INITIAL CRACK DETECTION IN CONCRETE PLATE AND SHELL STRUCTURES USING CONCEPT OF EARTHQUAKE GROUND MOTIONS

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DEDICATION

In the name of Allah, the Supremely Merciful and the Most Kind. This thesis is dedicated to my beloved parents and sister, who have always given me boundless moral supports and prayers.

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ABSTRACT

Many methods and sensors have been developed for crack detection in concrete structures and for earthquake ground motion detection, respectively. In a previous study, a seismo-accelerometer based on spring-mass strong motion seismo-accelerograph has been developed for the purpose of detecting earthquake waves travelling through the earth crust from the epicenter at faultline. This study aims to apply the method developed in previous study to detect wave from crack initiation point on the surface of plate and shell concrete as a new alternative for initial crack detection method. This study focused on the development of a downscaled seismo-accelerometer of previous study for better ease of use. Concrete plate and shell specimens were selected in this study as the travel of wave from crack initiation point in the specimen mimic to that of earthquake waves travelling through the earth crust from the epicenter at the faultline. Magnetometer technology and spring-mass system formed the fundamental design aspect of the seismo-accelerometer. In Objective 1, the seismo-accelerometer was designed using Finite Element Modelling to attain natural period of 1 second, required for spring-mass based strong motion accelerograph. The modelling yield natural period of 0.99475 second and verified experimentally with Harmonic Shake Table test yielding 1.2 seconds, which is in the acceptable range. Ground motion test was carried out at Ranau Meteorological Station and the results were compared with international earthquake database. Earthquakes detected are in Sabah and nearby regions. Crack induction tests on factory-ready concrete plate and shell specimens were carried out in Objective 2, where the results shown that the concept of ground motion detection can be used for crack detection purposes. The crack detection equations for factory-ready concrete plate and shell are $M_{crack,plate} = \log_{10}A + 0.6919$ and $M_{crack,shell} = \log_{10}A + 0.7115$, respectively. Objective 3 provides the proof that the ground motion detection can be applied for crack detection based on crack wave attenuation on structures such as concrete plate and shell which have the same configuration as earth crust, where the earthquakes occur. Thus, the seismo-accelerometer developed in the study can be used for earthquake ground motion detection if placed on the bedrock or ground, and can be used for crack detection if placed on structures with similar configuration to earth crust such as concrete plate and shell structures. This contributes towards both Structural Health Monitoring and Seismic Monitoring apart from providing an alternative method to existing methods in both fields.

ABSTRAK

Pelbagai kaedah telah dibangunkan untuk pengesanan rekahan pada struktur konkrit dan terdapat sensor yang telah sedia ada bagi tujuan pengesanan gegaran gempa bumi. Dalam kajian terdahulu, sebuah *seismo-accelerometer* telah dibangunkan berdasarkan konsep *seismo-accelerograf* untuk daya gegaran kuat bagi tujuan pengesanan gelombang gempa yang bergerak melalui kerak bumi dari pusat gempa di garis rekahan bumi. Matlamat kajian ini adalah untuk mengaplikasikan kaedah yang dibangunkan dalam kajian terdahulu untuk mengesan rekahan awal pada permukaan konkrit plat dan tempurung. Kajian ini menumpukan kepada pembangunan *seismo-accelerometer* yang diskalakecilkan berdasarkan kajian terdahulu untuk lebih mudah digunakan. Spesimen konkrit plat dan spesimen tempurung dipilih dalam kajian ini kerana keadaan pergerakan gelombang dari titik permulaan rekahan pada specimen mimik kepada keadaan gelombang gempa yang bergerak melalui kerak bumi dari pusat gempa pada garis rekahan. *Seismo-accelerometer* dibangunkan berasaskan teknologi magnetometer dan sistem spring-beban. Dalam Objektif 1, *seismo-accelerometer* direkabentuk menggunakan Pengmodelan Unsur Terhingga untuk mencapai tempoh semula jadi 1 saat, yang diperlukan untuk *seismo-accelerograf* gegaran kuat yang berasaskan sistem spring-beban. Tempoh semula jadi 0.99475 saat dicapai melalui pengmodelan dan disahkan dengan Ujian Gegaran Harmonik yang menghasilkan tempoh semula jadi 1.2 saat, yang berada dalam julat yang boleh diterima. Ujian gegaran gempa bumi dijalankan di Stesen Meteorologi Ranau dan keputusan dibandingkan dengan data gempa bumi antarabangsa. Gempa bumi yang dikesan adalah di Sabah dan kawasan sekitar. Ujian aruhan rekahan terhadap spesimen konkrit plat dan tempurung dari kilang telah dijalankan dalam Objektif 2, di mana keputusan menunjukkan konsep pengesanan gegaran gempa bumi boleh digunakan untuk tujuan pengesanan rekahan. Persamaan pengesanan rekahan untuk spesimen konkrit plat dan tempurung dari kilang masing-masing adalah $M_{rekah,plat} = \log_{10}A + 0.6919$ dan $M_{rekah,tempurung} = \log_{10}A + 0.7115$. Objektif 3 membuktikan bahawa pengesanan gegaran gempa bumi berdasarkan jarak dan intensiti gegaran gelombang gempa bumi boleh diaplikasikan untuk pengesanan rekahan berdasarkan pelemahan gelombang rekahan pada struktur seperti plat dan tempurung konkrit yang mempunyai konfigurasi yang sama dengan kerak bumi, di mana gempa bumi berlaku. Oleh yang demikian, *seismo-accelerometer* yang dibangunkan dalam kajian ini dapat digunakan untuk pengesanan gempa bumi jika diletakkan pada batuan atau muka bumi, dan boleh digunakan untuk pengesanan rekahan jika diletakkan pada struktur-struktur dengan konfigurasi yang sama dengan kerak bumi seperti struktur plat dan tempurung konkrit. Hasil kajian ini akan menyumbang kepada kedua-dua Pemantauan Kesihatan Struktur dan Pemantauan Seismik, selain menyumbang sebagai kaedah alternatif kepada kaedah sedia ada dalam kedua-dua bidang.

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LIST OF ABBREVIATIONS

ANN	-	Artificial Neural Network
GA	-	Genetic Algorithm
MD	-	Mahalanobis Distance
MTS	-	Mahalanobis Taguchi System
PSO	-	Particle Swarm Optimization
TM	-	Taguchi Method
UTM	-	Universiti Teknologi Malaysia
XML	-	Extensible Markup Language

LIST OF SYMBOLS

δ	-	Minimal error
D, d	-	Diameter
F	-	Force
v	-	Velocity
p	-	Pressure
I	-	Moment of Inersia
r	-	Radius
Re	-	Reynold Number

CHAPTER 1

INTRODUCTION

1.1 Introduction

Structural integrity and reliability are concerns for civil and industrial structures, especially for important civil structures such as schools, hospitals, emergency facilities, dams, petrochemical industries, communication facilities and nuclear power plants (Curadelli, 2011). Many parts of the structures nowadays are formed by concrete plate. Concrete, which is a quasi-brittle materials, exhibit a large fracture process zone in which the material undergoes progressive softening damage (Bazant et. al., 1995).

In general, the structural damage in concrete structures began with crack initiation, followed by crack propagation and acceleration (Adnan, et. al, 2015). There are many types of cracks in concrete such as diagonal cracks, horizontal cracks, splitting cracks, corrosion cracks, plastics shrinkage concrete cracks, expansion concrete cracks, heating concrete cracks andconcrete cracks caused by overloading. Many factors contributed to the cracks such as poor concrete quality, improper structural design, insufficient concrete cover, improper curing, poor material quality, poor workmanship, overloading, and severe environmental conditions, Among existing methods for crack detection and measurements include visual inspection, ultrasonic inspection, radiographic/ x-ray inspection, eddy current testing, liquid or dye penetrant inspection, acoustic inspection and vision based and image processing which are typically convoluted with artiificial neural network.

The propagation of crack in a structural part leads to an important displacement discontinuity (Bouchard et. al., 2003). Since the appearance of crack in structures signifies a start of failure, it is vital to detect a crack at the beginning of its appearance (Khoram et. al., 2012). Without proper structural health monitoring measures and subsequent corrective actions, the flaws in the damaged structures could lead to catastrophic failures.

1.2 Problem Statement

Cracks most often occur in very highly stressed parts and therefore, undetected cracks could in turn lead to catastrophic damages (Zhang, 2006). Among the major flaws in the concrete structures are multi-site damages and hidden cracks in locations that are difficult to access. If small damages are detected, the structure may be returned to operational condition whereas if substantial damages are detected, the structure may require repair and rehabilitation (Rytter, 1993). This initial structural damage diagnostic help to determine the structure current serviceability and remaining service life, consequently contributing towards better economic and safety aspect of the structure maintenance. At present, using Non-Destructive Test (NDT) method to detect damage of structures has become a hotspot and difficult issue (Yan et. al., 2007). NDT form parts of Structural Health Monitoring scientific procedures which include identification of operational and environmental loads acting on the structural components, recognition of damage caused by the loading and observation the damage growth (Radzienski et. al., 2011).

Visual inspection by itself does not provide useful information until visible defects such as cracks start to appear in the structural members, often quite late into the fatigue life of the structure (Adnan et. al, 2003). Hence, a method capable of detecting the formation of crack is vital especially in the field of structural health monitoring.

Many methods have been developed for crack detection in concrete structures and existing sensors were also already developed for earthquake ground motion detection. This study aims to provide an alternative method of initial crack detection on concrete plate and shell by applying the ground motion detection concept developed in previous work by Rosaidi (2009). The wave from initial crack travelling through concrete plate and shell mimics the way the seismic wave travelling from the epicenter located on faultline of the earth crust. However, previous work by Rosaidi (2009) did not explore the application towards initial crack detection. This concept is however may not be suitable for column and beam concrete as the way the stress from the load distributed in the column and beam are different than plate and shell concrete structures. Eventhough concrete plate and shell structures may not form main structures, many important facilities such as water containment facilities and nuclear facilities adopt plate and shell in the design. In term of safety, allowable crack for water containment structures is 0.2 mm whereas the allowable crack limit for nuclear containment facilities is 0.1 mm, which is much more critical than the limit for typical structures at 0.3 mm. Thus, the method proposed to be explore in this study may complement existing techniques of crack detection, especially for concrete plate and shell structures.

1.3 Research Objectives

This study focuses on the proof of concept of applying concept of detecting earthquake ground motion developed in previous study by Rosaidi (2009) to detect crack in concrete plate and shell structures, to provide an alternative crack detection method which can complement existing better techniques such photo imaging and neural network.

The specific objectives of this study are:

1. To develop a seismo-accelerometer to detect earthquake ground motion using concept of strong motion mass-spring mechanism in detecting surface vibration.
2. To establish/ perform proof of concept for initial crack detection on concrete plate and shell specimens using the concept of earthquake ground motion detection.
3. To validate the results of crack detection with the piezotronic accelerometers on laboratory-made concrete plate and shell specimens. To validate the proof of concept for attenuation of wave from crack initiation point.

1.4 Methodology

This study focused on development of a seismo-accelerometer based on previous work by Rosaidi (2009) which was based on spring-mass strong motion seismo-accelerograph with magnetometer technology, designed to detect earthquake ground motion detection, and application of that concept to detect initial crack on concrete plate and shell structures. The seismo-accelerometer developed in this study is however downscaled from 20 cm to 5 cm to provide better ease of use and the selection of materials is based on the Finite Element Modeling to achieve natural period of 1 second, which is required for the design of spring-mass strong motion seismo-accelerograph to ensure the suspended mass remain in initial position when the seismo-accelerometer subjected to excitation from the wave.

In Objective 1, Finite Element Modelling SAP2000 Software was used in the design stage to select suitable materials for the construction of the seismo-accelerometer to adhere to natural period of 1 sec, required for spring-mass based strong motion accelerograph. Ground motion test was carried out in Ranau Meteorological Station and the results were compared with international earthquake database. Earthquakes detected are in the Sabah and nearby regions. Research flow for Objective 1 is as summarized in Figure 1.1.

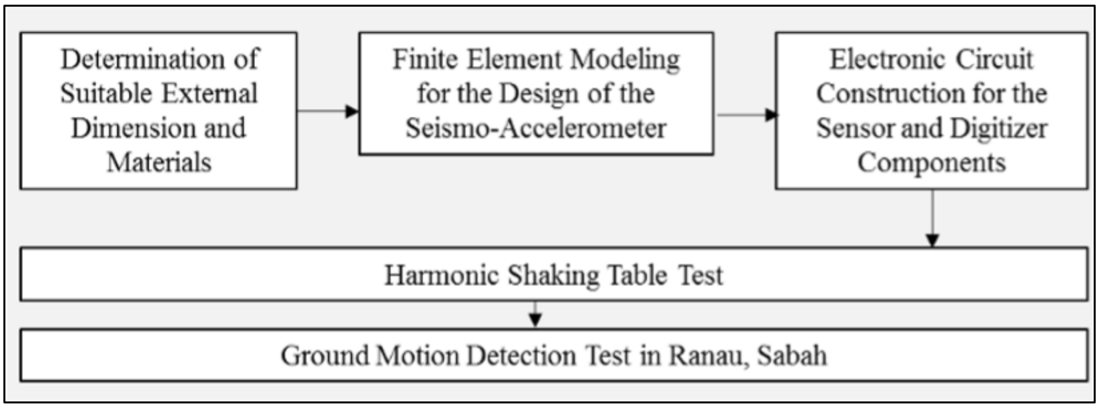

Figure 1.1 Flowchart for Objective 1

Crack induction tests on factory-ready concrete plate and shell specimens were carried out in Objective 2, as proof of concept that the earthquake ground motion detection concept can be applied to detect initial crack in plate and shell concrete. In Objective 2, the initial crack is induced at the middle of plate and shell specimens while the seismo-accelerometer and piezotronics accelerometer was both placed at a fixed distance of 30 cm from the location the initial crack is induced, but on the opposite sides. Research flow for Objective 2 is as summarized in Figure 1.2.

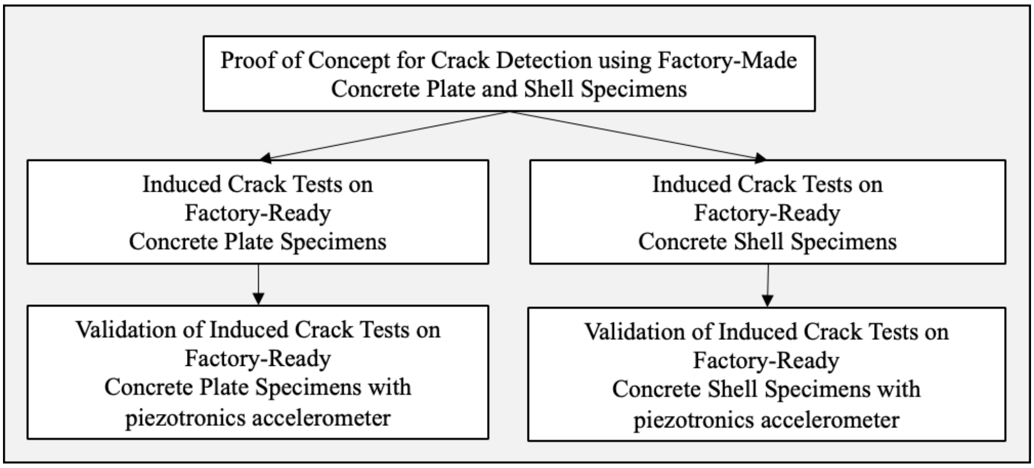

Figure 1.2 Flowchart for Objective 2

Further crack induction tests on laboratory-made concrete plate and shell specimens were carried out in Objective 3 as proof of concept that the ground motion detection which are based on distance and intensity of earthquake ground motion wave can be applied for crack detection based on crack wave attenuation on structures such concrete plate and shell structures. Research flow for Objective 3 is as summarized in Figure 1.3.

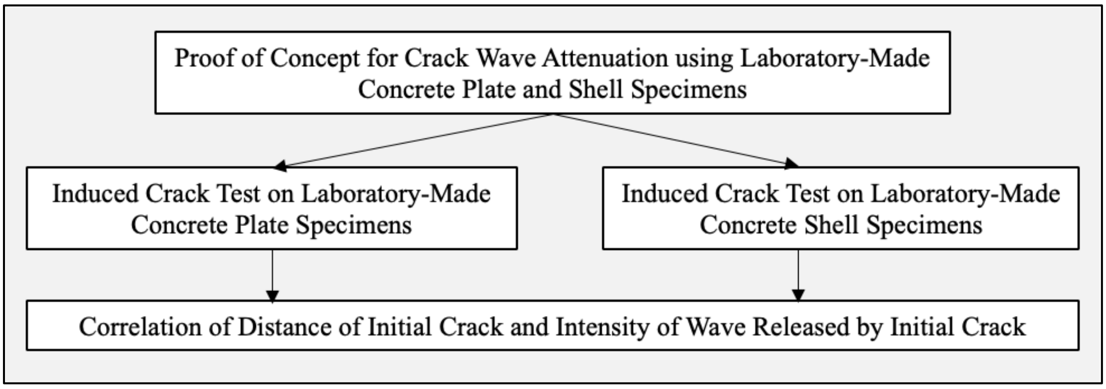

Figure 1.3 Flowchart for Objective 3

1.5 Scopes and Limitations of Study

The scopes and limitations of the study are as follow:

i. The seismo-accelerometer developed in this study is based on the previous work by Rosaidi (2009). The previous generation seismo-accelerometer was developed for earthquake ground motion detection. In this study, the seismo-accelerometer is intended to be applied for crack detection.

ii. The physical size of the seismo-accelerometer developed in this study (5 cm x 5 cm x 5 cm) was down-scaled from the previous generation seismo-accelerometer (20 cm x 20 cm x 20cm) for ease of use purposes.

iii. In Objective 1, Finite Element Modeling Modal Analysis using SAP2000 simulation software was used to design and select suitable material to construct the down-scaled seismo-accelerometer to achieve the natural period of 1 second, which is the required property of a strong-motion accelerograph.

iv. In Objective 1, the natural period of 1 second of the seismo-accelerometer was verified experimentally using the Harmonic Shaking Table at Geoscan Pte. Ltd. in Singapore. The exact natural period obtained from the data acquisition system of the Harmonic Shake Table was used to be compared with the natural period obtained from the Finite Element Modelling during the design stage of the Seismo-Accelerometer.

a. To complete Objective 1, Ranau Meteorological Station in Sabah was selected to test the ground motion detection function of the seismo-accelerometer as Ranau is one of the area with highest seismic activities in Malaysia and the result was verified with the data from international database which compiles the data from multiple meteorological stations around the world.

b. Objective 2 focused on proving the concept of applying the global earthquake ground motion detection on earth crust to the local concept of crack detection on concrete structures, whereby the intensity of crack above the ambient noise wave enable the crack to be differentiated from the ambient noise, like the waves from earthquake can be differentiated from ambient noise in the event of earthquake if the seismo-accelerometer are placed of ground or bedrock. The waves are induced by the cracks on earth crust (active faults) in term of seismic waves (primary and secondary waves).

c. In Objective 2, concrete plate and concrete shell structures were used to test the crack detection function of the seismo-accelerometer as the travel of wave in the plate and shell specimen does mimic that of the earthquake waves travelling through the earth crust from the epicenter at the faultline. This concept is however may not be suitable for column and beam concrete as the way the stress from the load distributed in the column and beam are different than plate and shell concrete structures. In the concrete plate and shell, the waves are transferred mostly from its local vibration wave propagated through the material. The concrete plate and concrete shell specimens used in Objective 2 are factory ready as the focus at this stage is on Proof of

Concept (POC) of the mechanism of crack detection using the concept of ground motion detection rather than on the material properties of the specimens.

d. The readings from the Seismo-Accelerometer through-out the cracking process in Objective 2 was verified with piezotronics accelerometer placed equidistant from the point where crack is induced on the specimen by gradual load from the hydraulic jack.

e. In Objective 3, crack induction was performed on laboratory-made concrete plate and shell specimens with additional accelerometer to enable correlation of crack detection with that of material properties of the specimens and the attenuation of crack waves with distance, whereby the closest accelerometer to the current crack source recorded higher values of acceleration compared to accelerometer at farther distances.

f. The factory-ready concrete plate and shell specimens used in Objective 2 are for proof of concept that the concept of earthquake ground motion detection can be applied to detect initial crack on concrete plate and shell structures. However, in Objective 3, laboratory-made concrete plate and shell specimen was used to provide proof of concept for wave attenuation relating distance and intensity of the crack wave. Grade 20, Grade 25 and Grade 30 are used as these are among the most commonly used concrete grade in construction."

1.6 Research Significance

The seismo-accelerometer developed in the study can be used for earthquake ground motion detection if placed on the bedrock or ground and can be used for crack detection if placed on structures with similar configuration to earth crust such as concrete plate and shell structures. This contributes towards both Structural Health

Monitoring and Seismic Monitoring apart from providing an alternative method to existing methods in both fields.

1.7 Thesis Outlines

This research is presented in seven chapters to achieve the research aim and three objectives. This thesis has been structured to present the research in such arrangement:

Chapter 1 discusses the background, significance, research scope, objectives, and the significance of the research and limitation of study.

Chapter 2 includes literature review related to crack phenomenon and mechanisms, structural health monitoring, concrete plate structure, concrete shell structure, various crack detection method as well as previous works on Tri-Axial Seismo-Accelerograph by Prof. Ir. Dr. Azlan Adnan and Dr. Mohd Rosaidi Che Abas.

Chapter 3 describes the general research framework and the methodology involved for each objective of the research.

Chapter 4 summarizes and discusses Objective 1 on the Finite Element Modeling (FEM) simulation design and construction of the Seismo-Accelero-Crackometer sensor device as well as the ground motion detection test in Ranau, Sabah.

Chapter 5 summarizes and discusses the experimental results of the induced crack tests on the factory-ready concrete plate and shell specimens for proof of concept of crack detection using earthquake ground motion detection technique, and validation with the piezotronics accelerometer results.

Chapter 6 summarizes and discusses the experimental results of the induced crack tests on the laboratory-made concrete plate and shell specimens. The effect of material properties and crack wave attenuation were also investigated.

Chapter 7 concludes the findings of the overall research works that was undertaken.

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