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Analysis and Analytical evaluation of multi site damage in fuselage structural joint

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***ABSTRACT- There are many factors which are threat for structural integrity in the aging aircraft.MSD is one of the factors which affect the structural integrity of the aircraft. For the constant amplitude loading conditions on the fuselage structure induces identical stress fields at the riveted holes. As the pressurization cycles increases it initiates small fatigue cracks under the riveted head. These cracks propagate coalesce and finally leads to failure. The failure takes place in two ways one is due to catastrophic failure and other is due to plastic collapse between two adjacent riveted holes. The failure mechanisms are studied by calculating stress intensity factor by using MVCCI method. These two failure mechanisms will decide the service life of the fuselage structure*.**

Index terms- **Damage tolerance, Fatigue, Fuselage, MSD, pressurization**

I. INTRODUCTION

MSD problem particularly exists in aging aircraft in a longitudinal joint. A fuselage of a commercial aircraft typically undergoes a cycle of pressurization for every single flight operation. These cycles of pressurization would result in fatigue cracking near the rivet holes of the fuselage panel. In the initial stage the crack is difficult to detect because it is hidden by the rivet head or it is hidden by paint. The presence of a single crack in the joint is not dangerous damage. The typical joint consists of multiple rivet rows. Thus load can be transferred by a sufficient number of rivets. However, the highly dangerous are cracks at several followed rivets. They are an example of multi-site damage (MSD). The MSD is defined as the simultaneous occurrence of many small fatigue cracks at multiple locations in a structural component. The presence of the crack in the riveted lap joint does not mean that service life of the aircraft should be terminated. According to fracture mechanics, the crack would propagate at some finite speed for some time unless the crack length reaches some critical value.

Aloha accident is one of the best examples for MSD type of structural failure. In 1988, Aloha Airlines suffered a tragic accident where a portion of the fuselage tore away from the plane during a routine flight. The investigation concluded that the crack did not arrest at the fuselage frames because of the multiple sites where cracking had initiated. Fig. 1 shows MSD structure failure in aloha aircraft as shown below.

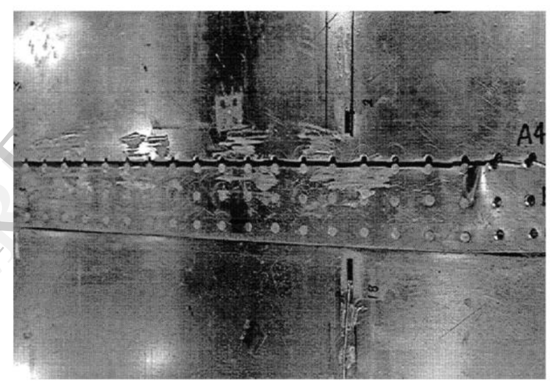

Fig. 1 MSD structure failure in Aloha aircraft

The literature survey reveals that MSD reduces residual strength and fatigue strength and hence overall structural integrity. Consequently, the residual strength of a panel with a leading crack and MSD cracks is known to be lower than that of a panel with the same leading crack without MSD [2].hence detailed failure investigation is carried for butt splice joint with doubler plate and loaded rivets.

Material taken for the analysis of model is AL 2024-T3 .The physical properties of AL 2024 T3 are shown in the following Table 1

Table 1

Properties	AL 2024-T3
density	27.21 N /mm^3
Youngs modulus	70000 Mpa
fracture toughness	80 Mpa√m
poisons ratio	0.3
yield strength	360 Mpa
ultimate strength	483 Mpa

The Chemical properties of AL 2024 T3 are shown in the following Table 2

Table 2

component	% of composition
Al	90.7-94.7 %
Chromium	Max 0.1 %
Cu	3.8-4.9 %
Ferrous	Max 0.5 %
Magnesium	1.2-1.8 %
Manganese	0.3-0.9 %
Titanium	Max 0.15 %
Zinc	Max 0.25 %
other	Max 0.15 %

II. GEOMETRICAL CONFIGURATION

Fuselage is modeled with the skinof 2000mm diameter, length 2000mm and 2mm thickness. The two splice joints are joined by doubler plate having size of 200 x 103 x 2 mm thickness. Skin and doubler plate is joined by rivets having 6mm diameter. The two longitudinal plates are separated by a gap of 2mm. The fuselage is subjected to an internal pressure of 10 psi. The rivet configuration for the model is as shown in the fig. 2

III. FINITE ELEMENT ANALYSIS:

Here two types of analysis are carried out.

Global analysis:

In this analysis the whole component is analyzed to know the stress distribution along the component and the failure prone areas. FEA of the Fuselage is carried out with quad 4 type of elements and rivets are considered as 1D element. For this panel, all the six degrees of freedom are arrested on either sides of the panel and internal pressure is applied as uniformly distributed normal outward load on the shell panel. Due to internal pressurization fuselage deforms outwards and induces both hoop and longitudinal stresses.

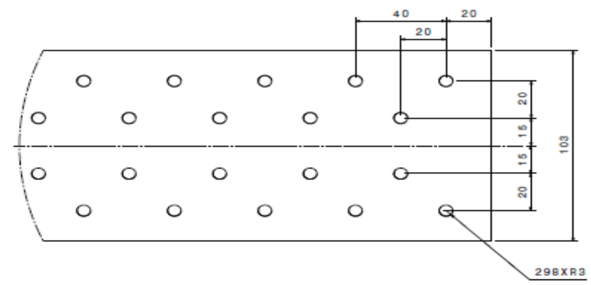

Fig. 2 Rivets configuration

Hoop stresses are perpendicular to the direction of crack propagation. Hence hoop stress will have significant influence on the crack growth.

From this analysis it is evident that the stress concentration is high at the riveted holes, so a local analysis is carried out to study the crack behavior around the riveted holes. This stresses are analytically evaluated by calculating hoop stress.

Hoop stress (σ_c) = $\frac{pd}{2t}$

Where σ_c–Hoop stress in Mpa

P – Internal pressure in N

d – Diameter of fuselage in mm

t – Thickness of fuselage in mm

Hoop stress

$$\sigma_c = \frac{10 \times 0.0007 \times 9.81 \times 2000}{2 \times 2}$$

Hoop stress σ_c= 34.335 Mpa

Local Analysis:

Here the failure prone segment is selected from a global analysis and modeled for the flat panel of length 600 mm and width 200.For the flat panel model same stress is applied as obtained for the global analysis. Flat panel Model configuration is as shown in the fig 4.

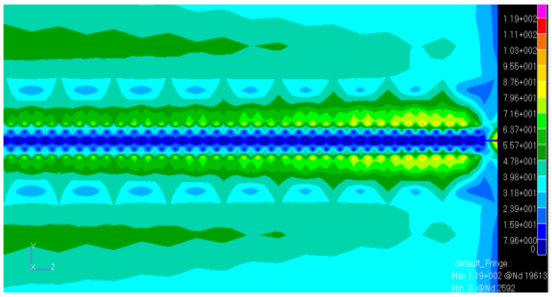

Fig. 3 Stress distribution in the global analysis

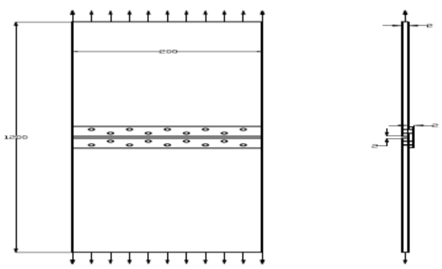

Fig. 4 Flat panel configuration for local analysis

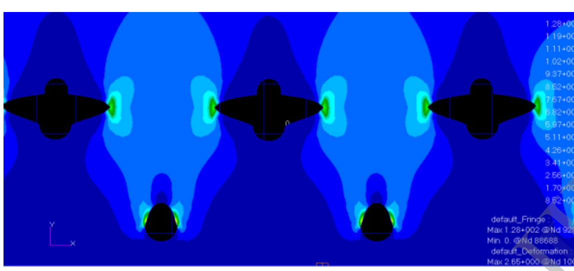

Fig. 5 Stress distribution at the tip crack in the flat panel

Flat panel analysis is carried out, a quad 4 element which is having 4 nodes, six degrees of freedom is used for panel and 1d element is used for rivets. Around the riveted holes fine mesh is carried out with an element length of 1mm.One end of the plate is constrained for all degrees of freedom and other end is subjected to uniaxial tensile load of 68.67 N. The elements are arrested for out of plane. Multi point constraints are used for transmitting loads and deformation from rivets to structure. Since in real structure for the same boundary conditions the rivets will make contacts with upper skin of the holes in the direction opposite to applied load and lower skin (doubler plate) makes contacts with rivets in opposite direction of upper skin contacts.

Fig. 5 shows Stress distribution for the 8mm crack length.

Failure Mechanisms

Generally failure of the structure takes place by two ways

Fracture:

According to fracture mechanics whenever SIF is exceeds the fracture toughness of material failure takes place. This type of failure is commonly observed in the structures.

i.e. $K_I \geq K_{IC}$

Where K_I – stress intensity factor.

K_{IC} – critical stress intensity factor.

The stress intensity factor at the tip of the crack is calculated by using Modified virtual crack closure integral(MVCCI)method. MVCCI method is best method for finding SIF by using fem approach. This procedure involves

$$K=\sqrt{G \times E}$$

Where

G-Energy release rate in N/mm

E- Modulus of elasticity in Mpa

$$\frac{\boldsymbol{\Delta f \times \Delta v}}{\boldsymbol{2 \times \Delta a \times t}}$$

Where

Δf-Grid point force in N

Δv-crack opening displacement in mm

Δa-element length at the crack tip in mm

t -Thickness of the panel plate in mm

Considering the following analysis for 5th iteration of 10mm crack length of 40 mm pitch rivet hole, where the SIF (k) for mode I can be calculated as

$$G = \frac{\Delta f \times \Delta v}{2 \times \Delta a \times t}$$

$$G = \frac{38.472 \times 0.0122 \times 9.81}{2 \times 2 \times 1}$$

$$\underline{G = 1.1546 \text{ N/mm}}$$

$$K=\sqrt{G \times E}$$

$$K=\sqrt{1.1546 \times 70000}$$

$$K=28.12 \text{ Mpa}\sqrt{\text{m}}$$

$$K_I \geq K_{IC}$$

Hence failure not takes place by fracture for the crack length of 10 mm

Plastic collapse condition:

This type of failure condition exists when the average stresses between two adjacent cracks exceeds the yields strength of the material which is called as net section yielding or plastic collapse. For the different crack lengths the stress intensity factor was calculated, also for the same crack length, net section yielding will be calculated between two advancing crack tips by taking an average value of the elemental stresses obtained between the two crack tips. The elemental stress at the crack tip will be higher and gradually decreases as moved away from the crack tip and it attains least value at center in-between the crack tips. The average values of all the elemental stresses are then compared with the yield strength of the material Al 2024-T3 is 362 N/mm. The plastic collapse for the 40 mm pitch rivet hole is calculated by taking average of elemental stresses between two adjacent crack tips for each iteration in increasing order of crack lengths. For the crack length of 10 mm, the average of elemental stress is σ_{avg} =84.786 Mpa.

Therefore $\sigma_{avg} \leq \sigma_y$

Hence failure is not takes place by plastic collapse at the crack length of 10 mm.

IV. RESULTS AND DISCUSSIONS

The stress intensity factor value is calculated for periodicincrease of crack length. For each crack length, the stress intensity factor value is compared with the fracture toughness of the material $80\ \mathrm{Mpa}\sqrt{\mathrm{m}}$. Table 3 shows the results of stress intensity factor values for gradual increase of crack lengths.

The graph in the Fig. 6 shows the crack analysis result which is obtained for crack length versus stress intensity factor value. The distance between two rivet hole edges are 34mm, from the result, it is found that at the half crack length of 16 mm the stress intensity factor value does not reaches the fracture toughness valueof the material, where the material does not leads to failure through fracture.

Table 3

sl no	Half crack length (mm)	K_I (Mpa? m)	K_{IC} (Mpa?m)	? $_{avg}$ (Mpa)	? $_y$ (Mpa)
1	2	20.052	80	42.236	360
2	4	21.05	80	49.834	360
3	6	22.62	80	57.43	360
4	8	24.95	80	68.12	360
5	10	28.12	80	84.786	360
6	12	31.92	80	118.34	360
7	14	39.21	80	167.84	360
8	15	45.62	80	228.63	360
9	16	59.79	80	376.05	360

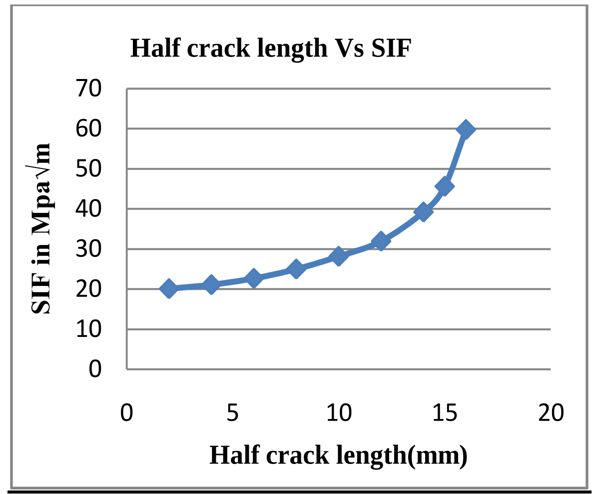

Fig. 6 half crack length Vs SIF

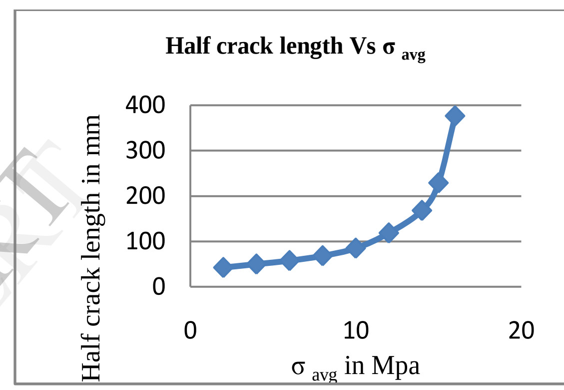

Fig. 7 Half crack legth Vs σ_{avg}

The graphical view is shown clearly. Similarly the net section yielding calculations are done bymeans of taking the average stress value between the two advancing crack tips and it is compared with the yield strength of the material. Table 3 shows the results of net section yielding for gradual increase of crack lengths. From the result, it is found that at the crack length of 16 mm, material crossed the yield strength value of material, where it leads to material yielding failure. The following Fig. 7 shows the graph of net section yielding result which is plotted for crack length versus average yield stress of the material for different crack lengths.

V. CONCLUSION

The global and local analysisis carried out for the fuselage of a commercial aircraft.In the present work only the fuselage with splice through butt joint has been analyzed. Fatigue loads due to internal pressurization acting on the fuselage, stress concentration will be high at rivet holes locations of the fuselage joint, which causes the initiation of cracks on all rivet hole edges due to uniform stress acting on the fuselage due to internal pressurization. The present study deals only with MSD, so the loads considered are only internal pressurization. Taking all the above points into consideration modeling and finite element analysis of fuselage and its local segment was carried out and from that work, some of the information's are concluded as follows

1. The material Al 2024T3 was a good structural material because of its properties and Fuselage model was meshed with 2D elements such as quad 4 and 1 D element for rivets elements; loads and boundary conditions were applied.

2. Stress analysis of the global model of the fuselage has been carried out to observe the hoop stress distribution on skin is equal to the analytical value of the hoop stress 34.5N/mm2. And it is observed that maximum stress found at the riveted locations.

3. Stress analysis for the local panel which was taken from global fuselage model was carried out to observe the hoop stress on panel obtained as 34.5N/mm2, and it was observed that at rivet holes the stress was more. The stress analysis of the riveted local section of the fuselage splice joint is carried out and the uniform stress distribution of 360 N/mm2 are observed at all the rivet holes, which are indicating the Multi-Site Damage with the initiation of crack.

4. For the different half crack lengths of 2, 4, 6, 8, 10, 12, 14, 15,16mm stress intensity factor was found out using MVCCI method and net yielding between the two cracks tips were calculated by taking average of elemental stresses between the two adjacent crack tips for the pitch length of 40mm.

5. It was observed that stress intensity factor does not exceeded the fracture toughness of the material but plastic collapse (net section yielding) takes place at the crack length of 16mm that is the net section average yield stress between the cracks was 376.05 N/mm2, whereas yield strength of the component was 362 N/mm2 and SIF at the crack tip was 59.79Mpa√mm, whereas the fracture toughness for 2mm material is 80 Mpa√mm the yield strength of the material The net section between the two advancing crack tip failure was due to the net section yielding (plastic collapse) of the material.

6. Also, one can conclude that if there is a crack in a rivet holes means; one should not assume that the component will fail only due to fracture mode, from the current case it was observed that the component will also fail due to plastic collapse.

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