한국마린엔지니어링학회지 제33권 제1호, pp. 112~119, 2009. 1 (ISSN 1226-9549)
Journal of the Korean Society of Marine Engineering

Effect of Multiple Circular Holes on Fatigue Crack Growth Path

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(Manuscript : Received November 3, 2008 ; Revised : December 31, 2008 ; Accepted January 22, 2009)

Abstract : The mechanical fastening has some advantages in respect of the fastening strength and disassemble of the fastened parts. However, at the same time it has some dangerous factors, can cause fatigue crack initiation and propagation due to not only the static loading such as cargo and passengers but also the dynamic loading like vibrations which occur in the engines and the propellers. For this reason, the strength evaluation for the mechanical fastenings along with the sophisticated and detailed mechanical design and the safety evaluation should be executed. In this paper, we were carried out experiments to study fatigue crack growth paths in structures containing the multiple circular holes. It was investigated that how circular holes are affected on fatigue crack growth paths using the specimen consists of A5052-H112, which is widely used as the ship materials. It was found from the experimental results that the fatigue crack as if it is drawn to circular holes when crack tip approach to circular holes. However, it did not go into circular hole if there is the next circular hole. Therefore, the clarification of mechanism on the fatigue crack initiation and the propagation in structures containing the multiple circular holes can be expected in this study.

Key words : Fatigue crack growth behavior; Multiple circular holes; Stress intensity factor

1. Introduction

The machine constructions such as the ships and the offshore structures are built by assembling various member subjects. Although the assembling methods of such the member subjects are various, the most representative examples are the methods by the mechanical fastening and the welding. The mechanical fastening method has been widely used until now for the advantages of simplicity disassembly and assembly.

On the other hand, this method can possibly cause declining of the overall structural strength due to the contact pressure by bolts and rivets in the fastening part. Moreover it may lead to the fracture of structure owing to the stress concentration around circular holes, which it is machined on the base metal to fasten bolts and rivets, of fastening part.

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Any accidents due to fracture of the ships and the offshore structures can have major negative consequences, including serious injury or loss of life, severe environmental damage, and substantial economic loss.

Therefore, the structural safety assessment of the ships and the offshore structures is serious problem.

In other words, It is very much required that studies on the fatigue crack initiation and growth for optimized design and the safety assessment. For these reasons, a number of research on fatigue mechanism in mechanical fastening part are carried out by many researcher so far. However, most of these are studies on the crack initiation and growth from the mechanical fastening part[1]~[5].

Additionally, It is difficult to ensure the safety in the mechanical fastening part only in such researches. So, it is necessary to also study the case in which the fatigue crack is grown toward the mechanical fastening part after is initiated from any random place. Consequently, the some studies have been carried out as follows. Knazawa, T. and Machida, S. calculated the elastic energy of crack growth when a finite plate is subjected to the fastening force by rivet, besides, verified the effect as the crack arrester from fracture mechanical experiments.

By the experimental consequences, the stress intensity factor is increased while the crack tip is approaching the mechanical fastening part, and then after approached the maximal value, it is slowly decreased to the minimal value[6].

Nishioka, T. and Maruoka, A. matured the simulation technology which agree with the experimental result on the dynamic fracture path in structure containing multiple circular holes. According to the study, when the crack grows toward circular holes, the crack tip grows like it is sucked down to the circular hole, and then the path of crack growth meanders through the specimen by the effect of the multiple circular holes. Furthermore, the stress intensity factor increase and decrease for being influenced by the multiple circular holes[7].

However, these results were about dynamic fracture. Therefore, it is also necessary to study that the characteristics of fatigue crack growth while fatigue crack is growing toward multiple circular holes.

For these reasons, this study was aimed at investigating the effect of multiple circular holes on fatigue crack growth as the basis of study on mechanical fastening part.

2. Fatigue crack growth test

2.1 Specimen and test equipments

In order to materialize the members containing the multiple circular holes which are machined in structure for mechanical fastening such as the riveting and the bolting, the specimens with the geometry and dimension as illustrated in Fig.1 were manufactured. The geometry and the dimension were determined by the *ASTM* test methods and existing studies on *Mode I*[7][8].

As the material of specimen the Aluminum alloy *A5052-H112*, which is widely used as the structural materials of the ships and the offshore structures, is used. Table 1 and 2 show the chemical compositions and the mechanical properties.

Table 1 Chemical Compositions (wt.%)

Al	Cr	Cu	Mn
95.7-97.7	0.15-0.35	Max 0.1	Max 0.1
Mg	Si	Fe	Zn
2.2-2.8	Max 0.25	Max 0.4	Max 0.4

Table 2 Mechanical Properties of A5052-H112

Ultimate Tensile Strength	262MPa
Tensile Yield Strength	214MPa
Elongation at Break	10%
Modulus of Elasticity	70.3GPa
Poisson's Ratio	0.33
Fatigue Strength	124MPa
Shear Modulus	25.9GPa

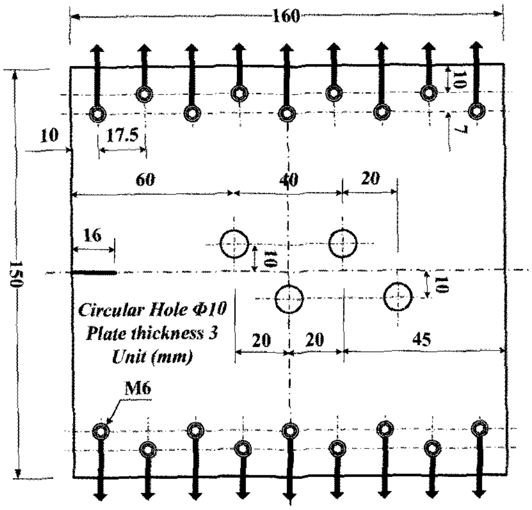

Fig. 1 Geometry of specimen

As shown in Fig.1, the crack initiation was induced by processing *16mm* notch, *10%* of the whole width, with wire slot cutting machine in specimen. The four circular holes of *10mm* in diameter were machined by drilling to investigate the effect of the circular hole on fatigue crack growth when the fatigue crack tip comes closer to the circular holes. These circular holes were arranged in zigzags at an angle of *45°*. It was fitted on the jig to lead the fatigue crack growth as illustrated in Fig. 2.

The specimen may be subjected to the not only tension load, the load condition in this experiment, but also the out-of-plane moment and the force by the rotation since the fatigue crack is grown to some extent.

Therefore we devised the jig as shown in Fig. 2 in order to restrain them.

In the first place, the out-of-plane moment was restrained by inserting *'C'* between the specimen and jig. In the next place, the force by the rotation was restrained by contacting *'B'* with *'A'* as shown in Fig.2.

The geometry of jig was manufactured in reference of *ASTM E647-12 -Middle Cracked Tension Panel Test setup.*[8]

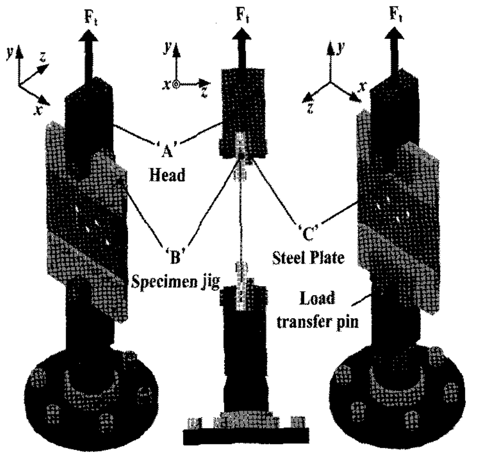

Fig. 2 The jig for fatigue crack growth experiment

2.2 Experimental conditions and experimental processes

The hydraulic servo pulse was used as the experimental equipment, *100 kN* of total capacity, and the specimen was set up on the experimental equipment using the jig as shown in Fig. 3.

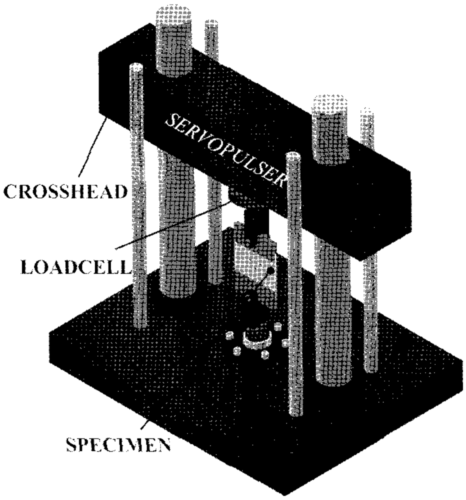

Fig. 3 Fatigue experiment equipment

This experiment was carried out by displacement control. The speed of the repeated displacement is *20Hz*. Fig.4 shows the profile of displacement.

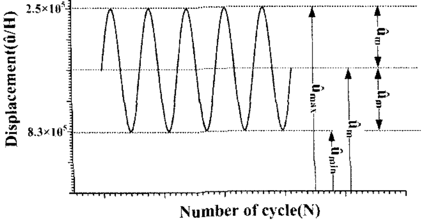

Fig. 4 Displacement sequence

The fatigue crack growth length was measured in both the horizontal direction-x and the perpendicular direction-y direction. And the crack lengths on each measuring point were calculated by the Equation (1).

$$a_i = a_{i-1} + \sqrt{(\Delta x^2 + \Delta y^2)} \tag{1}$$

3. Experimental Investigation

3.1 Fatigue crack growth behavior

Fig. 5 shows the initial stress distribution on the specimen as a result of the finite element analysis with test condition. As shown in Fig. 5, the stress concentration occurs around the circular hole. In addition, It is observed that the high stress fields being generated by the mutual interaction with the angle of 45 degree between the circular hole and other one.

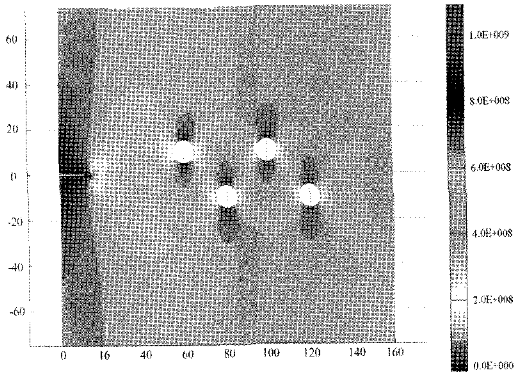

Fig. 5 Initial stress distribution by FEM

Fig. 6 shows the relationship between the number of cycle and the fatigue crack growth length. The experiment was continued until the fatigue crack tip go into the last circular hole and the final number of cycle was *1.07×10^7*. For the quantitative evaluation the fatigue crack growth length was represented in the ratio of the width of the specimen to the fatigue crack growth length. And the number of cycle was expressed in the cycle ratio which is ratio of the final number of cycle to that at the measuring point.

The aspect of the fatigue crack growth seemed to be safely accelerated to T_I which accounts for about *75%* of total number of cycle.

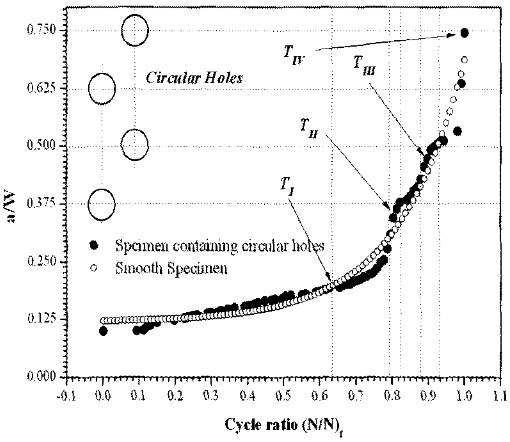

Fig. 6 Fatigue crack extension observations

The rapid acceleration phenomenon of the fatigue crack growth appears from T_I where the fatigue crack tip is influenced by the first circular hole. However, in the vicinity of T_{II}, which is the center of the first circular hole, the retardation phenomenon is occurs.

This phenomenon started to appear when the fatigue crack tip entered the range of the circular hole diameter then disappeared getting out of it. The acceleration of the fatigue crack was seen to T_{III} but the speed was lower than its highest one.

The retardation phenomenon also appeared in the range of the second circular hole diameter.

In passing by T_{III}, velocity of the fatigue crack growth increased rapidly. The aspect was not noticeable since the acceleration level was great even if similar aspects seemed to appear as those in the first and second circular holes.

Although, the fatigue crack tip did not go into the third circular hole, went into the last circular hole without next circular holes. The path of the fatigue crack will be specified in the next section.

3.2 Fatigue crack growth path

Fig. 7 shows the fatigue crack growth path after the experiment. In Fig.8 the path is easily represented with the graph which shows the fatigue crack growth quantity in perpendicular or horizontal directions, x and y direction.

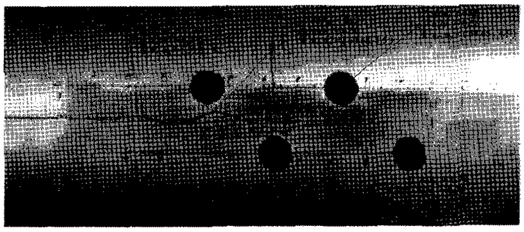

Fig. 7 Photography of the fatigue crack growth

As shown in these two Figures, the fatigue crack tip changed its growth direction due to it was influenced by the first circular holes.

Then the crack tip was grown toward the circular hole as if it were absorbed to the circular hole. However at Γ_{II} point, which is a little away from the center of first circular hole, the fatigue crack changed its growth path to the second circular hole.

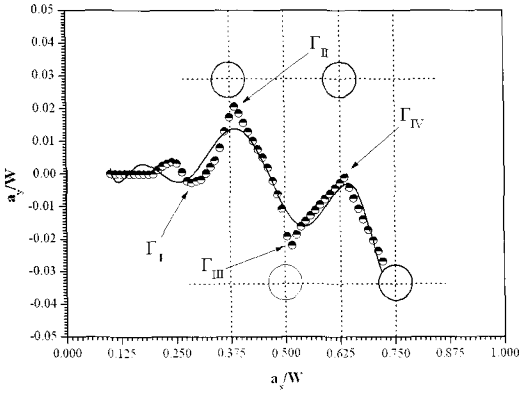

Fig. 8 Fatigue crack growth path

Γ_{II} was identified as range the high stress field, which was formed by the interaction between the circular holes. It appeared similarly in Γ_{III} and Γ_{IV}.

When there are multiple circular holes in the structure, the crack approached the circular hole. However the fatigue crack tip changed its growth path influenced by the next circular hole. It is the same result as the one of the dynamic fracture path experiment on the material with the multiple circular holes. [7]

In the case of fatigue fracture the growth of the crack meandered influenced by the circular hole without going into it. However when there is not the next circular hole, the fatigue crack tip go into the circular hole as shown in Fig.7.

3.3 Stress intensity factor and the fatigue crack growth velocity

The fatigue crack growth velocity evaluated the by Equation (2) and (3), the secant method, in the ASTM testing method.[8]

$$(da/dN)_{\bar{a}} = (a_{i+1} - a_i)/(N_{i+1} - N_i) \tag{2}$$

$$\bar{a} = (a_i + a_{i+1})/2 \tag{3}$$

The tendency of fatigue crack growth velocity was stable since crack initiation.

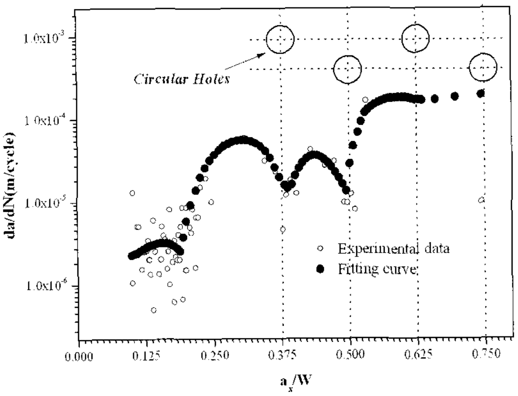

Fig. 9 Fatigue crack growth velocity

However, when the crack grow toward the first circular hole, the crack growth velocity rapidly increases reaching the maximum value at the point which is *10 mm* away from the center, and then rapidly decreases in the vicinity of the first circular hole. Although such aspect is similar also between the first and second circular holes, the velocity was lower than in vicinity first circular hole because of the interaction between circular holes. Such experimental results could be explained by the stress distribution which is calculated by finite element analysis.

As shown in Fig.10, when the fatigue crack is grown into under the first circular hole where the stress distribution is lower, the fatigue crack velocity began to be reduced because of the shielding effect by the circular hole.

Fig.11 shows the history of the stress intensity factor which is calculated from the finite element analysis. The stress intensity factor is represented in the ratio of the initial stress intensity factor(K_{I0}) to the ones of each path. As shown in Fig.11, the stress intensity factor gradually increases as it comes closer to the circular hole having the maximum value just before it grow inside the range of the circular hole diameter. Then it started to decrease making the minimum value just before it gets out of the range of the circular hole diameter. Such aspect is the same as other circular holes. By these results, it was proven that the fatigue crack growth velocity was controlled by the stress intensity factor.

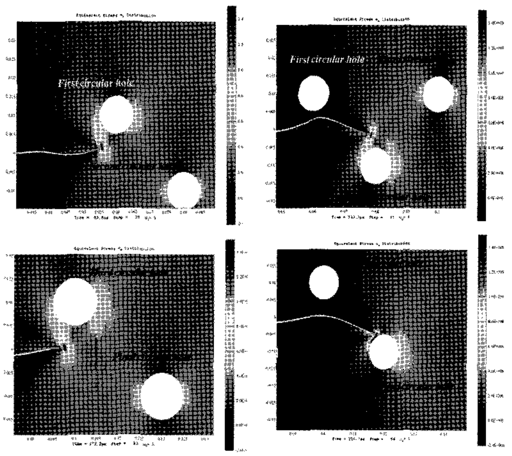

Fig. 10 Stress distribution by FEM

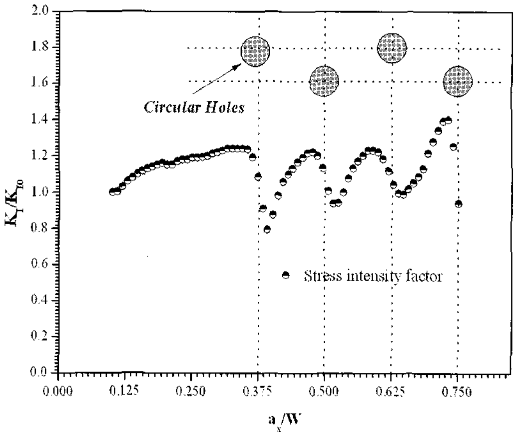

Fig. 11 History of stress intensity factor by the fatigue crack growth

4. Conclusions

This study is aimed at investigating the influence on the fatigue crack growth of the circular holes. The fatigue crack growth experiment carried out by manufacturing the specimen with multiple circular holes.

The results are follows.

(i) It is proven that fatigue crack grows as if it was absorbed to the circular hole and the crack tip continuously grow toward a next circular hole without going into the circular hole when there are next circular holes.

(ii) The fatigue crack growth velocity and the stress intensity factor continuously fluctuated during fatigue growth process due to influence of the circular holes.

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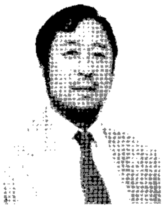

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