Computer Simulation to Assist the Life Assessment and Life Extension of Ageing Air Crafts

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Abstract

The emphasis on the remaining life assessment and life extension of ageing air craft is linked to the aspects of reliability, safety and performance. This is closely linked to two major technical streams: 1) an accurate assessment of the current status of the air craft components and systems, and 2) a robust mechanism to predict the remaining "cycles to fail" of the same. By adopting the latest developments in testing techniques, fracture mechanics and non-linear finite element methods, it is now possible to make more accurate prediction of the remaining life of air craft systems. Further, by the same techniques, it is also possible to assess the impact of remedial measures such as conventional or laser shot peening on the life extension.

This multi disciplinary activity calls for several agencies to work in tandem. Good deal of investments are required in terms of capacity building, training, technology absorption schemes for personnel from various entities involved in the life extension for ageing air crafts in India.

ProSIM and its technology partners in UK and USA are involved in the life extension programs. ProSIM engineers and its resource persons have worked earlier on projects related US Air Force, Rolls Royce, GE, SNECMA and have a good multidisciplinary background of materials, design, FEM, and fracture mechanics. ProSIM can contribute significantly to the efforts of Indian Air Force in its pursuit of extending the life of existing air crafts.

1. Introduction

Today, we have a large fleet of ageing aircraft, mainly from the Russian origin. The cost of replacement of spares and the cost of induction of new fleet is steeply increasing. There is, hence the need for adopting the technologies for the remaining life assessment and implementing the technologies for life extension. These two technologies include testing and evaluation techniques, and computer simulation techniques.

Today, globally there is a big pool of expertise is available in the life extension strategies applied to a variety of sectors including in nuclear reactors, pressure vessels, piping structures apart from the air crafts. For the sake of simplicity, we present this paper in three parts viz., 1) typical work flow involved in the life estimation, 2) a brief overview of NDE techniques and 3) brief description of application of computer simulation (FEM) techniques for crack growth, stress concentration estimation and estimation of cycles to failure.

1.1 Typical work flow for estimation of remaining life and life extension

Firstly, a methodology of applying the fatigue and fracture mechanics to the life extension system has to be developed. This has 3 stages:

a) R&D stage – development of computer simulation models
b) Testing, validation Fine tuning of model and
c) Application of model for the given component system / types.

In the R&D stage, significant time, effort and expert resources have to be deployed. Delivery mechanisms have to be clearly defined. Mission type approach has to be built into the projects. Below is a sequence of activities for the R&D stage of life extension program.

a) **Definition of the project**: A component system has to be identified. The data available from field records, service manuals have to be collated. The project has to be framed with clear deliverables and stages. Here the difficulty will be to decipher the data from the service manuals and make it amenable to the FEM system. Care to be taken in the definition of the operating and loading conditions in a manner which can be incorporated to the FEM procedures. This calls for very close interaction between the engineers at the maintenance command, BRDs, service providers (such as ProSIM), RCMA, and CAMILAC.
b) **Testing of current condition of the component / system**: An evaluation of the current condition by suitable NDE techniques is essential. This will also call for an analysis of the data collected during the service overhauls. The testing should indicate the extent of degradation of the component due to service life utilized.
c) **Reverse Engineering and 3D model generation**: A 3D CAD model is essential for any FEM analysis. As the design data and drawings for the components and systems are not available, the same has to be generated by the reverse engineering. Here the CAD model of entire assembly /system has to be generated. This will be essential to get the loading conditions specified to the FEM preprocessor.
d) **Material Property Data generation:** Appropriate material property data will have to be generated. These include the stress-strain behavior, the SN Curves at operating temperatures, and other fracture mechanics properties, creep data. Other temperature dependent thermo-mechanical property data are also required. There are techniques available to use minimum number of testing experiments and use very little quantity of material for testing. Miniature test coupons are routinely used now in material testing and extrapolate the data to bulk properties.
e) **FEM Analysis of the system to extrapolate the loads on component chosen:** This stage gives an estimation of loads, stresses, deflections and strains. This stage will generate the data that can be used for calculation of crack formation and propagation parameters. This stage will also indicate the probable location of the

cracks (crack nucleation sites), which are deciphered by an analysis of stress concentration factors, shear stress and tensile principle stress planes.

f) **Estimation of Crack Propagation: Fatigue and Fracture Analysis:** Here the stresses and loads will be applied to predict the life of the component under normal circumstances of operation. The crack growth kinetics and the failure assessment are established. In this stage, the cycles to fail of a given system are predicted. The effects of residual stresses, residual plastic deformation (due to hysteresis), creep-fatigue interaction etc., are incorporated.

g) **Life Extension:** In this stage suitable measures to enhance the life are adopted. Before the scheme is implemented, the procedures (such as hole expansion, laser shot peening) can be simulated on computer to obtain the strain paths and residual stresses. The resultant net stresses can be taken into account to verify the suitability of the procedure for life extension. Further, the life to fail after the procedure for life extension can be assessed by computer simulation.

2. Establishing the present condition of the component:

For evaluation of the residual life of a component, studying and establishing the present condition of a component is the most critical one. The frequency of inspection of specific components will be controlled by the kinetics of crack growth, which in turn, depends on material/structure behavior and actual service conditions including:

a). Examining and locating any cracks, dents, flaws present in the component
b). Determine the size, shape and direction of flaws
c). Examine for effect of corrosion, plasticity etc.

All these require sophisticated NDT and measuring techniques. Following are some of the NDT techniques for the detection of crack.

2.1 Magnetic Particle Inspection:

The part to be tested is magnetized. Finely milled iron particles coated with a dye pigment are then applied to the specimen. These particles are attracted to magnetic flux leakage fields and will cluster to form an indication directly over the discontinuity. This indication can be visually detected under proper lighting conditions. A schematic is shown in figure 1[1]. Figure 2 shows a component to be tested. Figure 3 shows a crack detected.

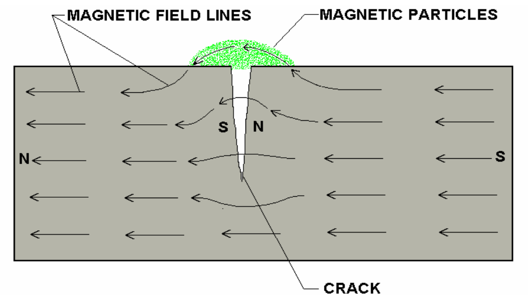


Figure 1: Magnetic inspection

Figure 2**:** Component to be inspected

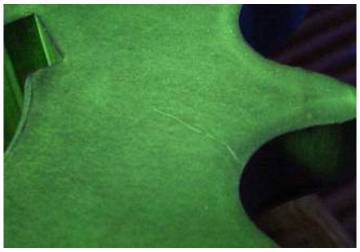


Figure 3**:** After inspection

2.2 Eddy current testing:

Eddy current testing is particularly well suited for detecting surface cracks. Here a small surface probe is scanned over the part surface in an attempt to detect a crack. Schematic is shown in figure 4[1].

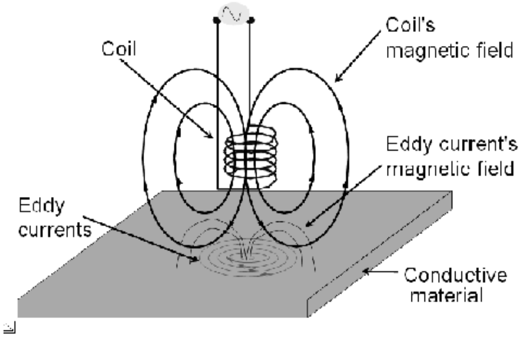


Figure 4**:** Eddy current testing method

2.3 Ultrasonic Inspection (Pulse-Echo)

High frequency sound waves are introduced into a material and they are reflected back from surfaces or flaws. Reflected sound energy is displayed versus time, and inspector can visualize a cross section of the specimen showing the depth of features that reflect sound. Figure 5[1] shows the ultrasonic inspection technique.

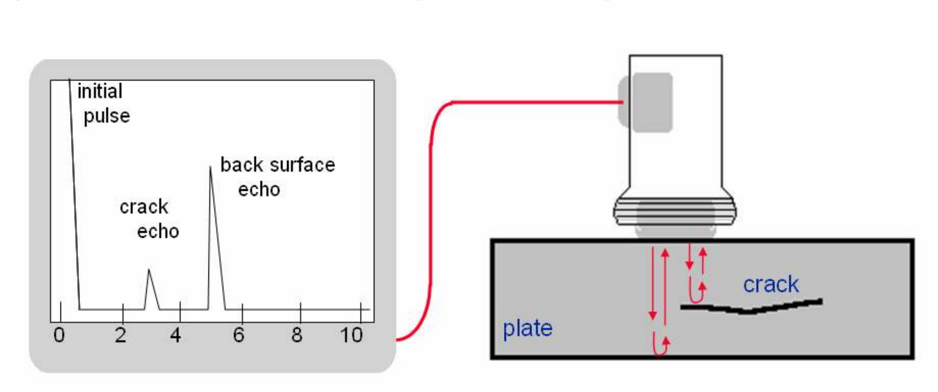


Figure 5**:** Ultra sonic inspection method

3. Fatigue [2]:

When a component is subjected to variable loading stress, based on the structural changes that occur in the component, the fatigue process is divided into the following stages.

1. Crack initiation-includes the early development of fatigue damage which can be removed by suitable thermal annealing.
2. Slip band crack growth-involves the deepening of the initial crack on planes parallel to plane of high shear stress.
3. Crack growth on plane of high tensile stress-involves growth of well defined crack in direction normal to maximum tensile stress.
4. Ultimate ductile failure-occurs when the crack reaches sufficient length so that the remaining cross section cannot support the applied load

4. Failure assessment of the component by Finite Element Method:

There are many commercial FEM packages are available in the market for the failure assessment of the structure by fatigue crack growth.

ZENCRACK is a fracture mechanics tool that uses the FEM, to predict 3D crack propagation. ZENCRACK is capable of using J-integral or displacement based results for calculating fracture mechanics parameter.

5. Case Study 1[3]:

5.1. Comparison of FEM predicted crack growth with and experimental crack growth

In this case study, FEM simulation has been carried out for the following component shown in figure 6. FEM results are compared with the actual result from the experiment of the component [13]. The prediction of crack growth by using ZENCRACK is matching with the actual condition reported in literature by other research workers.

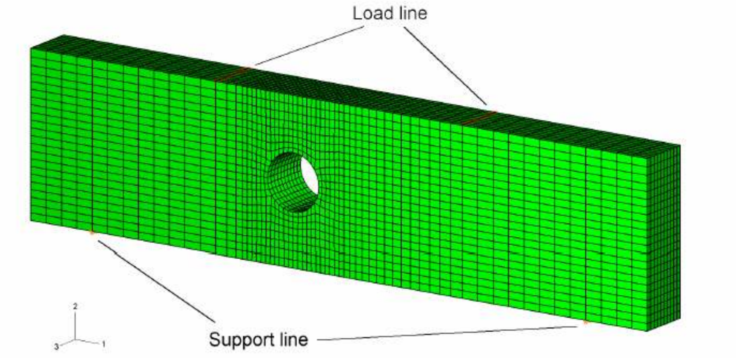


Figure 6: Meshed model

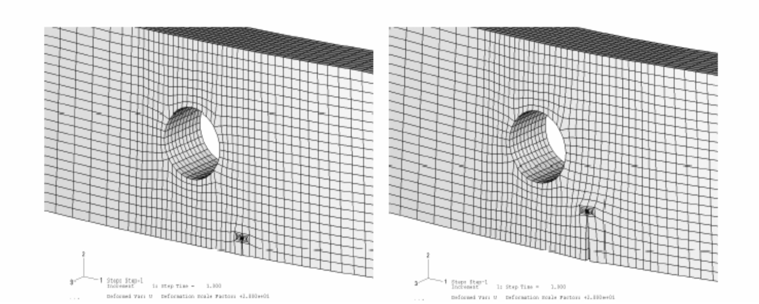
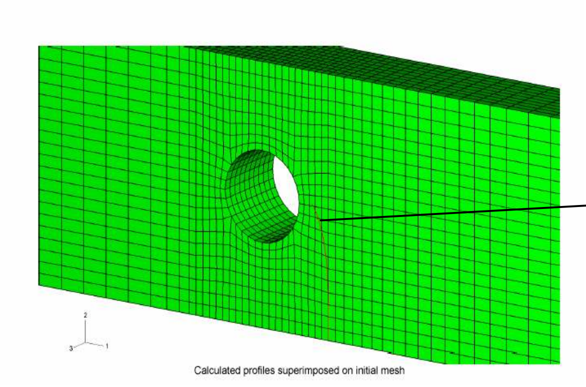


Figure 7: Progress of Crack growth predicted in FEM



Calculated
profile of the
crack growth

Figure 8: Calculated crack growth profile

Following figure 9 shows the comparison between the ZENCRACK crack prediction and experimental crack growth. It is seen that FEM results from ZENCRACK are matching with the experimental results. The theory of crack propagation, fracture and failure in ZENCRACK is rigorously developed and tested. It is being used for lifing studies all over the world. A detailed description of the theory is beyond the scope of this paper. It is intended to give a broad overview in this paper.

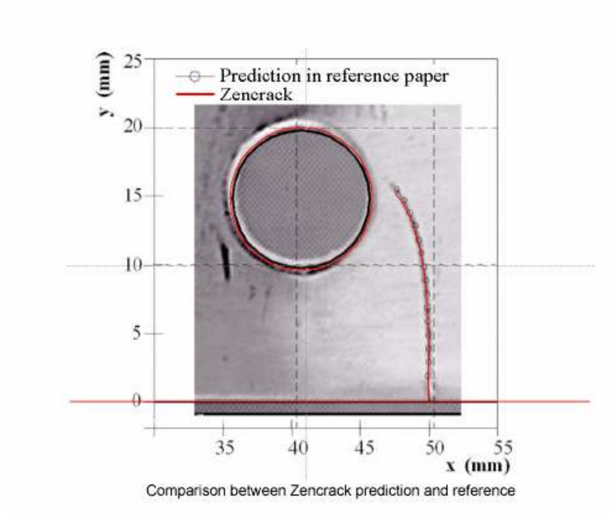


Figure 9: Comparison of results of FEM predictions by Zencrack and Esperiments[13].

6: Case Study 2[4]: Generation of Failure Assessment Diagram (FAD) using ZENCRACK.

6.1 Generic Procedure to create a FAD

a) Undertake a linear elastic FEA and determine the J-Integral values, Jelas
b) Undertake a plastic FEA and determine the J-Integral values, Jtotal=Jelas+Jplas
c) Determine the reference load of plastic collapse (Pref)
d) Draw the failure assessment diagram using points (Kr,Lr):
    Kr = (Jelas/Jtotal)½
    Lr = P / Pref
e) Draw the vertical cut-off. Depends on the material property.
    For some materials:
    Lr(max) = flow stress / yield stress
f) Assess a point on the FAD (to know if it is safe and acceptable or not)

The procedure for assessing the acceptability of any given crack size is to calculate the parameters Lr and Kr. The point representing the coordinates (K_r ,L_r) is plotted on the appropriate assessment diagram. If this point lies inside the assessment diagram, the crack is considered safe, whereas if it lies outside the curve, the crack is considered unsafe.

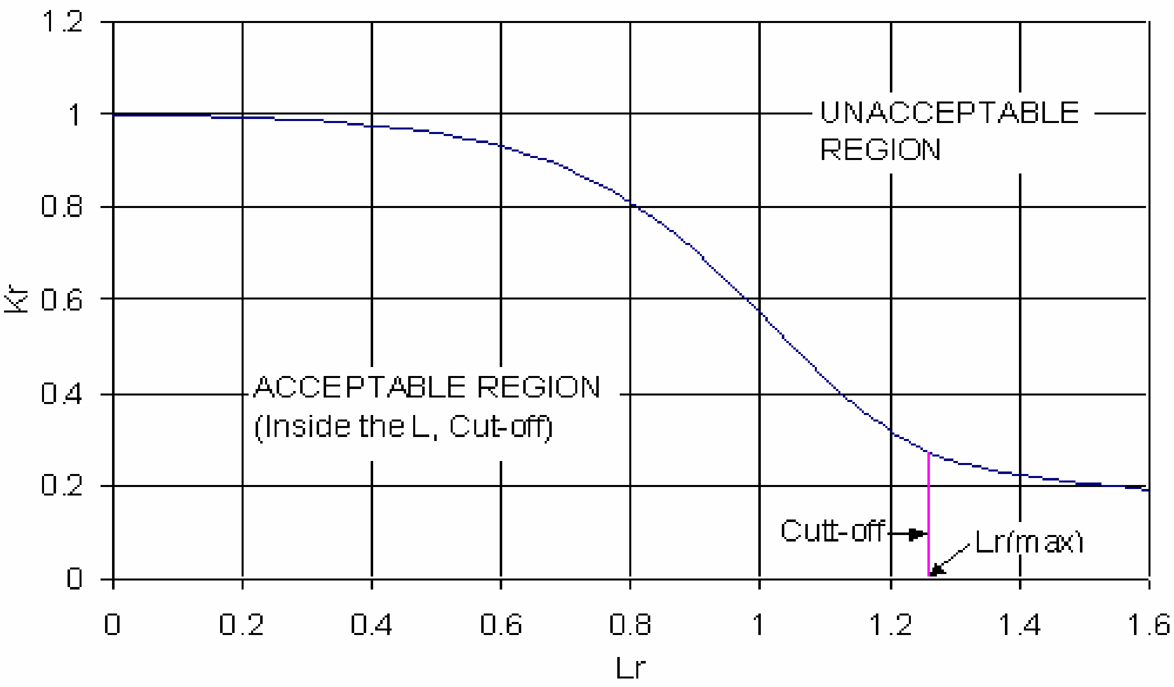


Figure 10: Failure assessment diagram (FAD)

6.2. Obtaining P_{ref}

$$\left.\frac{J_{total}}{J_{elastic}}\right|_{P=P_{ref}} = 1+\frac{0.002E_y}{\sigma_{ys}}+\frac{1}{2}\left(1+\frac{0.002E_y}{\sigma_{ys}}\right)^{-1} \quad (1)$$

where,

E_y = Modulus of Elasticity (MPa:psi),

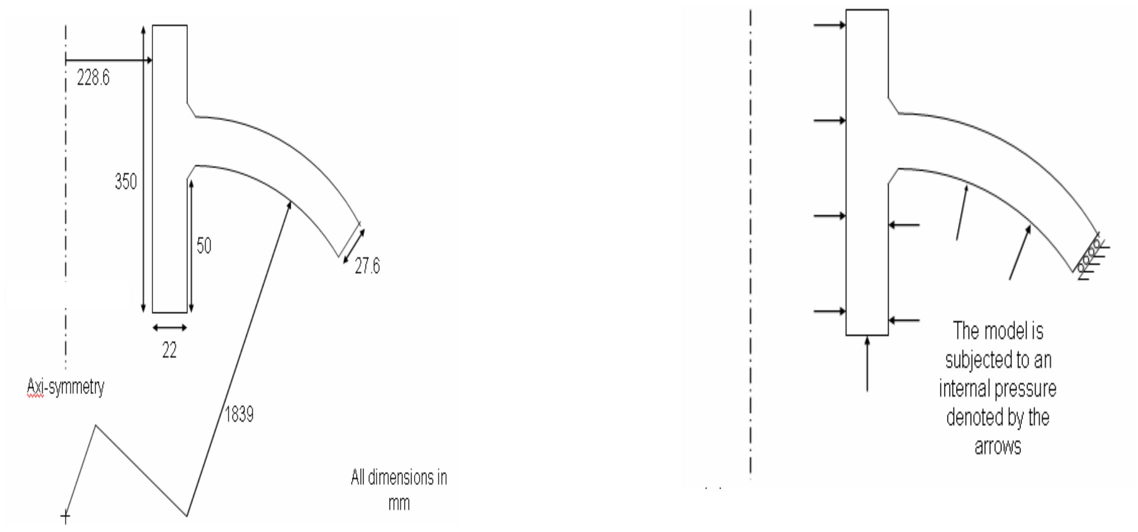
P = Characteristic applied load (or stress) such as internal pressure, axial force, bending moment or a combination thereof,

P_{ref} = Reference load (or stress) defined as the load at which the ratio $J_{total}/J_{elastic}$ reaches the value defined by Equation (1) and

σ_{ys} = 0.2% offset yield strength (MPa:psi).

6.3. Axi-symmetric model is used for the life assessment

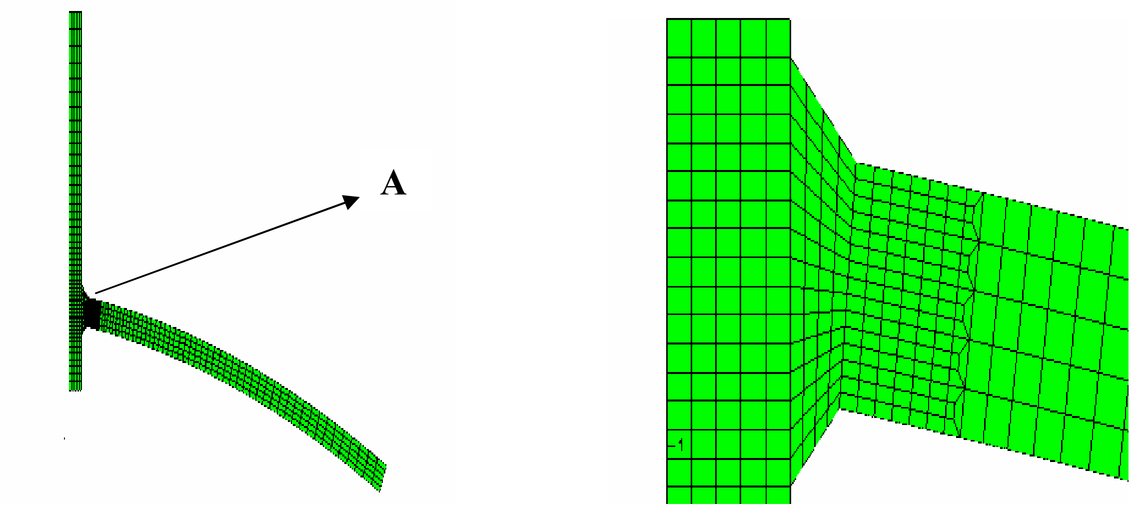
The model used for the analysis is an axi-symmetric structure which is subjected to internal pressure. The details of loading and boundary conditions are as shown in the following figure 11.



Dimensioning of the model

Boundary and loading conditions

Figure 11. Component for generating failure assessment diagram



Meshed model

Enlarged region of mesh

Figure 12 Meshed FEM model and enlarged view.

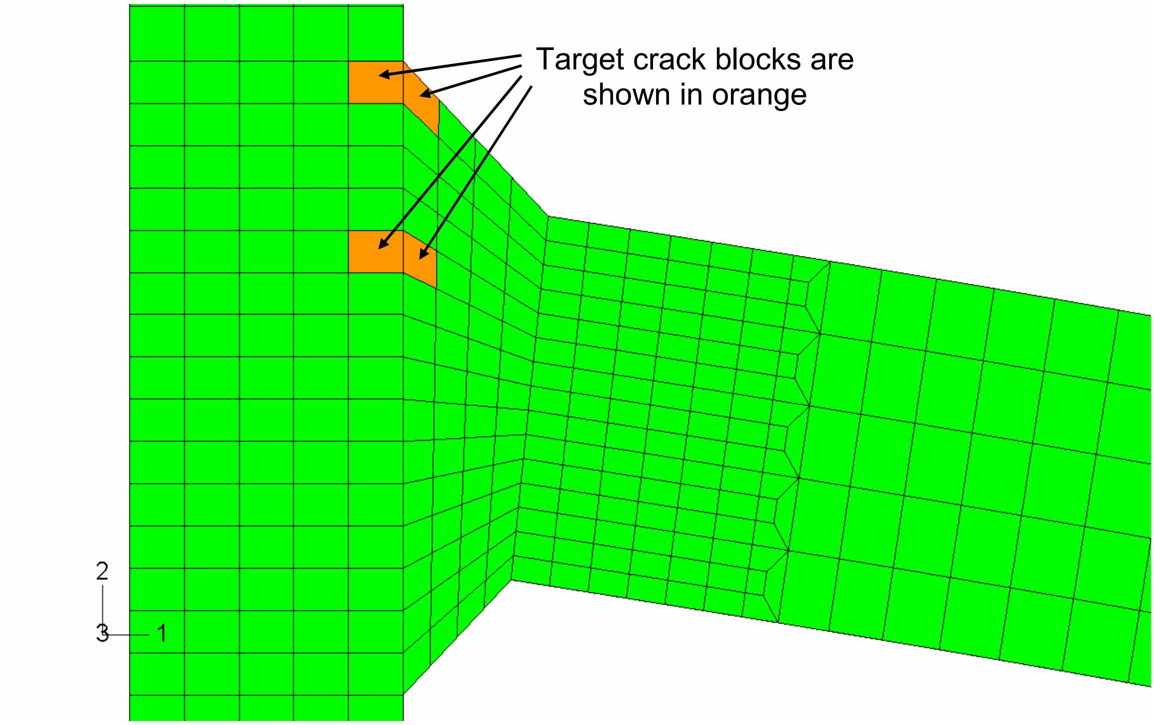


Figure13: Un cracked model – Area of defect

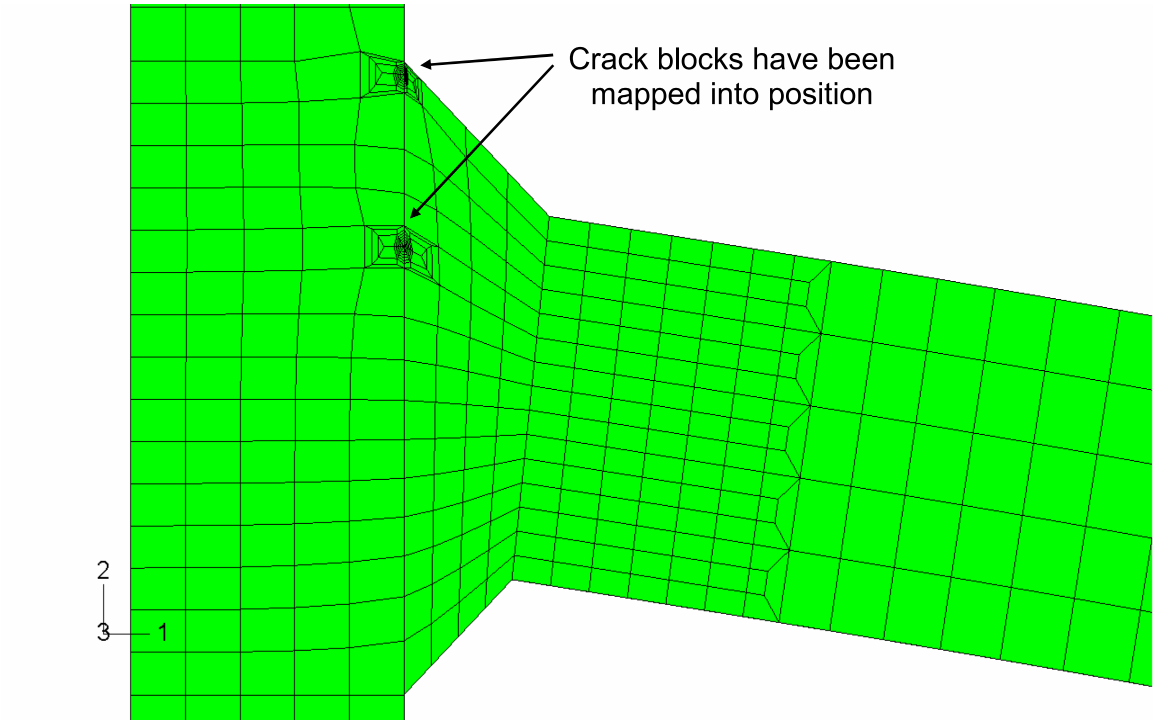


Figure14: Cracked model – Area of defect

Contour plots for maximum principal stress and maximum principal strain at crank front 1 (CF1) and crank front 2 (CF2) are plotted as shown in figure 15 and figure 16. We can see from the contour plots, the stress and strain in the crack front 1 is higher compared to crack front 2.

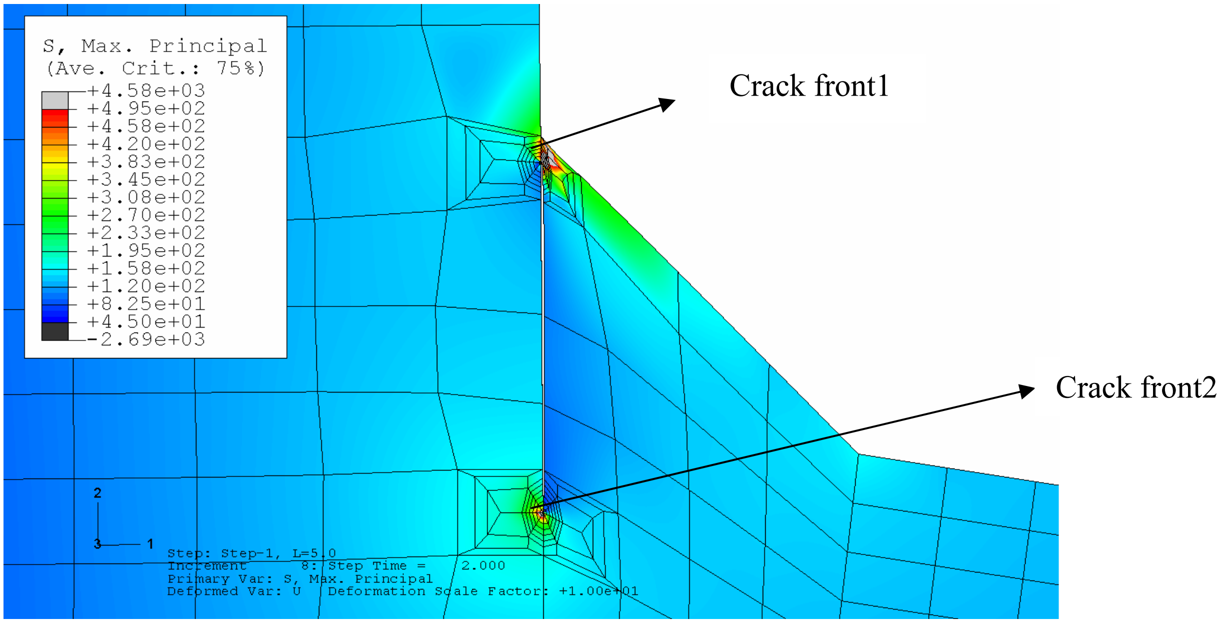


Figure 15: Maximum principal stress

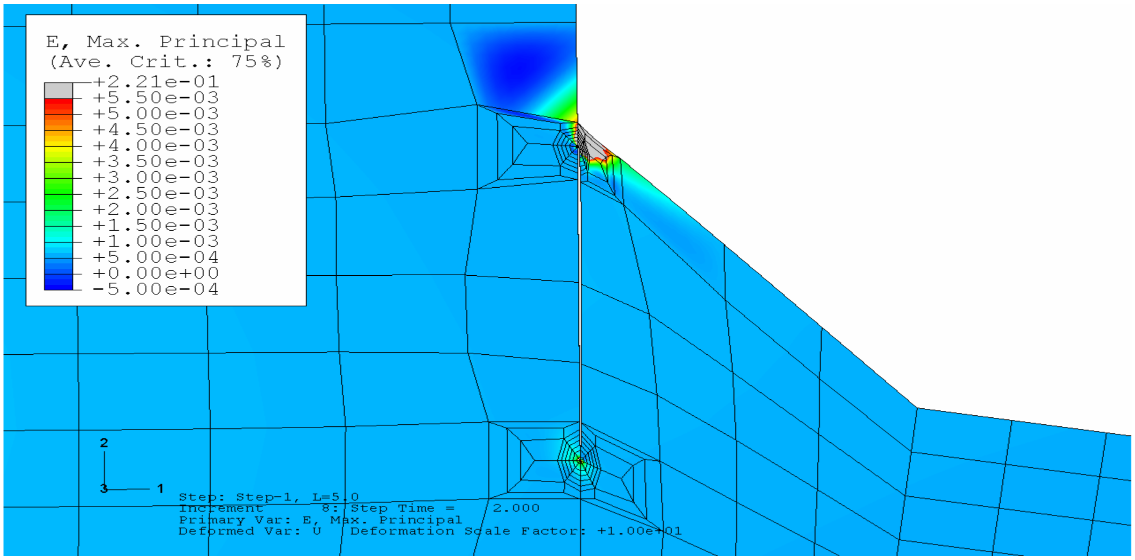


Figure 16: Maximum principal strain

After running the simulation, the energy release rates in the crack front region1 and crack front region 2 are plotted as shown in the figure 17. From graph we can observe that that energy release rate in crack front region1 is more compared to crack front region 2.

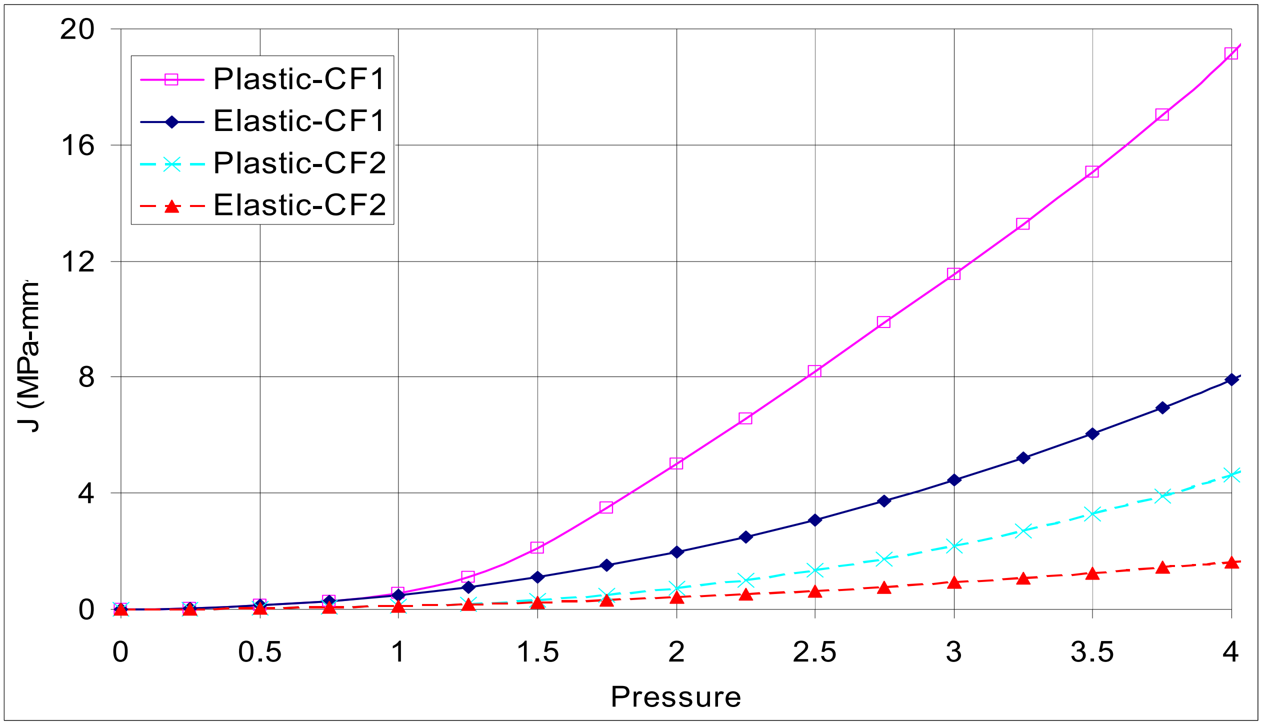


Figure 17: Energy release rates

Graph is plotted for Jela/Jtotal for the pressure in the crack front region 1 and in Crack front region 2.

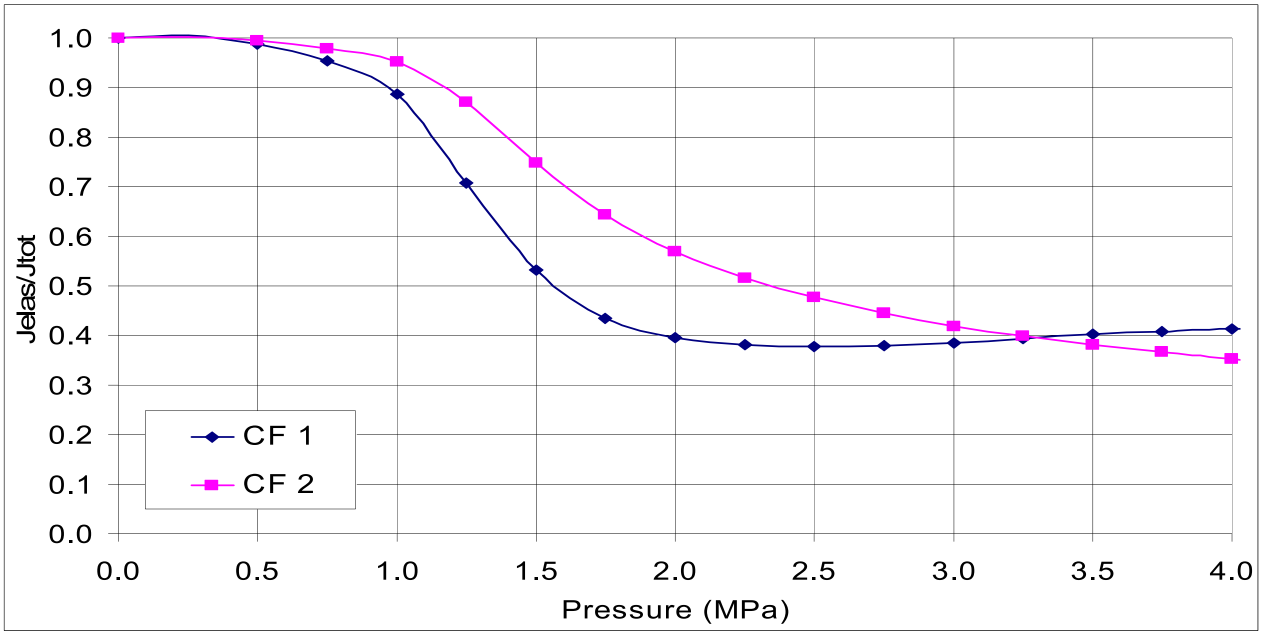


Figure 18: Jelas/Jtotal

6.4. FAD (using equation 1)

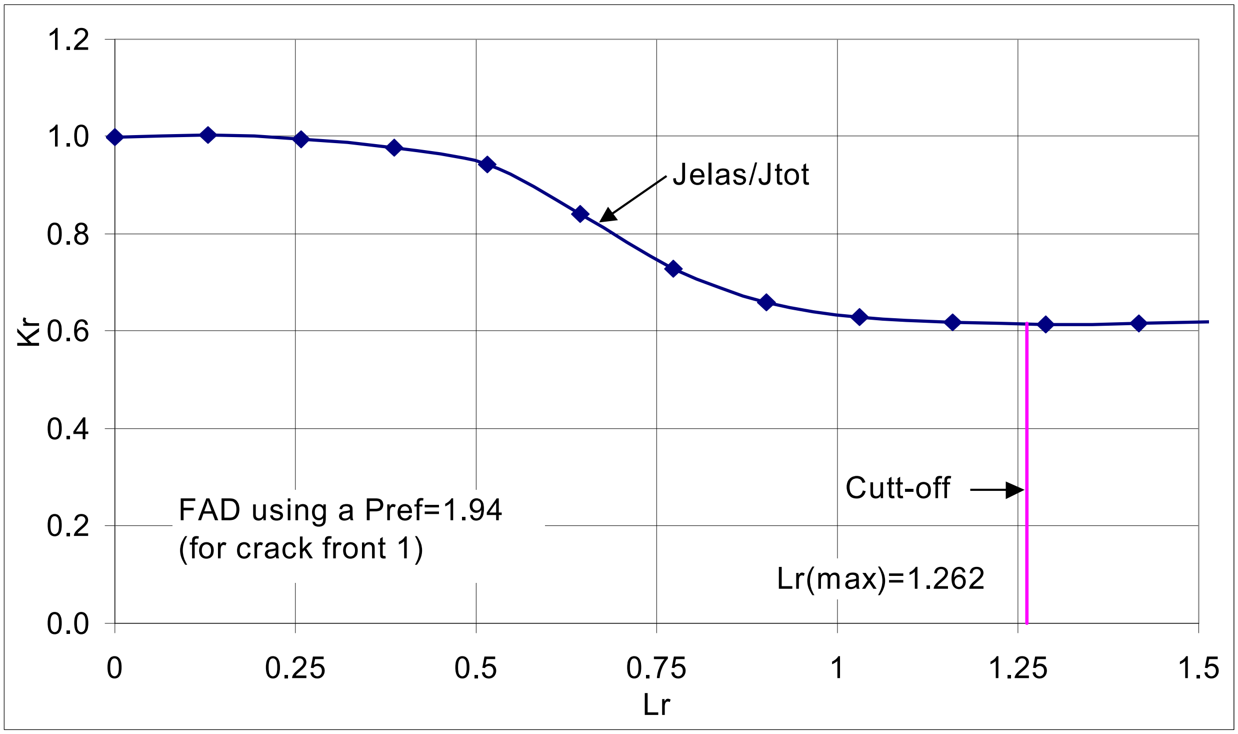


Figure 19: Failure assessment diagram

7. Issues in numerical modeling of crack growth prediction:

Any crack growth analysis must be based on the calculation and use of the fracture mechanics parameters. Such parameters encapsulate and describe the local effect of the crack on a component.

Having evaluated fracture parameters for particular crack in a component under a given load, the next task is to convert that information into crack growth. This requires the knowledge of the load history and appropriate material crack growth data. In most of the cases this will be fatigue based cyclic loading .growth is calculated over a number of load cycles or an elapsed time respectively.

The difficulty imposed by real-life problems are further compounded by the complex 3D geometries that are involved. Further complications may be introduced from a variety of sources including residual stress effects, propagation along dissimilar material interface and propagation in non-metallic materials or metal which are non-homogeneous, anisotropic materials.

A critical issue that must be addressed in 3D FE fracture mechanics analysis is that of mesh generation. Component geometries are complex and time consuming to model in the uncracked forms. Defects often occur at geometrically difficult locations e.g. welds, chamfers etc. Initial crack size of correct size and shape must be inserted into the component at the correct location in the FEM model. The modeling will become much more complicated if the structure is having multiple cracks.

8. Material details:

In any numerical modeling technique, assigning proper material properties is very important factor. If the material properties are not correctly given, the solution we get will be wrong. Material properties have to be obtained by conducting experiments under different loading conditions. Details about metallurgical properties of original material and effect of aging, temperature, creep and fatigue are required. A complete description of the data to be generated and the testing processes is beyond the scope of this paper. Reader is suggested to look to reference[14] for further details.

9. Life extension methods:

Ultimate failure occurs when the crack reaches critical size, when the structure cannot support the applied load. Practically all fatigue failures start at the surface for many common types of loading like bending and torsion.

Since fatigue failure is dependent on the condition of the surface, anything that changes the quality of the surface will greatly alter the fatigue life. Extending the fatigue life of an existing crack is done by strengthening methods and repair methods. Techniques like shot peening, heat treatment, clamping and repair welding are adopted. The effect of these can be incorporated in the FEM models and qualitatively assessed for their effect.

10. Surface Modification methods and Fatigue [5]:

Fatigue cracks initiate at free surface, surface treatments can be significant. There are different methods of surface treatment to reduce enhance the fatigue properties.

10.1 Surface treatment –thermal

Various heat treatments like nitriding, carburizing can produce higher strength at the surface which significantly increase fatigue strength. Following table 1[3] gives brief idea about how surface treatment can improve the fatigue strength.

Endurence limit(ksi)		
Geometry	Nitriding	Not nitrided
without notch	90	45
half –circle notch	87	25
V notch	80	24

Table 1: Effect of nitriding on endurance limit

10.2 Surface treatment-mechanical: Shot peening:

The shot peening is hammering technique with a spherical shot which aim is to create a residual stresses on the surface of metal. This improves resistance to fatigue.

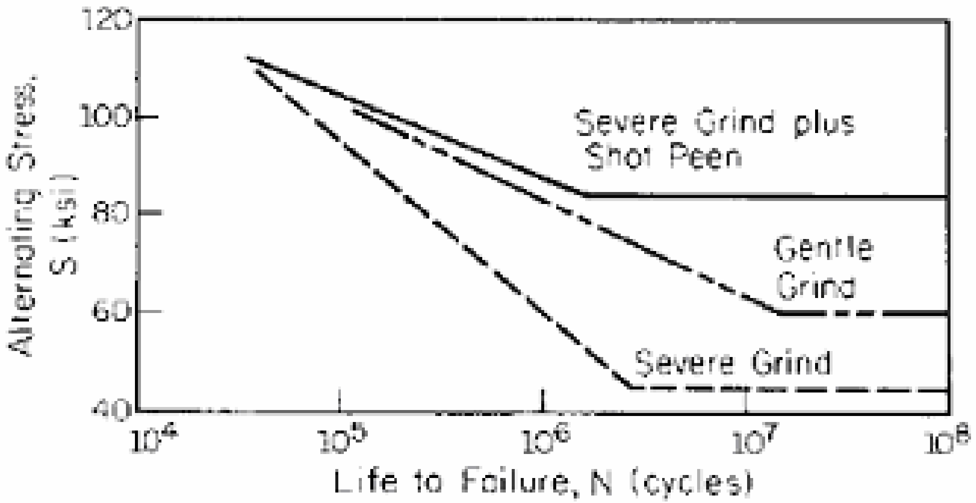


Figure20: Comparison of SN curves for different treatment conditions

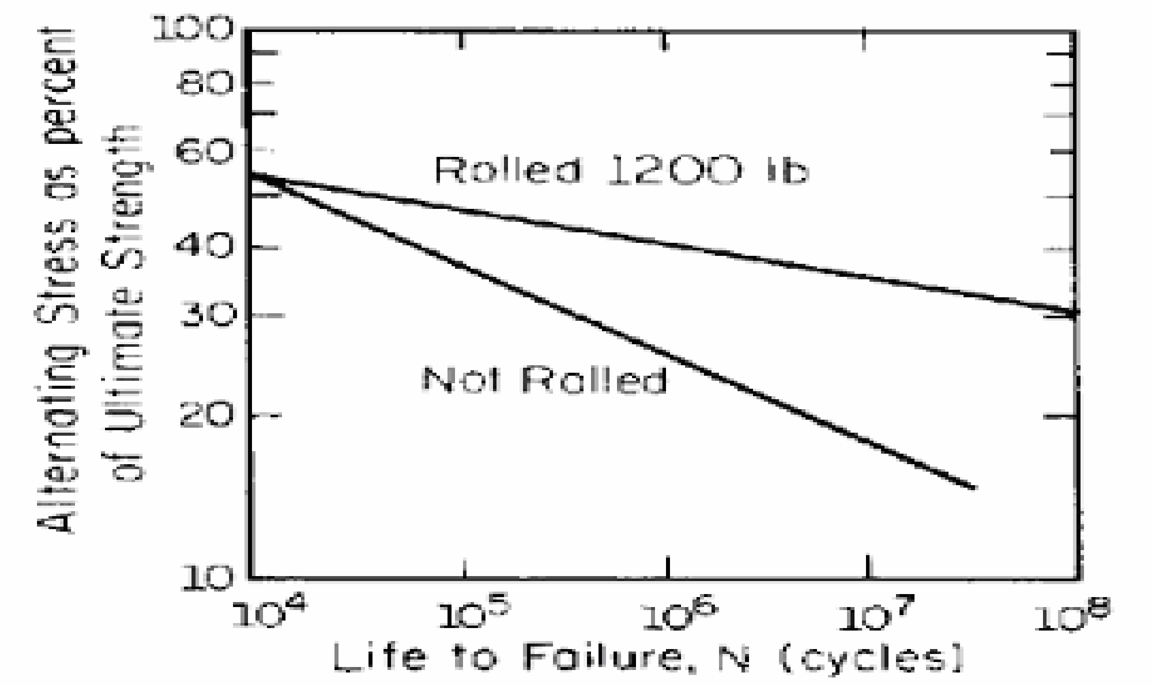


Figure21: Cold rolling surface treatment technique

11. Fatigue design guideline:

1. Consider fabrication method, specify strict requirement when needed
2. Choose proper surface finishes, but not overly severe
3. Provide suitable protection against corrosion
4. Consider pre-stressing when feasible, to include shot peening and cold working
5. Consider maintenance, to include inspection, and protection against corrosion, wear, overheating.
6. Consider temperature effect.

12. Conclusion:

ProSIM R&D Center has the expertise, infrastructure, and the network with academic and research laboratories in India and abroad. ProSIM is involved in the life extension projects. Application of FEM based simulation of crack formation, propagation is a key component of the life assessment strategy. In this papers authors have shown a validated crack propagation model and a methodology to generate the failure assessment diagrams.

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