Method of arresting crack growth for application at a narrow working space

Chobin MAKABE*, Kaito NAKA** and Md. Shafiul FERDOUS*

*Department of Mechanical Systems Engineering, University of the Ryukyus
1 Senbaru, Nishihara, Nakagami-gun, Okinawa 903-0213, Japan
E-mail: makabe@tec.u-ryukyu.ac.jp

**Graduate student, Graduate School of Engineering and Science, University of the Ryukyus
1 Senbaru, Nishihara, Nakagami-gun, Okinawa 903-0213, Japan

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Abstract
The many fracture accidents in engineering applications are related to fatigue crack initiation and growth. Therefore, the inspection of fatigue crack initiation and the arrest of crack growth are very important for the safe operation of a machine and the maintenance of a structure. Non destructive inspection has been developed in order to prevent a fracture accident resulting from the cracks or defects. When a crack initiates in machine equipment, continuous observation of the crack is carried out and the crack growth is arrested by some method. To arrest the crack growth, stop-holes are drilled at the crack tips in a case of initiation of a small number of cracks. Drilling the stop-hole is an effective method to prevent crack growth because it reduces stress concentration at the crack tip. Application of residual stress around the stop-holes and making a plastic hardening zone around the crack tips are effective to arrest crack growth. Applying a patch for repairing cracked parts is more effective than drilling stop-holes. In practical cases, patches are applied to repair cracked parts in airplane bodies, bridges, etc. However those methods cannot be used in some cases, because of the conditions of working space, for example. In this paper, an example of the application of a crack arrester at a car facility is introduced. Then, the effectiveness of the crack arrester is discussed. When many cracks are initiated and working space is very small, the crack arrester is a good tool for repairing the cracked parts. It is necessary to develop a method for stopping crack growth in order to replace cracked equipment, because new equipment should be designed carefully for preventing crack initiation again.

Key words: Fatigue, Crack growth, Stop-hole, Crack arrester, Stress concentration, Residual stress

1. Introduction

Drilling a stop-hole at a crack tip is effective to stop crack growth. Therefore, the effectiveness of drilling stop-holes was investigated by Ayatollahi, et al., (2014), Crain, (2010), Song, et al., (2004), Ghfiri, et al., (2000), Shin, et al., (1996), Noda and Matsu (1995), etc. Larger sizes of hole diameter had better be chosen for repairing the cracked part to reduce the stress intensity level effectively. However, there is a limitation on the diameter of the stop-hole applied at the cracked part. Creating a plastic hardening zone and a compressive residual stress zone in the vicinity of the crack tip or around the stop-hole are effective for stopping crack growth, even if a relatively small-diameter hole is applied (for example, Makabe, et al., 2009). In some practical cases, the repair of cracked components should be done under working conditions in a production facility or at a construction site (Naka, et al., 2013 and Uchida, 2007). In such cases, the cracked parts or equipment cannot be moved to a special repair-shop.

Some technical methods of arresting further crack growth in fatigued materials have been proposed, including the method related to stop-holes. Drilling a stop-hole at the crack tip is employed as an easy method, and this method has been improved. For examples as shown in Fig. 1, a bolted stop-hole and pinned stop-hole were proposed. Also, a patch was attached to the cracked part to repair a damaged structure (Baker, 1997, O’Donoghue and Zhuang, 2002, etc.).
Sometimes, those methods were applied to arrest crack growth in a structure or in a machine component. Applying a patch is more effective than drilling a stop-hole to repair a cracked component. However, patches are difficult to attach in some situations, for example, the initiation of many cracks in a component. Also, the welding method could not be used for repair in some cases.

![Diagram of stop-holes](image1)

**Fig. 1** Types of stop-hole, (a) Original stop-hole, (b) Pinned stop-hole, (c) Bolted stop-hole

![Diagram of crack initiation](image2)

**Fig. 2** Crack initiation at a car production facility, (a) Lifting equipment for car, (b) Crack initiation position, (c) Example of applying a stop-hole to prevent crack growth

![Diagram of crack arresters](image3)

**Fig. 3** Example of applying a bolted stop-hole and crack arrester, (a) With rail, (b) Without rail

In the previous work (Naka, et al., 2013), crack arresters were used instead of patches to stop the crack growth. Unfortunately, many cracks were initiated at a facility of a car production company. The cracks were initiated in some pillars which supported car lifting equipment. Four rails were attached to one pillar with many rail support plates. More than 100 cracks initiated in the rail support plates. For the first trial, a hole was drilled at each crack tip. However it did not work as shown in Fig. 2. Because of conditions of working space, the limitation of a maximum diameter of a stop-hole was about 10 mm. Also, the lengths of some cracks were longer than 200 mm. Detailed conditions of the cracking situation was written in the previous report. Figure 3 shows an example of the application of a crack arrester and a stop-hole. As shown in the parts cut out of a repaired pillar (Fig. 4), cracks were stopped from growing by attaching a crack arrester and bolting or pinning a stop-hole. In the previous paper, we did not report whether replacement of a cracked pillar with a new pillar could be done safely. That replacement was finished during a long vacation for the company staff without special interruption of car production. Thus, the cracks were stopped by the proposed arresting method which was applied as a temporary technique.
In the present report, we summarize the effectiveness of a bolted stop-hole and crack arrester again. Some contents of the previous report (Naka, et al., 2013) only written in Japanese are rewritten in the present paper. In the previous report, results of experiments were introduced in the case of a specimen with one side-edge crack. We would like to show the effect of bolting a stop-hole in the case of a specimen with both-sides edge cracks, too. It is expected that the effects of crack arrester and stop-hole on stopping crack growth is affected by the condition of crack initiation which is related to specimen geometry. Now, in the case of the repair at car company, the bolting to stop-drilled hole and crack arrester was carried out from front side of pillar surface, because repair work was difficult to done at inside of the pillar.

Here, the present study just investigated the effect of the crack arrester and stop-hole. Those results are not exactly related to the real case of crack growth at the pillar. But, the tendency and mechanism of arresting the crack growth can be shown.

Fig.4 Cracked part, (a) Stop-holes and crack arresters for a long crack, (b) Stop-holes for a relatively short crack

2. Materials and Experimental Procedures

Two cracked pillars were replaced 7 months later and 12 months later, respectively, with new pillars after temporary repair by crack arrester and stop-hole. The number of times the car lift moves up and down in 12 months is about $10^5$. It was the maximum number of loading cycles till the replacement of pillars. According to that real example, the number of cycles to the endurance limit was set at $10^5$ in the present experiment at the laboratory. Also, applied stress conditions were determined in the situation of cracked pillars for testing during emergency conditions. The purpose of the present method is not to stop the crack growth permanently. So we set the expectation of a finite number of maximum loading cycles.

<table>
<thead>
<tr>
<th>C</th>
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<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Fe</th>
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<td>0.12</td>
<td>0.21</td>
<td>0.6</td>
<td>0.015</td>
<td>0.012</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Table 1  Chemical composition (mass, %)

<table>
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<tr>
<th>$\sigma_y$ [MPa]</th>
<th>$\sigma_B$ [MPa]</th>
<th>$\sigma_T$ [MPa]</th>
<th>$\phi$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>630</td>
<td>1070</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 2  Mechanical properties of the material ($\sigma_y$: Yield stress, $\sigma_B$: Tensile strength, $\sigma_T$: True fracture stress, $\phi$: Reduction of area).
Fig. 5 Examples of specimen and crack arrester (mm), (a) Specimen with one-side slit, (b) Crack arrester

Fig. 6 Specimen with stop-hole, (a) One-side crack with stop-hole, (b) Center crack with stop-holes, (c) Both-sides cracks with stop-holes (longer ligament), (d) Both-sides cracks with stop-holes (shorter ligament)

Fig. 7 Patterns of applying a stop-hole and a crack arrester in the case of a one-side crack, (a) Basic, (b) Normal stop-hole, (c) Pinned stop-hole, (d) bolted stop-hole, (e) Normal stop-hole with crack arrester, (f) Pinned or bolted stop-hole with crack arrester, (g) Pinned stop-hole with crack arrester, (h) Normal stop-hole with crack arrester
Fig. 8. Test specimens with both-sides edge cracks, (a) The case of a normal and bolted stop-hole, (b) Comparison of the effect of friction of washers A and B on crack initiation, (c) Specimen for testing the effect of crack arresters

Fig. 9 Geometry of the washers (a) Comparison of the sizes of washers, (b) Photograph of washer B

The material used was a structural rolled steel plate. The chemical composition and mechanical properties are shown in Tables 1 and 2, respectively. Figure 5 shows the basic geometry of the specimen with one side slit. Slits were cut in the specimen and were regarded as cracks, and stop-holes were drilled at the slit bottoms (or crack tips). Also, examples of the shape of crack arresters are shown. Figures 6 (a)-(d) show the positions of slits and holes. Figures 7 (a)-(d) show the drilling conditions of stop-holes and bolting conditions. Also, crack arresters were used to prevent crack growth effectively. Figures 7 (e)-(h) show the positions of the crack arresters. Because no one could reach inside a pillar box, a nut could not be used. Instead, female screws or thread ridges were made into the body of the pillar in the case of car facility. In the case of the present experiment, a female screw was made in some specimen’s body, too. Now, effect of conditions to attach crack arresters on stopping crack growth will be discussed with Fig. 13 shown in the later.

In normal stop-hole, pin and bolt were not used. In some cases, a pin was inserted into a stop-hole, or a bolt was used at a stop-hole. In this study, those stop-holes are called pinned stop-holes and bolted stop-holes, respectively. Also, the crack arresters were attached in addition to drilling stop-holes, in some cases. When a specimen with a normal stop-hole was used, a hole of 10 mm in diameter was drilled. When a pin of 0.45 % carbon steel was inserted into a hole, a hole of 9.6mm in diameter was drilled. The diameter of the pin was 4% larger than that of the stop-hole. A female screw was made into the body of a specimen corresponding to metric thread ‘M10’, in the case of a bolted stop-hole. A high tension type of hexagonally headed bolt was used with a plane washer and a spring lock washer. The bolt material was chromium molybdenum steel which contains 0.35% carbon (Japanese Industrial standard, SCM435).

Fatigue tests were performed with a hydraulic servo-type testing machine. Applied stress level referred to the loading conditions which were expected from the design. A stress level of 30 MPa was regarded as the maximum applied stress at the crack initiation sites. In the main experiments at the laboratory, variable stress was set from – 15 MPa to 45 MPa in the case of a specimen with a one-side crack. The maximum cyclic stress was higher than the design stress and the minimum stress was compression. Compression was not expected to happen at the crack initiation sites at the pillar. Thus, the applied stress conditions in the experiment were more severe than the loading conditions at operation. The stress ratio $R$ was – 1/3, and the frequency was 10 Hz, in the main tests.

A photograph of the specimen was taken by a digital camera before and after the testing, and crack initiation and growth were observed by an optical microscope. Due to the conditions of bolting, crack initiation behavior was hard to detect on the bolt head side of the plane. Therefore, the main observation was performed on the opposite side of the bolt head (On both sides of the specimen, prior observation was done at the crack initiation sites).
When normal stop-holes were drilled at crack tips in the center-crack specimen of Fig. 6 (b) and the both-sides edge crack specimen of Fig. 6 (c), no new crack initiated from the normal stop-hole even after applying cyclic stress of $10^5$. As shown later, the stress concentration factors of those specimens had a relatively low value. In those specimens, the stop-hole would work without pin insertion or bolting. Next, we examined the case of a longer initial crack in a both-sides edge cracks specimen (Fig. 6 (d)). We would like to show the effects of the stop-hole and crack arrester in the case of other types of specimens which is different from the specimen with a one-side edge crack.

The stress concentration factor of the specimen in Fig. 6 (d) is higher as shown in the later. So, when normal stop-holes were applied for testing, the specimen broke within 100 cycles of stress application. In the main tests, applied cyclic maximum stress $\sigma_{\text{max}}$ was 45 MPa, stress ratio $R$ was -1/3, and frequency was 10 Hz. The other three patterns of testing were performed. Also, in the case of that specimen, the effect of the washer was examined because the crack growth behavior can be compared at both sides of the specimen simultaneously. The crack opening displacement in the vicinity of stop-hole influences crack initiation and growth from the stop-hole. Also, it is assumed that the friction between the specimen surface and washer affects the crack initiation and growth from the stop-hole. Therefore, the crack growth behavior at the side with washer is different from that at the side without washer.

The test sections of the specimens used in those tests are shown in Fig. 8. In one case, the effect of a bolted stop-hole with normal washer (Washer A is the same type of washer used in the previously explained testing by Naka et al., (2013)) on arresting crack growth was examined. In this case, a normal stop-hole was machined on one side of the slit, and a bolting was applied to the stop-hole on the other side as shown in Fig. 8 (a). The effect of the friction between the specimen surface and washer surface on the crack growth was examined using the specimen of Fig. 8 (b). In this case a bolted stop-hole was used with washer A (normal type) and Nord-lock washer (washer B). Also, the effect the amount of torque used to attach the crack arrester had on arresting crack growth was examined by using the specimen of Fig. 8 (c). Figure 9 shows the geometry of washers A and B.

3. Experimental Results and Discussion

3.1 Stress concentration at hole bottom of a drilled stop-hole

The main specimen used was a side-edge crack specimen. Before the experiments were performed, the stress concentration was calculated by code ANSYS. Also, that calculation accuracy was checked by comparison with the calculation results from the programs of two-dimensional body force method which developed by Nisitani and Saimoto, 2003. The qualitative tendency of stress distribution at hole-bottom was compared in the cases of specimens with a side-edge crack, a center crack and both-sides edge cracks. Table 3 shows the calculation results of maximum stress $\sigma_{\text{max}}$ at hole-bottom and the maximum value of crack opening displacement $\delta_{\text{max}}$ when the applied stress $\sigma$ at upper and lower edges are of uniform value. Where, the value of $\delta_{\text{max}}$ is the value at $\sigma_o=100$ MPa.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$\delta_{\text{max}}$ [mm]</th>
<th>$\sigma_{\text{max}}/\sigma_o$</th>
</tr>
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<tbody>
<tr>
<td>Fig. 6 (a)</td>
<td>0.98</td>
<td>27.3</td>
</tr>
<tr>
<td>Fig. 6 (b)</td>
<td>0.12</td>
<td>8.3</td>
</tr>
<tr>
<td>Fig. 6 (c)</td>
<td>0.12</td>
<td>9.3</td>
</tr>
<tr>
<td>Fig. 6 (d)</td>
<td>1.78</td>
<td>13.7</td>
</tr>
</tbody>
</table>

Where the ligament size was the same as shown in Fig. 6 (a), (b) and (c), the value of $\sigma_{\text{max}}$ is clearly higher in the case of the specimen with a side-edge crack (Fig. 6 (a)). Also that value of Fig. 6 (a) is somewhat higher than the case of the shorter ligament size of Fig. 6 (d). Thus, it was found that the stress concentration and crack opening displacement became higher in the case of the specimen with a side-edge crack because the bending moment occurs at the ligament. That situation is due to the unsymmetrical shape of the specimen. Therefore, we carried out main tests by using a specimen with a side edge-crack to do tests with severe stress conditions. Also, the limitation of the testing machine capacity was related to the loading conditions.
The experiments were performed with reference to those calculations, and the tendencies of stress distribution were also affected when the pin was inserted into the stop hole or bolting was applied at the stop hole. The crack opening displacement affects crack growth behavior, and the effects of bolting at a stop-hole and attaching a crack arrester is effective to decrease the crack opening displacement.

Figure 10 shows examples of stress distribution in the cases of Fig. 6. It was found that the higher stress concentration was observed in the case of Fig. 6 (a) (the specimen with a side-edge crack).

Now, the calculation was performed with half of the specimen in the case of the specimen with a side edge-crack, with a quarter of the specimen with center crack and with both-side-edge cracks, in consideration of the symmetrical conditions of the specimen.

3.2 Effect of crack arrester on crack growth behavior
3.2.1 In the cases of specimen with a side-edge crack with endurance cycles of $10^5$

The crack length $c$ measured from the bottom of stop-hole or the edge of washer is defined as shown in Fig. 11. Thus, crack length $c$ was the length of a new crack initiated from a stop-hole, or the length measureable after the crack was detected by microscope on the bolt head side.

Arresting the crack growth was investigated in the present study by the following methods. First method: Stress concentration is reduced by drilling a stop-hole at the crack tip. Second method: Pin is inserted into drilled stop-hole. Because the hole was expanded, the material around the hole was elongated and compressive residual stress developed in a circumferential direction around the hole due to the elastic plastic deformation behavior in the vicinity of the hole (The elongated area around the stop-hole was compressed due to the motion of plastic-elastic deformation of material...
outside of that area). Third method: Bolts were tightened into screw-threaded stop-holes. Tensile stress acted in the axial direction of the hole by tightening the bolt, and the friction between the specimen surface and the washer in the vicinity of the hole reduced the cyclic deformation at the hole bottom. Fourth: The crack arrester was attached across the crack face. The crack opening displacement was reduced because a part of the stress concentrated at the ligament was re-distributed by the crack arrester.

Figures 12 (a) and (b) show the relationships between the amount of repeated stress \( N \) and the crack length \( c \). Applied maximum cyclic stress \( \sigma_{\text{max}} \) was 45 MPa and stress ratio \( R \) was -1/3. In these cases, the crack length \( c \) was measured on one side of the specimen plane. The data for normal stop-hole and pinned stop-hole are shown in Fig. 12 (a). The slit specimen without stop-hole broke within the application of 50 stress cycles (This data is not shown in Fig. 12 because the specimen suddenly broke). Even, in the case of a normal stop-hole, the specimen broke within \( 10^4 \) stress cycles. The crack grew rapidly and crack length \( c \) over 8 mm was observed within the application of \( 10^4 \) cycles. The endurance limit to test is \( 10^5 \) cycles which is considered the replace period of the facility. It was confirmed that the method for extending fatigue life by stop-hole did not work. Also, the method where the pin was inserted into the stop-hole did not work either. Due to the unsymmetrical specimen geometry, a bending moment was developed and the specimen grip edge on the actuator side was moving up and down and also to the right and left sides during the cyclic deformation. Consequently, gaps between the surface planes of pin and hole were initiated and some compressive residual stress was released.

However, when the crack arrester was attached across the crack face, the crack growth behavior was improved and the specimen did not break even with the number of stress cycles over \( 10^5 \). In the case of Fig. 12 (a), the data for two types of specimen with crack arrester are shown. In the case of one of them, the pin was inserted into a stop-hole drilled at the crack tip and the crack arrester was attached along the edge of the specimen (Fig. 7 (f)). In another case, the pin was inserted into the hole in which the hole center was 15 mm from the crack tip and a 0.9 mm initial crack initiated from the slit edge (Fig. 7 (g)). In this case also, the crack arrester was attached. As shown in Fig. 12 (a), the rapid crack growth was not observed in those two cases in which the crack arrester was attached. It is discussed from Fig. 10 and Table 3 that the bending moment and crack opening displacement were reduced by attaching crack arrester, and fatigue life was improved. Now, the torque of tightening the bolt to attach the crack arrester was 52 Nm.

![Fig. 11 Definition of crack length \( c \) from stop-hole edge, slit edge or edge of washer](image)

![Fig. 12 Crack growth curves, (a) In the case that pin was inserted into hole and crack arrester was attached, (b) In the case of bolted stop-hole](image)
Figure 12 (b) shows the results for the bolted stop-hole. The data for a normal stop-hole is also plotted. The crack length \( c \) reached about 10 mm at about \( 5 \times 10^5 \) of the number of stress cycles in the case of 55 Nm of bolting torque, and at about \( 7 \times 10^5 \) in the case of 89 Nm. Bolting at the stop-hole with higher torque was more effective than inserting the pin into the stop-hole in the present study’s conditions. Also, higher torque at bolting resulted in longer fatigue life. In Fig. 12 (b) the cases of attaching a crack arrester are also shown. When the lower bolting torque, that is \( T = 24 \text{Nm} \), was applied to attach the crack arrester or to screw the bolt into the stop-hole, the fatigue life did not improve much. Even when the stop-hole was not bolted, longer fatigue life was obtained by attaching a crack arrester with higher torque (\( T = 89 \text{Nm} \)). Therefore, using the crack arrester was the best method in the present trial.

3.2.2 Applying crack arrester to endure the cyclic limit of \( 5 \times 10^5 \)

The effectiveness of attaching a crack arrester for the improvement of fatigue life was investigated further in the present section. The number of cars lifted is \( 10^5 \) per year. So, the endurance limit of the specimen for fatigue failure was set \( 10^5 \) times in the previous section. Crack initiation was not checked from the inner side of the pillar, and two pillars were replaced 7 and 12 months later after the attaching the crack arrester and drilling the stop-hole. Figure 3 shows the conditions of the places where the crack arrester was attached and stop-hole was drilled. The repaired parts were cut out from the old pillar as shown in Fig. 4. No crack initiated from the stop-hole.

It is better that the repaired equipment endure more year of operation. So, the effect of the crack arrester to improve fatigue life was investigated further. In this section’s experiments, the endurance limit of fatigue life was set at \( 5 \times 10^5 \); then, the tests were carried out.

Figure 13 shows the arrangement of the crack arrester and stop-hole in those tests. Three types of crack arrester arrangement were used with a bolting torque of 52 Nm. The influence of the position of the crack arrester on fatigue life was also checked. Applied cyclic maximum stress \( \sigma_{\text{max}} \) was 45 MPa and stress ratio \( R \) was \(-1/3\). In those cases, crack growth behavior was observed from both sides of the specimen surfaces; that is, the specimen surface where the crack arrester was attached and the opposite side of that surface. In Fig. 13, the back side is the specimen surface which has a crack arrester, but there is no crack arrester on the front side. The bolt head was on the surface where the crack arrester was attached.

As shown in Fig. 13, the specimens were distinguished by types A – E. Two crack arresters were attached and a normal stop-hole was applied in the case of type A. The crack arrester was set at the specimen side edge and the bolted stop-hole was applied in the case of type B. In the cases of types C – E, a normal stop-hole was applied. The crack arrester was set at the specimen side edge in the case of type C. The crack arrester was set near the stop-hole in the case of type D. In the case of type E, a crack arrester was set at the specimen side edge before testing; then, after a new crack initiation, another crack arrester was added at the position near the stop-hole.

Figure 14 shows the experimental results with crack growth curves. New crack did not initiate at the stop-hole in the cases of types A and B even if \( 5 \times 10^5 \) cycles were applied. That means that repaired equipment can be used more safely when the crack arresters are attached in a similar manner to types A and B. Now in Fig. 14, the front side shows the specimen surface without a crack arrester or bolt head. Also, the cracks were observed on both front and back sides.

The crack was initiated before the cyclic number reached \( 5 \times 10^5 \) where one crack arrester was set as in types C and D. In the case of type D, where the crack arrester was set near the stop-hole, the crack length became over 10 mm before the number of cycles reached \( 10^5 \). However, in the case of type C, the number of cycles until the crack length became over 10 mm was close to \( 4 \times 10^5 \). Therefore, it was found that the better position for the crack arrester was at the side edge of the specimen when one crack arrester was set.

It was found from the data of type E that the crack growth rate decreased by adding the crack arrester after the crack initiation. The arrow in the vertical direction shows the point at which the crack arrester was attached after crack initiation. The slope showing the relation between the crack length \( c \) and number of cycles \( N \) was changed at that point. That means that the crack growth rate was improved by attaching the crack arrester as well as decreasing the driving force for crack opening.

Figure 15 shows photographs of broken crack arresters. In the cases of types C and D, it was found that the crack arrester broke after crack initiation from the stop-hole. In the cases of types A, B and E, the crack arresters were not broken when tests were finished. It is assumed that the crack arrester broke when the crack opening displacement became larger after crack initiation from the stop-hole. As shown in Fig. 14, crack growth life was improved when the
crack tip opening displacement was decreased due to attaching a second crack arrester. But, it is also expected that the breaking behavior of the crack arrester can be applied to the detection of crack initiation. For example, it is expected that crack initiation from crack arrester can be detected by using a strain gage and we can know the crack initiation from crack arrester before a material broke. That condition should be examined in the future. The design of the crack arrester will be important when the crack arrester is applied to machine equipment. It is important that the crack initiation life was shorter on the front side than on the back side. However, after a crack initiated at the back side, rapid crack growth happened on that side. Therefore the detection of crack initiation is very important when crack initiation is monitored on the back side only. In the case of the present experiment, the rapid crack growth was observed by application of short cycles after we confirmed crack initiation on the back side.

![Fig.13 Some methods of attaching a crack arrester to the cracked specimen, (a) Type A, (b) Type B, (c) Type C, (d) Type D, (e) Type E](image)

![Fig. 14 Crack growth curves for specimens with crack arrester](image)

![Fig. 15 Broken crack arrester, (a) In the case of type C, (b) In the case of type D](image)

### 3.3 In the cases of both-sides edge cracks specimen

Figure 16 (a) shows the results in specimen of Fig. 8 (a). The applied stress was varied from -30 MPa to 30 MPa (Stress ratio $R = -1$), and from -15 MPa to 45 MPa ($R = -1/3$). It was found that crack initiation occurred more easily in the case of a normal stop-hole. Because the maximum cyclic stress is higher, the crack initiation cycle in the case of $R = -1/3$ is shorter than that of $R = -1$.

Figure 16 (b) shows the comparison of the effect of friction between the washer surface and the specimen surface by using the specimen of Fig. 8 (b). Testing was performed with variation range of stress from -15 MPa to 45 MPa ($R = -1/3$). It is well known that the Nord-lock washer (= washer B) is a useful tool to prevent losing the bolt. In this experiment, the normal washer was placed between the bolt head and the Nord-lock washer, and the strong friction was created between the Nord-lock washer and the specimen surface. The friction force per unit area is higher in the case of using the Nord-lock washer. However, it was found that the number of crack initiation cycles was larger in the case of washer A (normal washer) than in the case of washer B. Because the crack initiation side was opposite to the bolt head side, the effects of surface friction on the bolt head side were not related to the crack initiation behavior. The effects of friction due to attaching a washer should be examined when the nut is applied.
Figure 16 (c) shows the effect of the attachment torque of the crack arrester on the behavior of new crack initiation at a normal stop-hole. Applied cyclic maximum stress $\sigma_{\text{max}}$ was 45 MPa and stress ratio $R$ was -1/3. When torque $T$ was 30 Nm to attach the crack arrester by bolts, crack initiation was not observed at the stop-hole edges till $5 \times 10^5$ cycles. When torque $T$ was 20 Nm and 10 Nm, the crack initiated at the stop-hole and the specimen was broken within $3 \times 10^5$ cycles. Therefore, it was understood that the crack arrester was useful to improve the crack growth behavior and the applied torque for attaching the crack arrester by bolt is important to extend the fatigue life. Also, it is found from the data of Fig. 16 that attaching a crack arrester is more effective to improve fatigue life. Longer fatigue life was obtained in the case of data with $T=30$ Nm in Fig. 16 (c).

In the present report, methods of arresting crack growth were shown when repair was done from one-side of a cracked material. If a cracked part is repaired from both-sides of a material, the crack growth can be stopped more effectively. For example, the crack opening displacement would be decreased more effectively by attaching a crack arrester on both sides of a material. For the safety drive of a machine and the maintenance of a structure, monitor and repair of damaged parts should be done carefully.

![Fig. 16 Crack growth curves in the tests with specimen of Fig. 8, (a) Specimen type of Fig. 8(a), (b) Fig.8 (b), (c) Fig.8 (c)](image)

**4. Concluding Remarks**

The methods of arresting crack growth were investigated. Stop-holes were drilled at the crack tips and crack arresters were attached at the cracked parts. The main results of the present experiments are summarized as follows: (1) The effect of a stop-hole on arresting crack growth was different, depending on the specimen geometry. In the case of the one-side edge crack specimen used in this study, drilling a stop-hole without inserting a pin or bolting it did not work to arrest crack growth.
The attachment position of a crack arrester affected the crack initiation behavior. Also, the attachment torque on the crack arrester influenced crack initiation behavior at the stop-hole, when the crack arrester and stop-hole were simultaneously applied.

When a crack arrester was used for test, a number of stress cycles to crack initiation and a crack growth was improved.

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References


