ANALYSIS OF ACOUSTIC EMISSION DATA FOR ACCURATE DAMAGE ASSESSMENT FOR STRUCTURAL HEALTH MONITORING APPLICATIONS

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Abstract

Structural health monitoring (SHM) refers to the procedure used to assess the condition of structures so that their performance can be monitored and any damage can be detected early. Early detection of damage and appropriate retrofitting will aid in preventing failure of the structure and save money spent on maintenance or replacement and ensure the structure operates safely and efficiently during its whole intended life. Though visual inspection and other techniques such as vibration based ones are available for SHM of structures such as bridges, the use of acoustic emission (AE) technique is an attractive option and is increasing in use. AE waves are high frequency stress waves generated by rapid release of energy from localised sources within a material, such as crack initiation and growth. AE technique involves recording these waves by means of sensors attached on the surface and then analysing the signals to extract information about the nature of the source. High sensitivity to crack growth, ability to locate source, passive nature (no need to supply energy from outside, but energy from damage source itself is utilised) and possibility to perform real time monitoring (detecting crack as it occurs or grows) are some of the attractive features of AE technique.

In spite of these advantages, challenges still exist in using AE technique for monitoring applications, especially in the area of analysis of recorded AE data, as large volumes of data are usually generated during monitoring. The need for effective data analysis can be linked with three main aims of monitoring: (a) accurately locating the source of damage; (b) identifying and discriminating signals from different sources of acoustic emission and (c) quantifying the level of damage of AE source for severity assessment.

In AE technique, the location of the emission source is usually calculated using the times of arrival and velocities of the AE signals recorded by a number of sensors. But complications arise as AE waves can travel in a structure in a number of different modes that have different velocities and frequencies. Hence, to accurately locate a source it is necessary to identify the modes recorded by the sensors. This study has proposed and tested the use of time-frequency analysis tools such as short time
Fourier transform to identify the modes and the use of the velocities of these modes to achieve very accurate results. Further, this study has explored the possibility of reducing the number of sensors needed for data capture by using the velocities of modes captured by a single sensor for source localization.

A major problem in practical use of AE technique is the presence of sources of AE other than crack related, such as rubbing and impacts between different components of a structure. These spurious AE signals often mask the signals from the crack activity; hence discrimination of signals to identify the sources is very important. This work developed a model that uses different signal processing tools such as cross-correlation, magnitude squared coherence and energy distribution in different frequency bands as well as modal analysis (comparing amplitudes of identified modes) for accurately differentiating signals from different simulated AE sources.

Quantification tools to assess the severity of the damage sources are highly desirable in practical applications. Though different damage quantification methods have been proposed in AE technique, not all have achieved universal approval or have been approved as suitable for all situations. The b-value analysis, which involves the study of distribution of amplitudes of AE signals, and its modified form (known as improved b-value analysis), was investigated for suitability for damage quantification purposes in ductile materials such as steel. This was found to give encouraging results for analysis of data from laboratory, thereby extending the possibility of its use for real life structures.

By addressing these primary issues, it is believed that this thesis has helped improve the effectiveness of AE technique for structural health monitoring of civil infrastructures such as bridges.
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<tr>
<td>SHM</td>
<td>Structural Health Monitoring</td>
</tr>
<tr>
<td>NDT</td>
<td>Non-Destructive Testing</td>
</tr>
<tr>
<td>NDE</td>
<td>Non-Destructive Evaluation</td>
</tr>
<tr>
<td>AE</td>
<td>Acoustic Emission</td>
</tr>
<tr>
<td>STFT</td>
<td>Short Time Fourier Transform</td>
</tr>
<tr>
<td>WT</td>
<td>Wavelet Transform</td>
</tr>
<tr>
<td>PLB</td>
<td>Pencil Lead Break</td>
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<tr>
<td>TOA</td>
<td>Time of Arrival</td>
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</table>
Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature: ____________________________

Date: ____________________________
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Chapter 1: Introduction

This chapter begins by outlining the background of the research (Section 1.1), followed by the objectives and the scope of the research (Sections 1.2 and 1.3 respectively). Section 1.4 details the original contribution of this work. Finally, Section 1.5 presents an outline of the remaining chapters of the thesis.

1.1 BACKGROUND

Structural health monitoring (SHM) refers to the procedure used to assess the condition of structures so that their performance can be monitored and any damage can be detected early. Early detection of damage and appropriate retrofitting will aid in preventing failure of the structure and save money spent on maintenance or replacement and ensure the structure operates safely and efficiently during its whole intended life. Hence, a need exists for a reliable technique capable of assessing structural health of engineering structures and giving early indication of underlying damage. Various SHM methods are applied in the fields of mechanical, civil and aerospace engineering.

As civil infrastructures get older, monitoring their structural integrity and devising and improving monitoring methods are both gaining priority for owners, engineers and researchers. Bridges constitute one class of aging infrastructure that requires effective SHM tools, especially due to their economic significance (high building costs) as well as their direct effects on public safety and well being. Many bridges in use today were built decades ago and are now subjected to increased loads or changes in load patterns than originally designed for. These loads and deterioration with age can cause localized distress and may even result in bridge failure if not corrected in due time. Large amounts of money are spent on building and maintenance of bridges all around the world. In Australia, there are about 33500 bridges with a replacement value of about 16.4 billion dollars and annual maintenance expenditure of about 100 million dollars [1]. In USA, out of a total 597,377 bridges, 164,971, that is, around 27.6 percent were identified as being either structurally deficient or functionally obsolete [2].
Bridge failures, though rare, can cause huge financial losses as well as loss of lives. A recent example is the I-35W highway bridge (of steel truss arch bridge type) collapse in Minnesota, USA in August 2007, which resulted in 13 deaths and injuries to hundreds of people. A flaw in the design which involved the use of a metal plate that was too thin to serve as a junction of several girders was found responsible for the crash [3]. Though the bridge was only about 40 years old, the increase in weight due to concrete structures and construction materials on the deck created added strain to the weak spot, eventually leading it to failure [3].

Story bridge, an iconic bridge in Brisbane, (shown in Figure 1-1) is a steel truss cantilevered bridge constructed between 1935 and 1940 and consists of 12,000 tons of structural steel, 1,650 tons of reinforcing steel and 1,500,000 rivets [4]. For maintenance, the bridge is currently repainted every 7 years using 17,500 litres of paint and there is approximately 105,000 square metres of painted steel surfaces [4]. Recently, it has been reported that stress fractures are emerging along the West Gate Bridge in Melbourne and that continued maintenance would be needed to monitor and repair those cracks, with maintenance costs projected to be $150 million dollars over the next 15 years [5, 6].

The facts and figures above prove the importance of early damage detection and timely planning of appropriate retrofitting/maintenance in continual safe performance of bridges and in achieving potential economic benefits. Visual inspection by trained inspectors has been the traditional means of bridge monitoring. But visual inspection alone cannot detect all damage, for example, cracks in hard to reach areas, cracks just starting to initiate or cracks hidden by layers of paint may go undetected by visual inspection alone. Hence, better and more reliable techniques are often required for better crack detection, especially at the earliest stage.

Acoustic emission (AE) technique is one SHM tool that enables early crack detection. It is based on the phenomenon whereby high frequency ultrasonic waves are generated from rapid release of energy inside a material, for example, from initiating and growing cracks. These waves can be recorded by means of appropriate sensors and the recorded signals can then be analysed to extract valuable information about the nature of the source of emission. High sensitivity to crack growth, ability to monitor hard to reach areas and ability to perform real time monitoring are some of
the features that make AE technique an attractive tool for SHM of big civil infrastructures. However, the use of AE technique for monitoring civil infrastructures is fairly new and several challenges still exist; especially regarding the need for analysis of large volume of data generated during the monitoring process.

Figure 1-1 Story bridge – an iconic bridge in Brisbane [7]

1.2 OBJECTIVES OF THE RESEARCH

The primary goals of any SHM tool are threefold: locate the damage, understand the nature of damage and quantify the damage. The main aim of this research is to address these three goals in the context of AE technique by focussing on effective analysis of recorded data, which is a big challenge in AE technique. The area of application is targeted mainly towards civil infrastructures such as bridges, though the tools and techniques used are equally applicable in monitoring of other engineering structures.

The main objectives of this research can further be expressed as follows:

(1) Accurate source localization

Ability to accurately locate the source of emission as long as the signals reach the sensors is one of the advantages of AE technique. But complications arise as AE waves can travel in different forms (modes) that have different velocities. Further mode conversions, signal reflections, superposition and attenuation can lead the sensors to record different modes. To accurately determine the location of the AE
source, proper identification of wave modes is necessary, as velocities and times of arrival of the modes at the sensors are the two important parameters needed to calculate the location. This study will develop a model to identify the wave modes by means of signal processing tools such as short time Fourier transform and use their velocities for source location calculations. Further, by identifying different modes recorded by a single sensor and using their velocities, source location in one dimension can be calculated using a single sensor rather than two needed in general method. The possibility of reducing the number of sensors needed for data capture is desirable and will be explored in this study.

(2) Source differentiation

Another major problem behind successful use of AE technique is the presence of sources of emission other than crack growth, such as rubbing of components or impacts from outside sources. These spurious noise signals often mask the signals from crack activity; hence discrimination of genuine signals from spurious noises is very important to achieve good monitoring results. This work will develop models that use different signal processing tools for differentiating signals from different AE sources. Furthermore, in theory, it is stated that in-plane (crack type) and out-of-plane (impact type) sources emit AE waves with different wave modes. By simulating such sources and then identifying and comparing amplitudes of the wave modes recorded, this study will aim to explore modal analysis as source differentiation approach.

(3) Severity assessment

During data analysis, it is desirable to have quantification tools to assess the severity of the damage sources, so that appropriate action can be taken as soon as possible. Though different damage quantification methods have been proposed in AE technique, not all have been deemed suitable for use in all situations. Further, the use of amplitudes of AE signals alone has been found unsuitable for such purposes. Hence, $b$-value analysis, which involves the study of distribution of amplitudes of signals, and its modified form (known as improved $b$-value or $Ib$ value analysis), will be investigated for suitability for damage quantification purposes. So far, these methods have been used mainly for brittle materials such as concrete and rocks; therefore, this study will investigate the application for ductile materials such as steel.
By treating all three vital issues together, it is believed that this study has solved the problem of effective data analysis in AE technique to a certain extent, thereby increasing its applicability as a SHM tool.

1.3 SCOPE OF THE RESEARCH

Although AE technique has been in use for over 50 years or so, effective analysis of data is still a major challenge. Hence, the major scope of this research is focus on the development of tools for analysis of recorded AE data to achieve accurate source identification, effective signal discrimination and reliable severity assessment. This can be expected to increase the effectiveness of acoustic emission technique as a structural health monitoring tool.

The study will mainly focus on analysis of acoustic emission waves travelling through steel structures, as steel is very common construction material. In addition to crack initiation and growth, two common sources of AE in big engineering infrastructures are impacts of and rubbing between two components. Laboratory experiments will be carried out to simulate these common sources of AE. Most experiments are carried out in thin plates and beams, which are used extensively in engineering structures. Though no real life testing could be carried out due to time constraints and other practical reasons, it is believed that tests carried out in laboratory closely mimic the real-life scenarios.

The scope of the research and data analysis algorithm proposed can be summarised in Figure 1-2. For data analysis, two major approaches are taken – study of signal parameters and study of recorded waveforms. Use of time, frequency and simultaneous time-frequency domain information are used for waveform based analysis. Then, source location calculations are based on identifying particular wave modes and using information on their times of arrival. Similarly, tools such as cross-correlation, coherence, energy distribution in different frequency bands and comparison of amplitudes of different modes are used for source discrimination. Analysis of signal amplitudes using b-value analysis is used for severity assessment. Detailed discussions on different aspects of the model will be presented in later sections and chapters.
1.4 ORIGINALITY AND SIGNIFICANCE OF THE RESEARCH

Major significant contribution of this research can be summarized as follows:

- One of the original contributions of this work includes the development of a model that: (a) uses short time Fourier transform (STFT) analysis to study energy distribution of signals in different frequency bands and apply this information to identify different wave modes, signal reflections and possible noises; (b) uses the velocities of identified modes for more accurate source location calculations, and (c) explores that the identification of modes further...
improves source localization by reducing the number of sensors needed for data capture.

- Another contribution of this study is the development of a model to achieve source discrimination using the following tools: (a) Coherence and cross-correlation functions in judging similarity or uniqueness of two waveforms; (b) identification and comparison of the amplitudes of AE wave modes to distinguish in-plane (crack like) and out-of-plane (impact type) source signals; (c) energy distribution in different frequency bands using short time Fourier transform to distinguish AE signals from crack, impact and rubbing, which are the three main sources of AE in structures such as bridges.

- By applying improved b-value (Ib value) analysis for data obtained from three-point bending tests of steel specimens, this study found that the lowest Ib value can predict the onset of plasticity in ductile materials and thus provides an early warning and act as a way to assess the level of severity during testing.

To summarize, the major innovation of this project is the development of data analysis methods that intelligently combine several signal processing tools to enable the study of AE wave features and parameters from the recorded data in order to address all three important issues of locating the damage source, discriminating different sources of emission and assessing the severity of damage. As explained earlier, combining these three vital aspects needed for an effective SHM system, it is believed that this thesis has helped make AE technique more applicable for use in monitoring of engineering infrastructures.

**Publications of research outcomes**

The outcomes of this research have resulted in the following publications:

**Journal articles**


Book chapters


Peer reviewed conference papers


1.5 THESIS OUTLINE

This thesis consists of 6 chapters. Chapter 1 has provided the background and scope of the study followed by the original contributions of the thesis.

Chapter 2 presents detailed introduction to acoustic emission technique, its advantages and challenges in the area of AE monitoring, with special focus on its use for structural health monitoring of big civil infrastructure such as bridges. An extensive literature review was conducted to explore different aspects of AE
monitoring and issues related to AE such as wave theory and signal processing and past uses and gap in research.

Chapter 3 presents the model proposed, the experimental setup, results, discussions of findings and conclusions from experiments to address the first goal of this study, that is, identification of AE wave modes for accurate source localization. As plates are common components in bridge structures and AE wave propagation is complex in such structures, experimentation is carried out to identify modes and use their velocities for accurate localization in a thin steel plate. AE sources needed are simulated by breaking pencil leads on the surface, as these are found to give crack like signals. Short time Fourier Transform is extensively used for identification.

Chapter 4 the discusses the model proposed, the setup used, results, discussions of findings and conclusions from experiments to address the second goal of this study – development of tools for identification and differentiation of AE signals from different sources. Various sources of AE such as impacts and rubbing are simulated in laboratory. Three point bending test is carried out in steel specimens to receive signals from actual crack growth.

Chapter 5 presents theory, experimental setup, results, discussions of findings and conclusions from studies addressing severity assessment for damage quantification. For this purpose, continuous deformation AE signals are collected from tensile tests on steel specimens. b-value and Ib value analyses are then performed by studying distribution of AE amplitudes.

Chapter 6 presents the results from the use of AE monitoring for a scale bridge model in laboratory. By using pencil lead breaks to generate crack like signals and using signals from impacts of two components of the model bridge, different aspects in signal propagation, such as how far AE signals can travel, and transmission of signals through bolted connections are studied.

Chapter 7 finally presents the overall conclusions and findings of the study and also discusses scope for future work.
Chapter 2: Background and Literature Review

This chapter begins with an introduction to the fields of structural health monitoring (Section 2.1) and acoustic emission technique (Section 2.2), followed by literature reviews on the following topics: use of AE technique for structural health monitoring of engineering structures, with primary focus on big civil infrastructures such as bridges (Section 2.9) and existing challenges in the use of AE technique (Section 2.10). Section 2.11 highlights the implications from the literature and develops the conceptual framework for the study.

2.1 STRUCTURAL HEALTH MONITORING

2.1.1 INTRODUCTION

Structural health monitoring (SHM) is a field that has received a considerable amount of attraction in various fields of engineering, with rapidly increasing use. The term SHM itself has been described by authors in various ways. Achenbach [8] defines SHM as a system that provides continuous or on-demand information about the state of a structure, so that an assessment of the structural integrity can be made at any time, and timely remedial actions may be taken as necessary. Farrar and Worden [9] define damage as changes introduced in a system that adversely affects its current or future performance and SHM as the process of implementing a damage identification strategy. Sohn et al. [10] explain the process of SHM as observing a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of the system’s health.

A range of techniques is available for health monitoring of structures. Aircraft, pipelines, nuclear reactors, bridges and dams are some of the structures regularly monitored by SHM methods. Sensors are used to measure parameters such as
displacement, velocity, acceleration, strain, temperature and pressure and after analysis of data, appropriate measures taken.

2.1.2 METHODS FOR STRUCTURAL HEALTH MONITORING

Visual inspection by trained personnel has been the traditional means of monitoring big structures such as bridges. Though simple, visual inspection may not be successful in locating all sources of damage, so a need exists for more reliable methods. A wide array of methods is now available for structural health monitoring of bridges. These methods can be broadly classified as global and local methods. Vibration based monitoring techniques usually give the global picture (hence referred to as ‘global methods’), indicating the presence of damage in the entire structure, and can also locate and assess the damage. These are based on the principle that the changes in the global properties (mass, stiffness and damping) of a structure cause a change in its modal properties (such as natural frequencies and mode shapes). The modal properties or the quantities derived from them such as modal flexibility and modal strain energy can then be used for damage identification [11-13]. These global methods are common in use and often involve the use of accelerometers to measure the vibration of the structure at selected locations, followed by calculation of the modal properties. The main drawback of the use of vibration based method in large structures such as bridges is that due to the large size some damage may only cause negligible change in dynamic properties and thus may go unnoticed. Moreover, in order to find the exact location of damage, local methods are often better alternatives.

Several non-destructive evaluation/testing (NDE/NDT) techniques are available for local structural health monitoring. As the name implies, these techniques do not involve the destruction of the specimen during the testing. Most commonly used non-destructive techniques are based on the use of mechanical waves (for example, ultrasonic and acoustic emission techniques), electromagnetic waves (such as, Magnetic particle testing, Eddy current testing and radiographic techniques) and fibre optics (though they can be used for global monitoring). A summary of common methods that can be used for SHM of big civil infrastructures such as bridges is presented in Table 2-1. Further details on these methods can be found in [14-16].
### Table 2-1 Common SHM methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Principle</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual inspection</td>
<td>Trained personnel inspect bridges in regular intervals to check the presence of any signs of damage and recommend appropriate retrofitting if necessary.</td>
<td>- Simple</td>
<td>- Hard to locate small or cracks hidden by layer of paint or rust</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Use of dye penetrant can facilitate visual inspection.</td>
<td>- Cracks due to corrosion or fatigue may go undetected until they reach critical stage [17].</td>
</tr>
<tr>
<td>Tap test</td>
<td>- Tapping the surface of the object, for example bridge decks, with a small hammer and comparing the response to known good area [14].</td>
<td>- Simple method</td>
<td>- Tapping process can be time consuming and tedious if needed to monitor large area.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Mechanical hammers have been developed with sound analyser to aid in detection.</td>
<td></td>
</tr>
<tr>
<td>Vibration monitoring techniques</td>
<td>- Changes in the global properties (mass, stiffness and damping) of a structure cause a change in its modal properties (such as natural frequencies and mode shapes). - The modal properties or the quantities derived from them such as modal flexibility and modal strain energy, can be used for damage identification [12] [13]</td>
<td>- Usually provides only global information, that is, information about the state of the whole structure (though some models have been developed that can determine local damage location [13]) - Can be applied for complex structures.</td>
<td>- Because of large size of bridges, some damage may only cause negligible change in dynamic properties and thus may go unnoticed. - Changes in temperature, moisture and other environmental factors may also produce change in dynamic characteristics [11].</td>
</tr>
<tr>
<td>Method</td>
<td>Advantages</td>
<td>Disadvantages</td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
<td></td>
</tr>
</tbody>
</table>
| Fibre optics                  | - Capable of sensing a variety of perturbations, mainly used to sense strain and temperature  
- The three sensing mechanisms of optical fibres are based on intensity, wavelength, and interference of the lightwave [18]. | - Costly  
- Need highly trained professionals |
| Magnetic particle testing     | - Use powder to detect leaks of magnetic flux [16]                           | - Not applicable for nonferrous materials |
| Eddy current testing         | - Presence of a flaw changes the eddy- current pattern [14]                  | - Expensive and can be used only for conducting materials  
- Sensor mounting can be troublesome |
| Radiographic                 | - Radiographic energy source generates radiation and is captured by recording medium in other side of specimen. | - Large size of equipment  
- Health hazard |
| Ultrasonic                   | - Transducers are used to introduce high frequency waves into a specimen and receive the pulses.  
- Inhomogeneities in the material induce changes to the propagating waves. [20]. | - Expensive  
- Coupling of sensor with the specimen surface may create problem  
- Requires generation of source signal  
- Real time detection |
Acoustic emission (AE) waves arise from the rapid release of energy inside material, for example from crack initiation. AE waves can be recorded by sensors and then analysed to extract information about the source of emission. - Highly sensitive - Ability to locate damage that acts as emission source as soon as it occurs - Passive technique, no energy need to be supplied (unlike ultrasonic method) - Background noises affect monitoring in large structures - High sampling rates generate large volumes of data

2.2 ACOUSTIC EMISSION TECHNIQUE

Acoustic emission (AE) waves are elastic stress waves that arise from the rapid release of energy from localized sources within a material [21]. Some common sources of AE in engineering materials are initiation and growth of cracks, yielding, failure of bonds, fibre failure and pullout in composites. AE technique involves recording the waves produced in a structure by means of sensors placed on the surface and analysing these signals to extract the information about the nature of the source. A diagrammatic representation of acoustic emission phenomenon can be seen in Figure 2-1, where under the application of stress the structure cracks and the crack acts as a source of AE waves which propagate in all directions. A sensor attached on the surface records the waves and the signals are sent to the AE acquisition system for further analysis. It is noted here that only active or growing cracks give rise to stress waves and if cracks are present but do not grow, no AE is received.
An interesting analogy can be made to acoustic emission phenomenon by comparing it to earthquakes, which can be regarded as largest natural occurring emission sources. Earthquakes release seismic waves which are elastic waves that propagate through the earth and are detected by means of a network of seismometers located around the world [22]. Analysis of these recorded seismic waves can provide the location and depth of the source.

A list of the materials in which AE has been measured and source mechanisms thought to cause AE can is presented in Table 2-2.
Table 2-2 Materials in which AE has been measured and source mechanisms causing AE [22]

<table>
<thead>
<tr>
<th>Materials in which AE has been measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals</td>
</tr>
<tr>
<td>Ceramics</td>
</tr>
<tr>
<td>Polymers</td>
</tr>
<tr>
<td>Composites (including those with metal, ceramic and polymer matrices and a wide variety of reinforcement materials)</td>
</tr>
<tr>
<td>Wood</td>
</tr>
<tr>
<td>Concrete</td>
</tr>
<tr>
<td>Rocks and geologic materials</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Potential AE sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcrack sources such as intergranular cracking</td>
</tr>
<tr>
<td>Macrocrack sources such as fatigue crack growth</td>
</tr>
<tr>
<td>Slip and dislocation movement</td>
</tr>
<tr>
<td>Phase transformations</td>
</tr>
<tr>
<td>Fracture of inclusion particles</td>
</tr>
<tr>
<td>Fracture of reinforcement particles or fibres</td>
</tr>
<tr>
<td>Debonding of inclusions or reinforcements</td>
</tr>
<tr>
<td>Realignment of magnetic domains</td>
</tr>
<tr>
<td>Delamination in layered media</td>
</tr>
<tr>
<td>Rockbursts</td>
</tr>
<tr>
<td>Fault slip (Earthquakes)</td>
</tr>
</tbody>
</table>

**Advantages**

Some of the advantages of AE technique over other SHM techniques are presented below:

1. The most significant advantage of AE technique is its high sensitivity to crack growth, enabling cracks to be detected at very early stages. It has been found to be sensitive enough to detect newly formed crack surfaces down to a few hundred square micrometers and less [23].
2. Small defects, occurring even in hidden or hard-to-reach areas, can be detected as long as signals can travel to the sensor. It is possible to determine the location of the source using the times of arrival of signals at different sensors and this is another advantage of AE technique.

3. AE technique enables real time monitoring of a structure, as signals originate as soon as crack occurs. Real time analysis of the recorded signals can then provide continuous information about the nature of the source.

4. AE technique can be used to monitor without interfering the normal activity of a structure, for example, monitoring of bridges can be done without stopping the traffic flow, thus increasing its practical value.

5. AE is a passive technology, in sense that no external energy needs to be supplied, but energy arising from the defect within a structure itself is utilized.

6. Although AE is primarily used as a local technique to monitor a certain location of a structure, with increased number of sensors it can be used as semi-global or global technique to monitor a larger area or a complete structure.

AE differs from most other NDT methods in two primary ways. First, the signals originate in the material itself, not from an external source. This contrasts AE with other non-destructive method such as ultrasonic where response to a signal introduced in a specimen is studied [24]. Second, AE detects movement while most methods detect existing geometrical discontinuities [25]. The major differences between acoustic emission technique compared with other inspection methods can be summarized in Table 2-3.
Table 2-3 Characteristics of acoustic emission technique compared with other inspection methods [25]

<table>
<thead>
<tr>
<th>Acoustic Emission</th>
<th>Other methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detects movement of defects</td>
<td>Detect geometric form of defects</td>
</tr>
<tr>
<td>Requires stress</td>
<td>Do not require stress</td>
</tr>
<tr>
<td>Each loading is unique</td>
<td>Inspection is directly repeatable</td>
</tr>
<tr>
<td>More material sensitive</td>
<td>Less material sensitive</td>
</tr>
<tr>
<td>Less geometry sensitive</td>
<td>More geometry sensitive</td>
</tr>
<tr>
<td>Less intrusive on plant/process</td>
<td>More intrusive on plant/process</td>
</tr>
<tr>
<td>Requires access only at sensors</td>
<td>Requires access to whole area of inspection</td>
</tr>
<tr>
<td>Main problems: noise related</td>
<td>Main problems: geometry related</td>
</tr>
</tbody>
</table>

2.3 BRIEF HISTORY OF THE USE OF AE TECHNOLOGY

Though the earliest recorded observation of audible acoustic emission were made in the 8th century, the initial studies forming the base of modern day AE technique were made by Joseph Kaiser in 1950s in Germany [26]. Kaiser discovered a phenomenon, now known as Kaiser effect, which states that AE is not generated in a structure unless the previously applied load is exceeded. After the initial theoretical studies on AE, the first practical application of AE technique was during the testing of rocket-motor casings in 1964, which was rapidly followed by applications in diverse areas, such as petrochemical, nuclear, aerospace and construction industries [27]. First application of AE technique to monitor bridges was reported in early 1970s and, later in the same decade, the US Federal Highway Administration undertook more tests on bridges. More information about the earlier studies can be found in [28, 29]. More recent studies and their findings will be discussed in later sections.
2.4 AE DATA ANALYSIS APPROACHES

Two broad approaches can be identified for analysis of recorded AE data: traditionally used parameter-based approach and newer waveform-based approach. More

(a) Parameter based analysis

In parameter based approach, signal parameters are used to assess the extent of damage. A typical AE signal along with commonly used parameters is seen in Figure 2-2. Commonly used parameters are defined next.

Figure 2-2 Parameters of AE signals [29]

Threshold: Recording is triggered once the output signals reach a set threshold value. This value is set to remove as much noise as possible, but care should be taken so that weak signals are not missed by setting too high threshold.

Hit: A signal that exceeds the threshold and causes a system channel to accumulate data is known as hit, thereby describing an AE event. Event rate is the number of events/hits per time.

Amplitude: Peak voltage of the signal waveform is a term of interest as it is closely related to the magnitude of the source event [30]. Amplitude of the signals is expressed in volts or in AE decibel scale where 1μV at the sensor is defined as 0 dB.

\[
\text{dB} = 20 \log \left( \frac{V_{\text{max}}}{1 \ \mu\text{V}} \right) - \text{(Preamplifier gain in dB)}
\]
Rise time: Rise time is the interval between the time a signal is triggered and the time the signal reaches the maximum amplitude.

Duration: Duration is the interval between the time a signal is triggered and the time the signal decreases below the threshold value.

Energy: Energy of the signal is another parameter that conveys information about the strength of the AE source. Various ways of expressing energy exist, such as area under the amplitude curve, RMS (root mean square) etc. Energy as measured area under rectified signal envelope can be seen in Figure 2-3. Absolute energy is derived from the integral of the squared voltage signal divided by the reference resistance over the duration of the AE waveform packet [31].

Counts: Counts are the number of times a signal crosses the threshold with the duration. In Figure 2-2, one hit with five counts are seen. Count rate is also used regularly and denotes the number of counts per unit time.

Number of hits and number of counts can be used to quantify an AE activity. The energy is often preferred to interpret the magnitude of source event over counts as it is sensitive to both amplitude and duration, and less dependent on the voltage threshold and operating frequencies [30].

Other useful parameters include average frequency (calculated by dividing counts by duration) and RA (Rise-time divided by Amplitude), which can be used to sort signals from tensile and shear cracks [30].
A brief outline of acoustic emission parameters and the information they convey about the source event has been summarised in Table 2-4.

Table 2-4 Acoustic emission parameters and their information about the source event [33]

<table>
<thead>
<tr>
<th>Domain</th>
<th>Parameter</th>
<th>Information about the source event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time domain variables</td>
<td>Rate</td>
<td>Rate of damage occurring</td>
</tr>
<tr>
<td></td>
<td>Peak amplitude</td>
<td>Intensity of source event, orientation</td>
</tr>
<tr>
<td></td>
<td>Relative arrival times</td>
<td>Source location</td>
</tr>
<tr>
<td></td>
<td>Duration or count</td>
<td>Energy of source event</td>
</tr>
<tr>
<td></td>
<td>Waveform</td>
<td>Structure of source event</td>
</tr>
<tr>
<td></td>
<td>Energy</td>
<td>Energy of source event- damage type</td>
</tr>
<tr>
<td>Frequency domain variables</td>
<td>Frequency spectrum</td>
<td>Nature of source event</td>
</tr>
<tr>
<td>Time-frequency domain variables</td>
<td>Spectrogram</td>
<td>Energy distribution of source event through time</td>
</tr>
<tr>
<td></td>
<td>The time variation of each frequency component</td>
<td>The intensities of source frequency components</td>
</tr>
</tbody>
</table>

(b) Waveform based analysis

As discussed in the previous section, in parameter based analysis only some of the parameters of the AE signal are recorded, but the signal itself is not recorded. This minimises the amount of data stored and enables fast data recording. But with the availability of better sensors and higher computing resources, it is now possible to perform quick data acquisition and record complete waveforms, [34]. This waveform based approach offers better data interpretation capability than parameter based approach by allowing the use of signal processing techniques and in aiding in signal-noise discrimination [35].
Though waveform shape is affected by the nature and geometry of the medium of propagation, it still contains information about the nature of the source. So analysis of waveforms can be expected to provide information about the nature of the source and help in distinguishing different sources of AE. Frequency analysis of recorded waveforms is the most commonly used tool and is done by means of Fourier transform or time-frequency analysis methods such as Short time Fourier transform and wavelets. Frequency analysis can be carried out during post processing of the data or even in real time as fast computing ability is available nowadays.

Two basic types of AE signals are usually seen: transient and continuous signals, as shown in Figure 2-4. Transient signals or bursts occur only for a short duration whereas continuous signals occur for longer period of time. Transient signals often arise from fracture or crack growth and continuous signals are mainly noise signals [24].

![Continuous and burst AE signals](image)

**Figure 2-4 Continuous and burst AE signals [36]**

The main disadvantage of waveform based approach is the generation of large volume of data. The frequency of AE waves can range from few kHz till few MHz, and in order to ensure all frequencies are recorded sampling rate should be at least higher than twice the maximum frequency of the signals, according to the Nyquist criterion. For example, to record the signals of frequencies of up to 400 kHz, sampling rate should be higher than 800 kHz. Because of the high sampling rates, signals of even small duration will be of large data size. Despite this drawback, the waveform based approach is still widely used because of the advantages it offers in
signal processing. Furthermore, AE waves travel in different modes and waveform based analysis is necessary to understand the modes of travel.

2.5 AE WAVE MODES

AE waves are elastic stress waves and travel in solids in various modes. Four main types of AE waves can be identified as: longitudinal waves, transverse waves, surface waves and Lamb (plate) waves. Reflected waves and diffracted waves are also usually present. These waves are governed by the same set of partial differential wave equation, but require satisfaction of different sets of physical boundary conditions [37]. A general overview of the AE wave modes is given next.

**Longitudinal and shear waves**

Both are collectively known as body or bulk waves. Longitudinal waves are also known as compression, primary or P waves. In longitudinal waves, particles oscillate in the direction of wave propagation. Transverse waves are also known as shear or S waves and the oscillations occur transverse to the direction of propagation. Mode conversions can occur between P waves and S waves. A diagrammatic representation of longitudinal and transverse wave modes can be seen in Figure 2-5.
Surface waves

Surface waves also known as Rayleigh waves travel on the surface of semi-infinite solid. They arise due to the interaction of longitudinal and shear waves on the surface and travel with velocity slightly slower than that of shear waves. Figure 2-6 shows the propagation of surface waves.

Lamb waves

Lamb waves are commonly seen in plate like structures. They consist of two basic modes: an extensional or symmetric (S₀) mode that often appears as higher-velocity but lower-amplitude waves preceding flexural or asymmetric (A₀) mode [38, 39], see Figure 2-7. Higher order modes (S₁, A₁, S₂, A₂) can occur too. The velocity of the Lamb wave modes depend on thickness of the plate and frequencies.
Dispersion curves which are based on the solution of Lamb wave equations (explained in Appendix A) show the variation of the modes with the product of plate thickness and frequency [28]. Propagation of basic lamb wave modes is illustrated in Figure 2-8.

![Dispersion Curves](image)

**Figure 2-7** Early arriving symmetric (extensional) mode and later asymmetric (flexural) modes [38]

![Symmetric and Asymmetric Lamb Waves](image)

**Figure 2-8** Symmetric and Asymmetric Lamb waves [28]

### 2.6 INSTRUMENTATION FOR AE MONITORING

Detection, amplification, filtering and analysing of signals are some of the important issues in AE technology. AE monitoring system typically consists of
sensors, preamplifiers and AE acquisition and analysis system - a simple layout of AE measurement chain can be seen in Figure 2-9.

Figure 2-9 AE measurement chain [24]

Sensors are placed on the surface of a structure to record acoustic emission signals. Sensors are available in wide range of shapes and sizes, see Figure 2-10. Good coupling of the sensors to the test specimen is necessary for effective transmission of AE signals. Sensors are attached on the surfaces using magnetic holders, glues or even rubber bands and tapes. A layer of couplant such as vacuum grease and oil is applied between the two surfaces. Operating frequency range is important during sensor selection. The common frequency range for AE testing in civil infrastructures is 100-300 kHz [28].
Piezoelectric sensors are most commonly used types of sensors in AE monitoring. Piezoelectric elements convert mechanical vibrations into electrical signals, and vice versa. A typical AE sensor of PZT (Lead Zirconate Titanate, commonly used piezoelectric material) element transforms elastic displacement of 1 pm ($10^{-12}$ m) into electrical signals of 1 μV [41]. Wear plate is mounted on the surface and piezoelectric element lies inside a protective housing. A simple schematic of AE sensor can be seen in Figure 2-11.

![Figure 2-10 Different types of sensors [40]](image)

![Figure 2-11 AE sensor of the piezoelectric element [41]](image)

Selection and optimal placement of sensors are both important for detecting damage. As AE waves propagate in a material their amplitude decreases (the process
is known as attenuation). Attenuation can be calculated using the exponential relationship:

\[ A_f = A_0 e^{-\alpha d} \]  \hspace{1cm} (2.1)

where \( A_f \) is the amplitude at the sensing location, \( A_0 \) is the initial amplitude at the source location, \( \alpha \) is the attenuation coefficient and \( d \) is the distance travelled by the waveform [38].

Reasons for attenuation include dispersion, scattering and conversion to other forms of energy such as heat. Material properties affect attenuation, for example waves attenuate faster in concrete compared to steel. Due to attenuation, waves can be recorded only up to a certain distance and this places a limit on the distance of separation of the sensors. The number of sensors can also be limited by the available channels in signal analysing systems, access to bridge locations or because of economic reasons. Therefore, careful selection of regions of structures where flaws are likely to occur is necessary for sensor placement.

In terms of frequency response, sensors can be divided into two types: broadband or wideband and resonant. Sensor response charts, which describe the behaviour of sensor over a frequency range, for resonant and broadband sensors can be seen in Figure 2-12. The two lines in Figure 2-12 represent two different ways of measuring sensor response (not discussed here, details can be found in [41]). However, it is seen that the resonant sensor is active in a smaller range of frequencies while the broadband sensor is active in wider frequency ranges. Resonant sensors are preferred in practical applications due to better signal to noise ratio. On other hand, broadband sensors have low sensitivity and may record additional background noise [42]. However, as resonant sensors tend to resonate at their characteristic frequency regardless of the source, they may distort the original wave [43]; so care is needed to pick appropriate frequency range for resonant sensors.
AE signals generated are often too small to be detected; hence preamplifiers are used to amplify the signals recorded by the sensors before further processing. Typical amplification gain range from 40 to 60 dB. The amplifiers are either prebuilt into the sensors or can be used separately and have possibility to set frequency filter range. Amplified AE signals are then fed into AE data acquisition system attached with a personal computer. Using acquisition and analysis softwares, raw data can then be processed to evaluate the parameters of the signals, visualise and record the waveforms, perform other signal conditioning tools and plot the results.

Figure 2-12 Responses of (a) resonant sensor, (b) broadband sensor [40]
2.7 SIGNAL PROCESSING TOOLS

Recording of AE signal waveform is itself not enough, the signals need to be processed for assessment and quantification of damage. Some commonly used signal processing methods for analysing AE signals include time series analysis, Fourier transform (FT), Short timed Fourier transform (STFT, also known as Gabor or windowed Fourier transform) and wavelet transform (WT). FT is a commonly used tool to identify the frequency contents of a signal. But the main disadvantage of FT is that information about time of occurrence of frequency components is lost. To obtain both time and frequency information simultaneously, STFT and WT are both useful. STFT involves multiplying a signal with a short window function and calculating the Fourier transform of the product. The window is then moved to a new position and the calculation is repeated. This gives both time-frequency information of the whole signal. But due to the use of constant window length, resolution is fixed in both time and frequency domain. Compared to fixed length window size of STFT, wavelet analysis uses windowing technique with variable sizes. Long time interval windows are used where more precise low-frequency information is needed, and shorter regions are used where high-frequency information is desired [44]. Wavelet analysis, thus, breaks a signal into different levels, where each level is associated with a certain band of frequencies in the signals. A brief description of mathematical details of STFT and WT is given in Appendix B.

WT has been used in areas like AE signal analysis, fracture mode classification of AE signals from composites and detection of a signal in low signal to noise cases [45]. Qi et al. [46] and Qi [47] used wavelet based AE analysis to identify signals of different frequency ranges with different failure modes of composites. Wavelet based filter techniques have proved useful in enhancing signal-noise ratio (SNR) [11, 48, 49]. Wavelets have been shown to be useful in other SHM methods as well - a summary of the uses in various SHM applications can be found in [50].

2.8 AE GENERATION DURING METAL DEFORMATION

Different mechanisms are responsible for AE generation in different materials, as seen in Table 2-2. AE generation during the deformation of a ductile material such as steel has been a topic of study of a number of studies.
The stress and strain variation in a typical ductile material, along with the determination of the yield point by the offset method can be seen in Figure 2-13.

![Stress-strain Diagram](image)

Figure 2-13 (a) Stress-strain diagram of a typical ductile material; (b) determination of yield strength by the offset method [51]

The difference in brittleness from ductility can be characterized by the stress strain curve seen in Figure 2-14, where an absence of inelastic strain before failure is observed.

![Stress-strain Curve](image)

Figure 2-14 Stress-strain curve in brittle material [52]

During tensile deformation, maximum AE activity has been found to occur near the yield region [53]. Han et al. [54] performed uniaxial tests on steel specimens
and divided the total duration into four stages – (1) the micro-plastic deformation stage, (2) the yielding stage, (3) the strain hardening stage and (4) the necking and fracture stage, with the two initial stages generating most high energy AE signals, as seen in Figure 2-15. Similar results were obtained by Mukhopadhyay et al. [55] during the study of tensile deformation of annealed and cold-worked AISI 304 stainless steel, see Figure 2-16.

![Figure 2-15 Stress versus strain along with AE energy [54]](image)

![Figure 2-16 Stress-strain curve and r.m.s. voltage](image)
2.9 AREAS OF APPLICATIONS OF AE TECHNIQUE

2.9.1 GENERAL AREAS OF APPLICATION

AE has been successfully applied for a wide range of materials, such as metals, concrete, composites, wood and rocks. AE technique is routinely used to monitor pressure vessels, aerospace structures, rotating machinery, tool wear, pipes, weld analysis, machine faults and corrosion. Three main application areas can be identified as: (a) structural testing and surveillance, (b) process monitoring and control, and (c) material characterization and testing [27]. One of the most successful applications of AE technique today is inspection of pressure vessels, see Figure 2-17. With sensors placed in arrays to monitor the entire pressure boundary, the vessel is subjected to pressures typically 10 percent above the previous operating levels, but well below the vessel pressure rating. The test pressures are applied in stepwise levels up to the peak stress, while monitoring the AE activity during each of these pressurization segments [21].

Figure 2-16 Stress versus strain along with AE RMS for AISI type 304 stainless steel (a) annealed and (b) cold worked 10% [55]
2.9.2 APPLICATION FOR SHM OF BRIDGES

AE technique is well suited for the study of integrity of bridge structures as it is able to provide continuous in-situ monitoring and is also capable of detecting a wide range of damage mechanisms in real time [17]. A brief survey of previous studies have exploring the use of AE technology for monitoring bridge structures made of different materials is presented in Appendix C. Further information on use of AE technique for SHM of bridge structures can be found in [15, 57-59].

From summary in Appendix C, it is clear that AE technique has been attempted for early damage detection and health assessment of bridge structures in a number of studies. Experimental studies in laboratory have generally given encouraging results, whereas real life tests have suffered mainly from the presence of other sources that give rise to signals that can mask the signals from cracks. Most studies have been targeted towards local monitoring, that is, the areas where crack presence is known are monitored using a number of sensors to determine the crack activity and to assess the nature of the source. Some other studies have attempted to use AE technique as a global or semi-global technique, that is, to monitor the whole structure or a large part of it. For such applications, a number of sensors is placed over a larger area of bridge/structure for general scanning. The areas around the sensors with pronounced

Figure 2-17 A pressure vessel under test using AE sensors [56]
AE activity are further monitored for local damage presence. Though parameter based approach and waveform based approach have both been used, the latter is preferred nowadays as powerful computing sources are available and real time assessment of damage source is possible.

2.10 CHALLENGES IN USING ACOUSTIC EMISSION TECHNIQUE

From the review of the applications of AE technique in previous section as well as review of other relevant literature, three main challenges can be identified in successful application of AE monitoring technique: accurate source localization, signal differentiation and damage quantification. These are discussed further in following sections.

2.10.1 SOURCE LOCALIZATION

Time of arrival method

Ability to find the location of damage, which acts as the source of emission, is one of the important aspects of AE monitoring process. Time of arrival (TOA) method is a common way of determining the source location. In TOA method, several sensors are placed on the surface of a structure and the location of source is identified by comparing arrival times of the signals at the sensors and using triangulation techniques [28, 60-62].

Arrival time is the instant a signal crosses a preset threshold value. This threshold amplitude is an important parameter in AE studies as it describes the point at which the system starts recording the signal waveform [63]. It is noted here that threshold values are often set in order to remove as much low amplitude noises as possible, but care must be taken so that no genuine signals are missed. Conditions during the testing often dictate the value set.

TOA principles for one dimensional and two dimensional cases are discussed next. Linear source location is applicable in one dimensional structure such as a truss member. A simplified illustration of linear source location is given in Figure 2-18.
If distance between two sensors $S_1$ and $S_2$ is known ($D$), the distance between the source and sensor $S_1$, $L_1$ can be calculated as:

$$L_1 = c \cdot T_1, \quad L_2 = c \cdot T_2, \quad L_1 - L_2 = c (T_1 - T_2) = -c \Delta t,$$

$$(2.2)$$

where $T_1$ and $T_2$ are the times of arrival of signal at two sensors, $\Delta t$ is the time difference $T_2 - T_1$ and $c$ is the speed of AE waves.

An illustration of two dimensional source location can be seen in Figure 2-19. Three sensors $S_1$, $S_2$ and $S_3$ are placed on the surface of a structure at locations $(x_1, y_1)$, $(x_2, y_2)$ and $(x_3, y_3)$. The location of the source, to be determined, is $(x_s, y_s)$. The distances between the sensors are $D_1, D_2$ and $D_3$ (which are known), and the distances between the source and the sensors are $d_1, d_2$ and $d_3$ (need to be solved). $t_1$, $t_2$ and $t_3$ are the times the signal reaches sensors $S1$, $S2$ and $S3$ respectively.
Using the derivations as made in [60], the distance $d_1$ can be written to be:

$$d_1 = \frac{D_1^2 - \Delta t_1^2 \cdot c^2}{2(\Delta t_1 \cdot c + D_1 \cos(\theta - \theta_1))} \quad (2.3)$$

$$d_1 = \frac{D_2^2 - \Delta t_2^2 \cdot c^2}{2(\Delta t_2 \cdot c + D_2 \cos(\theta_3 - \theta))} \quad (2.4)$$

where angles $\theta$, $\theta_1$, and $\theta_3$ are marked in Figure 2-19 and

$$d_2 - d_1 = c(t_2 - t_1) = \Delta t_1 \cdot c \quad (2.5)$$

$$d_3 - d_1 = c(t_3 - t_1) = \Delta t_2 \cdot c \quad (2.6)$$

$\Delta t_1$ and $\Delta t_2$ are time differences $(t_2 - t_1)$ and $(t_3 - t_1)$ and $c$ is the wave speed.

The location of the source is given by

$$x_s = x_1 + d_1 \cos \theta \quad (2.7)$$

$$y_s = y_1 + d_1 \sin \theta \quad (2.8)$$

Using a suitable iteration scheme, the values of $\theta$ are varied and the value that minimises the error between two calculated source locations is used to identify the location.
TOA method has been in use for long time, but a number of studies have reported that complications can arise when used in larger structures; as mode conversions, dispersion and attenuation of waves may result in sensors recording the arrival of different wave modes that have travelled with different velocities [62, 64, 65].

Gorman [66] pointed out that since the fundamental modes (extensional and flexural modes) are dispersive, multiple wave velocities may result in incorrectly locating the damage in plates, depending on which mode triggers the timing circuitry used for location of the damage.

Ding et al. [67] state that an AE source can rapidly become distorted by the presence of several modes travelling at different speeds, and through contamination by reflections and mode conversions; and use wavelets to determination of AE wave arrival times for source location purposes in thin plastic plates.

By performing tests in thin composite plates, Jeong and Jang [68] have also found that when the propagating wave is dispersive, error could occur in the source location because the AE pulse changes shape due to dispersion.

**Source location using modal analysis technique**

Due to complications with TOA method as discussed above, another source location method gaining popularity is by means of modal analysis (that is, by identification and analysis of AE wave modes). If two modes of a signal arriving at a sensor can be identified and the velocities of the modes (c₁ and c₂) known, then difference in time of arrival of the modes, Δt, can be used to calculate the distance between the source and the sensor as follows:

\[
D = \Delta t \left( \frac{c_1 \cdot c_2}{c_1 - c_2} \right)
\]  

(2.9)

Finding the location of the source by using modal analysis has received considerable attention. This allows AE technique to be used as a global or semi-global technique, that is, to monitor the whole structure or larger area, as separation of modes becomes pronounced as distance increases from the source. Another interesting feature of modal analysis is reduction in the number of sensors needed for
data capture. In one such study, Maji et al. [39] performed AE tests initially on steel beams and plates and then on real bridge. Location of AE events was based on the arrival of Lamb wave modes (extensional mode and flexural mode) at a transducer. Fast Fourier transform (FFT) was performed to identify peak frequencies and necessary high pass and low pass filtering was carried out to collect desired frequency waves. Modal method was found effective for monitoring a long range of distances.

Holford et al. [17] performed tests on steel bridges using Lamb wave theory to find source location. High pass and low pass filters were applied to the source waveform and the arrival times of different frequency components were recorded. They also pointed out that waveform acquisition settings must ensure capture of the first arrival of both modes.

2.10.2 NOISE REMOVAL AND SOURCE DIFFERENTIATION

AE signals are often masked by noises, arising from traffic or other environment sources as well as from other sources such as rubbing of the parts and loosening of bolts. Lozev et al. [29] performed field testing in five bridges as well as laboratory fatigue tests to characterise the AE associated with steel cracking and various sources of noise in a typical bridge environment. Monitoring was done on areas where cracks had been discovered, such as pin and hanger connections with crack, cracked web of girder that had been retrofitted and cracked welded region. AE technique was found suitable in distinguishing active and benign cracks but presence of spurious noise sources was identified as the main impediment to the successful use of AE in bridge inspection.

Similarly, Gong et al. [69] used AE technique to detect fatigue crack initiation and to monitor fatigue crack growth on steel railroad bridges. Weld repairs, edges of bolt and rivet holes and connected areas were identified as locations mainly likely to experience fatigue crack. AE technique was concluded to be successful in finding new cracks, in identifying active cracks and in validating the effectiveness of repairs; but noises such as rubbing and fretting of bridge parts were identified as troublesome as they generated high frequency signals similar to crack growth signals.
Sison et al. [70] studied AE in steel bridge hanger with known fatigue cracks by recording and analysing full waveform to obtain in-depth knowledge of noises and crack related AE. They found that passing traffic and rubbing of the bridge components generated AE signals that mask the signals from active cracks, but frequency and signal features could be used to distinguish noises from crack related AEs.

As difficulty in distinguishing damage growth-related emissions from other background noises has been identified as the most serious obstacle in AE monitoring, different suggestions have been made for noise suppression. These include high-pass frequency filtering (removes low frequency noise), signal threshold filtering (remove low amplitude noise), spatial filtering using guard sensors and analysis of signal characteristics [71]. An example of the use of guard sensors can be seen in Figure 2-20.

![Figure 2-20 Use of guard sensors](image)

In Figure 2-20, signals from the crack are picked up by the sensors S2 and S3 before the other two. If sensors S1 and S4 pick up signals before sensors S2 and S3, they are likely from other sources and are rejected.

By identifying the area of AE origin, source location techniques can be useful to discriminate between known flaw and extraneous noises, especially when AE is used to monitor a region with a potential of crack initiation or to monitor if an
identified crack is active or not [70, 72]. However, in addition to primary emissions (produced by crack extension or deformation at the crack tip), secondary emission (crack face rubbing and crushing of corrosion products between crack faces) can give rise to AE signals [70]. Hence, it may be necessary to differentiate between the primary and secondary emission signals even though their origin location is the same.

Several studies have attempted to use AE signal parameters in order to distinguish signals from different sources. In a study of crack growth in steel bridge hanger, mechanical and fretting noises were found to have longer duration and rise times compared to crack signals [70]. During study of failures in high-strength tendon of prestressed concrete bridges by acoustic emission, signal duration and amplitudes could be found capable of distinguishing real damage (wire break) from traffic noises or artificial sources (rebounding hammer) [73]. Li and Ou [74] state that differences in amplitude, duration time, rise time and frequency ranges are effective ways to differentiate between noise, continuous AE waveform and burst AE waveform; and filter and floating threshold and guard sensor can be used to remove ambient noise. Generally higher strain rate sources such as crack propagation are found to give higher amplitude signals compared to plastic deformation [36]. In such a scenario, simple technique as signal threshold filtering can be used to remove low amplitude noises.

As discussed earlier, the parameter based approach is simple and recording parameters alone lessens the data storage burden; but it has several drawbacks. For example, use of parameters alone is unable to distinguish between the actual AE waves produced by a fracture event and the reflections from the edges of propagating medium [75]. Noises can produce higher amplitude signals, if they occur close to the sensor. Moreover, factors such as signal energy absorption, geometric spreading, dissipation of acoustic energy and dispersion can cause decrease in signal amplitude (known as attenuation) as they travel away from the source [22]. Hence relying on amplitude or energy analysis may be inaccurate in distinguishing crack signals from noises. Furthermore, waveform based approach provides frequency information of the signals and allows the use of signal processing tools for removing noises.

Search for similarity among signals or signal uniqueness can help in source discrimination, as similar source mechanisms often emit similar signals if effects due
the path of propagation and recording sensor characteristics are negligible. Features of signals from crack growth were found to be similar in the study by Gong et al. [69]. In study by Sison et al. [70], signals from crack face rubbing were found to be similar and signal appearance was manually checked in both time and frequency domains to identify repetitive waveforms.

Knowledge of frequency contents of recorded waveform signals provides valuable information on the nature of the source. Frequency analysis is usually done using traditional Fourier transform method. In studies of composites, different damage mechanisms, such as matrix cracking, fibre debonding and fibre breaking have been found to emit AE signals in different frequency bands [76]. Similarly, using AE to study different chemical systems, and performing frequency spectra analysis of the resulting signals, different chemical processes could be distinguished [77].

Often spurious noises are found to be of lower frequency and in such cases high-pass frequency filtering can be used to remove these noise; but some rubbing can produce higher frequency signals [69]. Energy distribution in different frequency bands using wavelet analysis, has been used to identify different potential failure modes in composites [47] and differentiate fracture types in thermal barrier coatings [78]. Time-frequency analysis techniques such as wavelets and short time Fourier transform, though common in applications of AE technique in tools inspection and machining, have not yet found widespread use for analysis of AE data from monitoring of civil structures.

2.10.3 DAMAGE QUANTIFICATION FOR SEVERITY ASSESSMENT

Quantitative AE analyses are still hard for applications to actual bridge structures, as standardized procedures are not available for all types of bridges, as most recommendations cater for bridges under unique conditions of loading, materials, etc. [79]. Quantifying damage level has been attempted using different AE parameters or a combination of these. Some of the approaches and their applications are discussed next.


**General methods**

Ledeczi et al. [80] used number of events to measure activity and average amplitudes of the events to measure intensity and developed an index based on these values as shown in Figure 2-21.

![Figure 2-21 AE classification in terms of intensity (vertical axis) and activity (horizontal axis) [80]](image)

Using the relation between acoustic emission count rate and stress intensity factor range (Equation 2.11) and results from laboratory tests, Gong et al. [69] devised a way to categorise crack into five different levels, as shown in Figure 2-22 and described in .

\[ N' = A(\Delta K)^n \] (2.10)

where A and n are experimental constants. This is similar to well-known Paris Law of fatigue crack propagation, given as:

\[ \frac{da}{d\eta} = C(\Delta K)^m \] (2.11)

where \( \frac{da}{d\eta} \) is crack growth rate and C and m are experimental constants.
Figure 2-22 Typical relationships among the crack safety index, crack growth rate, count rate and ΔK for bridge steels [69]

Table 2-5 Relationships among the crack safety index, crack growth rate, count rate and ΔK for bridge steels explained [69]

<table>
<thead>
<tr>
<th>Range of ΔK</th>
<th>Crack Safety Index</th>
<th>Crack Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ≤ ΔK &lt; 10</td>
<td>1</td>
<td>Minor defect</td>
</tr>
<tr>
<td>10 ≤ ΔK &lt; 20</td>
<td>2</td>
<td>Slow crack growth</td>
</tr>
<tr>
<td>20 ≤ ΔK &lt; 30</td>
<td>3</td>
<td>Requires repair</td>
</tr>
<tr>
<td>30 ≤ ΔK &lt; 40</td>
<td>4</td>
<td>Dangerous</td>
</tr>
<tr>
<td>40 ≤ ΔK</td>
<td>5</td>
<td>Imminent failure</td>
</tr>
</tbody>
</table>

A method, proposed by the Japanese Society of Non-destructive Inspection (NDIS) is dependent on two parameters: load ratio and calm ratio [81, 82]. Load ratio (also known as Felicity ratio) is the ratio of the load at the onset of AE activity in subsequent loading to the previous load. Load ratio of greater than 1 indicates good condition while less than 1 indicates damage presence. Similarly, calm ratio is the ratio of the number of cumulative AE activities during the unloading process to the total AE activity during the last loading cycle up to the maximum. Generation of AE during unloading is an indication of structural instability, as no AE is generally recorded in this phase in a structure with good condition [81]. Assessment chart based on the load and calm ratios is shown in Figure 2-23.
Another way of analysing the accumulated state of damage in a material in terms of acoustic emissions can be done by defining a damage parameter, D as follows: [83, 84]

\[ D = \sum 10^{3 \cdot A_{\text{dB}}/20} \]  

(2.12)

where \( A_{\text{dB}} \) is the amplitude of signals in dB. This parameter has mainly been applied for concrete and rocks.

**Intensity analysis using historic and severity indices**

Another common approach for damage quantification is intensity analysis using the historic and severity indices. The historic index is defined as a measure of the change in signal strength throughout the test [42, 79]. Historic index is a form of trend analysis with the objective of locating significant changes in the slope of the cumulative signal strength versus time curve [82]. It aims to compare the signal strength of the most recent hits to all the hits, and is calculated as follows [85]:

\[ H(I) = \frac{N}{N - K} \cdot \left( \frac{\sum_{i=K+1}^{N} S_{oi}}{\sum_{i=1}^{N} S_{oi}} \right) \]  

(2.13)

Similarly, the severity index is the average signal strength for a certain number of events having the largest value of signal strength [85]. It is calculated as follows:
In Equations 2.14 and 2.15, \( H(I) \) = historic index at time \( t \), \( N \) = number of hits up to and including time \( t \), \( K \), \( J \) = empirically derived constant based on material type, \( S_{oi} = \) signal strength of the \( i^{th} \) event. \( K \) values for metals depend on \( N \) and are given in [79]. The maximum values of historic index and severity index are then plotted on an intensity chart divided into zones of damage and the location of the point in the chart will indicate the level of damage.

The intensity chart used for analysis of concrete bridges by Golaski et al. [42] is shown in Figure 2-24, with regions indications as follows: A – minor emission, B – small defect, C – significant defect, further evaluation required; and D,E – major defect, immediate shutdown and follow-up non-destructive examination needed.

![Intensity chart](image)

**Figure 2-24 Severity- historic index chart for analysis of concrete bridges [42]**

Similarly, the intensity charts developed for metal piping systems is shown in Figure 2-25 - as regions progress from A to E, intensity increases and the recommended actions range from no follow-up needed to major defect requiring immediate shut-down and follow-up inspection [85].
It has been seen that AE peak amplitude is a commonly used parameter for severity assessment as more serious sources tend to generate AE with large peak amplitude. But care should be taken as the use of amplitude alone can be misleading, as the accumulated damage increases the materials’ attenuation rate due to scattering at the cracks – thus, making even a high amplitude signal severely attenuated before being recorded by the sensors [86]. Hence, it is better to study the amplitudes through their cumulative distribution that uniquely changes as the damage is accumulated. With the evolution of damage, this slope of the distribution decreases, meaning that the ratio of the large energy AE events to that of the small relatively increases in the total population of AE events [86]. This approach for damage quantification, which is gaining popularity, is known as the b-value analysis. The b-value analysis takes analogy from seismology, where events of larger magnitude occur less frequently than events of smaller magnitude – the relationship being expressed by Gutenberg-Richter formula as [83, 87]:

$$\log_{10} N = a - b M_L$$  \hspace{1cm} (2.15)

where $M_L$ = Richter magnitude of the events, $N$ = the number of events with magnitudes in the range $M_L \pm \Delta M/2$, and $a$ and $b$ are the empirical constants. The above formula is modified for AE technique and can be written as:
\[
\log_{10} N = a - b' A_{dB}
\]  

(2.16)

where \(A_{dB}\) is the peak amplitude of the AE events in decibels and can be expressed as:

\[
A_{dB} = 10 \log_{10} A^2_{\text{max}} = 20 \log_{10} A_{\text{max}}
\]  

(2.17)

b value is then expressed as:

\[
b = 20b'
\]  

(2.18)

Thus, b-value is the slope of the log-linear plot of frequency versus amplitude of AE events. It has been found to change during different stages of damage, for example when microcracks occur in the early stages of damage, the b-value is high but becomes low when macrocracks begin to occur [83]. This fact makes the b-value a likely candidate to judge damage progress [88].

**Improved b-value (Ib value) analysis**

It has been found the distribution of frequency versus amplitude of AE events is not always linear. Hence, the b-value analysis method has been recently modified by using statistical values of amplitude distribution (mean and standard deviation) and the newer method is referred as improved b-value (Ib-value) [89]. The Ib value can be expressed as:

\[
I_b = \frac{\log_{10} N(\omega_1) - \log_{10} N(\omega_2)}{(\alpha_1 + \alpha_2) \sigma}
\]  

(2.19)

and

\[
\omega_1 = \mu + \alpha_1 \sigma, \quad \omega_2 = \mu - \alpha_2 \sigma
\]  

(2.20)

where \(\mu\) is the mean amplitude, \(\sigma\) is the standard deviation of amplitude distribution and \(\alpha_1\) and \(\alpha_2\) are constants. Ib value improves calculation by selecting the amplitude limits of the linear range of the cumulative frequency distribution data of AE [90]. Ib-value is usually calculated for a certain number of events (generally ranging from 50 to 100) during the test. An example of Ib-value calculation during loading of concrete beam can be seen in Figure 2-26, where in Stage III of loading, I-
b reaches to a value of slightly below 0.05 indicating the onset of macro-damages beyond yielding [89].

Similarly, the change in Ib-value against uniaxial compressive stress (0–100% failure stress) at various stages of loading of granite (a type of rock) is shown in Figure 2-27. The results show sharp changes in Ib-value corresponding to the various stages of rock deformation and crack formation, growth and coalescence. The transitions from stage V to stage VI and from stage VI to stage VII (stages marked in the Figure 2-27) can be considered to be most useful for the identification of critical state of damage and prediction of failure time of the test rock [90].
Figure 2-26 Loading curves of a reinforced concrete beam with corresponding Ib-values [89]
SUMMARY

From the literature review, it can be seen that AE has a potential to be used as a structural health monitoring tool for big engineering infrastructures such as bridges. However, effective analysis of large volume of data generated during testing remains as a challenging issue. Instrumentation and sensor technology have been reasonably well developed and collection of data has been greatly simplified. But how to manage the great volume of data to gather relevant information is on the forefront of research. An intelligent combination of various data processing techniques is essential and scope exists to address this issue.

Main findings from the review of the literature can be summarised as follows:

- AE generation is affected by material property as well as size and geometry of the propagating medium. Furthermore, big structures such as bridges vary in shapes, sizes, materials used for construction, loads and environmental

Figure 2-27 Changes in Ib-value against uniaxial compressive stress (0–100% failure stress) at various stages of loading of granite [90]
conditions they are subjected to. The use of monitoring technique such as AE in different bridges presents unique practical challenges in each application.

- Though laboratory results on the use of AE for health monitoring of bridge structures look promising and some field tests have given encouraging results, effective analysis of recorded data to extract relevant damage related information is still a big challenge. One identified approach is the use of time-frequency analysis of signals using STFT and wavelet transform.

- An advantage of AE technique is the ability to determine the location of the source of emission. To accurately locate the source, it is important to know the velocity of the AE waves. But AE waves can propagate in a variety of modes that travel with different velocities. Mode conversions are frequent and size and geometry of test specimen affect the modes of travel. Thus, understanding wave propagation modes is necessary for source location. This is also significant in other methods such as ultrasonic which use Lamb waves to detect damage. Frequency analysis of signals can shed light into wave propagation modes.

- Noisy environment of bridges presents challenges in the use of AE method. A range of sources can give rise to AE signals; hence, a way to identify and distinguish the real signals from spurious ones is necessary. Tools to judge signal similarity with a set of known defect signals can be used for source identification and differentiation purposes. Another, tool that has potential is identification and comparison of the amplitudes of the different modes.

- Though several methods have been proposed for damage quantification and severity assessment of AE sources, they have been used only for specific cases and not found approval in all cases. Hence, scope exists for investigation of these methods for specific structure or material. b-value and improved b-value are some of the attractive methods for damage quantification. Further, quantifying the level of damage has been attempted mainly for concrete bridge structures; hence, scope still exists for investigation of the applications of those tools for steel structures.
AE technique is one of the many techniques currently used and further explored for bridge health monitoring. No one technique can be expected to be sufficient and give fault proof results all the time. Use of different techniques to supplement each other is the best way to properly monitor a bridge. Integration of AE with other tools such as vibration based technique can be an efficient tool.

This thesis will aim to fill some of the knowledge gaps identified above in the next chapters by addressing three main issues: a) accurate source localization, b) source identification and differentiation and c) severity assessment for damage quantification.
Chapter 3: Accurate localization of AE sources

This chapter describes the background, experimental setup, results and subsequent analysis carried out to achieve the first objective stated in Chapter 1, namely effective analysis of acoustic emission data to achieve accurate source location. Section 3.1 discusses the plan of the study and the proposed method. Section 3.2 discusses the experimental setup, instrumentation and settings in detail. Section 3.3 provides the results and discussion on the results. Finally Section 3.4 summarizes the main findings of the study.

3.1 PLAN OF STUDY AND PROPOSED MODEL

Ability to locate the source of emission is an important advantage of AE technique. Source location is usually carried out using the popular time of arrival (TOA) method (discussed in Section 2.10.1), where the differences in arrival times of signals at different sensors and velocity of the waves are used to find the location of the source using triangulation techniques. Again as discussed earlier, complications can arise in TOA method when used in larger plate like structures; as factors such as mode conversions, dispersion and attenuation of waves may result in sensors recording the arrival of different wave modes that have travelled with different velocities. Since this will create errors in the source location calculations, proper identification of the modes is needed to determine the velocity and time of arrival of the same mode at all sensors.

In this study, a model is developed to identify the modes of AE waves in plate like structures using time-frequency analysis technique such as short time frequency analysis (STFT). Tests are carried out in a thin steel plate and results are analysed using the developed model to check if more accurate source location results can be obtained by using the velocities of particular identified modes. Furthermore, the model uses the velocities and differences in times of arrival of extensional and flexural wave modes to calculate source location by using a single sensor.
Artificial AE sources needed for the tests can be generated by means of pencil lead break (PLB), also known as which is also known as Hsu-Nielsen source. Breaking pencil leads on a surface has been found to generate crack like signals; hence, they are often used as simple ways of generating sources of acoustic emission in experiments and sensor calibration [22]. The temporal characteristics of a standard pencil lead break source (specified according to ASTM E976 standard, which uses 3 mm of 2H leads, ASTM- American Society for Testing and Materials) can be seen in Figure 3-1.

![Temporal characteristics of an ASTM E976 standard pencil lead-break source](image)

Figure 3-1 Temporal characteristics of an ASTM E976 standard pencil lead-break source [91]

Plate like structures are common in civil, aerospace and other applications, hence it is desirable to perform studies on them. Results and findings from this study can be expected to lead to a better understanding of modal nature of AE signals and its importance in source location calculations.

### 3.2 EXPERIMENTATION

Experiments were carried out in a steel plate, which formed the deck of a slab-on-girder bridge model, and had dimensions of 1.8 m by 1.2 m and thickness of 3 mm, see Figure 3-2. AE data acquisition system used for experimentation was micro-disp PAC (Physical Acoustics Corporation) system with four channels, with three R15α PAC sensors (resonant at 150 kHz, marked as S1, S2 and S3 in Figure 3-2) and
preamplifiers with a gain set at 40 dB and filter frequency range of 20-1200 kHz. Regarding the nature of sensors used, it is noted that though resonant sensors can distort the signal frequency components, they provide better signal to noise ratio signals and hence are appropriate for noisy environment [22]. Sensors were held by magnetic hold down device and a layer of grease was usually applied between the sensor and the surface for better contact. The specifications of an R15α sensor are given in Table 3-1.

![Figure 3-2 Experimental specimen for source location experiment](image1)

![Figure 3-3 μ-disp PAC (Physical Acoustics Corporation) system with four channels PAC](image2)
Figure 3-4 (a) Preamplifier providing a choice of amplification of 20 dB, 40 dB or 60 dB, (b) R15α Sensor [92]

Table 3-1 Specifications of R15α sensor

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Frequency Range</td>
<td>50 - 400 kHz</td>
</tr>
<tr>
<td>Resonant frequency</td>
<td>150 kHz</td>
</tr>
<tr>
<td>Physical dimensions</td>
<td>19 mm diameter x 22.4 mm height</td>
</tr>
<tr>
<td>Weight</td>
<td>34 grams</td>
</tr>
<tr>
<td>Case material</td>
<td>Stainless Steel</td>
</tr>
</tbody>
</table>

A bandpass filter of 20-400 kHz was set in the software control of the data acquisition system. Data was acquired at a sampling rate of 1 MHz for a duration of 15 ms (one sample per 1 μs). A threshold value was set at 60 dB for experiments. (Note: AE dB is calculated as: \( \text{dB}=20 \log \left( \frac{V}{V_{\text{ref}}} \right) - \text{(preamplifier gain)} \), where reference voltage \( V_{\text{ref}}=1 \mu \text{V} \); 60 dB corresponding to amplitude of 0.1 V). Though experimental conditions were relatively noise free, the higher value of threshold was used as in real life testing significant noises could be present, thereby requiring higher threshold value. Acquisition of data by the system was triggered as the signals exceeded this threshold amplitude voltage. Use of memory buffer in data acquisition system allowed recording of pre-trigger signal. The length of the pre-trigger signal was set to 256 μs for all experiments.
AE signals were generated by breaking 0.5 mm pencil leads at selected locations on the plate, and in each position pencil lead break tests were done twice. To harmonize the tests, the pencil was held at the same angle to the surface using a circular Teflon ring around it (see Figure 3-6) and same lengths of leads were broken for every test. It is noted that though reflections might occur, their amplitudes would be smaller than the crack related signals.

Figure 3-5 Locations of the sensors (at positions (0,0), (1.2,0) and (0.6,1.8) m denoted by ‘x’) and pencil lead break emission sources on the plate (denoted by ‘o’)

Figure 3-6 Pencil lead break apparatus
From recorded data, differences in arrival times of signals at three sensors were calculated manually. To calculate the source locations, velocity of AE waves was needed. Values of longitudinal wave velocity and transverse wave velocity were first used as reference values for initial source location calculations. Longitudinal wave velocity was calculated as $c_L = \sqrt{\frac{E}{\rho}} = 5188 \text{ m/s}$ and the transverse velocity as $c_T = \sqrt{\frac{E}{2\rho(1+\nu)}} = 3218 \text{ m/s}$. The following values were used as material properties of steel: Young’s modulus, $E = 210 \text{ GPa}$; density, $\rho = 7800 \text{ kg/m}^3$ and Poisson’s ratio, $\nu = 0.3$. By comparing calculated locations with exact locations, influence of wave velocities in source location by TOA method was investigated. Due to the plate like nature of the specimen, it could be expected that Lamb waves were the main mode of wave propagation. Hence, accurate identification of wave modes and exploration for the presence of Lamb wave modes were then attempted. Next source location calculations were carried out using various identified modes.

### 3.3 RESULTS AND DISCUSSION

#### 3.3.1 SOURCE LOCATION RESULTS

**Sample calculation**

The arrival times of the signals at three sensors (when they hit the threshold) for the first AE source at (0.3, 0.6) m are as follows:

$t_1 = 8.8749655\text{s}; t_2 = 8.8751095\text{s}; t_3 = 8.87515375\text{s}.$

From these, time differences in arrivals are calculated as follows:

$\Delta t_1 = t_2 - t_1 = 0.000144\text{s}; \Delta t_2 = t_3 - t_1 = 0.00004425\text{s};$

The other parameters can be stated as follows:

Radius of the sensor, $R_s = 0.009\text{m}$.

$x_1 = 0 + R_s, y_1 = 0 + R_s, x_2 = 1.2 - R_s, y_2 = 0.0 + R_s, x_3 = 0.6 - R_s, y_3 = 1.8 - R_s;$

$D_1 = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} = 1.1820 \text{ m}$

$D_2 = \sqrt{(x_1 - x_3)^2 + (y_1 - y_3)^2} = 1.8746 \text{ m}$

$D_3 = \sqrt{(x_2 - x_3)^2 + (y_2 - y_3)^2} = 1.8803 \text{ m}$
$c = c_L = 5188 \text{ m/s.}$

$$\theta_1 = \tan^{-1}\left(\frac{y_2 - y_1}{x_2 - x_1}\right) = 0$$

$$\theta_3 = \tan^{-1}\left(\frac{y_3 - y_1}{x_3 - x_1}\right) = 1.2551$$

Numerical iterations were performed by varying $\theta$ and calculating $d_1$ using the relations in Equations 2.3 and 2.4. The value of $\theta$ that gave the lowest error between the two calculations of $d_1$ was used to calculate the location of source as follows:

$$X_{s1}(i)= x_{1}+d_1\cos(\theta) = 0.076 \text{ m},$$

$$Y_{s1}(i)= y_{1}+d_1\sin(\theta) = 0.4558 \text{ m}.$$ 

Similar calculations were done for all emission sources and the results are presented graphically in Figure 3-7, with exact positions, calculated positions and sensor locations appropriately marked. MATLAB codes used for source location calculations, including the times of arrival of signals at three sensors for other locations, are presented in Appendix D.
Figure 3-7 Source location using (a) longitudinal, (b) transverse wave velocities
From Figure 3-7a, it is seen that the use of $c_L$ does not give good match between the exact and calculated locations. For example, for AE sources at (0.3, 1.2) m, locations were calculated at positions outside the area and for one AE source at (0.9, 1.2) m, location was calculated at a position well outside the range (and therefore not shown in Figure 3-7a). Using $c_T$ gives much better correlation as seen in Figure 3-7b, except for the same AE source at the location (0.9, 1.2) m. This could be due to poor quality of pencil lead break data. It is also noted that for several cases, calculated positions for two different tests in one location are very close to each other and hence overlap in the diagram (as indicated by thicker plus signs).

But overall, the results show that threshold based method is generally reliable in determining source location, as long as the speed of the recorded wave is accurate, which means proper wave mode identification is important.

### 3.3.2 Modes Identification

As discussed earlier, Lamb waves are primary means of propagation of AE in plates. Hence, to study the presence of Lamb waves and identify the different wave modes, it was found useful to study the waveforms recorded by sensors in detail. One pencil lead break at position (0.3, 0.9) m was used as a sample, and the waveforms of signals recorded by three sensors for this source were analysed. These are shown in Figure 3-8, along with the preset threshold value (dotted line). Due to pre-trigger option set, signal of length 256 μs is recorded before the actual threshold crossing. For clearer view, only initial recorded portions are shown.
Chapter 3: Accurate localization of AE sources
Chapter 3: Accurate localization of AE sources

Figure 3-8 Initial portions of signals recorded by (a) sensor S1, (b) sensor S2 and (c) sensor S3 for pencil lead break AE source at position (0.3, 0.9) m

From plots in Figure 3-8, three major distinct wave modes are visible in the initial part of the signals: first, early arriving waves with amplitude smaller than threshold; second, a small packet that crosses the threshold; and third, a higher amplitude mode. As the initial low amplitude signals do not cross the threshold, they do not trigger a hit, thus do not record the time of arrival in the data acquisition system. After the third high amplitude mode, waves with lower amplitudes arrive. Similar patterns were also present in waveforms from sources at other locations.

The signals in Figure 3-8 were analysed further to determine the velocities of the modes. For signal in Figure 3-8a it is observed that the initial mode arrives at around 140 µs, with the triggering wave component arriving at 257 µs (as pre-trigger value was set at 256 µs). Using the velocity of the triggering wave as $c = 3218\text{ m/s}$ (as this value gave good source location results), the distance between the source and signal (0.9487 m) and a time difference of 117 µs; the velocity of the initial wave can be calculated to be around $5335 \text{ m/s} = \frac{0.9487 \text{ m}}{(0.9487/3218 \text{ m/s}) - 117 \times 10^{-6} \text{ s}}$. Similarly, for signal in Figure 3-8b, a time difference of 157 µs and distance of 1.27 m gives the velocity of initial arriving mode as $5344 \text{ m/s}$. Signal in Figure 3-8c gives
a similar result as Figure 3-8a, as sensors S1 and S3 are equidistant from the source. More discussion on these velocity values will be carried out later.

Frequency analysis can be expected to provide more information about the wave modes and will be carried out in the next section.

3.3.3 FREQUENCY ANALYSIS

Fast Fourier Transform (FFT) is a commonly used tool for obtaining frequency contents of a signal. FFT was performed on initial 1000 μs duration of the signal recorded by the three sensors for the source discussed in Section 3.3.2. The results are shown in Figure 3-9. Most frequencies are found to lie in the range of 40 to 180 kHz, though small peaks occur between 200 and 300 kHz. However, as discussed earlier, information is lost regarding their time of occurrence. One possibility is to perform FFT analysis on different parts of the signal, for example, on the initial portion consisting of fast arriving low amplitude signals and on segments consisting of other higher amplitude modes. But small sizes of the samples gave caused poor resolution, making results inconclusive.
Figure 3-9 Fourier transforms of the signals recorded by (a) S1, (b) S2 and (c) S3 for source location at position (0.3, 0.9) m (initial 1000 μs length used)

To overcome the deficiencies of FFT and to obtain simultaneous time and frequency representation, short time Fourier transform (STFT) and wavelet analyses were carried out next for the same signal. Results of the STFT analysis, carried out
using the time-frequency toolbox [93], are shown in Figure 3-10, where squared STFT coefficients are plotted in the logarithmic scale.

Figure 3-10 STFT plot (in logarithmic scale) of the signals recorded by (a) S1, (b) S2, (c) S3 for source location at position (0.3, 0.9) m
For comparison, wavelet transform was calculated for signal recorded by S3 with Vallen wavelet software [94] and is shown in Figure 3-11.

![Wavelet plot](image)

**Figure 3-11 Wavelet plot [94] of the signal recorded by S3 for source location at position (0.3, 0.9) m (Linear scale)**

From Figures 3-10 and 3-11 (clearer in Figure 3-10, as this is in logarithmic scale), it is seen that waves with frequencies between 100 to 180 kHz arrive at the beginning. At around 260 µs, waves with frequency of 300 kHz appear, thus coinciding with the arrival of the triggering mode. Then shortly afterwards, waves with a large variation in frequencies arrive. The frequencies gradually decrease from around 180 kHz to 40 kHz, with peak values at around 150 kHz and 50 kHz. These frequency values correlate to the values seen in Fourier transform in Figure 3-9. The late arrival of low frequency waves is due to dispersive nature of flexural Lamb waves.

In addition to the early arriving waves discussed above, several other similar patterns (patch of frequency around 300 kHz followed by waves with frequencies decreasing from around 150 to 40 kHz) are also present later in time. These are likely to be the waves reflected from the edges, as wave reflections are common. Analysis of waveforms recorded by sensors S1 and S2 and as well as waveforms for other sources gave results with similar patterns.

### 3.3.4 INVESTIGATION OF LAMB MODES

As mentioned earlier, dispersion curves present the velocities of Lamb wave modes with respect to frequency and thickness of the plate. The curves showing the variation in group velocities of different Lamb modes with respect to frequency, for a
plate of thickness 3 mm, are shown in Figure 3-12. Only extensional (symmetrical, $S_0$) and flexural (asymmetrical, $A_0$) modes are shown here as higher frequency waves needed for higher modes to exist were not seen in experimental results.

![Dispersion curves for steel plate of thickness 3 mm](image)

Figure 3-12 Dispersion curves for steel plate of thickness 3 mm [94]

For frequencies $f$ between 100 kHz and 180 kHz, group velocity of around 5200 m/s is seen for $S_0$ mode. This value matches the result derived earlier for initial fast arriving component. For the hit triggering mode of 300 kHz, velocity (3218 m/s) matches the velocity of flexural mode ($A_0$) predicted by the dispersion curve. But in previous studies, flexural waves have been found generally to be of lower frequencies than extensional waves [39, 62]. Hence, it is likely this 300 kHz mode is horizontally polarised shear (SH) wave, which is another wave mode found to occur in plate like structures [95, 96]. Moreover, this 300 kHz mode is seen to be non-dispersive while flexural waves are dispersive in nature.

High energy wave mode with frequency of 150 kHz arriving at around 300 µs (see Figure 3-10 and Figure 3-11) is most likely to be the flexural wave $A_0$. Lower frequency waves arriving late confirm dispersive nature of flexural modes. Again using the velocity of triggering wave as 3218 m/s and the distance travelled by waves as 0.9487 m, the velocity of the high energy 150 kHz wave mode (arriving about 40
μs later than triggering mode) can be calculated to be 2833 m/s \([= 0.9487 \text{ m/s}/(0.9487/3218) + 40.10^{-6}]\) and that of 50 kHz mode (arriving about 200 μs later) to be 1918 m/s. Both values closely match the values from dispersion curve.

Another way to check velocities of extensional and flexural modes is by means of the classical plate theory. The plate theory predicts the velocities of extensional and flexural modes in an isotropic plate as follows:

\[
c_e = \left[\frac{E}{\rho (1 - \nu^2)}\right]^{1/2}
\]

(3.1)

\[
c_f = \left[\frac{Et^2}{12 \rho (1 - \nu^2)}\right]^{1/4} \omega^{1/2}
\]

(3.2)

where \(t\) is the plate thickness and \(\omega\) is angular frequency [62]. As seen in the formulae, dispersive relation is predicted for flexural waves (velocity dependent on frequency) and non-dispersive for extensional waves. Calculations give \(c_e = 5440 \text{ m/s}\) and \(c_f = 1216 \text{ m/s}\) for 50 kHz mode and \(2107 \text{ m/s}\) for 150 kHz mode. Comparing these values with values calculated before, it is seen that though \(c_e\) matches the calculated value of initial wave mode as well as that predicted by the dispersion curve, \(c_f\) values are much smaller than the calculated values. This is because plate theory is approximate (as shear effects are neglected) and is found to be adequate in lower frequency range only, hence it is not suitable for higher frequencies observed here [22].

3.3.5 USE OF EXTENSIONAL MODE FOR SOURCE LOCATION CALCULATIONS

Next, extensional modes were used for source location calculations. Identifying the arrival of initial modes, time differences were calculated and source location were determined using these values and the extensional wave mode speed of 5200 m/s. The results are shown in Figure 3-13, using the same notations for actual and calculated positions and sensor locations as Figure 3-7.
The actual and calculated positions show a very good match. It is observed that even the AE source at position (0.9, 1.2) m that gave large error before (see Figure 3-7) gives accurate result this time. To investigate this, the waveforms of the signals recorded by three sensors were investigated. It was found that for signal recorded by one of the sensors, the early arriving extensional mode exceeds the threshold rather than the hit triggering mode of 300 kHz seen in other waveforms, see Figure 3-14. Hence this point of time was recorded as the time of arrival, creating error of location calculation in the earlier cases.
It is further noted that extensional modes could be identified in this analysis by time domain signals themselves. In noisy environment however the low amplitude waves can be masked by noise signals, but it is believed that simultaneous time-frequency analysis (by STFT and WT) will help differentiate the extensional waves from spurious noises.

### 3.3.6 SOURCE DISTANCE BY SINGLE SENSOR METHOD

Next, some results are presented from other experimental tests to illustrate the source-sensor distance calculation using a single sensor. Arrival times of extensional and flexural modes in each sensor and frequencies of dominant flexural modes were extracted from experimental data and are tabulated in Table 3-2. Distances were then calculated between sensor – source pairs using the relation:

\[
D = \frac{\Delta t \cdot c_1 \cdot c_2}{(c_1 - c_2)}
\]  

(3.3)

where \(c_1\) and \(c_2\) are velocities of different modes and \(\Delta t\) is the time difference in arrival of these modes (same as Equation 2.9). These values are also presented in
Table 3-2, along with the exact distance of each source from the three sensors. In most data, dominant flexural modes with highest amount of energy (derived from STFT and wavelet analyses) had frequencies in 140-170 kHz range. The arrival time of the hit triggering SH mode was 257 μs in all cases, as pre-trigger recording of 256 μs was set during the experiments, as discussed earlier. The velocities of extensional, flexural and threshold hitting SH mode were taken as 5200 m/s, 2800 m/s (average value for the range 140-170kHz) and 3218 m/s respectively.

As seen in Table 3-2, the use of velocities and differences in times of arrival of extensional and flexural wave modes (or extensional and SH modes) in a single sensor to calculate distance between the sensor and the source generally gives good results. Average absolute errors between exact and calculated distances are about 0.04 m in both cases while relative errors are about 4 %. This compares well with the results documented in [97], where relative errors of 8-14 % are found for AE source location using one sensor and two components. Using this approach, it is possible to use only two sensors to find source location on two-dimensional surface (for example, by calculating the intersection of two circles with the distance travelled as the radius and the sensor location as the centre).

Table 3-2: Calculation of distance between source and sensor using velocities of modes recorded by single sensor

<table>
<thead>
<tr>
<th>Source Position (m)</th>
<th>Exp. no.</th>
<th>Sensor</th>
<th>Arrival time of extensional (EXT) mode (μs)</th>
<th>Arrival time of flexural (FLX) mode (μs)</th>
<th>Frequency of FLX mode (kHz)</th>
<th>Actual distance between source and sensor (m)</th>
<th>Distance using EXT and hit triggering SH mode (m)</th>
<th>Distance using EXT and FLX modes (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.6,0.6)</td>
<td>1</td>
<td>S1</td>
<td>155</td>
<td>300</td>
<td>160</td>
<td>0.85</td>
<td>0.85</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S2</td>
<td>153</td>
<td>300</td>
<td>152</td>
<td>0.85</td>
<td>0.87</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S3</td>
<td>106</td>
<td>303</td>
<td>160</td>
<td>1.20</td>
<td>1.26</td>
<td>1.20</td>
</tr>
<tr>
<td>2</td>
<td>S1</td>
<td>151</td>
<td>298</td>
<td>160</td>
<td>0.85</td>
<td>0.88</td>
<td>0.88</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>151</td>
<td>303</td>
<td>152</td>
<td>0.85</td>
<td>0.88</td>
<td>0.88</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>104</td>
<td>300</td>
<td>160</td>
<td>1.20</td>
<td>1.27</td>
<td>1.19</td>
<td></td>
</tr>
</tbody>
</table>
### 3.4 CONCLUDING REMARKS

In this study, the modes of AE waves in plate-like structures were identified using time-frequency analysis approach. Tests carried out in a thin steel plate were analysed using the developed method and it was found more accurate location can be obtained by using the velocities of a particular identified mode. Also, the model used the velocities and differences in times of arrival of extensional and flexural wave modes to calculate source location accurately by using a single sensor.

Main findings of this chapter can be summarised as follows:

- Results show that using fixed threshold amplitude and the time of hit is not always successful in accurately determining the source location and it may be necessary to study waveform and its frequency components to identify the recorded mode and use its velocity.
Simultaneous time-frequency representation of signals by means of short time Fourier transform and wavelet analysis provides excellent ways to identify the wave modes. This becomes more significant when some modes may be lost among the noises with increasing sensor to source distance.

Reflected wave patterns could also be seen in the waveforms. This raises one significant problem with AE modal analysis, which is distortion of the signals due to wave reflections from the edges of the plate as well as mode conversions. Hence, even though identification of early arriving modes is easy, late arriving modes are often hard to identify accurately. One option is placing sensors away from the edges, but some reflection is inevitable.

Flexural mode is easier to identify than weaker extensional mode and often travel longer distances, hence the use of flexural modes for source location is an attractive option. But it is necessary to identify the time of arrival of the same frequency component at all sensors and excessive signal reflections from the edges make it harder.

Although waves reflections from the edges was of major concern, three patterns were consistently present in initial parts of the waveforms analysed: low amplitude (weak) fast arriving waves, threshold hitting waves and high energy late arriving ones, which were then identified as extensional modes, SH modes and flexural modes respectively. SH modes (horizontally polarised S wave) which are non-dispersive in nature and travel with constant velocity have been predicted in similar studies by Dunegan [95].

Use of the extensional mode in source location calculations gave very accurate results. Extensional modes are early arriving components and are free from the effects of the reflected waves; hence it is believed their use is best for source location calculation.

Setting of a lower threshold could have identified the arrival of the earlier, smaller amplitude mode. But setting of lower threshold would pick low amplitude noise signals. As discussed previously, even though the experiments in this study were carried out in fairly noise free environment; in
actual practical applications noises are present and too low threshold would contaminate the recorded signals.

- It is found that only initial short duration signal is useful for analysis, but this is not a serious disadvantage as AE from crack like source is often transient in nature with short rise time (time between triggering of hit and highest amplitude). Further, calculations performed were manual but automatic is desirable especially for long term remote monitoring applications.

- Use of a single sensor to find the distance from the source is an attractive option and it is possible to extend this idea to two-dimensional case by using two sensors.

- Use of STFT to study energy distribution in signals and applying this information to identify signal reflection and possible noises; use of extensional mode in source location calculations; and study of the presence of SH modes are some of the novel contribution of this work compared to previous works in this area.
Chapter 4: Source identification and discrimination

This chapter describes the developed model, experimental setup, results and subsequent analysis carried out to achieve the second objective stated in Chapter 1, namely effective analysis of acoustic emission data to achieve accurate source identification and differentiation. Section 4.1 provides the plan of study and description of the proposed model. Section 4.2 discusses the experimental setup, instrumentation and settings in detail. Section 4.3 provides the results and discussion on the results. Finally, Section 4.4 summarizes the main findings of the study.

4.1 PLAN OF STUDY AND PROPOSED MODEL

As discussed in Chapter 2, some common sources of spurious AE signals in big civil infrastructure are impacts and rubbing of different components and they can mask genuine crack growth related signals. Therefore, it is very important to have techniques for signal discrimination. This study proposes a model that uses following tools in order to discriminate signals from different sources:

a) Signal uniqueness and similarity

As discussed in Section 2.10.2, comparing similarity of signals can be used as a tool for signal discrimination. As manual checking of similarity can be tedious and in cases of large number of signals can be impossible, in this study the following tools are used to check if two signals are similar or not: the cross-correlation coefficients in time domain and magnitude squared coherence (MSC) in frequency domain. The cross-correlation coefficients give a measure of the similarity of two time series shifted along each other, with the maximum value indicating the maximum correlation of the two signals at certain time shift [98, 99]. Mathematically, the cross-correlation function relating two signals \( f_1(t) \) and \( f_2(t) \) can be written as:

\[
r_{xy}(\tau) = \int_{-\infty}^{\infty} f_1(t) \cdot f_2(t + \tau) \cdot dt
\]

(4.1)
where \( \tau \) is a time-shift imposed upon one of the signals and cross-correlation function \( r_{xy} \) is a continuous function of the imposed time-shift \( \tau \) [100].

Similarly, MSC of two signals is calculated using power spectral densities \( (P_{xx} \text{ and } P_{yy}) \) and cross power spectral density \( (P_{xy}) \) of the signals as follows [44, 48]:

\[
C_{xy}(f) = \frac{\left| P_{xy}(f) \right|^2}{P_{xx}(f) \cdot P_{yy}(f)}
\]

(4.2)

For two identical signals, MSC value of 1 is obtained over the whole frequency range, while lower values occur for unrelated signals.

**b) Energy distribution in different frequency bands**

Performing short-time Fourier transform (STFT) on recorded signal results in a matrix of coefficients, \( C(\omega_i, \tau_j) \), by discretization in both frequency \( (\omega) \) and time \( (\tau) \) domains. \( |C(\omega_i, \tau_j)|^2 \) can then be used to represent energy contents (spectral density) of the signal in joint time and frequency domains, with the resulting plot known as spectrogram. To study energy distribution with frequency, energies across the total time are then summed and the values normalized with respect to the total energy across all times and frequencies, as follows:

\[
E(\omega) = \frac{\sum_{j=1}^{N} C(\omega_i, \tau_j)}{\sum_{i=1}^{M} \sum_{j=1}^{N} C(\omega_i, \tau_j)}
\]

(4.3)

where \( M \) and \( N \) are number of discretisation in frequency and time domains respectively. \( E(\omega) \), representing the energy ratios against frequencies, can then be used to study the energy distribution in different frequency bands. Though energy-frequency analysis can be done using Fourier transform alone, it is noted that study of simultaneous time-frequency distribution conveys important information regarding signal discrimination.

**c) Modal analysis for source differentiation**

In addition to accurately locating the source, modal analysis can provide information about the nature of the source generating the waves. Different sources produce signals dominated by a particular mode, for example, sources acting in the
plane of a material such as crack growth will produce signals with large extensional mode whereas out-of-plane sources such as friction and noise will produce signals with more flexural components [95, 101]. Hence, comparison of the amplitudes of the modes can yield valuable information regarding source type [17, 102].

For uniqueness analysis, pencil lead breaks and ball drops are used as two sources of AE. Source discrimination is attempted using cross-correlation, magnitude squared coherence and energy distribution. Furthermore, it has been mentioned in past studies that recorded AE waveforms are influenced by three factors: source type, sensor characteristics and medium of propagation [103, 104]. Hence, in addition to the first experiment that deals with the effects of source type, the next tests will attempt to study the effects of distance of propagation and sensor type on the signal waveforms recorded.

For modal analysis, crack like signals (in-plane) and impact like signals (out-of-plane) are simulated by performing PLBs on the surface and the edge. In addition to AE signals from crack, two other common sources of AE in structure such as bridges are rubbing and impacts between two members. Rubbing and impact type AE signals are simulated in laboratory and signals from real crack are obtained from three point bending tests of steel specimens. Using the three tools described above, discrimination of the recorded signals is attempted.

4.2 EXPERIMENTATION

4.2.1 UNIQUENESS ANALYSIS FOR TWO SOURCES OF AE SIGNALS

Two sources of AE signals were generated by (a) breaking 0.5 mm pencil leads and (b) dropping steel balls (6 mm diameter) from a height of 15 cm on a 4 m long steel beam. Experimental setup can be seen in Figure 4-1. As discussed earlier, breaking pencil lead is a standard method for simulating acoustic emission signals as it provides a fast rise time or step function like transient force similar to real AE sources and easily reproducible signal waveforms [22]. Also, as discussed earlier in Section 3.2, in order to bring uniformity to the tests, equal lengths of pencil leads were broken while holding the pencil at the same angle to the surface using a circular Teflon ring around it. While pencil lead breaks were used to simulate crack like signals, ball impacts were done to simulate impacts of two components - another
common source in real life applications. Ten sets of each type were carried out. Breaking pencil leads and dropping steel balls on the surface of a specimen are common ways of simulating AE signals and are used in a number of other studies, such as [91, 105-107].

A four channel µ-disp PAC (Physical Acoustics Corporation) system was used for data acquisition. Two R15α sensors (manufactured by PAC, resonant at 150 kHz) were placed at distances of 1.5m and 3 m (named S1 and S2 respectively) from the source location to record the AE signals. The sensors were coupled to the test specimen using vacuum grease and magnetic holders. Preamplifiers were used along with the sensors with gain set at 40 dB. (AE dB is calculated as: \( dB = 20 \log \left( \frac{V}{V_{ref}} \right) \), where reference voltage \( V_{ref} = 1 \, \mu\text{V} \).) The signals were bandpass filtered between 20-400 kHz using the software control of the data acquisition system, as most signals were expected in this range. For each hit, data was acquired at a sampling rate of 1 MHz (one sample per 1 μs) and recorded for a duration of 15 ms. A threshold value of 60 dB was set for initiation of the recording process. Though experimental conditions were relatively noise free, the higher value of threshold was used as in real life testing significant noises could be present, thereby requiring higher threshold value.

![Experimental set-up for simulation of two sources](image)
Recorded signals were then analysed to investigate if the signal parameters and different signal processing tools could accurately differentiate signals from the two sources. MATLAB (2009, The MathWorks, Natick, MA) commands ‘xcorr’ and ‘mscohere’ were used to calculate cross-correlation coefficients and magnitude squared coherence of the signals respectively. The command ‘xcorr’ (with option ‘coeff’ to normalise the sequence) gives the value of 1 for two identical signals in time domains, whereas ‘mscohere’ gives values lying between 0 and 1 which indicate how well two signals correspond to each other at each frequency; with the value of 1 indicating exact match [44]. Maximum cross-correlation values and average MSC values in frequency range of 20 kHz to 400 kHz were used to check signal similarity.

4.2.2 STUDY OF THE DISTANCE OF PROPAGATION AND SENSOR CHARACTERISTICS ON SIGNAL WAVEFORMS

Next sets of experiments were carried out to study the effects of the distance of propagation and sensor characteristics on the recorded signal waveforms. It is assumed that in all cases that coupling of the sensor to the surface is identical and therefore there are no additional effects due to coupling.

Effect of distance of wave propagation on signal waveforms

An R15α sensor was placed on the surface of a long steel beam (dimensions: 1m x 25 mm x 5 mm) and was used to record ten pencil lead breaks carried at a distance of 15 cm away. The same sensor was then moved so that the distance of propagation changed to first 30 cm and then 45 cm, see Figure 4-2. Ten pencil lead breaks were carried out for each location.

![Figure 4-2 Setup: same sensor to record similar signals at three distances in a rectangular beam (X- location of AE source, circles – sensor positions)](image)


Effect of sensor types on signal waveforms

Four sensors: two R15α, one R6α (resonant type sensor developed by Physical Acoustics Corporation, resonant frequency 60 kHz, operating frequency range 35-100 kHz) and one WSα (broadband sensor developed by Physical Acoustics Corporation, operating frequency range 100-900 kHz), were placed at the four corners of a steel plate and pencil lead were broken at the middle of the plate (thus equidistant from all sensors).

4.2.3 MODAL ANALYSIS OF IN-PLANE AND OUT-OF-PLANE AE SIGNALS

To simulate in-plane and out-of-plane sources, PLBs were performed on the edge and on the surface of one end of a C-beam, see Figure 4-4. Two R15α sensors placed at the distances of 0.5 m and 2.5 m from the edge were used to record the AE signals and five tests were carried out for each type. The signals were then analysed to identify the modes, using time-frequency analysis tool and difference in arrival times of the signals at the two sensors.
Figure 4-4 (a) Simulation of in-plane (denoted by ‘x’) and out-of plane (denoted by ‘*’) sources, (b) Dimensions of the C beam

4.2.4 ENERGY DISTRIBUTION IN FREQUENCY BANDS FOR DIFFERENTIATION OF THREE COMMON TYPES OF AE SIGNALS

**AE signals from real crack**

AE signals from real growing crack were collected from three point bending test of a rectangular steel specimen - 300 mm long, 25 mm wide and 10 mm thick, with a small $45^\circ$ through cut notch in the middle to initiate the crack growth, using a INSTRON tensile machine with a 50 kN load-cell (at a loading rate of 2 mm/min), see Figure 4-5. Four channel micro-disp PAC (Physical Acoustics Corporation) system was used for data acquisition. Two R15α sensors (manufactured by PAC, resonant at 150 kHz) were placed at two ends of the specimen to collect AE signals. The sensors were coupled to the test specimen using vacuum grease and magnetic holders. Preamplifiers were used with gain set at 40 dB. The signals were bandpass filtered between 20-400 kHz using the software control of the data acquisition system, as most signals were expected in this range. To set the threshold value for recording and ensure sensors were performing correctly, pencil lead breaks (5mm, HB leads) were carried out near the crack tip and recorded signals were observed. The value of 60 dB was decided as this value was found to prevent the recording of lower amplitude reflected signals from the pencil lead break tests as well as remove
low amplitude signals generated at the loading point from the roller directly above the crack during a trail test.

Figure 4-5 Intron Tensile testing machine used for three point bending

AE signals from impacts

Impact signals were simulated by dropping steel balls (6 mm diameter) from a height of 15 cm on the middle of a thin steel beam (4m long, 75mm wide, 5 mm thick). An R15α sensor was placed at a distance of 1 m from the impact location to record the signals. Instrumentation and settings used during the experimentation are identical to the ones used for the three point bending tests.
**AE signals from rubbing**

Rubbing was simulated by allowing a steel piece (200x135x12 mm$^3$) to slide along an inclined steel beam (920x300x10mm$^3$) resting on a laboratory jack, with two sensors placed underneath the inclined beam, see Figure 4-7. To get rubbing AE signals, the angle of incline of the beam was slowly raised till the piece started to slide using the adjustment screw in the jack. The angle of incline was found to be 29.3° when sliding started, giving the coefficient of friction to be 0.56. Again, instrumentation and settings used are identical to the ones used for the three point bending tests.
4.3 RESULTS AND DISCUSSION

4.3.1 UNIQUENESS ANALYSIS FOR TWO SOURCES OF AE SIGNALS

*Parameter analysis*

Some common parameters of the AE signals obtained from the two set of experiments recorded by sensors S1 and S2 are given in Table 4-1 and Table 4-2 respectively.

Figure 4-7 (a) Diagrammatic representation of experiment setup to simulate signals from rubbing, (b) Lab jack with adjustable height used adjust height.
Table 4-1: Parameters of signals recorded by S1

### PENCIL LEAD BREAKS

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Table 4-2: Parameters of signals recorded by S2

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From the data in Table 4-1 and Table 4-2, it can be seen that rise times are smaller for PLBs compared to BDs; while other parameters are higher for BDs -
indicating that the ball drops imparted higher energy in the beam compared to the pencil lead breaks. Rough estimates of frequency can be done by dividing counts by duration and give average values of 47 and 45 kHz for PLBs and 37 kHz for BDs. Increase in rise time but decrease in other signal parameters between readings of sensors S1 and S2 is understandable as strength of the signals decreases further they travel from the source.

In summary, analysis of signal parameters shows that PLBs have shorter rise times and higher frequency contents compared to BDs and these parameters can be used as differentiating criteria. This observation agrees with literature where rise-time has been mentioned as possible parameter in distinguishing crack signals from noises. Instead of using rise time, the ratio of rise-time to amplitude (RA) has found use lately [30]. More discussion on frequency contents by means of detailed waveform analysis follows in next section. Some limitations of parameter based approach become evident clearly, for example large variation in rise time values of PLBs in Table 4-1 (ranging from 224 to 369 µs) and rise time value of 804 µs which is much higher than average of 510 µs in Table 4-2 (PLB experiment number 7).

**Waveform analysis**

Typical pencil lead break (PLB) and ball drop (BD) signals recorded by sensor S1 along with their time-frequency STFT representation calculated using Time-frequency toolbox [93] are shown in Figure 4-8 and Figure 4-9 respectively. Only initial 2 ms of data were used for analysis purposes and energy spectra (spectrogram) in logarithmic scales are shown in the figures.
Figure 4-8 PLB signal (upper) along with its STFT representation (below),

Figure 4-9 BD signal (upper) along with its STFT representation (below)

Figure 4-8 and Figure 4-9 show that ball drop signal has higher energy levels but concentrated in lower frequency bands compared to the pencil lead break signal.
Energy distribution in time-frequency domain was then studied for rest of the PLB and BD signals, using formulation described in Equation 4.3. Values of these energy ratios against frequencies for ten PLBs and ten BDs are shown in Figure 4-10 and Figure 4-11 respectively.

![Figure 4-10](image1.png)

**Figure 4-10** Distribution of energy against frequencies for PLB signals

![Figure 4-11](image2.png)

**Figure 4-11** Distribution of energy against frequencies for BD signals
For PLB signals most energy lies around two peak frequencies of 70 kHz and 170 kHz and small peak at 300 kHz. On the other hand, for BD signals energy is distributed around 70 kHz only. Hence, this distinct distribution of energy in different frequency levels can act as a suitable guide for source differentiation.

To study signal uniqueness, the first PLB signal (in Figure 4-8) was used as a template signal to perform cross-correlation and magnitude squared coherence with rest of the signals recorded by the same sensor (MATLAB codes shown in Appendix D). The results are summarized in Figure 4-12.
Two clusters are clearly visible – the cluster with higher values (indicated by ‘+’) correspond to the values from comparison of the template PLB with other PLBs while smaller values (indicated by ‘o’) correspond to the comparison with BD signals. Summarizing the results, cross-correlation of the template PLB signal with remaining nine PLB tests gave an average maximum value of 0.87 (in the range between 0.80 and 0.91) while that value for cross-correlation between the PLB and ten BD signals was 0.48 (in the range between 0.38 and 0.54). Further, the average MSC values of the template PLB with the other PLB signals lie in the range 0.71 – 0.75, while mean MSC values of the PLB signal with other ten BD signals recorded by S1 lie in the much smaller range of 0.25 – 0.35 with a mean value of 0.29.

Similarly, using the first BD signal (in Figure 4-9) as the template signal for comparison, the results shown in Figure 4-13 were obtained.
Chapter 4: Source identification and discrimination

Figure 4-13 (a) Maximum cross-correlation coefficients, (b) Average magnitude squared coherence values between the template BD and rest of the signals.

Again, higher values are seen when comparing the template BD with other BDs (indicated by ‘+’) while smaller values are seen during comparison with the PLB signals (indicated by ‘o’).

A sample plot of cross-correlations between two PLB signals and a similar plot between PLB and BD signals are shown in Figure 4-14. High cross-correlation
(maximum value 0.86) is seen for two PLB signals (Figure 4-14a) while low value of only about 0.3 is seen between PLB and BD signals (Figure 4-14b).

![Cross-correlation between two PLB signals](image)

(a)

![Cross-correlation of PLB and BD signals](image)

(b)

Figure 4-14 (a) Cross-correlation between two PLB signals (b) Cross-correlation of PLB and BD signals

A typical plot of MSC values versus frequencies between two PLB signals and between PLB and BD signals are shown in Figure 4-15a and Figure 4-15b respectively. Figure 4-15a shows closer match of frequencies between the signals in the range 20 - 400 kHz, with an average value of 0.73. On the other hand, Figure 4-15b indicates less coherence in that range, with average MSC value of 0.27.
Figure 4-15 MSC values versus frequencies for (a) two PLB signals and (b) one PLB and one BD signal

Thus, very distinct differences in maximum cross-correlation and average magnitude squared coherence values are seen between signals from like and unlike sources. It proves the suitability of using these parameters as criteria for signal discrimination when a signal from a known source is available as template for comparison.
Comparing signal waveforms recorded by different sensors

Next, cross-correlation analysis was performed between the template PLB signal (same as used before) recorded by the sensor S1 and each of the ten PLBs recorded by the sensor S2. This gave the maximum values of cross-correlation coefficients between 0.13 and 0.17, with a mean value of 0.14. This is even lower than the value of 0.48 obtained in earlier analysis between the PLB and BD signals recorded by the same sensor S1.

Similar analysis was then carried out by calculating magnitude squared coherence between the template PLB signal recorded by sensor S1 with each of the ten PLB signals recorded by sensor S2. The values obtained for average MSC were between 0.16 and 0.2, with a mean value of 0.18. As earlier with the cross-correlation coefficients, this value is lower than the value of 0.29 obtained earlier between PLB and BD signals recorded by the sensor S1.

Energy distribution with frequency (calculated as done previously from STFT spectrogram using formulation in Equation 4.3) for ten PLB and ten BD signals recorded by the second sensor S2 were then studied. They are shown in Figure 4-16 and Figure 4-17 respectively.

![Figure 4-16 Distribution of energy against frequencies for PLB signals recorded by sensor S2](image-url)
Figure 4-17 Distribution of energy against frequencies for BD signals recorded by sensor S2

Both distributions show similarity to the ones seen by the sensor S1, as seen in the Figure 4-18 and Figure 4-19 where averaged values for ten signals for each sensor plotted are against each other.

Figure 4-18 Average values of energy against frequencies for PLB signals recorded by sensors S1 and S2
Thus, different sources signals recorded by same sensor have been found to have higher coherence and cross-correlation compared to same source signals recorded by different sensors at different distances. This shows that sensor characteristics and distance of propagation have effects on resulting signal waveforms. But, among three criteria used in this study, energy distribution with frequency proved better equipped in distinguishing different sources even when recorded by different sensors at different distances.

4.3.2 STUDY OF THE INFLUENCE OF DISTANCE OF PROPAGATION AND SENSOR CHARACTERISTICS ON SIGNAL WAVEFORMS

Energy distributions with frequency for the signals recorded for the tests described in Section 4.2.2 are presented next.
Figure 4-20 Variation of energy with frequency for PLBs in steel beam at three locations using the same sensor.

Figure 4-21 Variation of energy with frequency for PLBs in steel plate for four equidistant sensors.
From Figure 4-20, it is seen that energy distributions with frequency in three cases are mostly similar when the same sensor is used even if the distances of propagation are different. From Figure 4-21, it is seen that energy distributions with frequency for four sensors are different when different sensors are used, even though the source and the distance of propagation are both same. There is some similarity between the same sensor type signals (two R15α sensors - indicated by blue and black coloured curves), especially the regions of peak energy. However, the distribution is very distinct when compared with other sensor types. It is further noted that R6α sensor is active in lower frequency range while WSα is active in wider frequency range, hence energy distribution with frequency is seen to match with the sensor properties.

The results from these tests prove that the sensor type and characteristics play a major role in characteristics of waveforms recorded compared to the distances of propagation of signals.

4.3.3 MODAL ANALYSIS OF IN-PLANE AND OUT-OF-PLANE AE SIGNALS

Typical in-plane PLB (IPLB) and out-of-plane PLB (OPLB) source signals and their time-frequency distribution calculated using STFT toolbox [93] are shown in Figure 4-22. It is noted that due to the length of pre-trigger used, the recorded signals start at 256 μs. The initial arriving mode and the highest energy mode are both highlighted.

The time-frequency plots show squared STFT coefficients, thus representing energy in the signals, and are presented in logarithmic scale for clearer visualisation of the modes. From time domain and time-frequency domain plots, it is clearly seen that the initial arriving modes are different in amplitudes (energies) between in-plane and out-of-plane sources. From time-frequency plots, the frequency of the early arriving mode is found to be around 150 kHz. Most of the signal components including the peak amplitude/energy modes also lie in that frequency region.
(a) In-plane PLB recorded by the sensor at the distance of 0.5 m from the source

(b) Same in-plane PLB as (a) recorded by the sensor at the distance of 2.5 m
Figure 4-22 In-plane and out-of-plane PLB signals along with time-frequency representation

As the difference in arrival times $\Delta t$ of the initial mode at two sensors are recorded by the data acquisition system, it can be used to calculate the speed of this mode, $c$ (assuming constant speed) as follows:
\[ x_1 = ct_1, \quad x_2 = ct_2 \]
\[ c = \frac{x_2 - x_1}{t_2 - t_1} = \frac{x}{\Delta t} \]  

(4.4)

where \( x_1 \) and \( x_2 \) are the distances between the source position and the first and second sensor respectively and \( x = x_2 - x_1 = 2 \) m. The average value of \( \Delta t \) recorded for five IPLBs was 0.0003755 s and that for OPLB was 0.000377 s. Thus, the average velocity of earliest mode can be calculated to be 5303 m/s for the IPLBs and 5305 m/s for the OPLBs.

Dispersion curves can be used to calculate theoretical velocities of Lamb wave modes. Dispersion curves for steel plates of thickness 2 mm are given in Figure 4-23, from which it can be seen that the velocity of 150 kHz extensional mode matches the calculated values of 5303 and 5305 m/s above. Hence we conclude that the initial mode is the extensional Lamb mode.

![Dispersion curve](image)

Figure 4-23 Dispersion curve for plate of thickness 2 mm, S0 – symmetric/extensional mode and A0 – antisymmetric/flexural mode [94]

However, from Figure 4-22, the slower modes are very hard to identify accurately. From analysis of rest of the signals, the mode with peak energy was found to occur at varying time intervals after the initial mode; hence same velocity could not be calculated using the relation in Section 2.10.1 and therefore, it was concluded that the highest energy mode was not flexural mode. Due to the narrow width of the specimen, it is very common that waves get reflected from the surfaces and mix and get superimposed with the actual waves making mode identification harder.

With the inability to identify the flexural mode exactly, another approach was used - comparing the amplitude of the hit triggering initial modes with the maximum
amplitude of the signals. From calculations, the average ratio was 0.7 for the nearer sensor and 0.4 for the farther sensor for edge PLBs (in-plane sources). For surface PLBs, the corresponding values were 0.08 and 0.03 for the two sensors. Thus, very large differences observed show the possibility of the use of ratio of the amplitude of the extensional mode to the peak amplitude for source differentiation purposes. It is noted here that the concept of measured amplitude ratio has been suggested in previous studies such as [17, 102], as discussed in Section 4.1 in Page 81.

**4.3.4 ENERGY DISTRIBUTION IN FREQUENCY BANDS FOR DIFFERENTIATION OF THREE COMMON TYPES OF AE SIGNALS**

Results from 2mm/min loading three point bending experiment (load and cumulative AE hits in one sensor versus time) are shown in Figure 4-24a. Load follow three distinct patterns - first increasing linearly up to around 12 kN, then yielding started with the load reaching a peak of around 18 kN, followed by nonlinear decrease in load till the time the test was stopped. The curve of cumulative AE hits also has varying slopes. The initial slope was very low- occurring when the crosshead hit the specimen, but then the slope steadily increased and mostly followed the trends in the load profile. Once the peak load has passed, there are very few hits though crack growth occurring was observed. The variation in absolute energies of hits with time is shown in Figure 4-24b. Absolute energy is derived from the integral of the squared voltage signal divided by the reference resistance (10k-ohm) over the duration of the AE waveform packet [31]. Signals with highest energy can be attributed to crack growth. Signals with very low energies are likely to have occurred due to reflections of the signals from the edges and can be neglected.
The highest energy signal occurring at around 150 s is shown in Figure 4-25a. Time-frequency analysis is done using short time Fourier transform using Time-Frequency toolbox [93]. Similarly, typical impact and rubbing signals obtained can
be seen in Figure 4-25b and Figure 4-25c respectively. In all plots, the energy values are in logarithmic scale for clarity. To study energy distribution with frequency, ten signals of each type were collected. Energies across the total time (squared STFT coefficients) were summed and the values normalized with respect to the maximum energy as described in Section 4.1. The distribution of energy against frequencies (averaged for ten signals of each type) is shown in Figure 4-26.
Figure 4-25 (a) Typical crack signal and its STFT analysis, (b) typical impact signal along with its STFT analysis, (c) typical rubbing signal along with its STFT analysis

From Figure 4-25, rubbing signals are seen to be of continuous type compared to transient nature of crack signals. Impact signals are also transient but reflections
persist and continue for longer duration compared to the crack signals. Also visible is that energy is concentrated in lower frequency region for the impact signal, while crack and rubbing signals have energies spread out in higher frequency regions – but distribution in frequency is very distinct in the two cases, as for rubbing frequencies occur uniformly throughout the time period.

From energy distribution plot in Figure 4-26, impact signal is found to have frequencies of around 60 kHz. For rubbing signals, two peaks of frequencies of around 70 kHz and 120 kHz are visible. In addition to frequency components of 70 kHz and 120 kHz, another peak of around 200 kHz is present for the crack signal. Thus, distinct distribution of energies with frequencies is found for three main types of AE source signals; hence, this can act as source differentiation criterion.

4.4 CONCLUDING REMARKS

This section has highlighted one of main challenges of AE monitoring technique – the need for source discrimination, and discussed the model developed in this study to perform this task. The model was tested using data from several simulated laboratory experiments. Some important observations and findings from the analysis are summarized below:

- Traditional parameter based method is simple but large variation in data is one of the major drawbacks of this approach. Further, valuable information is missed when whole waveforms are not used for analysis; hence waveform based approach is becoming the more preferred option.

- The basis of waveform based analysis is that recorded signals are often found to be representative of the nature of the source in spite of some inevitable effects due to propagation paths of AE waves and sensor characteristics. Since signals from similar sources should be similar in nature, uniqueness of recorded AE signals can be used as source discriminating criterion.

- If a template signal from a known source is available, it can be compared with subsequently obtained experimental signals using cross-correlation values and average magnitude squared coherence values to perform source differentiation.
• Sensor characteristics play very important role on the nature of signal waveforms; hence for waveform analysis to be successful, it is best to carry out experiments with the same sensor or same type if more than one is required.

• Though study of signal waveforms is beneficial, there are several problems in waveform based approach of data analysis, such as complex nature of propagation of AE waves (due to presence of a number of modes), AE waves undergoing multiple reflections between source and sensor (implying AE waves recorded by a sensor may have travelled along different paths) and distortion of the signals due to resonant nature of sensors used [107]. Hence, a combination of several criteria may be needed in waveform based approach.

• It is often difficult to identify all modes. In this study, in a narrow beam the earliest mode could be identified and verified, but it was hard to identify the late arriving ones. Hence, another technique of comparing the amplitudes of the earliest arriving mode with the maximum amplitudes of the signals was proposed and this is one of the significant contributions of this research work.

• Time-frequency analysis tools such as STFT are valuable in visualizing reflected signals and understanding AE wave modes [108]. Since frequencies were found to lie in a narrow band, variable resolution at different frequency levels (as provided by wavelet analysis) was found unnecessary. Moreover, compared to other tools available for joint time-frequency representation, STFT is simpler and easier to implement [109].

• Crack signals are transient in nature. Impacts also give transient signals but rubbing signals are continuous. Energy distribution in different frequency bands was found to be distinct for these three sources. Hence, this can act as a suitable criterion for distinguishing signals from different sources. However, care is needed to interpret results as there are numerous factors can affect AE signal waveforms, such as dimensions of the medium, the paths the signals travel, signal reflections and mode conversions. It is very difficult to take every factor into account; however, it is believed that energy distribution with frequency can still convey information about the nature of the source.
Chapter 5: Damage quantification for severity assessment

This chapter describes the background, experimental setup, results and subsequent analysis carried out to achieve the third and final objective stated in Chapter 1, namely effective analysis of acoustic emission data to assess severity of the sources using appropriate damage quantification tools. Section 5.1 provides background to the problem and plan of the study. Section 5.2 discusses the experimental setup, instrumentation and settings in detail. Section 5.3 provides the results and discussion on the results. Finally, Section 5.4 summarizes the main findings of the study.

5.1 PLAN OF STUDY AND MODEL USED

In real life testing, large number of AE signals is often present; hence it is impractical to carry out waveform analysis on each recorded signal. A better and practical way is to analyse some of the parameters of the signals such as amplitudes. Furthermore, such analysis can be used to quantify the level of damage to devise a measure for assessment of severity of sources by using tools discussed in Section 2.10.3. As discussed in that section, improved b-value (Ib value) further improves b-value calculation by selecting the amplitude limits of the linear range of the cumulative frequency distribution data of AE. The use of Ib value analysis is increasing and so far has been mainly used for damage quantification in brittle materials such as concrete and rocks [90, 110, 111].

Though promising results have been obtained for brittle materials, to best of the author’s knowledge, very limited work has been done for ductile materials such as steel. Since steel is very common in engineering infrastructures, it is desirable to see the application of Ib value analysis for steel structures. Damage mechanisms and sources generating AE are different in ductile materials compared to brittle materials as discussed in Sections 2.2 and 2.8. Therefore, this section aims to explore the use of Ib value analysis for damage quantification in ductile material like steel.
Three point tensile tests on steel specimens are convenient methods of simulating crack like AE signals in laboratory environment and will be used in this study. Similar tests have been carried out in other studies to study deformation behaviour of ductile material, again as discussed in Section 2.8. The recorded data will then be subjected to \(I_b\)-value analysis to check if the lowest \(I_b\) value corresponds to most severe damage case.

5.2 EXPERIMENTATION

Three point bending tests on rectangular steel specimens - 300 mm long, 25 mm wide and 10 mm thick (with a small 45° through cut notch in the middle to initiate the crack growth), were performed, see Figure 5-1. INSTRON tensile machine with a 50 kN load-cell was used to apply loads to the specimen at loading rates of 1 and 3 mm/min (in addition to the test with loading rate of 2 mm/min carried out earlier, described in Section 4.2.4). Settings and instrumentation details for recording of AE signals for 2 mm/min loading case were described in Section 4.2.4 and identical ones were used for other cases. It is again noted that 60 dB was decided as a threshold value as this was found to prevent the recording of lower amplitude reflected signals from the pencil lead break tests as well as remove low amplitude signals generated at the loading point from the roller directly above the crack during a trail test. The complete loading process and deformation of the steel beam were also recorded by means of a video camera.

For loading rates of 2 mm/min, two further tests were conducted. First test was carried out with an identical specimen, but the loading was stopped when the load reached the peak value. For the next test, a specimen of same dimensions but without a notch was loaded continuously in order to get pure yielding without any crack growth. All tests carried out are summarised in Table 5-1.

Table 5-1 Summary of all experimental setup

<table>
<thead>
<tr>
<th>Loading Case No.</th>
<th>Loading rate</th>
<th>Specimen</th>
<th>Loading time</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1 mm/min</td>
<td>Notched</td>
<td>Till maximum bending</td>
</tr>
</tbody>
</table>
None of the specimens broke during the tests. Loading was stopped when no more significant AE emission were received (except in case V, where AE signals continued to be received and test was stopped when the specimen started to slip).

After completion of the tests, in order to investigate whether the observation of crack surfaces provides more information on sources of AE generation, the surfaces were studied using a scanning electron microscope (SEM), see Figure 5-2. For this, the specimens were first cut into appropriate sizes using Struers Discotom-6 cut-off machine, see Figure 5-3. Before placing the specimens in the scanning electron microscope, the surfaces were polished and cleaned as per guidelines provided with the scanning microscope.

<table>
<thead>
<tr>
<th></th>
<th>Loading Rate</th>
<th>Condition</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>2 mm/min</td>
<td>Notched</td>
<td>Same as case I</td>
</tr>
<tr>
<td>III</td>
<td>3 mm/min</td>
<td>Notched</td>
<td>Same as case I</td>
</tr>
<tr>
<td>IV</td>
<td>2 mm/min</td>
<td>Notched</td>
<td>Till load reached the maximum value</td>
</tr>
<tr>
<td>V</td>
<td>2 mm/min</td>
<td>Unnotched</td>
<td>Same as case I</td>
</tr>
</tbody>
</table>
Figure 5-1 Experimental set up for three point bending tests

Figure 5-2 FEI Quanta 200 Scanning Electron Microscope
(http://www.aemf.qut.edu.au)
5.3 RESULTS AND DISCUSSION

5.3.1 PHYSICAL AND SCANNING MICROSCOPIC OBSERVATIONS

The three specimens (Loading cases I-III) after the completion of the loading are shown in Figure 5-4. As expected, the three underwent different amounts of deformations, with the specimen loaded with 3 mm/min undergoing maximum deflection.
Some observations from the Loading case II (2 mm/min loading in notched specimen) at selected times, showing deformation of specimen and progression of crack, are presented in Figure 5-5. The time when first significant crack was observed to naked eyes was at 410 s.

Figure 5-5 Different stages of damage (2 mm/min case) at selected times of 0, 200, 410, 500, 615 and 720s (clockwise from top left, crack seen at 410s marked)
For Loading case IV, where the loading was stopped after it reached the peak, a very small crack was seen to originate at the notch root, see Figure 5-6.

![Figure 5-6 Specimen after the loading is stopped at the peak (Loading case IV)](image)

Some observations of the fracture surfaces from SEM are presented next in Figure 5-7.

(a) Specimen subjected to 1 mm/min loading (Loading case I)
Chapter 6: Damage quantification for severity assessment

(b) Specimen subjected to 2 mm/min loading (Loading case II)

(c) Specimen with loading stopped at peak (Loading case IV)

Figure 5-7 Observations of fracture surfaces with scanning electron microscope for three specimens
In Figures 5-7a and 5-7b, large number of conclave depressions known as dimples (or half-microvoids) are visible. Also visible in both figures are the darker slag inclusions. Some dimples are also visible in Figure 5-7c, though not as conspicuous as seen previously. However, as the crack has just initiated, no inclusions are visible.

A plastic fracture has been found to occur as the result of the growth and coalescence of microvoids formed during the last stages of deformation and during crack propagation [112]. Hence, the formation of microvoids is a possible source of AE generation in metal deformation. Another source of AE is the fracture of inclusions. However, more detailed and complex analysis is required to sort AE signals arising from different mechanisms and to study the levels of damage from the microscopic study of fracture surfaces. Therefore, this will not be considered further in this study.

5.3.2 ANALYSIS OF LOAD AND AE SIGNAL PARAMETERS

The variations of load with time for three point bending tests of all loading conditions, along with the amplitudes (in dB scale) and absolute energies of the hits, are shown in Figure 5-8 to Figure 5-12. For clear view, only data up to the time of 500 s are included.

It is interesting to note that in Figure 5-5, first signs of crack are visible to naked eyes at only around 410 s, but most of the acoustic emission hits are already found to occur before that time, as seen in Figure 5-9. After this, the load value decreases and the crack continues to grow but new AE hits occur very slowly, showing that most energy is already generated in the phases before the actual crack growth is observed. It is also noted that only small crack growth is visible when the loading was stopped when it reached the peak (Figure 5-6).
Figure 5-8 Variation of force, amplitude and absolute energy with time (1 mm/min)

Figure 5-9 Variation of force, amplitude and absolute energy with time (2 mm/min)
Figure 5-10 Variation of force, amplitude and absolute energy with time (3 mm/min)

Figure 5-11 Variation of force, amplitude and absolute energy with time (2 mm/min, stopped at peak load)
In Figure 5-8 to Figure 5-12, it is seen that the load initially increases linearly and during this elastic region, only few AE with smaller amplitudes and smaller absolute energies arise. After the initial linear region, yielding starts and during this plastic region, load value increases slower than before. Also observed is that, there is a large number of AE signals with higher amplitudes (reaching maximum of around 100 dB) and higher absolute energies in the region of transition between the elastic and plastic deformations. These observations match the results obtained in previous studies discussed in Section 2.8.

Further, in Loading cases I-III, the load value reaches maximum and then starts to drop. During the phases where load is decreasing, very few AE signals are recorded though the crack growth is clearly visible, see Figure 5-5 for 2 mm/min loading case. The initial conclusion is that in ductile metals, origin of plasticity is the main source of AE generation. In case IV, the loading was stopped at the peak and as mentioned earlier, on physical observation very small crack was seen to be present, see Figure 5-6. In case V, with loading on unnotched specimen, the load keeps on increasing and AE continue to occur throughout the loading.
5.3.3 B AND IB VALUE ANALYSIS

*b-value analysis*

For b-value analysis, distribution of the frequency (number) of AE hits with amplitude as well as with that of cumulative frequency were carried out. A sample result for 2 mm/min loading case is shown in Figure 5-13, where the amplitudes of the AE hits ranged from 60 dB (threshold level) to 100 dB.

![Graph showing frequency and cumulative frequency of AE hits against amplitude](image)

Figure 5-13 Frequency (linear, dashed line) and cumulative frequency (logarithmic, solid line) of AE hits against amplitude

b-value is calculated as follows (Equations 2.15-2.18):

\[
b' = \frac{(3.4)/(100-60)}{} = 0.095 \text{ (See Figure 5-13 for values)}
\]

\[
b = 20 \times b' = 1.9
\]

It is observed from Figure 5-13 that the cumulative distribution does not show linearity in the whole range of amplitudes, but only in the earlier or middle portion. Similar trends were seen for other loading cases as well. Hence, Ib value is preferred over b-value as for former only linear region is selected for calculation of the slope, using the mean of the amplitudes and the standard deviation.
Ib-value analysis

Ib-value analysis was performed to calculate the slope value in the linear region, using the formulation described in Equations 2.19 and 2.20. Instead of performing analysis for total number of events, it is better to do it for a set of certain number of events and plot the Ib value with time, as this provides the information of damage severity throughout the testing. Calculations were performed using sets of 100 events with a lag of 20 events as done in [110] – that is, the Ib value is first calculated for the group of the events 1-100, then 21-120, followed by 41-140 and so on. A sample calculation of Ib value for the first set of 100 events of 1 mm/min loading is presented next; see Figure 5-14. It is noted that final Ib-value is calculated by multiplying the slope by 20 to make it compatible with b-value analysis as suggested in [89].

Sample calculation of Ib value

\[ \mu = 70.72 \text{ dB} \quad \text{Mean of amplitude values} \]

\[ \sigma = 8.69 \text{ dB} \quad \text{Standard deviation of amplitude values} \]

\[ a_2 = 71 \text{ dB} \quad \text{Amplitude just higher than } \mu \]

\[ a_1 = 62 \text{ dB} \quad \text{Amplitude just below } \mu - \sigma \]

\[ N_2 = 43 \quad \text{Total number of events with amplitude } \geq a_2 \]

\[ N_1 = 90 \quad \text{Total number of events with amplitude } \geq a_1 \]

\[ Ib' = \frac{\log_{10}(N_1) - \log_{10}(N_2)}{(a_2 - a_1)} = 0.0356 \]

\[ Ib = Ib' \times 20 = 0.7128 \]
Figure 5-14 Cumulative frequency of AE hits with amplitude (for first 100 set of events of 1 mm/min loading case)

Ib-value analysis was then performed for all five loading cases and the results showing the variation in Ib-value with time are shown in Figure 5-15. MATLAB codes are shown in Appendix D.
Chapter 6: Damage quantification for severity assessment

(b)

(c)
It is observed from the plots in Figure 5-15 that the lowest Ib values are in the range of 0.45-0.55 and occur when transition from elastic to plastic deformations occur or at early stages of plastic deformation as seen in Figure 5-8 to Figure 5-12. For three loading rates of 1, 2 and 3 mm/min on notched specimens, the times of
occurrence of the lowest Ib values vary as shown in Figure 5-16. As expected, higher the loading rate, earlier the lowest Ib value occurs.

![Graph showing variation of the time of occurrence of lowest Ib value with the loading rate](image)

Figure 5-16 Variation of the time of occurrence of lowest Ib value with the loading rate

As the regions of transition between elastic and plastic deformations have been previously found to be the areas of significant AE generation, the occurrence of lowest Ib value has provided an accurate indication of damage occurrence. Further, higher activity (large number of AE events per time) and higher intensity events (events with higher amplitude/energy) are also seen around the same time. These observations further prove that the instance of damage initiation is predicted by the lowest Ib-value.

**Study of physical processes of AE generation to study fluctuation in Ib values**

Previous works on Ib value have indicated that there is a physical AE source generation explanation for all rapid changes in Ib value. Growth and coalescence of microvoids formed during the last stages of deformation and during crack propagation are sources of plastic deformation which in turn results in large number of AE signals. As most AE signals were generated near plasticity region, we
conclude that AE generation is due to the microvoids, and therefore this is likely source for occurrence of the lowest Ib values. Another source of AE is the fracture of inclusions and this may be responsible for fluctuations in AE generation and hence rapid changes in Ib values. The scanning electron microscope pictures (in Figures 5-7) show presence of both microvoids and slag inclusions; therefore these events are some of the likely sources for AE generation, thereby affecting how Ib-values change during loading. However, finding exact source of AE generation at different stages of loading and finding exact reason for fluctuation in Ib values are both very complex and outside the scope of this thesis. Some recommendations for possible future work will be presented in the conclusion of this chapter.

5.3.4 COMPARISON WITH OTHER METHODS

As discussed in Section 2.10.3, history and severity analysis are other methods used for damage quantification. The results from Ib analysis are next compared with the results from history and severity analysis, calculated using Equations 2.13 and 2.14. The plots of Ib value, history index, H(I) and severity index Sr with time (shown only up to 200 s) are presented in Figure 5-17.
Figure 5-17 Comparison of the results from lb value analysis with history and severity analysis for (a) 1 mm/min, (b) 2 mm/min, and (c) 3 mm/min loaded specimens
The highest value of history index $H(I)$ and steepest change in severity index $S_r$ are found to occur well before the lowest $I_b$ value in all three cases. Hence, $I_b$ value analysis seems to be better criterion to judge the severity of sources. It is noted that this discrepancy may be due to the fact that both $H(I)$ and $S_r$ depend on empirical values and for calculations previous values mentioned in literature were used.

5.4 CONCLUDING REMARKS

This section has explored damage quantification in steel structures using improved $b$-value technique. Some important observations and findings from the analysis are summarized below:

- Though several tools have been applied for damage quantification for assessment of severity of AE sources, not all of them have received approval in all cases. Rather than analysing the amplitudes of the signals, amplitude distribution has been found to convey more information about the damage level. Hence, tools studying the amplitude distribution such as $b$-value analysis and improved $b$-value analysis have great potential.

- Furthermore, statistical analysis by means of $b$ value and $I_b$ value are good ways to judge damage progression when a large number of signals are present and it is not possible to analyse waveforms individually.

- Most studies on the use of $I_b$-value have so far been done in brittle materials such as concrete and rock, where values of around 1 have been seen at around the fracture point. But mechanisms of AE generation vary between brittle and ductile materials, where plastic deformation rather than fracture is the primary source of AE.

- The minimum values of around 0.5 occur at around the yielding point; hence this value can act as a suitable guide in further testing as a precursor of damage, which in case of ductile materials is the initiation of plastic growth.

- It is necessary to perform extensive experimentation with specimens with different dimensions, material properties and loading cases to come up with accurate values and this is recommended for future work. In this study thicker ductile beams were used which did not crack but continuously
deformed. Hence focus of Ib value analysis was its suitability for plasticity analysis and the minimum Ib values (of around 0.5) were found to indicate the earlier stages of plastic deformation. Further tests are recommended on brittle materials as well as thinner specimens, so that behaviour can be studied during events of fracture.

- Fatigue crack tests should also be carried out as they represent more realistic crack growth scenario. AE signals from such tests can be analysed using the Ib value algorithm developed in this study.

- In this study, we attempted to study the physical process responsible for AE generation by studying fracture surfaces using scanning electron microscope. However, surfaces at only two stages were studied: one after the loading had caused significant bending of the beam and another after stopping the test when crack initiated. Hence, scope exists for more detailed analysis of physical processes by stopping tests at different instances and studying the grain boundaries and fracture surfaces. This will also shed more light on the occurrence of rapid changes in Ib values.
Chapter 6: Application in scale bridge model

6.1 INTRODUCTION

This section aims to apply some of the tools developed in previous sections to demonstrate the practical use of AE technique in real life monitoring scenario. For this purpose, some tests were carried out in a scale model of truss bridge\(^1\) in Queensland University of Technology laboratory, see Figure 6-1. Three sensors placed in three different locations of the bridge are also shown in Figure 6-1.

![Scale bridge model with three sensors attached](image)

Figure 6-1 Scale bridge model with three sensors attached (S1, S2, S3)

AE signals were first generated by pencil lead breaks (PLB) on selected locations of the structure to simulate crack like signals. Two sets of five PLBs were

\(^1\) Designed by Mr Craig Cowled, PhD research scholar, Queensland University of Technology.
carried out on gusset plates while two other sets were carried out at beams, on locations marked in Figure 6-2. Next, impact signals were simulated by lifting the cross-bracing to maximum allowable height and then allowing it to impact the horizontal beam (five times); location is again marked in Figure 6-2. Nomenclature and specifications of different components of the bridge are given in Figure 6-2 and Table 6-1.

![Figure 6-2 Locations of AE source (X 1,2,3,4- PLBs, O-Impact) and nomenclature of some components of the scale model bridge](image)
Figure 6-3 Gusset plate (location of source 1) along with bolted connections

Table 6-1 Dimensions of some members of the scale bridge model

<table>
<thead>
<tr>
<th>Structural components</th>
<th>Section type</th>
<th>Length (mm)</th>
<th>Cross-section dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top chord</td>
<td>Square hollow</td>
<td>450</td>
<td>20 x 1.6</td>
</tr>
<tr>
<td>Bottom chord</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical web</td>
<td>Square hollow</td>
<td>900</td>
<td>20 x 1.6</td>
</tr>
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<td>Diagonal web</td>
<td>Square hollow</td>
<td>1006</td>
<td>20 x 1.6</td>
</tr>
<tr>
<td>Vertical web at support</td>
<td>Square hollow</td>
<td>1800</td>
<td>30 x 3.0</td>
</tr>
<tr>
<td>Horizontal beam</td>
<td>Square hollow</td>
<td>900</td>
<td>50 x 2.0</td>
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<tr>
<td>Cross-bracing</td>
<td>Flat bar</td>
<td>1273</td>
<td>20 x 3.0</td>
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<tr>
<td>Gusset plate</td>
<td>Flat bar</td>
<td>110</td>
<td>75 x 3</td>
</tr>
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</table>

6.2 RESULTS

*Pencil lead break signals*

Pencil lead break signals generated at location 1 as recorded by three sensors are shown next in Figure 6-4.
Figure 6-4 PLB signals recorded by three sensors S2, S3 and S1, along with times of arrival (red dashed line indicates threshold)

A sample frequency analysis of signal in Figure 6-4a by means of Fourier transform is presented in Figure 6-5, where frequency contents are mainly seen in the range between around 60 and 200 kHz.
From values of differences in times of arrival and appropriate speed of wave modes, locations can be calculated. The values of times of arrival at different sensors for all tests are tabulated in Table 6-2. The values are omitted if recorded by only one sensor; as difference in arrival times is needed for source location calculations and that requires recording by two sensors.

Table 6-2 Times of arrival of the signals at the sensors (in seconds, SN- recording sensor number, no times given when recorded by single sensor)

<table>
<thead>
<tr>
<th>Exp No.</th>
<th>SN</th>
<th>PLB 1</th>
<th>SN</th>
<th>Impact</th>
<th>SN</th>
<th>PLB2</th>
<th>SN</th>
<th>PLB3</th>
<th>SN</th>
<th>PLB4</th>
</tr>
</thead>
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<td>2</td>
<td>33.751307</td>
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<td>2</td>
<td>5.40806225</td>
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<td>1</td>
<td>5.8522045</td>
<td>1</td>
<td>4.736294</td>
<td>3</td>
<td>5.70653825</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Here, the reverse calculations were performed - by using the known distances of three sensors from the source (0.35 m, 0.08 m and 0.76 m for sensors 1, 2 and 3 respectively for PLBs at location 1), the velocities of the AE waves were calculated. One dimensional source localization principles discussed in Section 2.10.1 were used here and velocity is calculated by modifying Equation 2.2.

$$c = \frac{D - 2L_1}{\Delta t}$$  \hspace{1cm} (6.1)
where $D$ is the distance between the sensors, $L_1$ is the distance to the closest sensor and $\Delta t$ is the time difference in arrival.

For first PLB source at location 1, times of arrival were 33.751307s, 33.75140025s and 33.75146175s for sensors S2, S3 and S1 respectively.

For S1-S2 combination, $c = (0.84-2\times0.08) \text{ m/s} / (33.75146175-33.751307) \text{ s} = 4394 \text{ m/s}$.

Similarly, for S1-S3 combination, $c = (1.11-2\times0.35) \text{ m/s} / (33.75146175-33.75140025) \text{ s} = 6666 \text{ m/s}$.

Also, for S2-S3 combination, $c = (0.43-2\times0.08) \text{ m/s} / (33.75140025-33.751307) \text{ s} = 2895 \text{ m/s}$.

Hence, large variation is seen among the velocity values calculated. Other PLB calculations yielded similar values with wide range.

It was also observed that PLBs at location 3 were recorded by all three sensors, but in two different orders: Sensors 1-2-3 in two cases and Sensors 1-3-2 in three cases. PLB signals at location 4 were recorded by sensor 1 in all cases and sensor 2 in two cases, but not by sensor 3. The maximum distance travelled by waves when recorded by sensor 2 is 1.456 m (PLB at location 4, length of diagonal web and bottom chord), travelling through four sets of bolted connections. This indicates AE signals are capable of travelling considerable distance through a number of different components. However, it is also noted that the signals were recorded by Sensor 2 in only two out of five classes, so some randomness prevailed.

**Impact signal**

A sample impact signal and its FFT can be seen in Figure 6-6.
It was observed that the impact signals were weak and recorded by only one sensor (S2); hence, time difference between two sensors could not be obtained and source location calculation could not be performed. From frequency analysis the peak amplitude was found to be very close to 0 kHz, implying that the signals recorded could be vibration signals.

Figure 6-6 (a) Sample impact signal, and (b) its FFT
6.3 DISCUSSIONS AND CONCLUSION

The main aim of the study described in this chapter was to test AE monitoring in a simple setting that resembles real life situation. The main findings from this study can be summarised below:

a) AE signals were found capable of passing through the connections between two joined components, even though it was hard to ascertain how much was through the bolts or through the contacts of two surfaces.

b) Large variation in calculated velocities shows complexities in wave propagation once the signals cross the interface between two surfaces or through the bolts.

c) AE signals could travel long distances, so with availability of a system with large number of channels, a whole structure or a large part of it can be monitored. The sensor that receives the signal first is closest to the source of emission and its vicinity can be checked for further damage analysis.

d) It was hard to identify the wave modes though time-frequency analysis. Recorded signals can be affected by reflections from the edges as well as by distortions of the modes once they pass through the bolted connections and welds and these may mode identification hard.

e) Crack like and impact signals had different waveform shapes, amplitudes and frequency distribution, hence could be distinguished easily.

f) Some vital differences with previous applications in plates and beams become evident - uncertainty in path of travel of AE waves and some randomness in data were observed.

To conclude the chapter, it can be said that practical use of AE technique in real life monitoring of structures such as bridges has many challenges. Weld repairs, edges of bolt and rivet holes and connected areas are the locations in a bridge mainly likely to experience cracking [69], so for monitoring these areas should be focussed upon. Complex shape of structure can change wave propagation pattern and how waves travel through bolted connections or surfaces in contact is not entirely clear, hence more investigation is recommended in this area.
Chapter 7: Conclusions

7.1 CONCLUSIONS

Aging infrastructure and the financial burden on replacing and maintaining them has compelled engineers and researchers to investigate tools to assess current state and detect damage as early as possible. Acoustic emission technique is one technique that has received considerable interest as a non-destructive testing tool. Ability to detect crack at earliest phase due to very high sensitivity to crack growth is the most attractive feature of this technique. Due to high frequency of the acoustic emission signals, data burden is often large; hence finding ways to analyse the large volume of data to extract meaningful information is a big challenge and has become an active area of research lately. Some of the desired information includes finding the location of damage accurately; identifying different sources of emission and being able to differentiate real signals from spurious noises; and devising ways to quantify the level of damage so that level of severity can be assessed.

This study focussed on these three issues and developed tools by intelligently combining different signal processing methods. These three areas were discussed in Chapter 2 under the challenges and treated separately in Chapters 4, 5 and 6. General analysis approaches included parameter based, waveform based and statistical analysis based tools. Main findings from experimentation, data analysis and model development of each of the main issues have already been presented at the end of the chapters. To summarize all the findings, the following comments can be made:

a) From literature review it is clear that AE propagation in thin plate like structures is complicated because of dispersive nature of AE waves. Hence this study aimed to analyse AE wave modes in thin plates and devised methodology to identify AE modes and use their velocities to achieve more accurate source localization results compared to traditional methods. The findings are applicable in other areas as plate like structures are common in civil, aerospace and other applications. Use of STFT to study energy distribution in signals and applying this information to identify signal reflection and possible noises; use of extensional mode in source location
calculations; and study of the presence of SH modes are some of the original findings of this work.

b) Different tools were proposed and used for source differentiation purposes. The study has confirmed that identification of AE wave modes not only helps in accurate source location but comparison of their amplitudes also help in distinguishing in-plane sources such as crack growth from out-of-plane sources such as impacts. In addition, the use of coherence and cross-correlation functions and energy distribution in different frequency bands using short time Fourier transform can become suitable diagnostic tools to discriminate signals from different sources.

c) In real life monitoring of bigger structures, recording and analysis of all waveforms can be tedious. Hence, statistical approaches such as b-value analysis or its improved version become necessary. The analysis of distribution of AE signal amplitudes by means of improved b-value can act as a suitable damage quantification tool for steel structures. This study has found that yielding in ductile material like steel, which is the instance of damage initiation, can be predicted by the lowest Ib-value. Ib-value analysis has previously been used for brittle materials; hence by exploring the use in ductile material and obtaining promising results, this study has laid foundation for further detailed work in future. However, damage quantification is one of the biggest challenges in AE technique; as mechanisms of AE generation, propagation of AE waves and recording of the signals can differ depending on a wide number of factors; some of which include - different monitoring environments, shapes and sizes of the monitored structures and other factors such as sensor selection. It is further noted that research is being carried all around the world to achieve more accurate and viable solutions for quantification purposes.

d) Though no tests could be done in a real life structure, some tests carried out in scale bridge model provided some interesting results. Transmission of AE waves can occur through bolted connections, though this leads to complication with wave velocity calculation.

As final remarks, it can be said that the overall outcome of this research is utilisation of simulated and real acoustic emission sources to develop tools that intelligently combine several signal processing and analysing methods in order to accurately locate the damage source, discriminate different sources of damage and
assess the severity of sources. It is believed that the use of these tools will help make the use of AE technique more promising for structural health monitoring applications.

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Some recommendations for future work are presented next:

- Application of the techniques proposed in this study for real life monitoring purposes should be the main focus of future work. Though some tests were planned, due to time constraints they could not be carried out and all experiments are laboratory based. Tests were carried out to mimic real life conditions; hence it is believed the techniques discussed here are readily applicable in the real life scenario. Environmental factors, added complexity in shape and size of structures and presence of a wide range of AE sources can bring added challenges during real life testing. But the basic theory behind the data analysis remains the same; hence results from experimental tests remain strongly relevant.

- Source localisation by identifying modes of AE waves should be attempted in plates and beams of bigger and complex dimensions and sizes, as accurate localization can be complicated due to signal reflection, attenuation and dispersion.

- Testing in real life situations may introduce additional spurious signals such as due to environmental factors such as rain. Tools proposed for source discrimination in this study can be tested to check if they can successfully distinguish the signals.

- For severity assessment, bigger structures must be subjected to loading in future. Displacement based loads (loading at constant strain rate) were used in this study. Higher loading rates and fatigue testing using cyclic loading should be attempted in future. Though wide range of parameters such as dimensions or material of the specimen can result in variation in recorded AE signals and tests can’t be performed to account for all those; still Ib- value can be
confirmed with further tests on ductile and brittle materials of different dimensions and material properties.
Bibliography


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Appendices

APPENDIX A: WAVE EQUATIONS

Lamb wave equations, also known as Rayleigh-Lamb equations, can be written as [37]:

For symmetric modes,

\[
\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2 pq}{(q^2 - k^2)^2}
\]

(A1)

For antisymmetric modes

\[
\frac{\tan(qh)}{\tan(ph)} = -\frac{(q^2 - k^2)^2}{4k^2 pq}
\]

(A2)

where

\[
p^2 = \left(\frac{\omega}{c_L}\right)^2 - k^2
\]

(A3)

\[
q^2 = \left(\frac{\omega}{c_T}\right)^2 - k^2
\]

(A4)

Wavenumber, \( k = \frac{\omega}{c_p} \)

(A5)

c_p, the phase velocity of the Lamb wave mode is given by:

\[
c_p = (\omega/2\pi)\lambda \quad c_p = \omega/k
\]

(A6)

\( \omega \) is the circular frequency.

Group velocity of wave is given by:

\[
c_g = \frac{d\omega}{dk}
\]

(A7)

c_L is longitudinal velocity and c_T is transverse velocity.
APPENDIX B: SIGNAL PROCESSING TOOLS

A large number of resources are available that provide detailed information on signal processing tools. A brief discussion on Fourier transform, Gabor transform and wavelet transform is presented next:

**Fourier transform**

Fourier transform converts a signal from time domain to frequency domain. A signal $f(t)$ can be decomposed by its Fourier transform $F(w)$ as

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} F(w) e^{iwt} \, dt \quad \text{(B1)}$$

where

$$F(w) = \int_{-\infty}^{+\infty} f(t) e^{-iwt} \, dt \quad \text{(B2)}$$

This means that the signal $f(t)$ can be decomposed into a family with harmonics $e^{iwt}$ and the weighting coefficient $F(w)$ represent the amplitudes of the harmonics in $f(t)$ [113].

Fast Fourier transform (FFT) provides an efficient way to calculate discrete Fourier transform (DFT).

For non-stationary signals (changing frequency content in the signal), such as AE signals, Fourier transform has a disadvantage as time information of frequency components is lost.

**Short Time Fourier transform**

The short-time Fourier transform (STFT), also known as windowed Fourier transform or Gabor transform, provides both time and frequency information (unlike Fourier transform where time information is lost). STFT involves multiplying a signal $f(t)$ with a short window function $g(t-\tau)$ centred at time $\tau$ and calculating the Fourier transform of $f(t) g(t-\tau)$. The window is then moved to a new position and the calculation is repeated. Mathematically, this can be written for a signal $f(t)$ as [63]:

$$G(w,\tau) = \int_{\mathbb{R}} f(t) g(t-\tau) e^{-iwt} \, dt \quad \text{(B3)}$$
**Wavelet transform**

A wavelet is a waveform of effectively limited duration that has an average value of zero. Wavelet analysis involves the breaking up of a signal into shifted and scaled versions of the original (or mother) wavelet [44]. This can be compared with Fourier transform where sinusoids of infinite duration are used. Some common wavelet functions used can be seen in Figure B-1.

![Wavelet Examples](image)

*Figure B-1 Some common wavelets [48]*
Appendices

Figure B-2 Shifting and scaling operations
(http://www.wavelet.org/tutorial/wbasic.htm)

Better frequency resolution; Poor time resolution: for low frequencies
Better time resolution; Poor frequency resolution: for high frequencies

Figure B-3 Comparison of signal processing techniques [44]
Wavelet transforms have advantages over traditional Fourier transforms for representing functions that have discontinuities and sharp peaks, and for accurately deconstructing and reconstructing finite, non-periodic and/or non-stationary signals (http://en.wikipedia.org/wiki/Wavelet). Wavelets are suitable for signals with short duration of higher frequency and longer duration of lower frequency components.

CONTINUOUS WAVELET TRANSFORM (CWT)

For a signal \( x(t) \), CWT can be calculated as:

\[
\text{CWT}(a, \tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \psi \left( \frac{t - \tau}{a} \right) dt
\]  

where \( a \) and \( \tau \) are the scaling and shift (position) parameters of the wavelet function \( \psi(t) \), respectively. For each scale \( a \) and position \( \tau \) the time-domain signal is multiplied by shifted and scaled versions of the wavelet function. Scale is related to the frequency of the signal.

DISCRETE WAVELET TRANSFORM (DWT)

The DWT of a discrete time series \( x(n) \) can be written as:

\[
C_{j,k} = 2^{-(j/2)} \sum_{n} x(n) \psi(2^{-j} n - k)
\]  

where \( \psi(n) \) is the wavelet function and \( 2^{-(j/2)} \psi(2^{-j} n-k) \) are scaled and shifted versions of \( \psi(n) \) based on the values of \( j \) (scaling coefficient), and \( k \) (shifting coefficient) and is usually written as \( \psi_{j,k}(n) \). The \( j \) and \( k \) coefficients take integer values for different scaling and shifted versions of \( \psi(n) \) and \( C_{j,k} \) represent the corresponding wavelet coefficients [50].

Plot of wavelet coefficients on a time-scale grid is known as the scalogram. The square of amplitude of the wavelet coefficients can also be plotted with respect to time and scale to form wavelet maps which can be interpreted as the time-scale distributions of the signal energy [50].

Discrete wavelet algorithm developed by Mallat uses multi resolution analysis based on approximations and details. The approximations are the high-scale, low-frequency components of the signal and the details are the low-scale, high-frequency components [44]. The filtering process basically operates as follows: the original
signal, $S$, passes through low pass and high pass filters and gives rise to two signals, $A$ and $D$ (standing for approximations and details), see Figure B-4a. The decomposition process can be multilevel to form the wavelet decomposition tree, see Figure B-4b.

$$S = A_1 + D_1$$
$$= A_2 + D_2 + D_1$$
$$= A_3 + D_3 + D_2 + D_1$$

(a)  

Figure B-4 (a) Filtering process for DWT, (b) Multilevel wavelet decomposition [44]

In wavelet packet analysis, details and approximations are both split to produce wavelet packet decomposition tree.

Figure B-5 Wavelet packet analysis [44]
**APPENDIX C: SUMMARY OF SELECTED STUDIES ON THE USE OF AE TECHNIQUE FOR SHM OF BRIDGE STRUCTURES**

(The studies are sorted according to material of bridge structure)

<table>
<thead>
<tr>
<th>Study</th>
<th>Aims, studied feature and specimen</th>
<th>Analysis technique/procedure</th>
<th>Major findings / Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steel bridges</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gong et al. [69]</td>
<td>- To detect fatigue crack initiation and to monitor fatigue crack growth on steel railroad bridges.</td>
<td>- Inspection records, engineering judgements, results from FEA or strain gauge were used to select monitoring sites. - Weld repairs, edges of bolt and rivet holes and connected areas acted as most sources. - Parameter based approach (AE count rate).</td>
<td>- AE is successful in finding new cracks, in identifying active cracks, in validating the effectiveness of repairs and in providing damage assessments. - Background noise conditions create problems.</td>
</tr>
</tbody>
</table>
| Lozev et al. [29] | - To characterise the AE associated with steel cracking and various sources of noise in a typical bridge environment - Field testing in five bridges as well as laboratory fatigue tests. | - Local monitoring: Focus on defined critical areas – areas where cracks have been discovered, such as pin and hanger connections with crack, cracked web of girder that had been retrofitted, cracked welded region. - Use additional data from strain monitoring - Moving vehicles act | - AE is suitable for this purpose and can distinguish active and benign cracks. - Presence of spurious noise sources is main impediment to the successful use of AE in bridge inspection. - Uniqueness of waveforms can be used to distinguish sources but manual classification is hard when a large
<table>
<thead>
<tr>
<th>Major</th>
<th>Sub-point 1</th>
<th>Sub-point 2</th>
<th>Sub-point 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major 1</td>
<td>- Laboratory tests on compact tension specimen were used to help clarify the AE signal characterization.</td>
<td>as source of loading</td>
<td>number of waveforms is present.</td>
</tr>
<tr>
<td></td>
<td>- Threshold was set such that no AE was detected when no vehicles were passing.</td>
<td>- Sensor location, strain gauging data and frequency analysis of waveform were used.</td>
<td>- It is suggested that attempt should be made to correlate changes in waveform characteristics to actual progress of crack.</td>
</tr>
<tr>
<td>Maji et al. [39]</td>
<td>- To study location of AE events in steel plates, I-beams as well as field application on a real bridge</td>
<td>- Identification and separation of Lamb wave modes.</td>
<td>- Progressive attenuation of longitudinal waves precludes their use in locating the source of AE events in larger scale. Modal method is better.</td>
</tr>
<tr>
<td></td>
<td>- Use of theory of wave propagation and digital signal processing (FFT and high pass and low pass filtering)</td>
<td>- Use of Fast Fourier transform (FFT) for frequency analysis</td>
<td>- Possibility to reduce the number of transducers.</td>
</tr>
<tr>
<td></td>
<td>- Source location, strain magnitude, location in strain cycle and uniqueness of waveforms could be used to effectively distinguish between primary (from crack extension or deformation at crack tip) and secondary (fretting and rubbing noise due to crack closure or noise from fracture of corrosion products)</td>
<td>- Use of a two sensor array along with guard sensors to screen out noise signals.</td>
<td>- In field investigation AE generated as heavy vehicles passed on the bridge.</td>
</tr>
<tr>
<td>Sison et al. [70]</td>
<td>- To study fatigue cracking in a steel bridge hanger known to have cracks</td>
<td>- Full waveform analysis along with source location and strain gauge monitoring</td>
<td>- Source location, strain magnitude, location in strain cycle and uniqueness of waveforms could be used to effectively distinguish between primary (from crack extension or deformation at crack tip) and secondary (fretting and rubbing noise due to crack closure or noise from fracture of corrosion products)</td>
</tr>
<tr>
<td>Mckeefry and Shield [114]</td>
<td>- To detect fatigue crack propagation and to check effectiveness of retrofits in repairing crack growth.</td>
<td>- Source location and a state of stress criteria were used. - Strain gauges were used to study stress distribution.</td>
<td>- Propagating crack and extinguished crack could be detected by AE monitoring. - It is necessary to inspect the retrofit periodically to check for continued crack growth.</td>
</tr>
</tbody>
</table>

- AE signals from crack can be masked by background noises, such as traffic noise, rubbing and fretting noise from bolted plates and hinged components, and rain. Background noises can be distinguished from crack related AEs because of their lower frequency contents and much longer rise times. - Similarity in shape and frequency spectra could be found for few waveforms, but manual classification of large number is impractical. - Continuous monitoring over long term is better option as crack activity can vary from time to time.
- Laboratory study and field implementation.
- Lab setup was designed to model field conditions of the cracked girders.

| Holford et al. [17] | - AE source location in steel bridges
- 12 m I-beam in laboratory
- Composite construction of bridge with a concrete road deck supported by steel box girders
- Suspect areas identification by FE analysis to help in monitoring

| - Use of Lamb waves theory as alternative to time of arrival method (based on first threshold crossing at an array of sensors) for source location
- Signal-sensor source location is possible.
- Use of high pass and low pass filters and measure of the arrival times of different frequency components of Lamb wave modes.
- Waveforms from lab tests were compared with those from experimental studies.

| - Waveform acquisition settings must ensure capture of the first arrival of modes.
- Wave dispersion and attenuation effects may affect TOA method.
- In large plate like structures, Lamb waves are dominant mode of disturbance propagation.
Symmetric and asymmetric modes of lamb waves are significant, higher modes not so important
- Flexural mode has low frequency (<100 kHz) while extensional mode has high frequency (>100 kHz), frequency filtering can separate those.
- A sensor with high sensitivity in the range of 30-300 kHz is preferred.
- Different sources may produce signals
dominated by a particular mode, so this knowledge may provide information about the nature of the source. (E.g., sources acting in the plane of a material such as crack growth will produce signals with large extensional mode whereas out-of-plane sources such as friction and noise will produce signals with more flexural components.)

| Concrete bridges | Colombo et al. [81] | - Quantitative assessment of damage in concrete beams subjected to cycles of loading and unloading, in laboratory - To use AE energy as a parameter to evaluate the damage of a concrete structure. - To find a criterion that quantitatively | - Use of energy based relaxation ratio defined as the ratio of average energy during unloading phase to average energy during loading phase - Japanese Society of Non-destructive Inspection (NDIS) proposed an Kaiser effect based criterion to assessment concrete structures, the criterion depending on two parameters: load ratio and calm ratio | - Though AE is a suitable method to assess concrete bridge, processing of AE data is not trivial. - Load ratio = load at the onset of AE activity in subsequent loading/the previous load. (>1 : good condition, < 1 damage present) - Calm ratio = number of cumulative AE activities during the unloading process/total AE activity during the last loading cycle up to the maximum - Relaxation ratio > 1 |
| Shigeshi et al. [32] | - To evaluate the potential of AE for cost effective in-situ long term monitoring of bridge condition  
- Old masonry bridge with added reinforced concrete (RC) deck and beams (specimen represent both kinds) with cracks and signs of damage. | - Use of dynamic response of the bridge to traffic loading, that is vehicles act as signal excitation  
- Study of AE parameters, mainly energy and hits during test s lasting 2 to 6 hours. | - AE is a suitable method for condition assessment of bridges as crack growth is detected and position of crack tip can be determined early before they are noticed during visual inspection.  
- Invisible internal cracks release much energy compare to large wide visible cracks.  
- For extended tests proper fixing methods needed for sensors.  
- Masonry has great attenuation, so AE events have lower energy. |
|---------------------|-----------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Yuyama et al. [73]  | - Detection and location of corrosion induced failure in high-strength tendon of prestressed concrete bridges | - Bridges monitored for 24 days and AE signals due to vehicle pass were evaluated to characterize noise features.  
- Study of AE parameters: number of | - AE feature analysis and parameters such as signal duration and amplitudes can distinguish real damage (wire break) from traffic noises or artificial sources (rebounding hammer). |
| Laboratory tests in three kinds of beams as well as two highway bridges (small corroding specimen attached to beams in bridges) | Hits, rise time, amplitudes, energy and duration | Movement of traffic produces a lot of AE signals. |
| Corrosion induced by charging anodic current to tendon. | Attenuation during the wave propagation was measured. | Linear source location was accurately performed in high number of cases. |
| Yoon et al. [45] | AE parameters and as well as waveform analysis by fast Fourier transform and wavelet transform. | Complicated wave paths (e.g. due to boundary between two members) create difficulty in source location calculation. |
| Damage characterization and identification in RC beams under flexural loading | AE is a suitable method to study damage mechanisms in concrete |
| Different beams in lab, corrosion induced in some | Different sources of damage such as microcrack development, localised crack propagation and debonding of the reinforcing steel have different characteristic AE responses |
| | Cross plot of amplitude versus duration can identify different loading stages |
| | Frequency shift with increasing damage in RC beams |

Polymer/
| Composites | Rizzo and di Scalea [115] | - Damage identification in carbon-fibre-reinforced-polymer bridge stay cables  
- Large scale lab tests  
- Different loading conditions for three different cable types | - Counts, amplitudes and energy of signals as well as waveform analysis  
- Study of frequency content of AE signals | - Amplitude and frequency of signals can be used to correlate with the type of damage  
- AE is suitable for in situ long term health monitoring of cables  
- Acoustic attenuation and dispersion phenomena are important for large scale testing. |
|------------|------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
|            | Gostautas et al. [85] | - To study structural performance of glass fibre-reinforced composites bridge decks and to characterize damage  
- Specimen subjected to static loading (three point bending) and repaired ones compared with originals | - Use of Felicity Ratio (FR) to check the Kaiser effect and the Felicity effect  
- Intensity analysis | - Main damage types in composites are fibre breakage, matrix cracking and delamination (separation of layers)  
- FR is similar to load ratio, but is defined as load at which AE events are first generated upon reloading to previously applied maximum load.  
- FR is a useful tool to identify the initiation and onset of permanent damage. |
| Masonry bridges | Melbourne and Tomor [116] | - Location and identification of | - AE amplitude, hit rate and absolute energy | - AE has potential for assessing and monitoring |

Appendices
| damage in large scale masonry arch barrels in laboratory. | masonry arch bridges. Different materials have different acoustic transmission characteristics and signal transmission loss is much higher in masonry compared to concrete. |
| Static and cycling loading | Gradual build up of AE events prior to visual observation of crack shows the potential of AE technique to record crack development history and to approximate crack location to the nearest sensor. |
APPENDIX D: IMPORTANT MATLAB CODES

1. Source location codes
% Source location in deck on girder bridge model 1.8m by 1.2m
% Plate divided into 6 by 4 squares (0.3 m)
% Three sensors used.

clc,clear

% (xi,yi)= coordinates of the sensor i
rsen=18/2*1e-3; % radius of sensor
x1=0+rsen;  y1=0+rsen;
x2=1.2-rsen; y2=0.0+rsen;
x3=0.6-rsen; y3=1.8-rsen;

D1 = sqrt((x1-x2)^2+(y1-y2)^2);
D2 = sqrt((x1-x3)^2+(y1-y3)^2);
D3 = sqrt((x2-x3)^2+(y2-y3)^2);

% Speed of sound in steel, (longitudinal)
E=210e9; den=7800; nu=0.3;
c=sqrt(E/den);

% Times of arrival at three sensors ti(j)
% i=sensor number, j=experiment number

% For location1, that is (0.3, 0.6)
t1(1)=8.8749655;t2(1)=8.8751095;t3(1)=8.87515375;
t1(2)=8.07543825;t2(2)=8.075582;t3(2)=8.075626;

% -------------------------
% for location2, that is (0.6, 0.6)
t1(3)=11.41020775;t2(3)=11.4102105;t3(3)=11.4103235;
t1(4)=7.7791035;t2(4)=7.77910325;t3(4)=7.77921725;

% -------------------------
% for location3, that is (0.9, 0.6)
t2(5)=7.94742675;t1(5)=7.94755075;t3(5)=7.94760875;
t2(6)=8.55514925;t1(6)=8.55528675;t3(6)=8.555342;

% ------------------------
% for location4, that is (0.3, 0.9)
t1(7) = 6.33308475; t3(7) = 6.33309075; t2(7) = 6.33318975;
t1(8) = 7.6317845; t3(8) = 7.63179075; t2(8) = 7.6318905;

% ================
% for location5, that is (0.9, 0.9)
t3(9) = 12.81391025; t2(9) = 12.8139255; t1(9) = 12.81401375;
t3(10) = 7.889023; t2(10) = 7.889032; t1(10) = 7.88912375;

% ================
% for location6, that is (0.3, 1.2)
t3(11) = 6.88708625; t1(11) = 6.88726175; t2(11) = 6.887349;
t3(12) = 6.74288525; t1(12) = 6.74306075; t2(12) = 6.74314825;

% ================
% for location8, that is (0.6, 1.2)
t3(13) = 9.083288; t1(13) = 9.08352075; t2(13) = 9.08352975;
t3(14) = 6.81887975; t1(14) = 6.819111; t2(14) = 6.81911975;

% ================
% for location9, that is (0.9, 1.2)
t3(15) = 6.03275225; t2(15) = 6.0329355; t1(15) = 6.03299725;
t3(16) = 6.972884; t2(16) = 6.972913; t1(16) = 6.9731245;

modanaly = 0;

if modanaly == 1,

% Data from modal analysis (extensional mode)

t1(1) = 8.8749655 - (256 - 179) * 1e-6;
t2(1) = 8.8751095 - (256 - 110) * 1e-6;
t3(1) = 8.87515375 - (256 - 99) * 1e-6;
t1(2) = 8.07543825 - (256 - 175) * 1e-6;
t2(2) = 8.075582 - (256 - 108) * 1e-6;
t3(2) = 8.075626 - (256 - 100) * 1e-6;

t1(3) = 11.41020775 - (256 - 153) * 1e-6;
t2(3) = 11.4102105 - (256 - 153) * 1e-6;
t3(3) = 11.4103235 - (256 - 106) * 1e-6;
t1(4) = 7.7791035 - (256 - 151) * 1e-6;
t2(4) = 7.7791035 - (256 - 151) * 1e-6;
t3(4) = 7.77921725 - (256 - 104) * 1e-6;
t2(5)=7.94742675-(256-174)*1e-6;
t1(5)=7.94755075-(256-125)*1e-6;
t3(5)=7.94760875-(256-97)*1e-6;
t2(6)=8.55514925-(256-185)*1e-6;
t1(6)=8.55528675-(256-125)*1e-6;
t3(6)=8.555342-(256-101)*1e-6;
t1(7)=6.33308475-(256-142)*1e-6;
t3(7)=6.33309075-(256-138)*1e-6;
t2(7)=6.33318975-(256-99)*1e-6;
t1(8)=7.6317845-(256-142)*1e-6;
t3(8)=7.63179075-(256-137)*1e-6;
t2(8)=7.6318905-(256-97)*1e-6;
t3(9)=12.81391025-(256-141)*1e-6;
t2(9)=12.8139255-(256-126)*1e-6;
t1(9)=12.81401375-(256-100)*1e-6;
t3(10)=7.889023-(256-139)*1e-6;
t2(10)=7.889032-(256-133)*1e-6;
t1(10)=7.88912375-(256-97)*1e-6;
t3(11)=6.88708625-(256-173)*1e-6;
t1(11)=6.88726175-(256-104)*1e-6;
t2(11)=6.887349-(256-64)*1e-6;
t3(12)=6.74288525-(256-174)*1e-6;
t1(12)=6.74306075-(256-106)*1e-6;
t2(12)=6.74314825-(256-63)*1e-6;
t3(13)=9.083288-(256-187)*1e-6;
t1(13)=9.08352075-(256-92)*1e-6;
t2(13)=9.08352975-(256-81)*1e-6;
t3(14)=6.81887975-(256-184)*1e-6;
t1(14)=6.819111-(256-91)*1e-6;
t2(14)=6.81911975-(256-80)*1e-6;
t3(15)=6.03275225-(256-175)*1e-6;
t2(15)=6.0329355-(256-98)*1e-6;
t1(15)=6.03299725-(256-86)*1e-6;
t3(16)=6.972884-(256-171)*1e-6;
t2(16)=6.972913-(256-251)*1e-6;
t1(16)=6.9731245-(256-87)*1e-6;
end

% ==========================
Xcal=[];Ycal=[];
for jj=1:15

dt1=t2(jj)-t1(jj);
dt2=t3(jj)-t1(jj);
dt3=t3(jj)-t2(jj);

del1=dt1*c;
del2=dt2*c;
del3=dt3*c;

theta1=atan((y2-y1)/(x2-x1));
theta3=atan((y3-y1)/(x3-x1));
i=0;
for theta=0:0.0001:pi/2+pi/6;
i=i+1;
d11=0.5*(D1^2-del1^2)/(del1+D1*cos(theta-theta1));
d12=0.5*(D2^2-del2^2)/(del2+D2*cos(theta3-theta));

Xs1(i)=x1+d11*cos(theta);
Ys1(i)=y1+d11*sin(theta);

Xs2(i)=x1+d12*cos(theta);
Ys2(i)=y1+d12*sin(theta);

error1(i)=abs(Xs1(i)-Xs2(i));
error2(i)=abs(Ys1(i)-Ys2(i));

error(i)=error1(i)+error2(i);
thetacalc(i)=theta;
end

[Y,j]=min(error); % Selecting the position corresponding to minimum error

Xcal=[Xcal;Xs1(j)];
Ycal=[Ycal;Ys1(j)];
figure
hold on;
plot(Xcal,Ycal,'k+');
set(gca,'XTick',0:0.3:1.2)
set(gca,'YTick',0:0.3:1.8)
grid on

x=[0.3 0.6 0.9 0.3 0.9 0.3 0.6 0.9];
y=[0.6 0.6 0.6 0.9 0.9 1.2 1.2 1.2];

hold on;plot(x,y,'ko') % Exact source location positions

Senposx=[0.009,1.2-0.009,0.6];
Senposy=[0.009,0.009,1.8-0.009];

hold on; plot(Senposx,Senposy,'kx') % Exact sensor positions

2. Performing cross-correlation for signal similarity

p = load plbsigs; % Load PLB signals, 1st one is template
b = load bdsigs; % Load BD signals

maxxc=[]; % Array to hold maximum cross-correlation values

i=1;

for j=1:2:20

    [xc,lag] = xcorr(p(:,i),p(:,j),'coeff');
    maxxc=[maxxc,max(xc)];

    if j==2
        figure;plot(lag,xc); % Sample plot
    end
end
3. Performing magnitude squared coherence for signal similarity

\[ p = \text{load plbsigs}; \] % Load PLB signals, 1st one is template, 20 signals, recorded by 2 sensors
\[ b = \text{load bdsigs}; \] % Load BD signals

\[ \text{simil1} = []; \] % Array to hold mean magnitude squared coherence
\[ i = 1; \]

\[ \text{for } j = 3:2:20 \]
\[ \quad [c1,F1] = \text{mscohere}(p(:,i),p(:,j),[],[],[],1e6); \]
\[ \quad l = \text{length}(c1); \]
\[ \quad \text{newl} = \text{round}(l*0.8); \] % S(0 till 400 kHz)
\[ \quad \text{simil1}(j) = \text{sum}(c1(1:newl))/\text{newl}; \]
\[ \quad \text{if } j == 2 \]
\[ \quad \qquad \text{figure; plot(F1,c1); } \] % Sample plot
\[ \quad \text{end} \]
\[ \text{end} \]

4. Ib-value analysis

\[ \text{clc, clear} \]

\[ \text{load tphae} \text{load1mmpermin } \] % Load AE parameters (tphae) and load parameters
\[ i = 1; tphaenew = []; \]

\% AE data sort into sensor 1 and sensor 2 and remove data with duration of 0 (likely reflected signals)

\[ \text{tphae1} = []; \text{tphae2} = []; \]
\[ \text{for } i = 1: \text{length(tphae)} \]
\[ \quad \text{if } tphae(i,2) == 1 \&\& tphae(i,8) > 0 \]
\[ \quad \qquad \text{tphae1} = [\text{tphae1}; \text{tphae}(i,:)]; \]
\[ \quad \text{elseif } tphae(i,2) == 2 \&\& tphae(i,8) > 0 \]
\[ \quad \qquad \text{tphae2} = [\text{tphae2}; \text{tphae}(i,:)]; \]
\[ \quad \text{end} \]
\[ \text{end} \]

\% Improved b-value
p1=tpbae1; Ib=[]; tt=[];
noevents=100; overlap=80; nn=0;
param=9; % 9=amplitude, 14=absolute energy, 7=energy
method=2; % 1 for PAC, 2 for Shiotani

while (nn+noevents)<length(p1)
    set1=nn+1:nn+noevents;
    meanp1=mean(p1(set1,param));
    stdp1=std(p1(set1,param));

    if method==1 % Ib value (PAC)
        alpha1=1; alpha2=1;
        a1=meanp1-alpha1*stdp1; a2=meanp1+alpha2*stdp1;
    elseif method==2 % Ib value Shiotani
        a2=ceil(meanp1); a1=floor(meanp1-
            stdp1);
        alpha2=(a2-meanp1)/stdp1; alpha1=-
            (a1-meanp1)/stdp1; [alpha1, alpha2];
    end

    aa1=find(p1(set1,param)>=a1); N1=length(aa1);
    aa2=find(p1(set1,param)>=a2); N2=length(aa2);
    Ibvalue = (log10(N1)-log10(N2))/(a2-a1);
    Ib=[Ib; Ibvalue];
    tt=[tt; p1(set1(noevents),1)];
    nn=nn+(noevents-overlap);
end

figure;
plot(tt-p1(1,1), Ib*20, '-k'); xlim([0 500]); xlabel('time(s)'), ylabel('Ib x 20')

% =============================================
% Compare with severity and historic indices
% =============================================

comparewithindices=1; % 1 for comparision , 0 for non comparision

if comparewithindices==1
    p1=tpbae1;
    % H and Sr (in terms of time)
    phits1=1:length(p1); [p1, phits1];
    for i=1:length(p1)
        N = phits1(i);
    end
end
if N<=15 K=0;
elseif N>=16 & N<=75, K=N-15;
elseif N>=76 & N<=1000, K=0.8*N;
elseif N>=1001, K=N-200;
end

K=round(K);
SoiK = sum(p1(K+1:N,14));
Soi = sum(p1(1:N,14));
H(i) = N/(N-K)*SoiK/Soi;

% Severity (Can only increase or remain constant as load increases, Gostautas)

Samp=p1(1:N,14);
Sampsort=sort(Samp,'descend');
if N<10 J=N;
else J=10;
end

Sr(i)=1/J*sum(Sampsort(1:J));

figure;

subplot(3,1,1);plot(tt-tpbae1(1,1),Ib*20,'-');xlim([0 200]);title('1 mm/min unnotched');ylabel('Ib value');
subplot(3,1,2);plot(p1(:,1)-p1(1,1),H,'-');xlim([0 200]);ylabel('H(I)');
subplot(3,1,3);plot(p1(:,1)-p1(1,1),Sr,'-');xlim([0 200]);xlabel('time (s)'), ylabel('Sr');

end

% b values in different stages: elastic, plastic
% For 2 mm/min loading: 25s ==> tpbae1(1:340); 350s ==> tpbae1(341:2350);rest
% bvalueindiffstages=0;
if bvalueindiffstages==1;

    p1=tpbae1; Ib=[]; tt=[];

end
param=9; % 9=amplitude, 14=absolute energy, 7=energy

method=2; % 1 for PAC, 2 for Shiotani

set1=[1:340]; set2=[341:2350]; set3=[2351:2557]; % 2 mm/min
loading % Perform for each stage
meanp1 = mean(p1(set1,param));
stdp1 = std(p1(set1,param));

if method==1 % Ib value (PAC)
alpha1=1;alpha2=1;
a1=meanp1-alpha1*stdp1;a2=meanp1+alpha2*stdp1;

elseif method==2 % Ib value Shiotani
a2=ceil(meanp1);a1=floor(meanp1-
stdp1);
alpha2=(a2-meanp1)/stdp1; alpha1=-(a1-
meanp1)/stdp1;[alpha1,alpha2];
end

aa1=find(p1(set1,param)>=a1); N1=length(aa1);
aa2=find(p1(set1,param)>=a2); N2=length(aa2);
Ibvalue = (log10(N1)-log10(N2))/(a2-a1);
Ibvalue*20

end