DAMAGE TOLERANCE EVALUATION OF AN AIRCRAFT SKIN STRUCTURE BY MVCCI TECHNIQUE (2D ANALYSIS) USING MSC – NASTRAN / PATRAN

K.S.Vishwanath Vashisht

Assistant Professor, Department of Aerospace Engineering, Amity University, Haryana, India.

Abstract

An Aircraft is a light weight airbreathing semi-monococque complex aerostructure comprising of longerons, bulkheads, stiffeners, stringers, lugs, bolts and joints, ribs and other special forms of structures. In its service, it has to sustain aerodynamic, structural, propulsive, fatigue and impact loads. Even though the load carrying agents are the stiffening materials, the loads are firstly faced by the aircraft skin in the form of shear loads and later on transferred to the stiffening structures inside. In the present study, A small portion of the aircraft skin is considered and is analyzed by Damage Tolerance technique, ie, by assuming a minute flaw to be present at the time of manufacturing itself or by other processing efforts. While in operation, due to the crack initiation, the accumulated crack propagates to critical sizes leading to catastrophic failure. The main objective of this paper is to determine the normalized stress intensity factor in the opening mode K_I for a finite width plate in uniform tension with a central crack. The report will start with a brief review of fracture proceeding further with the concept of Stress Intensity Factor in opening mode, i.e., K_I, and common design strategies (Assumptions) to assure the structural integrity of components and of the role that stress intensity factor plays through different modes of failures. And it also covers an overview of energy approach and stress intensity approach to a problem. Using MSC NASTRAN/PATRAN, Stress Intensity Factor in opening mode, K_I is found by MVCCI technique and is validated with the theoretical results obtained by Feddersen empirical modeling.

Keywords: *Crack Propagation, Damage Tolerance, Energy Release Rate, Fracture Toughness, MVCCI, Stress Intensity Factor.*

--***--

1. INTRODUCTION

Many components of the modern industrial world in real are subjected to fluctuating loads and consequently they may fail through fatigue. Even though large stress concentrations are avoided by designing the structure for a reliable factor of safety, the material dislocations that are formed at the time of production or other processing efforts cannot be avoided, and therefore must be taken into consideration. Also microscopic imperfections can cause the structures to fail as and when they propagate and grow with time[1]. Until fracture studies were developed, whenever a crack was observed in a component of the structure, it was either restored with a new component or repaired. The above mentioned procedures in the present day are unnecessary and sometimes too costly. On the other hand, the detection of a flaw in a structure does not automatically mean that it is not safe to use anymore. Under such situations fracture mechanics plays an important role [2]. It provides an insight to predict the manner in which failure might occur. The different conditions that can cause the failure of a structural component are yielding, deflection, buckling, fatigue, fracture, creep, resonance, impact and the environmental setting in which it operates [21]. For instance, mild steel exhibits brittle fracture when the temperature is less than 80°C and fibrous and shear type of fracture at room temperature and inter-granular creep failure at temperatures above 600°C [21]. Due to the unexpected mechanisms involved in the fracture process and the limited warnings before the catastrophic crack propagation, brittle fracture is the most interesting failure mode to analyze the propagation. This has been the main motivation to the study of fracture. [1-2]

2. LITERATURE REVIEW

In the mid twentieth century, scientists discovered and observed the initiation of micro cracks in the fatigue life of a material. Then onwards, the investigators started to observe and believe that there exists two phases under the cyclic loading of fatigue life, i.e., the crack initiation period and crack propagation period till fracture or rupture occurs [15]. This can be represented in a block diagram, as shown in Fig 1.

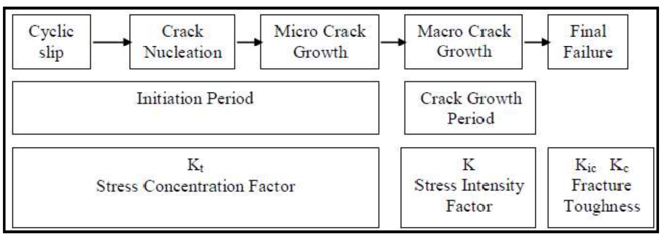


Figure 1. Crack initiation and propagation phases

Crack initiation is observed to occur at the tip of an existing crack or at some point of a free surface. A fatigue crack grows with each applied load cycle and hence crack growth per unit cycle da/dN is important. Initially da/dN is very small of the order of 10^{-10} m/cycle. As the crack grows, the stress intensity factor range, ΔK increases and da/dN also increases. The expression for K at the crack tip stress field used by Paris and his team by Irwin's theory is, [3].

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f(\Theta_{ij}) \quad (1)$$

where K is the stress intensity factor & r and θ are the polar coordinates. Equation (1) is an approxiamate solution valid for small values of r, i.e. $r < a$, where 'a' is the crack length. The stress intensity factor is represented by:

$$K = \sigma\sqrt{\pi a}\beta_T \quad (2)$$

where β_T is the geometry or correction factor [1].

Brittle fracture from a long time has been recognized as a phenomenon that is extremely confined to a small area. The methodology of fatigue and fracture has fracture toughness, stress and flaw size as variables and determines the behaviour of the system [1][20]. Although classical fracture mechanics does not particularly deal with the characterization of flaw size, position and orientation, it sets the fundamental principles necessary for the further development of more complex models that directly examine the random distribution of the defects. [2]

The crack propagation analysis of a structure under fracture mechanics can be characterized and computed by various methods shown in the Fig 2,3 and 4 below [7][18].

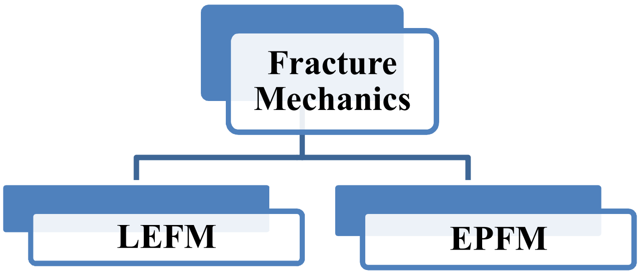


Figure 2. Methods for predicting the crack propagation

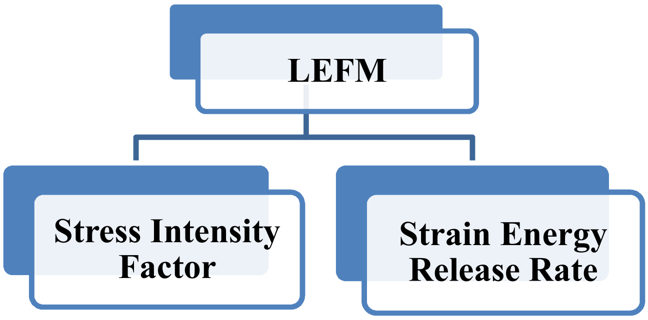


Figure 3. Methods for determining the SIF under LEFM approach

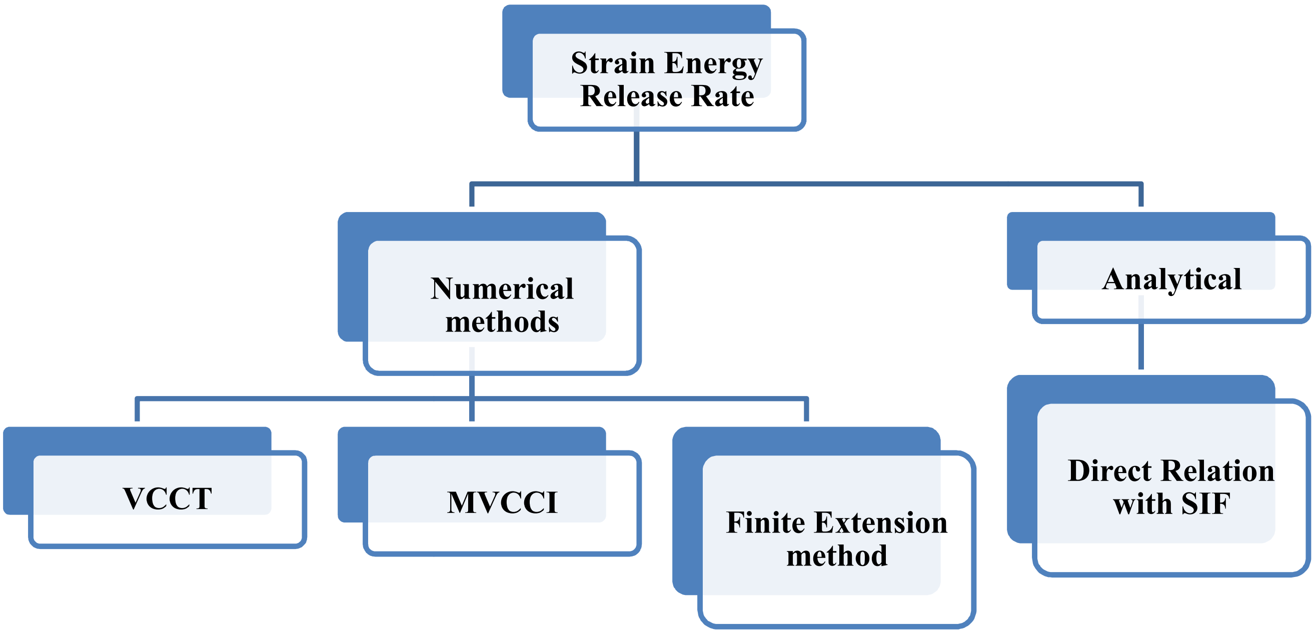


Figure 4. Different methods for calculating stress intensity factors under SERR

Linear Elastic Fracture Mechanics (LEFM) is employed when the deformation is observed at a small region near the crack tip. Fig. 5 shows a typical log (da/ dN) vs log ΔK curve [3]. In regions I and II, the size of the plastic zone is very small when compared with the size of the crack. Hence, principles of LEFM holds good. But in region III, the plastic zone size is large[19]. Hence, LEFM is not entirely correct and can be applied until our interest is the assessment of remaining life and not the residual strength [7]. When the case study is different, Elastic to Plastic Fracture Mechanics (EPFM) has to be employed.

The present study investigates the validation of stress intensity factors obtained by Feddersen's empirical solution with the values obtained from the FEA solver MSC NASTRAN/PATRAN by MVCCI technique.

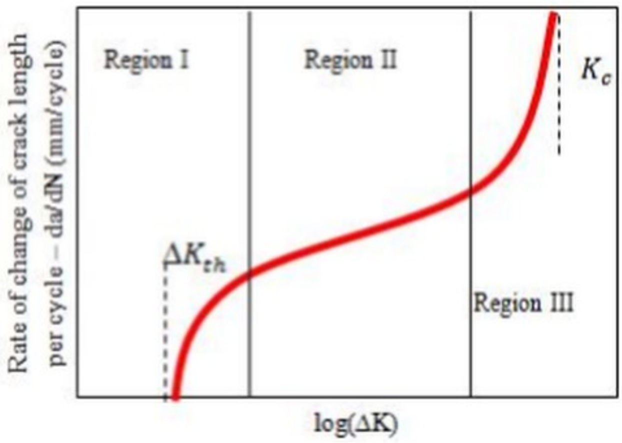


Figure 5. da/dn vs ΔK curve in log scale

3. METHODOLOGY OF MODIFIED VIRTUAL CRACK CLOSURE INTEGRAL TECHNIQUE (MVCCI):

3.1. Description:

The modified method is based on the same assumptions of Virtual Crack Closure Technique. That is the energy released ΔE when the crack is extended from a to a+Δa and a+Δa to a+2Δa is exactly the same amount of energy required to close the crack between the locations, i.e., Griffith's strain energy release. Along with this assumption, further it is assumed that, when the crack extends from a+Δa to a+2Δa, the state of stress does not change considerably. Hence the nodal displacements at the crack closed instant is nearly equal to the crack extended configuration. [5][12]

In this method, the nodal displacements and forces necessary to determine the energy that is required to close the crack can be established by a single step finite element analysis inspite of two as in virtual crack closure technique [11].

3.2. Analytical Studies:

The important factors at the crack tip zone are the strain energy release rate and stress intensity factors. The current problem deals with the opening mode. In MVCCI, strain energy release rate at any crack tip zone is obtained by considering an infinitesimal extension in crack and computing for the workdone necessary to make the specimen to get back to its previous crack configuration by closing the crack extension [9]. For opening mode, this is expressed as,

$$G = \frac{1}{2\Delta a}\int_0^{\Delta a} \sigma_y \Delta v dx.$$

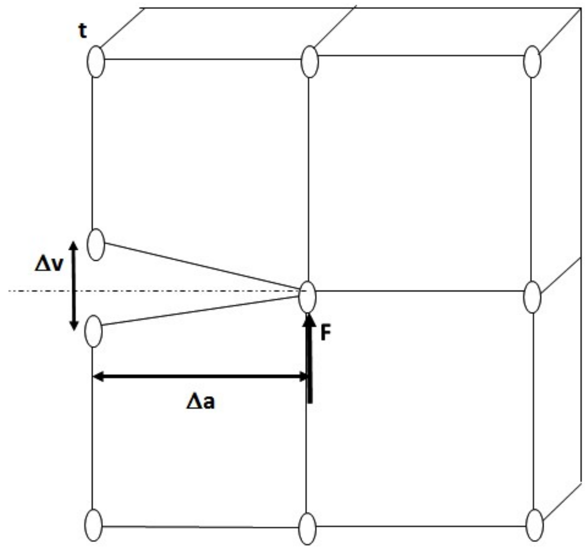
The stress intensity factor is calculated by modified crack closure integral (MVCCI) technique using quad 4 and quad 8 shell elements. Fig 6 shows the nodal forces and displacements for the 4 node and 8 node elements respectively.

The energy release rate for a 4-node quadrilateral element is [9],

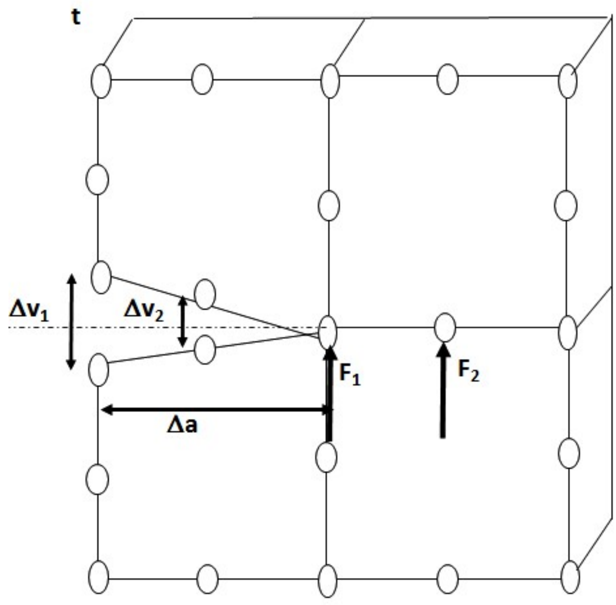
$$G = \frac{1}{2\Delta a} F\Delta v$$

The energy release rate for a 8-node quadrilateral element is [11][13],

$$G = \frac{1}{2\Delta a}(F_1\Delta v_1 + F_2\Delta v_2)$$



(a) 4 node quad element



(b) 8 node quad element

Figure 6. Modified crack closure method for (a) 4-node and (b) 8-node quadrilateral elements

Where, G = Strain energy release rate, Δa = elemental edge length at crack tip, Δv = differential displacement of opening node, F = grid point force at crack tip, t = thickness of plate at crack tip.

The stress intensity factor $K = \sqrt{G * E}$, where E is the elastic modulus.

The Feddersen Empirical Solution for the Specimen is given by,
$K_I = (\sec((\sigma * a)/(2*W)))^{0.5}$

3.3. Experimental Studies:

In the present study, MSC PATRAN is used for preprocessing and meshing. For post processing, MSC NASTRAN solver is employed. The procedure followed is shown in the Fig 7 below.

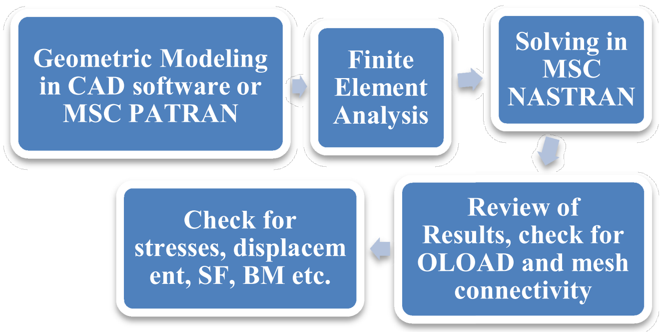


Figure 7. Block Diagram illustrating the procedure of FEA simulation

Geometrical Configuration:

Consider a 2D finite width plate in uniform tension with a central crack. The plate dimensions are given in the table below. The plate is subjected to a uniform edge pressure of 120 MPa. Material is Al 2024-T3 having E = 70000 MPa, υ = 0.3.

Table 1. Dimensions of the plate structure

SI NO.	Nomenclature	Dimensions (mm)
1	2W	60
2	2h	120
3	T	2
4	2a	10

3.3.1. Geometry Creation:

Create a 2D geometric model of the plate (In this case 1/4th plate model) with a central crack of 2a = 10mm , Width = 60, height = 10 and thickness t=2mm as shown in Fig 8 with the help of commands available in MSC Patran.

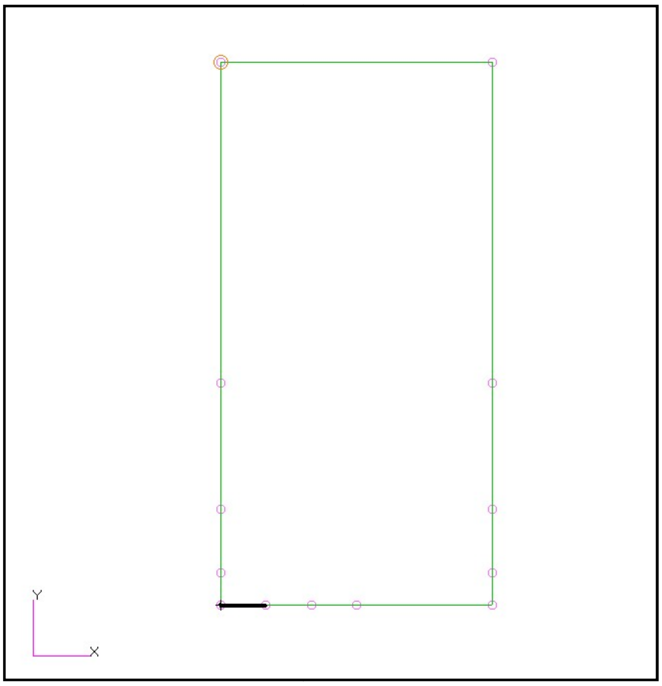


Figure 8. Geometric model of a quarter plate

3.3.2. Finite Element Meshing:

Create the finite element model for the quarter plate maintaining the element width (a/100) at crack tip as shown in Fig 9. At least four elements surrounding crack tip should be nearly square shape. All shell elements generated are quad4 and quad8 separately in two cases. Fig 10 shows the close up view of the meshed model.

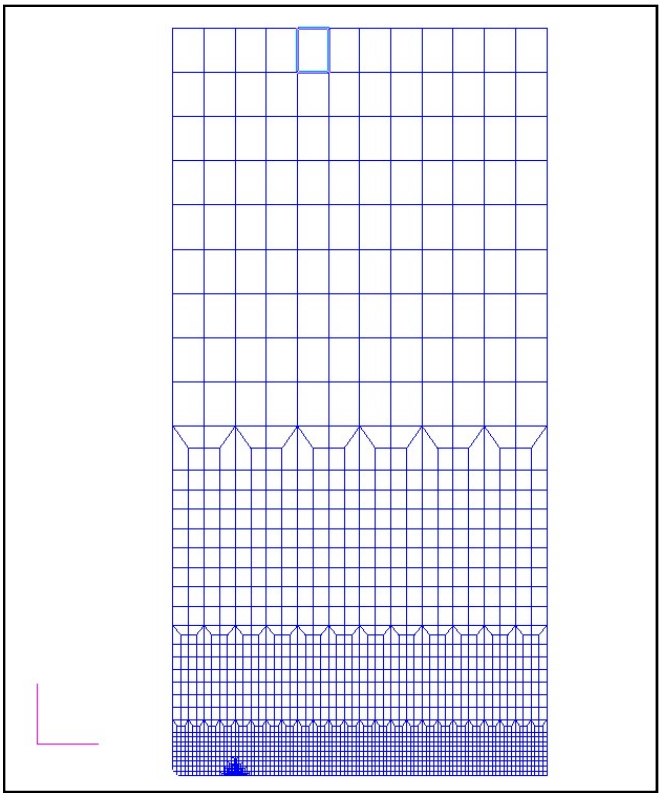


Figure 9. Meshing of quarter plate

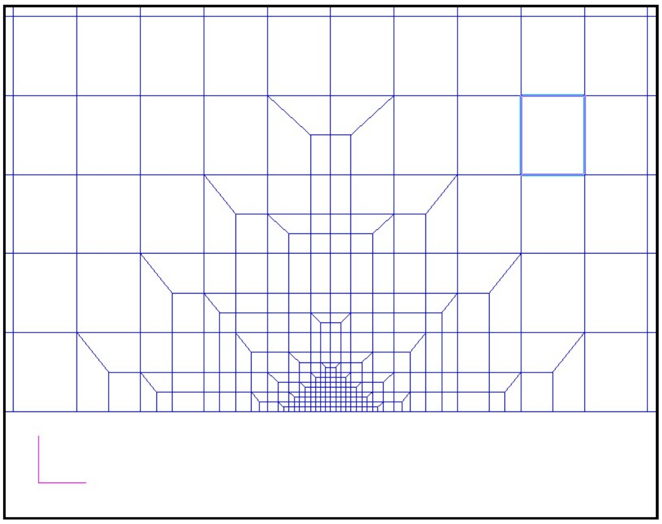


Figure 10. Closeup view of Meshed Plate

3.3.3. Loads & Boundary conditions:

A uniform distributed load of 120 MPa is applied on the top element free edge. [4] Due to symmetry, x-displacement & z-rotation is constrained at the left free edge and y, z linear displacements & x, y rotational displacements are constrained at bottom free edge (from crack tip to end of the width) to maintain 2d plain strain condition using quad4 shell elements in patran as shown in the Fig 11. (But 2d membrane elements can be used as plain stress elements with boundary conditions x-displacement constrained at the left free edge & y-displacements constrained at bottom free edge.)

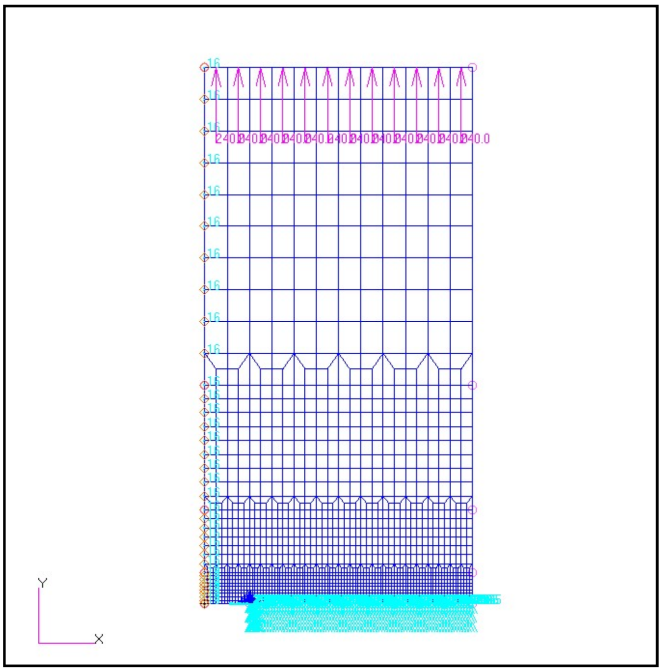


Figure 11. Loads & Boundary conditions over the meshed plate

3.3.4. Material property:

A material Al 2024-T3 is created by assigning E = 70000 MPa and σ = 120 MPa, υ= 0.3.

A thickness of 2 mm is also assigned to all shell quad4 elements.

3.3.5 Load Cases Creation:

For each load case, the boundary conditions and the load case name at the required crack length is assigned to identify the particular load case.

4. RESULTS AND DISCUSSION

From results obtained by FEA, the y-force & y-displacement at crack tip node are noted below as shown in Fig 12 and 13. [6-8]

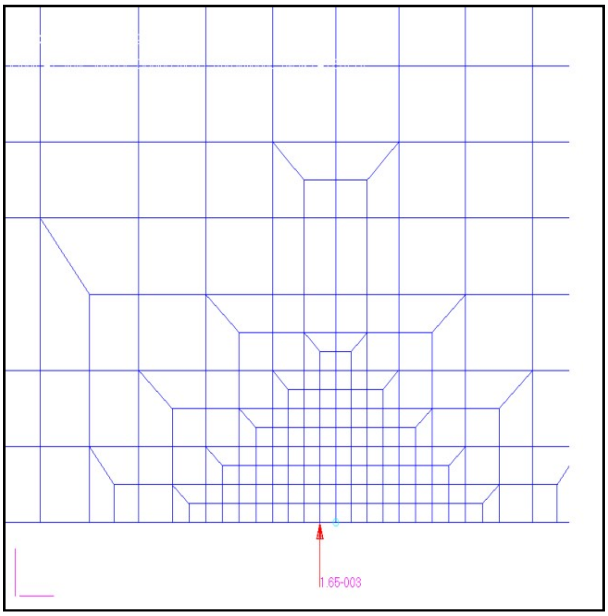


Figure 12. Crack tip opening displacement (1.65 E-03 mm) for Case-I (quad4)

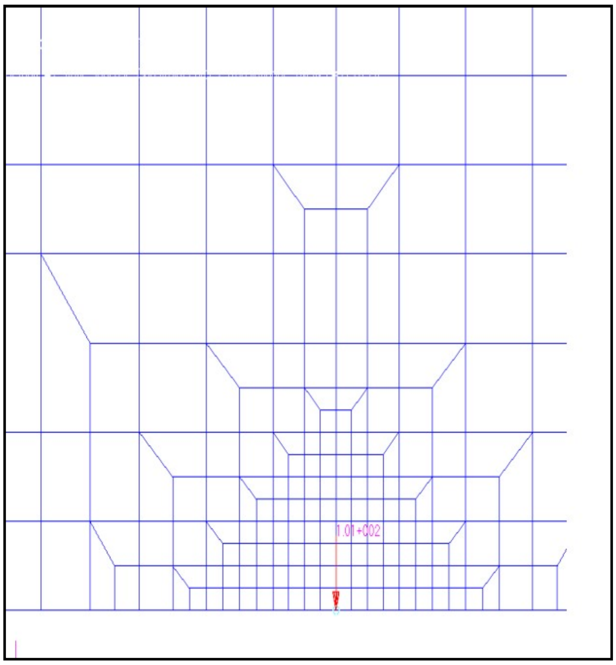


Figure 13. Force Fy at crack tip node (101 N) for Case-I (quad4)

For a crack length of 10mm,
Crack tip opening displacement, $\Delta v = 1.65x10^{-3}$mm
Force at the crack tip node, $F_y = 101$N.

Results are tabulated below for the different cases of Δa and crack lengths.
For Quad4 elements:

Table 2. Theoretical & Experimental values of SIF for Quad 4 elements

Crack Length 'a' (mm)	Element Width 'a/100' (mm) Δ a	K_I Empirical Solution	K_I Computed from FEA	% of Error
5	0.05	1.01749	1.013258	0.42
10	0.1	1.07457	1.07176	0.26
15	0.15	1.18921	1.184276	0.41
20	0.2	1.41421	1.414583	0.03

For Quad8 elements:

Table 3. Theoretical & Experimental values of SIF for Quad 8 elements

Crack Length'a' (mm)	Element Width 'a/100' (mm) Δ a	K_I Empirical Solution	K_I Computed from FEA	% of Error
5	0.05	1.01749	1.01656	0.09
10	0.1	1.07457	1.07258	0.18
15	0.15	1.18921	1.18625	0.25
20	0.2	1.41421	1.40629	0.56

The Stress intensity factors obtained by MVCCI approach through FEA solver and empirical approach for different stepwise infinitsimal increase in crack lengths is presented. From the results tabulated, it can be observed that the opening mode stress intensity factor increases proportionally with crack length. [10] SIF vs different crack lengths are plotted shown in Fig 14. From the comparison made in the plot, it is observed that the values of SIF obtained by Finite Element Analysis and empirical solutions are converging with less than one percent of deviation.

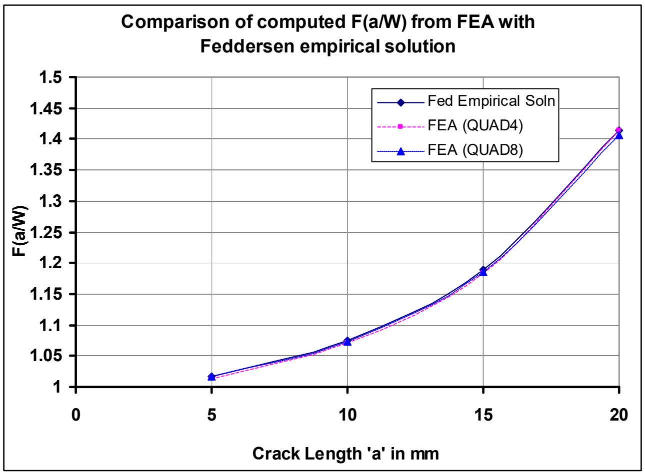


Figure 14. Comparison of SIF(K_I=F(a/w)) vs Crack length obtained from Analytical and experimental studies

5. CONCLUSIONS

A brief review of some of the methods, equations and criteria used for assessment of the structure has been presented. The damage tolerance evaluation for the structure by MVCCI technique is accomplished using the CAE tool MSC-NASTRAN/PATRAN.

The results obtained helps in setting the Damage Tolerance issues in the skin structures for the crucial aerospace components.

Hence the MVCCI methodology is valid to evaluate the fatigue and fracture problems by damage tolerance technique.

ACKNOWLEDGEMENT

I express my sincere gratitude to the engineers of Stress Analysis Team of Fatigue & Damage Tolerance group, Mahindra Satyam Bangalore and my friends Lokamanya Chikmath (Research Fellow, IIAEM) and Arun Sangam (Stress Engineer, Quest Global). I also thank my family and almighty for everything.

REFERENCES

[1] S.M.Beden et al.," Review of Fatigue Crack Propagation Models for Metallic Components", European Journal of Scientific Research ISSN 1450-216X Vol.28 No.3 (2009), pp.364-397.

[2] R.O. Ritchie," Mechanisms of fatigue-crack propagation in ductile and brittle solids", Materials Sciences Division, Lawrence Berkeley National Laboratory, and Department of Materials Science and Mineral Engineering, University of California, Berkeley, CA 94720-1760, U.S.A., International Journal of Fracture 100: 55–83, 1999.
[3] Robert.M. Engle, Jr.," Cracks, A Fortran iv Digital Computer Program for Crack Propagation Analysis ", Air Force Flight Dynamics Laboratory, Air Force Systems Command Wright-Patterson Air Force Base, Ohio.
[4] NASGRO 4.0 - Fracture Mechanics and Fatigue Crack Growth Analysis Software, Reference Manual, Version 4.02, September 2002, pp.44, Appendix-4.C3.
[5] E. F. Rybicki et al., "A finite element calculation of stress intensity factors by a modified crack closure integral", Engineering Fracture Mechanics, Vol. 9, pp. 931-938, 1977.
[6] Venkatesha B K et al.," Investigation of Fatigue Crack Growth Rate in Fuselage of Large Transport Aircraft using FEA Approach", Global Journal of Researches in Engineering ISSN: 2249-4596 Volume 14 Issue 1,2014.
[7] Surendran M et al.," Fracture Analysis of Structural Components with Multiple Site Damage – An overview", CSIR-Structural Engineering Research Centre, CSIR campus, Taramai, Chennai, India, Proc. of Int. Conf. on Structural and Civil Engineering 2012.
[8] Sukeerth D A, et al.," Damage Tolerance Evaluation for Wing Structure with Large Cutout ", International Journal Of Modern Engineering Research, Open Access.
[9] B.Dattaguru," Effect of Non-linear Behaviour of Joints on the Damage Tolerance Analysis in Aerospace Structures", Proc Indian Natn Sci Acad 79 No. 4 December 2013 Spl. Issue, Part A, pp. 553-562.
[10] Surendran M et al.," Stress Intensity Factors for Plates with Collinear and Non-Aligned Straight Cracks", International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering Vol:6, No:10, 2012.
[11] Ronald Krueger," The Virtual Crack Closure Technique: History, Approach and Applications", NASA/CR-2002-211628, ICASE Report No. 2002-10.
[12] Pietropoali Elisa," Virtual Crack Closure Technique and Finite Element Method for Predicting the Delamination Growth Initiation in Composite Structures", Advances in Composite Materials - Analysis of Natural and Man-Made Materials, ISBN 978-953-307-449-8.
[13] B. Dattaguru et al.," Overview of Aerospace Structures Research in India", 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference
17th
4 - 7 May 2009, Palm Springs, California, AIAA 2009-2931.
[14] G.S.Palani et al., "Numerically Integrated Modified Virtual Crack Closure Integral Technique for 2-D Crack Problems ", Structural Engineering and Mechanics, Vol. 18, No. 6 (2004) 731-744.
[15] Kiran Rao et al., S A Hakeem, K Badari Narayana, "Damage Tolerance Analysis of Aero Structural Components", Tata Consultancy Services Limited.
[16] P. M. S. T. de Castro et al., " Damage Tolerance of Aircraft Panels", Revista da Associação Portuguesa de Análise Experimental de Tensões ISSN 1646-7078.
[17] F. Carta et al.," Damage tolerance analysis of aircraft reinforced panels", F. Carta et alii, Frattura ed Integrità Strutturale, 16 (2011) 34-42; DOI: 10.3221/IGF-ESIS.16.04.
[18] ISSC Committee III.2: Fatigue And Fracture, 17th International Ship and Offshore Structures Congress, 16-21 August 2009, Seoul, Korea, Volume 1.
[19] J SCHIJVE. "Predictions on Fatigue Life and Crack Growth as an Engineering Problem. A State of the Art Survey", Fatigue 96, 1996.
[20] Srikanth et al., "Numerical Simulation and Fatigue Crack Growth Analysis of Through and Edge Cracked plates", IUP Journal of Mechanical Engineering/09746536, 20100201.
[21] E Orowan. "Fracture and strength of solids", Reports on Progress in Physics, 01/01/1949.

BIOGRAPHY

Mr. K.S.Vishwanath Vashishth is presently serving as Assistant Professor in the Department of Aerospace Engineering, ASET, Amity University Haryana. Prior to this served as Assistant Professor in the Department of Mechanical Engineering, Dronacharya College of Engineering, Gurgaon. Prior to that he was a Project Intern in the Stress Analysis Team of Fatigue & Damage Tolerance group at Mahindra Satyam (Mahindra Aerospace - Tech Mahindra), Bangalore, Karnataka.

He has participated in 4 International Conferences, 15 events of seminars, workshops and faculty development programmes.

Research interests include Fracture analysis of structures in mode1,
Proficient in MSC-PATRAN FEA solver and also certified by I.I.T. Kanpur for performing Flight lab experiments.

Has an earned Master of Technology in Aerospace Engineering - Aerospace Structures from Jain University and Bachelor's degree in Electrical & Electronics Engineering from VTU, Karnataka and professionally certified in a course titled "Advanced Diploma in Embedded Software Engineering" from ISM, Bangalore.