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Evaluation of Stress Intensity Factors at Tips of Multi-Site Cracks on Curved Panels using XFEM

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ABSTRACT

The current study is based on research that focused on multiple site damage phenomena on the curved panel that contained 3 rivet holes (6 cracks), In This study, two more rivet holes were added to the model, and the stress intensity factors are considered by using XFEM, the SIFs computations was accomplished for aircraft fuselage frame: un-stiffened panel with ten cracked rivet holes, for four different curvature diameters, subjected to uniform internal pressurization. The comparison of the results showed that conducted analyses revealed the results which can be useful in the assessment of fatigue crack growth rate, and fatigue life of curved aircraft configuration with multi-site damage. Also, the result comparisons of the two models showed that SIFs values increased by 12 times and the crack length increased by 4 times, as the stress concentration increased as a result of the rise of the holes.

تقييم عوامل شدة الإجهاد عند رؤوس الشقوق متعددة المواضع على الألواح المنحنية باستخدام طريقه العناصر المحدوده الممتده

مصطفي الدرويش[1] و خالد الدويب[1] و محمد بلعم[1] و سالم قراب[1] و نصر الدين الشويعر[2]

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الكلمات المفتاحية:
لوحات منحنيه
طريقه العناصر المحدوده الممتده
الكسر الموضعي المتعدد
معامل حدة الاجهاد

الملخص

اعتمدت الدراسة الحالية على بحث ركز على العديد من ظواهر الكسر الموضعي المتعدد على اللوحة المنحنية التي تحتوي على 3 فتحات برشام (6 شقوق)، في هذه الدراسة، تمت إضافة فتحتين برشام آخرين إلى النموذج، وتم أخذ عوامل شدة الإجهاد في الاعتبار من خلال باستخدام (XFEM)، تم إنجاز حسابات معاملات حدة الاجهاد (SIF) لإطار جسم الطائرة: لوح غير مدعم مع عشرة ثقوب برشام متشققة، لأربعة أقطار انحناء مختلفة، تخضع لضغط داخلي منتظم. أظهرت مقارنة النتائج أن التحليلات التي تم إجراؤها كشفت عن النتائج التي يمكن أن تكون مفيدة في تقييم معدل نمو شقوق التعب، وعمر التعب لتكوين الطائرة المنحنية مع الكسر متعدد المواقع. كما أظهرت المقارنات الناتجة للنموذجين أن قيم SIFs زادت بمقدار 12 ضعفًا وزاد طول الشق بمقدار 4 مرات، حيث زاد تركيز الإجهاد نتيجة لزيادة عدد الثقوب.

1-Introduction

The Aloha Airlines accident alerted the aviation professionals that it was easy to find multiple cracks in details of aircraft. These cracks then developed into multiple site damage (MSD) or widespread fatigue damage (WFD) when the stress grades of various details of aircraft structures had little difference. Compared with local damage, multiple site damage can make a series of more serious consequences: crack propagation for MSD is increased; the residual strength is reduced in a much shorter time due to the link-up of small cracks; additionally, the critical crack length is decreased obviously [1].

Over the years, many numerical approaches and techniques have been used to simulate fracture mechanics problems, among which the finite element method (FEM) is the most popular one. But recently, a relatively new extended finite element method (XFEM) has become more employed in these kinds of evaluations, because its major advantage is that it allows crack growth within the existing mesh, making the finite element mesh update obsolete. The XFEM has already been used to calculate SIFs for problems involving multiple,

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interacting cracks, resulting from MSD in [2], [3], as well as for the fatigue life estimation of the integral skin-stringer panel in [4]&[5] or even for a review of fatigue crack propagation modeling techniques using FEM and XFEM like in [6], assessment of fatigue crack growth based on 3D finite element modeling approach [7-9] and fatigue life of wing spare cross-section in [10].
In this study capacities, the difficulties of computational methods used in SIFs calculations in the case of multiple cracks on curved panels are confirmed.

2. Stress intensity factors evaluation for curved panels using XFEM analysis

The SIFs determination was carried out for the aircraft fuselage model: un-stiffened curved panel (dimensions L1×L2=600×400 mm, thickness=1.6 mm), with five cracked fastener holes (radii=2.4 mm, at distance b=25 mm), for four different curvature diameters (D=1.6 m, 2.4 m, 3.2 m, and 4 m). Each hole in the panel had two radial cracks, numbered from 1 to 10 and positioned as shown in Fig. 1.

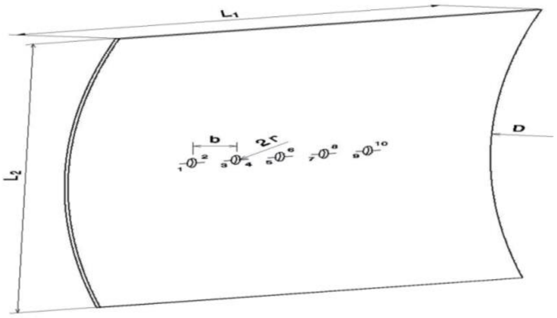

Fig. 1: Analyzed configuration with multiple cracks (not to scale)

Also, a uniform pressure was applied to the internal face of the model Fig. 2.

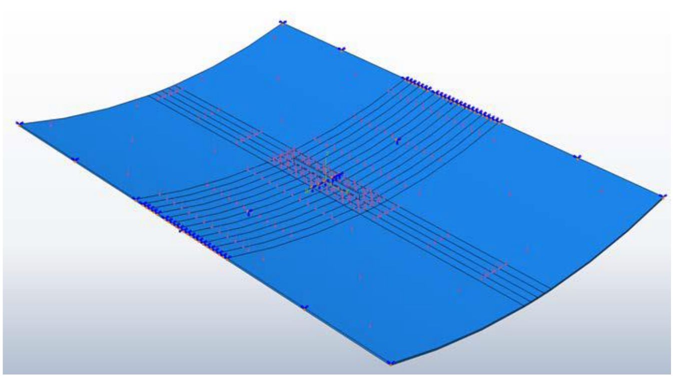

Fig.2 Panel with pressure load and boundary conditions
The characteristics of the final mesh are summarized in table 1.

Table 1: The characteristics of the final mesh.

D (m)	No. of steps (max.)	No. of nodes	No. of elements	Type of element
1.6	54	136360	107536	C3D8R
2.4	147	135230	106640	C3D8R
3.2	20	136360	107536	C3D8R
4	59	136340	107520	C3D8R

Firstly, the simulation results of 5 holes model will be presented as follows:
SIFs were calculated for each crack front and different crack sizes and maximum values of SIFs calculated along the crack fronts were used as a reference. Also, in this section SIF of the cracks from 1 to 10 were evaluated individually to investigate the effect of changing fuselage diameter from 1.6 m to 4 m. The SIF results were described in figures 3 and 4.
Figures 3 and 4 show the relationship between crack lengths and stress intensity factor histories, it can be seen that the longest crack 1 length was recorded when fuselage diameter (D) was equal to 2.4 m (C.L. =42.6233 mm, KI=14084.5 MPa√mm) followed by when D equal to 1.6 m (6.7426 mm, KI=5740.28 MPa√mm), then when D equal to 3.2 m (5.6411 mm, KI = 4366.58 MPa √mm) and lastly when D equal to 4 m (5.6118 mm, KI=4873.37 MPa√mm). It is important to mention that crack 1 when D is equal to 2.4 separated due to its length and the high values of SIFs. Also, the figures show the SIFs histories rise as the crack extends, in some distances unstable crack growth occurs at the end of the simulation (D=2.4 and 4 m).

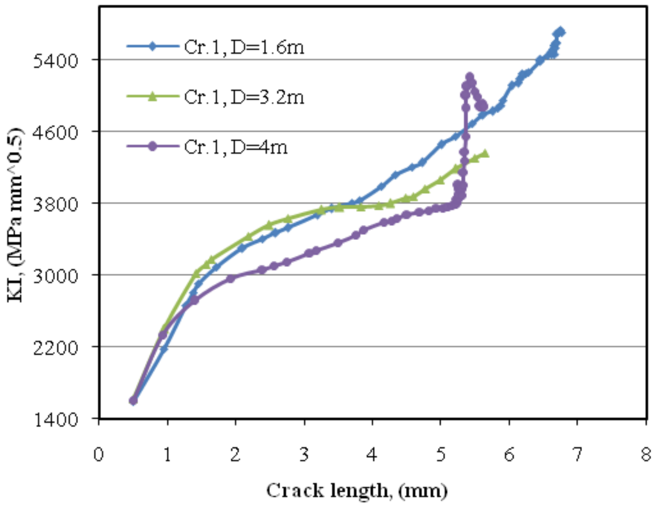

Fig.3 SIF histories of crack 1

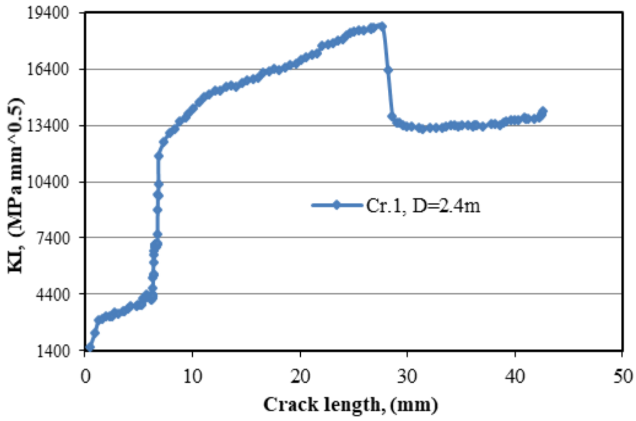

Fig.4 SIF histories of crack 1, D=2.4m

Figure 5 shows the variation of the SIFs with the crack lengths. The longest recorded crack length was crack 1, (C.L.=42.6233 mm, KI=14184.5 MPa √mm). Unstable crack growth for crack 1 occurred after step 26 as a result of the first link-up which took place between cracks 6 and 7 and causes a stress concentration in the rest cracks as presented in figure 6.

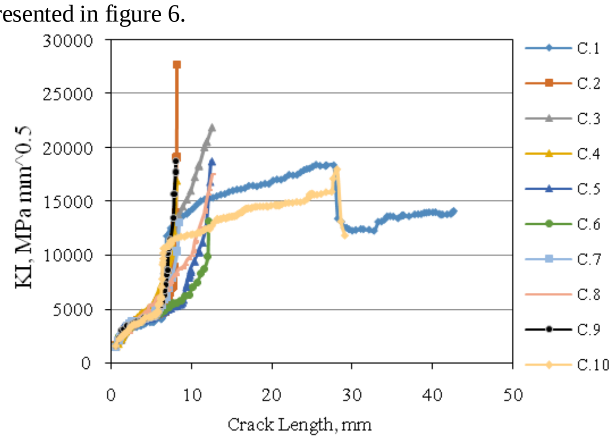

Fig.5 SIF histories of the cracks, D=2.4m

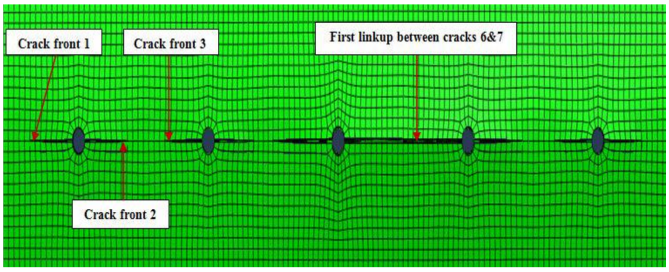

Fig.6 XFEM model of MSD after cracks opening (step 26), D=2.4 m

Figure 7 shows the second and the third linking up between cracks 4, 5, 8, and 9 which produce one lead crack.

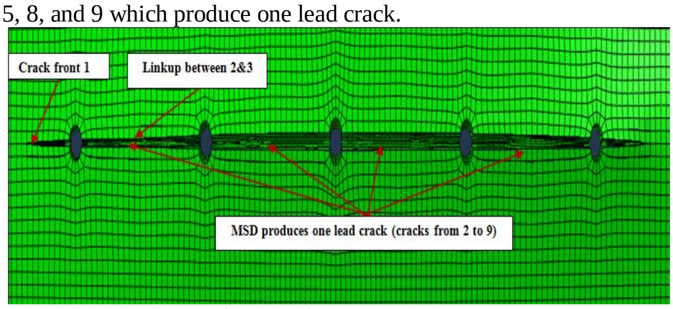

Fig.7 XFEM model of MSD after cracks opening (step 58), D=2.4 m

Figures 8 show the later crack extension stages after the final linkup between cracks from 2 till 9, crack 1 and 10 started to grow in a faster manner after that and it reaches 35.7693 mm just after 84 steps (after step 62). At the end of the simulation, crack 1 reached 42.6233 mm, and crack 10 reached 29.0878 mm at step 146.

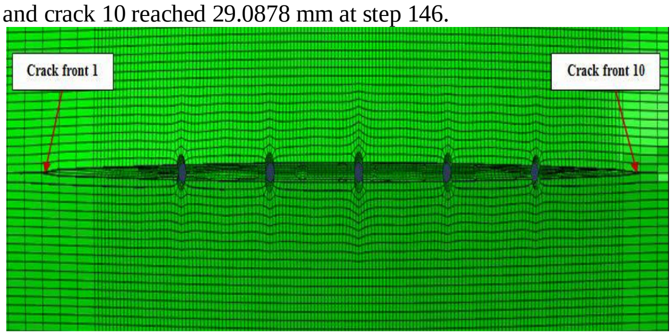

Fig.8 XFEM model of MSD after cracks opening (step 146), D=2.4 m

Secondly, the comparison of the results between the two models will be presented as follows:
Table 2 shows some selected results of the final crack lengths and the output stress due to the applied internal pressure (0.054 MPa), in the previous study:

Table 2: Selected results of the final crack lengths and the output stress due to the applied internal pressure (0.054 MPa), (the previous study)

3 Rivet holes case (Von Mises stress)

Step number	Max. stress value	Min. stress value
First loading step	3.68×10^{3}	4.016×10^{1}
40^{th} step (the last step)	2.667×10^{4}	3.348×10^{1}

Table 3 shows the final crack length and the corresponded SIFs values:

Table 3: the final crack length and the corresponded SIFs values

3 Rivet holes case (crack length vs SIF)

Crack number	final length	SIF
1	17.1846 mm	2870.65
2	17.81802 mm	6262.71
3	1.72654 mm	6273.94
4	1.67265 mm	3475.21
5	3.8838 mm	1640.88
6	2.9628 mm	1457.55

Table 4 shows some selected results of the final crack lengths and the output stress in that the applied internal pressure (0.054 MPa), the current study:

Table 4: Selected results of the final crack lengths and the output stress in that the applied internal pressure (0.054 MPa), (the current study)

5 Rivet holes case (Von Mises stress)

Step number	Max. stress value	Min. stress value
First loading step	3.798×10^{3}	3.174×10^{1}
40^{th} step (the last step)	3.046×10^{5}	2.507×10^{1}
The last step (step 147)	1.007×10^{5}	2.080×10^{1}

The cracks of 5 holes model which have the same crack position as the 3 holes model, the recorded results were as follows:

Table 5: The cracks of 5 holes model

Crack number	final length (mm)	SIF (MPa.$\sqrt{mm}$)
3	12.557 mm	21349
4	8.1057 mm	17528.3
5	12.4537 mm	17499.5
6	12.0705 mm	13119.3
7	8.4115 mm	13081.7
8	12.5041 mm	17479.4

The value of SIFs had a steep rise after adding two more rivet holes, as follows:
1-At first loading step the maximum stress increasing ratio was 3%
2-At step number 40 the stress increased by 11 times, knowing in the case of 5 holes had 147 simulation steps and the stress value at the last step was equal to 1.007×10^{5} MPa.
3- The maximum SIF value increased by 12 times.
4- The maximum crack length recorded when D=2.4 m (5 rivet holes) was equal to 42.6233 mm.
5- The crack 6 length (5 holes model) increased more than 6 times than the crack 3 length in the case of 3 rivet holes.
6- If the cracks arrangement for both models is considered from left to right, crack 1 length redoubled by 2.5 times and SIF value at the last step about 5 times

Conclusion

1- In the numerical example, cracks 2, 3, 4, 6, 8, and 10 had their longest length when D was equal to 2.4 m (the longest recorded length was to crack 10, CL= 29.0878 mm, but the longest recorded length, in this case, was recorded to crack 1 (42.6233 mm) when D was equal to 4 m. Cracks 3, 5, 6, 7, 8, and 10 had their shortest length when D was equal to 3.2 m (crack 6, 5.17194 mm), while the shortest length in this simulation recorded to crack 2 (2.3956 mm) when D was equal to 4 m
2- The linking up process between the multiple cracks which represents MSD phenomena occurred between all cracks in the case of D equal to 2.4 m, between cracks from 3 to 10 in the case of D equal to 3.2 m and 4 m.
3- The applied pressure in this simulation (figure 2) which produced high applied stress is considered too high due to the panel was not supported with stringers and this is the reason for the higher obtained SIFs values and the existing effect of the failure modes II and mode III.
4- Also this study indicated an increase in the number of rivet holes will be made corresponding increase in SIFs vales and crack lengths.
5- In this study, SIFs calculations – based on the implementation of XFEM in Morfeo/Crack for Abaqus software – were presented for three-dimensional un-stiffened panels of different curvatures with five cracked fastener holes subjected to pressure differential of 0.054 MPa. The main disadvantage of this method is the impossibility of the load application different from uniform tensile stress and this is why the difference between obtained SIFs was significant.
Analysis of XFEM results showed the considerable influence of un-stiffened panel geometry (i.e., a radius of the curvature) and applied boundary conditions on cracks' paths and their shapes. The

challenges and difficulties that XFEM implementation imposes are something that should be paid attention to in the next studies.

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