DAMAGE ASSESSMENT OF REINFORCED CONCRETE BEAM WITH VARIOUS DEPTHS BY USING ACOUSTIC EMISSION TECHNIQUE

By

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ABSTRACT

This study aimed at using the Acoustic Emission (AE) in Structure Health Monitoring (SHM), since three categories of reinforced concrete (RC) beams (a total of 12 RC beams) with difference depth of beams. The study sample were tested in four-point bending setup under monotonic and stepwise loading, each category of RC beams contained four beams, one beam for monotonic loading and three beams for stepwise loading. All beams encountered flexural failure mode. In collecting the AE data, MICRO -SAMOS (µSAMOS) Digital AE system and R6I sensor were used, as AEwin software was used to analyze the data. Moreover, visual observation was conducted to compare with the AE results. The main interest of this research was to investigate the capability of AE in locating the concrete specimen's cracks besides investigating the cumulative absolute energy for different mechanical behaviors of those cracks. On the other hand, Intensity Analysis (IA) method was used to quantified the damage level of the RC-beams associated with the crack flexural failure. The proposed method introduced that the differences of crack locations between visual observation and AE sources are between 25mm and 55mm. Also by comparing the visual observation to the AE result, when the cumulative absolute energy exceeds 1.0 x 10^6 attoJoule (aJ), the onset of the first crack occurs, and the recommended action at this stage is typically minor surface defects. Moreover, when the specimens affected by localization damage, the absolute energy increases dramatically for about five to seven times.

ABSTRAK

Penyelidikan ini adalah bertujuan untuk menggunakan *Acoustic Emssion* (AE) di dalam sistem pemantauan struktur kesihatan. Tiga kategori rasuk konkrit bertetulang dibina dengan perbezaan kedalaman rasuk dan setiap kategori mengandungi empat sampel dengan jumlah keseluruhannya 12 rasuk konkrit bertetulang. Semua sampel kajian diuji dengan mengenakan pembebanan lentur empat titik dan dikelaskan kepada pembebanan monotonik dan berperingkat. Di dalam kajian ini, setiap kategori rasuk konkrit bertetulang akan diuji dengan satu rasuk dikenakan bebanan monotonik dan selebihnya bebanan berperingkat. Berdasarkan pemantauan secara kasar, keseluruhan sampel ini mengalami mod kegagalan lentur, dan untuk mengumpul dan merekod kesemua isyarat AE data yang terlibat di dalam kajian ini, sensor jenis R6I dan sistem AE Digital MICRO-SAMOS (µSAMOS) digunakan bersama dengan perisian computer AEwin untuk menganalisis data. Selain itu, pengamatan secara visual juga dilaksanakan bagi membandingkan hasil analisis oleh AE. Objektif utama dalam kajian ini adalah untuk menyelidik dan mengkaji kebolehan AE dalam menentukan lokasi keretakan pada rasuk selain daripada mengkaji tenaga mutlak kumulatif untuk perilaku mekanikal yang berbeza bagi keretakan tersebut. Di samping itu, kaedah *Intensity Analysis* (IA) digunakan bagi menentukan tahap kerosakan dan kegagalan lentur pada rasuk berkenaan. Hasil penyelidikan ini mendapati bahawa teknik AE mampu menentukan dengan tepat lokasi keretakan mikro yang tidak dapat dilihat dengan mata kasar dan keretakan makro secara visual. Julat perbezaan adalah diantara 25mm dan 55mm. Berdasarkan kajian ini, didapati keretakan mikro akan terjadi apabila tenaga mutlak kumulatif melebihi 1.0×10^6 atto joule. Kesimpulanya penyelidikan ini mencapai objektif sebenar.

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DEFINITIONS

Acoustic Emission (AE): Elastic waves generated by the rapid release of energy from sources within a material.

Attenuation: Loss of amplitude with distance as the wave travels through the test structures.

Channel: A single sensor and the related instrumentation for transmitting, conditioning, detection and measuring a signal.

Couplant: A substance providing an acoustic link between the propagation medium and sensor.

Hit: A hit is the term used to indicate that a given AE channel has detected and processed an AE transient.

H-N Source: Also known as Hsu-Neilson or lead break; the industry standard calibration method, which involves fracturing a 0.5 diameter, 3mm long, 2h propelling pencil lead at 30° orientation.

Kaiser Effect: The absence of detectable AE until the previous maximum applied stress level has been exceeded.

Pencil Source: An artificial source using the fracture of a brittle graphite lead in a suitable fitting to simulate an AE event (also known as an Hsu-Neilson source).

Rayleigh Wave: Rayleigh waves are longitudinal and transverse waves which propagate in the bulk of the material combine in the region close to the surface.

Sensor: A device that converts the physical parameters of a wave into an electrical signal.

Signal Features: Measurable characteristic of AE signal, such as amplitude, AE energy, duration, counts, rise-time, that can be stored as a part of AE hit description.

Source: The place where an event takes place.

Source Location: The computed origin of AE signal.

Velocity: The speed at which an AE wave propagates from one sensor to another.

CHAPTER ONE

INTRODUCTION

1.1 Background

Natural shrinkage of the concrete during curing, thermal expansion and contraction can result in cracking and spalling, while flexure crack or shear crack can be caused by overloading. Therefore, proper design and placement of the reinforcement can provide the needed tensile strength to counteract the shrinkage. Moreover, structural cracks are active only if the overload condition continues or if settlement occurs. On the other hand, cracks can be due to mechanical loads which induce strains that can exceed the strain capacity of concrete (Musbah, 2010).

Recently, Structural Health Monitoring (SHM) has received much attention in the aerospace, mechanical, and civil engineering fields. A wide range of sensors including fiber optic, piezoelectric, shape memory alloys, dielectric, etc. have been successfully employed for SHM. In that regard, SHM consists of both active and passive sensing monitoring. According to Umesh and Ganguli (2011), sensors are installed on a structure only in passive sensing monitoring, as sensor measurements are constantly taken in real time while the structure is in service to compare this data with a set of (healthy) references data. Also, Sensors like fiber optic wires, strain gauges, Acoustic Emission (AE) sensors, etc. can be used for passive sensing. In another vein, in active sensing monitoring, the structure is excited by using actuators, as the dynamic response is measured by using sensors since the change in dynamic response will depend on the level of damage in the structure.

According to Degala (2008), AEs are defined as “the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material”. Moreover, he added that the elastic energy propagated as stress wave (AE event) in the structure that is detected by one or more sensors attached to or embedded in the structure. In the same vein, AE differs from most other NDT techniques in two points. First, the signal has its origin in the material itself, not in an external source. Second, AE detects movement, while most other methods detect existing geometrical discontinuities. In addition, different AE sources may produce different AE waveforms. The AE source mechanism results in different received signal if the source is oriented differently with respect to the geometry of the medium or the propagation path to detector.

Several decades ago, the AE has been widely used in local and global monitoring in concrete structure. Local monitoring is also used in observing the concrete sample with different reinforcement like steel fiber reinforced slab and carbon fiber reinforced polymer in slab (Degala, et. al., 2009). The AE behavior in these materials is observed and investigated in order to study the strength and durability of these reinforced structures.

2.1 Problem Statement

Reinforced concrete structures in service could be deteriorated as a result of heavy loads, fatigue and the aging of the structures. In addition to that, Excessive cracking is one of the common causes of damage or deterioration of the concrete in RC structures and results in huge annual cost to the construction industry. When the applied load exceeds the capacity of concrete, structural members will cause micro cracks, limitation of flexural crack, damage localization and failure.

There are many researches using NDT methods to detect and monitor building deficiency, which require occasional monitoring in order to maintain the health of building structures such as; Impact- Echo method, Ultrasonic Pulse Velocity Method, Infrared Thermography. etc. Based on the previous studies in chapter two, AE is the best method to explore the cumulative absolute energy for different mechanical behaviors of concrete cracking, which divided into four stages micro cracking, first visible cracking, distributed flexural cracking, damage location, and failure.

Thus, to be more precise in determining the defects and cracks, Acoustic Emission technique is one of the NDT that can be used in this task in local monitoring. Also the analysis of using the Intensity Analysis (IA) is used to assess the damage of the RC-beams associated with the flexural failure.

1.3 Objectives

This research mainly aims:

1) To investigate the capability of AE technique used in local health monitoring and locating the cracks in the concrete specimens.
2) To explore the cumulative absolute energy for different mechanical behaviors of concrete cracking.
3) To evaluate the damage of the RC-beams associated with the flexural failure, using Intensity Analysis (IA) method .

1.4 Scope of work

This research of AE mainly focuses on the local monitoring, as it focuses on investigating the wave propagation in concrete beams, using AE techniques. This study started with the literature review from different resources, then the preparation of the samples in the lab, which is three categories of reinforced concrete beams, with different beams depth (a total of 12-RC beams). After that the experiment setup with AE to test the samples based on visual observation and AEwin software. Then the data has been analyzed through the comparison of visual observation outputs and AE system outputs. On the other hand, to obtain a better insight into the significance of the AE collected data, data was quantified by using Intensity Analysis (AI) technique.

During Testing, the specimens were tested in four-point bending setup under monotonic and stepwise loading to detect the location of flexure crack. Moreover, the pencil lead break, known as Hsu-Neilson Source, was used to stimulate an artificial source through the samples. In the same vein, the AE signal data from testing was displayed as a (Cumulative of Absolute Energy vs X Position) graph, because this graph shows the location of the beams crack and can be used to compare with the visual observation**.**

Intensity Analysis (AI) method requires the accumulation of AE data obtained from successive loads stepwise. Moreover, the AI was used to characterize the flexural mechanisms in concrete beams during stepwise loading to failure tests.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter reviews the literature related to the present study. First, it provides an introduction to the main focus of the study. In the second section, which was classified into three subsections namely, properties of concrete, concrete deterioration, and techniques of building deficiency detection, related studies to concrete structures were reviewed. In the third, fourth, and fifth sections, the theory of AE, AE phenomena, and AE characteristics were explored, respectively. Moreover, some subsections that related to AE characteristics including; wave propagation, wave attenuation, wave velocity, method of measurement, and source location were navigated. In section six, the principles of AE techniques were considered. In seventh section, the damage assessment in concrete using parametric AE data was also discussed. This section branches into one more subsections which is Intensity Analysis. In section eight and nine, AE was explored in Global and local monitoring. At the end of this chapter, a brief summary of the related literature had been provided.

2.2 Concrete Structures

2.2.1 Properties of Concrete

Chowdhury and Basu (2010) stated that concrete is commonly considered as a three-phase composite; the first two phases are aggregates and bulk hydrated cement paste, and the third phase is the transition zone. They also reported that the paste has a complex microstructure consisting of solid phases, pores, and water with a high degree of heterogeneity. They reported that in order to make concrete construction high-quality and efficient, fresh concrete should have suitable consistency to answer to the environment and the structure and construction conditions of constructed building member, including environmental temperature, member shape, density of reinforcing bars, and carrying, compaction and finishing methods.

Aguado et al. (1995) stated that the general properties of concrete should possess certain physical and chemical properties such as tensile strength, low-level of permeability to avoid moisture and chemical attack and volume stability. He also discussed the basic of normal concrete has a high level of compression strength, while the tensile strength of concrete is relatively very weak. He also stated that the concrete can crack under its own weight, so there are many factors required to improve the behavior, strength, and properties of concrete, such as using reinforced steel bars or fiber and iron mesh, it is also prestressed with the use of steel cables to reduce the tensile strength of concrete; And also indicated that the other factor for strength is also related to the proportion and ratio of water and cement, the type of cement used and the strength of aggregate.

Workability is important property of concrete. This called about a high-performance concrete and various new types of concrete, such as self-compacting concrete and anti-washout underwater concrete, with high quality and efficient concrete construction (Chowdhury and Basu, 2010); and also can be achieved by determining the optimum water cement ratio, shape and size of aggregate and the level of hydration (Aguado et al. 1995).

Concrete curing is defined as the process of maintaining a satisfactory moisture content and favorable temperature in concrete during hydration of the cementitious materials (Fattuhi, 1986); and also a good curing ensures a moist environment for hydration. He also indicated that the strength and quality of the concrete influenced by the level of permeability and shrinkage, which at low level of permeability the strength and quality of the concrete will be increase (Aguado et al. 1995).

2.2.2 Concrete Deterioration

According to Musbah (2010), cracking of concrete, corrosion of reinforcement, spalling of the concrete cover, and surface scaling are the four most common and important types of deterioration of reinforced concrete. He also reported that the deterioration of concrete can result from: environmental factors, the original materials and workmanship, and improper maintenance such as prolonged exposure to moisture, application of waterproofing coatings, and saturation with chlorides due to the spreading of road de-icing salts on or nearby the concrete.

Cracking and spalling can be a result of natural shrinkage of the concrete during curing, thermal expansion and contraction, flexure or shear from overloading. Proper design and placement of the reinforcement can provide the necessary tensile strength to counteract the shrinkage. Shrinkage cracks are dormant and will not change with time. Thermal cracks will tend to widen and narrow with the cycles of the ambient temperature. Structural cracks are active only if the overload condition is continued or if settlement is occurring (Musbah, 2010).

2.2.2.1 Cracks in Concrete

According to Yoon et al. (2000), excessive cracking resulting from either or both restrained deformation and external loads is one of the most common causes or damage in concrete structures and results in huge annual cost to the construction industry. Civil engineers begin the process of rehabilitating and simulating long-term performance of the infrastructure using computer models, it is more critical than ever when they have a good understanding of the impact of cracks on performance.

Yoon et al. (2000) stated that the cracks play an important role in the performance of transportation structures. He also pointed out that while cracking is commonly observed in concrete structures, it is important to understand that all cracks may have different causes and different effects on long-term performance due to the confounding effects of design, traffic loads, and climatic conditions relevant to the structure.

The common types of cracks and distinguishes these cracks based upon when they appear in concrete, before hardening or after hardening. Figure 2.1 provides common causes for cracking in concrete structures (Yoon et al. 2000).

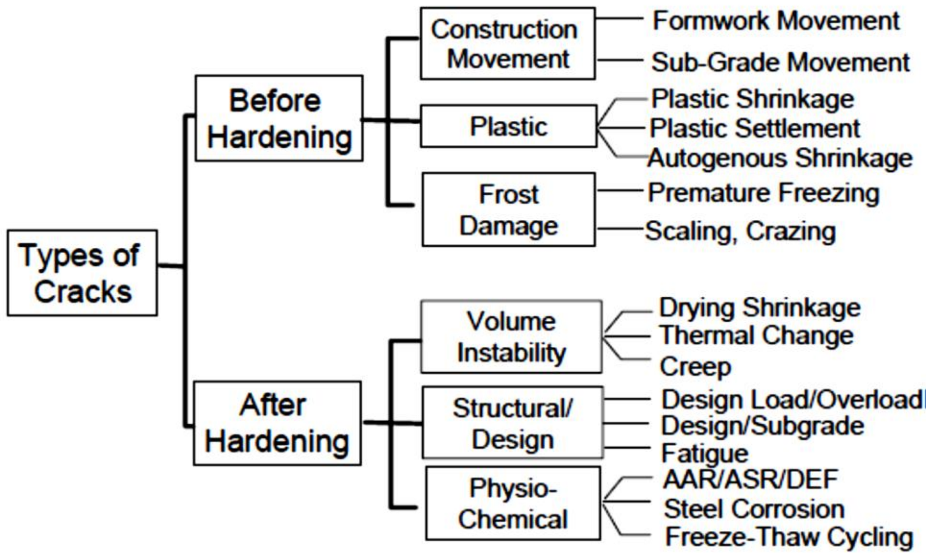

Figure 2.1: Common causes for cracking in concrete structures (Yoon et al. 2000).

Yoon et al. (2000) stated that cracks that occur before hardening are primarily due to settlement, construction movements, and excessive evaporation of water, are called plastic cracks. He also declared that plastic cracking can be predominantly eliminated through close attention to the mixture design, material placement, and curing. Cracks that occur after the concrete has hardened may be due to mechanical loading, moisture and thermal gradients, chemical reactions of incompatible materials (e.g., alkali-aggregate reactions) or environmental loading (e.g. freezing of water in unsound aggregate or paste).

Table 2.1 provides a summary of cracks due to environmental conditions, and shows when they are most likely to occur (Yoon et al. 2000).

Table 2.1: Classifications of Cracks (Yoon et al. 2000)

Type of Cracking	Form of Crack	Primary Cause	Time of Appearance
Plastic settlement	Over and aligned with reinforcement, subsidence under reinforcing bars	Poor mixture design leading to excessive bleeding, excessive vibrations	10 min to 3 h
Plastic shrinkage	Diagonal or random	Excessive early evaporation	30 min to 6 h
Thermal expansion and contraction	Transverse	Excessive heat generation, excessive temperature gradients	1 day to 2–3 weeks
Drying shrinkage	Transverse, pattern or map cracking	Excessive mixture water, inefficient joints, large joint spacings	Weeks to months
Freezing and thawing	Parallel to the surface of concrete	Lack of proper air-void system, non durable coarse aggregate	After one or more winters
Corrosion of reinforcement	Over reinforcement	Inadequate cover, ingress of sufficient chloride	More than 2 years
Alkali–aggregate reaction	Pattern and longitudinal cracks parallel to the least restrained side	Reactive aggregate plus alkali hydroxides plus moisture	Typically more than 5 years, but weeks with a highly reactive material
Sulfate attack	Pattern	Internal or external sulfates promoting the formation of ettringite	1 to 5 years

2.2.2.2 Shear and Flexural Cracking in Reinforced Concrete (RC) members

With reference to (Hassan, et al. 1991), the control of cracking in concrete structures is a desirable matter to satisfy durability and serviceability requirements. Shear sliding displacement (slip) which is related to shear opening displacement (width) is a main factor for fracturing of shear reinforcement, especially under cyclic loading. Conversely, Hassan, et al. (1991) pointed out that in the regions of constant bending moment only