EVALUATING THE REDUCTION OF STRESS INTENSITY FACTOR IN CRACKED PLATES WITH PIEZOELECTRIC ACTUATORS UNDER MIXED MODE LOADING

BY

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A thesis submitted in fulfilment of the requirement for the degree of Master of Science (Mechanical Engineering)

Kulliyyah of Engineering
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SEPTEMBER 2020

ABSTRACT

The characteristics of piezoelectric materials that can be used for actuation and sensing make it an adequate choice for active repair. However, the study on the implementation of active repair using piezoelectric materials is not fully explored, and it lacks practical examples and demonstrations. Hence, the motivations of this thesis are to conduct experiments on active repair using piezoelectric materials on a mixed mode (1 and 2) fracture structure and to observe its effects on the stress intensity factor (SIF). At the same time, to analyse how the active repair is influenced by a certain combination of fracture modes 1 and 2. For the experiments, the normal crack was used. By changing the loading angle on the normal crack specimen, the mixed mode loading (1 and 2) was applied. The approaches that are used for this thesis are mainly experimental approach with a minor finite element analysis (FEA) approach to determine the optimal strain gage locations. The results showed the reductions of SIFs in both modes 1 and 2, and the reductions were varied at certain angles. This study would benefit the repairing structure, especially on aircraft maintenance, where the fracture would occur in several combinations of fracture modes. On the other hand, active repair using piezoelectric materials would reduce the cost of maintenance in the long run.

خلاصة البحث

إنّ خصائص المواد الكهر ضغطية التي يمكن استخدامها للتشغيل والاستشعار تجعل خيارًا مناسبًا للإصلاح النشط. ومع هذه الخصائص؛ فإن الدراسة الخاصة بتنفيذ الإصلاح النشط باستخدام مواد كهر ضغطية لم يتم استكشافها بشكل كامل، وإضافة إلى ذلك تفتقر إلى الأمثلة العملية والإيضاحات التي تبين ذلك. ومن ثم، فإن دوافع هذه الأطروحة هي إجراء تجارب على الإصلاح النشط باستخدام مواد كهر ضغطية على شكل مختلط (1 و 2) بنية كسر وملاحظة تأثيرها على عامل شدة الإجهاد (SIF). في نفس الوقت، تهتم لتحليل كيفية تأثر الإصلاح النشط بمجموعة معينة من أوضاع الكسر 1 و 2. بالنسبة للتجارب تم استخدام الكراكي الطبيعي. عن طريق تغيير زاوية التحميل على عينة الكراكي العادية، ومن ثم تم تطبيق تحميل الوضع المختلط (1 و 2). فالأساليب المستخدمة في هذه الأطروحة هي نهج تجريبي بشكل أساسي مع نهج تحليل العناصر المحدودة الصغيرة (FEA) لتحديد مواقع قياس الضغط الأمثل. هذا وقد أظهرت النتائج انخفاضات SIF في كلا الأسلوبين 1 و 2 ، وتباينت التخفيضات في زوايا معينة. وعلماً أنّ هذه الدراسة ستفيد هيكل الإصلاح وخاصة في صيانة الطائرات، حيث أنه سيحدث الكسر في عدة مجموعات من أنماط التصدع. ومن ناحية أخرى، فإن الإصلاح النشط باستخدام مواد كهر ضغطية من شأنه أن يقلل من تكلفة الصيانة على المدى الطويل.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Mechanical Engineering).

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I certify that I have examined and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Mechanical Engineering).

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….………………………………..
Sany Izan Ihsan
Dean, Kulliyyah of Engineering

DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institution.

Awang Hadi Ifwat bin Awang Bujang

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ACKNOWLEDGEMENTS

In the Name of Allah, the Most Compassionate, the Most Merciful

I am grateful to Allah for the opportunity to carry out this research with patience and blessing from Him.

I am truly thankful to my supervisor and co-supervisor Prof. Dr Meftah Hrairi and Assistant Prof. Dr Jafar Syed Mohamad Ali, for their continuous guidance, knowledge and supports throughout the study from the beginning of my research until the end. Their advice and assistance have been a huge helping hand and have inspired me a lot in many different ways. Their deep knowledge and understanding, especially in the structural analysis, have helped me to understand this research and to be creative in developing new methods and solving problems.

At the same time, I would like to give my appreciation to my colleagues Muhammad Rahman, Tengku Afif and Aabid Hussain for their motivation and technical support. I would like to express my gratitude as well towards my fellow friends in the ECTMRG postgraduate lab for their cooperation and supports.

Furthermore, I would like to address my thanks to Hafizah for assisting me in using machines in UTHM. As in IIUM especially in Kulliyyah of Engineering, my thanks to Br. Zahir, Br. Farid, Br. Md. Noor, Br. Zakaria, Br. Ibrahim and Br. Safora for their assistance and cooperation.

My highest appreciation and gratitude would be towards my parents, Awang Bujang bin Awang Bakar and Siti Fuad binti Leman for their continuous support and motivation to me to keep on moving and learning until I am able to wrap up my research. With the accomplishment of this study, I hope somehow, I can pay their efforts and at the same times make them proud.

Last but not least, my thanks go to Department of Mechanical staffs that have directly and indirectly helped me in this research.

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LIST OF ABBREVIATIONS

FEA	Finite Element Analysis
LEFM	Linear Elastic Fracture Mechanics
NSIF	Normalized Stress Intensity Factor
SIF	Stress Intensity Factor
MOSFET	Metal Oxide Semi-Conductor Field Effect Transistor

LIST OF SYMBOLS

K_I	Mode I Stress Intensity Factor
P	Applied Load
u_y	Crack Displacement in the y-direction.
E	Young's Modulus of the Plate
Ep	Young's Modulus of the Piezoelectric Actuator
t	Plate Thickness
t_p	Piezoelectric Actuator Thickness
θ and r	Polar Coordinates at the Crack Tip
μ	Shear Modulus
S_1	Mechanical Strain
D_3	Electrical Displacement
E_3	Electric Field
$_{ss11}$	Mechanical Complaisance at zero Electric Field
ε_{33T}	Dielectric Constant at zero Stress
d_{31}	Piezoelectric Coefficient
V	Applied Voltage
σ_{Piezo}	Piezoelectric Actuator Stress
S_{Piezo}	Piezoelectric Actuator force
Δ	Delamination correction Factor
δ	Delamination opening displacement

CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW

This chapter, in general, explains this research that covers the background, problem statements, objectives, scopes and methodology. The first section contains the background and the overview of the research's topic and provides a basic understanding of the topic. The second section describes the problem statements of the current research with its justification. Following after is the research objectives that clarify the aims and purposes of the study. The scopes of research define which area of studies that are considered and involved in this research. The next section presents the research methodology showing the research flow from the beginning until the end of the research. Finally, the outline of the thesis is presented.

1.2 BACKGROUND

Repairing structures, especially in the automotive and aerospace industry, requires detailed attention for safety purposes and at the same time to prolong the service life of the structures. A conventional method of repairing structures that is currently being implemented is composite patch materials. Abundance of research has been conducted on the composite materials since it was introduced. It is being implemented in the industry since its functionality and safety have been proven. The fast-paced growth of technology nowadays has led to the development of material science with the introduction of smart materials. Kamila (2013), conducted a survey on the smart materials and stated that the smart material is defined as a material that receives an input and then produces useful output. The input and output could be in any forms such as electric or magnetic field, pressure and temperature. The essential part of the smart materials is analysing the input and corresponding with the effectual output. Most of the actions and processes involved in the application of smart materials do not require human interaction thus captivating the researchers' attention to learn and study more about it and to apply it in their area of research.

There are a lot of potentials in smart materials that can improve the sustainability of repairing structures in the automotive and aerospace industry. One of the typical smart materials is piezoelectric material. The piezoelectric material has attributes that can couple mechanical and electrical properties. There are two properties of the piezoelectric material which make it the most suitable option to be implemented in repairing the structure, namely, the direct and converse piezoelectric effects. The direct piezoelectric effect is when mechanical stress is applied to the piezoelectric material, and it produces an electric. Meanwhile, the converse piezoelectric effect is when an electric field is applied to the piezoelectric material, and it produces mechanical deformation or actuation (IEEE Standard, 1988).

The implementation of piezoelectric materials as smart materials in repairing structures is considered as an active repair. Therefore, based on these attributes, researchers have been exploring active repair using the piezoelectric materials and considering to replace the composite material patching for repairing structures. Repairing structure through active repair is carried out by locally induce a force and moment at the crack tip by using piezoelectric material where it will counteract the loss of strength and stiffness and decrease the singularity of the stress at the crack tip (Abuzaid et al., 2015). Repairing structure by implementing active repair using piezoelectric materials extends the service life of the damaged structure by locally inducing a mechanical force and restraining the stress distribution at the crack tip in real-time thus avoiding the damaged structure from yielding.

1.3 PROBLEM STATEMENTS

One primary purpose of repairing structure is to prolong its service life. This purpose is vital for the sake of safety and also to reduce the cost. For instances in the aircraft's maintenance, a damaged panel will be replaced immediately for the safety proposes, and it is costly. Furthermore, the structural repair is only preferred over the immediate replacement if the damaged is not significant (Katnam et al., 2013). In the aerospace industry, the necessity of the study of structural repair is demanding. The increasing number of ageing aircrafts around the globe has led to the demand for study on repair structure for safety purposes and to reduce the cost (Guijt & Verhoeven, 2001).

The service lifetime of the damaged structure can be extended by repairing them using composite materials that are currently being implemented. Structural repair using composite materials has its downside and among them are it alters the load path due to the load shift from the structure into the composite material, it is not adjustable to the external load changes, and it is not flexible (Nicolais & Baker, 2011). Changing and improving the repairing method to the active repair using piezoelectric material can solve these problems, and even more, it can extend the service life of the damaged structures longer than composite materials capable of. There are several advantages of using piezoelectric materials over the composite materials. One of the significant advantages of the implementation of smart materials is fewer human actions are required. Technically over time, the structure that was repaired with composite materials will have to be checked from time to time to ensure the effectiveness of the composite materials on the structure. On the other hand, active repair using piezoelectric materials will require less checking or periodically needs to be inspected. Besides that, active repair using piezoelectric materials avoid the additional stress concentration that may exist in the area of bonding that usually exists when using composite materials and aluminium plates for repairing structures in the automotive and aerospace field.

Therefore, active repair using piezoelectric materials is practical and worth to explore and also it can significantly impact the development of structural repair primarily in reducing the crack damage propagation, especially in the aerospace industry.

Based on the literature review, the study of active repair using piezoelectric materials mostly focus on the application on mode 1 fracture only. The study on mixed mode fracture, especially mode 1 and 2 is yet to be discovered. To the best of author knowledge, the study on the implementation of active repair using piezoelectric materials is not fully explored, and there are lacking practical examples and demonstrations except for study on mode 1 fracture. Thus, it is necessary to extend the application of active repair using piezoelectric material to all fracture modes, especially mixed mode, 1 and 2. Also, the fracture does not necessarily occur in mode 1 only. It also can occur under the combination of loading such tensile and shear loading that will cause the mixed mode 1 and 2 fracture.

1.4 RESEARCH OBJECTIVES

The main objective of this research is to study the effectiveness of piezoelectric materials that are integrated into an isotropic material that is under the mixed mode, 1 and 2 loadings. The details of the objectives are stated as below:

i. To device experiments of the repair of cracked structure using piezoelectric actuation under the mixed mode loadings 1 and 2.
ii. To evaluate the percentage reduction of stress intensity factor due to the active repair.
iii. To analyse the influence of crack inclination of the mixed mode fracture on the effectiveness of the active repair.

1.5 SCOPE OF RESEARCH

The main focus of the current research is to implement active repair using piezoelectric materials on isotropic materials that are under mixed mode loading. Active repair with mixed mode 1 and 2 are considered. Therefore, mixed mode 2 and 3 and mixed mode 1 and 3 are beyond the scope of this research. Linear elastic fracture mechanics is taken into account for the study. The fundamental scope of the research is mainly concentrated on:

i. Studying the electromechanical behaviour of the edge cracked isotropic plate under mixed modes loading integrated with the piezoelectric actuators.
ii. Preparing the numerical analysis to examine mixed mode stress intensity factor of the materials without the integrated piezoelectric materials.

iii. Comparing the numerical analysis above with passive repair that is considered at 0 V applied on the piezoelectric materials during the experiments.

iv. Methodology in determining the optimum strain gage location through numerical analysis and calculation.

1.6 RESEARCH METHODOLOGY

The focus of this research is to implement the active repair using the piezoelectric materials on edge crack isotropic plate that is under mixed mode 1 and 2. The following are the approaches that are incorporated to achieve the objectives. Followed by Figure 1.1 showing the flow of the research from the beginning until the end of the research.

i. The literature review on the related topics was carried out to find out the studies that have been conducted in the area of the current research and at the same time providing the overview of this thesis.

ii. The active repair using the piezoelectric materials was implemented in the experimental study. An edge cracked isotropic plate that is under mixed mode 1, and 2 loadings were used in the tests, and the effect of active repair using the piezoelectric material were investigated by evaluating the stress intensity factors.

iii. The comparison and discussion of the results and data obtained from the numerical analysis at passive repair and experimental study were conducted.

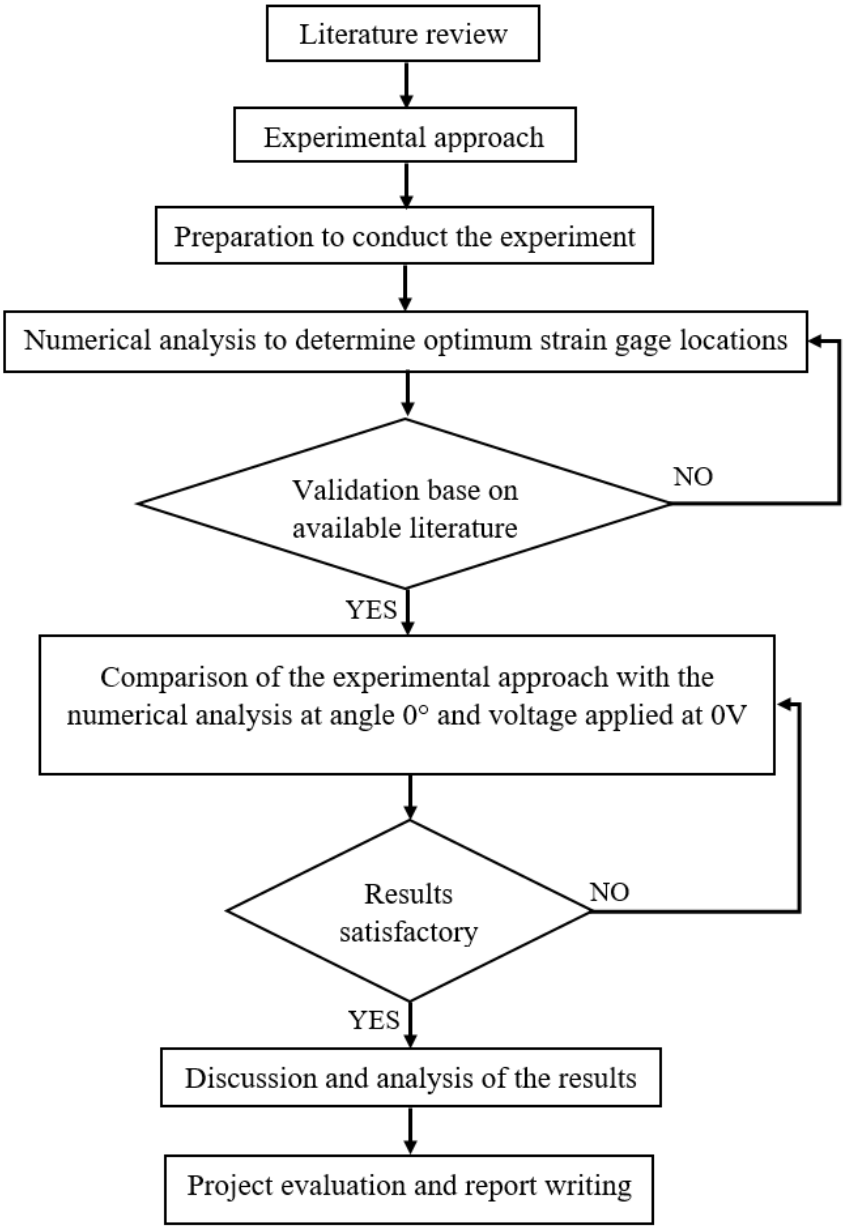

Figure 1.1 Research methodology

1.7 THESIS OUTLINE

The outline of this thesis is as followed:

i. Chapter 2 consists of the literature review on the topics related to the research.

ii. Chapter 3 presents the methodology of this study. It involves the methodology of the experimental approach to investigate the effect of active repair using piezoelectric materials on stress intensity factors and the finite element analysis to determine optimum strain gage locations. The preparation of mixed mode fixture to demonstrate mixed mode loading is also presented in this chapter.

iii. Chapter 4 shows the results obtain from the experiments conducted together with the discussion and analysis of the active repair using piezoelectric materials. The optimum location of the strain gage location is included in this chapter.

iv. Chapter 5 reports the conclusion of this thesis and the recommendation for some possible future works.

CHAPTER TWO

LITERATURE REVIEW

2.1 OVERVIEW

This chapter explains the literature reviews on the topics that are related to the active repair using piezoelectric patches on edge crack isotropic plate under mixed mode loading. The first section explains the methodology to determine suitable strain gages locations for accurate stress intensity factor measurement, followed by the literature of the strain gages based methods for calculating the stress intensity factor. The last section covers the application of piezoelectric patches on active repair of structures. Concluding the literature reviews, the observation and critical understanding from the author perspective are presented.

2.2 INTRODUCTION

Fracture occurs in three different loading modes which are opening, in-plane shearing and out-of-plane shearing or tearing corresponding to mode 1, 2 and 3, respectively, as shown in Figure 2.1.

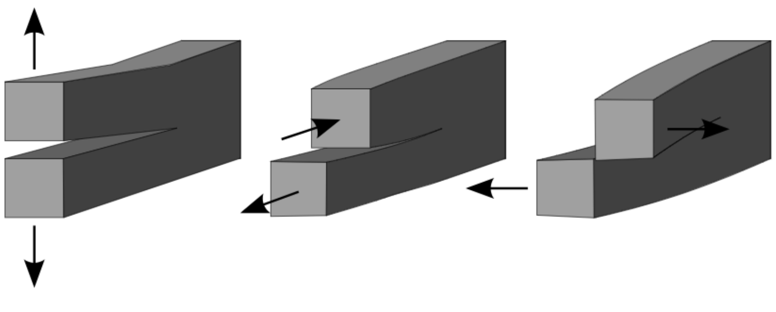

Figure 2.1 Mode 1, 2 and 3 loading condition (Dally & Sanford, 1987)

Combination of these modes affects the behaviour of the crack in terms of crack propagation, crack angle and failure analysis. Having mentioned that, there are relatively few studies conducted on mixed mode fracture compared to single mode fracture that is mostly in mode 1. Dally & Sanford, (1987) demonstrated the use of strain gages to measure the mode 1 stress intensity factor. Based on their study, the authors stated that the strain gradient could be minimized by placing the strain gages considerably far from the crack tip. Joshi & Bhosale, (2013) applied the strain gage method to measure the stress intensity factor of mode 1 where only one strain gage was used in the study. The numerical analysis and experimental data were compared, and the results were in good agreement, with small errors. Instead of using typical strain gages, Hamdi et al., (2017) used rectangular strain-rosette to measure mode 1 stress intensity factor.

Recently, researchers have started to study more about active repair using piezoelectric patches. These are due to the electromechanical properties of the piezoelectric itself that can be utilized in several different applications. The advantages of piezoelectric patches are its easiness to be applied, its lightweight and its relatively low cost making it a suitable choice to replace composite patches for maintenance and repairing structure especially in aerospace and automotive engineering. At the same time, the abilities to actuate and sense make piezoelectric patches applicable in structure health monitoring. The wide applications of piezoelectric patches create new opportunity to improve the service life of structures, most importantly for aerospace and automotive industries (Abuzaid et al., 2015b). In general, a lot of benefits can be gained through the application of piezoelectric materials.