Stress Analysis on Cracking Plate Structure For Reducing Stress Concentration

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Abstract. The structures which are subjected to load experience stress. If there is no discontinuity (defect), the stress is distributed in a particular pattern based on the type of stress. The crack is one defect that is frequently found in the plate structure, which causes stress concentration factor. In this paper, the treatments to reduce concentration factors are applied to plate structures under cracked conditions to investigate the treatment effect to reduce the stress concentration. For that purpose, the low-cost strain indicator using strain gauge integrated with Arduino Uno and computer is constructed to measure the stress distribution on cantilever aluminum plate in the normal conditions, crack, and crack with treatment. The treatments to reduce the stress concentration factor are applied in the form of the stop drill hole and additional hole. The result shows that the given treatment could reduce the stress concentration factor by around 11%. Even though the reduction of the factor was not significant, the treatment could be a fast and straightforward solution in decreasing the stress on the cracking plate structure.

Keywords: stress analysis, cracks, plate structure, strain indicator

1. Introduction

Many engineering structures are designed to expose the mechanical loadings. Because of the critical function, the structures are maintained to run its function with full integrity. So the structural health monitoring to detect damage in structures and measurement analysis to solve the problem in structures is carried out to ensure the structure's eligibility to perform the expediency [1-6].

When the structures are subjected to load, some parts will experience stress. If there is no discontinuity (defect), the stress is distributed in a particular pattern based on the type of stress. The crack is one of the defects found in the plate structure, which causes stress concentration. The stress concentrations will cause excessive stress, and the damage gets even worse.

Some methods have been investigated regarding the under-crack plate structure treatments for holding up or captivating crack growth [7-12]. Methods of captivating crack propagation such as drilling a hole at the crack tip [7-9], and drilling holes around the crack tip [10–12] have been proposed.

Murdani et al. [7] investigated the crack-growth arresting technique in the aluminum alloy, showing the effectiveness of additional holes following the drilling of holes at crack tips in retarding crack propagation. It was reported that crack propagation was postponed longer than by a stop-drilled hole alone. The research was then continued by investigating the stress concentrations at stop-drilled holes.
and additional holes [13]. The models used in the experiment are the plate under pure tension load. However, the plate in mechanical structures may experience various types of load.

In this study, the treatments to reduce stress concentration are applied to under-cracked cantilever aluminum plate structure to investigate the treatment's effectiveness in reducing the stress concentration. The treatments to reduce the stress concentration are applied in the form of the stop-drilled hole (stop hole) and additional hole (add hole). It is hoped that the effectiveness of providing the stop-drilled hole and additional hole on the under-crack cantilever plate structure will be demonstrated well.

2. Methods
The experimental set-up consists of several main components: cantilever aluminum plate as test specimens, fixed supports, strain gauge sensors, strain indicators, Arduino as simple DAQ, and personal computer (PC) are constructed and joined to measure and analyze the stress on crack plate. The set-up is presented in Figure 1. The aluminum plate cantilever dimension is 150 mm in length, 50 mm in width, and 2 mm in thickness.

![Figure 1. Experimental set-up or stress measurement and analysis](image)

The strain gauge sensor used in this research is BF 350-3 AA type, with specifications that can be seen in Table 1. The strain gauge is affixed to the test specimen's surface using an adhesive (glue) made from cyanoacrylate. The strain gauge used has a grid array type, single linear pattern. The strain gauge is connected by two jumper wires soldered to the solder tabs. The jumper cable from the strain gauge is connected to the strain indicator through the available ports.

| Specification                  | Value     |
|-------------------------------|-----------|
| Nominal resistance (Ω)        | 350       |
| Tolerance of resistance       | ±0.1 %    |
| Gauge factor                  | 2.00 – 2.2|
| Strain limit                  | 2.0 %     |
| Fatigue life                  | >107      |
| Gauge grid (mm) (l x w)       | 3.2 x 3.1 |
| Gauge backing (matrix) (mm)   | 7.4 x 4.4 |

The resistance of the strain gauge changes when it is deformed. Metal and semiconductor materials experience changes in electrical resistance when exposed to strain. The magnitude of the change in resistance depends on strain gauge deformation, material, and strain gauge design. Strain gauge
resistance is also a basic form for other transducers, such as load cells, pressure transducers, and torque meters [15].

The stress value's magnitude is determined using the relationship between stress and strain expressed through Hooke's law equation. The stress value from the measurement results is determined by [16]:

$$\sigma = E \varepsilon$$  \hspace{2cm} (1)

$E$ is the material elastic modulus (GPa) value, and $\varepsilon$ is the strain value from the strain gauge measurement results. The normal stress caused by bending moment theoretically is calculated using the following equation:

$$\sigma_{\text{max}} = \frac{M \cdot c}{I}$$  \hspace{2cm} (2)

Where $\sigma$ is the normal stress, $M$ is the bending moment, $c$ is the radius from the neutral axis to the surface, and $I$ is the beam's inertia section.

The stress concentration will cause a difference in the value of stress at a point far from discontinuity with the value of the stress at the crack tip. The stress-value ratio is expressed by the stress concentration factor ($K_t$), as in equation 3. The stress at the crack tip is expressed as the maximum stress ($\sigma_m$), while the stress that is far from the defect is expressed as the nominal stress ($\sigma_0$) [16].

$$K_t = \frac{\sigma_m}{\sigma_0}$$  \hspace{2cm} (3)

The flow chart of the experiments conducted in this research is presented in Figure 2. The experiments will be conducted in three different conditions.
The first condition is the health condition (normal) where there is no damage on the aluminum plate to ensure the measurement system runs appropriately, where the experimental result will be compared with the theoretical calculation. The second condition is the crack’s condition, where the single artificial crack is applied to the plate. These conditions are repeated with different sizes of a single crack. The third condition is the condition of crack with treatment. One-stop holes and additional holes are applied to the crack to reduce the stress concentration factor. The distribution of stress on the tip and area after the crack is measured to investigate the effect of treatment in reducing the stress concentration factor.

The measurement positions for health and crack conditions as the basic experimental analysis can be seen in Figure 3. The measurement positions for stress distributions are shown in Figure 4.

**Figure 2.** Flowchart of method used in the research

**Figure 3 (a).** Health condition

**Figure 3 (b).** Crack condition
3. Results and Discussion

3.1. Measurement in the normal condition
Table 2 shows the normal stress between theoretical calculation and experiment results in the condition without damage. The stress measurement using the strain gauge sensor again compared with the theoretical method. The percentage of errors are quite small, so the experiment results are still within reasonable limits. It means that the experiments by using the set-up explained in chapter 2 are considered to be ideal.

Table 2. Comparison of the normal stress between theoretical calculation and experiment result in the health condition

| Measurement Points | Load of 6.7 N Stress (MPa) | Error (%) | Load of 15 N Stress (MPa) | Error (%) |
|--------------------|---------------------------|-----------|--------------------------|-----------|
|                    | Theories                  | Experiment| Theories                 | Experiment|
| SG 1               | 28.71                     | 29.627    | 3.09                     | 63.73     | 66.427    | 4.06 |
| SG 2               | 14.85                     | 15.245    | 2.56                     | 32.96     | 33.795    | 2.47 |
| SG 3               | 0.99                      | 0.942     | 5.32                     | 2.197     | 2.116     | 3.8  |

3.2. Measurement in the crack condition
The stress measurements carried out in crack conditions are not much different from measurements in normal conditions. The difference only lies in the point of measurement. The measurement point is increased by 1 point for the crack condition, namely the critical area (close to the crack tip). The total point of measurement becomes 4 points. Figure 3 shows that the 4 points are SG 1 (5, 25), SG 2 (75, 25), SG 3 (75, 12.5), SG 4 (145, 25), where SG3 is the measurement point which closest to the crack tip. The sizes of the crack are varied in two forms for the 10 mm crack length. The first crack dimension is $t = 10$ mm and $a = 0.7$ mm. The second one is $t = 10$ mm and $a = 1$ mm. The crack sizes for the length of 15 mm are also varied in two sizes, where the widths are $0.7$ mm and $1$ mm. The load of 6.7 N (in the form of the mass) is applied at the cantilever's end.

Tables 3 and 4 show the experimental results of Stress measurements in the condition of crack with the crack length of 10 mm and 15 mm, respectively. From the tables, it can be seen that the more sharpness and the more length of crack causes an increase in stress. The high values of stress are measured on SG1, where the maximum bending moment happens at this point. Compared to the crack...
position measurement, the stress values slightly different for the length of the crack 10 mm, but the stress is raised when the length of the crack extended to 15 mm.

Table 3. Experimental results of stress measurement with the crack length of 10 mm

| Measurement Points | a = 1 mm Stress (MPa) | a = 0.7 mm Stress (MPa) |
|--------------------|-----------------------|-------------------------|
| SG 1               | 29.07                 | 30.461                  |
| SG 2               | 17.46                 | 17.72                   |
| SG 3               | 27.85                 | 29.35                   |
| SG 4               | 0.95                  | 0.98                    |

Table 4. Experimental results of stress measurement with the crack length of 15 mm

| Measurement Points | a = 1 mm Stress (MPa) | a = 0.7 mm Stress (MPa) |
|--------------------|-----------------------|-------------------------|
| SG 1               | 30.62                 | 31.12                   |
| SG 2               | 19.89                 | 20.00                   |
| SG 3               | 31.28                 | 31.76                   |
| SG 4               | 1.01                  | 1.02                    |

Figure 5 compares stress measurement with the normal condition and crack condition with different crack sizes. From the graphs can be analyzed that the crack enhances the stress on the plate. The value of stress at crack position rockets and goes beyond the stress point with maximum bending moment.

3.3. The stress distribution and stress concentration factor

In order to get the stress concentration factor of the cracking plate from the experimental data, the number of measurement points has to be enhanced. The addition of one measurement point is allocated to get the stress distribution under 6.7 N of the load. From the stress distribution, the maximum stress that occurs at the crack’s tip, and the nominal stress can be obtained to calculate the stress concentration factor. For that purpose, one more measurement point is added, as can be seen in Figure 4. So the number of measurement points becomes 5 points. The measurement points with coordinate are SG1 (75, 17.5), SG2 (75, 25), SG3 (75, 30), SG4 (75, 40) and SG5 (75, 45). The SG1 position is very close to the crack tip, and the maximum stress is available at this point. The Measurement points of SG2-SG5 are used to get the nominal stress by the average of measured stress from SG2 to SG5.
Table 5 shows the measurement results of stress distribution at the position of the crack. The SG1 is the maximum stress ($\sigma_m$), and the average of SG2 to SG5 is the nominal stress ($\sigma_0$). In order to calculate the stress concentration factor ($K_t$), Table 5 can be simplified and completed with the stress data, which are needed to get stress concentration data. Table 6 shows the stress concentration factor due to the crack.

| Table 5. The measurement results of stress distribution at the position of the crack |
| --- |
| | Length, $t$ | Width, $a$ | SG 1 (MPa) | SG 2 (MPa) | SG 3 (MPa) | SG 4 (MPa) | SG 5 (MPa) |
| --- | --- | --- | --- | --- | --- | --- | --- |
| 10 mm | 0.7 mm | 29.35 | 18.81 | 17.72 | 17.22 | 16.93 |
| 1 mm | 27.85 | 19.95 | 17.46 | 17.02 | 16.97 |
| 15 mm | 0.7 mm | 31.76 | 20 | 17.73 | 16.2 | 12.53 |
| 1 mm | 31.28 | 19.89 | 18.11 | 17.13 | 15.88 |

| Table 6. The stress concentration factor due to the crack |
| --- |
| | $t/a$ | $\sigma_{\text{max}}$ (MPa) | $\sigma_{\text{nom}}$ (MPa) | $K_t$ |
| --- | --- | --- | --- |
| 10 | 27.85 | 18.23 | 1.5277 |
| 14.28 | 29.35 | 17.81 | 1.6479 |
| 15 | 31.28 | 17.75 | 1.7622 |
| 21.42 | 31.75 | 16.62 | 1.9103 |

In Table 6 can be seen that values of $t/a$ are proportional to stress concentration factor $K_t$. Increasing the values of $t/a$ will raise the stress concentration factor, where the rise of crack length and the reduction of crack width increase $t/a$. So, the sharper notch and the more extended crack size upgrade the stress concentration factor.

3.4. The crack condition with treatment

Table 7 shows the stress measurement result of the crack cantilever plate under the load of 6.7 N with the treatment of a stop-drilled hole and an additional hole. It is shown that both applied methods to reduce stress concentration factors are useful. The stop hole reduces the stress concentration factor ($K_t$) by 3.76%. By increasing the size of the hole, $K_t$ is reduced by 4.41%. Applying the additional hole drops the value of $K_t$ by 11.23%.

| Table 7. Stress measurement results on the treated crack plate |
| --- |
| Condition | Stop hole | Add hole | SG 1 (MPa) | SG 2 (MPa) | SG 3 (MPa) | SG 4 (MPa) | SG 5 (MPa) | $K_t$ | % $K_t$ Reduction |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| crack | - | - | 31.76 | 20 | 17.74 | 16.2 | 12.53 | 1.911 | - |
| $t=15$ mm, $a=0.7$ mm | 3 mm | - | 32.22 | 20.75 | 17.84 | 17.8 | 13.68 | 1.839 | 3.76 |
| 4 mm | - | 32.36 | 20.98 | 17.94 | 17.98 | 13.97 | 1.826 | 4.41 |
| 4 mm | 4 mm | 30.72 | 22.24 | 18.8 | 18.35 | 13.04 | 1.696 | 11.23 |

The reduction of the stress concentration factor in cantilever aluminum plate is not significant, but treatment could be a fast and straightforward solution in decreasing the stress on the cracking plate structure.

4. Conclusions

From the analysis that has been conducted for stress measurement and the effort to reduce stress concentration factor, it is shown that the proposed stress measurement method on cracking cantilever
plate by using strain gauge and Arduino works well in measuring stress. The crack on the plate tends to propagate by the sign of high-stress value on the crack tip. The longer and sharper the crack, the higher the stress value on the crack tip, caused the rise in the stress concentration factor. For preventing the stress concentration factor magnifying, two kinds of treatment on the crack were conducted; stop-drilled hole and additional hole. The stop-drilled hole reduced the stress concentration factor by 4.4% and 11.23% for the additional hole. Even though the reduction of the factor is not significant, the treatment could be a fast and straightforward solution in decreasing the stress on the cracking plate structure.

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