New Crack Arresting Methodology Using Structural Optimizing Technique

طريقة جديدة لإيقاف نمو الشروخ باستخدام أسلوب التصميم الأمثل

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الملخص

ان عمل ثقب لايقاف الشرخ هى طريقة بسيطة و اقتصادية تستخدم لاصلاح أو حتى ايقاف شقوق اجزاء المنشأة خاصة التى لا نستطيع استبدالها مباشرة عند اكتشاف هذا الشرخ. أسس هذة الطريقة تعتمد على مبدأ ان عمل ثقب دائرى فى رأس الشرخ يحول هذا الشرخ الى حزأو ثلمة و بالتالى يقل تركيز الاجهادات علية . في هذه الدراسة، تم دراسة طريقة عمل ثقب ايقاف الشرخ بواسطة تخليق ثقب غير دائرى. تهدف هذة الدراسة الى الحصول على افضل شكل لهذا الثقب و الذى يعطى اطول زمن قبل انبثاق شرخ جديد من حافة هذا الثقب. الزيادة فى زمن انبثاق شرخ جديد تعتمد على طول الشرخ و القطر المبدئى للثقب. للحصول على الشكل الامثل للثقب تم عمل برنامج للتصميم الامثل بواسطة برمجيات العناصر المحددة (ANAYS) . وجد أن الزيادة فى عمر الاجهاد باستخدام الثقب ذو الشكل الامثل تتراوح ما بين 2 الى 9 مرات عن تلك الحالات المستخدم فيها الثقب الدائرى بحسب نصف القطر المدئى للثقب و طول الشرخ. تم دراسة تأثير شكل الثقب الامثل على عدة عينات ذات ابعاد مختلفة. وجد انه في جميع الحالات التى استخدام فيه الثقب ذو الشكل الامثل زاد عمر العينة ايما كانت ابعادها. تم الحصول على شكل الثقب الامثل العام الذى يمكن تطبيقه على اى عينة. يساعد ذلك المهندسين على استخدام شكل الثقب الامثل العام مباشرة فى التطبيقات العملية دون الحاجة الى عمل اى حسابات تماما مثل ما يحدث عند استخدام ثقب ايقاف الشرخ المتعارف علية فى المراجع. شكل الثقب الامثل يحافظ على المساحة الصافية للعينة مما يعنى نقص فى الاجهاد الاسمى بالاضافة الى نقص معامل تركيز الاجهاد هذا بعكس ما يحدث فى الطرق التقليدية لمحاولة تقليل معامل تركز الاجهاد. هذا وبمقارنة النتائج بالابحاث السابقة اثبتت مدى كفائة الشكل الامثل للثقب على زيادة عمر العينة.

Abstract

The stop-hole method is a simple and economic repair technique widely used to retard or even to stop the propagation of a fatigue crack in structural components that cannot be replaced immediately after the detection of the crack. Its principle is to drill a circular hole at or close to the crack tip to transform the crack into a notch, reducing in this way its stress concentration effect. In the present study, the stop-hole method was investigated with creating a non circular hole. The aim of the present work is to obtain an optimum stop hole shape that gives maximum fatigue crack initiation life. Fatigue crack initiation life depends at least on the crack size and on the hole diameter. An optimization technique had been used and a finite element program had been built to find this optimum shape of stop hole. It was found that the fatigue life obtained by using the optimum hole shape ranges from 2 to 9 times the fatigue life obtained by using the circular holes depending on the initial hole size and initial crack length. The effect of this optimum hole shape on crack reinitiating life for different specimen geometries has been studied. It was found that the optimum hole shape increased the initial fatigue life for all specimens used whatever its geometry was. A global optimum hole shape (which is practically suitable for all geometries) is defined. Global optimum hole shape helps engineers to use this global hole shape directly in practice without carrying out any calculation much like the use of the stop hole size found in the literature. Opposite to the traditional stress concentration factor minimization problem where the nominal area remains constant during optimization, here it is allowed to vary nominal area using design variables resulting in decreasing of the nominal stress in addition to decreasing of the stress concentration factor. This leads to higher fatigue life compared to previous studies.

Key words

Stop hole method, optimization, Optimum hole shape, initial fatigue life, finite element analysis.

1. Introduction

The effect of a geometrical discontinuity such as notch is to intensify the magnitude of the nominal stress in the vicinity of the discontinuity. The localized stresses may cause the metal in that neighborhood to undergo plastic deformation. Because the nominal stresses are elastic, an elastic-stress field surrounds the zone of plastically deformed metal in the vicinity of stress concentration. A fatigue crack initiates more rapidly as the magnitude of the local cyclic-plastic deformation increases. That is, when the material in the vicinity of the notch tip is subjected to stress ranges approximately equal to or larger than the yield stress of the material; the plastic deformation causes the material to deform along slip planes that coincide with maximum shear stress, which results in slip steps on the surfaces of the notch. These slip steps act as a new stress raisers that become the nucleation sites for fatigue cracks which initiate along the maximum shear planes and propagate normal to the maximum tensile stress component [1]. Crack arresting methods have different techniques such as branching of crack direction that can reduce crack growth rate or even stop it for a period of time, M.Shabara[2]. Other researches aimed to reduce the effect of these stress raisers, and as results of that increasing the crack initiation life, by using a stop hole method, H.Wua [3]. Some researchers investigated arresting crack initiation at stop-drilled hole by drilling ancillary holes around the principle stop hole A. Murdani [4]. Fatigue crack initiation life prediction had been evaluated by M.R. Khoshravan[5], by employing classical strain life concepts properly modified by short crack theory to model the stop-hole effect and investigated the best location of stop hole and its diameter. R. Shah [6] studied the effect of drilling holes in the vicinity of crack tips on the direction of the crack, time taken for the specimen to fracture, and the breaking load of the specimen. Others investigated the stress concentration factors for the stop drilled holes[7]. While others investigated how the stop drilling procedure improved the crack initiation life and the total fatigue life [8]. Some were interested in investigating the efficiency of crack arresting by drilling a stop-hole on riveted girders theoretically and by full-scale fatigue test series [9]. Investigation of The global optimum shape was similar to the plastic zone created around crack tip that means by drilling optimum shape, it removes all damage material, leaving material in virgin stat, so initial fatigue life increases many times.

inserting pins into holes drilled in the vicinity of the crack tips or the cold expanded hole had been studied by C. Makabe [10], who found that compressive residual stress, which occurred by inserting pins, was more effective to retard the crack growth than reducing the stress concentration around initial crack tips by drilling holes.

Based on the previous literature review, it was found that almost all researches deal with arresting the fatigue crack with drilling a circular hole. The effect of changing the hole shape has not been studied yet. Therefore the objective of this study is to introduce a new method for improving the crack initiation life by stopping crack growth with modifying the hole shape using optimization technique. The optimum shape of stop hole at the crack tip will maximize the crack initiation life of a precracked component subjected to fatigue loading without decreasing nominal area of specimen.

2. Work Plan

This is realized through the following steps to run automated structural optimizations:

1. Finite Element Method using ANSYS software package for nonlinear static analysis.

In this step the inputs are cyclic properties of specimen material, specimen geometry, boundary conditions, and loading conditions. The outputs of this step are local stresses and strains results.

2. Shape Optimization of the analyzed hole using ANSYS

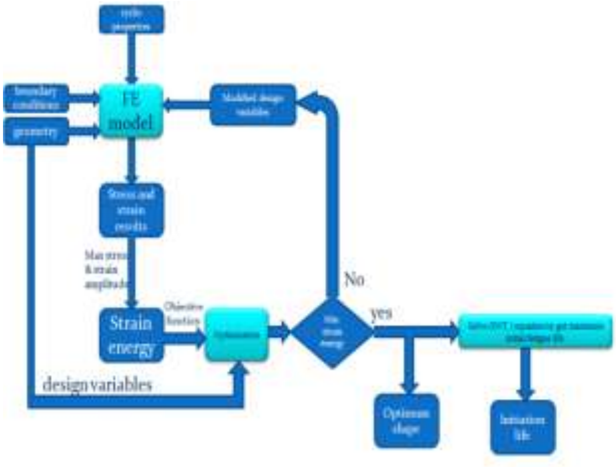
The maximum local stress and strain are picked up from the previous step, to calculate the strain energy which will be used as an objective function. The input to this step is the design variables, and the objective function. The outputs of this step are the optimum hole shape and minimum strain energy.

3. Initial fatigue life prediction

The minimum strain energy resulted from optimization step is input to MATLAB to solve nonlinear Smith Watson and Topper (SWT) equation to get maximum initial fatigue life.

The flow chart of hole shape optimization method is given in Figure 1.

Fig.1 Flow chart of hole shape optimization method



3. Modeling and Analysis

3.1 Model Geometry

The studied model is rectangular block, with 80 mm length, 40 *mm* width, and 10 *mm* thickness. The circular edge notch has a radius, r, of 1.5 *mm*, and propagated sharp crack length, a, of 6 *mm*. The radius R, of the hole at the crack tip equals 1 *mm* [11], as illustrated in Fig. 2

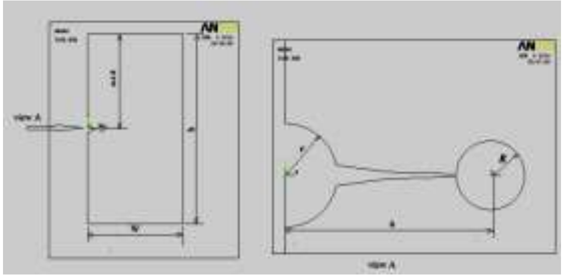


Fig.2 Model geometry

3.2 Finite element analysis and loading conditions

A two-dimensional simulation finite element model using ANSYS software package was used. The material used in this analysis was RQC-100 steel with mechanical properties shown in Table 1. In this model it was assumed that the material is homogeneous and isotropic, i.e., without imperfections or damages.

Table 1: RQC-100 steel mechanical properties [12]

Modulus of elasticity (GPa)	**207**
yield strength *(MPa)*	**600**
Ultimate tensile strength *(MPa)*	**930**
Poisson's ratio	**0.3**

Eight-node plane element (Plane 82) is adopted, because these quadrilateral elements can deal with problems when analyzing about a point, like the crack tip. A very fine mesh with element size equals 0.1*mm* has been utilized around the area of interest (the crack stop hole edge) and a relatively courser mesh far from the stop hole edge has been used in order to save simulation time. The total number of nodes, and elements, and DOF are shown in Table 2. The finite element mesh is illustrated in Figure 3.

Table 2 Total number of nodes, elements, and DOF for fine mesh and course mesh.

	Fine mesh	Course mesh
NODES	**49616**	**2504**
ELEMENTS	**16441**	**737**
DOF	**297696**	**15024**

Fig 3. Fine mesh around hole and courser mesh far from the hole

Due to the symmetry of the model, only half of the part was modeled to increase the efficiency of the optimization procedure as in Fig 3. Due to the high stress and strain gradients around the hole edge, it is critical to choose Elastic-plastic nonlinear static analysis type with small displacement to capture these gradients. Methods for analysis in that case are usually based on the relation between deformations, stresses, and number of loading cycles. Symmetrical constraints were placed on the specimen along the axis of symmetry. As along this boundary, the elements cannot move vertically or rotate, while along the notch and hole, the elements could move freely because it was not attached to the symmetric plane. All constrains and loading conditions are shown in Figure 4.

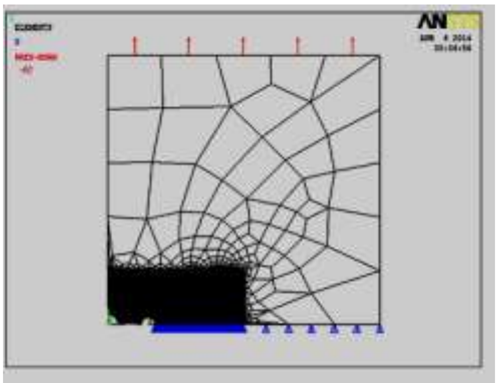


Fig. 4 Constrains and loading conditions

Applied stress is a uniaxial cyclic stress with stress ratio equals, *-1* and peak value, 90 *MP* at the model top line as illustrated in Figure 4. Each load step occurred after one unit of time. The load steps were also broken up into substeps in which a fraction of the load was applied over an interval of time between the maximum and minimum loads. When solution is done, the maximum local stresses and strains are obtained at the hole surface. These values of stresses and strains are used to calculate crack initiation life using Smith Watson and Topper (SWT) equation [13], which can be solved using MATLAB software

3.3 Optimization analyses

Objective function

An optimization program was carried out using ANSYS software in order to find the optimum shape of the stop hole. The objective function of this research was to obtain the optimum hole shape which is corresponding to the minimum value of strain energy ($\sigma_{max}\varepsilon_a$) in order to maximize the crack initiation life (*$2N_f$*).

To evaluate objective, the strain life method is usually used to determine the number of cycles required for the fatigue crack initiation, where it is assumed that the crack is initiated at the point of the largest stresses in the material. To determine crack initiation life, Smith Watson and Topper (SWT) equation (1) can be used as follows:

$$\sigma_{max}\varepsilon_a = \frac{\left(\sigma_f'\right)^2}{E}\left(2N_f\right)^{2b} + \sigma_f'\varepsilon_f'\left(2N_f\right)^{b+c} \quad (1)$$

Where:

$2N_f$ is number of reversals up to crack initiation, ε_a is total strain amplitude, σ_{max} is the maximum equivalent Von Misses stress, *b* is the fatigue strength exponent, σ_f' is the fatigue strength coefficient, ε_f' is the fatigue ductility coefficient and, *c* is the fatigue ductility exponent. Material characteristics of RQC-100 steel [12] under cyclic loading are: b=-0.07; σ_f' =1240 *MPa*; ε_f'=066 ; and c=-0.69**.**

FE program results showed that the maximum Von Misses stress was maximum at the stop hole edge which agreed with ref. [14] results. Because fatigue cracking normally occurs at the surface, Von Misses stress is a more appropriate criterion.

By using MATLAB software, relationship between strain energy and initial fatigue life for RQC-100 steel is plotted as illustrated in Figure 5. The curve showed that:

$$min(\sigma_{max}\varepsilon_a\ ) \rightarrow max\left(2N_f\right)$$

Design variables

The geometric representation of the designed boundary for optimization technique was chosen so that an effective geometry could be represented by the least possible amount of parameters. Therefore, half of the hole was modelled by a spline connecting 7 key points having polar coordinates (R,ɵ). The design variables are chosen to be the radial coordinates of theses key points as R1, R2, R3, R4, R5, R6, and R7. The angles, ɵ, of the key points are changed from 0 to 178^o with a constant increment value equals 30^o. These angles are kept constant during optimization. The design variables are shown in Figure 6.

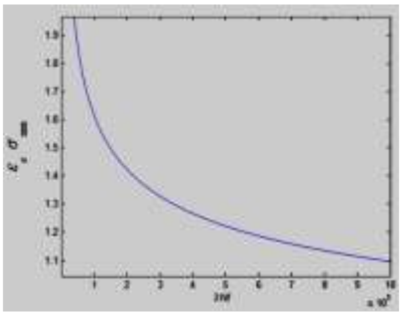


Fig.5 The objective function for the optimization program is to minimize strain energy to maximize the crack initiation life

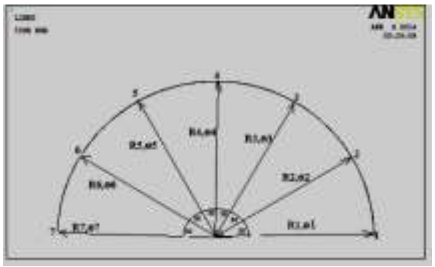


Fig.6 design variables

The initial values of design variables was initially started from the circular hole shape. (As illustrated in Fig 6). The initial value for *R1* to *R7* was *1 mm*. These variables were arranged from R1 at hole edge, up to R7 towards free edge of the specimen. Design variables were allowed changed within the range of [0.5 to 1.5] *mm*. In the ANSYS program, several different optimization tools and methods are available. In this work the first order method was chosen because, this method uses derivative information, of gradients of the dependent variables with respect to the design variables. It is highly accurate and works well for problems having dependent variables that vary widely over a wide range of design space. However, this method can be computationally intense

4. Results

4.1 Optimization results

After optimization process was completed, the values of design variables was changed to values listed in Table 3. These values define the optimum hole shape which accomplish the objective function. As illustrated in Table 3.

Table 3: Optimized design variables which define the optimum hole shape

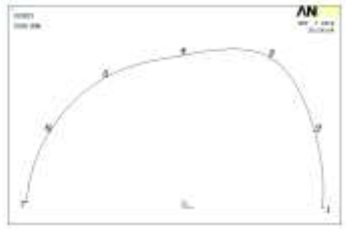
N^o	1	2	3	4	5	6	7	
R	0.9030	0.9836	1.1162	0.9767	0.9689	0.9802	1.0006	
ɵ^0	0^0	30^0	60^0	90^0	120^0	150^0	178^0	

Table 3 indicates that the optimum hole shape doesn't increase the size of initial circular hole, it just reshape it as illustrated in Fig. 7. This indication has a significant important for nominal stress and stress concentration as will be investigated in detailed later.

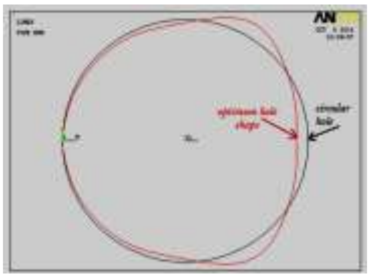


Fig. 7 Comparison between optimum hole size, and circular hole size

To confirm the effectiveness of the optimum shape two checks are made:

1. Optimum hole shape influence on initial fatigue life

Initial fatigue life was calculated for both of circular and optimum hole shapes. It's found that initial fatigue life using circular hole was 868600 cycles, while using optimum hole shape increases initial fatigue life to 5525000 cycles as illustrated in Figure 8.

2 Optimum hole shape influence on stresses and strains

The optimum hole shape reduces Von Mises stress, and VonMises strain at hole edge. The maximum reduction of stress, and strain occurred at hole edge, which is the most probably location for crack initiation, as illustrated in Figures 9, and 10 respectively. The high stress gradient close to the hole was reduced, resulting in a better stress distribution as illustrated in Figure 11.

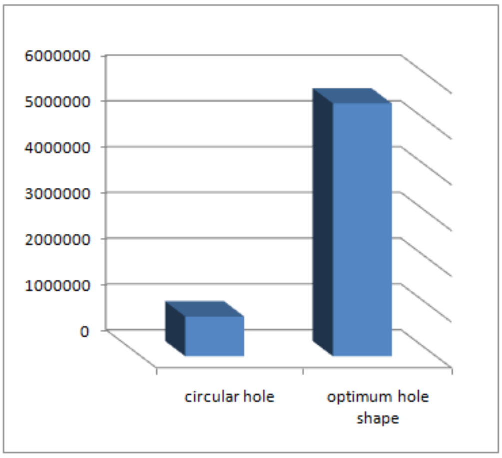


Fig.8 Initial life using optimum hole shape and initial life using circular hole shape

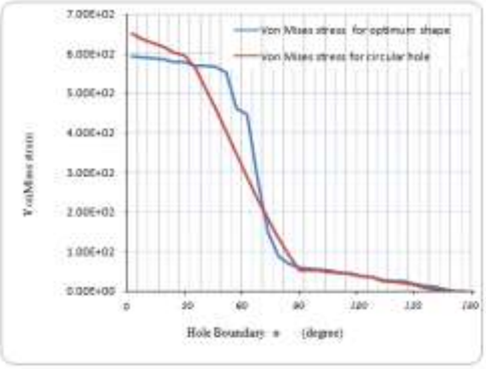


Fig.9VonMises stress using optimum hole shape and using circular hole shape

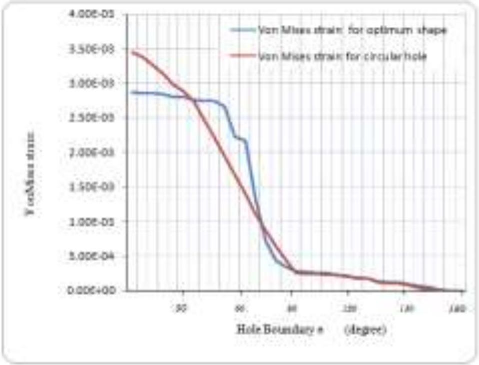


Fig.10 Von Mises strain using optimum hole shape and using circular hole shape

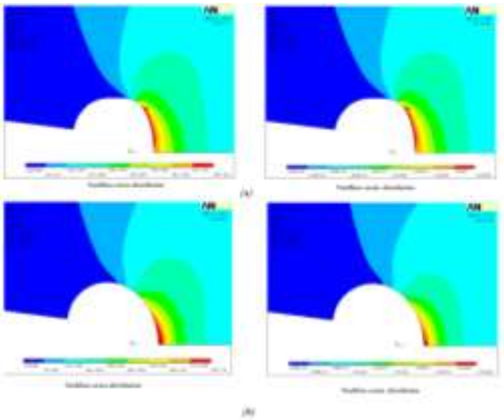


Fig. 11 Stress and strain distribution for (a) optimum hole shape (b) circular hole shape

4.2 The effect of optimum hole shape on fatigue initiation life for different specimen geometries

The model geometry has four configuration parameters height h, width W, initial crack length a, and the initial stop hole radius R as shown in

Figure 12. *R* will be changed during optimization process; however its initial value can be obtained using previous researches [15, 16, 17 and 18]. It is found necessary to get a global optimum hole shape [it is called global to point out that it is suitable for all geometries]. If succeeded, it will help the engineers to use it directly in practice, much like the use of the stop hole size found in the literature. In order to validate this optimum shape, it is important to study the effect of using this optimum shape on fatigue life for different specimen geometries. According to load direction for this model the most important configuration parameter is the width W. Therefore, the other two parameters, *a* and *h* will be normalized by *W*, The ratio, a/*W* has a significant importance on stress distribution, [19]. *a/W* is varied from 0.1 to 0.3. For every value of a/*W* ratio different, h/*W* values are examined to get its effect on optimization results as illustrated in Figure 12.

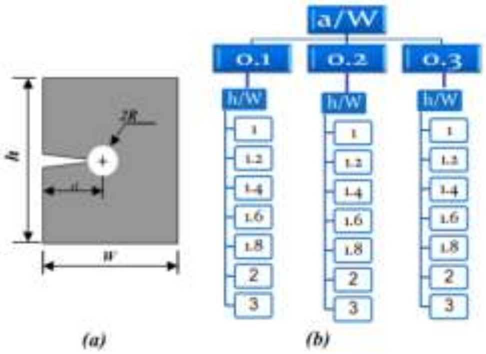


Fig. 12 (a) The most important geometrical parameters (b) Flow chart of geometries which have been tested in this study

Each case has its own optimization program and produce its own optimum hole shape. Figures 13 and 14 respectively illustrate the relation between the maximum stresses and strains obtained at the crack stop hole for different values of *h/W*. These figures illustrate the comparison between the stresses and strains using circular hole, the optimum hole shape, and the optimum shape obtained for each *h/W* value. It is found that the global optimum hole shape results are close to each *h/W* optimization results. That signifies the ability of applying optimum hole shape for all cases and getting nearly optimum results for each geometry. That has a significant importance in practical field.

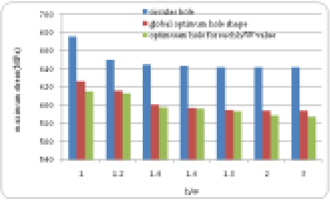


Fig.13 comparison of maximum stress at hole edge for circular hole, optimum hole shape, and hole shape obtained from optimization results for each h/W geometry

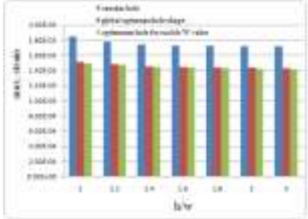


Fig.14 comparison of maximum strain at hole edge for circular hole, optimum hole shape, and hole shape obtained from optimization results for each h/W geometry

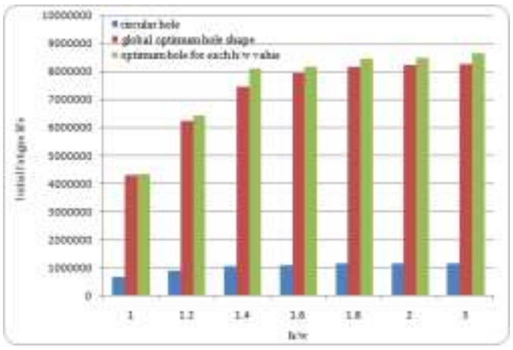


Fig. 15 Initial fatigue life at hole edge for circular hole, optimum hole shape, and hole shape obtained from optimization results for each h/W geometry at a/W=0.1

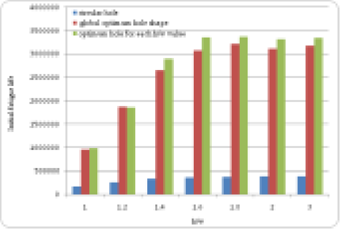


Fig. 16 Initial fatigue life at hole edge for circular hole, optimum hole shape, and hole shape obtained from optimization results for each h/W geometry at a/W=0.2

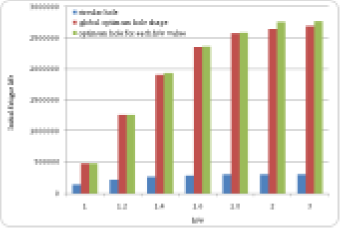


Fig. 17 Initial fatigue life at hole edge for circular hole, optimum hole shape, and hole shape obtained from optimization results for each h/W geometry at a/W=0.3

The effect of changing the h/W values on the initial fatigue life is illustrated in Figures 15, 16, and 17 for *a/W* equals 0.1, 0.2, and 0.3, respectively. These figures illustrate the initial fatigue life when using circular hole, global optimum hole, and the optimum hole shape obtained for each h/W geometry. It is noticed that the values of initial fatigue life using global optimum hole shape for all cases nearly similar to those optimum shape obtained for each *h/W*.

It was found that the optimum shape gave results better than circular hole up to 9 times. It's found from all previous Figures that increasing h/W values increased the fatigue life, while increasing a/W values reduced the fatigue life.

4.3 The effect of optimum hole shape on nominal area

As illustrated in Figure 18 The ligament size $\left(l = W - (a + R1)\right)$ has a significant importance on calculating the nominal area and nominal stress value. R1 equals 1 mm for circular hole while R1 equals 0.9030 mm that means the nominal area increased using optimal hole shape that leads to decrease of nominal stress as illustrated in Figure 19.

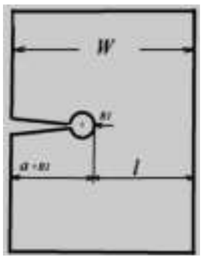


Fig. 18 Schematic illustration of the specimen ligament size used in the numerical simulation.

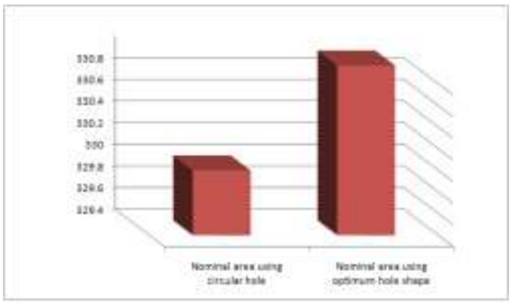


Fig.19 the nominal area increases using optimum hole shape

4.4 The effect of optimum hole shape on stress concentration

To study the effect of optimum hole on the stress concentration. Two identical specimen models are tested. At the first specimen a circular stop hole was applied with a radius of *2 mm*, and at the other specimen an optimum hole was applied with initial radius 1 *mm*. That means the area of the optimum hole was nearly half the area of circular hole. As well known from previous studies; stress concentration is decreased as the radius of stop hole increased. But using optimum hole can reduce stress concentration even if optimum hole size was nearly half circular hole size as illustrated Figure 20.

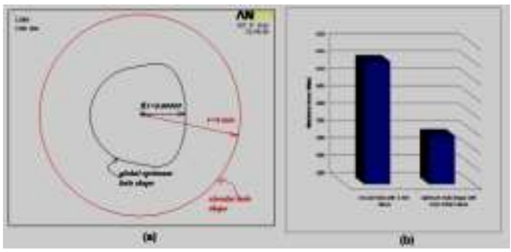


Fig. 20 (a) size comparison between optimum hole and circular hole (b)maximum stress comparison between optimum hole and circular hole

5. Discussion

In order to validate the results of global optimum hole shape, it was compared results of other published researches.

5.1 validation of optimum hole shape to analytical calculation results of ref. [3]

Ref. [3] constructs an analytical prediction initial fatigue at the stop-hole roots by local strain life procedures. A finite element model had been made to imitate model of ref. [3] by using the same material type used in the research. The same loading conditions, the same model configuration, and of course the same stop hole radius. It was found that the initial fatigue life difference between ref. [3] and the model carried out by this analysis was about 0.6% of ref. [3] results. Then on the same finite element model, the optimum hole was used instead of the circular hole. Initial fatigue life was calculated again. Results showed that the initial fatigue lives increased by nearly 7.62 times, these results are illustrated in Figure 21.

5.2 Validation of optimum hole shape to the ancillary holes method of ref. [4]

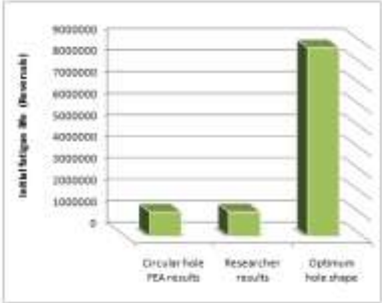


Fig.21 comparison between reference [3] results and finite element results for circular hole and optimum hole

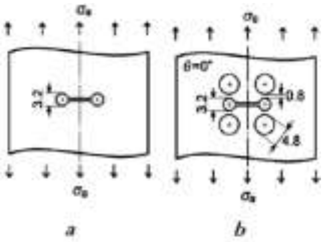


Fig..22 Schematic representation of the hole drilling method (a) base type (b) ancillary holes method

According to ref. [4] the maximum reduction of stress concentration was obtained by arranging four ancillary holes around stop hole. The diameters of the ancillary holes were chosen to be larger than that of the stop hole, as illustrated in Fig. 22. Ref. [4] results indicate that initial fatigue life increased to 6 times more than base type model (model of using stop hole only). But ancillary hole method has some disadvantages such as, it requires a space to drill ancillary holes, so it is only suitable for plate with infinite dimension, it requires removal of solid plate area which has a bad effect on specimen strength, and although using ancillary hole decrease the maximum stress at stop hole edge, it creates other high stress concentrations at ancillary holes edges. A finite element model was created to imitate reference [4] base type model. Then the initial fatigue life was calculated, difference between the initial fatigue life of ref. [4] base type model and the model carried out by this analysis was about 0.5%, it was within the acceptable difference range. Then the optimum hole was used instead of circular hole, Results showed that the initial fatigue life increased for 5.3 times as illustrated in Figure 23. Optimum hole method results increase of initial fatigue life very close to ancillary hole without need to remove any part of plate material and can be practically drilled at any geometry as illustrated in Fig. 24.

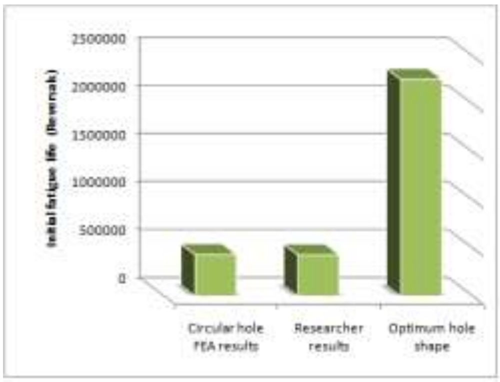


Fig. 23 comparison between reference [4] results and finite element results for circular hole and optimum hole

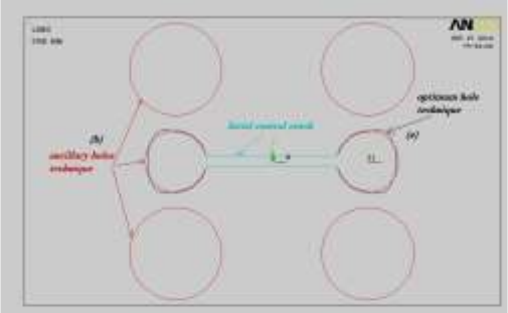


Fig 24 material removal of solid plate area (a) when using optimum hole (b) when using ancillary holes

5.3 Validation of optimum hole to experimental results of ref. [20]

Ref. [20] evaluates experimentally, and numerically the maximum stresses at the end of the stop hole. Three different hole diameters of 5, 10, and 15 mm have been examined. A finite element model was built using the same procedure explained before but in this case the comparison issue is the maximum stress results at stop hole edge. The difference between experimental results of ref[20] and results of FE model carried out by this study was about 5.9% for the specimen with hole diameter D=5 mm, 3% for D= 10, and 4.6% for D=15, it was within the acceptable difference range. By applying the global optimum hole, maximum stress has decreased for all cases as illustrated in Figure 25 While initial fatigue life has increased as illustrated in Figure 26

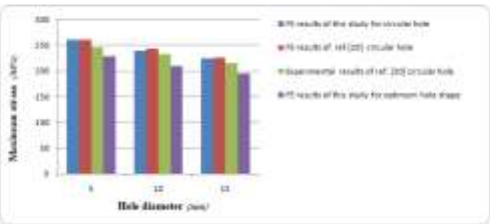


Fig. 25 Comparison between maximum stress for circular hole of reference [20] and maximum stress for global optimum hole shape

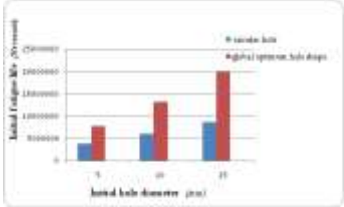


Fig. 26 Comparison between life for circular hole of reference [20] and initial life for the optimum hole shape

5.4 Relationship between the size and shape of plastic zone ahead of crack tip, and the size and shape of optimum hole

FE model with crack is constructed as illustrated in Figure 27. Then plastic zone size is calculated using fracture mechanics theories [21]

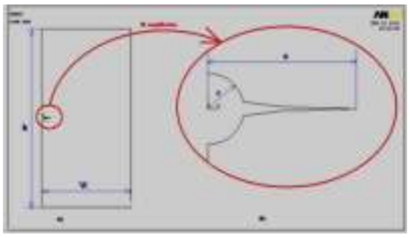


Fig. 27 model with a unrepaired crack (a) whole model (b) magnification of crack region

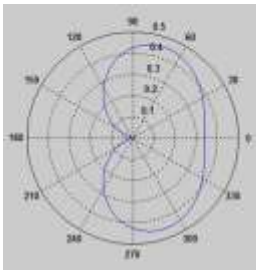


Fig.28 Plastic zone size

The plastic zone was determined and plotted using MATLAB software as illustrated in Figure 28 which agreed with results of ref. [22]. Then on the specimen the global optimum hole was applied at the crack tip. The global optimum hole was plotted as illustrated in Figure 29(b). At Figure 29 both of plastic zone and global optimum hole shape are plotted with respect to the same origin and are determined for the same model. Figure 29 specify two important results; first: the similarity of the optimum hole shape to the plastic zone shape, and second: the optimum hole shape size would be sufficient to remove almost all of the plastically deformed particles ahead of the crack tip as illustrated in Figure 29(b).

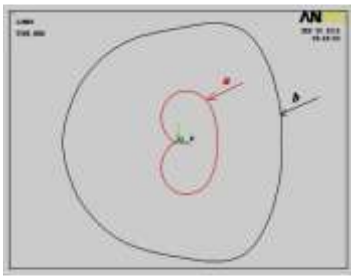


Fig.29 (a) Plastic zone size (b) Optimum hole shape size

5.5 Forming method of optimum hole shape

The optimum shape can be formed easily using Electrical Discharge Machining (EDM). Electrical Discharge Machining is an advanced machining technique that allows for precise, detailed cuts that were once thought to be out of reach with traditional machining. [23].

Conclusion

1. This study introduce an optimization program to reshape the crack stop hole in order to have the maximum increase of crack reinitiating life, without decreasing specimen nominal area
2. The optimum shape has been studied for different specimen geometrical configuration ratios. It had been found that in all cases the initial fatigue life was much greater for the optimum shape than for circular hole.
3. The initial fatigue life increase ranges from 2 to 9 times using the optimum hole shape compared to the circular hole shape for all tested geometries.
4. The optimum shape was similar to the plastic zone emanates around crack tip which denotes that, once optimum shape is drilled, it will removes almost all damage material, leaving material in virgin stat, so initial fatigue life increases many times.
5. The optimum hole shape increase specimen nominal area and reduce nominal stress.

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