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Determination of Stress Intensity Factor for a Crack Emanating From a Rivet Hole and Approaching Another in Curved Sheet

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Abstract: *Modern aircraft structures are designed using a damage tolerance philosophy. This design philosophy envisions sufficient strength and structural integrity of the aircraft to sustain major damage and to avoid catastrophic failure. The rivet holes location are one of the stress concentration region in fuselage skin. The current study includes a curved sheet with rivet holes is considered as part of the fuselage skin. During the service life of aircraft fatigue cracks will emanate from rivet holes simultaneously as they experience identical stresses due to internal pressure. In fracture mechanics, Stress Intensity Factor (SIF) is an important criterion to evaluate the impact of crack as the magnitude of SIF determines the propagation of crack. The objective is to investigate the SIF for crack emanating from one rivet hole and approaching another using Displacement Extrapolation Method (DEM) in F.E.M that would aid in the determination of the critical nature of such cracks.*

Keywords: *Fracture mechanics, stress intensity factor, rivet hole*

I. Introduction

Modern aircraft structures are designed using a damage tolerance philosophy. This design philosophy envisions sufficient strength and structural integrity of the aircraft to sustain major damage and to avoid catastrophic failure. However, structural aging of the aircraft may significantly reduce the strength below an acceptable level; this raises many important safety issues.

The most likely places for crack initiating and development are the rivet holes, due to the high stress concentration in this area. Such cracks may grow in time, leading to a loss of strength and the reduction of the lifetime of the fuselage skin as shown in fig 1.

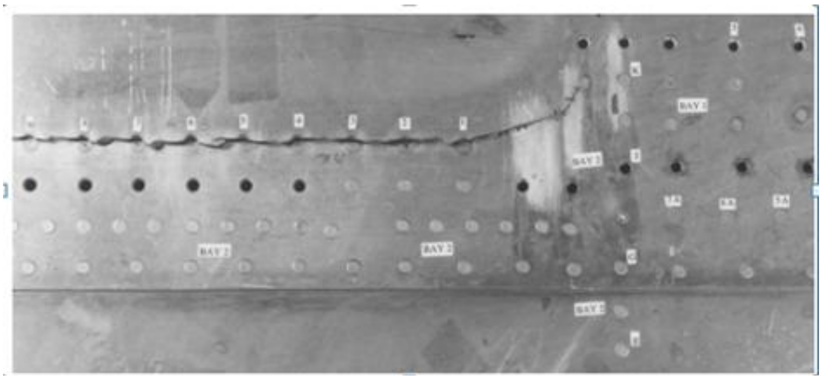

Fig.1. Larger crack formed by the link-up of fatigue cracks at adjacent rivets

The crack behavior must be assessed in order to avoid catastrophic failures. For this, the knowledge of the crack size, service stress, material properties and Stress Intensity Factor is required.

II. Fracture Mechanics

Fracture mechanics involves a study of the presence of the cracks on overall properties and behavior of the engineering component. The process of fracture may be initiated at defect locations like micro-cracks, voids, and the cavities at the grain boundaries. These defects can lead to the formation of a crack due to the rupture and disentanglement of molecules, rupture of atomic bonds or dislocation slip[3]. Cracked body can be subjected to three modes of loads as shown in Figure 2. In some cases, body may experience combination of the three modes.

1. Opening mode: The principal load is applied normal to the crack surfaces, which tends to open the crack. This is also referred as Mode I loading (Figure 2a).
2. In-plane shear mode: This mode corresponds to in plane shear loading which tends to slide One crack Surface with respect to the other. This is also referred as Mode II loading (Figure2b).
3. Out-of-plane shear mode: This is the tearing and antiplane shear mode where the crack surfaces move relative to one another and parallel to the leading edge of the crack (Figure 2c).

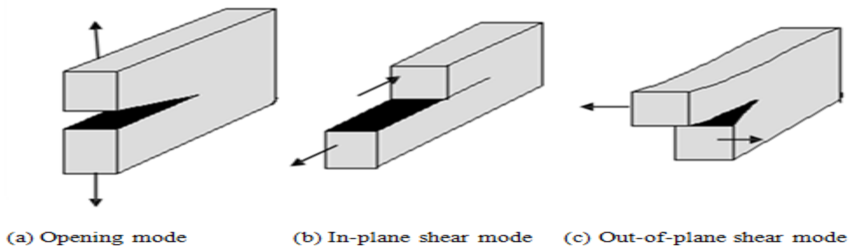

Fig. 2: Three modes of loading that can be applied to a crack

The Stress Intensity Factor (SIF) is one the most important parameters in fracture mechanics analysis. It defines the stress field close to the crack tip and provides fundamental information of how the crack is going to propagate. In this study, a typical and practical point matching technique, called Displacement Extrapolation Method (DEM) is chosen for the numerical analysis method. Plane strain assumption is valid for very thin walled structures; the evaluation of S.I.F (K_I) by Displacement Extrapolation Method (DEM) is as discussed below.

The stress intensity factors at a crack for a linear elastic fracture mechanics analysis may be computed using the KCALC command. The analysis uses a fit of the nodal displacements in the vicinity of the crack. The actual displacements at and near a crack for linear elastic materials are

U =$+\frac{K_{II}}{2G}\sqrt{\frac{r}{2\pi}}(1+K)$……………..….. (1)

V = $+\frac{K_I}{4G}\sqrt{\frac{r}{2\pi}}(1+K)$……………….. (2)

W = $+\frac{2K_{III}}{G}\sqrt{\frac{r}{2\pi}}$………………..….. (3)

Where: u, v, w = displacements in a local Cartesian coordinate system as shown in figure 3r, θ = coordinates in a local cylindrical coordinate system as shown in figure 3

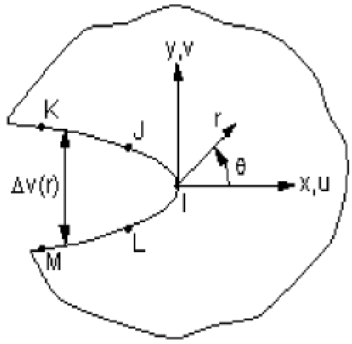

Fig. 3: Nodes Used for the Approximate Crack-Tip Displacements for Full crack Model
G = shear modulus

$K = \frac{\nu}{1+\nu}$In plane stress……….…………..….(4)

$K = 3 - 4V$ In plane strain ………………(5)

ν = Poisson's
For mode-I, SIF at crack tip is expressed as

$K_I = \sqrt{2\pi}\frac{4G\ |\Delta V|}{1+k\ \sqrt{r}}$……………………(6)

WhereΔV, is the motion of one crack face with respect to the other.

At points J and K. if, let r approaches zero

$$lim_{r\to 0}\frac{|v|}{\sqrt{r}} = A$$

$lim_{r\to 0}\frac{|u|}{\sqrt{r}} = B$.. (7)

$$lim_{r\to 0}\frac{|w|}{\sqrt{r}} = C$$

Therefore

$K_I = \sqrt{2\pi}\frac{4GA}{1+K}$ MPa $\sqrt{mm}$……………... (8)

$K_{II} = \sqrt{2\pi}\frac{2GB}{1+K}$ MPa $\sqrt{mm}$…………….. (9)

$K_{II} = \sqrt{2\pi}\frac{GC}{2(1+K)}$ MPa $\sqrt{mm}$……….... (10)

III. LOAD CALCULATION AND MODEL DIMENSION FORCURVED SHEET

The curved sheet considered as a part of the fuselage skin with the rivet holes. The load and model dimensions for the curved sheet are similar to fuselage as given below [5].

- Radius of the fuselage(R) = 1600 mm
- Thickness of the fuselage skin (t) = 1.8mm
- Diameter of the Rivet hole (D) = 4.8mm
- Internal pressurization (P_r) = 0.06695 N/ mm 2

All the edges of the curved sheet are subjected to symmetric boundary condition and pressure is applied on the area.
Hoop stress = (P_r*R) / t
Hoop stress (σ_h) = (0.06695*1600)/1.8
Hoop stress (σ_h) = 59.51N/ mm^2

IV. Material Used

Table 1: Material compositions

Component	Weight Percentage
Aluminum	90.7-94.7
Chromium	max 0.1
Copper	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, total	max 0.15

Table 2: Material Properties in Al 2024-T3

Properties	Material Aluminum 2024-T3
Density	27.27 N/ mm^3
Ultimate tensile strength	483 N/ mm^2
Tensile yield strength	362 N/ mm^2
Modulus of elasticity	72000 N/ mm^2
Poisson's ratio	0.33
Fracture toughness	98.90 MPa$\sqrt{m}$

V. Methodology

The objective of this work is to determine SIF for crack emanating from a rivet hole and approaching another in curved sheet as shown in figure 4. The objectiveis achieved by developing a model of a curved sheet with rivet hole and a through crack using CATIA V5 software. The CATIA model is imported to ANSYS.The FE model is meshed using 8-node quadrilateral doubly curved SHELL 93 elements in the pre-processor of the ANSYS software. A curved sheet with a crackwas meshed using three different mesh densities. Mainly, the area around the imperfection wasmodeled with a finer mesh.

As a part of the finite element work, a mesh sensitivity Study was conducted. Further, the crack tip singular elements were created using KSCON command. For this model there are 36 singular elements around the crack tip and the radius of the first row elements is Δa (Where Δa = a/100).The model is then solved (Static Analysis)

by subjecting it to an pressure of .06695MPa load with appropriate boundary conditions. Then the SIF is evaluated in general postprocessor by using KCALC command and parametric study is done for different thickness.

The geometry of the meshed test model with crack tip singular elements in ANSYS 12 is as shown in the Figure 5.

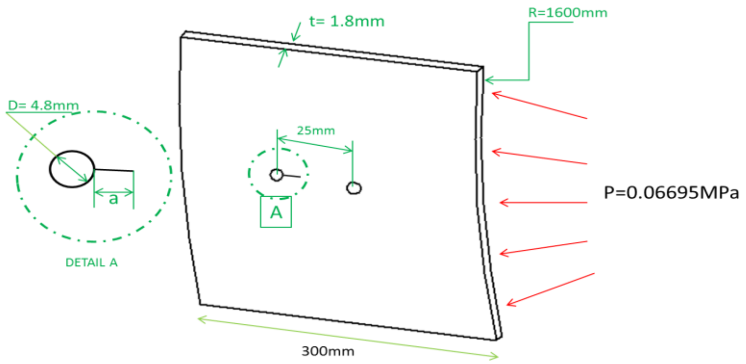

Fig 4: Geometry of model

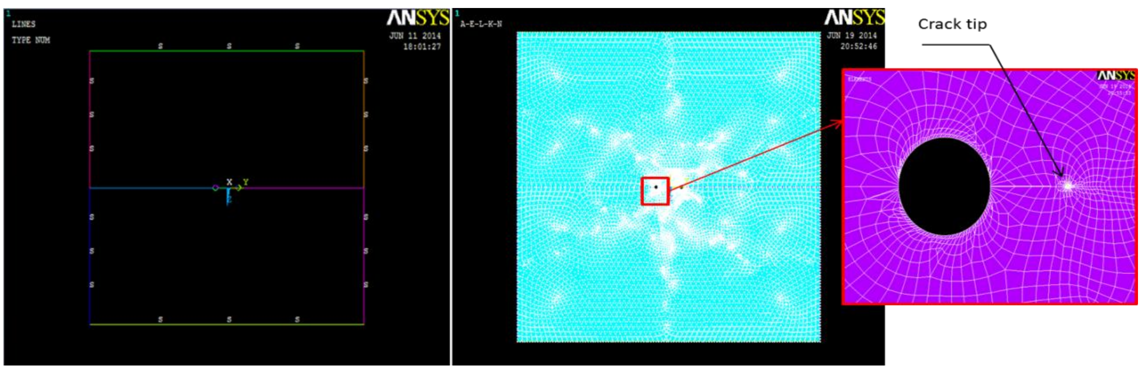

Fig 5: (a) Finite Element Model with Boundary Conditions (b) Meshed Finite Element Model (c) Zoomed View of Crack Tip Singular Elements

VI. Result And Discussion

The Figure 6 shows a pressurized cylindrical shell with varying longitudinal crack length. The theoretical formulae involved in the determination of mode 1 SIF of the crack is given below [3]. Mode I S.I.F (KI) is given by

$K_I(\text{Theo}) = \sigma\sqrt{\pi a} f_1(\alpha)$…………….. (11)

Where

$$f_1(\alpha) = \sqrt{(1 + .52x + 1.29x^2 - 0.07x^3)}$$

$$x = \frac{a}{\sqrt{(Rt)}}$$

The half crack length was varied from 20mm to 439.53mm .The maximum crack length in a given dimensions of cylindrical shell was determined using curvature parameter β.

$\beta = \frac{a}{\sqrt{(Rt)}} \sqrt[4]{12(1-\nu^2)}$……………. (12)

If $\beta = 8$for longitudinal cracks, thickness of the cylindrical shell is 10mm and radius of the cylindrical shell is 1000mm then the maximum crack length for given set of cylindrical shell dimension is 439.53mm

The values of mode 1 SIF from the procedure explained in the previous section is also determined for the same problem using FEA in ANSYS. Table 3 shows the values of SIF obtained by the theoretical and FEM.

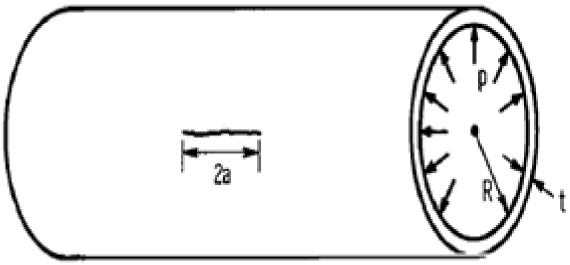

Fig.6: Longitudinal crack in internally pressurized cylinder

Table 3: Mode-1 S.I.F (K_I) Using FEA and theoretical K_I(Theo) for different Half Crack lengths

Half crack length (a) mm	**Model-1 S.I.F by FEA** MPa $\sqrt{mm}$	**Model-1 S.I.F by analytical** MPa $\sqrt{mm}$	**% error**
20	816.8	851.322	4.05
60	1837.6	1828.751	0.49
100	2981.4	2931.63	1.69
140	4114.8	4221.655	2.53
220	7166.7	7247.292	1.11
300	10694	10710.546	0.15
380	14644	14471.544	1.19
439.532	17812	17398.911	2.37

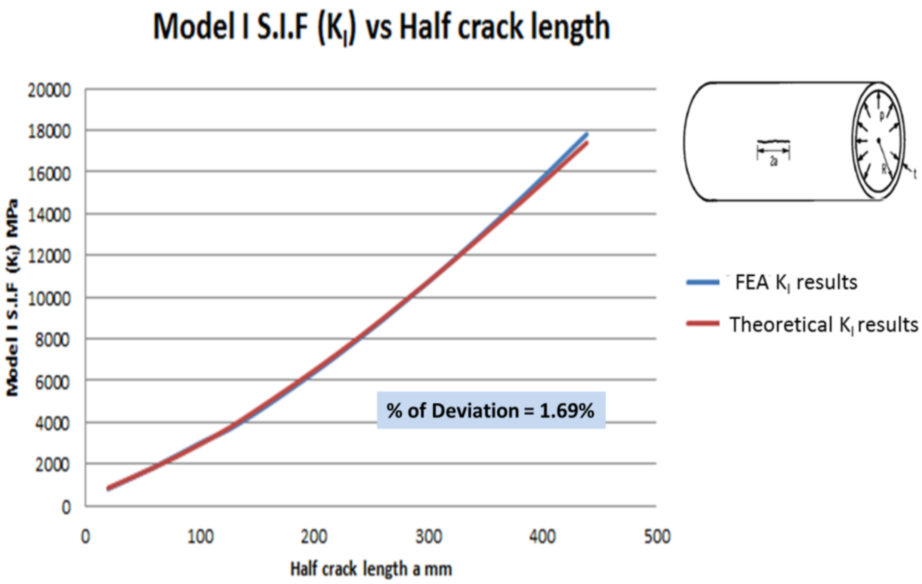

Fig.7: variation of theoretical and FEA values of S.I.F Vs crack length in Pressurized cylinder

Figure 7 shows the variation of theoretical and simulated FEA SIF values for various longitudinal crack length in pressurized cylinder. From the Figure it is indicated that the results which were obtained by using FEM are in good agreement with theoretical equation for a longitudinal through crack emanating in internally pressurized cylinder.

The average percentage of error between the FEA and theoretical SIF values is 1.69%, which is negligible.

Thus the proposed methodology to determine the Mode-1 S.I.F for longitudinal cracks in pressurized cylinder is validated against a standard procedure elucidated in literature [3].

The above procedure is used for "Determination of SIF for a Crack Emanating from a rivet hole and approaching another in curved sheet" the test models containing a through crack emanating from a rivet hole is meshed under plane strain condition it is internally pressurized and respective SIF's are calculated by varying half crack length(a).

$K_0(\text{Theo}) = \sigma\sqrt{\pi a_{eff}}$ MPa $\sqrt{mm}$

The specimen graphs are plotted to variation of normalized Stress Intensity Factor's (K_I/K_O), (K_{II}/K_O),),
(K_{III}/K_O),) with respect to (a/D) ratio is as shown in Figure 8(a),8(b),8(c) respectively.

The values of K_I,$K_{II}$and $K_{III}$with respect to (a/D) for thickens t=1.8 is as shown in table 4. It is observed that as the crack is initiated near the hole, the stress concentration at the hole has a strong influence on the stress intensity factor and makes the crack to propagate at faster rate. When crack approaches another hole there is sudden rise of stress intensity factor. This sudden rise is due to presence of stress concentration at another hole. The specimen graphs 8(a),8(b) and 8(c) shows that the Mode-I S.I.F (K_I) increases steadily as crack grows and rises suddenly when crack is near to another hole. It is clear that mode-I is high value and mode-II and mode-III are negligible. Therefore for crack emanating from on hole and approaching another in a curved sheet mode-I is more influencing for crack propagation. Through comparison it is observed that mode-II and mode-III have very less contribution for crack propagation hence can be ignored.

Table 4: The normalized Stress Intensity Factor (K_I/K_O), (K_{II}/K_O),(K_{III}/K_O) with respect to a/D ratio

a mm	a/D	K_I MPa	K_{II} MPa	K_{III} MPa	K_O MPa	K_I/K_O	K_{II}/K_O	K_{III}/K_O
6	1.25	278.76	2.364	3.74E-03	245.11	1.1372	9.64E-03	1.52E-05
8	1.67	299.57	0.967	8.94E-03	266.84	1.1226	3.62E-03	3.35E-05
10	2.08	328.24	1.50E-02	1.52E-02	286.93	1.1439	5.22E-05	5.28E-05
12	2.5	360.23	0.78599	1.05E-02	305.7	1.1783	2.57E-03	3.45E-05
14	2.92	387.06	5.10E-01	7.49E-03	323.39	1.1968	1.58E-03	2.32E-05
16	3.33	421.63	0.29899	1.62E-02	340.15	1.2395	8.79E-04	4.77E-05
18	3.75	482.45	2.58E-01	3.58E-02	356.13	1.3547	7.25E-04	1.01E-04
19	3.95	541.35	0.58028	4.32E-02	363.86	1.4877	1.59E-03	1.19E-04

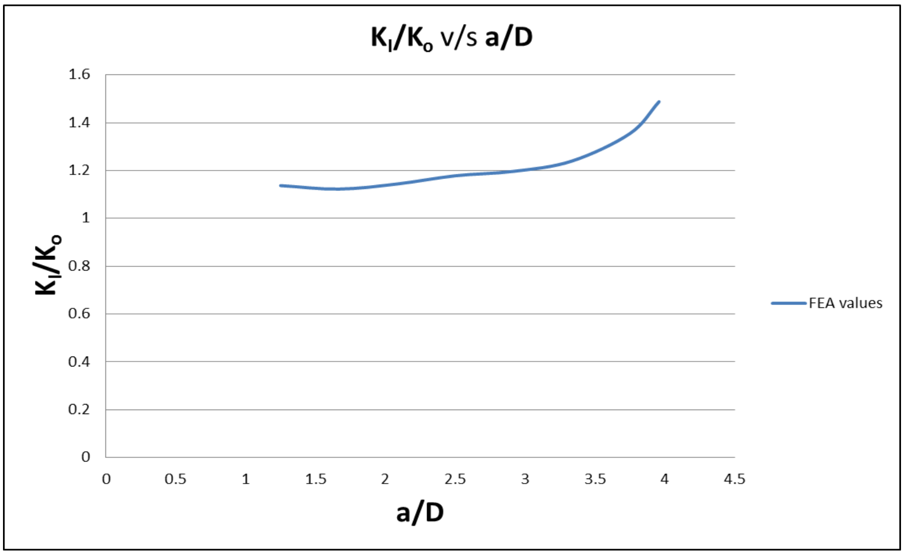

Fig 8(a): Normalized Mode-I SIF Vs a/D ratio by using Finite Element method

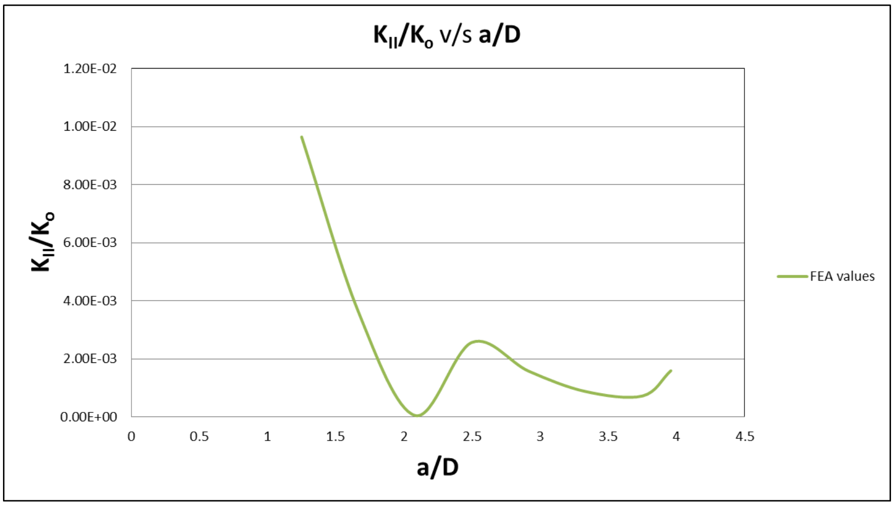

Fig 8(b): Normalized Mode-II SIF Vs a/D ratio by using Finite Element method

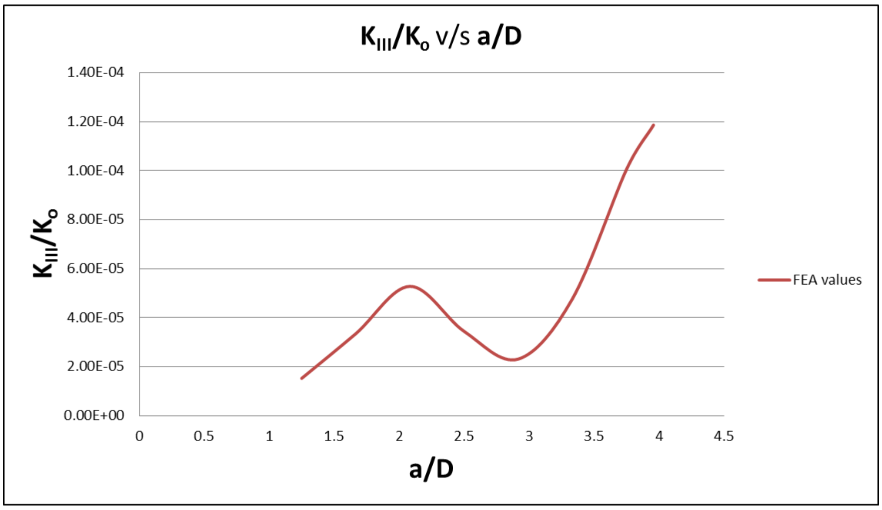

Fig 8(c): Normalized Mode-III SIF Vs a/D ratio by using Finite Element method

The parametric study is done for thickness 1mm, 2mm and 2.5mm, the values of K_I,$K_{II}$and $K_{III}$with respect to (a/D) for differentthickness is as shown in table 5 and corresponding normalized SIF values for mode-I, mode-II, and mode-III is shown if fig 9(a),9(b) and 9(c). It is observed thatSIF curves in fig 9(a) the normalized stress intensity for mode-I is very high for t =2.5mm compared to thickness 1mm and 2mm and for thickens t=2mm SIF is still lesser than thickens t=1mm, hence for taken dimensional parameter the thickness of the sheet should be nearly equal to 2mm which tends to lower crack propagation.

Table 5: The normalized Stress Intensity Factor (K_I/K_O), (K_{II}/K_O),(K_{III}/K_O) with respect to a/D ratio

For t=1mm

a mm	a/D	K_I MPa	K_{II} MPa	K_{III} MPa	K_O MPa	K_I/K_O	K_{II}/K_O	K_{III}/K_O
6	1.25	504.8	4.2804	2.75E-03	441.21	1.144126	0.009702	6.24E-06
8	1.67	565.89	0.28751	1.53E-02	480.33	1.178128	0.000599	3.18E-05
10	2.08	597.6	2.82E-02	3.79E-02	516.49	1.157041	5.45E-05	7.34E-05
12	2.5	657.91	1.4333	8.36E-03	550.28	1.195591	0.002605	1.52E-05
14	2.92	709.35	0.92056	5.84E-03	582.12	1.218563	0.001581	1.00E-05
16	3.33	775.66	0.5346	1.78E-02	612.3	1.266797	0.000873	2.90E-05
18	3.75	891.55	0.49397	7.38E-02	641.06	1.390743	0.000771	1.15E-04
19	3.95	1003.4	1.0952	1.88E-01	654.97	1.531979	0.001672	2.88E-04

For t=2mm

a mm	a/D	K_I MPa	K_{II} MPa	K_{III} MPa	K_O MPa	K_I/K_O	K_{II}/K_O	K_{III}/K_O
6	1.25	250.69	2.126	3.64E-03	220.6	1.136401	0.009637	1.65E-05
8	1.67	280.24	0.14227	7.79E-03	240.16	1.166889	0.000592	3.24E-05
10	2.08	294.99	1.34E-02	1.30E-02	258.24	1.142309	5.18E-05	5.03E-05
12	2.5	323.61	0.70628	1.02E-02	275.14	1.176165	0.002567	3.72E-05
14	2.92	347.57	0.45945	7.71E-03	291.06	1.194152	0.001579	2.65E-05
16	3.33	378.42	0.26987	1.52E-02	306.15	1.236061	0.000881	4.95E-05
18	3.75	432.76	0.22975	3.15E-02	320.53	1.350139	0.000717	9.82E-05
19	3.95	485.4	0.51815	3.27E-02	327.48	1.482228	0.001582	9.98E-05

For t=2.5mm

a mm	a/D	K_I MPa	K_{II} MPa	K_{III} MPa	K_O MPa	K_I/K_O	K_{II}/K_O	K_{III}/K_O
6	1.25	200.28	1.6985	3.32E-03	157.86	1.268719	0.01076	2.11E-05
8	1.67	223.76	0.11356	6.28E-03	171.85	1.302066	0.000661	3.65E-05
10	2.08	235.38	1.06E-02	9.54E-03	184.79	1.27377	5.76E-05	5.16E-05
12	2.5	258.03	0.56333	9.24E-03	196.88	1.310595	0.002861	4.69E-05
14	2.92	276.91	0.367	7.36E-03	208.27	1.329572	0.001762	3.54E-05
16	3.33	301.21	0.21601	1.29E-02	219.07	1.374949	0.000986	5.87E-05
18	3.75	344.09	0.18117	2.40E-02	229.36	1.500218	0.00079	1.05E-04
19	3.95	385.68	0.40964	1.78E-02	234.34	1.645814	0.001748	7.61E-05

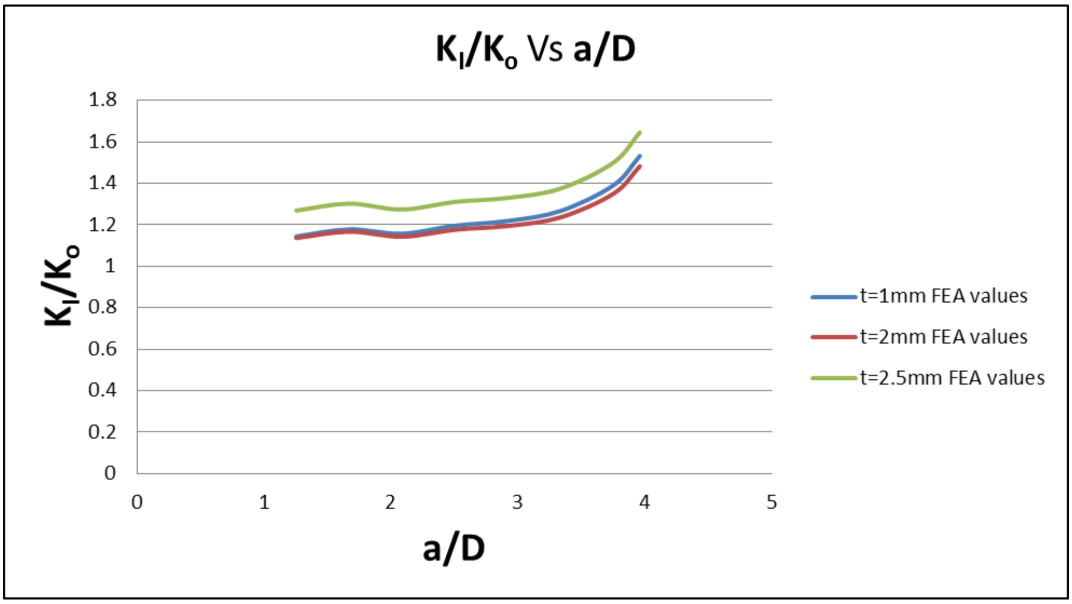

Fig 9(a): Normalized Mode-I SIF Vs a/D for variation of thickness

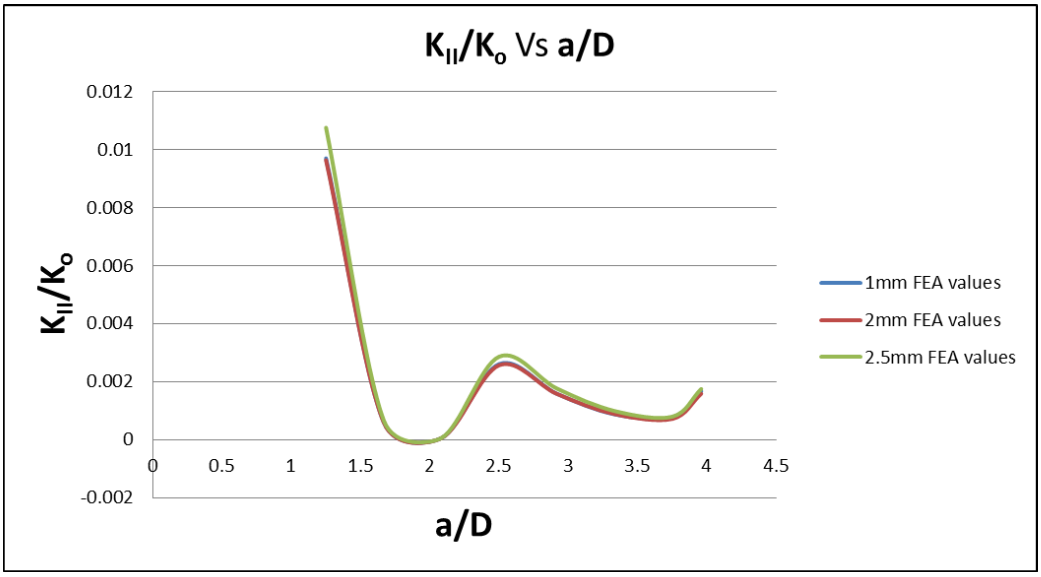

Fig 9(b): Normalized Mode-II SIF Vs a/D for variation of thickness

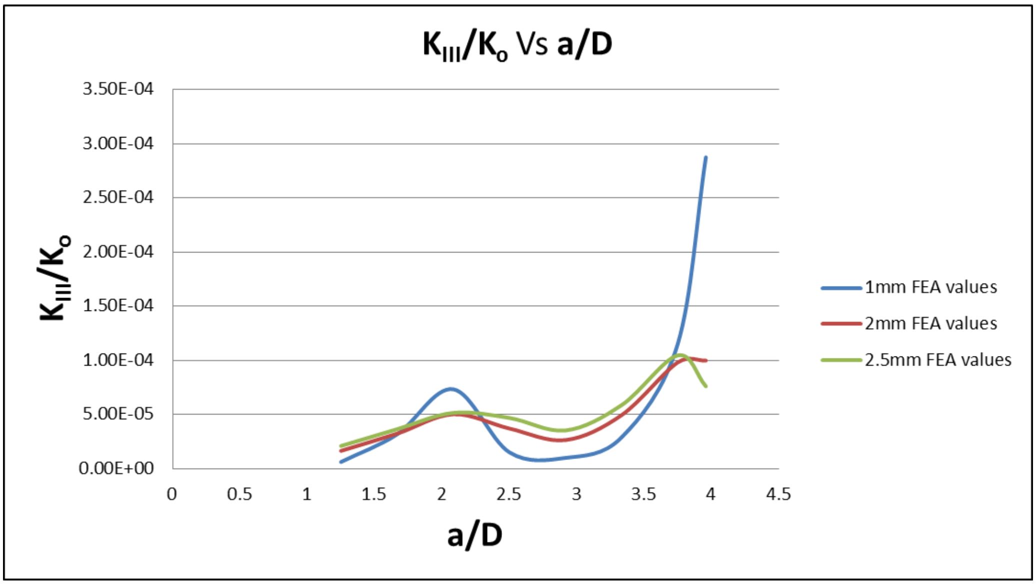

Fig 9(c): Normalized Mode-III SIF Vs a/D for variation of thickness

VII. Conclusion

The problem of determining stress intensity factors for a crack emanating from one rivet hole and approaching another in curved sheet is of prime importance in damage tolerance analysis and has relevance in the structural integrity evaluation of aging transport aircraft due to multisite damage. 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.

Stress Intensity Factor determination in this work which can be considered as a part of a thin sheet with rivet holes used in the aeronautical structures.

Taking all the above points into consideration modeling and finite element analysis for a part of the fuselage skin was carried and from that work, some of the information's are concluded as follows

- The curved is considered as part of the fuselage skin was created using a 3D modeling software tool according to the dimension and the 3D modeled component was imported to ansys tool for pre-processing. The curved sheet was meshed with 8 node SHELL 93 elements and loads and boundary conditions were applied.

- The material used was Al 2024-T3, which is widely used in aircraft industry for its good fatigue strength and corrosion resistance.
- Stress analysis of the model of the fuselage has been carried out to observe the hoop stress on skin is equal to the analytical value of the hoop stress 59.5 N/ mm^2 for t=1.8mm
- Finite element analysis is made for two rivet holes in a curved sheet without crack, it was observed that the rivet holes the stress concentration was maximum and concluded that rivet holes are the initiation of crack.

The method used in this report can be utilized for calculating the stress intensity factor for many other loading cases and many values of the crack length, thus providing important information for subsequent studies, especially for fatigue loads, where stress intensity factor is necessary for the crack growth rate determination.

The problem is intractable by continuum mechanics method. Experimental investigations are prohibitively expensive. Finite Element Modeling for computational fracture mechanics happens to be the right choice. Therefore, there is a real need to adapt computational procedures.
The presented stress intensity factors in this paper are essential to predict

1) Mixed mode fracture under static, dynamic and sustained loads
2) Residual strength
3) Crack growth life under cyclic loading conditions.

The results presented in this study conclusively prove that Finite Element Modeling using ANSYS software to be the right choice. The numerical results presented are believed to be quiet accurate.

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