Thermo-Mechanical Fatigue Analysis of a Stationary Jet Engine Component

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Motivation

- Jet engines work in highly transient conditions due to frequent and sharp maneuvers.
- Hence, the engine components are subjected to constantly changing temperatures and forces.
- In such hazardous and complex conditions, the components may fail in service. Thus, life assessment is a must.

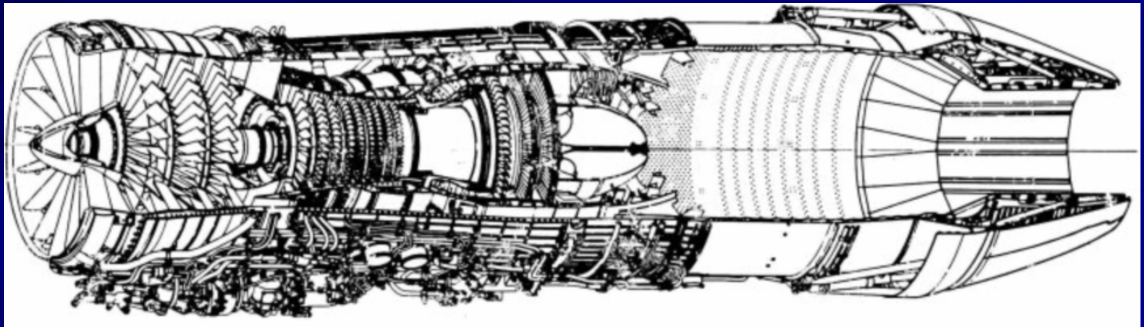
- The objective of this work is to assess thermo-mechanical fatigue life of a stationary component of a F110-GE-100 engine

Outline

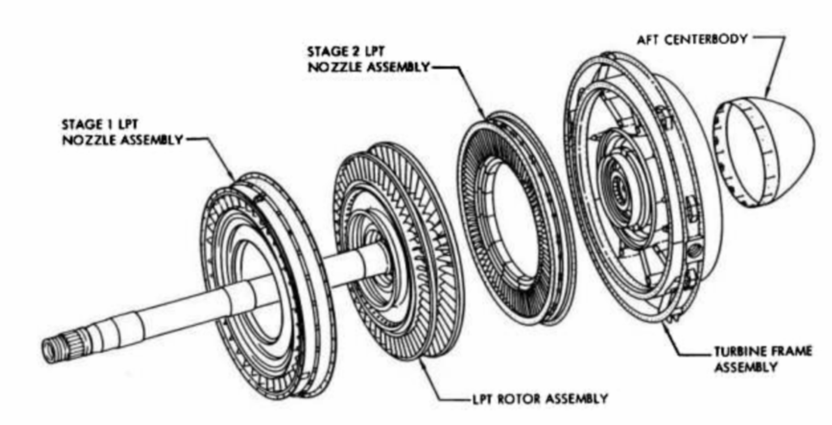
- The Engine
- Thermal Analysis
- Stress Analysis
- Fatigue Life Prediction
- Creep Life Prediction
- TMF Life Prediction
- Summary

The Engine

- The F110-GE-100 engine is an augmented, mixed-flow, turbofan engine. It consists of a high pressure system, a low pressure system and a variable area exhaust nozzle.

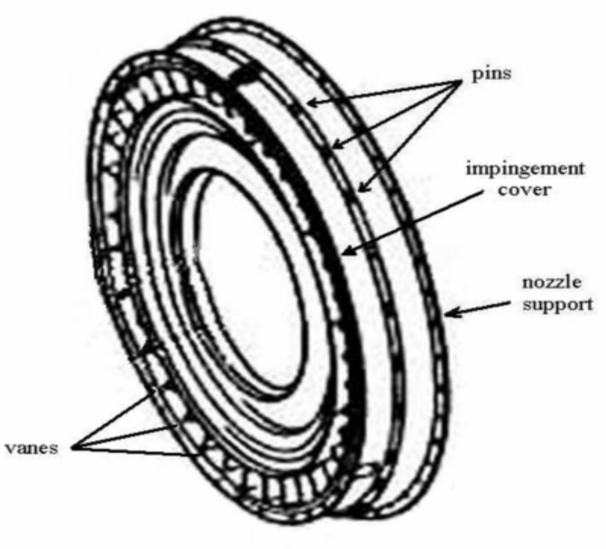


- The region of interest: First stage low pressure turbine (LPT)

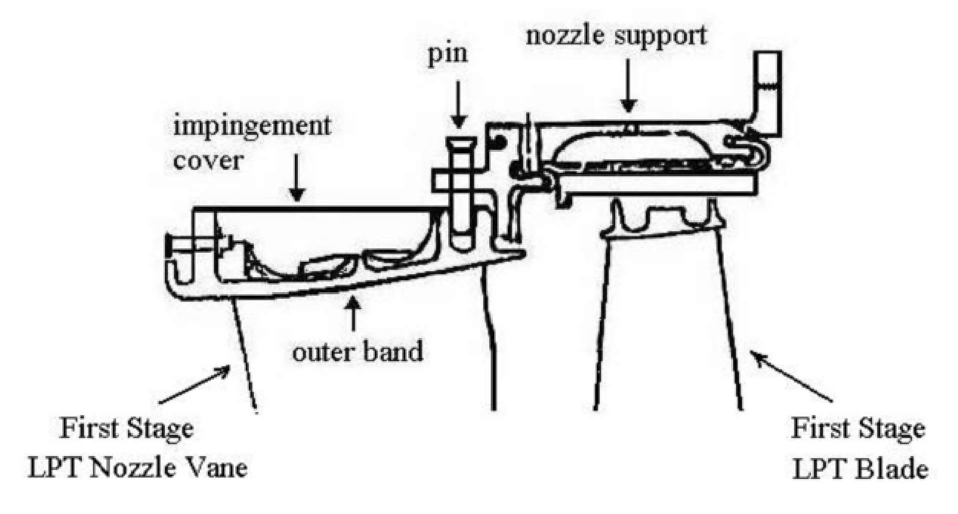


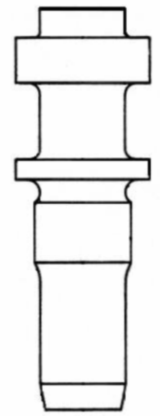
LPT TURBINE FRAME ASSEMBLY

The Region of Interest



FIRST STAGE LPT STATOR





The Pin

Practical experience shows that these pins are critical components whose failure may have serious consequences.

Failure Mechanisms

- Low Cycle Fatigue (LCF)
- High Cycle Fatigue (HCF)
- Thermo-Mechanical Fatigue (TMF)
- Creep
- Corrosion
- Erosion
- Fretting
- Wear

- Analysis of failure mechanisms requires detailed knowledge of stress and temperature fields throughout a mission.

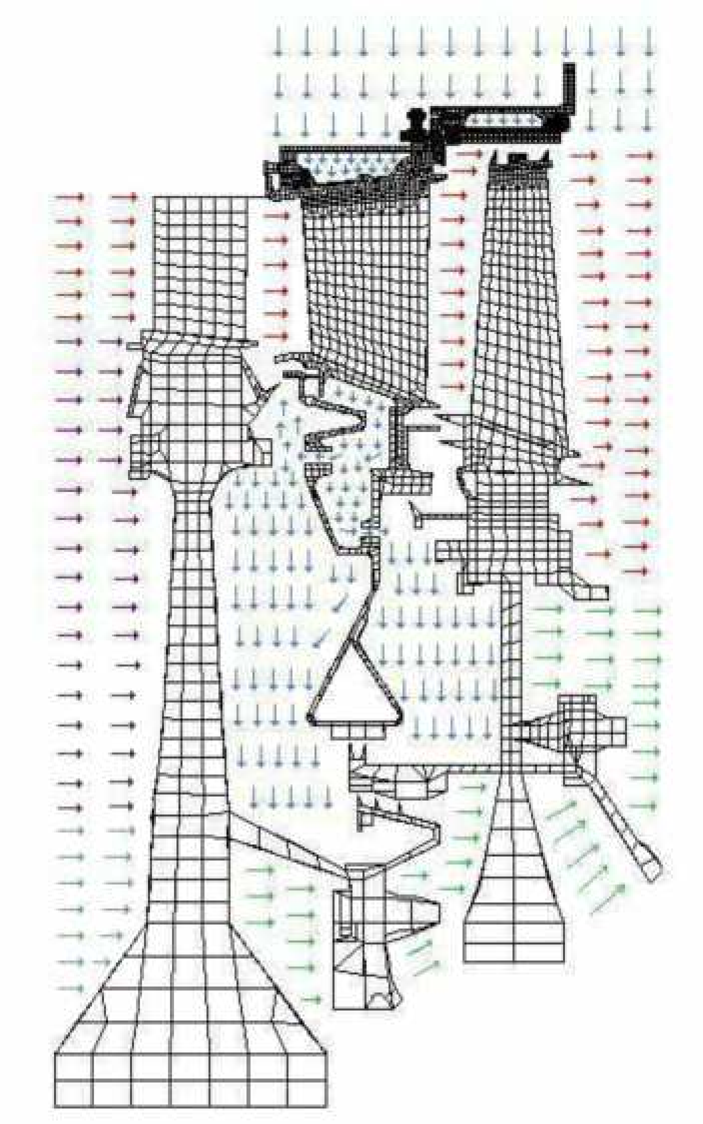
Thermal Analysis

- To obtain temperature history of the engine components at each phase of a given mission.

- Thermal model uses
  - mission profile
  - gas stream and cooling air temperatures
  - gas stream and cooling air velocities (convection)

- Convective velocities are calculated from the given
  - mass flow rates, static and total pressures and temperature

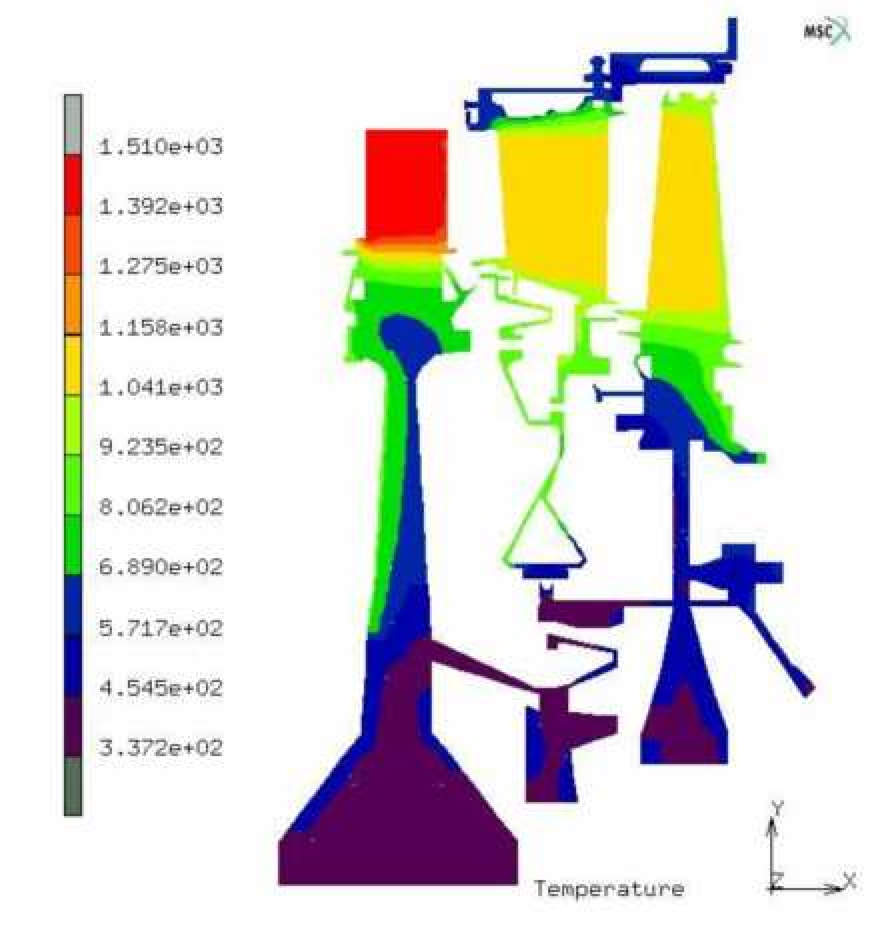
Using
  - continuity eqn.
  - Isentropic relations



Msc MARC is used as FEA solver.

Thermal Analysis Results

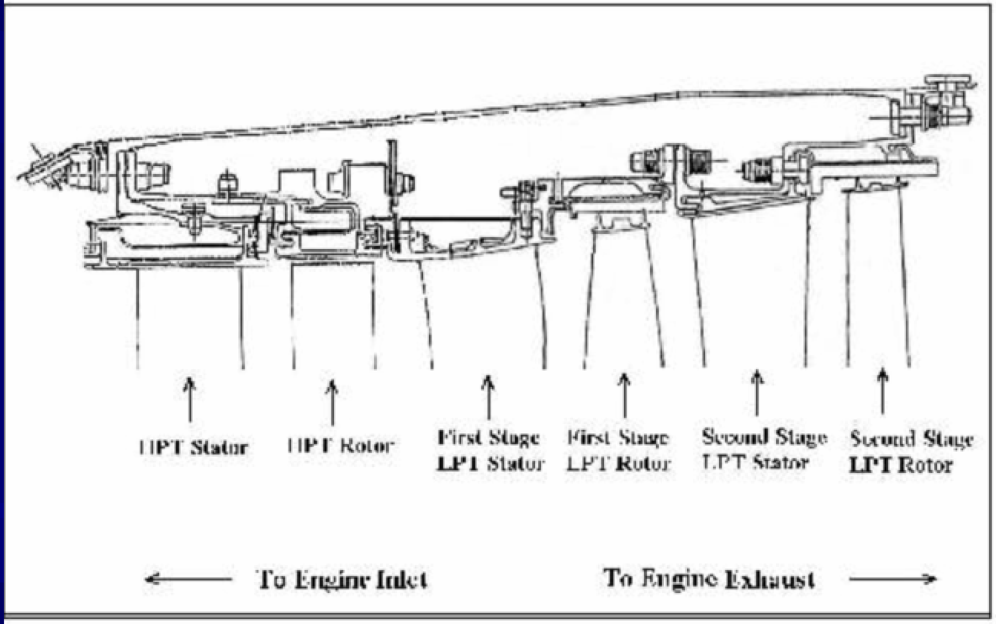
- Temperature distributions obtained from thermal analysis will be used in
  - stress analysis (thermal stresses)
  - creep damage assessment

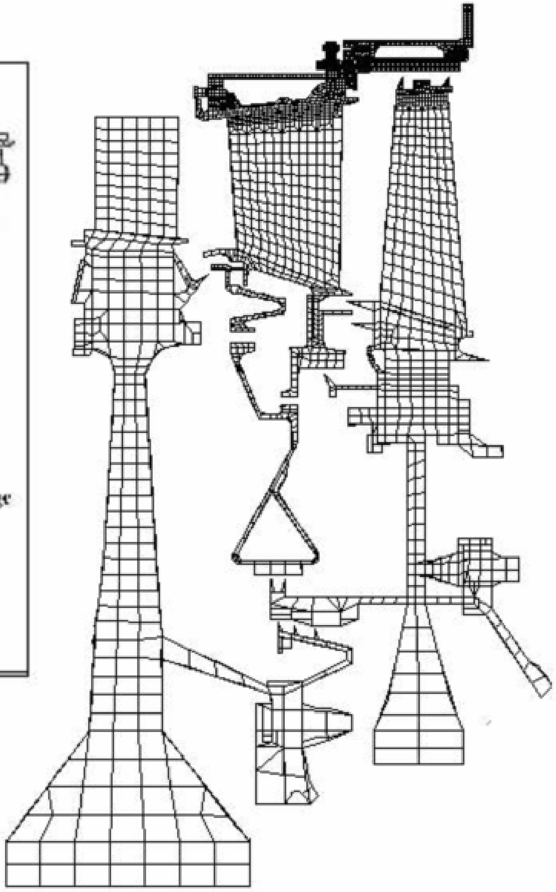


Temperatures are in Kelvin

Stress Analysis

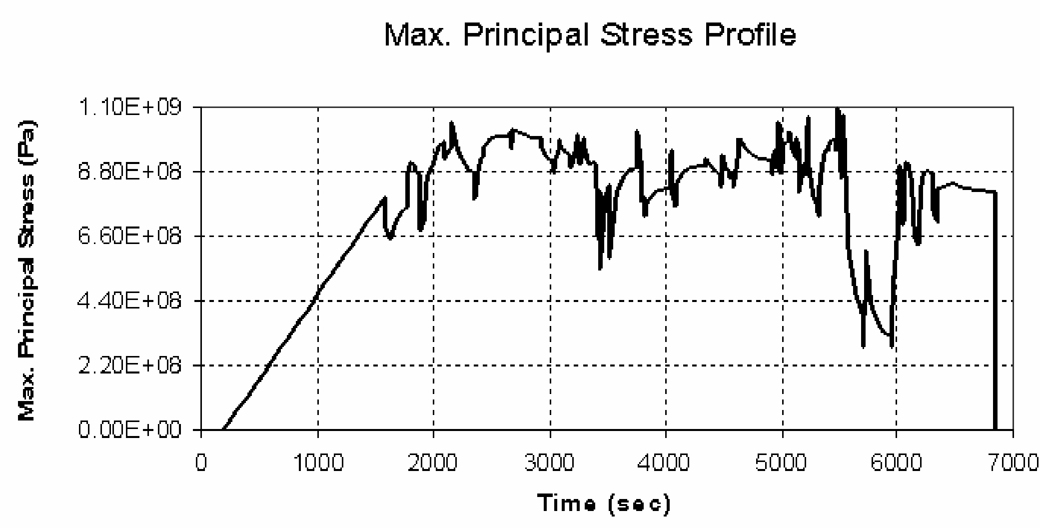
- Applied loading : Gas pressures (total pressure) and temperature
- The same mesh is used in both heat transfer and stress analysis.



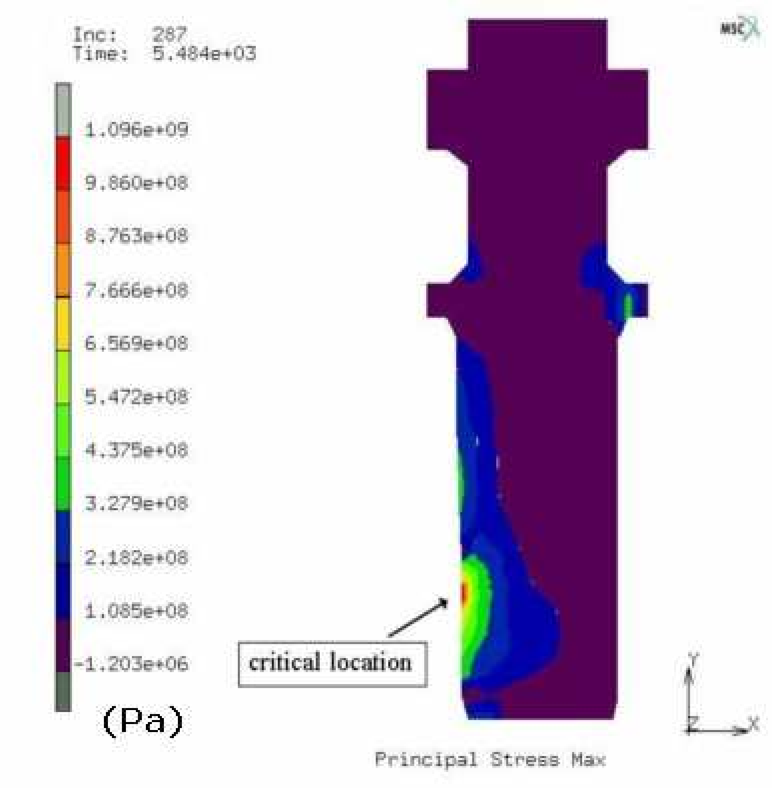


Boundary conditions

Stress Analysis Results



stress history at the critical location



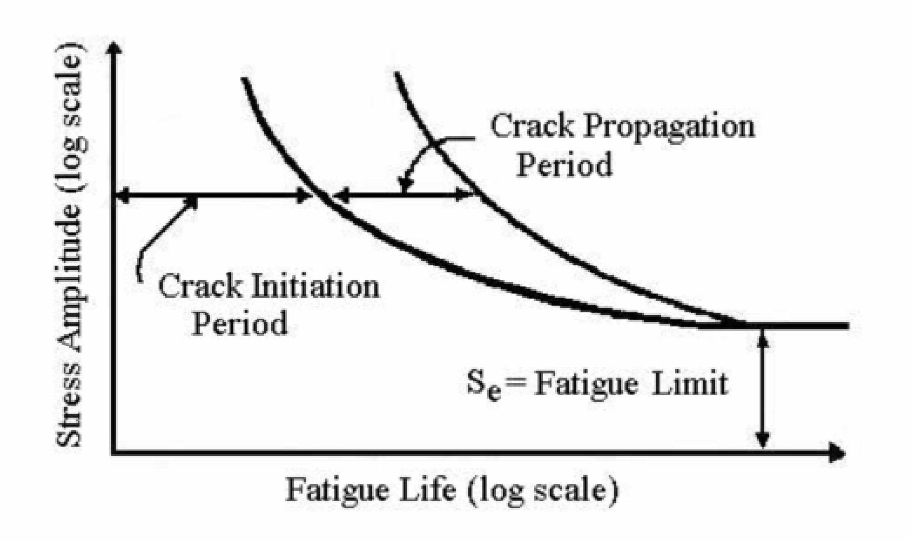
the critical location

Fatigue Life (N_f) Assessment

Fatigue life = $N_f = N_f^i + N_f^p$

Initiation life, N_f^i, is computed via strain-life relations.
Propagation life, N_f^p, is computed via fracture mechanics formulations.

- At high strain amplitudes (as in our case), the majority of the fatigue life is spent propagating a crack.



Fracture Mechanics Formulation

Simplest formulation : Paris Law

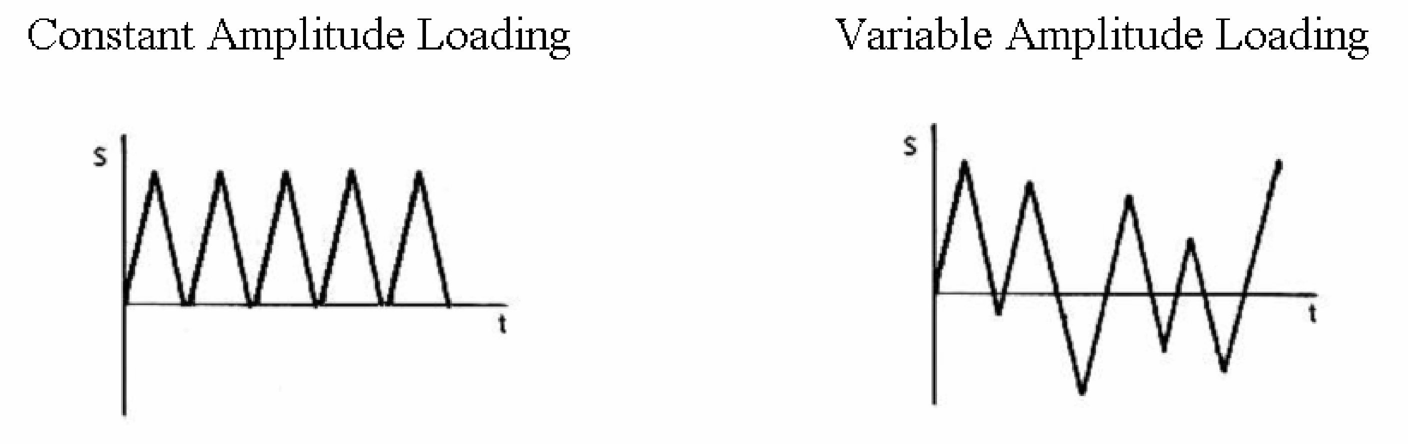
$$\frac{da}{dN} = C\left(\Delta K\right)^{n}$$

where

$$\Delta K = \beta\,\Delta\sigma\sqrt{\pi a}$$

β : geometry factor
σ : stress
a : crack length

However,


Constant Amplitude Loading

Variable Amplitude Loading

Paris Law is OK.

Need to use Retardation models

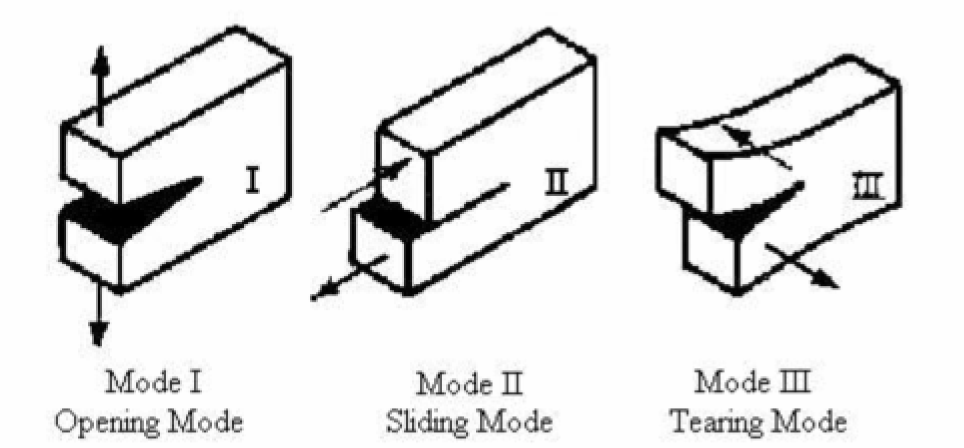
Retardation models
-Wheeler
-Willenborg
-Closure

* Retardation is the <u>reduction</u> in the crack growth rate after an <u>overload</u>.

Mixed-Mode Loading

- The pin is under mixed-mode loading conditions

- Mode I : opening (tensile) mode
  - crack faces are pulled apart
- Mode II : sliding (in-plane shear) mode
  - crack surfaces slide over each other
- Mode III : tearing (anti-plane shear) mode
  - crack surfaces move parallel to the leading edge of the crack

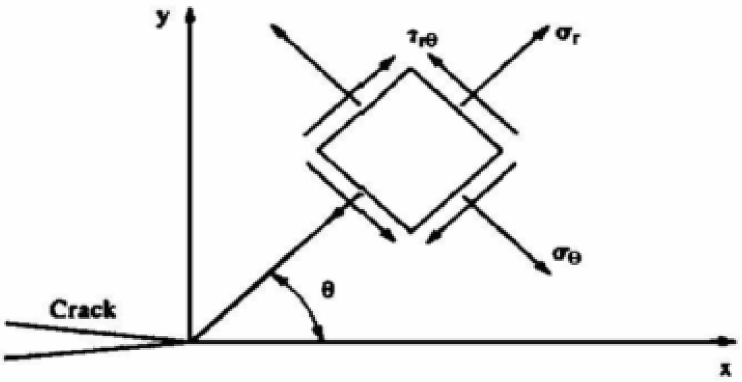


- Here we have mode I and II. Stress intensity factors K_I and K_{II} are computed via FEA.

Prediction of Mixed-Mode Crack Growth Directions

- MTS Criterion [Erdoğan & Sih]
  - crack propagation starts from crack tip along the radial direction on which the tangential stress becomes maximum

$$\frac{\partial\sigma_\theta}{\partial\theta} = 0 \quad \text{and} \quad \frac{\partial^2\sigma_\theta}{\partial\theta} < 0$$



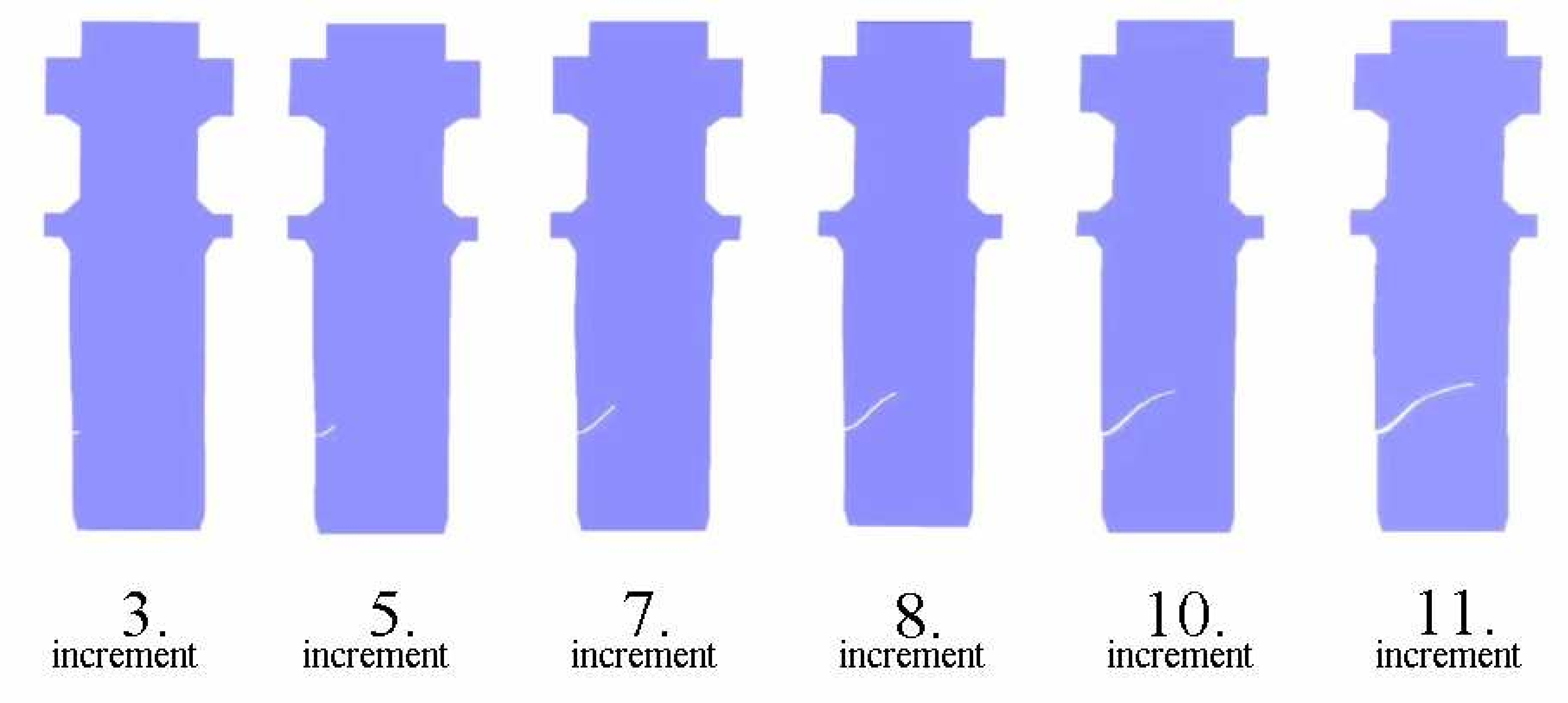
Using Westergaard expressions

$$K_I \sin\theta + K_{II}(3\cos\theta - 1) = 0$$

- S-Criterion [Sih]
  - a crack grows in a direction along which the strain energy density factor reaches a minimum value

Crack Growth

- Crack growth is predicted for discrete crack sizes.
- For each crack size, geometry factor is calculated (next slide).



Geometry Factor Calculations

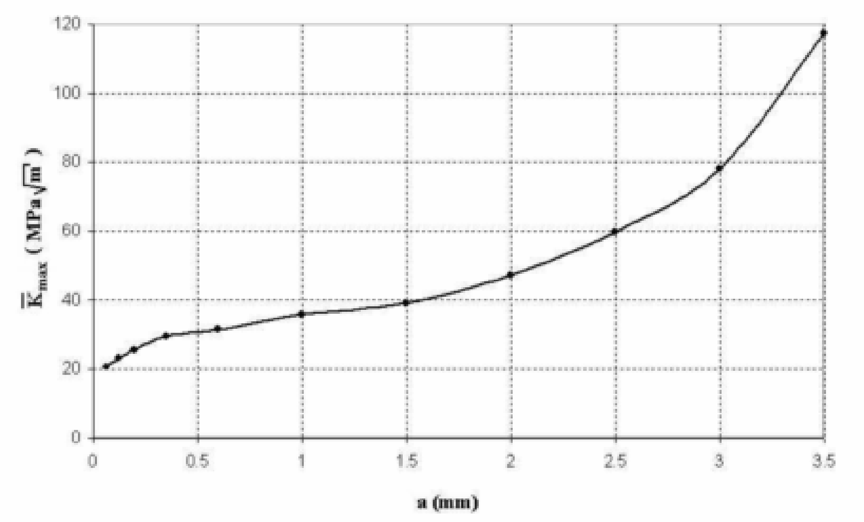
After calculating K_I, K_{II} and θ

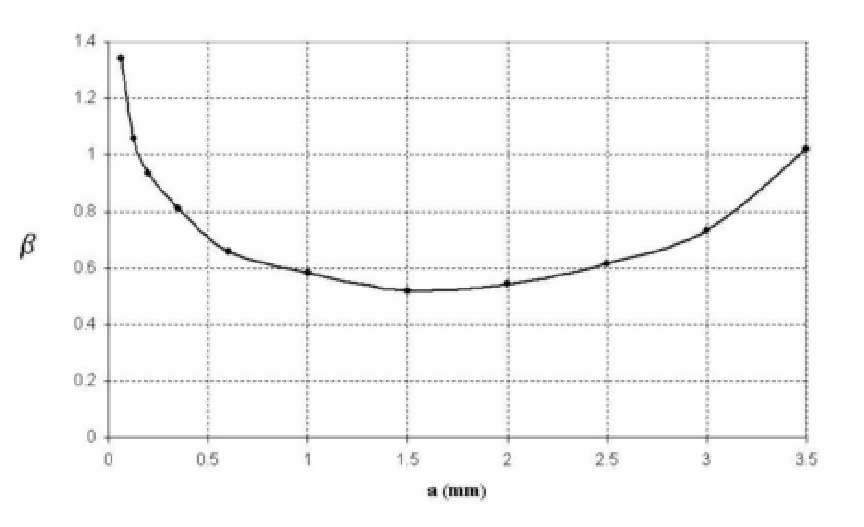
$$K_{eff} = \sqrt{K_I^2 + K_{II}^2}$$

- Crack propagation is simulated in AFGROW as mode type I with

- 11 discrete crack size are modeled
- Geometry factors are calculated from

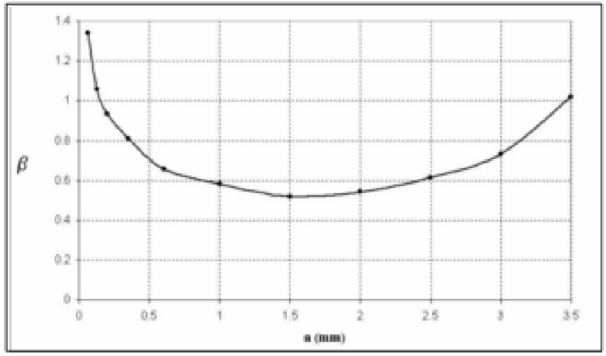
$$\beta = \frac{K_{eff}}{\sigma\sqrt{\pi a}}$$





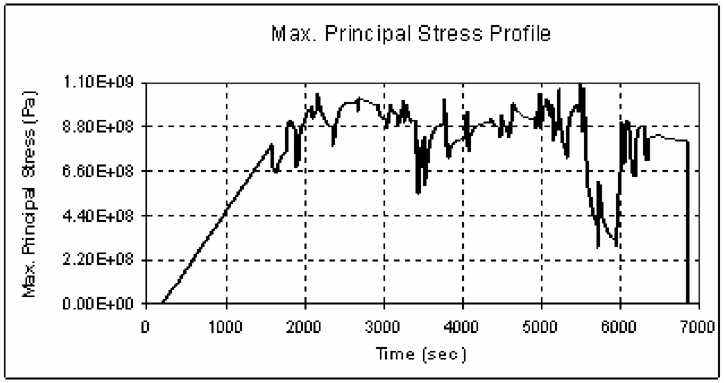
Fatigue Life Prediction by AFGROW

Inputs to AFGROW



&

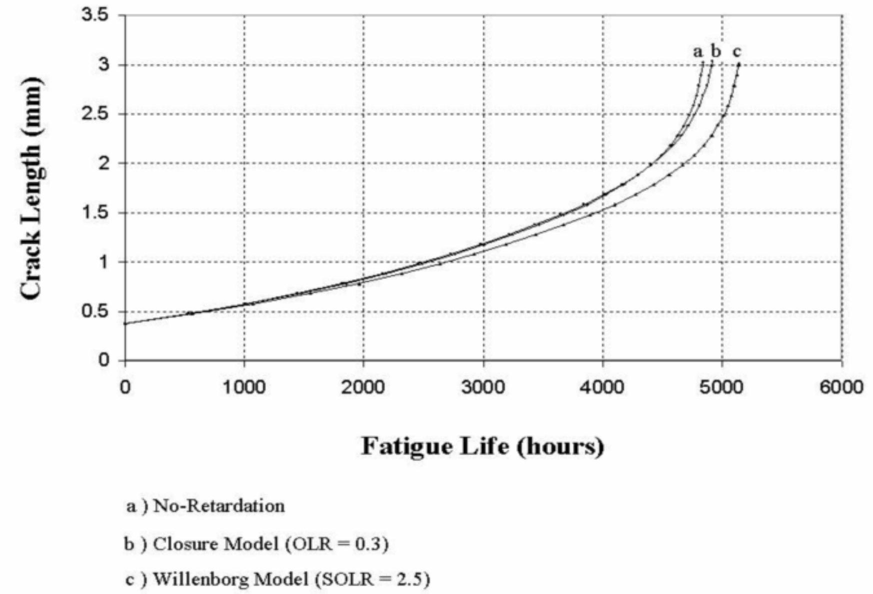
Without crack



Note : NDI minimum detectable flaw size is 0.015” (0.381 mm)

Outputs of AFGROW

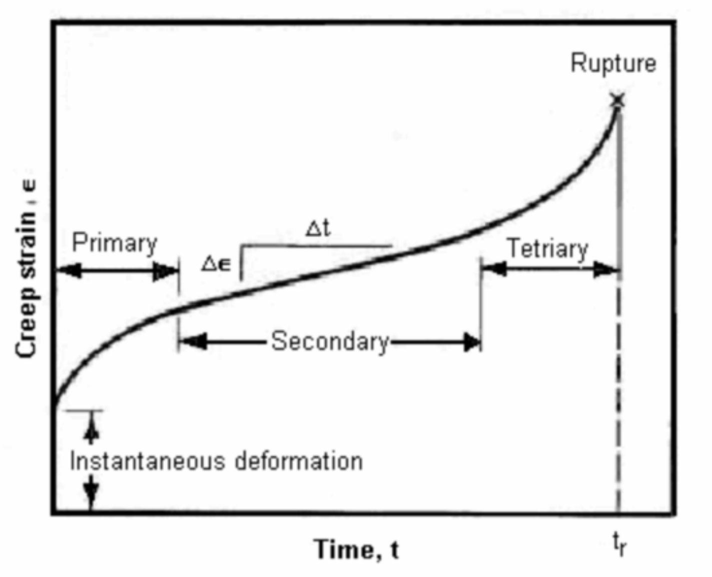
Case	Fatigue Life (N_f)
No-retardation	4837 hours
Closure Model (OLR = 0.3)	4919 hours
Willenborg Model (SOLR = 2.5)	5136 hours

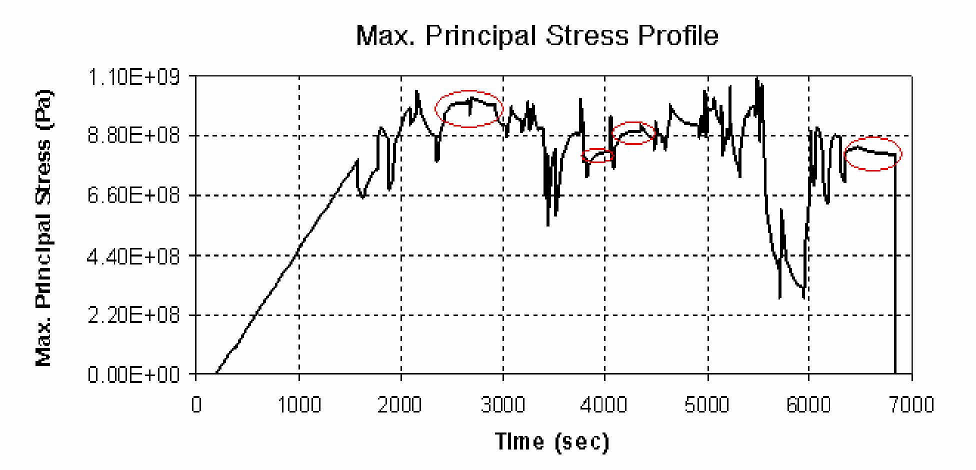


Creep Life Prediction

Creep is the inelastic deformation of a material that is subjected to a stress below its yield stress when that material is at a high homologous temperature.

➢ occurs in three stages (see figure)





- Hold times (t_h) are determined.
- For these hold periods,
  - creep rupture times (t_r) are calculated
- Creep life
  - $N_c = t_r / t_h$

TMF Life Prediction

- Fatigue Life (N_f)
- Hold Times (t_h)
- Creep Rupture Times (t_r)

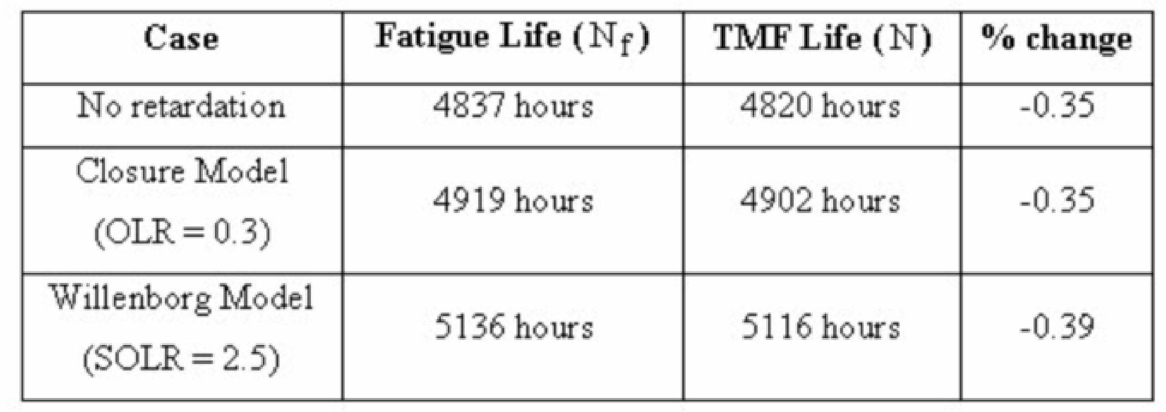
$\Big\}$ calculated earlier

Linear Damage Accumulation Method

$$\frac{N}{N_f} + \frac{N\,t_h}{t_r} = 1$$

Disadvantage:

- Disregards fatigue creep interaction



Case	Fatigue Life (N_f)	TMF Life (N)	% change
No retardation	4837 hours	4820 hours	-0.35
Closure Model (OLR = 0.3)	4919 hours	4902 hours	-0.35
Willenborg Model (SOLR = 2.5)	5136 hours	5116 hours	-0.39

Creep is NOT as effective as fatigue.

Comparison with Available Data

- MIL-STD-1783, ENSIP (Engine Structural Integrity Program) states that "all engine critical parts are to be designed to **twice** the life requirement."
- When retardation effects were neglected,
  - N = 4820 hours → the life requirement is 2410 hours.
- The component retirement time given by Turkish Air Force is around 1500-1800 hours as dictated by the technical orders.
- So, TMF results of this study is reasonable value. We calculated a larger value compared to retirement time given by Turkish Air Force. This makes sense since the pins should be removed before the whole life of the pins are spent.

Summary

- A finite element model of a segment of F110-GE-100 engine is generated by using MARC for thermal analysis.
- The same model and the output of thermal analysis are used in a stress analysis to determine the most critical location in the pin.
- A crack of varying lengths was modelled by using Msc MARC. K_I, K_{II}, crack propagation angle and geometry factor β are calculated for each crack length.
- Calculated geometry factors and the maximum principal stress profile of the critical location are used to predict the fatigue crack propagation life (N_f) by using AFGROW.
- Hold periods (t_h) are determined. Creep rupture times (t_r) are calculated.
- Thermo-mechanical fatigue life is assessed by using a linear damage accumulation model.
- Thermo-mechanical fatigue life calculated is a reasonable value compared to the component retirement time given by Turkish Air Force.

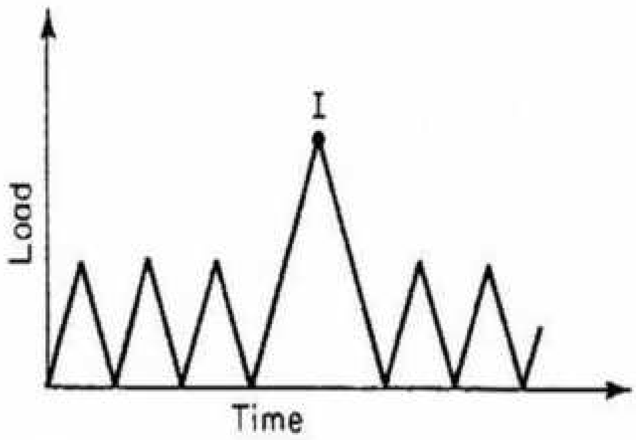
End of presentation

Next : Back-up slides

Crack growth retardation

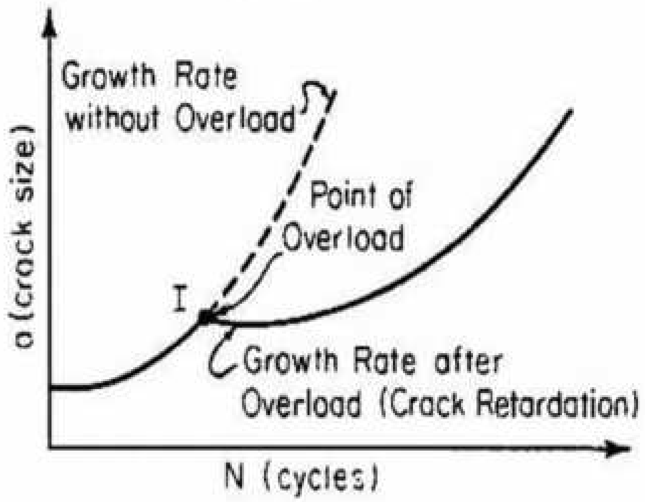
- Under constant amplitude loading conditions

Δa = function (present crack size,
applied load)



- Under variable amplitude loading conditions

Δa = function (present crack size,
applied load,
preceding cyclic history)

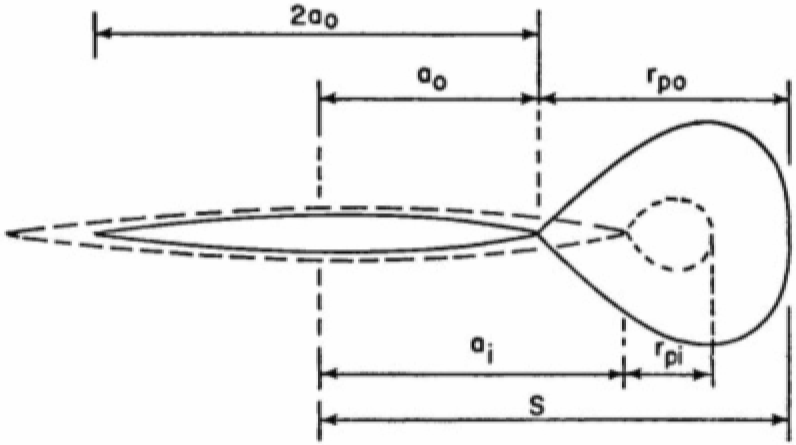


Retardation models

- Wheeler Model

$$C_p = \left[\frac{r_{pi}}{a_o + r_{po} - a_i} \right]^m = \left[\frac{r_{pi}}{s - a_i} \right]^m$$

$$(da/dN)_{retarded} = C_p \, (da/dN)_{linear}$$



- Willenborg Model

$$K_{max,\,eff} = K_{max} - K_{red} \qquad K_{min,\,eff} = K_{max} - K_{red}$$

$$K_{red} = \phi \left[K_{max,\,o} \sqrt{1 - \frac{a_i - a_o}{r_{po}}} - K_{max} \right] \qquad \phi = \left(1 - \frac{\Delta K_{thres}}{K_{max}} \right) (SOLR - 1)$$

- Closure Model

$$C_f = \frac{\sigma_{open}}{\sigma_{max}} = 1 - (1 - C_{f0})(1 + 0.6 \cdot R)(1 - R) \qquad K_{eff} = K_{max} - K_{open}$$

SIF Calculation by FEA

- Quarter Point Elements are used

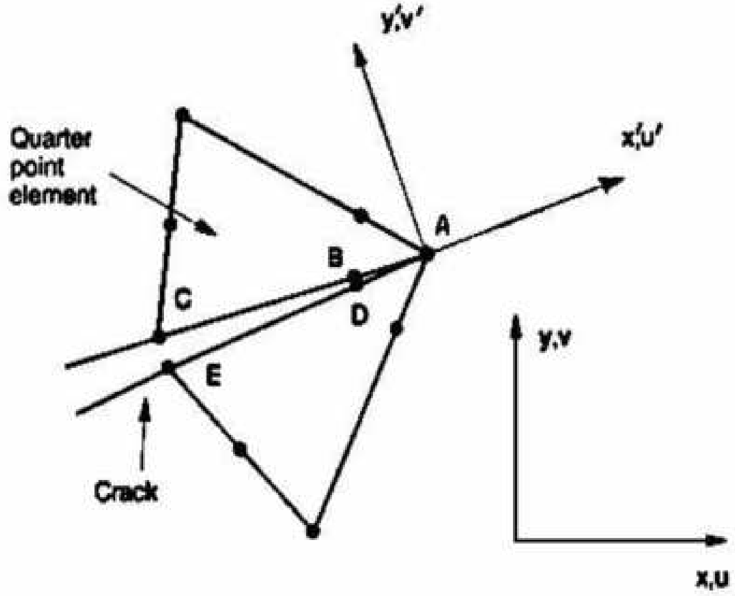
  to simulate the stress singularity at the crack tip

SIF Computation Techniques

Displacement Correlation Technique (DCT)

$$K_I^{DCT} = \frac{G}{\kappa+1}\sqrt{\frac{2\pi}{L_Q}}\,\{4(v'_B - v'_D) - (v'_C - v'_E)\}$$

$$K_{II}^{DCT} = \frac{G}{\kappa+1}\sqrt{\frac{2\pi}{L_Q}}\,\{4(u'_B - u'_D) - (u'_C - u'_E)\}$$



Quarter Point Displacement Technique (QPDT)

$$K_I^{QPDT} = \frac{2G}{\kappa+1}\sqrt{\frac{2\pi}{L_Q}}\,\{v'_B - v'_D\}$$

$$K_{II}^{QPDT} = \frac{2G}{\kappa+1}\sqrt{\frac{2\pi}{L_Q}}\,\{u'_B - u'_D\}$$

Direct Extrapolation Technique (DET)

SIF values for the nodes B and D, and then C and E are calculated.
Then, SIF at the crack tip node is calculated by using direct exptrapolation.