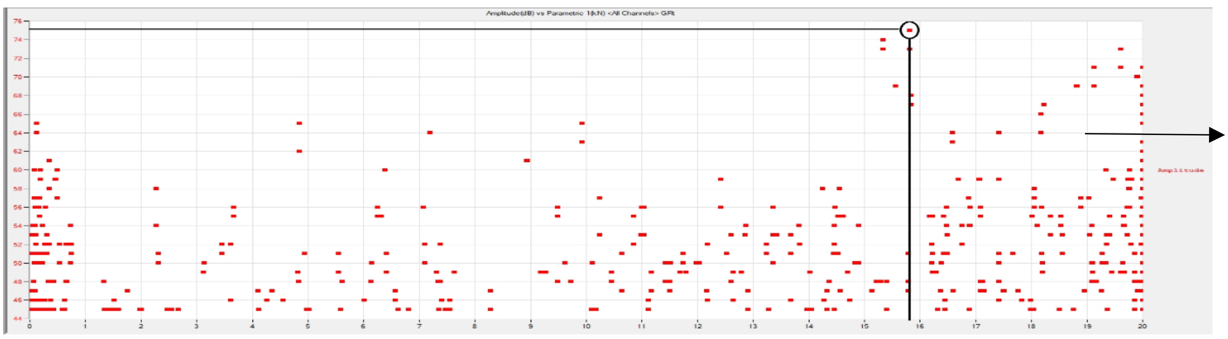


Loading Force (N) vs Stroke (mm)

Figure 108: Shimatzu-B2 force (N) vs stroke (mm)



Amplitude (dB) & Force (KN) vs Time (sec)



Amplitude (dB) vs Force (KN)

9. Appendices

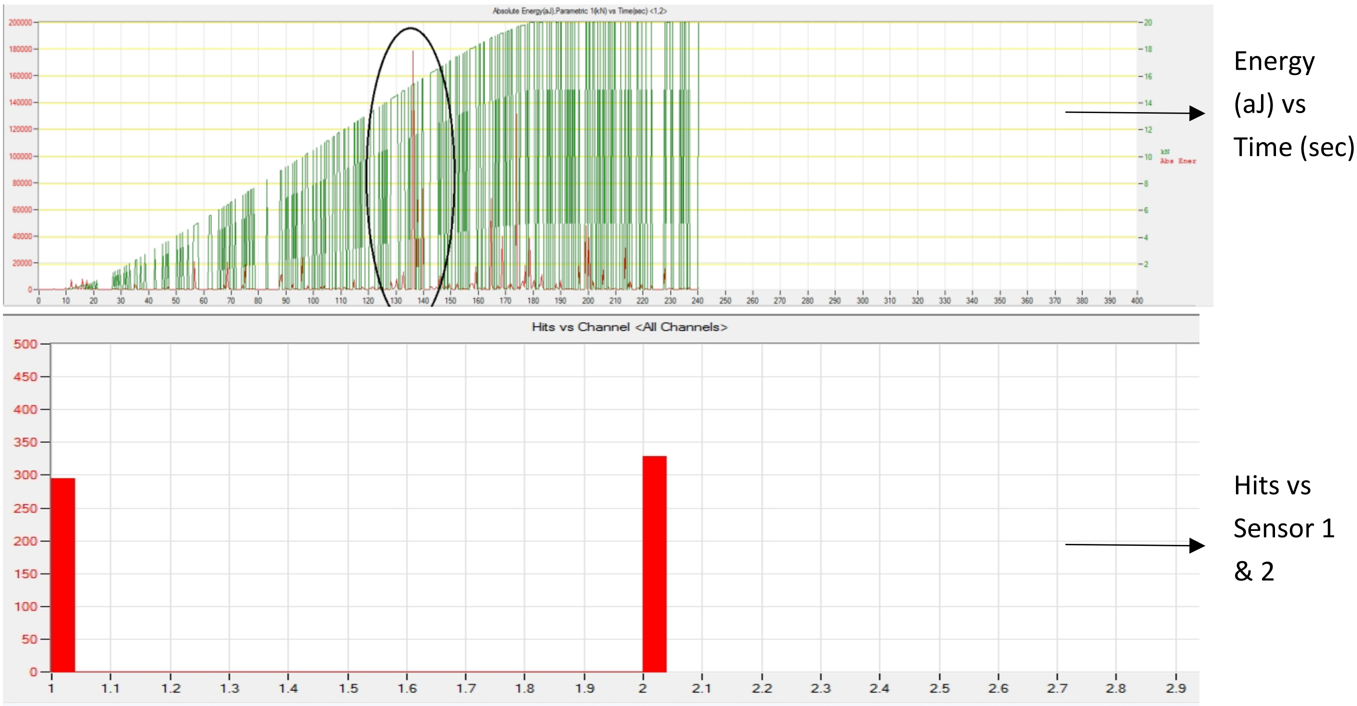


Figure 109: AE outputs for B2 sample

Table 50: yield point for B2 sample

F_b (N)	F_{SH} (N)	F_{AE} (N)
12950	18000	15500

Table 51: AE parameters for B2 sample

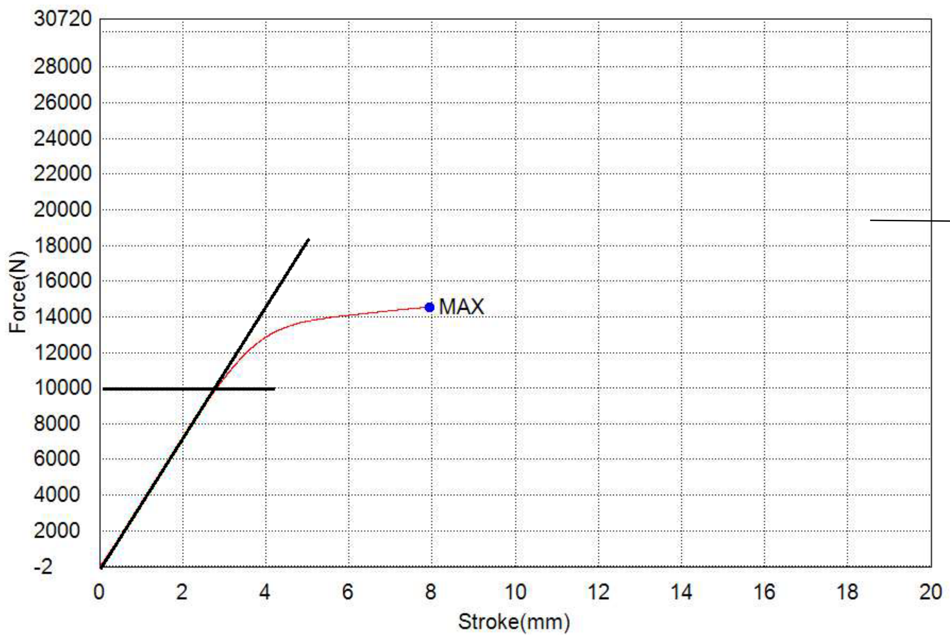
AE parameter	Yield stress point
Load (N)	15500
Signal Magnitude (dB)	74
Time (sec)	136
Number of Hits (S1, S2)	295,330
Energy (aJ)	1.8E+005

9. Appendices

Sample Test (B2R)

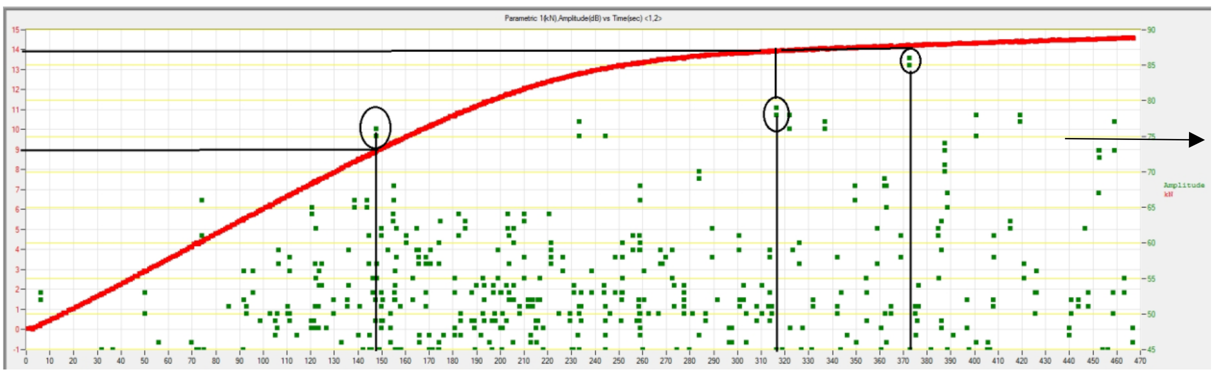
Table 52: Dimensions for B2R sample

Length (mm)	Width (mm)	Thickness (mm)	Yield stress (MPa)	F_b (N)	Distance between Sensors (mm)
500	29.4	19.74	390	8800	400



Loading Force (N) vs Stroke (mm)

Figure 110: Shimatzu-B2R force (N) vs stroke (mm)



Amplitude (dB) & Force (KN) vs Time (sec)

9. Appendices

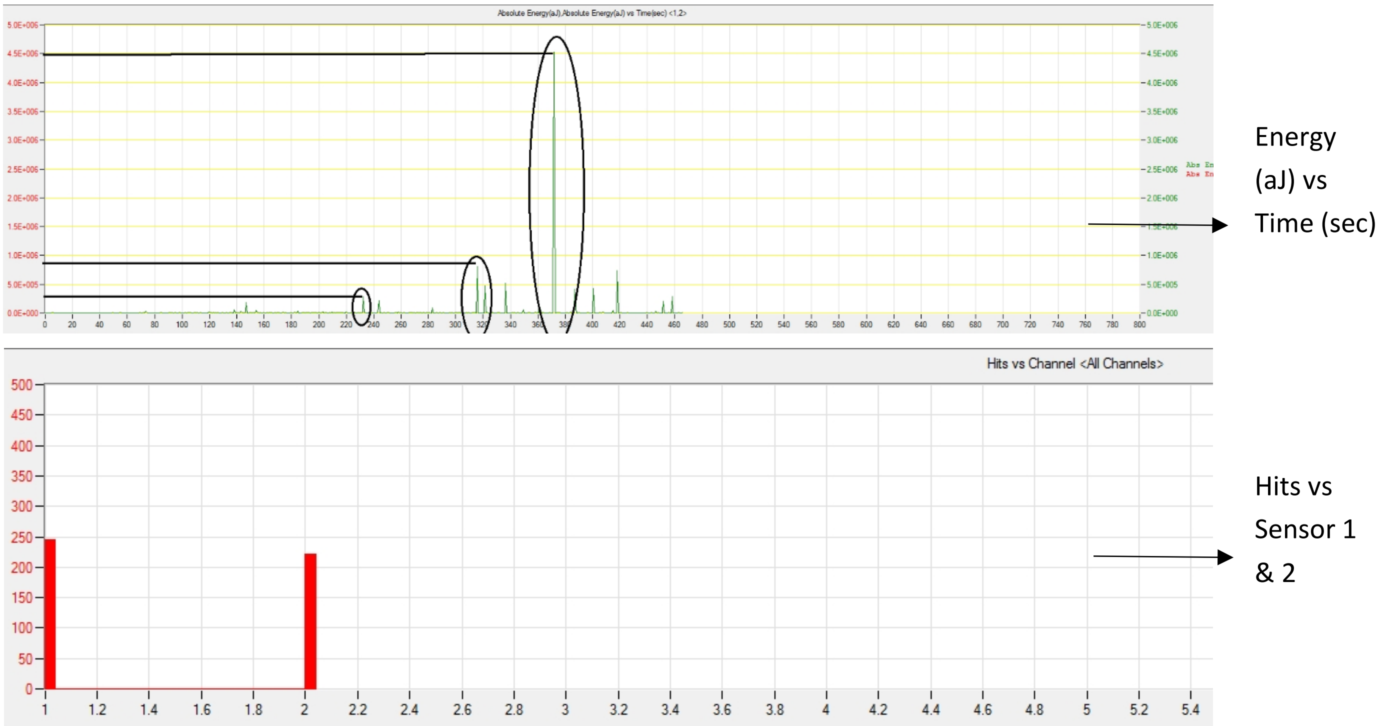


Figure 111: AE outputs for B2R sample

Table 53: yield point for B2R sample

F_b (N)	F_{SH} (N)	F_{AE} (N)
8700	10000	8800

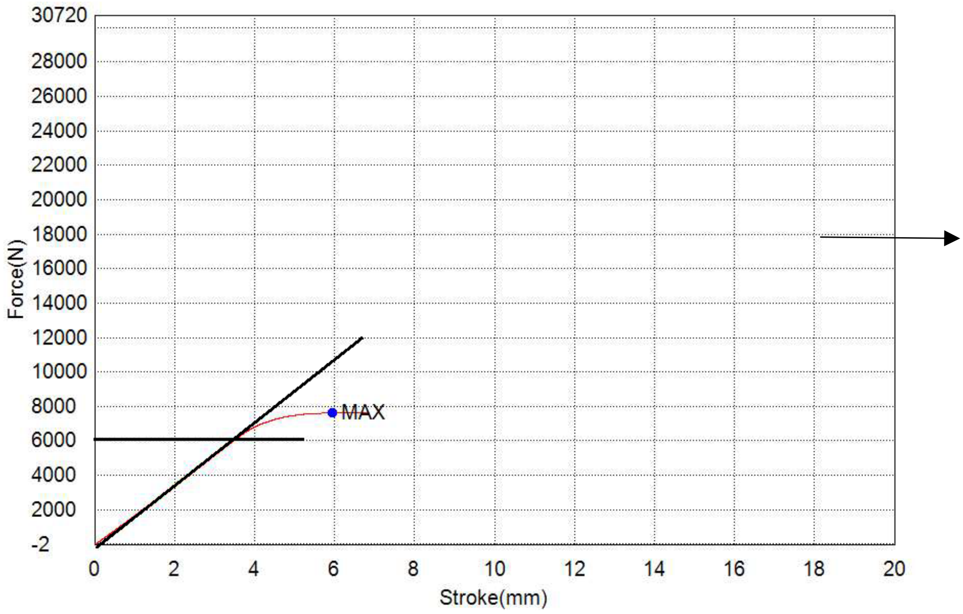
Table 54: AE parameters for B2R sample

AE parameter	Yield stress point	Stain hardening stage	Higher yield stress point
Load (N)	8800	13800	14000
Signal Magnitude (dB)	76	78	86
Time (sec)	147	318	372
Number of Hits (S1, S2)	245,225		
Energy (aJ)	2.5E+005	8.0E+005	4.5E+006

Sample Test (C1)

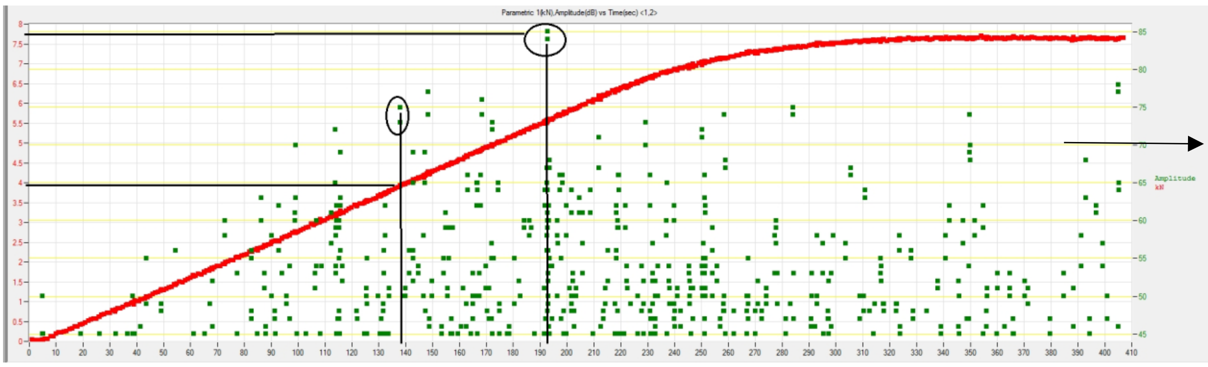
Table 55: Dimensions for C1 sample

Length (mm)	Width (mm)	Thickness (mm)	Yield stress (MPa)	F_b (N)	Distance between Sensors (mm)
1000	29.82	14.66	439	5450	900



Loading Force (N) vs Stroke (mm)

Figure 112: Shimatzu-C1 force (N) vs stroke (mm)



Amplitude (dB) & Force (KN) vs Time (sec)

9. Appendices

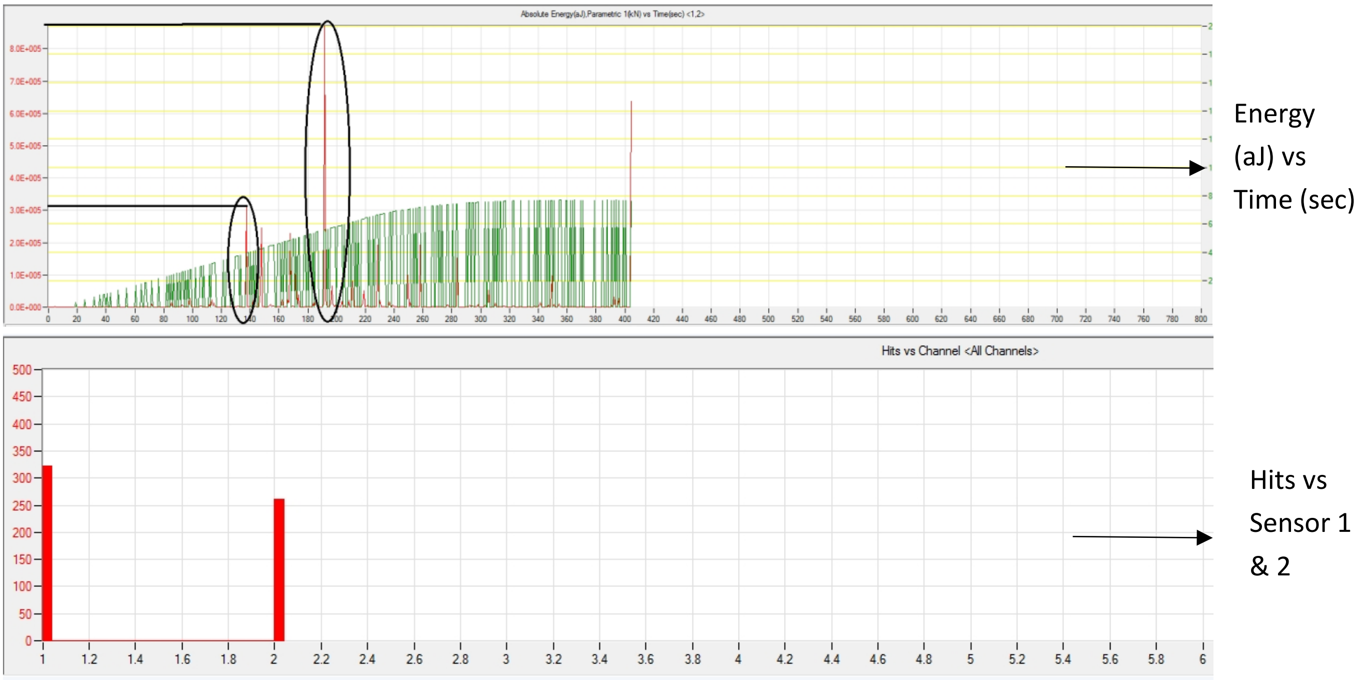


Figure 113: AE outputs for C1 sample

Table 56: yield point for C1 sample

F_b (N)	F_{SH} (N)	F_{AE} (N)
5450	6000	4000

Table 57: AE parameters for C1 sample

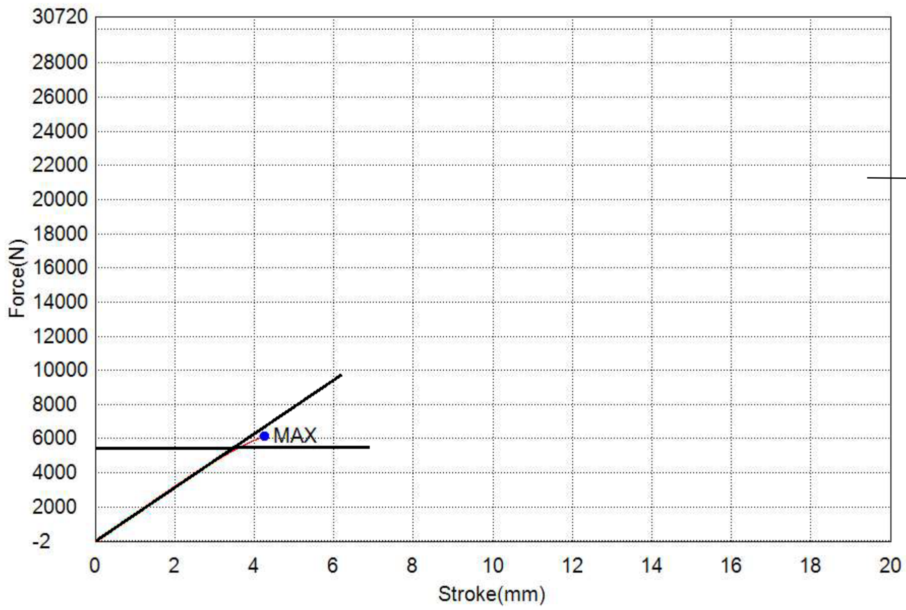
AE parameter	Yield stress point	Higher yield stress point
Load (N)	4000	5700
Signal Magnitude (dB)	75	85
Time (sec)	138	192
Number of Hits (S1, S2)	260-330	
Energy (aJ)	3.0E+005	8.8E+005

9. Appendices

Sample Test (C2R)

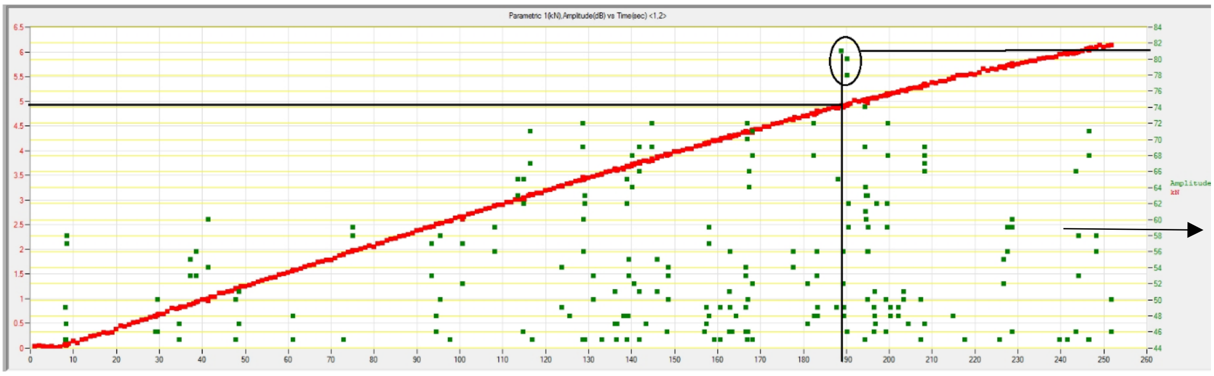
Table 58: Dimensions for C2R sample

Length (mm)	Width (mm)	Thickness (mm)	Yield stress (MPa)	F_b (N)	Distance between Sensors (mm)
1000	29.79	14.67	439	5500	900



Loading Force (N) vs Stroke (mm)

Figure 114: Shimatzu-C2R force (N) vs stroke (mm)



Amplitude (dB) & Force (KN) vs Time (sec)

9. Appendices

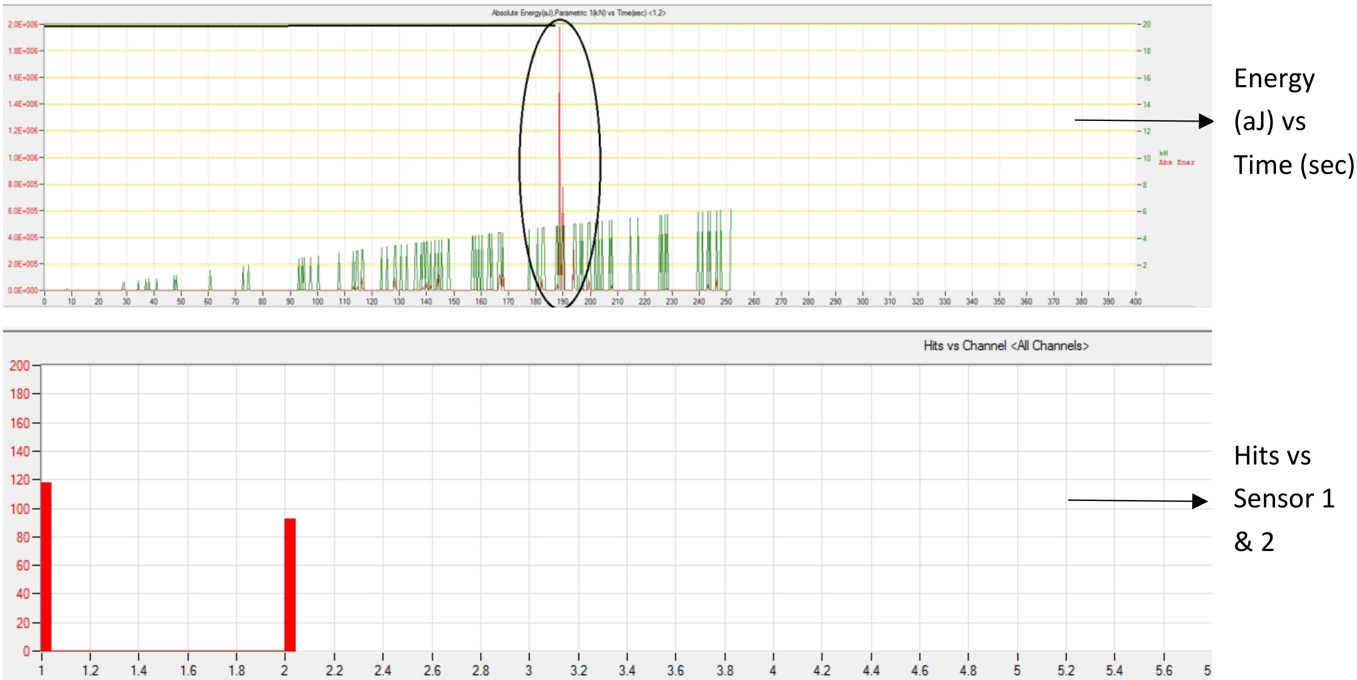


Figure 115: AE outputs for C2R sample

Table 59: yield point for C2R sample

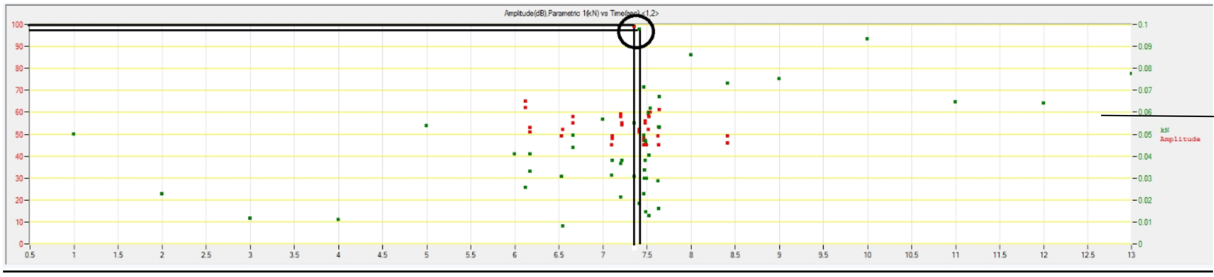
F_b (N)	F_{SH} (N)	F_{AE} (N)
5500	5700	4900

Table 60: AE parameters for C2R sample

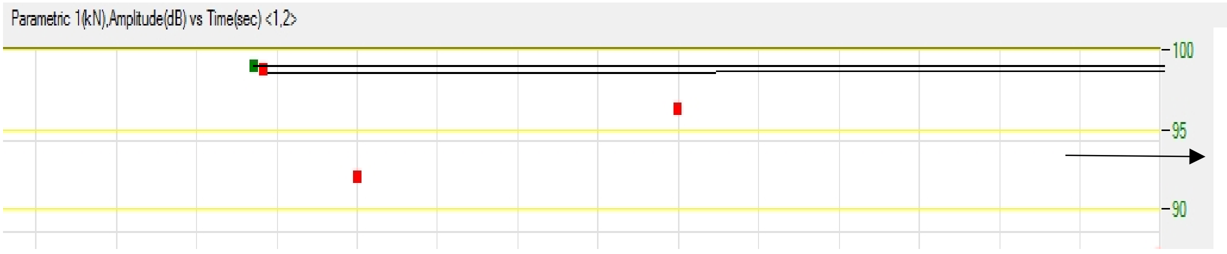
AE parameter	Yield stress point
Load (N)	4900
Signal Magnitude (dB)	84
Time (sec)	188
Number of Hits (S1, S2)	92,119
Energy (aJ)	1.98E+006

9. **Appendices**

Signal attenuation test

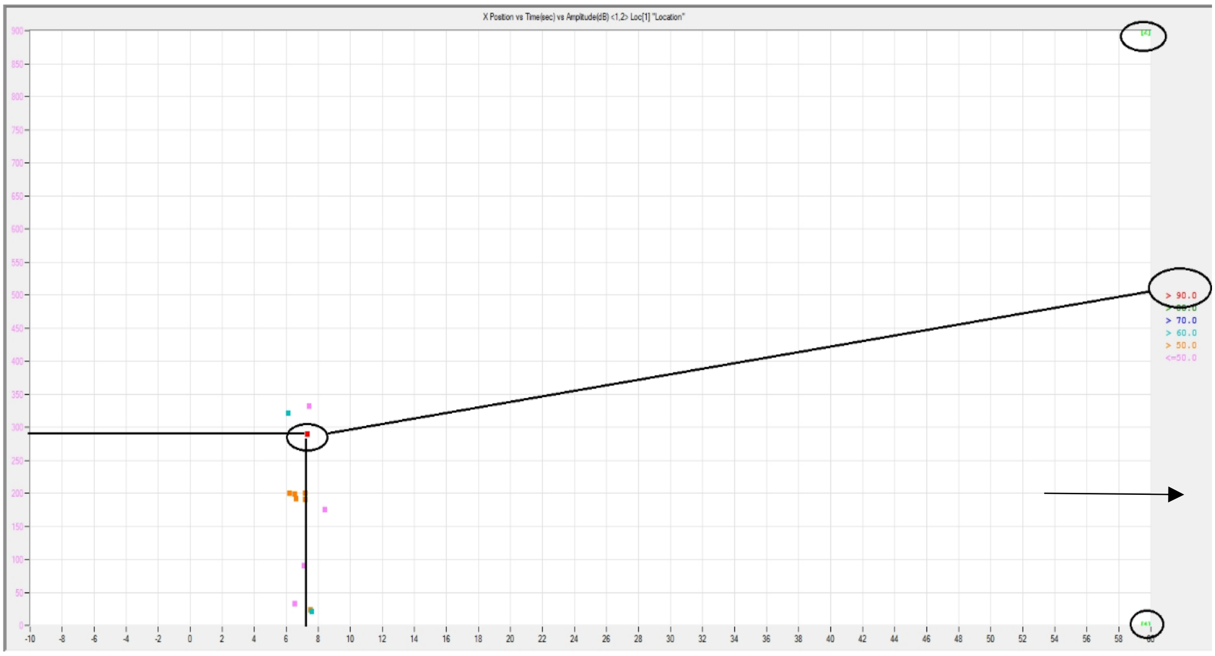


Amplitude (dB) vs Force (KN)



Amplitude (dB) vs Force (KN)

(large scale)



Position (mm) vs Force (KN), red dot (amplitude) for >90

Figure 116: AE parameters for PLB test on C1 sample (to identify signal attenuation)