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FRACTURE MECHANICS

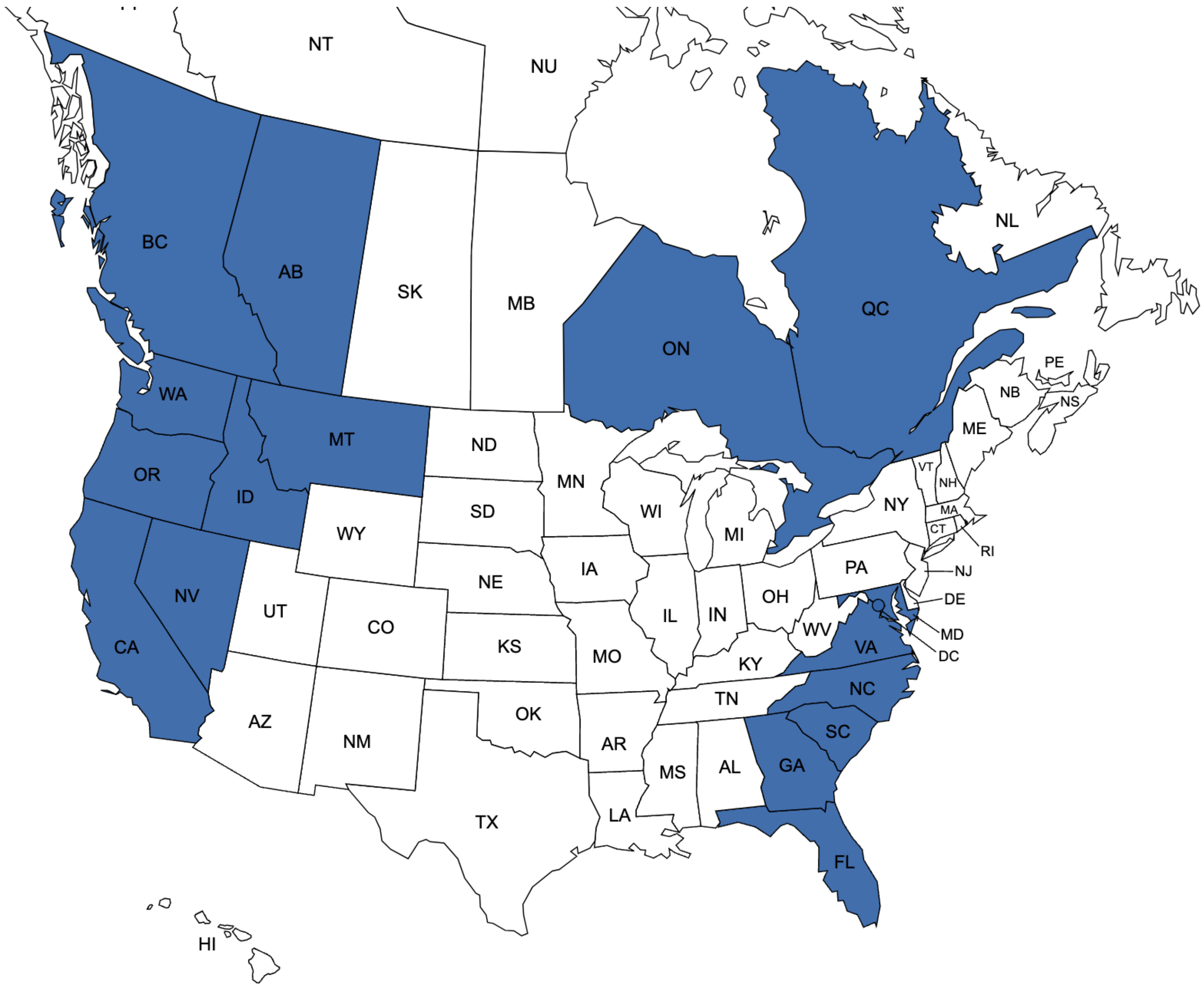
Ansys / ELITE CHANNEL PARTNER

TODAY'S AGENDA

- About Ozen Engineering, Inc.
- Fracture Mechanics Theory
- Fracture Mechanics Applications in Ansys
- Q&A

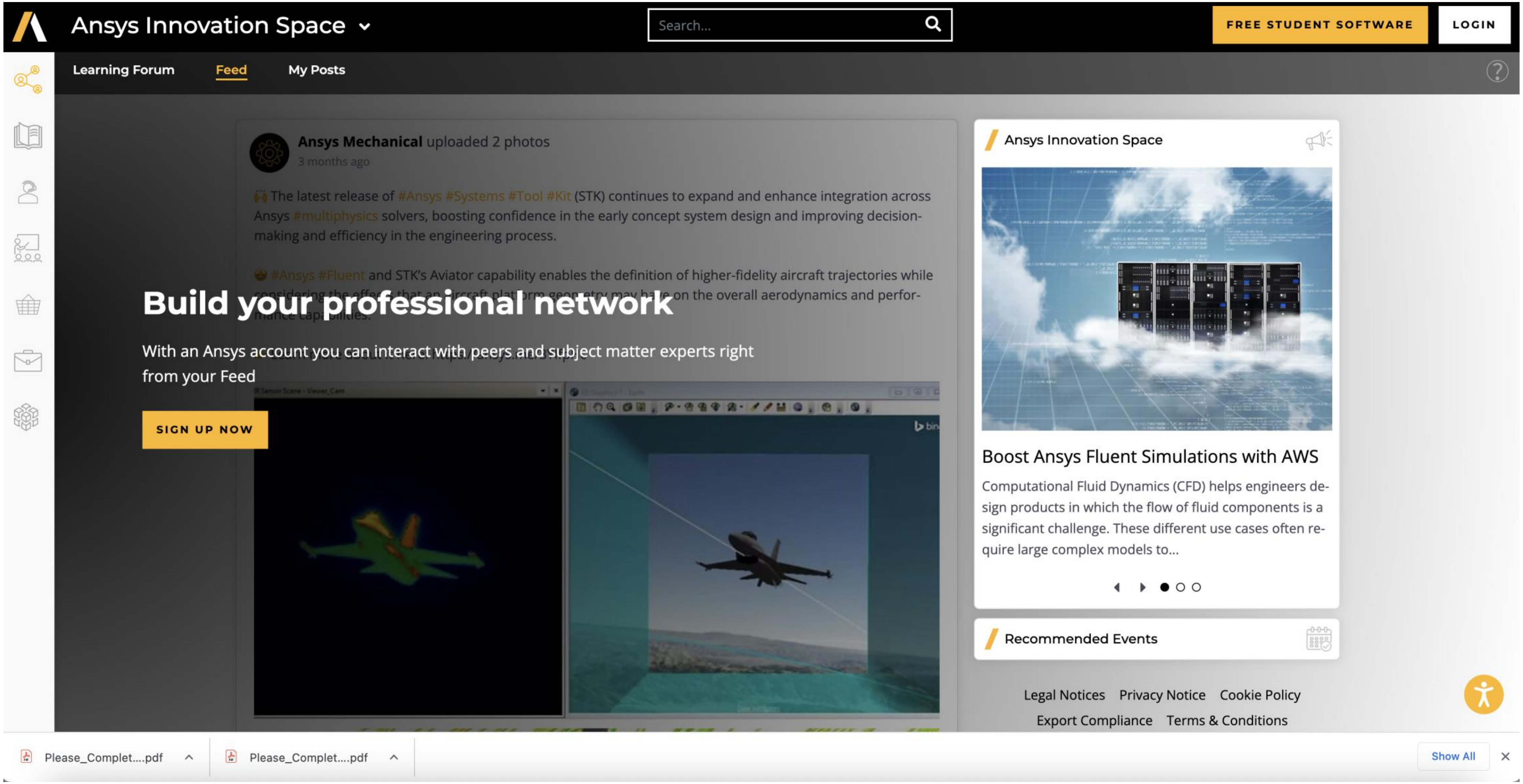
Our Ansys Sales Territory

- Sunnyvale, CA

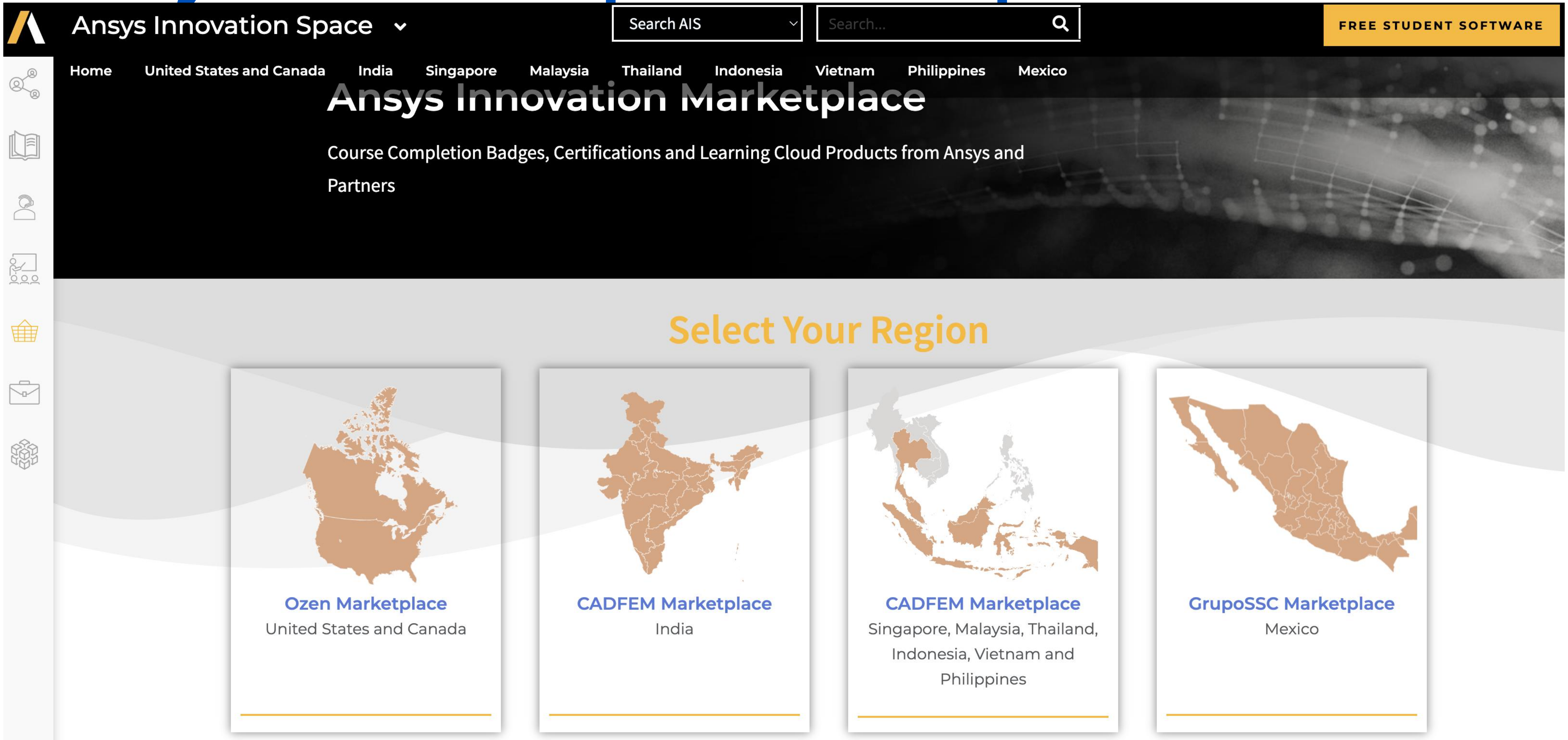


Columbia, MD
Durham, NC

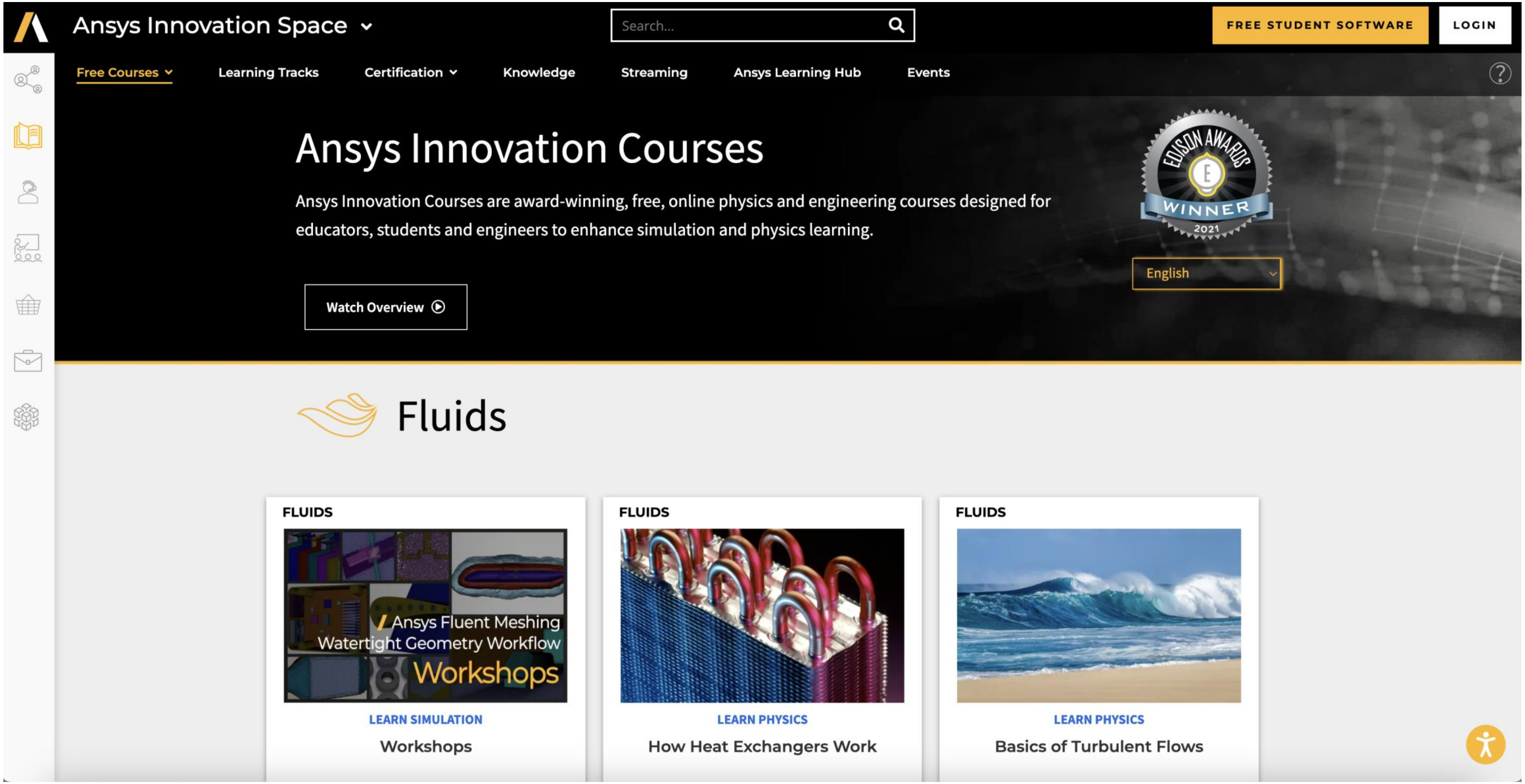
Ansys Innovation Space – It is a Community!



Ansys Innovation Space – Marketplace



Ansys Innovation Space - Courses



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Welcome Ozen Community

As an Ansys elite channel partner, Ozen offers customers best-in-class software tools, consulting, training, mentorship, and technical support. Now, powered by Dell Technologies, we have teamed up with Ozen to provide specialized benefits and solutions for you

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https://www.ozeninc.com/ozencon/

Join us for our Annual Simulation Conference!

DATE: FEBRUARY 22, 2024

LOCATION: THE COMPUTER HISTORY MUSEUM

This one-day conference will provide detailed insight into how leading companies are utilizing simulation to advance their product development. We will bring together ANSYS users, partners, developers, and industry experts for networking, learning, and sharing of new ideas.

Our conference is FREE to attend.
Register today!

Largest Annual Ansys Simulation Conference in Silicon Valley

Over 300 Engineers and more than 100 of the Most Innovative Hardware Companies in the Bay Area

Presentations from Leading Companies and Ansys Experts

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FRACTURE MECHANICS

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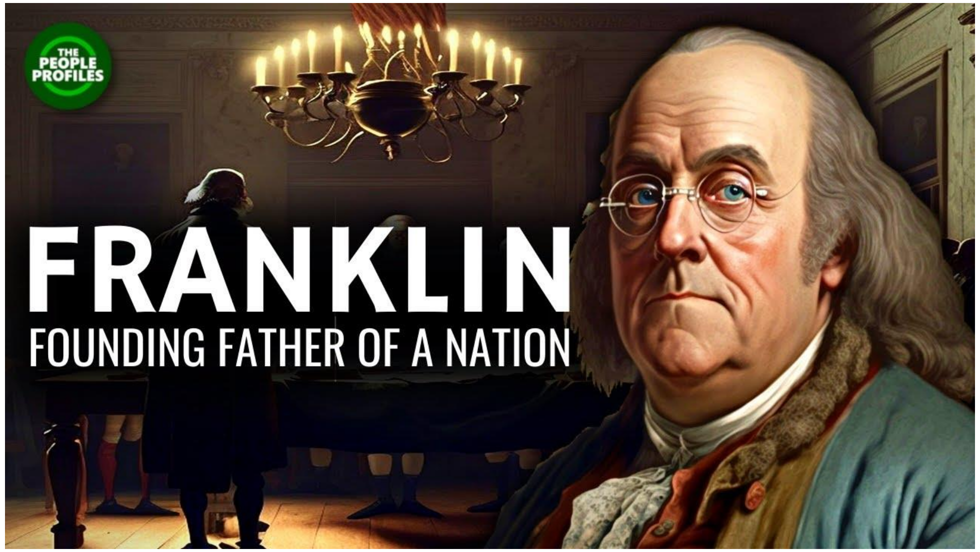
FRACTURE MECHANICS

- Benjamin Franklin:
  - "... but in this world nothing can be said to be certain, except death and taxes"
- Proposed modification:
  - "... in this world nothing can be said to be certain, except death, taxes, and fracture"



FRACTURE MECHANICS

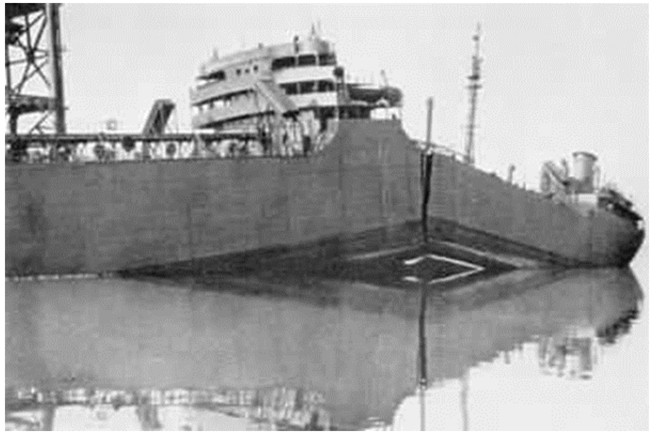
- According to a study by Batelle/National Bureau of Standards (NBS)
  - "… fracture costs US economy $119 Billion a year…" (1982 Dollars)
  - https://www.in2013dollars.com/us/inflation/1982?amount=1
  - indicates that $1 in 1982 is $3.19 in 2023
  - Therefore: **"… fracture costs US economy $380 Billion a year…"** (2023 Dollars)

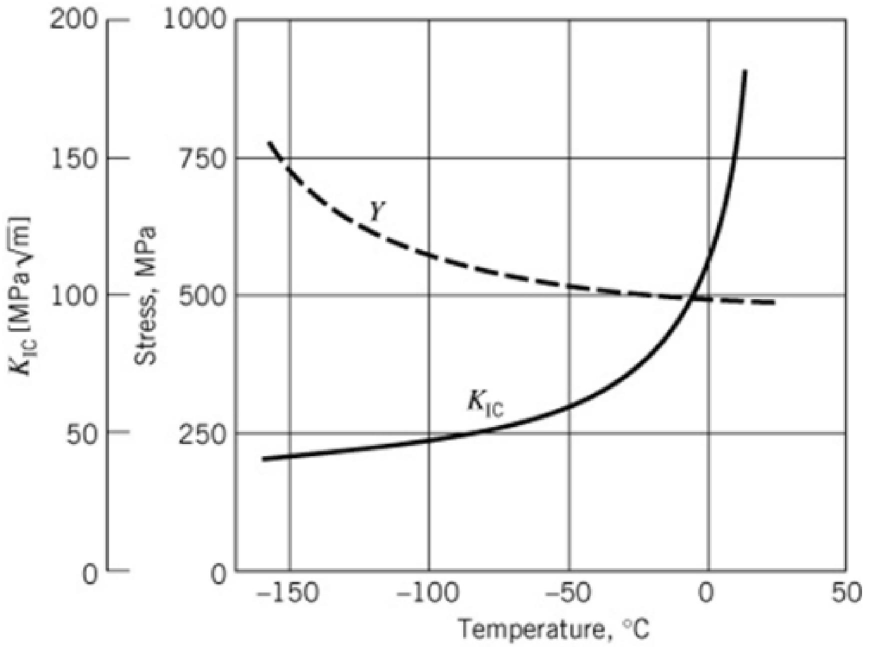
WHY IS FRACTURE MECHANICS IMPORTANT?

- Probably encountered in any industry dealing with structures
  - Automotive
  - Electronics
  - Healthcare
  - Aviation
  - Civil
  - Nuclear
  - Defense
  - Maritime
  - Semiconductor
  - ...

WHY IS FRACTURE MECHANICS IMPORTANT?

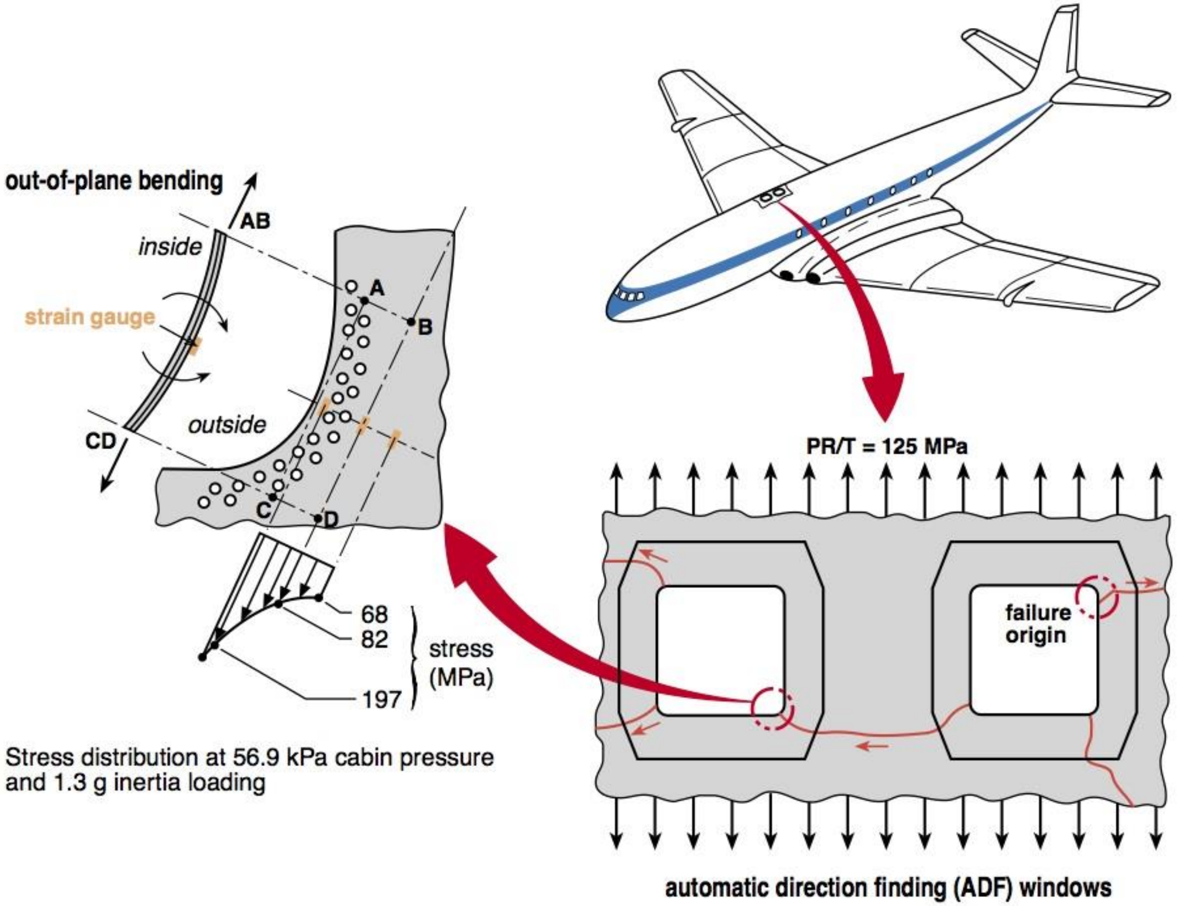
- (Liberty) Ships…





WHY IS FRACTURE MECHANICS IMPORTANT?

- Comet Airplanes...



WHAT IS FRACTURE MECHANICS?

- It is the study of flaws and cracks in materials

- Mostly deals with

    - Crack Initiation
    - Crack Propagation
    - Life Estimation

FRACTURE MECHANICS – ENGINEERING

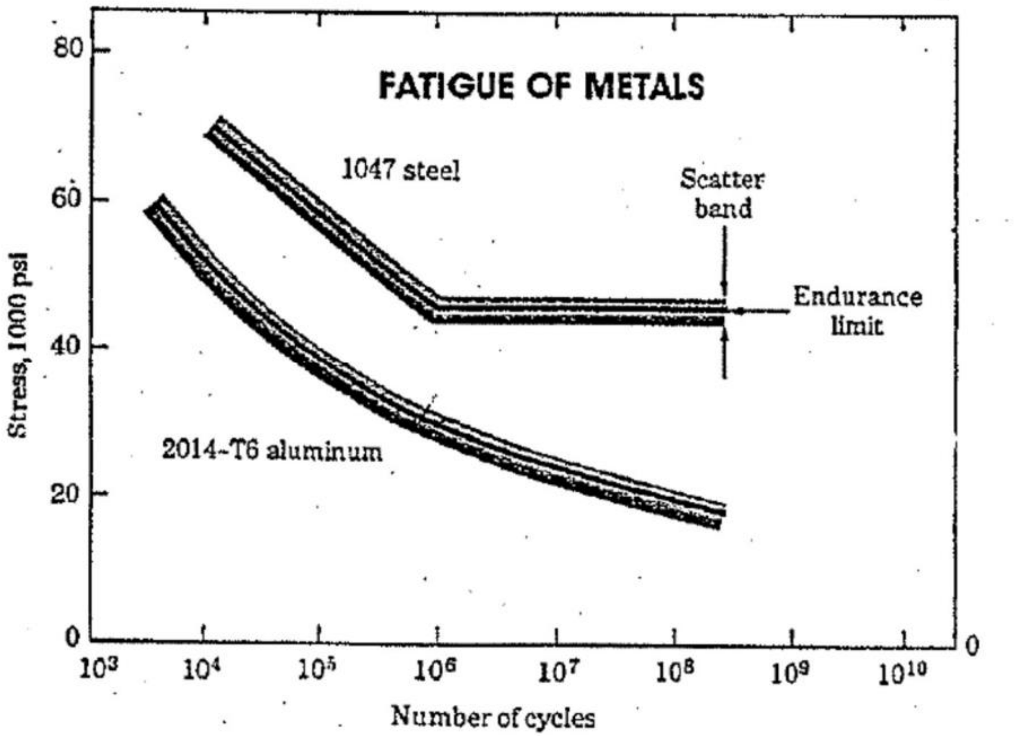
- Proposed practical engineering calculation (Life Estimation):

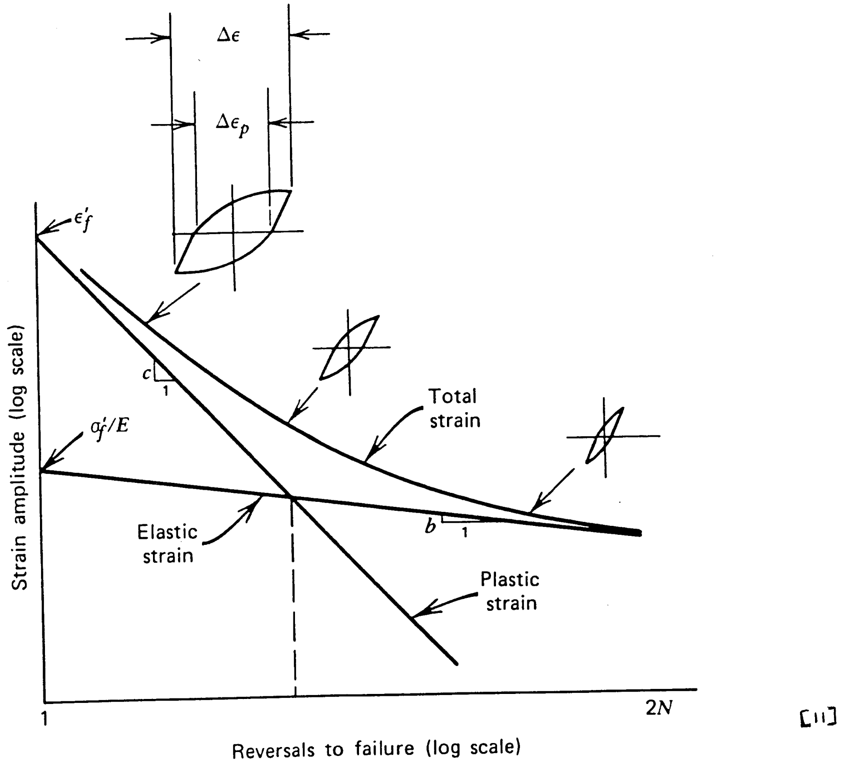
$$L_{total} = L_{fatigue/crack\ initiation} + L_{crack\ propagation}$$

TYPICAL FATIGUE CURVES

- Stress & Strain Based Fatigue Curves:

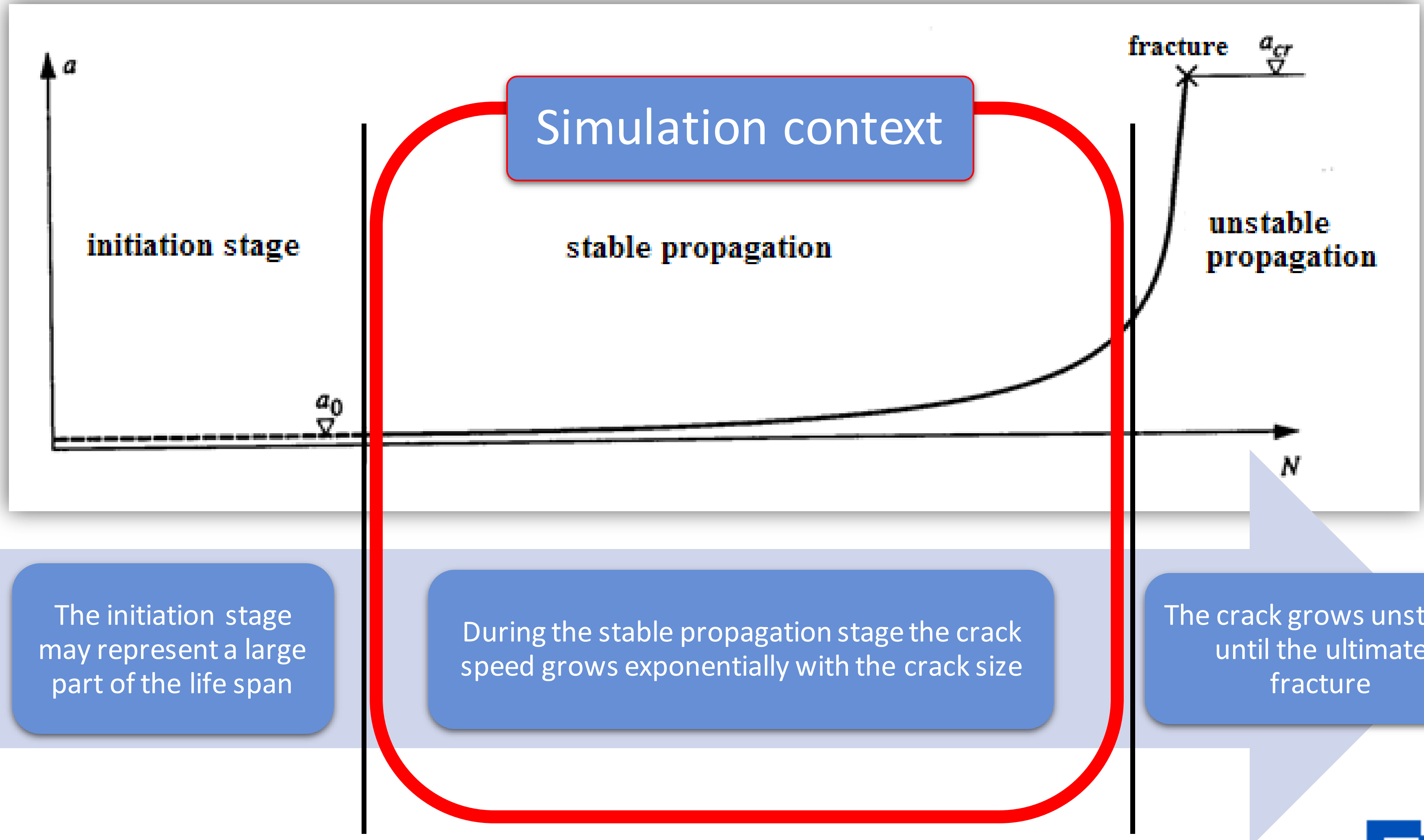
https://www.usna.edu/NAOE/_files/documents/Courses/EN380/Course_Notes/Ch12_Fatigue.pdf





CRACK INITIATION & PROPAGATION

- Life span definition for life estimation:



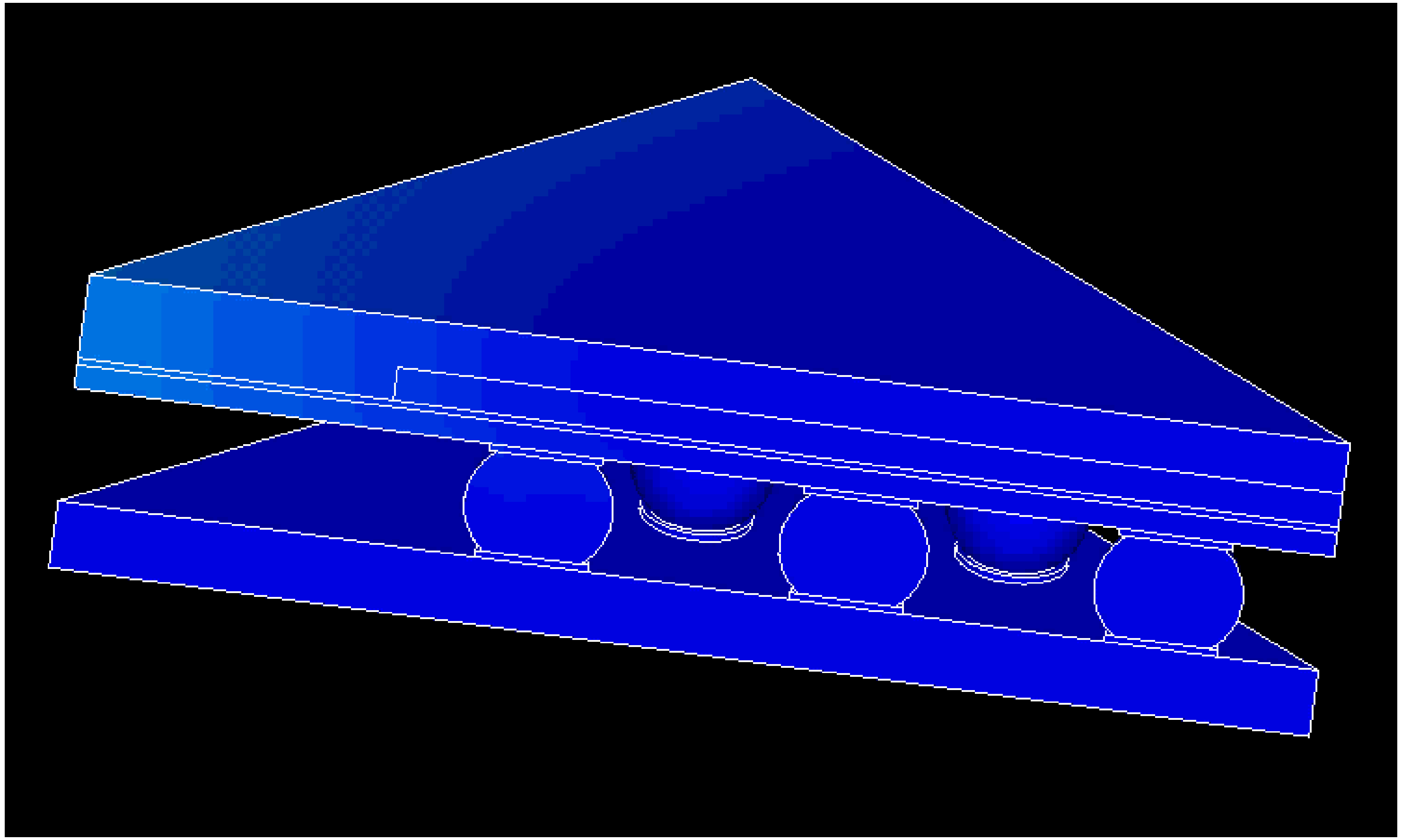
The initiation stage may represent a large part of the life span

During the stable propagation stage the crack speed grows exponentially with the crack size

The crack grows unstably until the ultimate fracture

CRACK INITIATION & PROPAGATION

- Air Asia 2014:



FRACTURE MECHANICS CLASS

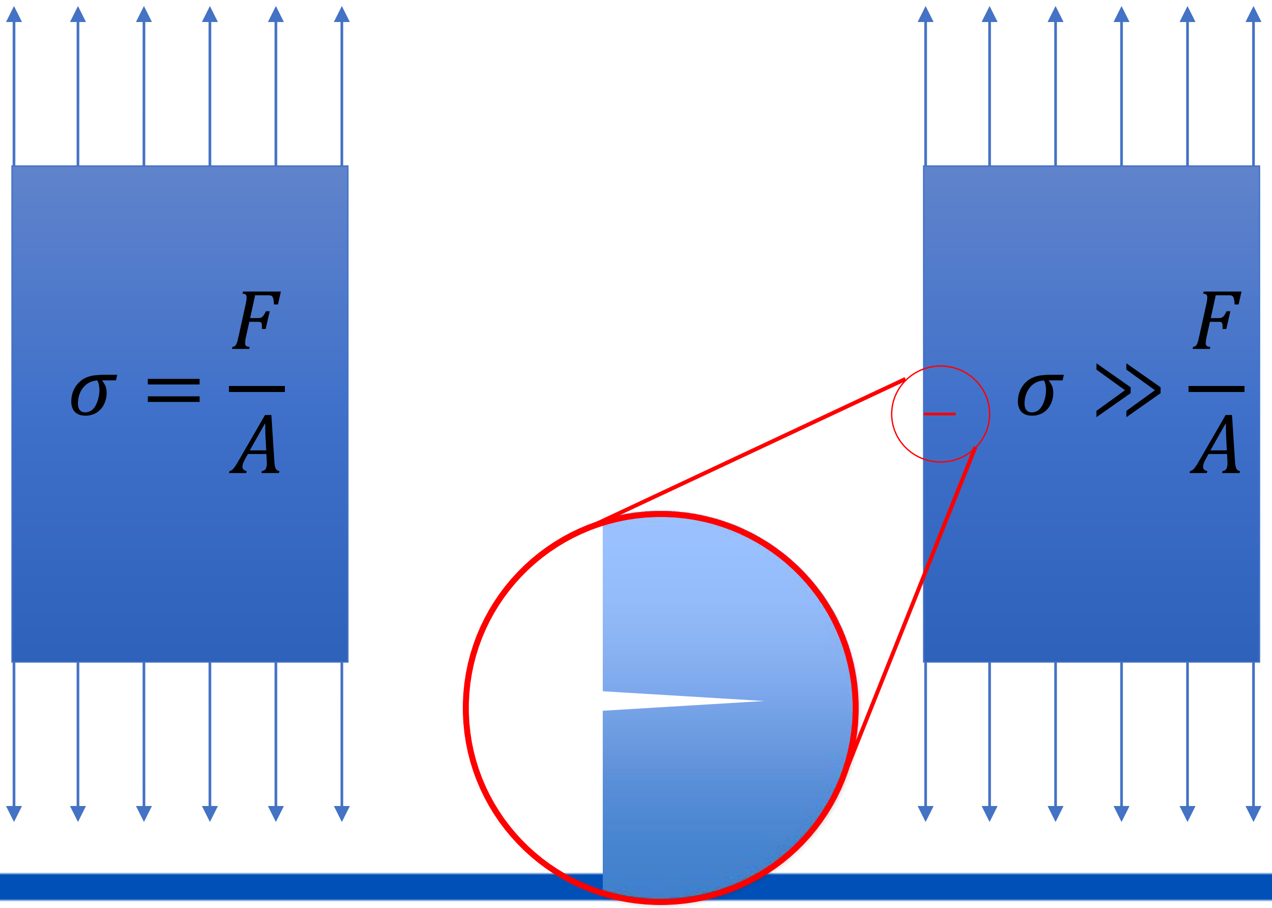
Our technical staff has prepared this training to include information about the history of fracture mechanics, modes of fracture, plane strain versus plane stress, airy stress function, deprivation of the stress field near the crack tip (William's solution). Here we will go over classical theories of failure, maximum stress criterion and solutions of example problems. Workshop #2 will cover the use of J integral for a two-dimentional model, application of crack initiation theories on the finite element model, fatigue crack growth, Paris law, Forman correction and Temperature effects.

Topics that will be covered include:

- History of Fracture Mechanics, Modes of Fracture, Plane strain versus Plane stress, Airy stress function, Derivation of the stress field near the crack tip (William's solution).
- Definition of Stress Intensity Factors (SIF's), Two-dimensional crack problem solutions, Discussion and procedure on how to set up the finite element models for the workshop problems in ANSYS
- Review and expansion on Mode II and Mode III fracture, Classical theories of failure, Maximum stress criterion, Solutions of example problems
- Crack initiation and crack propagation theories, Griffith's theory, Strain energy density criterion, J integral
- Fatigue crack growth, Paris law, Forman correction, Integration of the crack propagation equation, Temperature effects, Mixed mode crack propagation, Simulation of fracture toughness testing, Compliance method, R curve
- Workshops on how to model cracks in ANSYS Workbench, crack initiation, crack propagation simulations.

HOW TO FORMULATE FRACTURE MECHANICS?

- Strength of Material approach does not anticipate the presence of a crack or does via concentration factors
- Presence of cracks can significantly decrease the structural strength and reliability



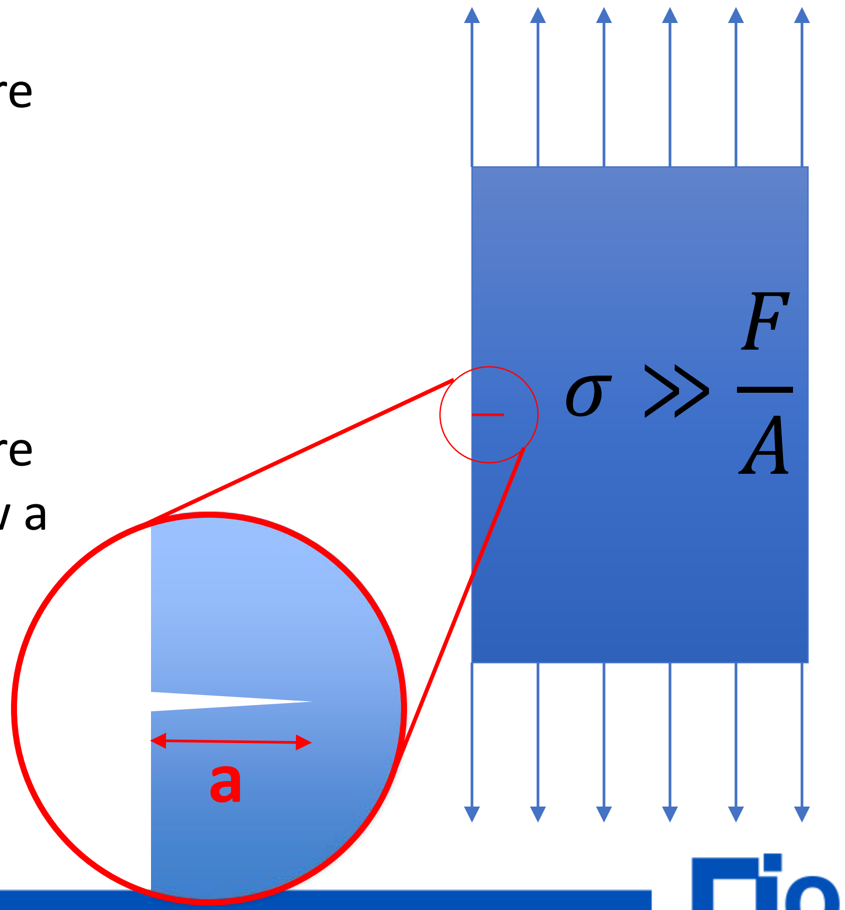
HOW TO RESOLVE FRACTURE MECHANICS?

- Flaw Size (a) is an important parameter in fracture mechanics approach
- Fracture Toughness replaces strength of material
  - For Linear-Elastic Fracture Mechanics (LEFM), fracture toughness of a material is determined from “Stress Intensity Factor”

$$K_I \rightarrow K_{IC}$$

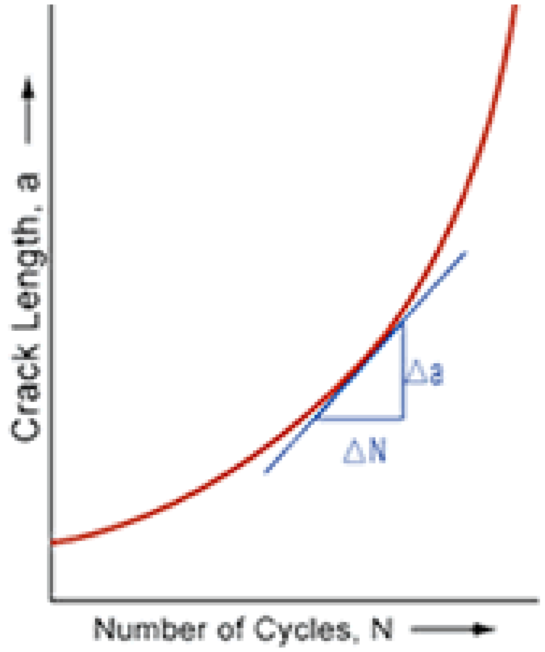
  - For Elastic-Plastic Fracture Mechanics(EPFM), fracture toughness is determined via energy required to grow a crack

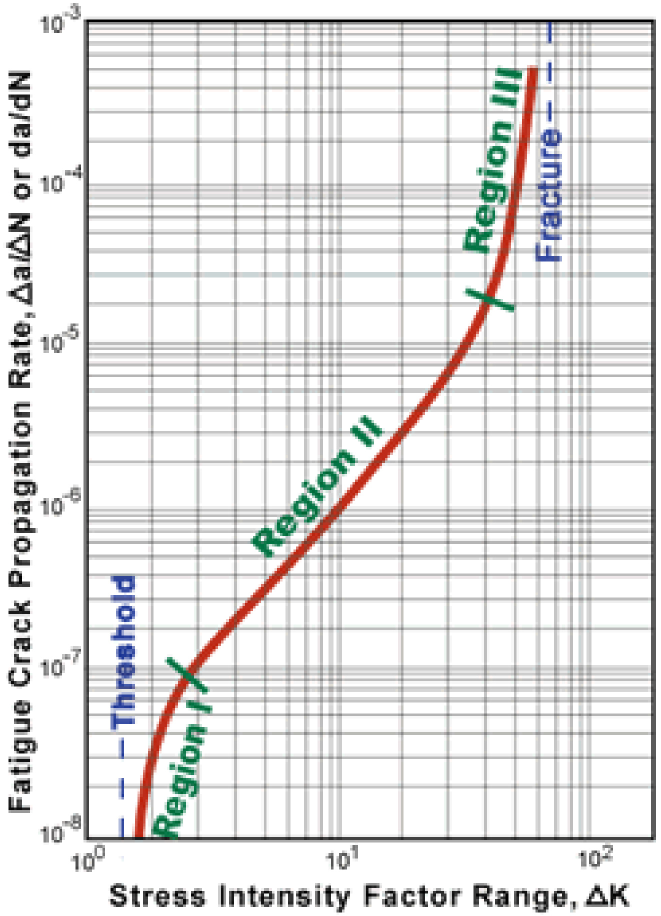
$$J_I \rightarrow J_{IC}$$



CRACK INITIATION & PROPAGATION

- Life span definition:





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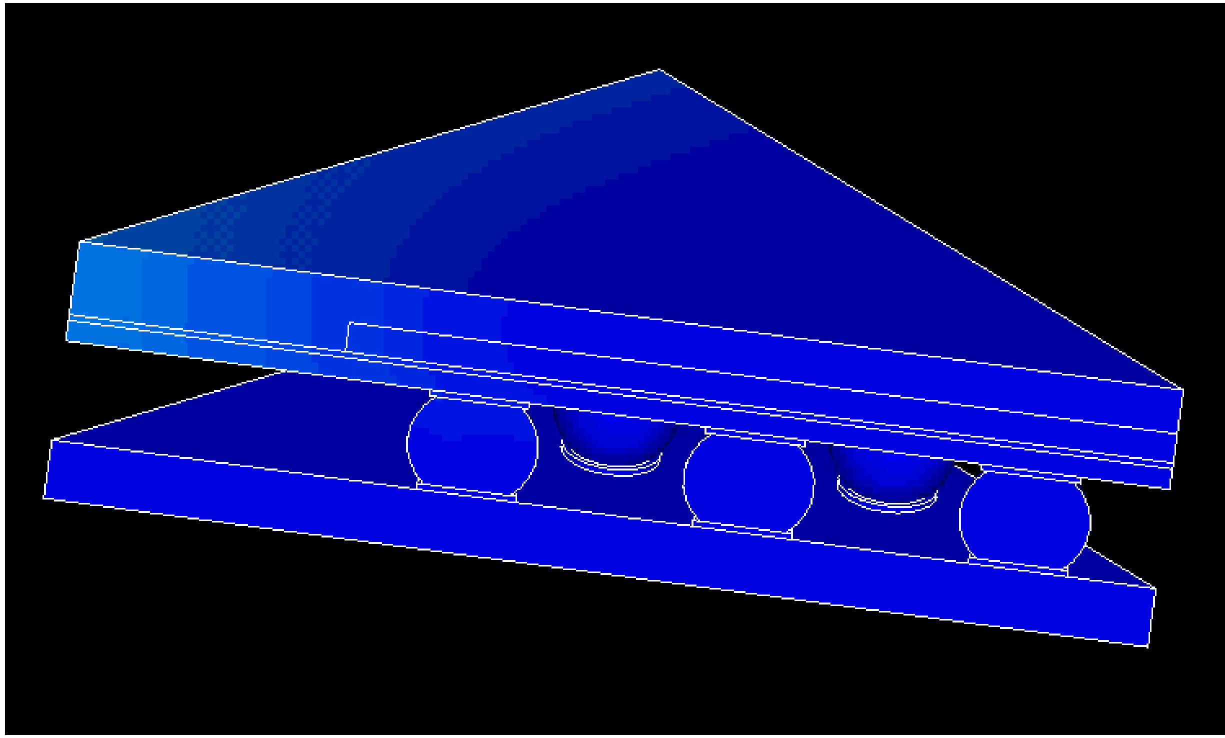
CRACK INITIATION

- Physically, cracks initiate from;
  - An imperfection
  - An already existing crack
  - A damaged (locally weakened) area

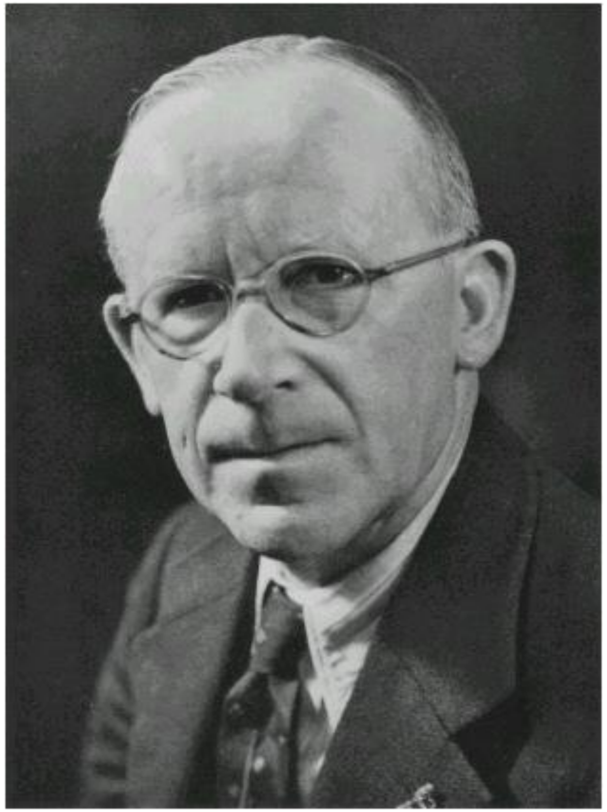
- A failure analysis must include;
  - Stress analysis
  - Failure criterion



THEORETICAL DEVELOPMENTS

- A. Griffith (1893-1963) published the results of his studies on brittle fracture
- He found the strength of glass depended on the size of microscopic cracks

$$S\sqrt{a} = CONSTANT$$



Alan Arnold Griffith FRS.
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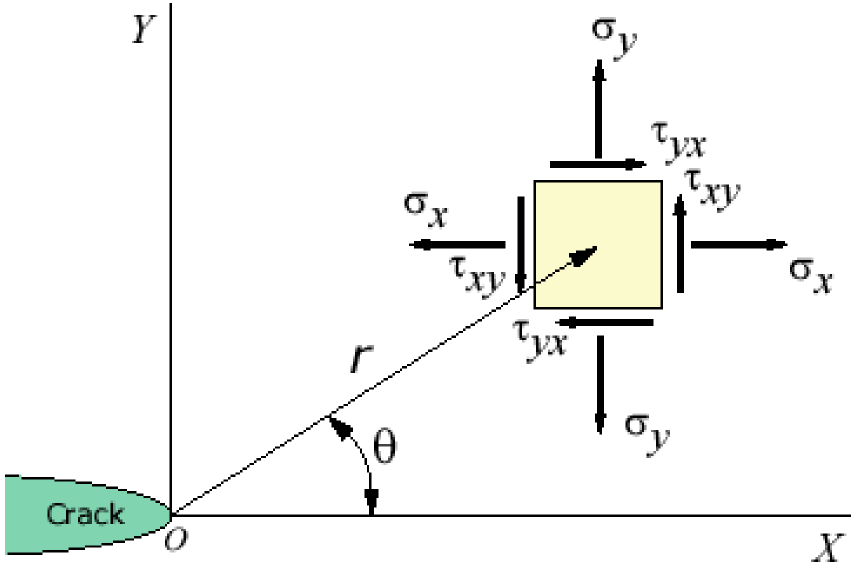
CRACK TIP STRESS FIELD

$$\sigma_x = \frac{1}{\sqrt{2\pi r}}\left(K_I \cos\frac{\theta}{2}\left[1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right] - K_{II}\sin\frac{\theta}{2}\left[2 + \cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right]\right)$$

$$\sigma_y = \frac{1}{\sqrt{2\pi r}}\left(K_I \cos\frac{\theta}{2}\left[1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right] + K_{II}\sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right)$$

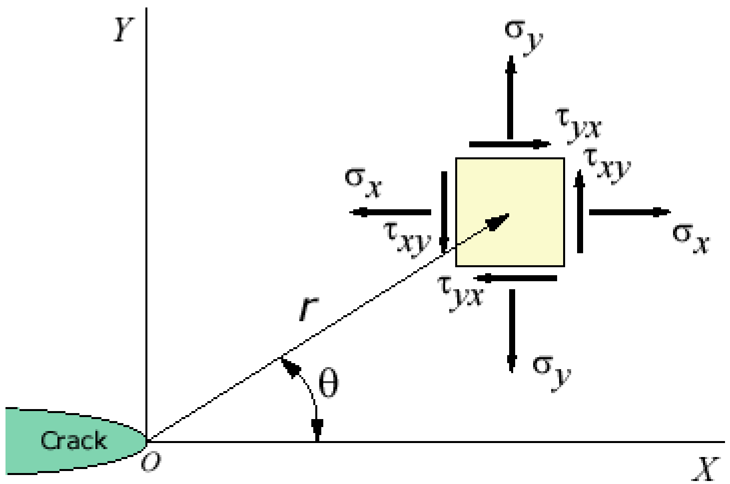
$$\tau_{xy} = \frac{1}{\sqrt{2\pi r}}\left(K_I \cos\frac{\theta}{2}\sin\frac{\theta}{2}\sin\frac{3\theta}{2} + K_{II\cos}\frac{\theta}{2}\left[1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right]\right)$$



CRACK TIP STRESS FIELD - For Theta = 0

$$\sigma_X = \sigma_Y = \frac{K_I}{\sqrt{2\pi r}} \quad \Rightarrow \quad K_I = \sigma_X \sqrt{2\pi r}$$

$$\tau_{XY} = \frac{K_{II}}{\sqrt{2\pi r}} \quad \Rightarrow \quad K_{II} = \tau_{XY} \sqrt{2\pi r}$$



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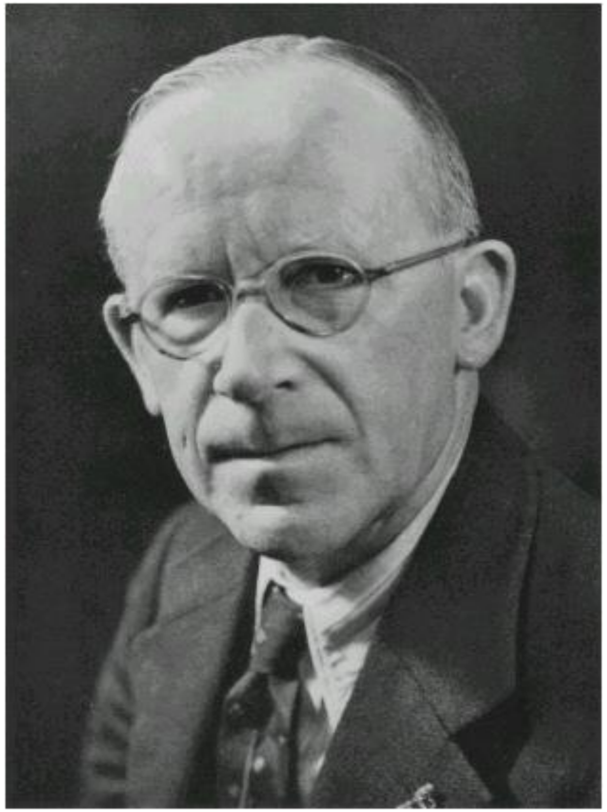

Alan Arnold Griffith FRS.
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STRESS INTENSITY FACTORS

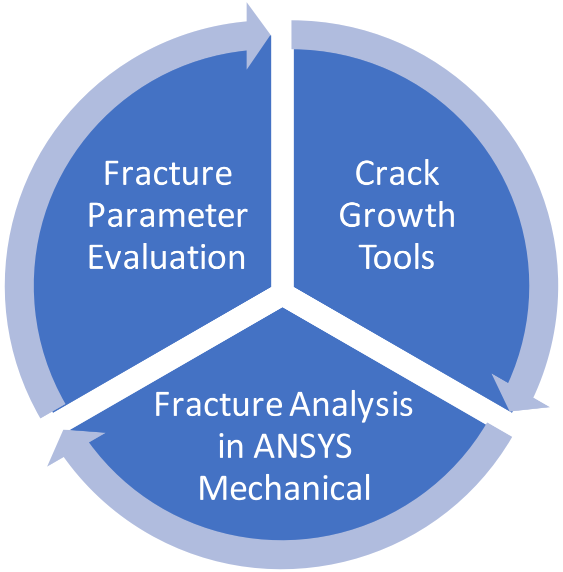
- When the load and crack size are kept below the threshold point of unstable crack extension, the magnitude of the stress field in the immediate vicinity of the crack tip is measured by the so-called “Stress Intensity Factor” [9] and it is associated with the stresses as given before. The distance “r” in the equations is always kept small but finite so that the stresses are bounded. The stress intensity factors are measures of the amplitude of the stress field covering the region surrounding the crack tip and should be distinguished from the stress concentration factor.

- It is also important to distinguish the difference between K_I ; K_{IC}

ANSYS FRACTURE MECHANICS PORTFOLIO

- …

- SIFs
- J-Integral
- T-Stress
- C* - Integral
- VCCT
- **Material Force**



- CZM
- VCCT
- XFEM

- Semi-elliptical Crack Modeling
- Arbitrary Crack Modeling
- Fracture Parameter Evaluation & Visualization
- Debonding and Delamination Analysis
- ANSYS Composite PREPPOST (ACP)
- ANSYS Customization ToolKit (ACT)

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FRACTURE PARAMETERS IN ANSYS

Parameter	Characterizes	Applicability	Note
Stress Intensity Factors K_I, K_{II}, K_{III}	Stress state near the crack tips	Linear isotropic elasticity	
J-integral	Strain energy release rate	Up to limited plasticity, isotropic	Direct relation to SIF in linear cases
T-Stress	Stress acting parallel to the crack faces	Linear isotropic elasticity and plasticity	Used for prediction of crack propagation direction
C* Integral	Crack tip stress and deformation fields	Steady-state creep behavior	
Energy release rate G for VCCT	Energy required to create newly formed crack surfaces	Linear isotropic, orthotropic or anisotropic elasticity	
Material force	Driving forces acting on any kind of inhomogeneity, including cracks	Linear and nonlinear materials (hyperelasticity, plasticity, etc.)	Equivalent to J in linear elasticity

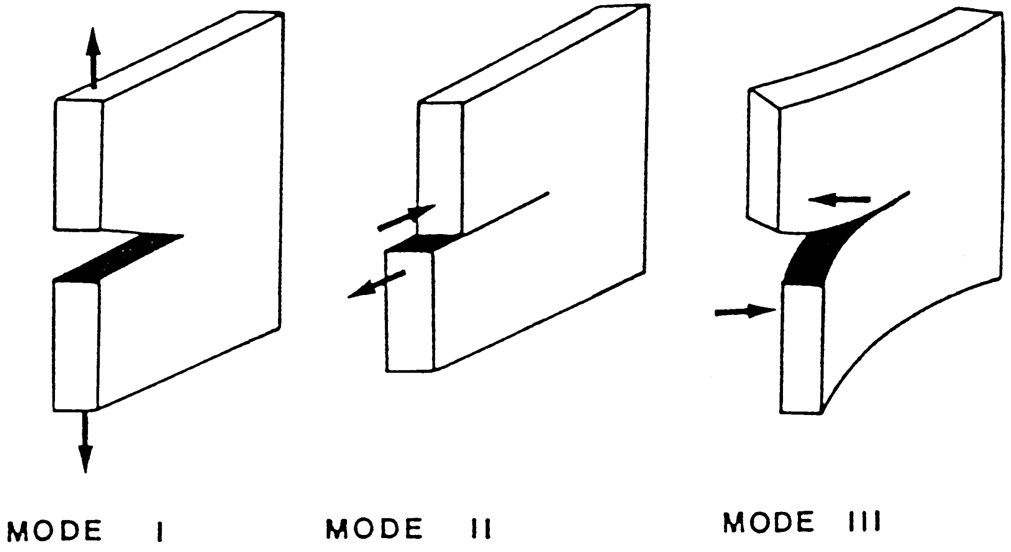
FRACTURE MECHANICS TABLE

- Which parameter is applicable for which assumption:

Method	Material Behavior
J-Integral	Linear isotropic elasticity Isotropic plasticity
Energy-Release Rate (VCCT Method)	Linear isotropic elasticity Orthotropic elasticity Anisotropic elasticity
Stress-Intensity Factor	Linear isotropic elasticity
T-Stress	Linear isotropic elasticity Isotropic plasticity
Material Force	Various (including plasticity, viscoelasticity)
C*-Integral	Creep

THREE MODES OF FRACTURE

- Mode I denotes a symmetric opening (opening or tension mode)
- Mode II denotes an antisymmetric separation (In-plane shear mode)
- Mode III denotes an antisymmetric separation (out-of-plane shear or tearing mode)
- Crack growth usually takes place in mode I or close to it.
- The crack "adjusts" itself such that the load is perpendicular to the crack faces.



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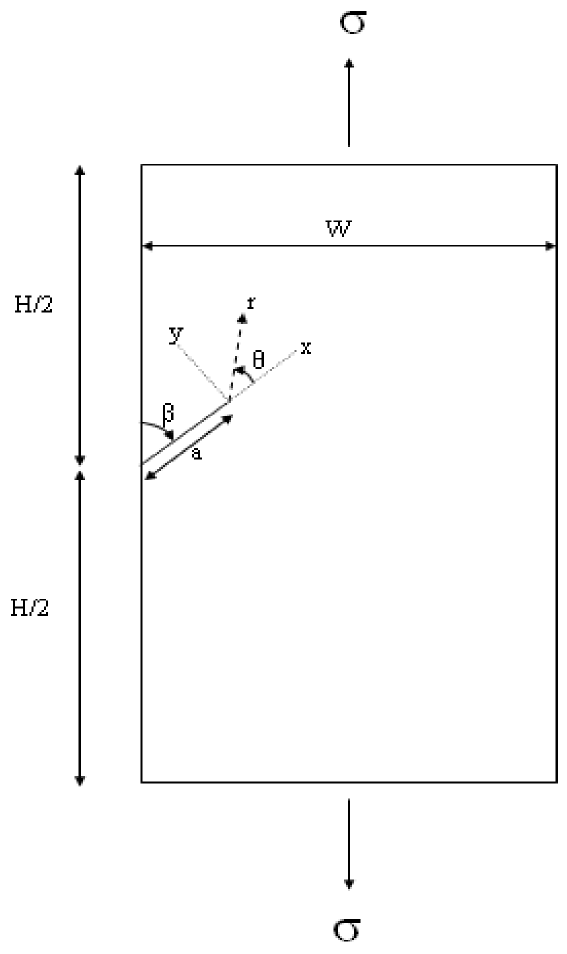
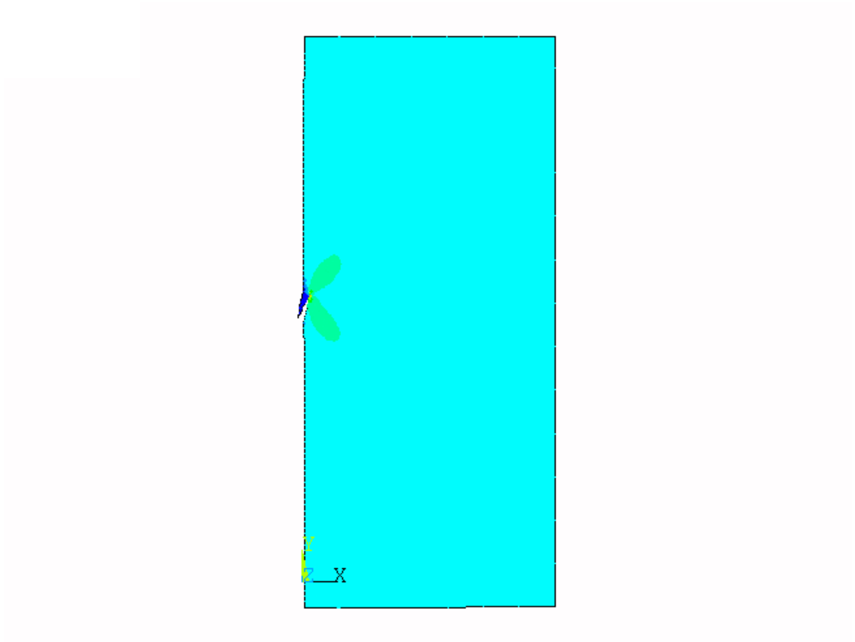
2-D EDGE CRACK PROPAGATION

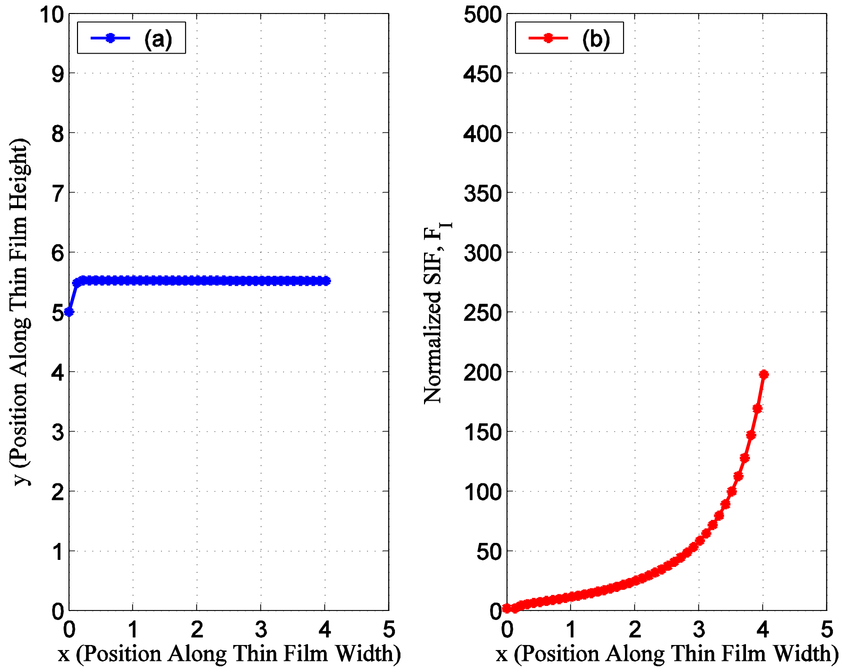
- 2 D Edge cracked plate analysis
- Can be solved both using fracture mechanics tools and cohesive zone elements in ANSYS.



2-D EDGE CRACK PROPAGATION



Crack Propagation Animation, β =15°

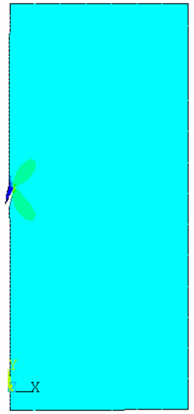


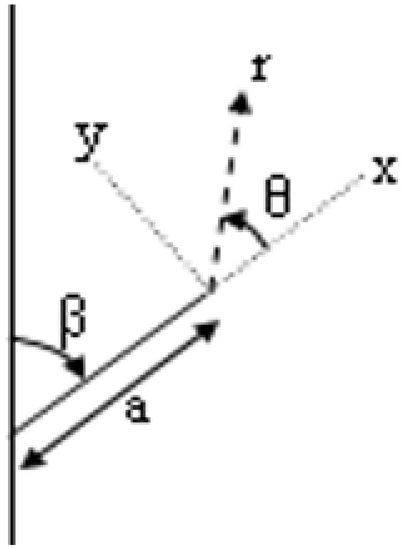
(a) Crack Propagation Path, (b) SIF, F_I; β =15°

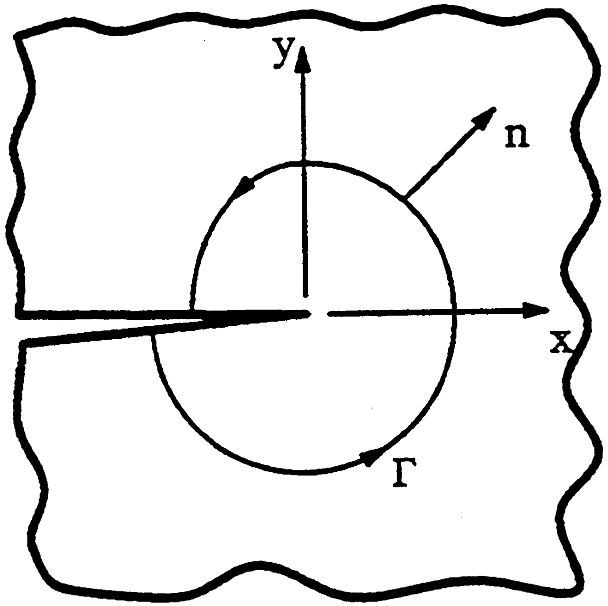
- Fracture parameters are calculated directly in Ansys Workbench.
- Crack initiation angle and energy release rate can be calculated from stress intensity factors.
- Cracks propagate straight (parallel to loading direction) to attain pure mode-I conditions.

WHICH DIRECTION CRACKS PROPAGATE?

- Strain Energy Density Criterion or
- Maximum Tangential Stress Criterion

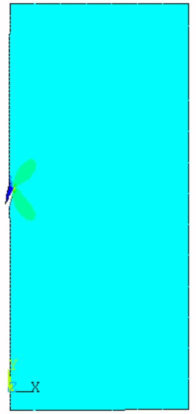






WHEN DO CRACKS PROPAGATE?

Static crack growth mechanics



ANSYS offers two common fracture criteria for static crack-growth simulation and a crack will grow based on the user-specified critical values of a given criterion:

- J-integral: crack growth occurs when $J = J_c$ or

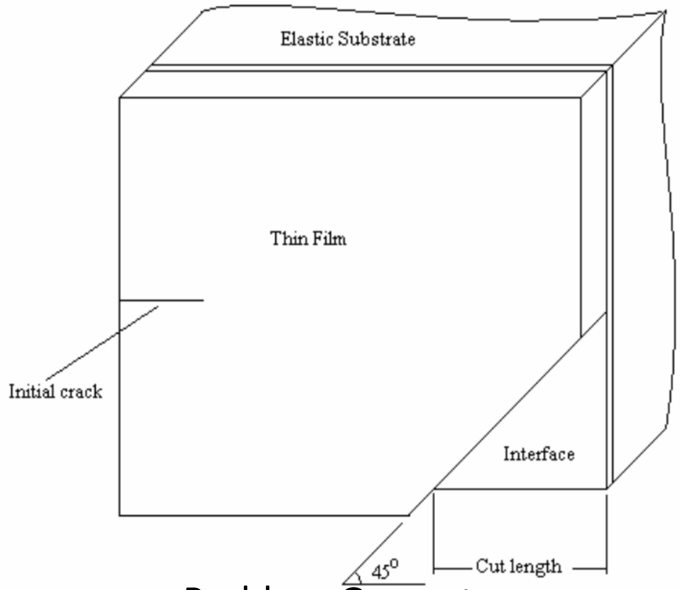
- Stress-intensity factor (SIF): crack growth occurs when $K_I = K_{Ic}$

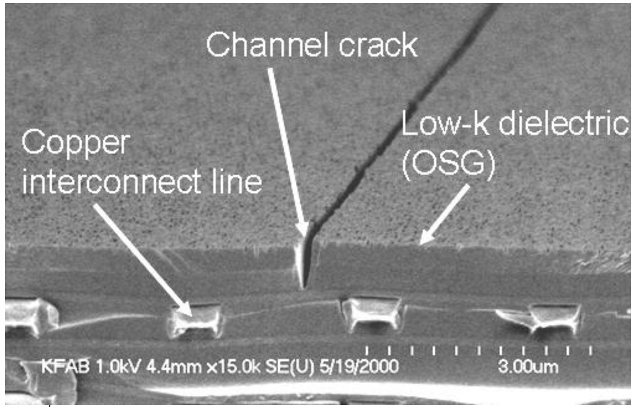
STRESS INTENSITY FACTOR

- The magnitude of stress field in the immediate vicinity of the crack tip is measured by the "Stress Intensity Factor"
- Stress Intensity Factor is a quantity determined analytically and varies as a function of the crack configuration and the external loads are applied
- Critical stress intensity factor is independent of the crack geometry and loading and may be regarded as a material constant.
- Typical critical stress intensity factor values are:

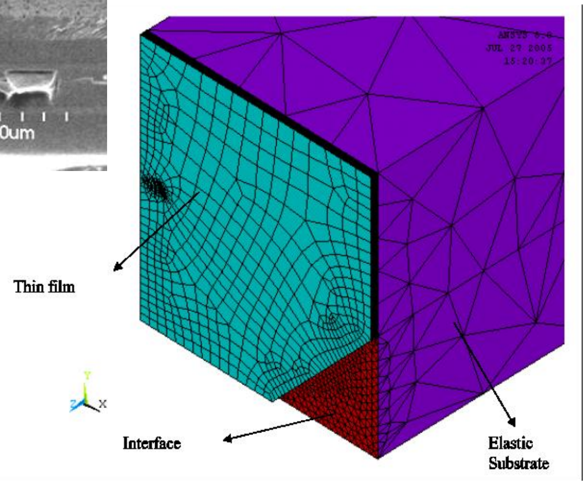
	Ultimate Strength	Critical Stress Intensity Factor
• AL 7075-T651	83 ksi	26 ksi $in^{1/2}$
• AISI 4340	280 ksi	40 ksi $in^{1/2}$

INTERFACE MODELING





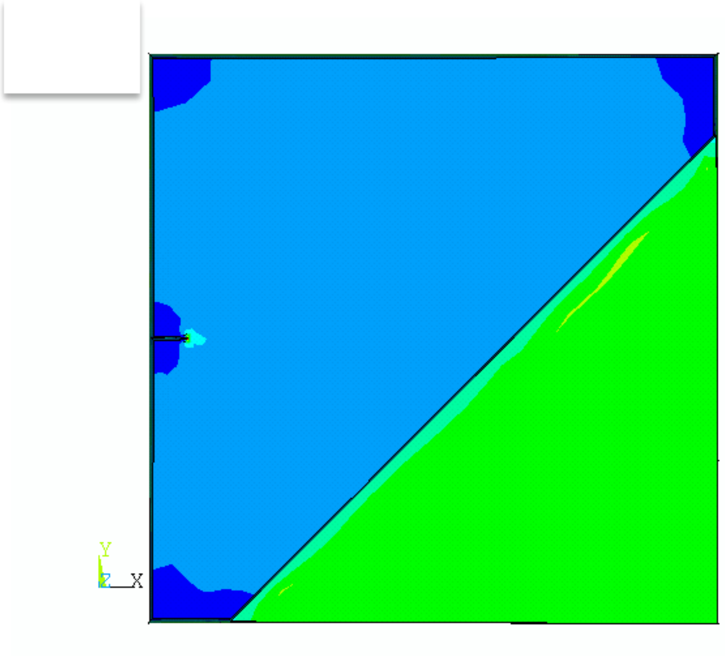
Problem Geometry



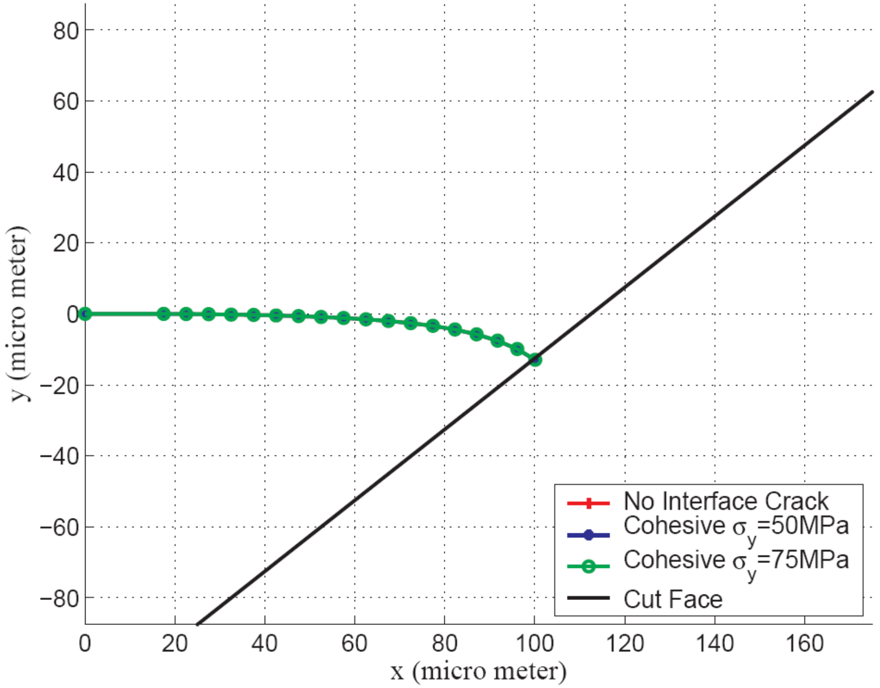
Finite Element Model

- Edge crack propagation in a thin film-substrate(SiO_2/Si) is studied.
- Effect of interface layer on crack propagation path is examined using cohesive zone elements.

3-D EDGE CRACK ANALYSIS IN THIN FILM-SUBSTRATE SYSTEMS



(a) Propagation Animation; Cut Length=150



(b) Propagation Path; Cut Length=150

- Crack propagation is performed quasi-statically. Fracture parameters are calculated at each propagation step and the geometry is updated for the next propagation step.
- Cohesive zone elements are placed between thin film and substrate to model interface.

A TYPICAL MANUFACTURING PROBLEM

- Maximum allowable surface crack size.
- During manufacturing, due to different processes, there may be unwanted surface cracks on the external surfaces.
- During quality inspection, these cracks can be red-flagged.
- What size cracks are allowable?
- An engineer will have to address this question by performing a stress analysis...

MAX ALLOWABLE SURFACE CRACK

- For a surface crack, at the onset of cracking:

  $K_{Ic} = 1.12 * s_c * SQRT(pi * a)$

  Where

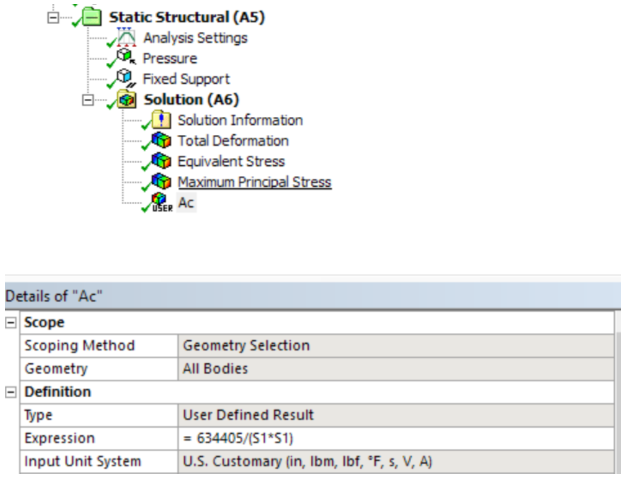
  K_{Ic} is the critical stress intensity factor (mat'l property)

  s_c is the maximum principal stress (max tensile stress – S1)

  a is the maximum allowable crack length

- If you solve for a (maximum allowable crack length):

  $a = (K_{Ic})^{\wedge 2} /(pi * 1.12^{\wedge 2} * s^{\wedge 2})$



- In ANSYS/Mechanical, a "User Defined Result" is created with the above formula which gives the "maximum allowable crack" contour plot:

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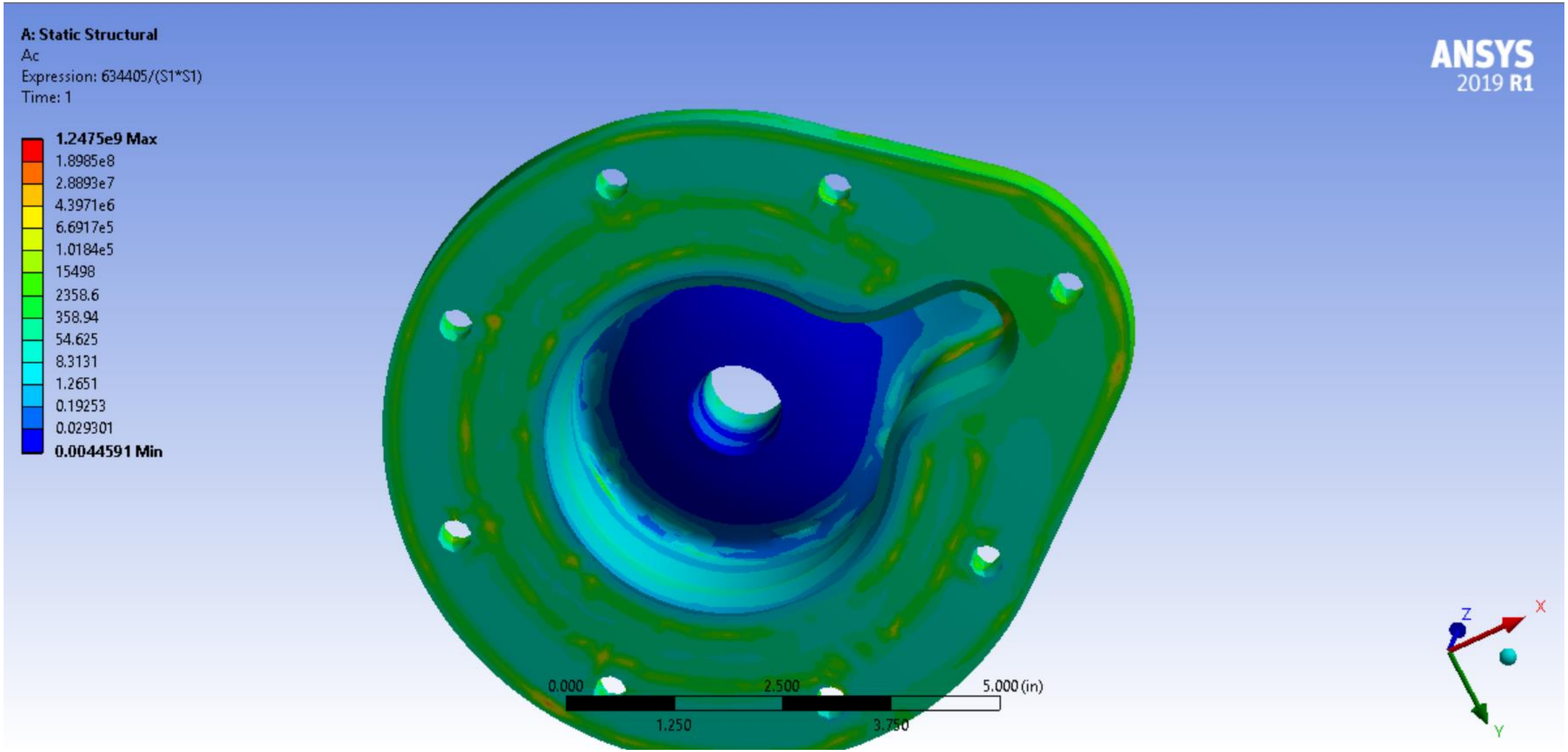
MAX ALLOWABLE SURFACE CRACK CONTOUR PLOT



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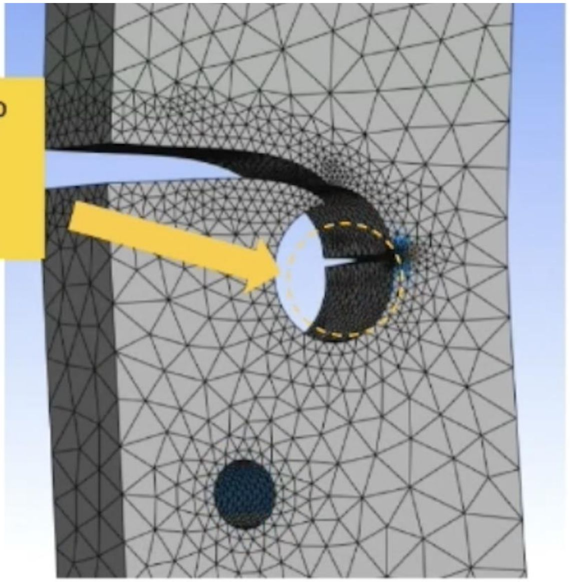
CRACK INITIATION & PROPAGATION

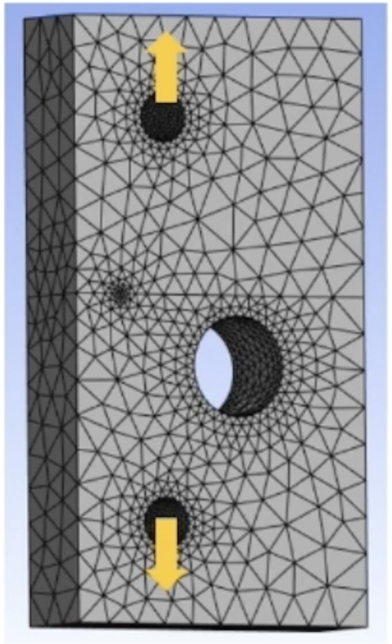
Crack-initiation and propagation with pre-existing crack

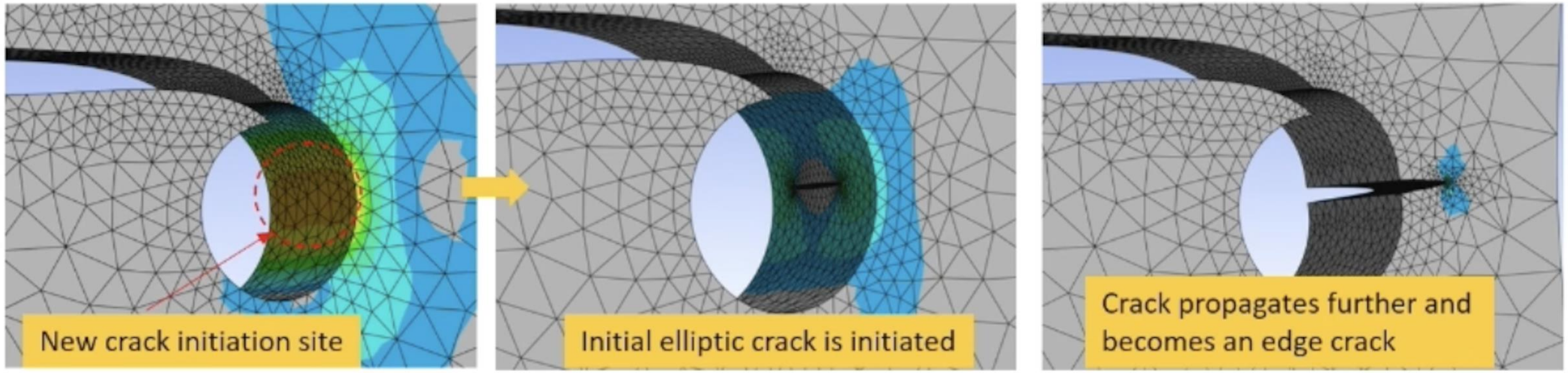
- Static crack growth with stress intensity factor criterion
- New crack initiation based on principal stress criterion

Initial edge crack propagates into the hole, new crack is then initiated after the criterion is reached and propagates further



- New crack is a predefined elliptical crack and will be inserted when the criterion is reached
- Subsequent crack growth follow SMART procedure





SUBMODELING OVERVIEW & CRACK GROWTH

Submodel Creation

↓

Meshing of Submodel & Inclusion of Cracks

↓

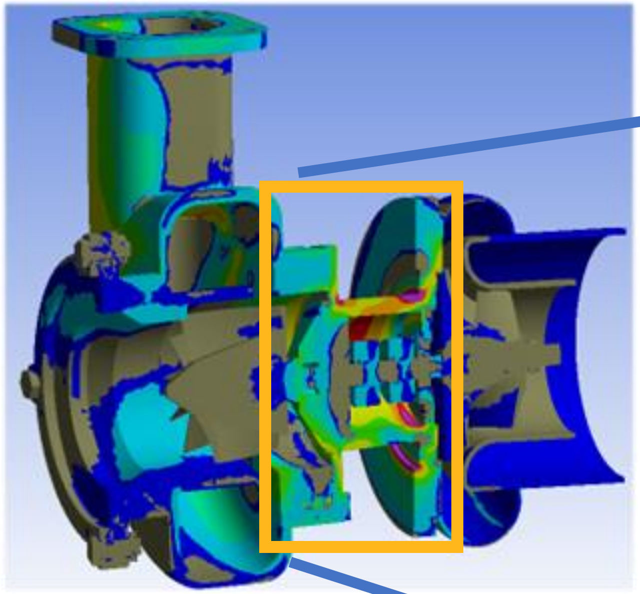
Crack Growth Definition

↓

Definition of Loads & Boundary Conditions

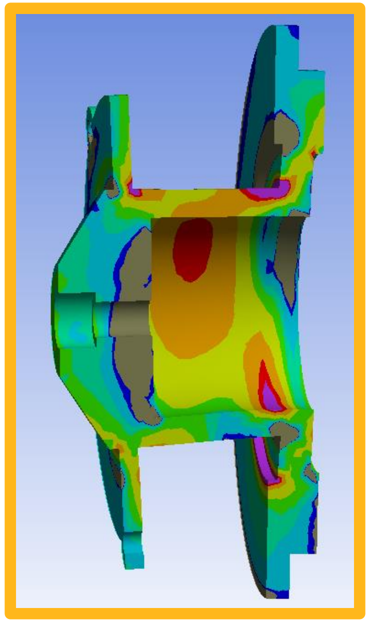
↓

Evaluation of Results



Find Locations of maximum stress

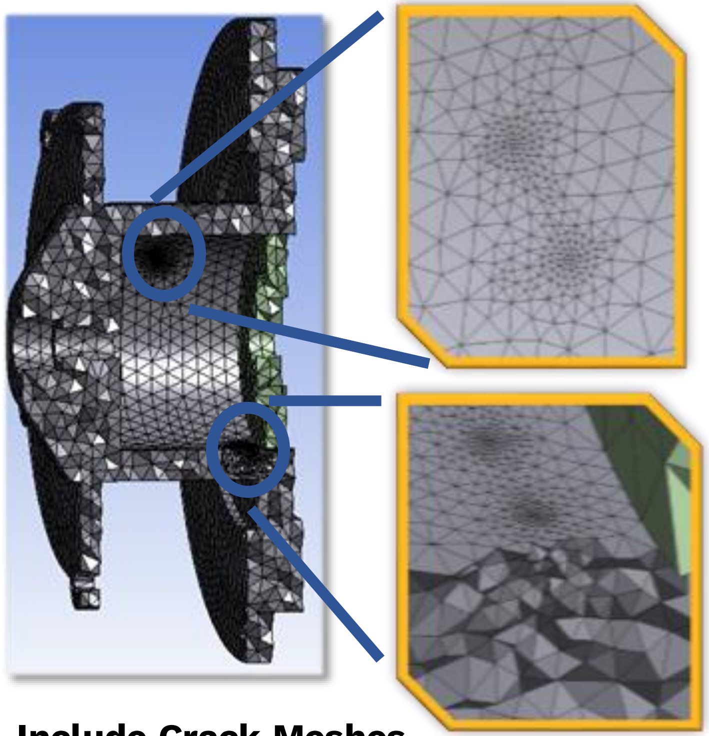
Submodel



SUBMODELING OVERVIEW & CRACK GROWTH

- Submodel Creation
- **Meshing of Submodel & Inclusion of Cracks**
- Crack Growth Definition
- Definition of Loads & Boundary Conditions
- Evaluation of Results

Meshing of Submodel



Include Crack Meshes

SUBMODELING OVERVIEW & CRACK GROWTH

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Meshing of Submodel & Inclusion of Cracks

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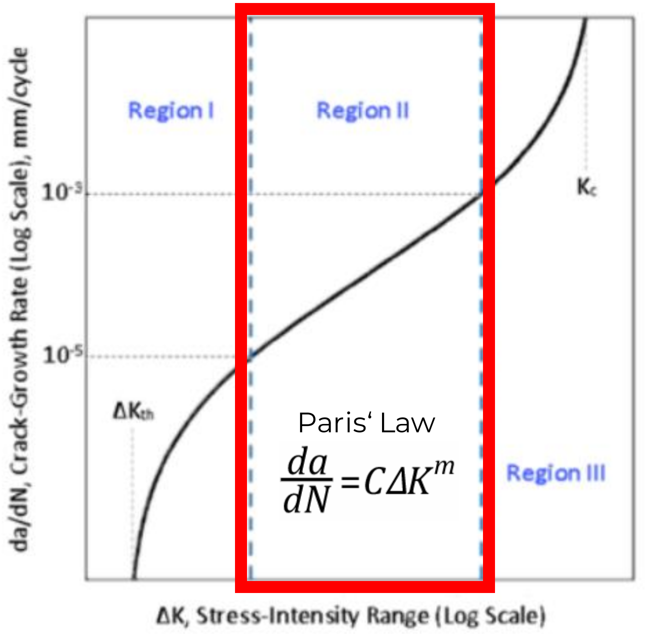
Evaluation of Results



Paris' Law	
Reference Units (Length, Force)	mm, tonne mm s^-2
Material Constant C	1E-12
Material Constant m	3

- Fracture
  - Semi-Elliptical Crack
  - Semi-Elliptical Crack 2
  - SMART Crack Growth
  - SMART Crack Growth 2

Details of "SMART Crack Growth"

Definition	
Analysis	Crack Growth
Method	SMART
Suppressed	No
Options for Crack Growth	
Initial Crack	Semi-Elliptical Crack
Crack Growth Option	Fatigue
Failure Criteria Option	Material Data Table
Material	Structural Steel
Crack Growth Law	Paris Law
Crack Growth Methodology	Life Cycle Prediction
Min Increment of Crack Extension	Program Controlled
Max Increment of Crack Extension	Program Controlled
Stop At Max Crack Extension	None
Stress Ratio	0,

Details of "Analysis Settings"

Step Controls	
Number Of Steps	1,
Current Step Number	1,
Step End Time	1, s
Auto Time Stepping	Off
Define By	Substeps
Number Of Substeps	10,
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Off
Solver Pivot Checking	Program Controlled
Large Deflection	Off
Inertia Relief	Off
Rotordynamics Controls	
Restart Controls	
Fracture Controls	
Fracture	On
SIFS	Yes
J-Integral	No
Material Force	No
T-Stress	No

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SUBMODELING OVERVIEW & CRACK GROWTH

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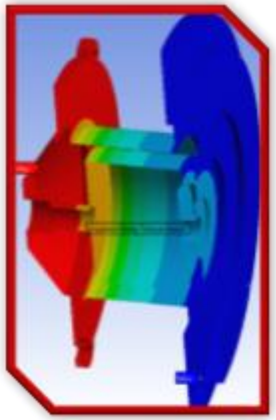
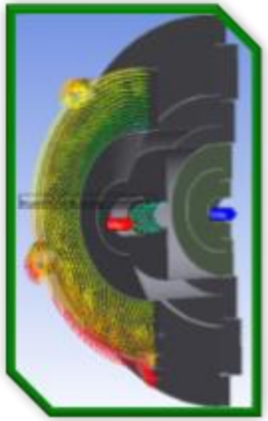
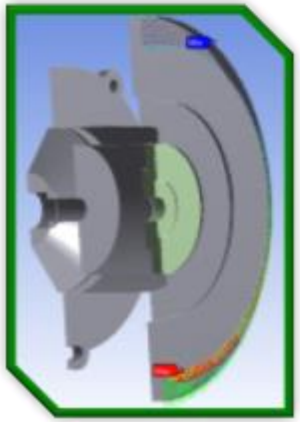






Easy **Import** and **Mapping**
of Loads from preceding Analyses

SUBMODELING OVERVIEW & CRACK GROWTH

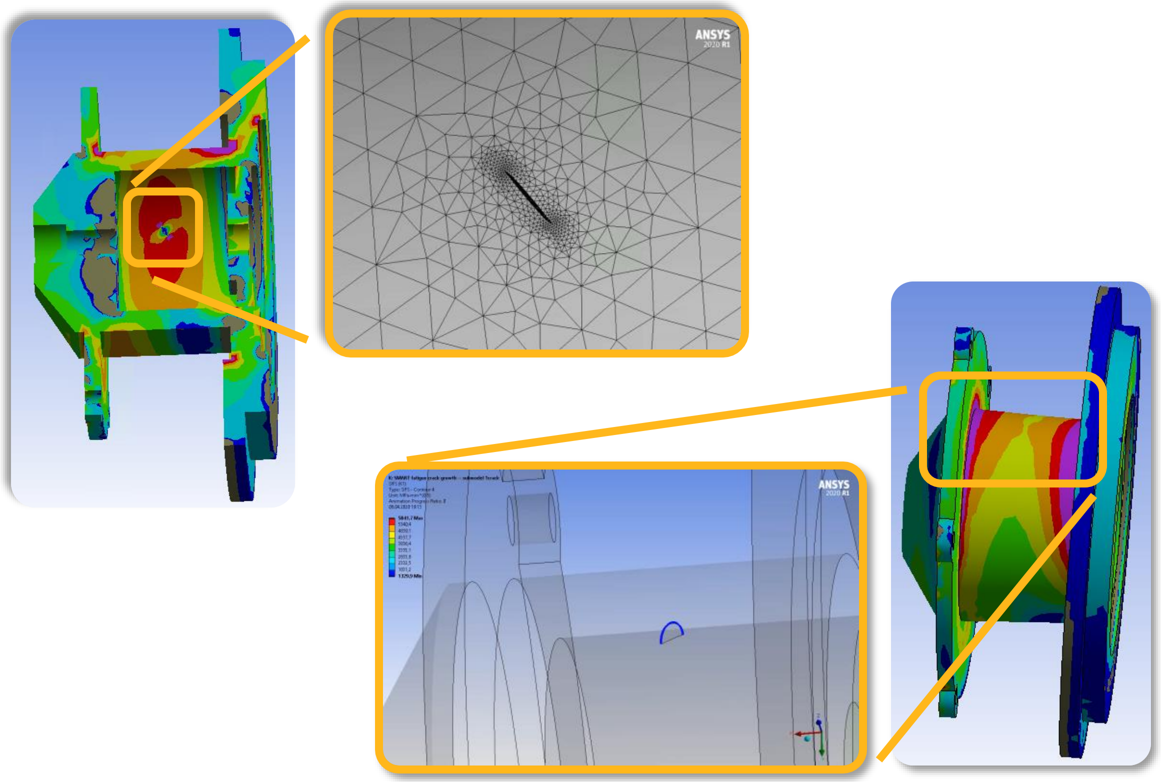
Submodel Creation

Meshing of Submodel & Inclusion of Cracks

Crack Growth Definition

Definition of Loads & Boundary Conditions

Evaluation of Results



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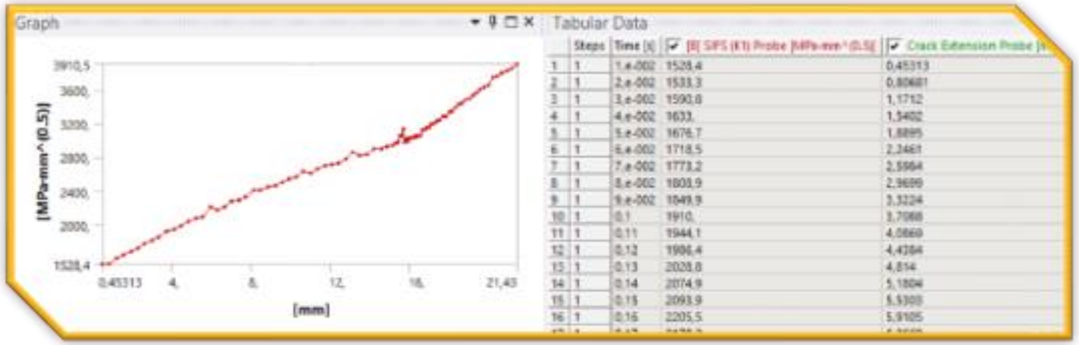
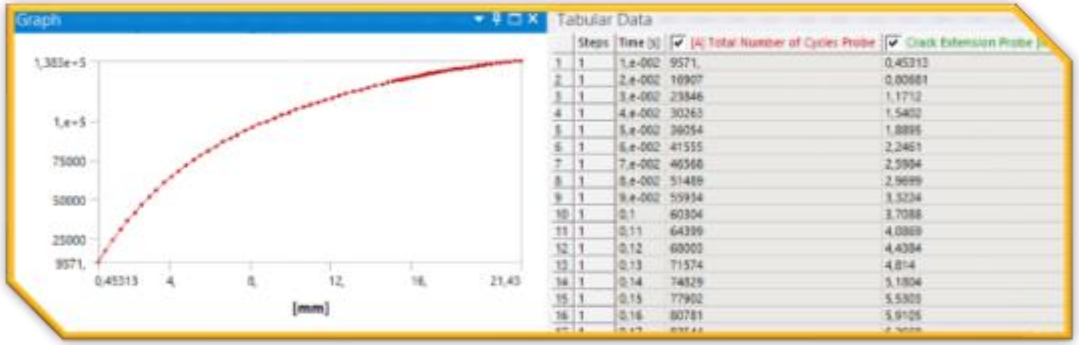
SUBMODELING OVERVIEW & CRACK GROWTH

- Submodel Creation
- Meshing of Submodel & Inclusion of Cracks
- Crack Growth Definition
- Definition of Loads & Boundary Conditions
- **Evaluation of Results**





CRACK GROWTH

Fatigue crack growth

A typical fatigue crack-growth law formulates the crack-extension increment as function of stress-intensity factor and stress ratio:

$$\frac{da}{dN} = f(K, R)$$

a - crack extension

N - fatigue cycle count

$\frac{da}{dN}$ - crack-growth rate per loading cycle due to fatigue

K - stress-intensity factor

R - stress ratio: $R = K_{min} / K_{max}$ (SIFS at minimum and maximum loads)

CRACK GROWTH

Paris' Law

$$\frac{da}{dN} = C \Delta K^m$$

- Paris' Law constants dependent on the material characteristics and stress ratio

- stress-intensity-factor range during the fatigue cycle:

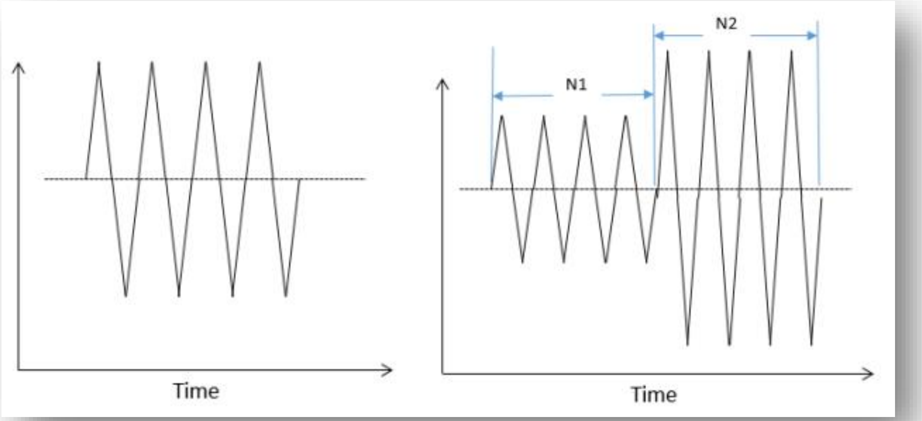
C m Paris' Law constants dependent on the material characteristics and stress ratio

ΔK Stress-intensity-factor range during the fatigue cycle: $\Delta K = (1 - R) \times K_{\max}$

- **Life-cycle (LC)**– Uses crack-extension increment Δa to calculate the load-cycle increment ΔN.
- **Cycle-by-cycle (CBC)** – Uses the load-cycle increment ΔN to calculate crack-extension increment Δa.

CRACK GROWTH – LOADING TYPES

Only cyclic loadings of constant amplitudes are allowed, as shown below:

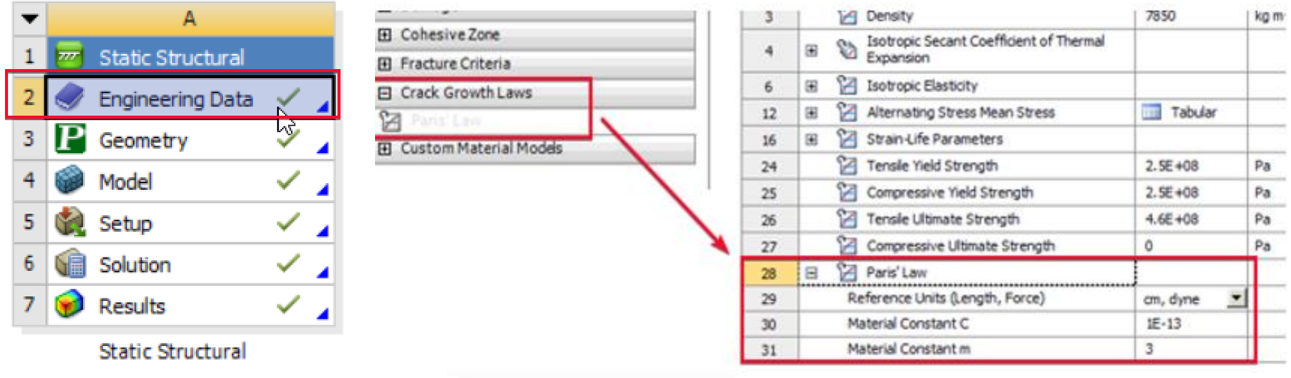


Life Cycle **Cycle-by-Cycle**

Life Cycle Method (LC)	Cycle-by-Cycle Method (CBC)
The LC method is typically used with constant-amplitude cyclic loads..	The CBC method is suitable for variable-amplitude cyclic loadings and overload simulations.

- **Life-cycle (LC)**– Uses crack-extension increment Δa to calculate the load-cycle increment ΔN.
- **Cycle-by-cycle (CBC)** – Uses the load-cycle increment ΔN to calculate crack-extension increment Δa.

ENGINEERING DATA – PARIS LAW



FRACTURE MECHANICS DOCUMENTATION

- Mechanical APDL
  - Mechanical APDL as a Server User's Guide
  - Advanced Analysis Guide
  - ANSYS LS-DYNA User's Guide
  - Acoustic Analysis Guide
  - ANSYS Parametric Design Language Guide
  - Basic Analysis Guide
  - Command Reference
  - Connection User's Guide
  - Coupled-Field Analysis Guide
  - Contact Technology Guide
  - Cyclic Symmetry Analysis Guide
  - Element Reference
  - Feature Archive
  - Fluids Analysis Guide
  - Fracture Analysis Guide
    - 1. Introduction to Fracture
      - 1.1. Understanding Fracture Mechanics
      - 1.2. Solving Fracture Mechanics Problems
      - 1.3. Learning More About Fracture Mechanics
    - 2. Evaluation of Fracture Mechanics Parameters
      - 2.1. J-integral Calculation
      - 2.2. VCCT Energy-Release Rate Calculation
      - 2.3. Stress-Intensity Factor (SIF) Calculation
      - 2.4. T-stress Calculation
      - 2.5. Material Force Calculation
      - 2.6. C*-integral Calculation
      - 2.7. Unstructured Mesh Method (UMM)
    - 3. Crack Growth Simulation, Interface Delamination, and Fatigue Crack Growth
      - 3.1. VCCT-Based Crack-Growth Simulation
      - 3.2. XFEM-Based Crack Analysis and Crack-Growth Simulation
      - 3.3. Modeling Interface Delamination with Interface Elements
      - 3.4. Modeling Interface Delamination with Contact Elements (Debonding)
      - 3.5. Fatigue Crack Growth

SUMMARY:

- Ansys can be used for fatigue calculation (not covered here)

- Ansys can be used for crack initiation site(s) determination

- Ansys can be used for crack propagation

$$L_{total} = L_{fatigue/crack\ initiation} + L_{crack\ propagation}$$

Thank you for watching!

Any questions?

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