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

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Abstract

The development and initiation of fatigue cracks are associated with the many fracture events that occur in engineering applications. Maintaining a structure and running a machine safely depend on inspecting for fatigue crack initiation and stopping crack propagation. To avoid accidents caused by cracks or faults, non destructive examination has been devised. When a crack starts to form in machine equipment, it is necessary to continuously monitor the fracture and find a way to stop its expansion. In the event of a limited number of cracks initiating, stop-holes are drilled at the fracture tips to halt the crack propagation. Because it lessens the concentration of stress at the fracture tip, drilling the stop-hole is an effective way to inhibit crack propagation. To halt the progression of cracks, it is helpful to provide residual stress around the stop-holes and create a plastic hardening zone around the fracture points. It is more effective to use a patch to mend fractured sections rather than drill stop-holes. Repairing damaged areas on aircraft hulls, bridges, and other real-world objects sometimes requires the application of patches. But such approaches aren't always applicable; sometimes, for instance, the working environment just isn't conducive to their utilisation. A crack arrester is shown in this study as an example of its implementation at an automobile facility. Next, we'll talk about how well the crack arrester works. If there are several initial cracks and the available working area is limited, the crack arrester might be an effective tool for restoring the damaged components. Because replacement equipment should be meticulously built to avoid fracture initiation again, it is essential to find a way to limit crack development before replacing damaged equipment.

Key words : Breakage, wear and tear, and stop-hole Arrester for cracks, Concentration of stress, residual stress

1. Introduction

By creating a stop-hole at the very point of a fracture, its further advancement may be halted. Consequently, the effectiveness of drilling stop-holes has been the subject of several research. These include works by Ayatollahi et al. (2014), Crain (2010), Song et al. (2004), Ghfiri et al. (2000), Shin et al. (1996), Noda and Matsuo (1995), and countless others. When fixing the damaged area, it is best to utilise bigger sizes of hole diameter in order to properly reduce the stress intensity level. But there's a limit to how big a stop-hole may be used on the broken part. The creation of a plastic hardening zone and a compressive residual stress zone around the fracture tip or the stop-hole may prevent the production of fractures even when utilising a relatively small-diameter hole (e.g., Makabe, et al., 2009). Repairing damaged components on the spot at a building site or manufacturing facility may be more practical at times

(Naka, et al., 2013; Uchida, 2007). In this case, getting the broken parts to a specialist repair shop is just not going to work

A number of technological methods have been proposed for preventing fractures in worn materials from further propagating, including the stop-hole technique. Making a stop-hole in the concrete at the fracture point is an easier and more effective option. Figure 1 shows bolted and pinned stop-holes that are examples of the solutions that were recommended.

O'Donoghue and Zhuang (2002), Baker (1997), and others state that a patch was also put to the damaged region to restore structural integrity.

On rare occasions, similar methods were used to prevent the advancement of fissures in structures or machine components. Instead of drilling a stop-hole, it is preferable to apply a patch to a cracked component. One situation where patches could be difficult to apply is when many cracks in a component begin to develop. Additionally, repairs were not always feasible using the welding process

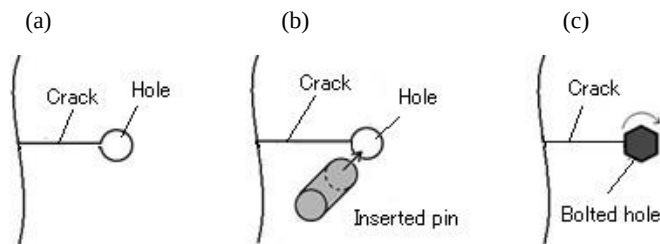


Fig.1 Types of stop-hole, (a) Original stop-hole, (b) Pinned stop-hole, (c) Bolted stop-hole

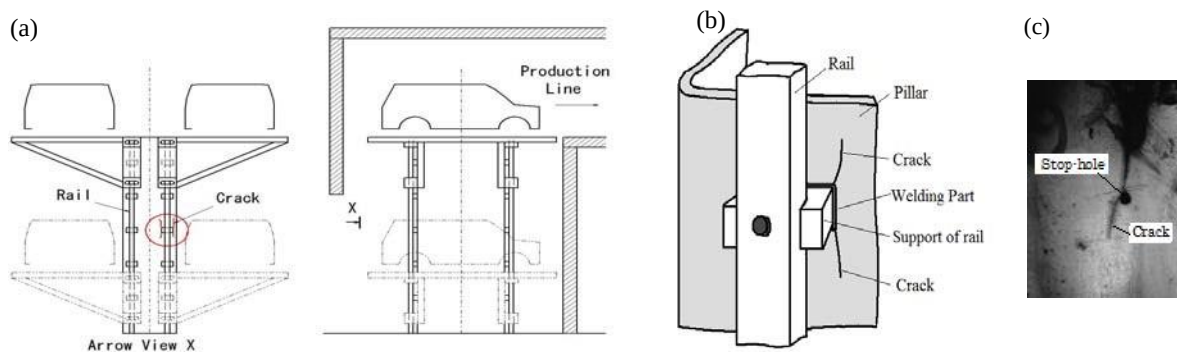


Fig. 2 Crack initiation at a car production facility, (a) Lifting equipment for car, (b) Crack initiation position, (c) Example of applying a stop-hole to prevent crack growth

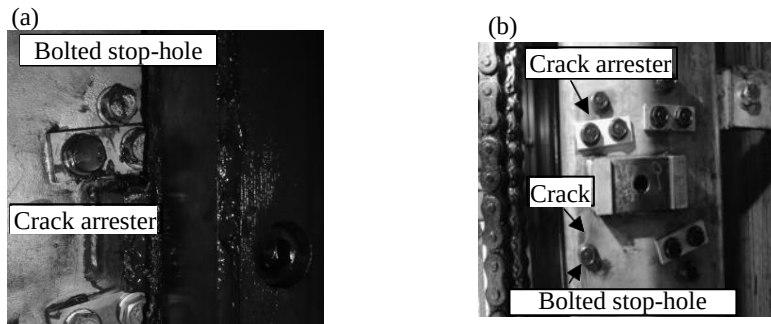
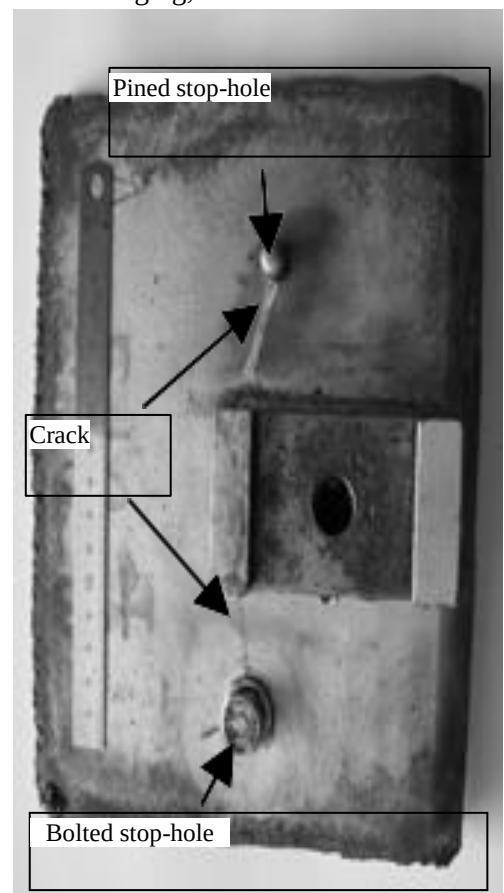


Fig. 3 Example of applying a bolted stop-hole and crack arrester

As opposed to patches, crack arresters effectively halted the growth of cracks, according to a prior research (Naka et al., 2013). Several fissures were found in a structure belonging to a car manufacturing enterprise. The pillars of the vehicle hoisting apparatus were the first to break. Four rails were attached to one pillar by use of multiple rail support plates. More than a hundred cracks appeared in the rail support plates. A hole was drilled into each fracture location in the first test. Unfortunately, we did not get the outcomes shown in Figure 2. Due to limitations in working space, the largest diameter of a stop-hole was set at about 10 mm. Not only that, but a few of the cracks were over 200 mm in length. There was a lengthy description of the cracking issue in the previous report. Figure 3 depicts the application of a crack arrester and stop-hole. Figure 4 shows the removed pieces of a repaired pillar that were reinforced with bolts or pins and crack arresters to prevent further crack propagation. The prior article did not state if it was safe to replace a damaged pillar with a new one. The replacement was finished when the company's personnel were on vacation, thus car production was not much affected. As a temporary measure, the proposed arresting method successfully sealed the fractures. We take a look at bolted stop-hole and crack arresters again to see how well they work. A previous paper (Naka, et al., 2013) was published in Japanese initially, however this research rewrites part of the information. In the previous publication, the results of an experiment were reported for a specimen that had one crack running down its length. Bolting a stop-hole should be shown even for specimens with edge fractures on both sides. The effects of crack arresters and stop-holes on arresting crack propagation are expected to change depending on the circumstance of crack initiation, which is related to specimen geometry. During the repair at the vehicle industry, bolts were fastened to the stop-drilled hole and crack arrester from the front side of the pillar surface. The restoration work inside the pillar proved

to be rather challenging, which caused this. This



inquiry just looked at the crack arrester and stop-hole functions. Those results do not provide a perfect picture of the pillar's fracture propagation status. Never prever

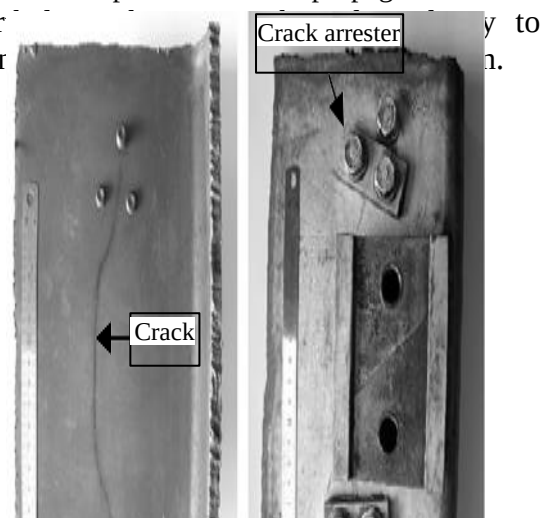


Fig.4 Cracked part, (a) Stop-holes and crack arresters for a long crack, (b) Stop-holes for a relatively short crack

2. Materials and Experimental Procedures

Two damaged pillars were temporarily stabilised using a crack arrester and a stop-hole, respectively, and then replaced with new pillars seven and twelve months later. Every year, around 105 journeys are conducted up and down the vehicle lift. It is possible that the pillars were not subjected

to any further loading cycles prior to their replacement. That real-world example served as the foundation for the present laboratory experiment, which employed 105 cycles to determine the endurance limit. The applied stress conditions were also defined in the event of cracked pillars for testing reasons during crises. The present method will not be able to stop the fracture from becoming wider in the long run. As a result, we prove the hypothesis of a finite maximum number of loading cycles.

Table 1 Chemical composition (mass, %)

C	Si	Mn	P	S	Fe
0.12	0.21	0.6	0.015	0.012	Bal.

Table 2 Mechanical properties of the material (σ_s : Yield stress, σ_B : Tensile strength, σ_T : True fracture stress, ϕ : Reduction of area).

σ_s [MPa]	σ_B [MPa]	σ_T [MPa]	ϕ [%]
600	630	1070	64

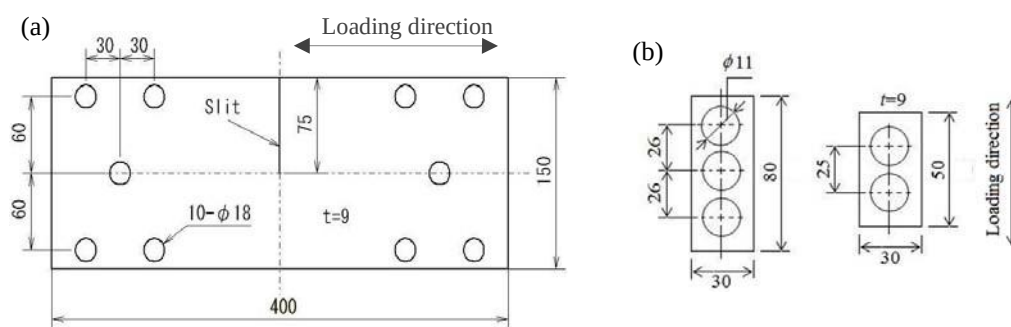


Fig. 5 Examples of specimen and crack arrester (mm), (a) Specimen with one-side slit, (b) Crack arrester

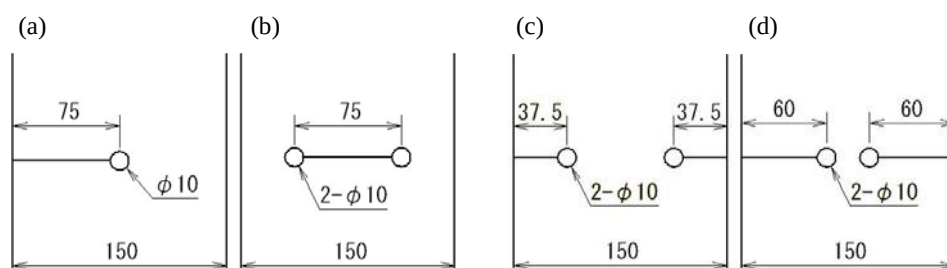


Fig. 6 Specimen with stop-hole, (a) One-side crack with stop-hole, (b) Center crack with stop-holes, (c) Both-sides cracks with stop-holes (longer ligament), (d) Both-sides cracks with stop-holes (shorter ligament)

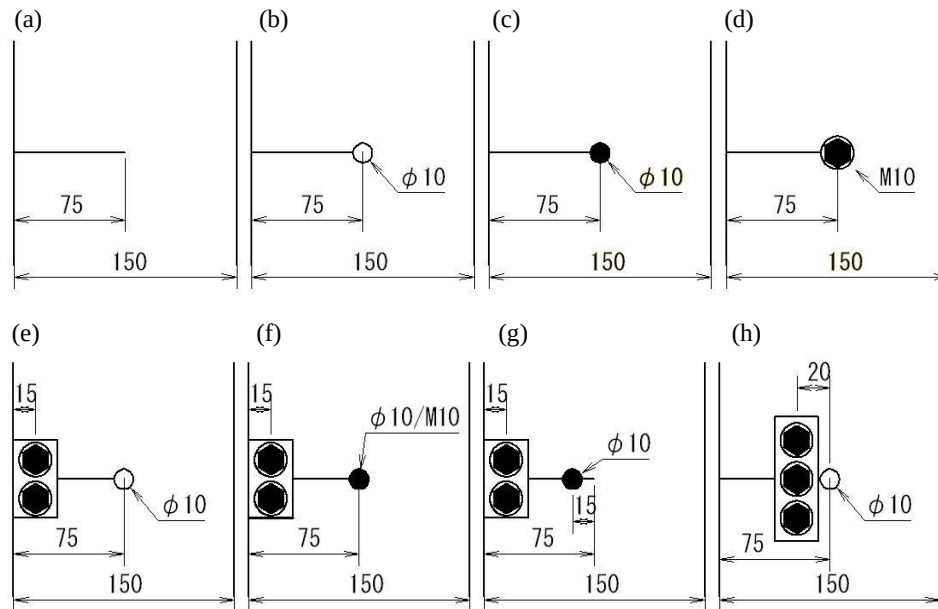


Fig. 7 Patterns of applying a stop-hole and a crack arrester in the case of a one-side crack, (a) Basic, (b) Normal stop-hole, Pinned stop-hole, (d) bolted stop-hole, (e) Normal

stop-hole with crack arrester, (f) Pinned or bolted stop-hole with crackarrester, (g) Pinned stop-hole with crack arrester, (h) Normal stop-hole with crack arrester

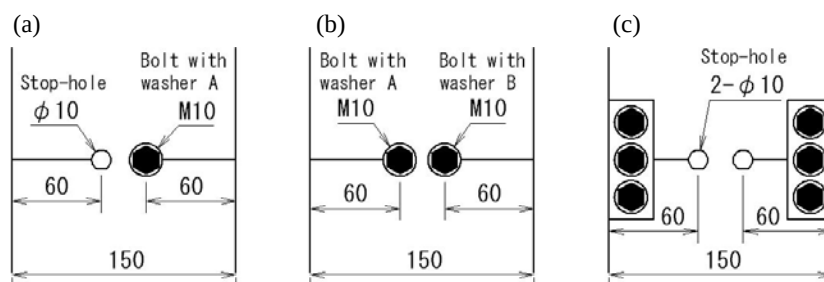


Fig. 8. Test specimens with both-sides edge cracks, (a) The case of a normal and bolted stop-hole, (b) Comparison of the effect of friction of washers A and B on crack initiation, (c) Specimen for testing the effect of crack arresters

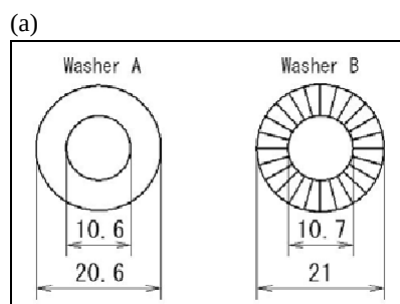


Fig. 9 Geometry of the washers (a) Comparison of the sizes of washers, (b) Photograph of washer B

The material used was structural rolled steel plate. While Table 1 displays the chemical composition, Table 2 displays the mechanical properties. For the sake of basic geometry, Figure 5 shows the specimen with only one side incision. To prepare the specimen, tiny holes were punched into it and filled with stop-holes; the holes at the bottoms of the holes were used as crack tips. There are also pictures showing the forms of the crack arresters. Figures 6 (a)-(d) show the positions of the slits and holes. Images 7 (a)-(d) show the circumstances for bolting and drilling stop-holes. The usage of crack arresters was also successful in avoiding the growth of cracks. Figures 7 (e)-(h) show the locations of the crack arresters. No one could ever get inside a pillar box, therefore nuts wouldn't work there. The body of the pillar was instead altered to include thread ridges or female screws for the car facility. A female screw was also surgically placed into the body of at least one creature in this specific experiment. Using Fig. 13 as an example, we will next discuss how various factors impact the efficiency of attaching crack arresters in slowing crack development. In traditional stop-holes, fasteners like pins and bolts are not used. Bolts or pins might have been used to secure a stop-hole in some cases. Pinched stop-holes and latched stop-holes are the terms used to describe these types of holes in this study. Along with the crack arresters, the drilling stop-holes were sometimes fixed. Bored a 10-millimeter-diameter hole for specimens with normal stop-holes. A pin made of 0.45% carbon steel was plunged into it to drill a hole 9.6 mm in diameter. In terms of diameter, the pin and stop-hole were 4 percent different. The specimen's body was machined to accommodate a female screw that corresponds to metric thread 'M10' in the case of a secured stop-hole. A high tension kind of hexagonally headed bolt was used in conjunction with a spring lock washer, a plane washer, and the other type of washer. The bolts were manufactured from SCM435 chromium molybdenum steel, which is the industry standard in Japan and has precisely 0.35% carbon. Fatigue testing were carried out using a device that resembled a hydraulic servo. Here, "applied stress level" referred to the design-based loading scenarios that were anticipated. We assumed a maximum applied stress of 30 MPa at the fracture starting spots. The major laboratory tests for specimens with cracked surfaces included subjecting them to stresses between fifteen and forty-five megapascals (MPa). At its lowest point, cyclic stress was compressive, and at its maximum point, it was larger than the design stress. The compression that happened at the

areas where the pillar's fractures started was unexpected. Consequently, the operational loading levels were lower than the experimental stress conditions. The main experiments used a stress ratio R of $-1/3$ and a frequency of 10 Hz. Before and after testing, digital photos of the specimen were taken using a camera, and fractures were seen using an optical microscope. It was challenging to detect fracture start activity on the bolt head side of the aircraft because of the bolting conditions. Consequently, the bolt head's back side was the principal site of inspection (prior examination had been done at the crack start points on both specimen sides).

Despite applying a cyclic load of 105 to the center-crack specimen (Fig. 6 (b)) and the both-sides edge crack specimen (Fig. 6 (c)), no new crack could be generated from the usual stop-hole. Later on, it was shown that such specimens exhibited stress concentration factors that were comparatively low-valued. There would be no need to place pins or bolts into those specimens for the stop-hole to function. Then, we looked at a specimen with fractures on both sides of the edges (Fig. 6 (d)) to see what would happen if the first crack was longer. Our goal is to demonstrate the effectiveness of the stop-hole and crack arrester on specimens that vary from the one with a single edge crack.

The specimen in Fig. 6 (d) has a larger stress concentration factor, as shown in the later.

Accordingly, the specimen cracked after 100 stress cycles when conventional stop-holes were used for testing. The primary tests were conducted with a frequency of 10 Hz, a stress ratio of $1/3$, and an applied cyclic maximum stress of 45 MPa. We also ran the other three test patterns. Furthermore, the specimen in question allowed for the simultaneous comparison of crack development behaviour on both sides, which allowed for the examination of the washer's influence. Crack initiation and development from the stop-hole are affected by the crack opening displacement near the stop-hole. Furthermore, it is believed that the rate of fracture initiation and stop-hole propagation is influenced by the frictional forces acting on the specimen surface and washer. Which is why the crack propagation behaviour on the side with the washer differs from the side without.

The specimens utilised in those tests are shown in Fig. 8, together with their test sections. An example of this is the study by Naka et al. (2013), which detailed the testing procedures and analysed the impact of bolted stop-holes with conventional

washers on crack arresting. Figure 8 (a) shows the process of bolting to a machined stop-hole on one side of the slit and a regular stop-hole on the other. In order to study how the friction between the specimen and washer surfaces affected the crack propagation, the specimen shown in Figure 8 (b)

was used. Washer B, a Nord-lock, and Washer A, a standard type, were both fastened to a bolted stop-hole. Using the specimen from Figure 8 (c), we also looked at how the torque used to connect the crack arrester affected the arresting of crack propagation. Washers A and B's geometry is shown in Figure 9.

3. Experimental Results and Discussion

Stress concentration at hole bottom of a drilled stop-hole

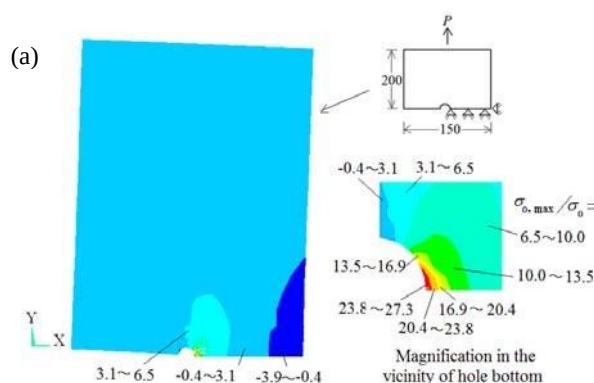
The main specimen used was a side-edge crack specimen. Before the experiments were performed, the stress concentration was calculated by code ANSYS. Also, that calculation accuracy was checked by comparison with the calculation results from the programs of two-dimensional body force method which developed 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 $\sigma_{\max}$ at hole-bottom and the maximum value of crack opening displacement $\delta_{\max}$ when the applied stress σ_0 at upper and lower edges are of uniform value. Where, the value of $\delta_{\max}$ is the value at $\sigma_0 = 100$ MPa.

Table 3

Variations in crack opening isplacement and stress concentration ($\delta_{\max}$; maximum crack opening displacement(mm), $\sigma_{\max}/\sigma_0$; non-dimensional

Specimen	$\delta_{\max}$ [mm]	$\sigma_{\max}/\sigma_0$
Fig. 6 (a)	0.98	27.3
Fig. 6 (b)	0.12	8.3
Fig. 6 (c)	0.12	9.3
Fig. 6 (d)	1.78	13.7

The specimen with a side-edge fracture (Fig. 6 (a)) obviously had a greater value of $\sigma_{\max}$ compared to the others, even though the ligament size was the same in all three cases. Also, compared to the situation of the smaller ligament in Figure 6 (d), that value in Figure 6 (a) is somewhat greater. The specimen with a side-edge fracture exhibited increased stress concentration and crack opening displacement due to the bending moment at the ligament. The specimen's asymmetry is to blame for it. Thus, in order to conduct testing under extreme stress circumstances, we used a specimen that had a side edge-crack for the major tests. There was a correlation between the loading circumstances and the testing machine's capacity limits.



Those computations served as a basis for the studies, which also took into account the effects of inserting the pin into the stop hole or applying bolting at the stop hole on the stress distribution tendencies. Bolting at a stop-hole

and installing a crack arrester effectively minimise the crack opening displacement, which in turn alters the behaviour of crack propagation.

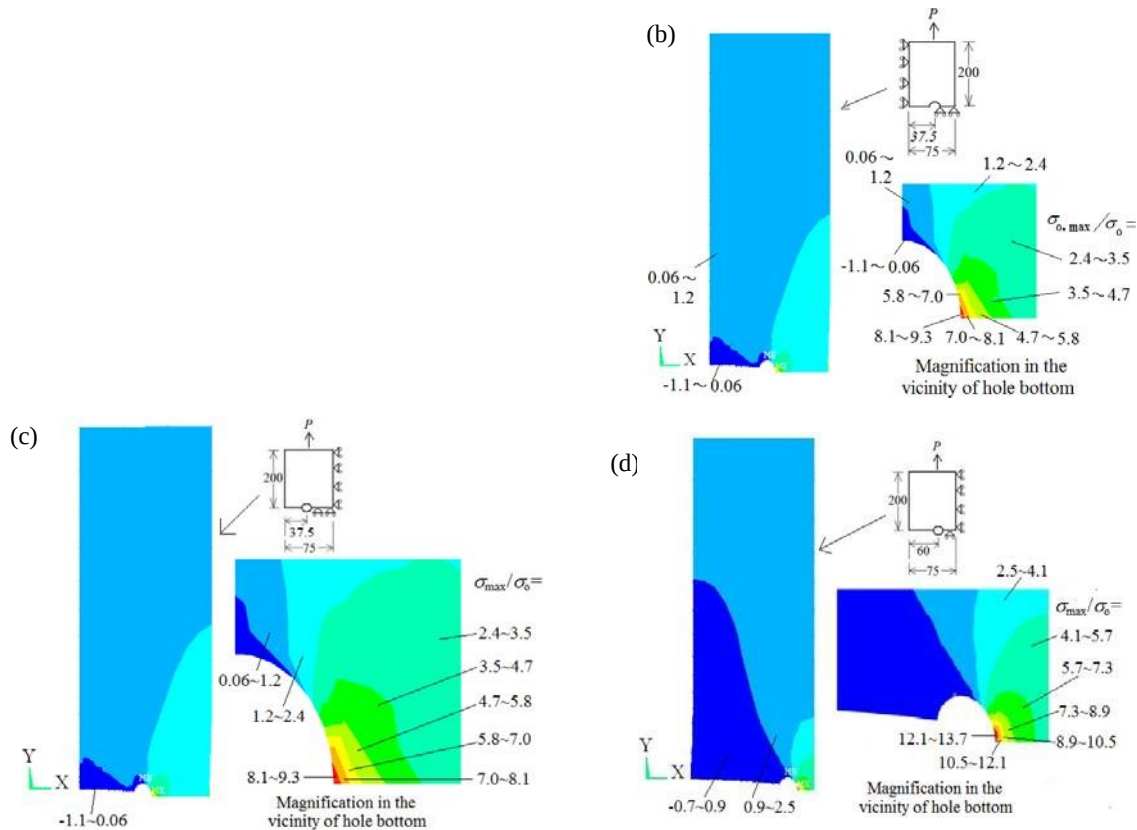


Fig. 10 Comparison of stress concentration, (a) In the cases of Fig. 6 (a), (b) In the cases of Fig. 6 (b), (c) In the cases of Fig. 6 (c), (d) In the case of Fig. 6 (d).

The stress distribution examples from Figure 6 are shown in Figure 10. Figure 6 (a) (the specimen with a side-edge break) showed the highest stress concentration. The specimen's symmetrical circumstances were taken into account while doing the

3.1 Effect of crack arrester on crack growth behavior

3.1.1 In the cases of specimen with a side-edge crack with endurance cycles of 10^5

Figure 11 shows the definition of the crack length c , which is measured from either the bottom of the stop-hole or the edge of the washer. So, the length of a new crack that started in a stop-hole or the length that could be measured after the bolt head side crack was identified under a microscope was called crack length.

In this research, we looked at the following ways for

calculations, which included using half of the specimen for specimens with side edge cracks, quarter of the specimen for specimens with centre fractures, and both-side-edge cracks.

halting the crack propagation. The first approach involves creating a stop-hole at the very tip of the fracture in order to lower the stress concentration. Method 2: The pin is put into the stop-hole that has been drilled. The material surrounding the hole was compressed as a result of the plastic-elastic deformation of the material, which caused the expanded hole to elongate the surrounding material.

As a result, compressive residual stress developed.

outside the specified region. The third technique used screw-threaded stop-holes being tightened with bolts. Tightening the bolt applied tensile stress in the hole's axial direction, whereas friction between the specimen's surface and the washer close to the hole dampened cyclic deformation at the bottom of the hole. The crack arrester was fastened across the face of the crack, which brings us to #4. Because the crack arrester redistributed some of the stress that had been centred at the ligament, the displacement of the crack opening was decreased.

There are correlations between the amount of repeated stress N and the crack length c , as shown in Figures 12 (a) and (b). With a stress ratio of $-1/3$ and . The failure of the stop-hole strategy to prolong fatigue life was verified. Additionally, the technique involving inserting the pin into the stop-hole was also unsuccessful. During the cyclic deformation, the specimen grip edge on the actuator side moved up and down and to the right and left sides, caused by the bending force caused by the specimen's asymmetrical shape. As a result, spaces were created between the pin and hole's surface planes, and compressive residual tension was relieved to some extent.

Attaching the crack arrester across the crack face enhanced the specimen's behaviour during crack propagation and prevented it from breaking even after more than 105 stress cycles. The data for two kinds of specimens with crack arresters are shown in

a maximum cyclic stress of 45 MPa, the stress was applied. In these instances, the specimen plane was seen from one side when the crack length c was measured. Figure 12 (a) displays the data for both the conventional stop-hole and the pinned stop-hole. (The data is not shown in Fig. 12 due to the specimen's abrupt breakage), the slit specimen without the stop-hole failed after 50 stress cycles. The specimen fractured after just 104 stress cycles, even with a standard stop-hole. Within 104 cycles, the fracture length c exceeded 8 mm and the crack expanded at a fast pace. The facility's replace period is 105 cycles, which is the endurance limit to test

Figure 12 (a). One of them had a pin threaded into a stop-hole bored into the very tip of the crack, with the crack arrester fastened along the specimen's edge (Fig. 7 (f)). Fig. 7 (g) shows an alternative scenario where the pin was put into a hole with a centre 15 mm from the crack tip and an initial 0.9 mm crack that started at the slit edge. The crack arrester was also fastened in this instance. Figure 12 (a) shows that in the two instances when the crack arrester was fastened, the rapid crack propagation did not occur. Attaching a crack arrester enhanced fatigue life and decreased bending moment and crack opening displacement, as shown in Figure 10 and Table 3. The bolt that fastened the crack arrester required 52 Nm of tension to be tightened.

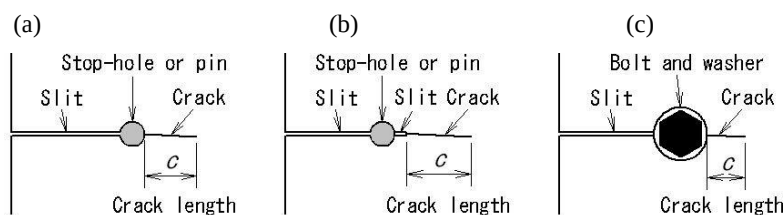
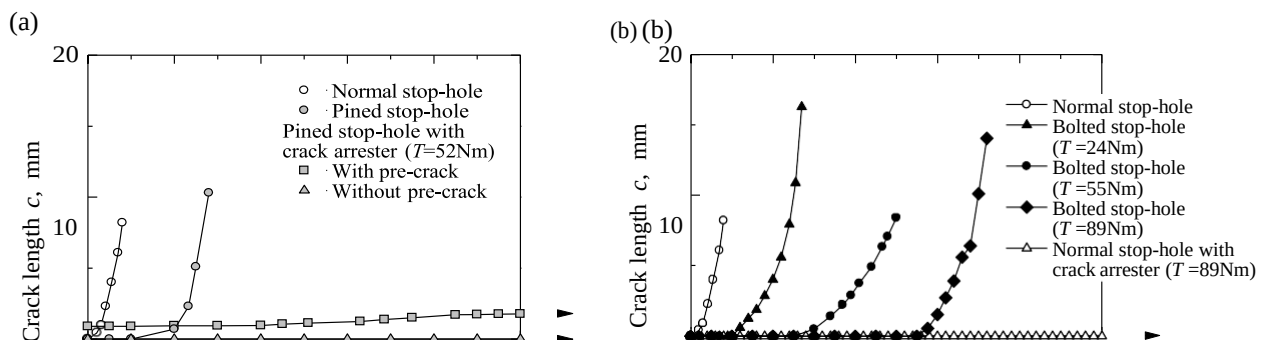


Fig. 11 Definition of crack length c from stop-hole edge, slit edge or edge of washer



0
0 0.2 0.4 0.6 0.8 1
Number of cycles $[\times 10^5]$

0
0 0.2 0.4 0.6 0.8 1
Number of cycles $[\times 10^5]$

Figure 12 (b) displays the outcomes for the stop-hole that is fastened. Additionally, the data for a standard stop-hole is shown. For bolting torques of 55 Nm and 89 Nm, respectively, the fracture length c reached about 10 mm at 5×10^4 and 7×10^4 stress cycles, respectively. Under the circumstances of the current investigation, using a larger torque to bolt at the stop-hole was more successful than using the pin to enter it. Fatigue life was also extended by increasing bolting

3.1.2 Applying crack arrester to endure the cyclic limit of 5×10^5

The current part delves deeper into the investigation of the usefulness of adding a crack arrester to increase fatigue life. Annually, 105 vehicles are hoisted. Accordingly, in the preceding section, the fatigue failure endurance limit of the specimen was fixed at 105. After mounting the crack arrester and drilling the stop-hole, two pillars were replaced seven and twelve months later, respectively, since the crack initiation was not examined from the inside of the pillar. The locations where the crack arrester was fastened and the stop-hole was bored are shown in Figure 3. Figure 4 shows the process of removing the damaged components from the old pillar. It was not the stop-hole that caused the fracture.

The refurbished equipment should be able to last for an additional year of operation. As a result, researchers dug more into how the crack arrester may lengthen fatigue life. The trials in this section were conducted using a fatigue life endurance limit of 5×10^5 .

In those tests, the crack arrester and stop-hole are arranged as shown in Figure 13. The bolting torque was 52 Nm, and three different crack arrester arrangements were used. Additionally, the effect of the crack arrester's location on fatigue life was examined. A stress ratio of $-1/3$ and an applied cyclic maximum stress of 45 MPa were recorded. In such instances, crack development behaviour was seen from both the surface of the specimen next to the crack arrester and the surface opposite it. Figure 13 shows that the specimen surface with a crack arrester is on the rear, whereas the front side is devoid of any such feature. Right where the crack arrester was fastened, you could see

torque. Figure 12 (b) also shows the instances of a crack arrester being attached. Attaching the crack arrester or screwing the bolt into the stop-hole with the reduced bolting torque ($T = 24 \text{ Nm}$) did not significantly increase the fatigue life. The fatigue life was extended even without bolting the stop-hole by fastening a crack arrester with a greater torque ($T = 89 \text{ Nm}$). That being the case, the crack arrester was the way to go for this trial.

The bolt head.

Types A–E were used to categorise the specimens, as seen in Figure 13. Type A included the use of two crack arresters and a standard stop-hole. The specimen's side edge was used to set the crack arrester, and in type B, the bolted stop-hole was applied. A standard stop-hole was used for kinds C–E. The crack arrester was positioned at the specimen's side edge for type C. In the type D example, the crack arrester was installed close to the stop-hole. When testing for type E, a crack arrester was first placed at the specimen's side edge; subsequent to the commencement of a new crack, a second crack arrester was put at the stop-hole.

Results of fracture development curves from the experiments are shown in Figure 14. Even after applying 5×10^5 cycles, no new cracks appeared at the stop-hole in types A and B. Attaching the crack arresters in a way similar to types A and B makes restored equipment safer to use. The specimen's surface, devoid of a bolt head or crack arrester, is shown on the front side of Figure 14. Additionally, fissures could be seen on the front and rear sides. Similar to types C and D, the crack was triggered before the cyclic number reached 5×10^5 , at which point a single crack arrester was set. When the crack arrester was positioned close to the stop-hole in type D, the crack length exceeded 10 mm prior to reaching 105 cycles. Type C, on the other hand, required almost 4×10^5 cycles to cause the fracture length to exceed 10 mm. After some trial and error, it was determined that setting the crack arrester near the specimen's side edge yielded the best results.

Based on type E data, it was discovered that inserting the crack arrester after the crack start slowed the crack development rate. The attachment site of the crack arrester upon crack initiation is shown by the vertical arrow. It was at that moment that the slope illustrating the relationship between crack length c and number of cycles N was altered. That is to say, by reducing the pushing power for crack opening and attaching the crack arrester, the crack development rate was improved.

Crack arresters that have cracked are seen in Figure 15. Crack arrester failure occurred after crack initiation from the stop-hole in types C and D. At the end of the testing period, the crack arresters in types A, B, and E had not cracked. After the crack started to expand from the stop-hole, the crack arrester probably snapped when the crack opening displacement grew too great. The crack growth life significantly enhanced, as seen in Figure 14,

Adding a second crack arrester reduced the displacement of the crack tip opening. However, it is also anticipated that the crack arrester's breaking behaviour may be used for crack start detection. Take strain gauges as an example. They are designed to detect fracture initiation from crack arresters and provide us the information we need before a material breaks. It is recommended to investigate the matter at a later date. When applying a crack arrester to machine equipment, the design of the device is crucial. The fact that the front side had a shorter crack initiation life than the rear side is crucial. Nevertheless, the rear side had quick crack propagation after a fracture was begun there. Thus, when fracture initiation is exclusively monitored from the rear side, the detection of crack start becomes critically crucial. After confirming fracture start on the back side, we found fast crack propagation in the current experiment by applying brief cycles.

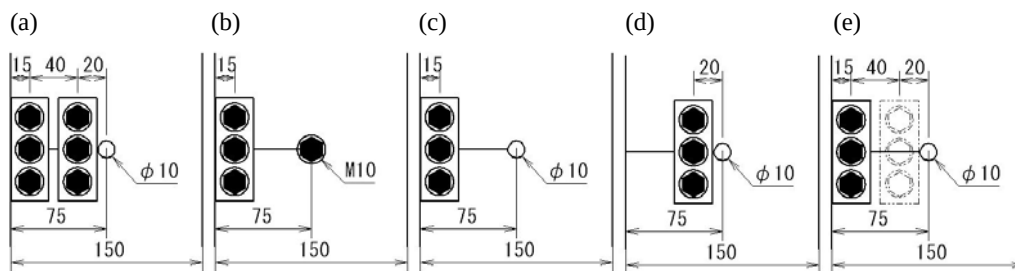


Fig.13 Some methods of attaching a crack arrester to the cracked specimen, (a) Type A, (b) Type B, (c) Type C, (d) Type D, (e) Type E

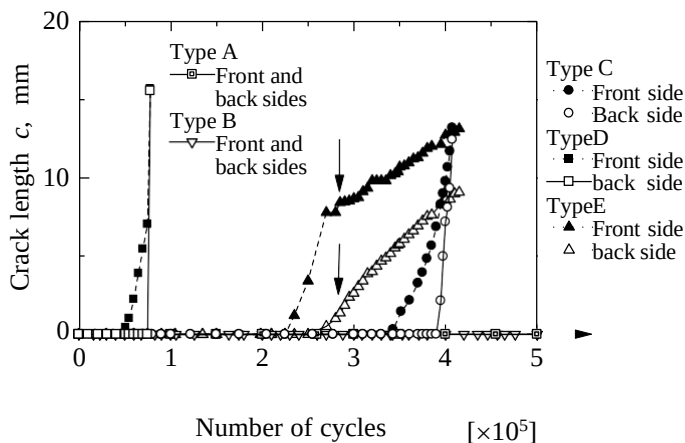


Fig. 14 Crack growth curves for specimens with crack arrester



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

3.2 In the cases of both-sides edge cracks specimen

Exhibit 16 (a) displays the outcomes in specimen 8 (a) of Figure 8. Between -30 MPa and 30 MPa, the applied stress was altered (Stress ratio $R = -1$), and between -15 MPa and 45 MPa, the applied stress was varied ($R = -1/3$). Researchers discovered that a typical stop-hole made fracture initiation easier. The fracture initiation cycle is shorter when $R = 1/3$ compared to $R = -1$ because the maximum cyclic stress is larger in the former case. Using the specimen from Figure 8 (b), Figure 16 (b) compares the effects of friction between the washer surface and the specimen surface. The range of stress variations tested ranged from -15 MPa to 45 MPa, with a correlation coefficient of $-1/3$. A well-known instrument for avoiding bolt loss is the Nord-lock washer, often known as washer B. For this experiment, we used a standard washer to sandwich the bolt head between the Nord-lock and the specimen surface, and we generated a lot of friction between the two. Using the Nord-lock washer results in a greater friction force per unit area. Washer A (the standard washer) had more fracture start cycles than washer B (the abnormal washer), according to the results. The surface friction effects on the bolt head side had no bearing on the fracture start behaviour as the two sides were orthogonal. Before applying the nut, check how the friction from the washer affects the joint.

New crack initiation behaviour at a typical stop-hole is shown in Figure 16 (c) by the influence of the crack arrester's attachment torque. A stress ratio of $-1/3$ and an applied cyclic maximum stress of 45 MPa were recorded. The margins of the stop-holes did not show signs of crack initiation until 5×10^5 cycles after applying a torque of 30 Nm to fasten the crack arrester with bolts. Within 3×10^5 cycles, the specimen cracked at the stop-hole when torque T was 20 Nm and 10 Nm. Consequently, it was deduced that the crack arrester served to enhance the behaviour of crack propagation and that the torque used to fasten the bolt securing the crack arrester was critical to prolong the fatigue life. Figure 16's data also shows that a crack arrester is the best way to increase fatigue life. Data with $T = 30$ Nm in Fig. 16 (c) showed a longer fatigue life.

When fixing a fractured material from only one side, the current research demonstrates ways to stop the crack from becoming worse. A more effective way to inhibit the crack propagation is to fix a broken component from both sides of the material. For instance, if a crack arrester were to be attached to both sides of a material, it would effectively minimise the displacement of the crack opening. It is important to carefully monitor and repair broken elements for the safety drive of a machine and the upkeep of a building.

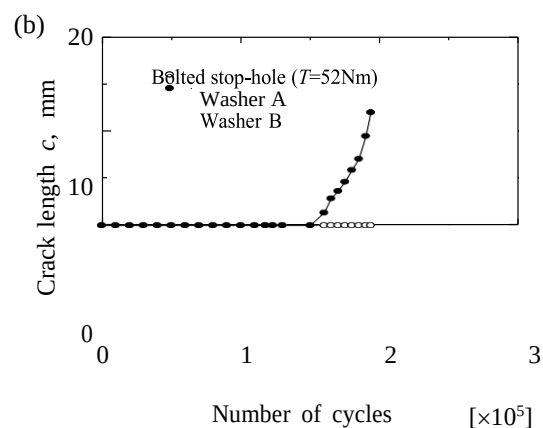
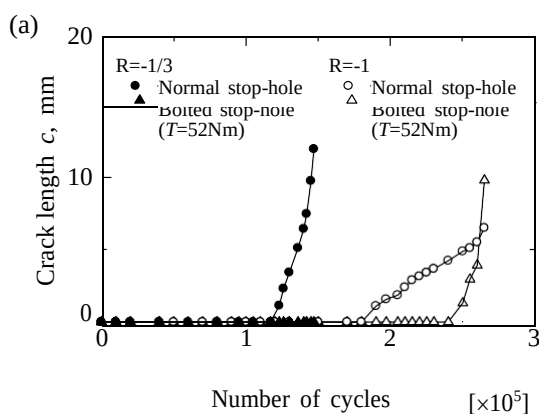


Fig. 16 Crack growth curves in the tests with specimen of Fig. 8, (a) Specimen type of Fig. 8(a), (b) Fig.8 (b), (c) Fig.8 (c)

4. Concluding Remarks

We looked at the ways to stop cracks from spreading. The crack tips were bored with stop-holes, and the cracked pieces were fastened with crack arresters. Here are the key takeaways from the current experiments:

(1) The shape of the specimen determined the efficacy of the stop-hole in arresting crack formation. Avoiding the use of a pin or bolt while drilling a stop-hole in the specimen with a one-side edge crack for this investigation did not prevent the fracture from progressing.

(2) The positioning of a crack arrester had an effect on how cracks were initiated. When both the crack arrester and the stop-hole were used at the same time, the attachment torque of the crack arrester affected how cracks were initiated at the stop-hole. The use of a crack arrester during testing improved the number of stress cycles required for crack start and propagation.

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