Structural Health Monitoring Using Acoustic Emission

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Abstract: This book provides useful and informative knowladge on the applications of the acoustic emission technique on reinforced concrete structure. It covers fundamental concepts of acoustic emission, principles of acoustic emission, source localisation, waves and acustic analysis method. This book will also encourage both contractors as well as the Public Work Department (JKR) to use the AE technique in structural health monitoring and deepen their understanding on the assessment of concrete superstructures using the AE techique.

Keywords: Acoustic Emission, localization, waves, AE signals

STRUCTURAL HEALTH MONITORING

USING ACOUSTIC EMISSION

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Content

Foreword

In developed countries such as the United States, the United Kingdom and Japan, Acoustic Emission (AE) has been used extensively in Structural Health Monitoring (SHM) to monitor and assess the structural integrity of bridges, aircrafts, dams and etc. However, many of the researchers, contractors and employees of the Public Work Department (JKR) in Malaysia are still not familiar with the SHM system especially when it comes to Reinforced Concrete(RC) structures such as the application of AE in the assessment of concrete damage mechanisms.

This book provides useful and informative knowledge on the applications of the acoustic emission technique on reinforced concrete structures. It covers fundamental concepts of acoustic emission, principles of acoustic emission, source localisation, waves and acoustic analysis methods. This book will also encourage both contractors as well as the Public Work Department (JKR) to use the AE technique in structural health monitoring and deepen their understanding on the assessment of concrete superstructures using the AE technique.

Preface

Reinforced concrete (RC) structures have been used in construction since ancient times in major and minor infrastructure such as bridges, dams, and buildings. However, RC structures face deterioration due to several problems such as ageing, disastrous damage due to earthquakes and other environmental effects. Globally, some of the concrete structures such as bridges and buildings in rural areas built over 30 years ago are now considered deficient by current conditions. These factors affect the condition and performance of RC structures. Consequently, the assessment of damage deterioration in concrete structures is in great demand and it is vital for maintaining the structures for both safety and economic reasons. In any assessment and monitoring system, it is pertinent to utilize a non-destructive (NDT) technique which is robust, reliable and provides real-time information on the condition of the structure. The applications of the AE technique in concrete structures have been utilized for more than half a century and it has been employed for early damage detection and characterization in concrete structures. This application is commonly used and established as a monitoring system in developed countries such as Japan, the United States, the United Kingdom and developing countries such as like China.

Structural concrete bridges are highly at risk in terms of their structural condition due to overloading compared to other structures. This condition occurs due to the daily increase of traffic loading on bridges. The most common defects found on superstructure concrete bridges are micro-cracking and macro-cracking. These types of damage are serious and have created great concern among the public.

In Malaysia, the most significant issue which has been discussed was the Middle Ring Road 2 (MRR2) flyover bridge at Batu Caves, Selangor, whereby 31 defective pillars out of 33 pillars were found on the flyover bridge. According to Malaysia Today (2008), the severe cracking

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List of Abbreviations

ABSE	-	Absolute Energy
AE	-	Acoustic Emission
AESUM	-	Acoustic Emission System User Manual
Amp	-	Amplitude
AFREQ	-	Average Frequency
ASTM	-	American Society of Testing Material
ASNT	-	American Society of NDT Testing
AST	-	Auto Sensor Test
CLT	-	Cyclic Load Test
CSS	-	Cumulative Signal Strength
CABSE	-	Cumulative Absolute Energy
HDT	-	Hit Definition Time
HLT	-	Hit Lockout Time
IA	-	Intensity Analysis
IEA	-	Intensity Energy Analysis
ISA	-	Intensity Signal Analysis
LS	-	Loading Set
NDT	-	Non-Destructive Testing
PA	-	Parameter Analysis
PAC	-	Physical Acoustic Corporation
PDT	-	Peak Definition Time
RC	-	Reinforced Concrete Structure
RT	-	Rise time
SAMOS	-	Sensor based Acoustic Multi Channel Operation System
SHM	-	Structural Health Monitoring
TOA	-	Time Of Arrival

List of Symbols

Δ_r	-	Residual Deflection
Δ_{max}	-	Maximum Deflection
P_{min}	-	Loading Minimum
P_{max}	-	Loading Maximum
P_{ref}	-	Loading Reference Point
V	-	Voltage of electrical signal
α	-	Angle Load deflection

Chapter 1

FUNDAMENTAL CONCEPTS OF ACOUSTIC EMISSION

"Today knowledge has power. It controls access to opportunity and advancement".

-Peter Drucker

1.1 Introduction

Structural health monitoring (SHM) refers to the process of implementation on early damage detection and characterization for engineering structures. Basically, early detection of damage and appropriate rehabilitation will aid in preventing structural failure, reducing maintenance costs and ensuring structural safety. Nowadays, SHM is widely used especially for continuous real-time monitoring systems with minimum labour involvement. Therefore, SHM has been given significant attention and is widely accepted in all engineering systems such as aerospace, mechanical and civil engineering. This system has been applied since a long time ago for assessing damage detection in structures and is mostly applied in the fields of aerospace and mechanical engineering.

In civil engineering, SHM is highly applicable for evaluating the condition and performance of structural systems especially for high loading structure conditions. The typical applications of SHM systems are carried out on high rise buildings, bridges, dams, river navigational facilities and etc. All these structures involve the public and require extensive safety measures on structure maintenance. However, it is important to avoid any unexpected failure to ensure the performance and functionality of the structure.

Concrete structures face several types of damage mechanisms and deterioration during its lifetime due to factors such as fatigue loading, frost damage, creep, high loading of structure due to the increasing traffic flow on bridges and severe environmental effects such as scaling, spalling and corrosion. Therefore the damage mechanism will shorten the service life-span of concrete structure. However, these interaction

Chapter 2

PRINCIPLES OF ACOUSTIC EMISSION

"The true sign of intelligence is not knowledge, but imagination".

-Albert Einstein

2.1 Introduction

Chapter 2 presents the fundamental and basics of AE and signal wave generation. AE wave will be generated are subjected to stress object. A highly sensitive tool will capture better results in terms of signal strength, absolute energy and rise time. The AE signal parameters indicate the type of wave generation during assessment.

2.2 General Principles of Acoustic Emission

Basically, an acoustic wave is generated when a solid object is subjected to stress. The term AE is derived from the phenomenon of sound generation in materials under certain stress levels and it is also known as stress wave emission. According to the American Society for Testing of Material (ASTM), AE is formally defined as a class of phenomena whereby transient elastic waves are generated by the rapid release of energy from a localized source with a material or transient wave.

AE can also be defined as stressed waves produced by sudden movement in stressed materials. The classic sources of AE are defects which are related to the deformation processes such as crack growth propagation and plastic deformation. In the elasto-dynamics process, AE has also been described as elastic waves due to dislocation motions. The AE principle of generation and detection is illustrated in Figure 2.1. When a structure is subjected to an external stimulus that means a change in pressure, load, or temperature, the energy of localized sources will be released in the form of stress waves which propagate to the surface and are recorded by sensors. As the stress level in the material increases, there will be an increase in wave emissions. Without the stress energy in

Chapter 3

ACOUSTIC EMISSION SOURCE LOCALIZATION

"Own more than thou showest, speak less than thou knowest.".
-William Shakespeare

3.1 Introduction

The most significant part in AE testing is the ability to locate an active source when the real data are available from one sensor to another sensor. This phenomenon is common in AE testing and is also known as the source location technique. The American Society for Nondestructive Testing (ASNT) has provided a number of source location techniques such as different techniques based on the number of sensors. The source location will be different depending on the number of sensors. A detailed explanation will be provided in the next subtopic.

3.2 Linear location

In the field of AE techniques, the localization of AE sources is important to determine and assess the active damage in the structural materials. The spatial source of an AE can be determined through the measurement of the arrival time of a transient signal using an array of sensors. The predominant method of source location is based on the measurement of the time differences between the arrivals of individual AE events at different sensors known as Time of Arrival (TOA).

Basically, TOA can be used for analyzing the three types of AE source locations such as, one, two and three dimensions. However, this research area gives more attention only to the linear and two-dimensional source locations. In general, one dimension of an AE source is also known as the Linear Location, of which a single position measurement axis is also sufficient to define the location of the sensors. In this case, it considers the three sensors attached on a linear structure pipe, as presented in Figure 3.1. With reference to Figure 3.1(a), if the first hit

Chapter 4

ACOUSTIC EMISSION WAVES

"An investment in knowledge always pays the best interest.".

-Benjamin Franklin

4.1 Introduction

This chapter presents AE wave emission and propagation in structures during the monitoring process. In general, primitive AE wave is released at a source. The primitive wave is essentially a stress pulse corresponding to a permanent displacement of the material. The ordinate quantities refer to a point in the material.

4.2 Wave Propagation

Basically, AE wave propagations in solid media are highly complex and are available in different modes according to the particle movement such as P-wave (Longitudinal), S-wave (Shear) and R-wave (Rayleigh) as shown in Figure 4.1.

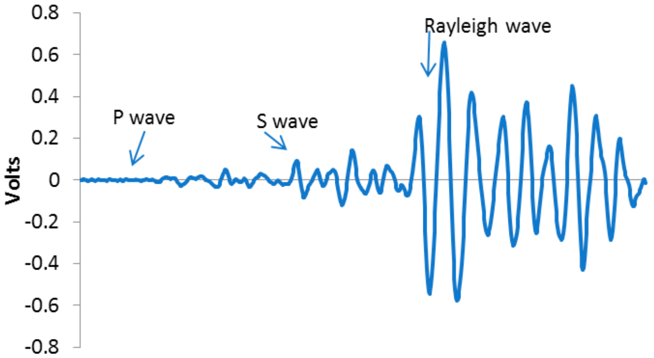

Figure 4.1. Example of AE signal

Chapter 5

ACOUSTIC EMISSION ANALYSIS METHOD

"The beginning of knowledge is the discovery of something we do not understand".

-Frank Herbert

5.1 Introduction

This chapter presents the analysis method in the evaluation of an AE signal system. This part covers analysis methods such as parameter analysis related to load and calm ratio. Other analysis methods such as RA Value, B-Value and Intensity Signal Analysis (ISA) and a new advanced method called the Intensity Absolute Energy Analysis (IAE) will also be explained in this chapter.

5.2 Parameter Analysis

A Parameter-based Analysis (PA) is a powerful and sophisticated method for AE analysis data parameters to evaluate and assess the material. This analysis method has been applied over the last few decades and it is currently known as the classical method of AE analysis. This method is capable of identifying wave bundles for particular parameters. Basically, AE wave parameters are indispensable in the description of the feature fracture phenomena with the occurrence rate or accumulated trend in the time domain. The AE signal feature parameters widely used in this analysis method are; hits, emission count, amplitude, rise time, duration and energy wave. In the analysis of AE parameters, the statistical value and combination among the parameters have been studied and proven for the fracture scale and degree of damage mechanism in the structures.

Some examples together with the most popular methods were applied in previous research such as the Kaiser effect, Felicity effect, Moment Tensor and Wavelet Analysis. Each of the methods possess its own characteristic AE signal and patterns to be solved and analyzed.

CHAPTER 6

REAL EVALUATION OF CRACK CLASSIFICATIONS THROUGH AE SIGNALS

"Knowledge is a treasure, but practice is the key to it."

-Lao Tzu

6.1 Introduction

This chapter contains a detailed description of the analysis carried out during real experimental work as well as crack recognition in concrete beam structures. In this section, two analysis methods with similar AE data parameters were employed for a detailed analysis on crack identification. Moreover, problems such as possible errors of the AE data source and preventive measures taken are discussed in this chapter.

b-value and RA value analysis methods were used in this book to analyse post-test AE signals for the fracturing process in RC beams. All these evaluation methods have been utilised and measured via the amplitude and frequency value parameters. These methods of analysis were proven to be sensitive to ignition and the growth of cracks within concrete material and structure.

This book considers of the use of *b*-value and RA value analysis for crack identification and classification. The b-value method demonstrates the development of the fracture process from the onset of micro-cracking to macro-cracking while the RA value analysis was used to classify the type of cracking which occurred. All these methods were analysed according to the AE event data recorded.

6.2 Real Cracking Observation

Figures 6.1(a) – (i) present the typical development of cracking as well as the fracture process from LS1 to LS8. All beams tested showed shear failure with an initiation on flexural cracks as clearly seen in Figure 6.1.

CHAPTER 7

RESEARCH STUDIES ON ACOUSTIC EMISSION IN CONCRETE

"All men by nature desire knowledge".

-Aristotle

7.1 Introduction

Chapter 7 presents the application of AE in concrete monitoring. AE research in concrete or civil engineering has been conducted since 1988 by Masayasu Othsu. However, research on AE applications continue till today in the pursuit of enhancing the performance and conditions of concrete structures.

7.2 Acoustic Emission Applications in Concrete Monitoring

AE is a very versatile and non-invasive way to gather information about a material or structure. It also suited for the study of structural integrity as it is able to provide continuous monitoring on a wide range of damage mechanisms in real time. A brief summary of previous studies which explored the AE technique in concrete monitoring is presented in Table 7.1.

From the summary in Table 7.1, it is clear that the AE technique has been employed for early damage detections such as first cracking occurrence in concrete either due to the loading condition or corrosion. In addition, the applications of this method have show improvement over the years. According to Table 7.1, the improvements have mostly been made on the material and geometry of structure. The most essential improvement is the type of analysis method. These analysis methods are the main factors in evaluating AE data parameters for identifying the damage classification in concrete structures.

Table 7.1 shows that previous research studies have analysed the post-test analysis by utilizing the AE hit data parameter on per channel

CHAPTER 8

CRACK MONITORING AT PRAI POWER SDN. BHD.

"Those who look for seashells will find seashells; those who open them will find pearls".

-Al Ghazali

8.1 Introduction

Problems in existing buildings are often referred to through terms such as "distress", "defects', "damage", "deterioration" and even "structural failure". A building is fundamentally a structural system comprising many components serving different structural and functional roles. Roofs, deck slabs, beams and columns are primary members transmitting and bringing the load from the roof down through the foundation to the soil stratum in a complete load path. When any of these components fails to function as designed or intended, problems arise.

Most of the buildings in Malaysia are of concrete construction. Contrary to the beliefs of the general public, concrete does experience durability and maintenance problems. Concrete may be susceptible to direct chemical or acid attacks, but by and large, cracking and spalling of concrete are the most common problems in Malaysia. Problems in concrete members often manifest themselves in the form of cracks. This had made diagnosis of the problem rather difficult. Cracking in concrete can broadly be categorized in terms of the nature and root source of the problem: load induced, corrosion induced and intrinsic problems. This way of categorization allows the building/structural inspector to assess the severity of the cracks and facilitate the proposal of a right solution.

The evaluation of the safety and reliability of reinforced concrete structures such as buildings is complex. Therefore, diagnosis and monitoring techniques are of importance in the evaluation of structural conditions and reliability. Acoustic Emission (AE) is used as a health monitoring tool to detect, identify and locate a variety of damage

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