Determination of stress intensity factor of actuated cracked aluminum plate using strain gages

Awang Hadi Ifwat bin Awang Bujang, Meftah Hrairi, Mohd Sultan Ibrahim bin Shaik Dawood

Abstract: The rapid development of smart and intelligent structure has led to the application of piezoelectric patches in repairing techniques. The advantage of using piezoelectric patch is that its behavior can be controlled by considering its electromechanical properties. The piezoelectric patch that can be used for sensing and actuation make it suitable to be used in active repair. In this paper, an experimental approach of active repair on an edge crack specimen using two piezoelectric patches was carried out. To observe the effect of the active repair, the stress intensity factor (SIF) was measured using strain data that was obtained from the strain gages located near to the crack tip. The edge crack specimen was put under Mode 1 loading condition as the active repair using piezoelectric patches was applied. The results showed reduction of SIF from the effect of the active repair.

Keywords: Active repair; Edge crack; Modes; Piezoelectric

I. INTRODUCTION

Active repair using piezoelectric actuator are widely studied because of its electromechanical properties that can be implemented in various application. Abuzaid et al. [1] stated that active repair is done by inducing a local force and moment on the crack by using piezoelectric actuator where it will counteract the loss of strength and stiffness and decrease the singularity of the stress at the crack tip. Active repair using piezoelectric actuator is suitable for the known crack location where it will stop or reduce the crack propagation and the stress concentration. There are several literature are found that are related to the application of piezoelectric actuator in active repair that are based on numerical and analytical approaches and relatively fewer literatures on experimental approaches. Wang et al. [2] have conducted an analytical analysis to study the active repair using piezoelectric patch on a cracked beam. From the analytical analysis, they found that as the distance between the piezoelectric patch and the crack increased, the voltage required decreased. It was found that using high voltages in active repair would not be advisable since it will cause partial crack at the crack tip. [3]. Koteswara et al. [4] carried out the study on active repair of cracked structure in two-dimensional plane strain FEA, particularly the effect of the piezoelectric actuator location in reducing stress singularity. The results of the study showed that the stress concentration was reduced and the location of the piezoelectric patches affected the voltage needed to be applied for active repair [4]. Instead of a one layer piezoelectric patches, Liu [5] used multi-layered piezoelectric patches to perform active repair on a cracked structure using FEA. The results showed stress intensity factor and strain energy density factor at the crack tip were reduced and the factors that affected the reduction were the number of layers, length and thickness of the piezoelectric patches [5]. A FEA approach to evaluate stress reduction using piezoelectric actuator patches in a center cracked plate was carried out by Abuzaid et al. [6]. It was found that the piezoelectric patch was effective in reducing stress intensity factor in extension mode but not in contraction mode. This is because in contraction mode, the piezoelectric patches produced additional strains that led to the increasing stress intensity factor [6]. Alaimo et al. [7] conducted a study on active repair using piezoelectric materials by applying boundary element method. This research found that the adhesive that was used to patch the piezoelectric material had a big influence on the performance of the repair [7]. In another study, Alaimo et al. [8] conducted boundary element analysis to find the effect of friction in the active repair using the piezoelectric patch on the delaminated structure and it was reported that the frictional effects can be neglected [8]. Wang and Quek [9] studied on the application of piezoelectric patches, which was repairing a delaminated beam. The delaminated beam can be repaired by removing the stress singularity at the tips of the delamination by using piezoelectric patches. At the same time, the effect of the voltages applied on the piezoelectric patches on the delaminated beam was studied. Analytical approach was carried out by Wang et al. [2] to study the effect between the force and location of the piezoelectric patch on the cracked beam. The results showed that the voltage required to repair the crack decreased as the location of the piezoelectric patch was further away from the crack [2].

There are several experimental techniques to investigate stress intensity factor (SIF) such as caustics, photoelasticity, compliance, strain gage technique. Among these methods, the strain gage tech-nique is relatively simple and straightforward because of the direct measurement of strains at the crack tip. Yue et al. [10] compared the caustics and the strain gage technique in determining SIF and based on the experiment, the strain gage technique was more consistent compared to caustics method and it only requires

Revised Manuscript Received on March 10, 2019.

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limited setup to conduct the experiment. Joshi and Bhosale [11] conducted experiments using strain gages technique to find the SIF of Mode 1 edge cracked specimens. Sarangi et al. [12] studied into more details of the strain gage technique where the strain gage radial location was studied using numerical approach to find the optimal radial location of strain gage in order to get accurate SIF. It was validated by a later study by the same authors [13] where the experimental study was conducted using the optimal strain gage location to determine SIF of Mode 1 edge cracked using strain gage technique. As demonstrated by Platz et al. [14], an experiment to reduce the fatigue crack propagation in aluminum plate by using the piezoelectric actuator patches was conducted. The objective was to reduce the rate of crack propagation by reducing stress intensity factor. Optimization on the location and the alignment of the piezoelectric patches were also considered and the FEA results showed that stress was reduced when the active repair was applied. Cyclic stress intensity factor was considered instead of stress intensity factor because of the fatigue loading, where maximum and minimum stress intensity factors were considered. The experimental results showed that about 20% crack propagation reduction when active repair was applied [14].

As mentioned in the first paragraph, there are only a few literatures can be found that conducted experiment of active repair using piezoelectric patch. The lacks of information and references that can be used to conduct the experiment of active repair using piezoelectric patches have not been sufficiently addressed in the literature. Therefore, this paper will add the literature that for the experimental approach of active repair using piezoelectric patches. The purpose of this paper is to apply the piezoelectric patches as a repair mechanism in active repair and at the same time, to reduce the SIF at the crack tip of an edge crack aluminum plates under Mode 1 loading by using the piezoelectric patches. Besides that, this article is intended to provide information regarding the experimental approach of active repair using piezoelectric patches.

II. MATERIALS AND METHODS

2.1 Specimen preparation

In order to prepare the specimen with the edge crack, several machining processes are involved. From a raw aluminium material with 1mm thickness, a shearing machine was used to cut the raw material into 38x200mm dimension. A 5mm in length notch was created using wire electro discharge machine (EDM) with the wire diameter is 0.06mm. Then, the specimen was clamped into the fatigue machine to create the crack, where the crack length, a, is 8.425mm measured from the edge. Figure 1 below shows the process described above. Meanwhile, Figure 2 shows the setup for creating the crack using the fatigue machine while Figure 3 shows the specimen with edge crack.

Fig. 1: Creating notch using wire EDM.

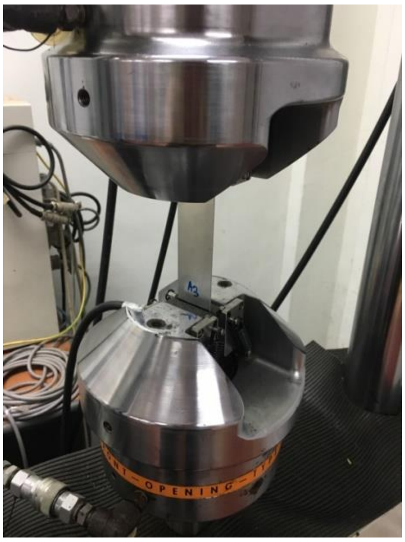

Fig. 2: Creating edge crack using fatigue machine.

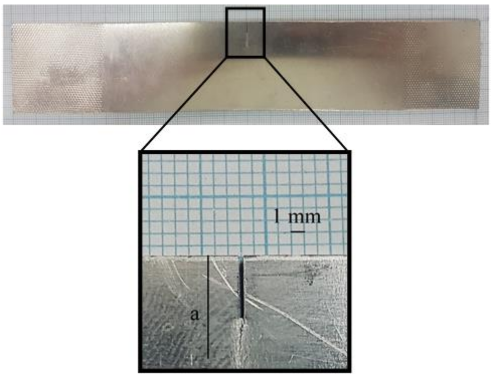

Fig. 3: Edge crack specimen.

2.2 Piezoelectric patch and strain gages configuration

Two piezoelectric patches are used. Both piezoelectric patch were glued using a weighted amount of Araldite 2014 that was calculated based on the study that was conducted by Abuzaid et al. [15]. The positions of the piezoelectric patches are shown in Figure 4. The gap in between the piezoelectric patches is 2mm with the edge crack at the centre. The positive and negative terminals of the piezoelectric patches were soldered with wires to connect the piezoelectric patches to the power supply for actuation effect.

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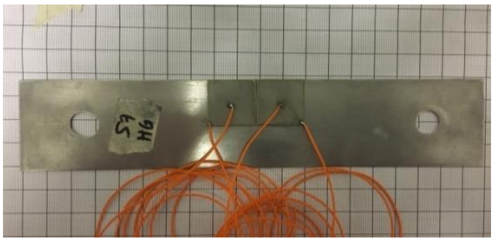

Fig. 4: Piezoelectric patch glued to the specimen.

Two strain gages are used to measure the strains at the crack tip. Strain gage 1 and 2 are located at the zone 2 and 3 respectively. The radial position, r and θ, and orientation relative to crack tip, α, are calculated using the properties of the specimen. The equation 1 and 2 are used to determine θ and α.

$$cos2\alpha = -\frac{(1-\nu)}{(1+\nu)} \quad (1)$$

$$tan\frac{\theta}{2} = -cot2\alpha \quad (2)$$

where the Poisson ratio, ν = 0.33.

Meanwhile, r is determined using the approach that was used by Sarangi et al. [12]. Figure 5 describes the zones around the crack tip. The strain gages were soldered to LAN cable using quarter-bridge connection.

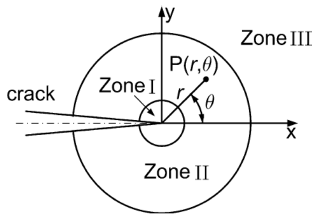

Fig. 5: The zones around the crack tip [5].

2.3 Tensile test

This test is to determine the effect of active repair using piezoelectric patches on the SIF of the crack tip by actively inducing mechanical forces near the crack tip that is under Mode 1 loading. Table 1 below shows the materials that are used to conduct the experiment and its properties.

Figure 6 below shows the experimental setup. INSTRON tensile machine is used where the specimen is attached to the jig in Mode 1 loading condition with applied stress of 1MPa. The voltages from 0V to 100V are applied on the piezoelectric actuator by using two power supplies that is connected in series. The frequency is set to 1kHz using the function generator and MOSFET. The strains upon the tensile test started were recorded using the strain gages that were connected to the computer through D4 data acquisition conditioner.

Table 1: Materials used and its properties

Parameter	Aluminium	PI 151	Kyowa Strain Gage	Araldite 2014
Density (kg/m^3)	2715	7800	-	1160
Poisson Ratio	0.33	0.34	-	0.3
Young Modulus (GPa)	68.95	-	-	5.09
Gage Factor	-	-	2.03	-
Grid Size (mm)	-	-	1	-

Fig. 6: Experiment Setup.

III. RESULTS AND DISCUSSION

The test was conducted three times and the average strains were taken. From the strains obtained, SIF can be calculated using equation (3) as defined below. Table 2 below shows the measured strains with the voltages applied. It can be observed that the SIFs at the crack tip as shown in the Table 2 show some reduction from the beginning until the end due the effect of active repair using piezoelectric patches. There are 19.99% and 42.10% reduction in strain gage 1 and 2 respectively when the piezoelectric patches were applied with voltages from 0V to 100V.

Formula to calculate SIF:

$$2G\varepsilon_{aa} = \frac{K_1}{\sqrt{2\pi r}}\left[kcos\frac{\theta}{2} - \frac{1}{2}sin\theta sin\frac{3\theta}{2}cos2\alpha + \frac{1}{2}sin\theta cos\frac{3\theta}{2}sin2\alpha \right] \quad (3)$$

where G is the shear modulus of the specimen, ε_{aa} is strain, K_1 is mode 1 SIF, k is $\frac{(1-\nu)}{(1+\nu)}$.

Table 2: The measured strains and calculated SIF along with the voltages.

Voltage (V)	Strain 1 (μm)	SIF 1	Strain 2 (μm)	SIF 2
0	8.33	234616.66	12.66	356617.30
10	7.33	206462.66	11.66	328463.30
20	7.33	206462.66	11.66	328463.30
30	7.00	197078.00	11.00	309694.00
40	6.66	187693.33	10.00	281549.00
50	6.66	187693.33	9.66	272155.30
60	6.66	187693.33	9.33	262770.70
70	6.66	187693.33	8.66	244001.30
80	6.66	187693.33	8.33	234616.30
90	6.66	187693.33	7.66	215847.30
100	6.66	187693.33	7.33	206462.70

The SIFs calculated above are divided by $\sigma\sqrt{\pi a}$ to get the normalized SIF (NSIF), where σ, is the stress applied on the specimen as shown in the Table 3 below. The curves of NSIF against voltage for both strain gages are plotted together with the curve from the literature [16] for validation as illustrated in Figure 7.

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Table 3: NSIF of strain gage 1 and 2.

Voltage (V)	NSIF 1	NSIF 2
0	1.31	1.99
10	1.15	1.83
20	1.15	1.83
30	1.10	1.73
40	1.04	1.57
50	1.04	1.52
60	1.04	1.46
70	1.04	1.36
80	1.04	1.31
90	1.04	1.20
100	1.04	1.15

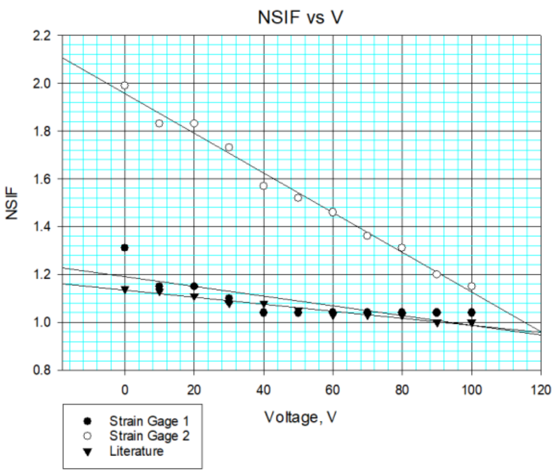

Fig. 7: NSIF vs Voltage.

It can be seen from the graph in the Figure 7 above, the NSIF for strain gage 1 when 10V was applied is 1.31 and it is getting closer to 1 as the voltage applied increases. Meanwhile, in strain gage 2, the NSIF was far from 1 and become closer to 1 as the voltages were increased but not as close as strain gage 1. The decreasing values of NSIFs as the voltages applied were increased, indicates the actuation effect of piezoelectric patch on the crack tip. The piezoelectric patches mechanically induced a local force onto the crack tip such that the piezoelectric patches try to close or to prevent the crack tip from propagating and to decrease the stress concentration from building up at the crack when the load is applied. As an indicator, the closer the NSIF to 1, the better the results are.

Besides that, and also based on the Figure 7, the NSIFs for strain gage 1 shows good agreement with the literature. Meanwhile, it can be observed that the NSIFs for strain gage 2 were larger compared to the literature. This is due to the location of the strain gages 2 that is located in the Zone 3 (refer to Figure 5). The Zone 3 is not a favorable location to measure strains as it contains a large number of coefficients in which requires a lot of strain gages to determine them. A different case for the strain gage 1 that is located in the zone 2 which is favorable and suitable to measure accurate strains that can be used to determine SIF. Table 4 shows the percentage error of NSIFs of strain gage 1 and 2 compared to the literature value at 100V. The percentage errors for both strain gages 1 and 2 are 4% and 15%, respectively. Hence, only strain gage 1 error is below 5% which is acceptable.

Table 4: Percentage error.

NSIF	Literature	Strain Gage 1	Strain Gage 2
100V	1	1.04	1.15
% error	-	4	15

IV. CONCLUSION

In this paper, the experimental approach of active repair using piezoelectric patches of edge cracked aluminium plate under Mode 1 loading and the determination of stress intensity using strain gages are presented. From the experiment, it was found that the strain gage located at zone 3 cannot be used to measure accurate strain data. This indicates the importance of strain gage location to measure accurate strain data. Besides that, the effect of active repair using piezoelectric patches increased as the voltages applied increases and that can be seen through the reduction of the SIF at the crack tip. This paper has provided the procedures and details to conduct the experiment of active repair using the piezoelectric patches on the edge crack aluminium specimen under tensile load which is Mode 1 loading condition with respect to the crack.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support by the Research Management Centre (RMC) at the International Islamic University Malaysia under the Research Initiative Grant Scheme (grant no.: RIGS17-045-0620). Also, the authors acknowledge the assistance and guidance from the technicians from the Electronic Lab and the Structural Lab.

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