STUDY ON FATIGUE DAMAGE OF CONCRETE BEAMS WITH VARIABLE NOTCHED DEPTH USING ACOUSTIC EMISSION TECHNIQUE

by

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KAJIAN KEROSAKAN KELESUAN TERHADAP KONKRIT YANG MEMPUNYAI KEDALAMAN TAKUKAN BERBEZA DENGAN MENGGUNAKAN TEKNIK PANCARAN AKUSTIK

oleh

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Tesis yang diserahkan untuk

memenuhi keperluan bagi

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TABLE OF CONTENTS

ACKNOWLEDGEMENT i

LIST OF TABLES vi

LIST OF FIGURES viii

LIST OF PLATES xi

LIST OF ABBREVIATIONS xii

LIST OF SYMBOLS xiv

LIST OF APPENDICES xvi

ABSTRAK xx

ABSTRACT xxii

CHAPTER 1: INTRODUCTION 1

1.1 General 1

1.2 Problem statement 2

1.3 Objective 3

1.4 Scope of work 4

CHAPTER 2: LITERATURE REVIEW 5

2.1 Fatigue of concrete 5

2.2 Structural health monitoring 9

2.2.1 Introduction 9

2.2.2 Methods for structural health monitoring 11

2.3 Acoustic emission technique 16

2.3.1 Introduction 16

2.3.2 Acoustic emission terminology 17

2.3.3 Types of acoustic emission wave 21

2.3.4 Source location 24

2.4 Acoustic emission analysis 25
2.4.1 b-value Analysis 25
2.4.2 Improved b-value (Ib-Value) analysis 29
2.4.3 Intensity analysis 31
2.5 Application of the acoustic emission in fatigue damage 34
2.6 Summary 36

CHAPTER 3: METHODOLOGY 38
3.1 Introduction 38
3.2 Specimen preparation 40
3.3 Concrete mix design 41
3.4 Compressive test 43
3.5 Instrumentation 45
3.5.1 Data acquisition and storage 45
3.5.2 Acoustic emission sensor and magnetic clamp 46
3.5.3 Cables 47
3.5.4 Fatigue testing machine 47
3.6 Fatigue Test 48
3.7 Instruments setup 49
3.7.1 Sensor mounting and sensitivity 50
3.7.2 Calibration 52
3.7.3 AEwin software setup 52
3.7.3 Fatigue test monitored by acoustic emission 55
3.7.4 Monitoring procedure 57
3.8 Summary 58

CHAPTER 4: RESULTS AND DISCUSSION 59
4.1 Introduction 59
4.2 Compressive test 61
4.3 Static test 62
4.4 Fatigue test 64
4.5 Acoustic emission basic signal parameters analysis 67
4.6 b-value analysis 81
4.7 Improved b-value (Ib-Value) analysis 88
4.8 Comparison between b-value and Ib-value 94
4.9 Severity analysis 96
4.10 Intensity analysis 101
4.11 Summary 109

CHAPTER 5: CONCLUSION 110
5.1 Conclusions 110
5.2 Recommendations for further research 113

REFERENCES 114
APPENDIX A: ACTIVITY DISPLAY ....
APPENDIX B: LOCATION DISPLAY ....
APPENDIX C: b-VALUE ANALYSIS ....
APPENDIX D: IMPROVED b-VALUE (Ib-VALUE) ANALYSIS ....
APPENDIX E: SEVERITY ANALYSIS ....
APPENDIX F: INTENSITY ANALYSIS ....
LIST OF PUBLICATIONS ....

LIST OF TABLES

		Page
Table 2.1	b-value quantitative results (Colombo et al. 2003)	28
Table 2.2	Significant of intensity zones (Gostautas et al., 2005)	33
Table 3.1	Details of concrete mix design	41
Table 3.2	Details of notch	43
Table 3.3	Total number of specimens tested	49
Table 3.4	Location of sensors	50
Table 4.1	Concrete cube compressive strength	61
Table 4.2	Maximum static load for each type of specimen	62
Table 4.3	AE data parameter for different type of notched beam	67
Table 4.4	b-value analysis for stage 7 (Type I beam)	82
Table 4.5	b-value data for Type I beam	83
Table 4.6	b-value data for Type II beam	84
Table 4.7	b-value data for Type III beam	84
Table 4.8	b-value data for Type IV beam	85
Table 4.9	Ib-value data for Type I beam	90
Table 4.10	Ib-value data for Type II beam	92
Table 4.11	Ib-value data for Type III beam	92
Table 4.12	Ib-value data for Type IV beam	92
Table 4.13	Severity data for Type I beam	97

Table 4.14 Severity data for Type II beam 98

Table 4.15 Severity data for Type III beam 98

Table 4.16 Severity data for Type IV beam 98

Table 4.17 Intensity data for Type I beam 104

Table 4.18 Intensity data for Type II beam 106

Table 4.19 Intensity data for Type III beam 106

Table 4.20 Intensity data for Type IV beam 106

LIST OF FIGURES

		Page
Figure 2.1	Schematic illustrating cyclic loading parameters (Fuch and Stephens, 1980).	7
Figure 2.2	Example of burst signals compared to a continuous emission of acoustic waves (Grosse and Ohtsu, 2008).	18
Figure 2.3	AE waveforms and parameter (Miller and Mclntire, 1987).	18
Figure 2.4	Longitudinal waves and shear waves (Muravin, 2010).	22
Figure 2.5	Rayleigh wave (Muravin, 2010).	23
Figure 2.6	Combination of AE waves (Muravin, 2010).	23
Figure 2.7	Typical intensity chart for concrete material (Degala et al., 2009).	33
Figure 3.1	Flow chart of the summary of work carries out.	39
Figure 3.2	Form work details.	40
Figure 3.3	Setup of the instruments.	49
Figure 3.4	Hsu-Nielsen method (ASTM, 1999).	51
Figure 3.5	AE hardware setup for AE channel setup.	53
Figure 3.6	AE hardware setup for AE timing parameter.	54
Figure 3.7	AE hardware setup for data sets/parametrics.	54
Figure 3.8	Layout page.	55
Figure 3.9	Schematic diagram of the connection.	57
Figure 4.1	The variation of ligament length (Otsuka et al., 2000).	63

Figure 4.2	Graphical representation of the loading history, load versus number of cycles.	65
Figure 4.3	Results from Type I beam (a) hits versus time (b) absolute energy versus time (c) signal strength versus time (d) amplitude versus time.	69
Figure 4.4	Results from Type II beam (a) hits versus time (b) absolute energy versus time (c) signal strength versus time (d) amplitude versus time.	72
Figure 4.5	Results from Type III beam (a) hits versus time (b) absolute energy versus time (c) signal strength versus time (d) amplitude versus time.	74
Figure 4.6	Results from Type IV beam (a) hits versus time (b) absolute energy versus time (c) signal strength versus time (d) amplitude versus time.	75
Figure 4.7	Signal strength value versus x-position (a) Type I beam (b) Type II beam (c) Type III beam (d) Type IV beam.	77
Figure 4.8	Absolute energy value versus x-position (a) Type I beam (b) Type II beam (c) Type III beam (d) Type IV beam.	78
Figure 4.9	Event location based on amplitude (a) Type I beam (b) Type II beam (c) Type III beam (d) Type IV beam.	80
Figure 4.10	b-value versus number of cycles for Type I beam.	86
Figure 4.11	b-value versus number of cycles for Type II beam.	86
Figure 4.12	b-value versus number of cycles for Type III beam.	86
Figure 4.13	b-value versus number of cycles for Type IV beam.	87
Figure 4.14	Variation of b-value versus number of cycles.	87

Figure 4.15 Ib-value versus number of cycles for Type I beam. 90

Figure 4.16 Ib-value versus number of cycles for Type II beam. 92

Figure 4.17 Ib-value versus number of cycles for Type III beam. 92

Figure 4.18 Ib-value versus number of cycles for Type IV beam. 93

Figure 4.19 Variation of b-value against number of cycles for all types of beams. 93

Figure 4.20 b-value and Ib-value against number of cycles for Type I beam. 95

Figure 4.21 b-value and Ib-value against number of cycles for Type II beam. 95

Figure 4.22 b-value and Ib-value against number of cycles for Type III beam. 95

Figure 4.23 b-value and Ib-value against number of cycles for Type IV beam. 95

Figure 4.24 Severity versus number of cycles for Type I beam. 100

Figure 4.25 Severity versus number of cycles for Type II beam. 100

Figure 4.26 Severity versus number of cycles for Type III beam. 100

Figure 4.27 Severity versus number of cycles for Type IV beam. 100

Figure 4.28 Variation of severity against number of cycles. 101

Figure 4.29 Intensity analysis for Type I beam. 105

Figure 4.30 Intensity analysis for Type II beam. 107

Figure 4.31 Intensity analysis for Type III beam. 108

Figure 4.32 Intensity analysis for Type IV beam. 108

LIST OF PLATES

		Page
Plate 3.1	Saw cutting machine.	42
Plate 3.2	Specimen with notched cut.	42
Plate 3.3	Compressive strength testing machine.	44
Plate 3.4	Hardware of the AE system, μ-SAMOS.	43
Plate 3.5	Sensor and magnetic clamp.	46
Plate 3.6	Bayonet neill-concelman (BNC) cable.	47
Plate 3.7	Fatigue machine Instron Type 8802.	48
Plate 3.8	The complete setup of the instruments.	56
Plate 4.1	Failure of specimen undergoing fatigue loading.	105

LIST OF ABBREVIATIONS

AE	Acoustic emission
SHM	Structural health monitoring
NDT	Nondestructive testing
IA	Intensity analysis
Ib-value	Improved b-value
BS EN	British Standard European Norm
TDOA	Time difference of arrival
ASTM	American Society for Testing and Materials
dB	Decibel
TOA	Time of arrival
HI	Historic index
S_r	Severity
SS	Signal strength
w/c	Water to cement ratio
HDT	Hit definition time
PDT	Peak definition time
HLT	Hit lockout time
RILEM	The International Union of Laboratories and Experts in Construction Materials, Systems and Structures
μ-SAMOS	Micro-SAMOS

PAC	Physical acoustic corporation
PCI	Peripheral component interconnect
BNC	Bayonet neill-concelman
FPZ	Fracture process zone

LIST OF SYMBOLS

S	Stress
N	Number of cycles
N_f	Number of cycles to failure
S_m	Mean stress
S_{max}	Maximum stress
S_{min}	Minimum stress
S_r	Stress range
S_a	Stress amplitude
R	Stress ratio
A	Amplitude in decibels
V	Voltage of peak excursion
V_{ref}	Reference voltage
d	Distance from first hit
D	Distance between sensors
V	Wave velocity
Δt	Time arrival delay
N	Number of events or hits
M	Earthquake (Richter) magnitude of the events or hits
b	b-value

a	Empirical constant a measure of the regional degree of seismicity
μ	Mean amplitude (AE)
σ	Standard deviation of amplitude distribution
α_1	Constant
α_2	Constant
$N(\omega_1)$	The accumulated number of AE events in which the amplitude is more than $\mu - \alpha_1\sigma$
$N(\omega_2)$	The accumulated number of AE events in which the amplitude is more than $\mu + \alpha_2\sigma$
S_{oi}	Signal strength of the *i*th hit
K	Empirically derived constant based on material
J	Empirically derived constant based on material
S_{om}	Signal strength of the *m*th hit where the order of m is based on magnitude of the signal strength
a_0	Length of notch depth
L	Cross section dimension of specimen
W	Load

LIST OF APPENDICES

Figure A.1	Results from Type I beam (Beam 2) (a) hits versus time (b) absolute energy versus time (c) signal strength versus time (d) amplitude versus time.
Figure A.2	Results from Type II beam (Beam 2) (a) hits versus time (b) absolute energy versus time (c) signal strength versus time (d) amplitude versus time.
Figure A.3	Results from Type III beam (Beam 2) (a) hits versus time (b) absolute energy versus time (c) signal strength versus time (d) amplitude versus time.
Figure A.4	Results from Type IV beam (Beam 2) (a) hits versus time (b) absolute energy versus time (c) signal strength versus time (d) amplitude versus time.
Figure A.5	Results from Type I beam (Beam 3) (a) hits versus time (b) absolute energy versus time (c) signal strength versus time (d) amplitude versus time.
Figure A.6	Results from Type II beam (Beam 3) (a) hits versus time (b) absolute energy versus time (c) signal strength versus time (d) amplitude versus time.
Figure A.7	Results from Type III beam (Beam 3) (a) hits versus time (b) absolute energy versus time (c) signal strength versus time (d) amplitude versus time.
Figure A.8	Results from Type IV beam (Beam 3) (a) hits versus time (b) absolute energy versus time (c) signal strength versus time (d) amplitude versus time.

Figure B.1 Signal strength value versus X-position (a) Type I beam (Beam 2) (b) Type II beam (Beam 2) (c) Type III beam (Beam 2) (d) Type IV beam (Beam 2).

Figure B.2 Absolute energy value versus X-position (a) Type I beam (Beam 2) (b) Type II beam (Beam 2) (c) Type III beam (Beam 2) (d) Type IV beam (Beam 2).

Figure B.3 Event location based on amplitude (a) Type I beam (Beam 2) (b) Type II beam (Beam 2) (c) Type III beam (Beam 2) (d) Type IV beam (Beam 2).

Figure B.4 Signal strength value versus X-position (a) Type I beam (Beam 3) (b) Type II beam (Beam 3) (c) Type III beam (Beam 3) (d) Type IV beam (Beam 3).

Figure B.5 Absolute energy value versus X-position (a) Type I beam (Beam 3) (b) Type II beam (Beam 3) (c) Type III beam (Beam 3) (d) Type IV beam (Beam 3).

Figure B.6 Event location based on amplitude (a) Type I beam (Beam 3) (b) Type II beam (Beam 3) (c) Type III beam (Beam 3) (d) Type IV beam (Beam 3).

Figure C.1 b-value versus number of cycles for Type I beam (Beam 2).

Figure C.2 b-value versus number of cycles for Type I beam (Beam 3).

Figure C.3 b-value versus number of cycles for Type II beam (Beam 2).

Figure C.4 b-value versus number of cycles for Type II beam (Beam 3).

Figure C.5 b-value versus number of cycles for Type III beam (Beam 2).

Figure C.6 b-value versus number of cycles for Type III beam (Beam 3).

Figure C.7 b-value versus number of cycles for Type IV beam (Beam 2).

Figure C.8 b-value versus number of cycles for Type IV beam (Beam 3).

Figure D.1 Ib-value versus number of cycles for Type I beam (Beam 2).

Figure D.2 Ib-value versus number of cycles for Type I beam (Beam 3).

Figure D.3 Ib-value versus number of cycles for Type II beam (Beam 2).

Figure D.4 Ib-value versus number of cycles for Type II beam (Beam 3).

Figure D.5 Ib-value versus number of cycles for Type III beam (Beam 2).

Figure D.6 Ib-value versus number of cycles for Type III beam (Beam 3).

Figure D.7 Ib-value versus number of cycles for Type IV beam (Beam 2).

Figure D.8 Ib-value versus number of cycles for Type IV beam (Beam 3).

Figure E.1 Severity versus number of cycles for Type I beam (Beam 2).

Figure E.2 Severity versus number of cycles for Type I beam (Beam 3).

Figure E.3 Severity versus number of cycles for Type II beam (Beam 2).

Figure E.4 Severity versus number of cycles for Type II beam (Beam 3).

Figure E.5 Severity versus number of cycles for Type III beam (Beam 2).

Figure E.6 Severity versus number of cycles for Type III beam (Beam 3).

Figure E.7 Severity versus number of cycles for Type IV beam (Beam 2).

Figure E.8 Severity versus number of cycles for Type IV beam (Beam 3).

Figure F.1 Intensity analysis for Type I beam (Beam 2).

Figure F.2 Intensity analysis for Type I beam (Beam 3).

Figure F.3 Intensity analysis for Type II beam (Beam 2).

Figure F.4 Intensity analysis for Type II beam (Beam 3).

Figure F.5 Intensity analysis for Type III beam (Beam 2).

Figure F.6 Intensity analysis for Type III beam (Beam 3).

Figure F.7 Intensity analysis for Type IV beam (Beam 2).

Figure F.8 Intensity analysis for beam Type IV (Beam 3).

KAJIAN KEROSAKAN KELESUAN TERHADAP KONKRIT YANG MEMPUNYAI KEDALAMAN TAKUKAN BERBEZA DENGAN MENGGUNAKAN TEKNIK PANCARAN AKUSTIK

ABSTRAK

Konkrit adalah bahan utama yang digunakan di dalam pembinaan termasuklah di dalam infrastruktur major dan infrastruktur minor seperti jambatan, lapangan terbang, jalan raya dan struktur lepas pantai yang dikenakan beban lesu. Pada masa kini, kajian kerosakan kelesuan terhadap struktur konkrit dengan menggunakan ujian tanpa musnah telah dikaji dengan meluas. Pancaran akustik (AE) adalah salah satu teknik ujian tanpa musnah yang berkesan untuk mengkaji kehadiran kerosakan di dalam struktur konkrit. Kajian ini adalah bertujuan untuk mengkaji penggunaan teknik AE di dalam sistem pemantauan struktur kesihatan yang dikenakan beban lesu terhadap konkrit yang mempunyai takukan. Objektif utama kajian ini adalah untuk mengkaji dan menyelidik keupayaan AE dalam menentukan tahap kerosakan empat jenis rasuk konkrit yang mempunyai nisbah kedalaman takukan kepada keitinggian rasuk yang berbeza yang dikenakan bebanan lesu.Empat jenis konkrit biasa yang dikaji telah dibina dengan berdimensi sama tetapi dibezakan oleh nisbah kedalaman takukan kepada ketinggian rasuk. Jumlah keseluruhan rasuk yang diuji adalah sebanyak enam belas rasuk dengan dikenakan terhadapnya bebanan lesu yang berbeza dan semakin meningkat amplitud beban berkitar secara berulangan dan berterusan dengan menggunakan mesin hidraulik kawalan servo yang mempunyai sistem tertutup. Kesemua sampel kajian diuji dengan mengenakan pembebanan lentur tiga titik dibawah bebanan monotonik dan berkitar dimana setiap jenis rasuk yang bertakuk mengandungi tujuh sampel, tiga rasuk diuji dibawah bebanan monotonik dan empat sampel rasuk diuji di bawah bebanan lesu. Di dalam proses mengumpul dan merekodkan kesemua isyarat AE data yang terlibat di dalam kajian ini, sensor jenis

R6I dan sistem AE digital Micro-SAMOS (μ-SAMOS) digunakan bersama perisian komputer AEwin untuk menganalisis data. Disamping itu, kaedah-kaedah b-value, Ib-value, analisis kerosakan dan analisis keamatan digunakan bagi menentukan tahap kerosakan terhadap rasuk bertakuk yang dikenakan bebanan lesu. Teknik AE telah berjaya digunakan untuk menentukan mekanisme kerosakan kelesuan dan mengelaskan tahap kerosakan semasa bebanan lesu ditingkatkan pada rasuk konkrit yang bertakuk.

STUDY ON FATIGUE DAMAGE OF CONCRETE BEAMS WITH VARIABLE NOTCHED DEPTH USING ACOUSTIC EMISSION TECHNIQUE

ABSTRACT

Concrete structure is the main materials used in constructions including the major and minor structure such as bridges, airports, highways pavements and offshore structure where this structures are subjected to the fatigue load. Concrete structure study on fatigue damaged by utilizing non-destructive testing (NDT) on concrete structure has been widely explored nowadays. Acoustic emission (AE) is one of the powerful NDT tool used for evaluating the damage occurrence in concrete structure. The present study emphasised on the using of AE in Structure Health Monitoring (SHM), on the notched beam samples undergoing fatigue loading. The main interest of this study was to investigate the capability of AE in quantifying the damage level of variable notch to depth ratios of concrete specimens which were subjected to fatigue loading. The four types of plain concrete beams with the same dimensions (100 x 200 x 600mm) but different notch to depth ratios was tested. A total of sixteen samples were tested under variables and increasing amplitudes of cyclic loading in closed loop servo-controlled hydraulic machine. The studied samples were tested in three points bending setup under monotonic and fatigue cyclic loading with each type of the notched beams contained seven beams; three beams for monotonic loading and four beams for fatigue cyclic loading. In order to detect and to collect the AE data, Micro-SAMOS (μ-SAMOS) digital AE system and R6I sensor type were used while data analyses were carried out using AEwin software. In addition, the b-value, the Ib-value, severity analysis and intensity analysis methods were applied to quantify the fatigue damage level of the notched beams undergoing fatigue loading. The AE technique was

successfully used to determine fatigue damage mechanism and to classify the damage level occurrence during an increasing cyclic loading on notched concrete beams.

CHAPTER 1: INTRODUCTION

1.1 General

Concrete structure is an important material used in the construction of major and minor infrastructures in the field of civil engineering. Concretes, which are the main materials, used in constructions of flyovers, bridges, and airport runaways. These structures must be able to sustain continuous large number of repeated and cycling loadings caused by vehicular traffic load, wave load and wind loading.

The cyclic loads give the possibilities of the structure to undergo fatigue failure. The deterioration of global concrete structures requires effective damage evaluation and repair methods. The ability of the detection of the structural damage at the earliest possible stage have been of interest throughout various engineering. Thus, the subject of Structural Health Monitoring (SHM) is a powerful non-destructive evaluation technique to ensure the safety and reliability of the structure in civil engineering.

Acoustic emission (AE) technique is one of the impressive technique in SHM. AE monitoring technique evaluates the signals generated within the structure, such as the crack growth under cyclic loads. It is able to describe the fracture and failure process (Kurz, 2006). This unique monitoring mechanism distinguishes itself from other non-destructive test methods making it the only method capable of giving real time information on the condition of the damaged structure (Kurz, 2006). In addition, this technique is also able to detect various types of damages such as fatigue cracks growth, corrosions and delamination.

1.2 Problem statement

In civil engineering, structures such as bridges, highways and marine structures are always subjected to cyclic fatigue loadings. Fatigue is a process of progressive permanent internal structural change due to repetitive loading. Fatigue may cause the structure to face structural fatigue failure. The fatigue loading is able to bring significant changes in the characteristics of the structures in which affects the stiffness, toughness and durability of the structures.

The fatigue mechanism is well understood phenomenon in metals. This is due to the characteristic of metal whereby the metal quality is highly controlled during manufacturing and thus has fewer defects. On the other hand, concretes have numerous flaws such as voids with various sizes, pre-existing of the micro-cracks in aggregates, and lack of complete bonds between the aggregate and matrix which may initiate a crack. The mechanism of fatigue behaviour of concrete is not well understood due to the heterogeneous microstructure characteristic of concretes.

In a concrete structure, the cracking is normally developed beyond the tensile strength of the material and the crack propagates in a direction which is perpendicular to the maximum stress. Generally, the failure of concrete structure is caused by the fatigue ruptures of concrete (Murthy et al., 2012).

The ageing concrete structure is facing several types of damage mechanism and deterioration during service. It is important to monitor and assess any damage in order to assist maintenance strategies and to provide accurate remaining life prediction.

With regards to these matters, a reliable evaluation method using AE technique is required to access the structural integrity and to monitor the damage in concrete structure undergoing fatigue cyclic loads. The quantification of the damage accumulation is needed to translate it into levels of deterioration so that appropriate actions can be undertaken to ensure the structures' safety.

The b-value analysis, Ib-value analysis, severity analysis and intensity analysis are applied in this study in order to present the level of deterioration and reliability of concrete structures. This study focused on the analysis of the damage detection in which analyses the output using signal based approach analysis.

1.3 Objective

The objectives of this research are listed below:

1. To study the effect of notch to depth ratios on the brittleness of concrete structures undergoing fatigue loads.
2. To study the characteristics of AE basic signal parameters such as AE signal strength, AE amplitude and AE absolute energy of plain concrete beam under fatigue loads.
3. To evaluate the fatigue damage in plain concrete beams with variable notch to depth ratios by using the b-value analysis, Ib-value analysis, severity analysis and intensity analysis.

1.4 Scope of work

The scope of work will focus on the fatigue testing of plain concrete with notch at the middle bottom of the beam. The notch acts as stress concentrator which is lower stress limit (Mallory, 2006). Moreover, the presence of notch is an effective way to initiate fatigue cracks. Cracks are initiated at notches due to the stress and strain concentrations (Zhang, 2011). Fatigue cracks usually appear near to the stress concentrators which lead to the appearance of fatigue cracking. Examples of crack initiators are holes, welds, notches, or regions where material structure changes (Peeker, 1997).

Sixteen samples of plain concrete beams were tested under fatigue three points bending test. The cyclic load used in this study is fatigue loading with variables and increased amplitude loading. Sixteen samples of beams in which four of them have different sizes of notch were tested under the variables and increased amplitude of loading. The specimens were tested in a closed loop servo-controlled hydraulic machine with a capacity of 250kN and with the presence of AE technique. The AE digital system was used to detect and to collect data throughout the test.

The fatigue test which used variable amplitude of loading was simulated in a range of cyclic load applied on structures which are subjected to fatigue load. Four types of analyses had been carried out in this part in order to quantify the damage occurred on plain with notch concrete beam. The analyses methods used were b-value analysis, Ib-value analysis, severity analysis and intensity analysis. These four analyses were selected due to their relevancy to this study.

CHAPTER 2: LITERATURE REVIEW

2.1 Fatigue of concrete

Fatigue is a type of fracture that occurs in materials subjected to change or various stresses over time (Kelly, 1997). Shah et al. (2012) defined fatigue as a process of progressive permanent internal structure change due to repeated loadings. The name fatigue is based on the concept that a material becomes tired and fails at a stress level below the nominal strength of the material. Failure due to fatigue mechanism is a major problem in many modern structures. Concrete bridges, airports, highway pavements and offshore structures are among the examples of structures subjected to repetitive loads of high stress amplitude rising from moving vehicles and ocean waves. Therefore, many researches have been carried out in the field to study the behaviour and mechanism of fatigue.

The relationship between stress and cycles to failures normally described by using S-N curves which is also known as Wöhler curve. This curve represents the relationship between the applied maximum stress, S, and the number, N, number of cycles to failure (Kelly, 1997).

According to Campbell (2008), a large number of cycles to failure is defined as high cycles fatigue which happens in the case where the number of cycles to failure, N_f, is greater than 10^5. On contrary, small number of cycles to failure indicated low cycle fatigue where the number of cycles to failure, N_f, is less than 10^5.

Applied stresses may be flexural (bending), axial (tension-compression), or torsional (twisting) in nature. Campbell (2008) mentioned that generally, there are three modes of fluctuating stress-times which might possibly occur, the first type is constant amplitude where the alternating stress varies from a maximum tensile stress to a minimum compressive stress of equal and same magnitude of loading.

The second type that is repeated constant amplitude which occurs when the maximum and minimum stress are asymmetrical relative to the zero stress level The final type is random cycling where the stress level may vary randomly in amplitude and frequency.

Normally, the tensile stress is considered as a positive stress whereas compressive stress is considered as negative stress. The term Fatigue Life (N_f) is described as the total number of stress cycles required to cause failure. According to Fuch and Stephens (1980) the fatigue life can be divided into three distinct stages which are:

i) Crack Initiation: Number of cycles required to initiate a crack. This results from dislocation pile-ups and/or imperfections such as surface scratches, voids, etc.

ii) Crack Growth: Number of cycles required to grow the crack in a stable manner to a critical size. Commonly this stage is controlled by stress level. Since most common materials contain flaws, the prediction of crack growth is the most extensively studied aspect of fatigue.

iii) Rapid Fracture: Very rapid critical crack growth occurs when the crack length reaches a critical value leads to fracture.

Shah et al. (2012) proposed that fatigue failure mechanism in concrete can be separated into three clear stages. The first stage involves with the flaw initiation stage which is associated to the formation of weak region. The second stage occurs due to progressive growth of initial flaw to a critical size and this stage is referred to as crack propagation stage. In the third stage, there is unstable rapid propagation of major cracks which leads to failure.

Figure 2.1 shows the schematic illustration of cyclic loading parameters.

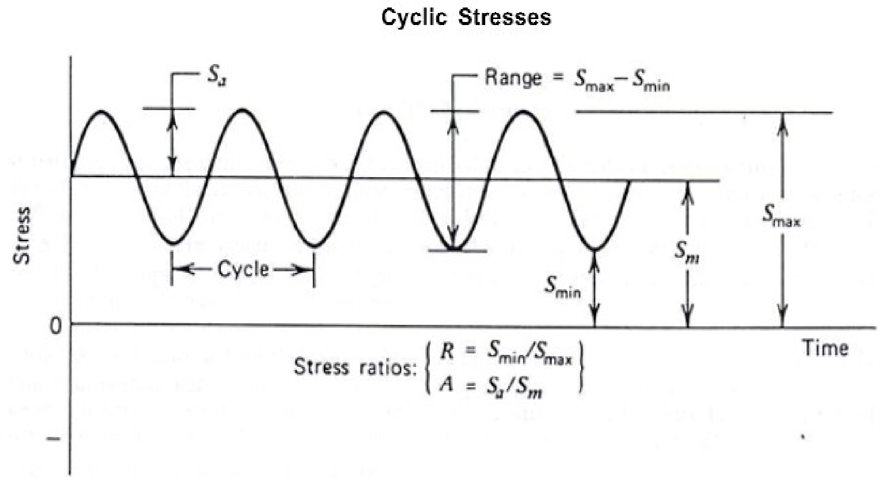

Figure 2.1: Schematic illustration of cyclic loading parameters (Fuch and Stephens, 1980).

The following parameters are utilized to identify fluctuating stress cycles (Campbell, 2008):

$$\text{Mean stress } (S_m)\text{: } S_m = \frac{S_{max} + S_{min}}{2} \tag{2.1}$$

$$\text{Stress range } (S_r)\text{: } S_r = S_{max} - S_{min} \tag{2.2}$$

$$\text{Stress amplitude } (S_a)\text{: } S_a = \frac{S_{max} - S_{min}}{2} \tag{2.3}$$

$$\text{Stress ratio (R): } R = \frac{S_{min}}{S_{max}} \tag{2.4}$$

Where:

S_{max} = Maximum stress (N/mm^2)

S_{min} = Minimum stress (N/mm^2)

Several researchers such as Shah et al. (2012), Sain et al. (2008), Deng et al. (2005), Toumi et al. (1998) and Oh et al. (1986) had performed the research to evaluate the fatigue performance on plain concrete.

In fatigue test, few sets of stress ratios are used for investigations. The selection of stress ratio is based on the tested material case study. Toumi et al., (1998) had decided to use the stress ratio of 0.93, 0.87, 0.81, 0.76 and 0.70 for upper boundary of cyclic load and selected the stress ratio 0.23 for lower boundary of cyclic load on all notched plain concrete specimens. A set of stress ratio consisting of 0.6, 0.65, 0.7, 0.8 and 0.9 were used for plain concrete specimens while 0.7, 0.8 and 0.9 were used for fibre reinforced concrete by Deng et al., (2005) in their study. Antonaci et al., (2012) had chosen 0.5 stress ratio of the maximum stress to be carried out on brickwork wall specimens.

In another case, Shah et al. (2012) conducted fatigue testing on notched plain concrete by using variable amplitude loading with step wise increase of loads. The amplitude loading used in this research differs from other researches which study the behaviour of concrete under fatigue testing. The load is increased by 0.5kN after every 500 cycles. The minimum load which is 0.2kN is kept constant for the cycles and specimens. The increased amplitude loading simulated different types of impact loadings on the structure.

The frequency of sinusoidal cyclic fatigue loading is decided based on the material, load range and fatigue life. Deng (2005) conducted fatigue fracture test by using sinusoidal wave form with a frequency of 2 Hz on both plain concrete and composite with carbon fibres samples. Yu et al. (2013) also used 2Hz frequency on steel specimens. However, Shah et al. (2012) and Toumi et al. (1998) performed test under load control with sinusoidal wave form of 1Hz frequency on plain concrete structures. Naaman et al. (1998) varied the range of frequency cyclic fatigue loading between 1Hz to 5Hz based on load range and expected fatigue life.

2.2 Structural health monitoring

The request of structural health monitoring (SHM) for evaluation of structural reliability is nowadays constantly increase and it is necessary to propose method of testing associated with the building and follow up of engineering structure.

2.2.1 Introduction

SHM is applied in various engineering fields to diagnose the condition of a structure or material. There are a few ways to define SHM as there is no standard definition of SHM found in the literature. Farrar and Worden (2007) described that SHM is a process of implementing a damage identification strategy in engineering infrastructure. They defined damages as changes introduced into the systems, which include changes to the boundary conditions and the system connectivity which adversely affect the system's performance.

In addition, Balageas (2006) mentioned that SHM aimed to give, at every moment during the life of a structure, a diagnosis of the "state" of the constituent materials, of the different parts, and of the full assembly of these parts constituting the structure as a whole. Whilst, Brownjohn (2007) described SHM as a continuous system identification of a physical or parametric model of the structure using time dependent data.

From the definition of SHM presented by several authors, SHM is a system that has the capability to collect time dependent data and is able to interpret the data in terms of structural performance states (Lu, 2008). Several techniques are available in SHM and most of them were non-destructive technique (NDT) which is widely used in this application as it is not harmful to the monitored structure.

SHM is widely applied to monitor bridges, dams, aircraft and pipelines. SHM is carried out to detect any damage occurred in the earliest stage. A few ranges of damage detections were applied in SHM.

NDT is a non-invasive technique used to determine the integrity of a material, component or structure. It is able to quantitatively measure certain characteristics of a structure or an object without causing harm, stress or destroying the test object (Diederichs, 2007).

The request of NDT for evaluation of structural stability and structural integrity is of high demand at present time. As the increasing worldwide demand in utilizing concrete in the construction, it is necessary to propose new method to evaluate the compatibility and stability of the structure without destroying it. The cracking of the concrete is the most serious and costly form of damage to concrete structures. NDT plays an extremely important role to ensure a cost-effective and safety matters.

2.2.2 Methods for structural health monitoring

There are several types of NDT methods applied. The reliability of the selected NDT method is an important issue in this application. However, it is only significant if the comparison of NDT method is referred and compared with the same task. Each of the NDT method has its own advantages and disadvantages depending on the materials and conditions of the tested specimens or structures. Some NDTs are preferable than others for a specific particular application while some NDTs are not well suited. The NDT methods are frequently used in concrete are visual inspection, rebound hammer, tomographic technique, ultrasonic pulse velocity and acoustic emissions (AE).

The fundamental of NDT method is the visual inspection method. Visual testing is the most reliable and significant NDT method. This method allows valuable information to the well trained eye (Ibrahim et al., 2002). In order to have better results in this inspection, magnifying glass is often used. Visual information feature is related to the workmanship during the construction and material deterioration. The deteriorations which normally develop in concrete materials are cracks, pop-outs and spalling.

Visual information gives information regarding preliminary indication to the condition of the structure and it allows formulation of a subsequent testing programmed (Ibrahim et al., 2002). The importance and benefits obtained from the visual inspection should not be ignored and a further inspection should be carried out. A wrong conclusion is mistakenly made due to the ignored of what appears on the structure from the results of visual inspection.

A detailed and full record of all observations from visual inspection should be made as the inspection proceeds to the next level. The damage location detected should be marked and addressed.

The presence of certain features for existing structure requires further investigation in generally indicated by visual inspection. This technique is considered to be the single most important component of routine maintenance. The visual inspection will also provide the basis for judgments relating to access and safety requirements when selecting test methods and test locations (Ibrahim et al., 2002).

An affordable and economical NDT method is the rebound hammer method. The rebound hammer is normally used to compare the various part of concrete structure and indirectly assess the concrete strength and the quality of the concrete (Hannachi et al., 2012). This method is able to cover a large area in a short period.

The rebound hammer consists of a spring controlled mass that slides on a plunger within a tubular housing. Once the plunger is pressed against the surface of concrete, it retracts against the force of the spring. After complete retraction, the spring is automatically released. On the spring controlled mass rebound, it takes the rider with it along the guide scale. By pushing a button, the rider can be held in position to allow readings to be taken (Kishore, 2002).

The reading of this NDT method is sensitive to the variation of the concrete surface. Thus several readings are required to be recorded at the necessary locations on the surface of the concrete. The average value is then determined. Standard from BS EN 12504-2 (58), (2001) recommends that not less than nine readings should be taken over an area of not exceeding 300mm square, with the impact points not less than 25mm from each other or from an edge. The results obtained from the rebound hammer technique are significantly influenced by several factors. The factors that influenced this technique are smoothness of test surface; shape, rigidity and size of the specimens; age of the specimen; internal moisture conditions of the concrete and surface; types of cement and types of coarse aggregate; carbonation of concrete surfaces (Bungey et al., 2006).

As a conclusion, the rebound hammer is a valuable qualitative tool since this method measures the relative surface hardness of the concrete. This test is necessary to be included with other tests such as compression test in order to confirm the actual strength of the concrete.

Recently, tomographic technique emerged as one of a common NDT method (Chai et al., 2011). Tomographic technique allows visualization, either in by cross sectional or three dimensional structure of structural interior in order to have the better identification of anomalous regions and determination of physical properties of measured area (Bond et al., 2000). Dines et al., (1979) explained that tomography is a technique for data processing that provides cross sectional images from the analysis. Tomography can be implemented in three basic forms: (i) parallel scanning and rotation which is usually used in medical computerized tomography; (ii) tow sided transmission employing two linear arrays of sensors; and (iii) four sided transmission (Bond et al., 2000).

The deterioration of the structure can be detected by using the results obtained from these methods. The resulting tomography has the potential to provide cross-sectional images of the structure that can be used to locate cracks, identify regions of structural damage, and other anomalies deep inside a massive concrete structure (Bond et al., 2000). Chai et al. (2011) used tomography method to identify the location of defect by applying the attenuation tomography as a complementary method to the travel time tomography. This method was found to be more promising in the determination of the location of flaws in concrete specimens.

The tomography method is also able to detect the flaws but this method does not show the exact location of the flaws. Furthermore, this method is only applicable if the structure is accessible from both sides of the structure. This method is relatively time consuming for thick structure but there is possible radiation hazard for the inspector.

Ultrasonic testing is one of the NDT method used in detection of flaws in materials. Ultrasonic testing uses the transmission of high-frequency sound waves that propagates in materials to detect and locate the discontinuities and changes in materials. This method is applicable for both non-metallic and metallic materials. By this method, surface and internal flaws such as voids, cracks, seams, blow holes, inclusions, and lack of bond can be precisely evaluated. High frequency acoustic waves induced by piezoelectric transducer have been utilized in ultrasonic testing.

A proportion of the signal energy is passed through to the other medium as the ultrasound signal travels from one medium into another medium, while the rest of the energy is reflected back. From the speed of ultrasound signals in various material densities and the properties of the reflected signal which has been measured including time difference of arrival (TDOA) and signal magnitude useful information about the examined material can be obtained. This information includes thickness, volume, temperature and number of various mediums was being able to be computed (Kouche et al., 2012).

The measurement of the velocity of ultrasonic pulses of longitudinal vibrations passing through concrete may be used for the following applications (Ibrahim et al., 2002):

- o Determination of the uniformity of concrete in and between members.
- o Measurement of changes occurring with time in the properties of concrete.
- o Correlation of pulse velocity and strength as a measure of concrete quality.
- o Determination of the modulus of elasticity and dynamic Poisson's ratio of the concrete.

The method is not very successful when it is applied to structures with cracks because the cracked faces are usually sufficiently in contact with each other. This allows the pulse energy to pass unimpeded across the cracks. If the concrete is surrounded by water and such that the crack is filled with water, the crack is undetectable since ultrasonic energy can travel through a liquid (Ibrahim et al., 2002). On top of that, this method is not able to detect the real time crack generation (Kaphle, 2012).

Another method of NDT is AE. AE is one of the effective methods which is used for real-time monitoring system (Shahidan et al., 2012). In addition, Shahidan (2012) reported that AE is differ from the others NDT methods due to this technique was able to detects the irreversible and real occurrence of damaged in the structure been tested. Furthermore, AE also able to be used for local, global and continuous monitoring.

Furthermore, the AE technique have the high sensitivity and able to detect the crack growth at very early stages. Finlayson et al., (2000) reported that AE has been found to be sensitive enough to detect newly formed crack surfaces down to a few hundred square micrometers and less.

2.3 Acoustic emission technique

AE technique is one of the automated method to monitor the structural health in the engineering structures. AE is a sensitive NDT technique capable of detecting many types of defects in various materials.

2.3.1 Introduction

AE technique is a powerful tool for NDT. Plastic deformation, fracture, crack initiation and growth are a few examples of phenomena occurred in AE (Raj, 2002). AE is classified as a “passive” NDT whereby it is usually had been used to identify the damage only (Grosse and Ohtsu, 2008). The passive nature of AE makes this technique an ideal technique for the monitoring and damage detection (Nair et al., 2010). AE technology was discovered since middle of the 20th century.

The dynamic nature of AE makes it a highly potential technique for monitoring the integrated critical structures and components in various industries such as nuclear and fossil fuel, power plants, aerospace, chemical, petrochemical, transportation, manufacturing and fabrication (Raj, 2002, Kaphle, 2012).

According to Raj (2002), the technique for monitoring and evaluating structural integrity by using AE technique is an excellent technique compared to other techniques because of its capability for:

1. Continuous monitoring.
2. Inspection of complete volume of component.
3. Issue of advance warning.
4. Detection and location of any crack initiation and propagation and system leaks.

5. The signals originate in the materials itself, not from an external source.

The AE technique is also regarded as a powerful technique of NDT method for examining the behaviour of materials deforming under stress (Nair, 2006). This technique can be used to listen to the events that lead to failure of materials using sensor act like material such as stethoscope (Nair, 2006).

2.3.2 Acoustic emission terminology

AE is technically defined as a class of phenomenon whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material (Carpinteri et al., 2009, Nair et al., 2010, American Society for Testing and Materials (ASTM) E 1316, 2006). The stress wave that propagates through the solid is caused by the energy released during the deformation process (Shah et al., 2010). The AE technique is different from other NDT because the AE technique is able to detect the energy released from the interior of tested object rather than external source. This powerful technique is also able to detect the dynamic process associated to the degradation of structural integrity (Shah et al., 2010).

There are two types of AE, namely, burst emission and continuous emission (Raj, 2002, Grosse and Othsu, 2008, Nor et al., 2011). Figure 2.2 shows the examples of burst signals and continuous emission of acoustic wave. Discrete or burst type of the AE can be described by a few parameters as shown in Figure 2.2. Continuous emission is characterised by low amplitude emissions. The amplitudes vary with AE activity. Burst emissions are characterized as short duration and high amplitudes pulses due to discrete release of strain energy. This type of emission occurs during crack initiation and propagation and the AE technique are better suited for this burst signal.

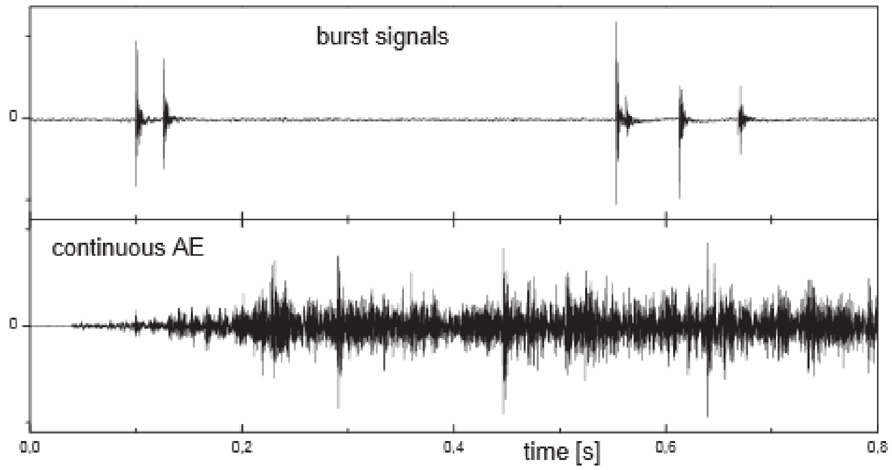

Figure 2.2: Example of burst signals compared to a continuous emission of acoustic waves (Grosse and Ohtsu, 2008).

The burst emission can be summarised by a number of basic parameters such as peak signal amplitude, rise-time, counts, duration and threshold. AE monitoring is usually carried out in the continuous background noise. The threshold set above the background noise. Important signal parameters include amplitude, duration, signal strength, and signal energy. Features of a typical AE signal are shown in Figure 2.3.

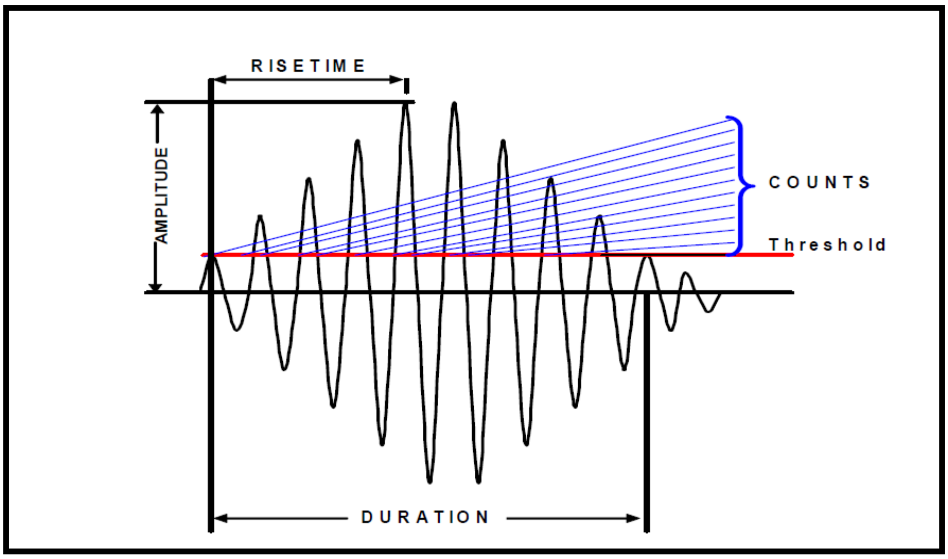

Figure 2.3: AE waveforms and parameter (Miller and Mclntire, 1987).

Figure 2.3 shows a typical AE electrical signal as a voltage versus time curve. The electrical signal identified as an AE signal generated by fracture phenomenon (Grosse and Ohtsu, 2008). AE parameters in the time domain are used to characterise the AE source mechanism such as crack growth and to determine the degree of its severity. Due to the complexity of AE signals, it is usually advantageous to study a combination of these parameters to establish source characterisation correlations.

Hit is defined as the detection and measurement of an AE signal on an individual sensor channel (ASTM E 1316, 2006). Grosse and Ohtsu (2008) explained hit as a signal that exceeds the threshold level and cause a system channel to accumulate data. It is frequently used to show the AE activity with counted number for a period.

AE event is described as local material change giving rise to AE (ASTM E1316). A single event can result in multiple hits at one or more sensors used (Xu, 2008).

In addition, voltage threshold is characterised as the voltage level on an electronic comparator such that signals with amplitudes larger than this level will be recognised. The voltage threshold may be user adjustable, fixed, or automatic floating (ASTM E 1316, 2006). It is usually used to selectively reject signals with smaller amplitudes, which may not provide useful information because it often corresponds to ambient, electronic, or electromagnetic noise. Background noise may be effectively eliminated during AE data acquisition by rejecting signals with peak amplitude voltage levels lower than a suitable threshold level, which is usually set slightly above the normal background noise level (Fowler et al., 1989).

Signal amplitude is defined as the maximum amplitude of AE wave and is measured in decibel (dB_{AE}) (Shah et al., 2010). This is an important parameter in AE inspection because it determines the detectability of the signal (Weber, 2011). Decibels are relative measures; each decibel increment corresponds to an increase of 12.2%. Voltage is converted to decibels using the following equation:

$$A = 20 \log \frac{V}{Vref} \tag{2.5}$$

Where:

A = Amplitude in decibels, (decibel scale runs from 0 to 100).

V = Voltage of peak excursion, and

V_{ref} = Reference voltage.

Peak amplitude of an AE signal is an indication of the source intensity (Pollock, 1995). Due to the various factors that may affect a transducer's response, peak amplitude of an individual signal may not provide significant information with regard to the source. However, when the amplitude related data are evaluated by means of statistical methods it could yield useful information (Pollock, 1981). Analysis of amplitude distribution may be used to increase the degree of reliability of the AE data (Fowler and Gray, 1979).

The time between AE signal start and AE signal end is called as duration (ASTM E 1316, 2006). It is the length of time from the first threshold crossing to the last threshold crossing of the signal. It is usually reported in microseconds. Duration of a signal is affected by the selection of the threshold level. The various sources of AE may produce different signal duration. Mechanical noise sources normally generate long-duration signals while the signal duration for an electrical pulse is generally less than 10 microseconds (Pollock, 1995).

Furthermore, rise-time is described as the time between AE signal start and the peak amplitude of that AE signal (ASTM E 1316, 2006). It is measured in microseconds. Rise-time measurement for AE signals may yield information similar to that obtained from signal duration.

Signal strength is defined as the measured area of the rectified AE signal, with units proportional to volt-sec (ASTM E 1316, 2006). Signal strength sometimes referred to as relative energy relates to the amount of energy released by the specimen (Nor et al., 2011). Signal strength is a function of both the amplitude and duration of the signal (Xu, 2008). As such, it is a much better measure of total acoustic emission than duration or amplitude alone. It is often used in evaluation criteria for AE testing of structures.

Signal energy is the energy contained in a detected acoustic emission burst signal, with units usually reported in joules or values that can be expressed in logarithmic form (ASTM E 1316, 2006).

The number of times the AE signal exceeds the threshold level during any selected portion of a test is defined as AE count (ASTM E 1316, 2006).

Frequency is the number of cycles per second of the pressure variation in a wave. Commonly, an AE wave consists of several frequency components which is average frequency, initial frequency and reverberation frequency.

2.3.3 Types of acoustic emission wave

AE waves can be classified as elastic waves. There are four main types of AE waves, namely, longitudinal waves, transverse waves, surface waves and Lamb (plate) waves (Kaphle, 2012).

Longitudinal or P-waves is the wave in which the oscillations occur in the direction of the wave propagation. The P-waves or called as compression wave travel at higher velocity than the shear waves. Thus P-waves arrive first at the sensor followed by shear waves or called as S-waves (Grosse and Ohtsu, 2008).

S-waves are also known as transverse waves is the wave in which the oscillations occurring perpendicular to the direction of the wave propagation (Kaphle, 2012).

The longitudinal wave can be propagated well through a solid and liquid medium due to the mechanism of propagation that involves the compression and expansion of particles (Muravin, 2010). Whilst, the transverse wave is weak when propagated in the liquid medium (Muravin, 2010). A diagrammatic representation of longitudinal waves and shear waves is shown in Figure 2.4.

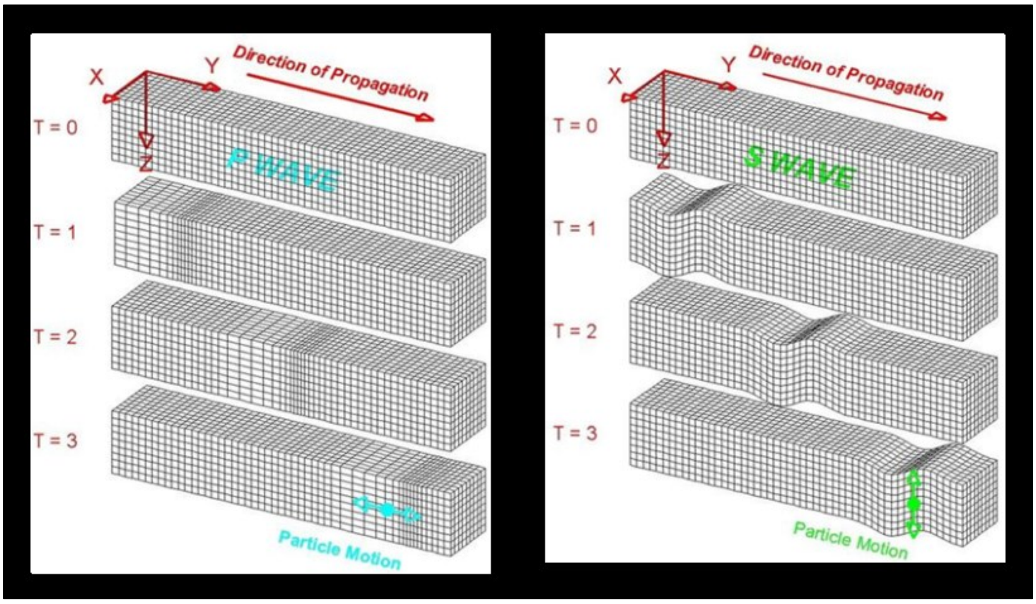

Figure 2.4: Longitudinal waves and shear waves (Muravin, 2010).

Rayleigh or surface wave is the wave with elliptic particle motion in planes normal to the surface and parallel to the direction of the wave propagation (Muravin, 2010). Figure 2.5 shows the propagation of surface waves. Figure 2.6 shows the propagation of combination of AE waves.

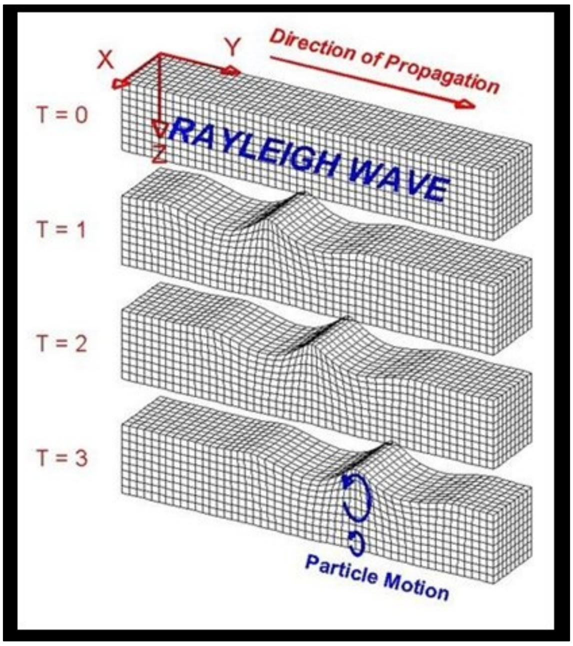

Figure 2.5: Rayleigh wave (Muravin, 2010).

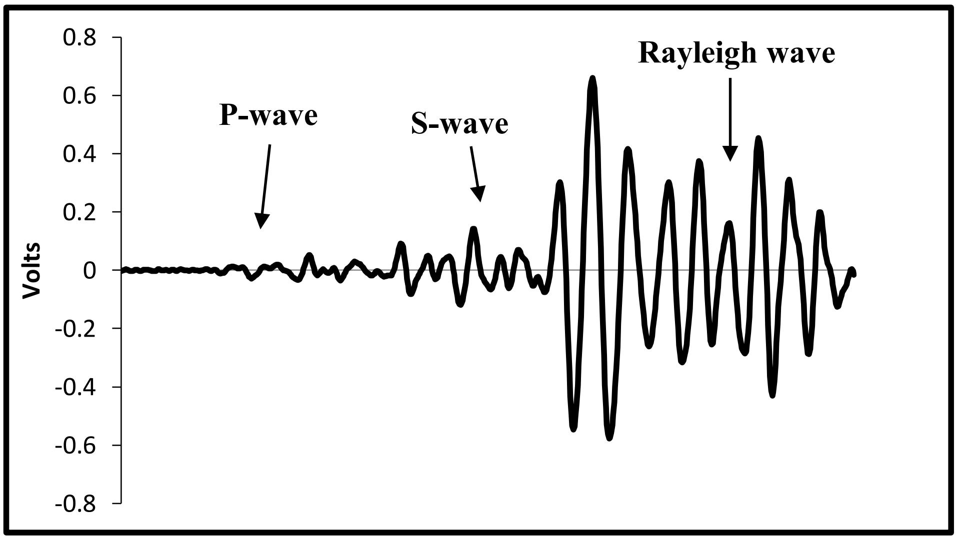

Figure 2.6: Combination of AE waves (Muravin, 2010).

2.3.4 Source location

The ability to locate sources of AE is one of the most important functions of the multichannel instrumentation system used in AE application process (Bruhns and Meschke, 2009). Source location is an important aspect that needs to be determined first for damage assessment. Location can be defined as the determination of the spatial position of an AE source from arrival time measurement using an array of sensors (Miller and Mclntire, 1987).

There several method in timing technique which is cross-correlation, coherence and time of arrival (TOA) that can be used. TOA can be used to analyse the source location for one, two and three dimension. The TOA technique is the technique used in this analysis.

Most of existing location procedures requires evaluation of time of arrival (TOA) of AE waves to sensors. TOA can detected as the first threshold crossing by AE signal, or as a time of peak of AE signal or as a time of first motion (Muravin, 2009). TOA can be evaluated for each wave mode separately (Muravin, 2009). For TOA source location in one dimension which is linear location, a single position along a measurement axis is sufficient to define the location of the source (Holford, 2000). Linear location is used throughout this analysis.

In linear dimension, the resulting stress wave will propagate in both directions at the same constant velocity if discrete AE events occur along the structure. It is based on evaluation of time difference between arrivals of AE waves to at least two sensors (Muravin, 2009). Wave velocity usually experimentally evaluated by generating artificially AE at knows distances from sensors (Muravin, 2009). Equation 2.6 shows the calculation the distance between the sensors.

$$d = \frac{1}{2}(D - \Delta t.V) \quad (2.6)$$

Where:

d = distance from first hit

D = distance between sensors

V = wave velocity

Δt = time arrival delay

2.4 Acoustic emission analysis

The quantification in AE is normally carried out from waveform analysis but there are various quantitative analysis techniques which can be carried out using AE parametric data. This technique had been proven to be a promising tool in testing (Nair, 2006). Quantifying the level of damage using different AE parameters or the combination of AE parameters has been attempted. In the next section, a few of important and frequently used techniques in damage quantification that been proposed by various researchers are discussed.

2.4.1 b-value Analysis

The b-value analysis had been extensively used in order to quantify the damage in a material. b-value is derived from the amplitude distribution data of AE following the methods used in seismology (Rao et al. 2005). The b-value is defined as log-linear slope of the frequency magnitude distribution of AE (Sagar et al., 2012, Rao and Lakshmi, 2005, Colombo et. al., 2003). The degree of damage in a structure is associated with the loads imposed and that caused the cracks formation.