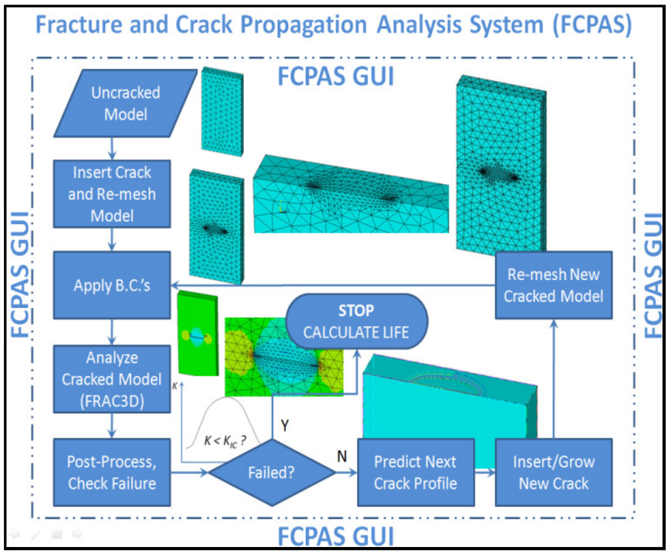
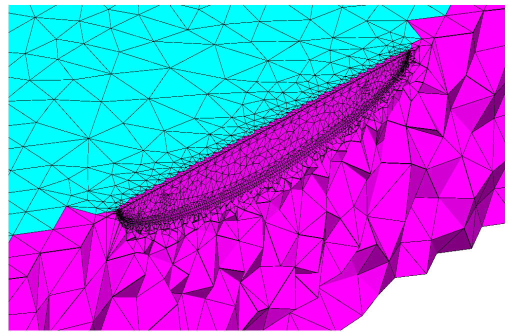
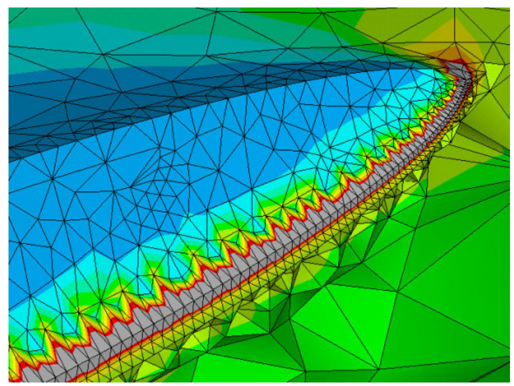
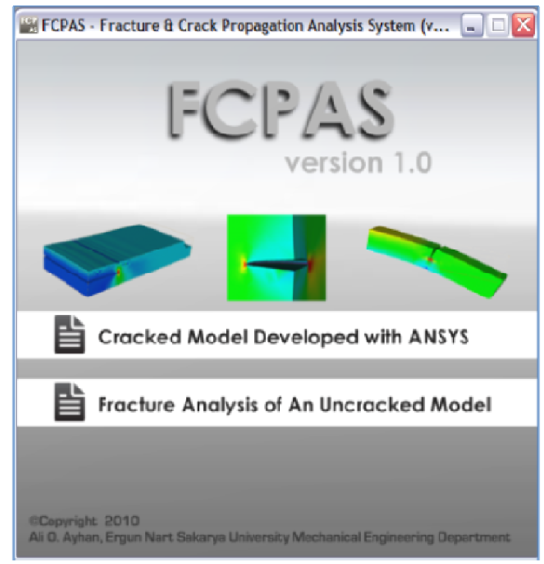
Modeling and Analysis of Three-Dimensional Cracks Using Unstructured Finite Elements









E. Nart, A. O. Ayhan*
Department of Mechanical Engineering
Sakarya University
54187 Sakarya, TURKEY
*E-mail: ayhan@sakarya.edu.tr

Agenda

- Fracture Mechanics – Motivation and Needs
- 3D Fracture Mechanics – Available Methods/Tools
- Enriched Finite Elements for 3D Fracture Mechanics
- FCPAS – Fracture and Crack Propagation Analysis System
    - *Fracture finite element models developed using ANSYS*
    - *Fracture finite element models developed by crack insertion into an uncracked model*
    - *Fracture analysis by three-dimensional enriched finite elements*
- Applications:
    - *Mode-I surface crack insertion into an uncracked finite-thickness plate*
    - *Inclined and deflected surface crack insertion into an uncracked finite-thickness plate*
    - *Fracture solutions by enriched finite elements*
    - *Fatigue crack growth analysis of Mode-I surface crack in a plate under cyclic bending load*
- Summary/Conclusions

Why Fracture Mechanics?

Schenectady T2 Tanker, January 16, 1943

- 152m long T2 tanker, 'Schenectady'
- 16 January 1943 (A few days after the sea trials)
- Breaks into two parts while lying at the harbor (Portland, Oregon)
- Still harbor water and about 4°C
- Light winds and air temperature about -3°C
- Sudden failure heard a mile away
- Fracture extended through the deck, the sides of the hull, the longitudinal bulkheads and the bottom girders.
- Central part of the ship rose clear of the water

Poor welding in highly stressed region

Ref: http://www.twi.co.uk/j32k/protected/band_13/oilgas_caseup31.html

Why Fracture Mechanics?

Aloha Airlines Flight 243, April 28, 1988

- April 28, 1988, 1:25 pm Hilo to Honolulu
- Rupture of fuselage at the top of its climb
- Senior flight attendant blown from the aircraft to her death
- The cockpit door and roof blown away
- Most passengers were injured, seven seriously

Undetected “fatigue damage”

Ref: http://www.volpe.dot.gov/infosrc/journal/30th/safety.html

Mechanical Life of A Part

LCF, HCF, Creep, Oxidation…

Fatigue & Creep CP, Fracture

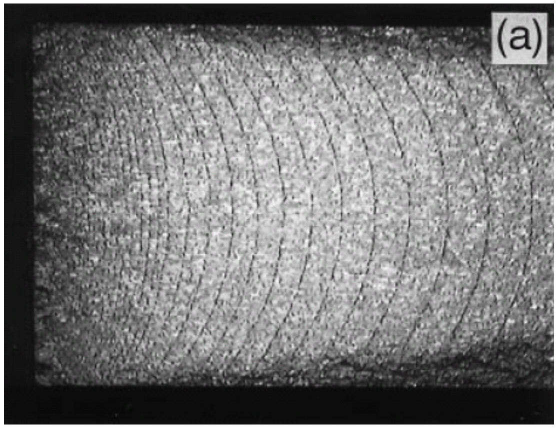
Crack Initiation + **Crack Propagation** = **Total Life**

S-N, Goodman, Creep Curves

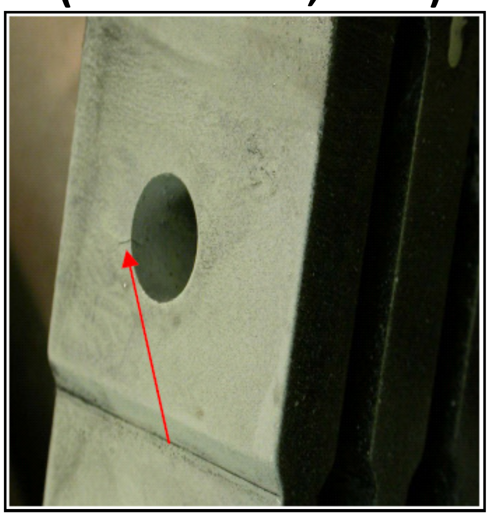
Fracture Mech., da/DN, da/dt Curves, K_{IC}

3D Fracture Mechanics – Motivation and Needs

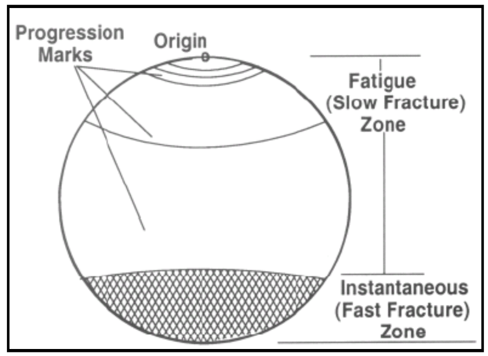
Aluminum Plate (Takashi et al, 2000)



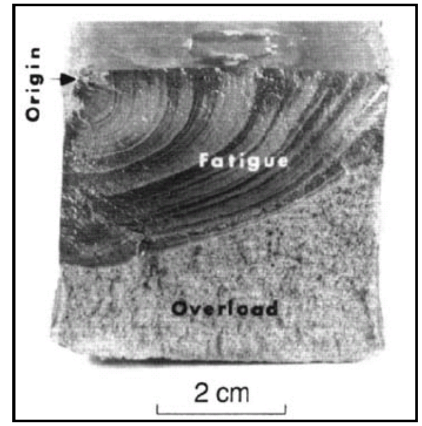
Turbine Bucket Dovetail (Dumas et al, 2006)



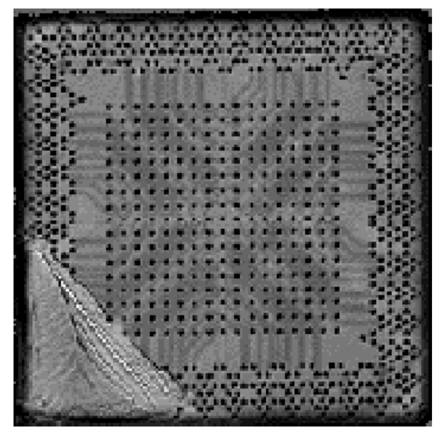
Fatigue Crack Propagation



A Machine Part (Dowling, 2002)



Electronic Package (D. Peterson, 1998)



Though many problems can be approximated by 2D methods, most real problems are 3D

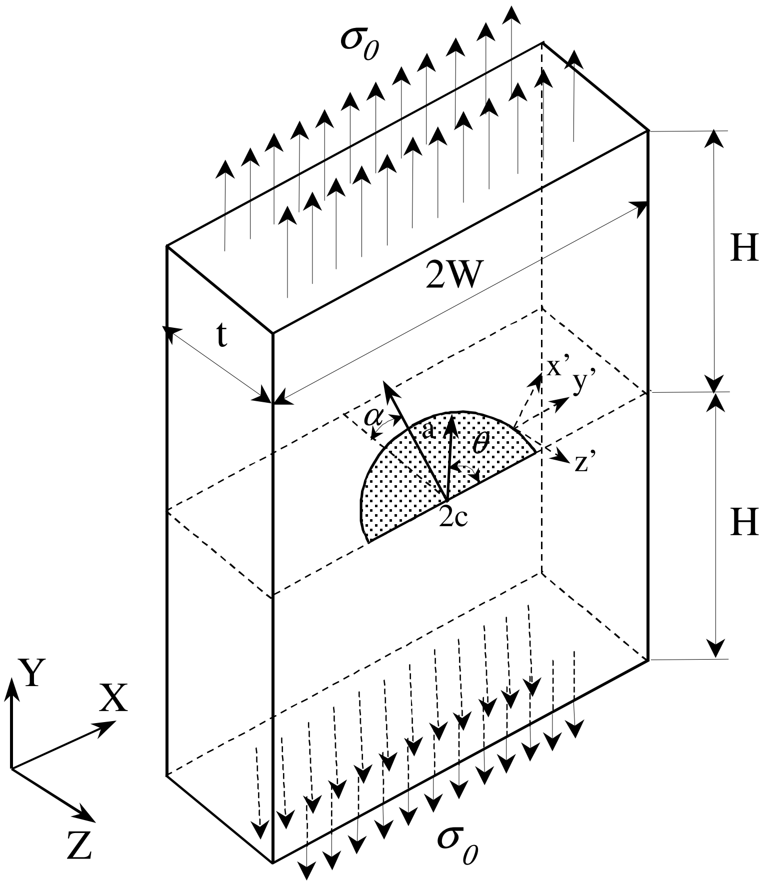
Agenda

- ❑ Fracture Mechanics – Motivation and Needs
- ❑ 3D Fracture Mechanics – Available Methods/Tools
- ❑ Enriched Finite Elements for 3D Fracture Mechanics
- ❑ FCPAS – Fracture and Crack Propagation Analysis System
  - ❑ *Fracture finite element models developed using ANSYS*
  - ❑ *Fracture finite element models developed by crack insertion into an uncracked model*
  - ❑ *Fracture analysis by three-dimensional enriched finite elements*
- ❑ Applications:
  - ❑ *Mode-I surface crack insertion into an uncracked finite-thickness plate*
  - ❑ *Inclined and deflected surface crack insertion into an uncracked finite-thickness plate*
  - ❑ *Fracture solutions by enriched finite elements*
  - ❑ *Fatigue crack growth analysis of Mode-I surface crack in a plate under cyclic bending load*
- ❑ Summary/Conclusions

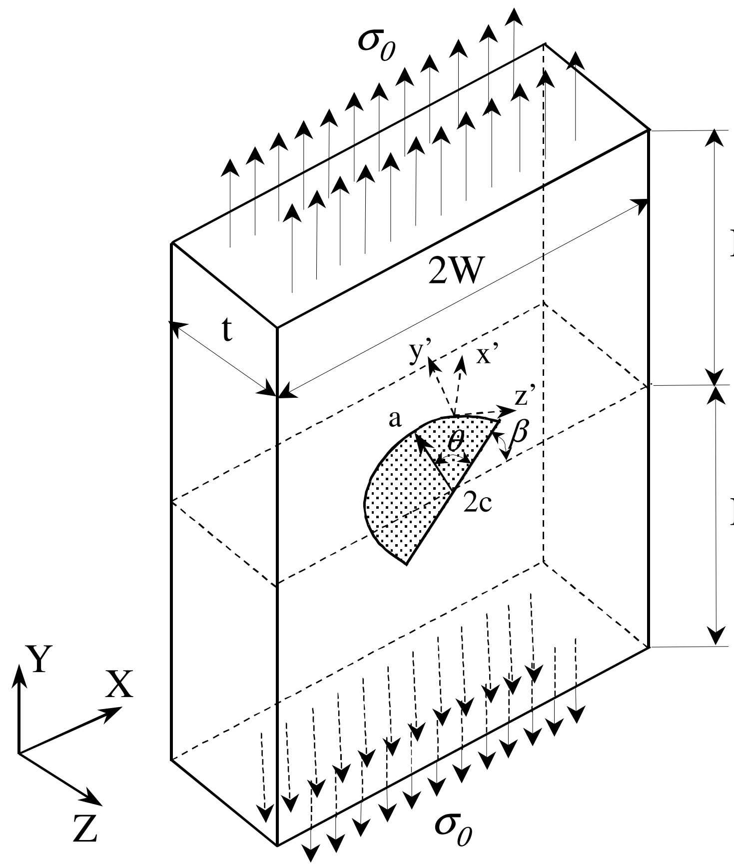
3D Fracture Mechanics

The Most Common Types of Cracks are Surface & Corner Cracks

Deflected Surface Crack



Inclined Surface Crack



3D Fracture Mechanics – Available Methods/Tools

Disadvantages

- Limited geometry or loading

Methods/Tools

- Alternating methods
- Boundary element methods
- Virtual Crack Extension Method
- Line-Spring Method

Advantages

- Quicker to solve, simple models and geometries

- Finite Element Methods

Disadvantages

- Model and mesh generation can be time consuming

Finite Element Methods

  - ➢ Quarter-point elements
  - ➢ J & Interaction Integral
  - ➢ Domain Integral
  - ➢ ***<u>Enriched Finite Elements (Topic of This Presentation)</u>***

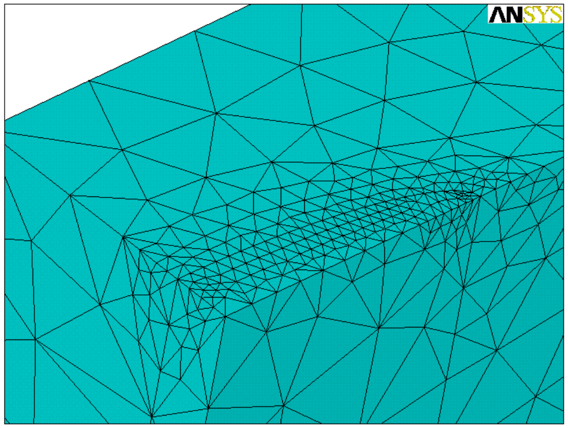
Advantages

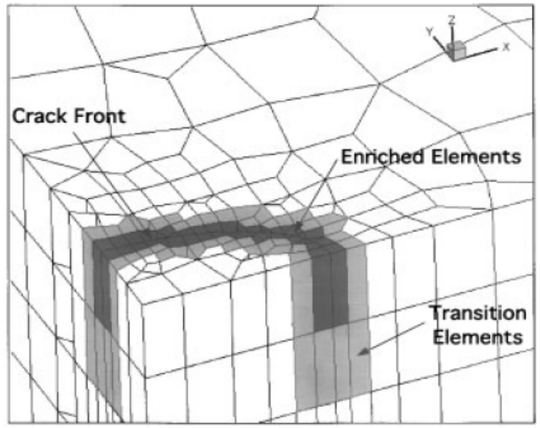
- Accurate representation of actual geometry and local loads near crack region
- *Multi-loading and material model capabilities*

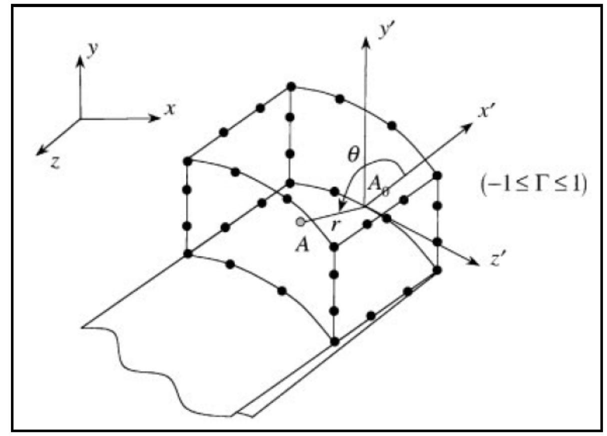
Agenda

- ❑ Fracture Mechanics – Motivation and Needs
- ❑ 3D Fracture Mechanics – Available Methods/Tools
- ❑ Enriched Finite Elements for 3D Fracture Mechanics
- ❑ FCPAS – Fracture and Crack Propagation Analysis System
  - ❑ *Fracture finite element models developed using ANSYS*
  - ❑ *Fracture finite element models developed by crack insertion into an uncracked model*
  - ❑ *Fracture analysis by three-dimensional enriched finite elements*
- ❑ Applications:
  - ❑ *Mode-I surface crack insertion into an uncracked finite-thickness plate*
  - ❑ *Inclined and deflected surface crack insertion into an uncracked finite-thickness plate*
  - ❑ *Fracture solutions by enriched finite elements*
  - ❑ *Fatigue crack growth analysis of Mode-I surface crack in a plate under cyclic bending load*
- ❑ Summary/Conclusions

Enriched Finite Elements for 3D Fracture Analysis







$$u(\xi,\eta,\rho) = \sum_{j=1}^{nodel} N_j(\xi,\eta,\rho)u_j + Z_0(\xi,\eta,\rho)\sum_{i=1}^{ntip} N_i(\bar{\xi})K_I^i\left(f_1(\xi,\eta,\rho) - \sum_{j=1}^{nodel} N_j(\xi,\eta,\rho) f_{1j} \right)$$

$$+ Z_0(\xi,\eta,\rho)\sum_{i=1}^{ntip} N_i(\bar{\xi})K_{II}^i\left(g_1(\xi,\eta,\rho) - \sum_{j=1}^{nodel} N_j(\xi,\eta,\rho) g_{1j} \right)$$

$$v(\xi,\eta,\rho) = \sum_{j=1}^{nodel} N_j(\xi,\eta,\rho)v_j + Z_0(\xi,\eta,\rho)\sum_{i=1}^{ntip} N_i(\bar{\xi})K_I^i\left(f_2(\xi,\eta,\rho) - \sum_{j=1}^{nodel} N_j(\xi,\eta,\rho) f_{2j} \right)$$

$$+ Z_0(\xi,\eta,\rho)\sum_{i=1}^{ntip} N_i(\bar{\xi})K_{II}^i\left(g_2(\xi,\eta,\rho) - \sum_{j=1}^{nodel} N_j(\xi,\eta,\rho) g_{2j} \right)$$

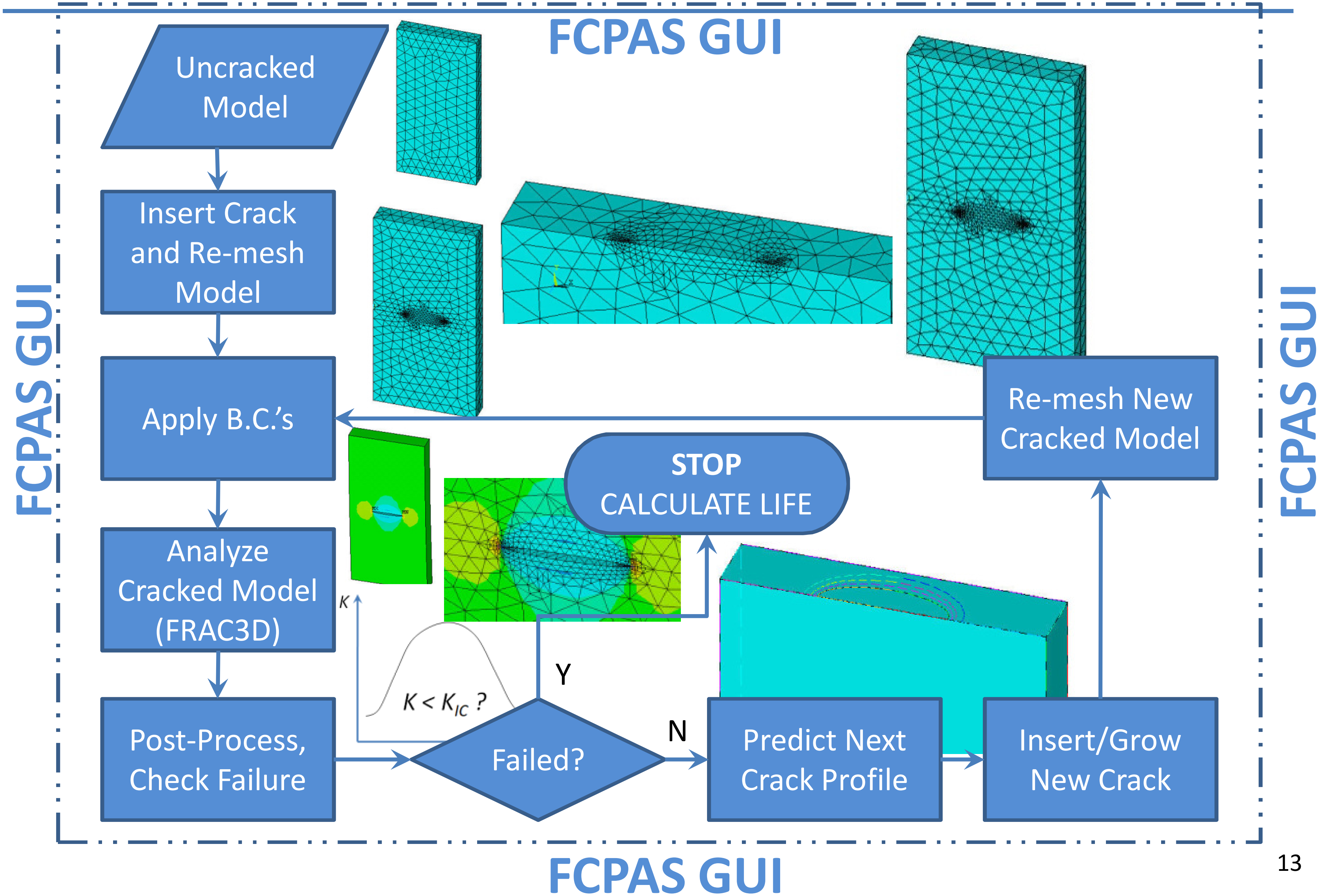
$$w(\xi,\eta,\rho) = \sum_{j=1}^{nodel} N_j(\xi,\eta,\rho)w_j + Z_0(\xi,\eta,\rho)\sum_{i=1}^{ntip} N_i(\bar{\xi})K_{III}^i\left(h(\xi,\eta,\rho) - \sum_{j=1}^{nodel} N_j(\xi,\eta,\rho) h_j \right)$$

Unknown Stress Intensity Factors Are Included in the FE Formulation & Solved for Directly

Agenda

- ❑ Fracture Mechanics – Motivation and Needs
- ❑ 3D Fracture Mechanics – Available Methods/Tools
- ❑ Enriched Finite Elements for 3D Fracture Mechanics
- ❑ FCPAS – Fracture and Crack Propagation Analysis System
  - ❑ *Fracture finite element models developed using ANSYS*
  - ❑ *Fracture finite element models developed by crack insertion into an uncracked model*
  - ❑ *Fracture analysis by three-dimensional enriched finite elements*
- ❑ Applications:
  - ❑ *Mode-I surface crack insertion into an uncracked finite-thickness plate*
  - ❑ *Inclined and deflected surface crack insertion into an uncracked finite-thickness plate*
  - ❑ *Fracture solutions by enriched finite elements*
  - ❑ *Fatigue crack growth analysis of Mode-I surface crack in a plate under cyclic bending load*
- ❑ Summary/Conclusions

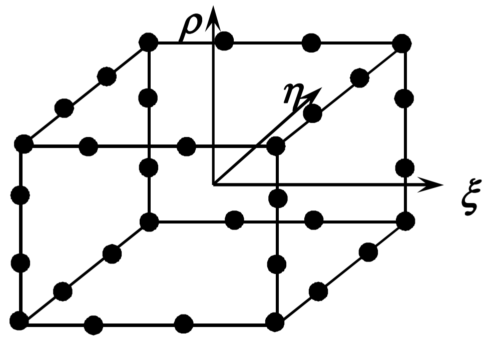
Fracture and Crack Propagation Analysis System (FCPAS)



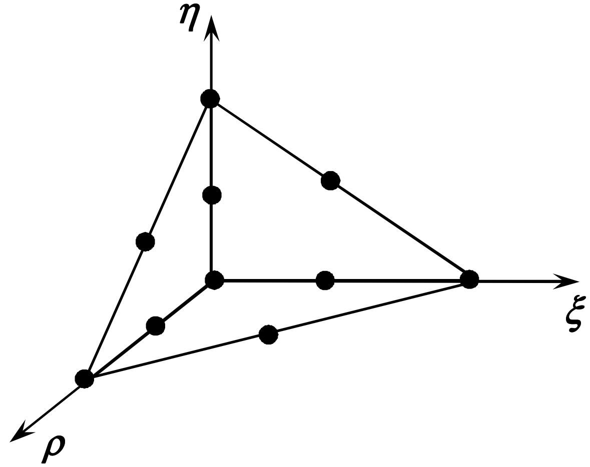
FRAC3D – FCPAS Solver for 3D Fracture Analysis

- Supported Element Types

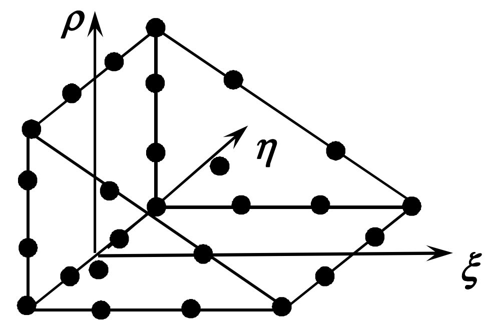
32-Node Hexahedron



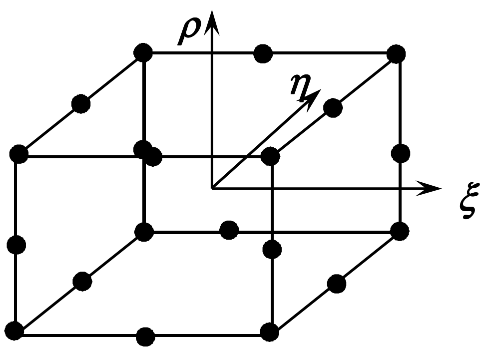
10-Node Tetrahedron



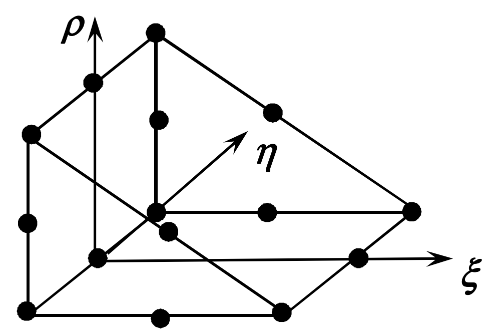
26-Node Pentahedron



20-Node Hexahedron



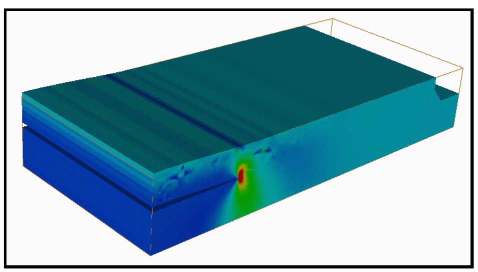
15-Node Pentahedron

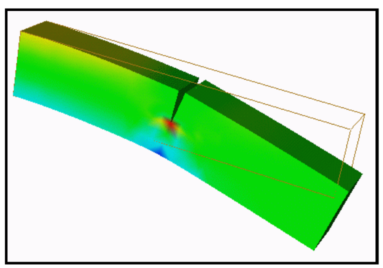


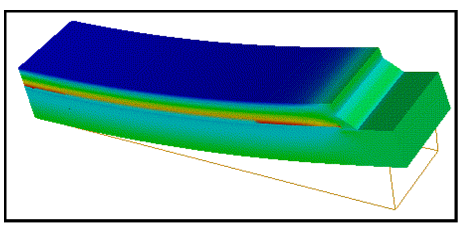
FRAC3D – FCPAS Solver for 3D Fracture Analysis

Boundary Conditions

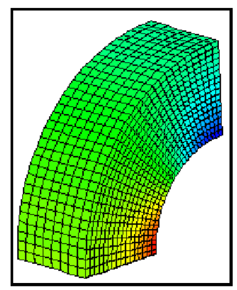
- Load Types
  - Pressure Loading on Surfaces
  - Concentrated Forces on Nodes
  - Thermal Loading
  - Inertia Loading
  - Centrifugal Loading

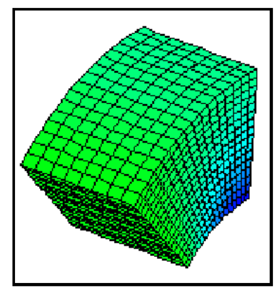


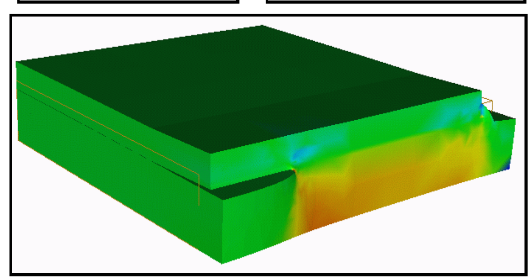




- Constraints
  - Displacement Constraints on Nodes
  - Constraints on Node Sets (Tied Nodes)
  - Displacements on Skew Edges
  - Sub-model BC's from ANSYS



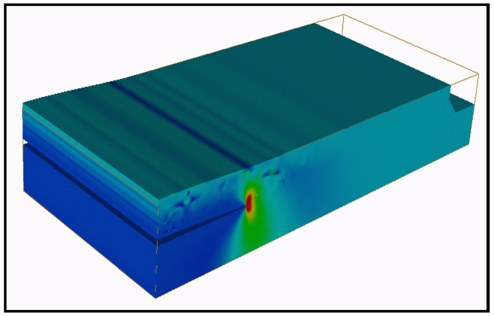


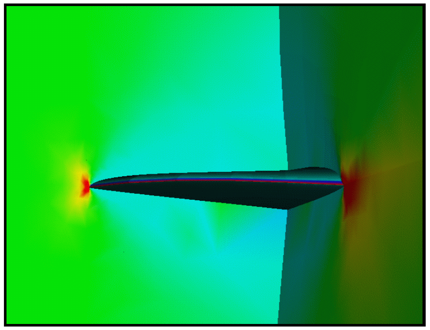


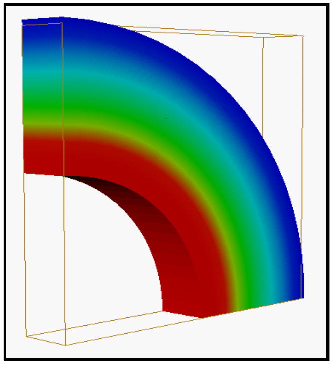
FRAC3D – FCPAS Solver for 3D Fracture Analysis

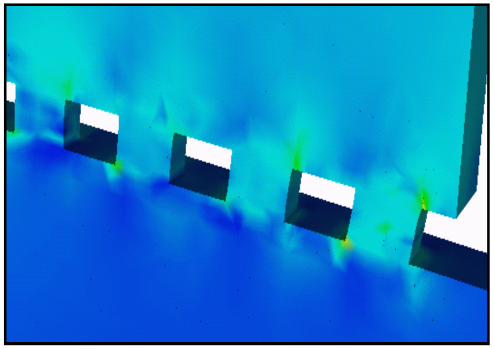
Analysis Types & Material Systems Supported

- Analysis Types
  - Elastic Stress Analysis
  - Elastic/Plastic Stress Analysis
  - Linear Elastic Fracture Mechanics w/ & w/o plasticity on uncracked material
  - Submodeling of ANSYS models
- Material Systems
  - Homogeneous Isotropic
  - Bi-material Isotropic
  - Homogeneous Orthotropic
  - FGM Isotropic
  - Elastic/plastic Isotropic







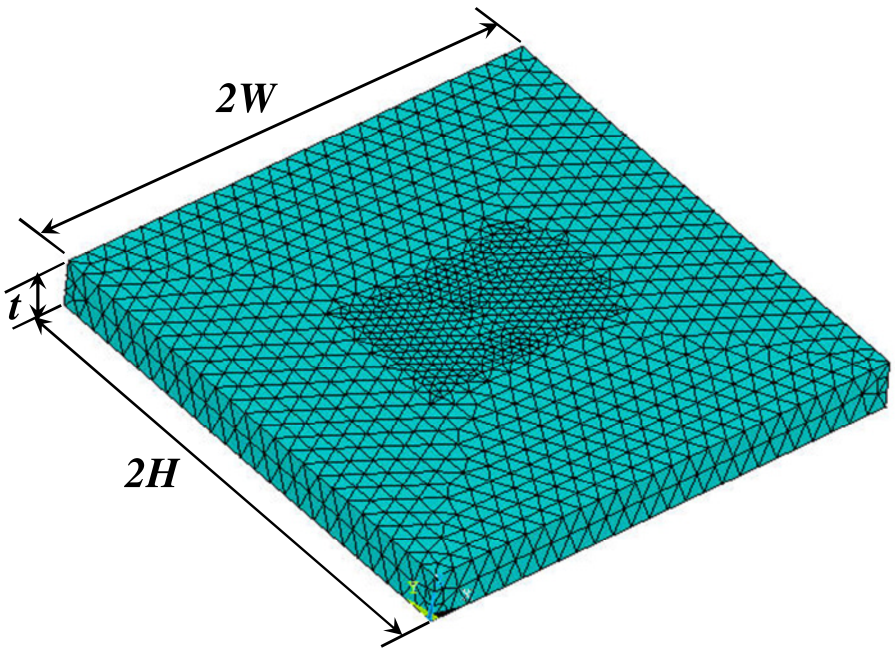


Agenda

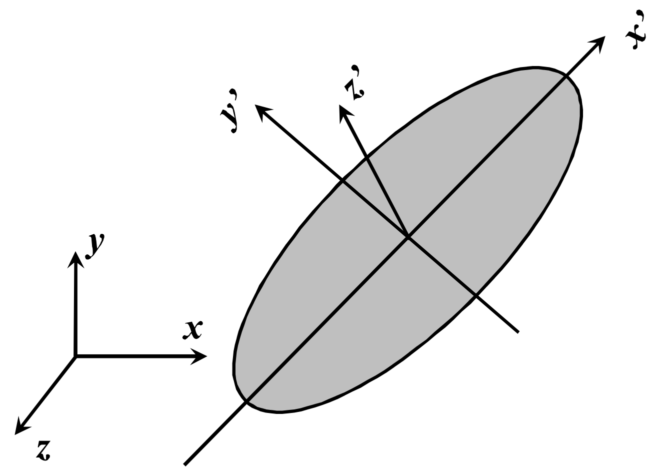
- Fracture Mechanics – Motivation and Needs
- 3D Fracture Mechanics – Available Methods/Tools
- Enriched Finite Elements for 3D Fracture Mechanics
- FCPAS – Fracture and Crack Propagation Analysis System
    - *Fracture finite element models developed using ANSYS*
    - *Fracture finite element models developed by crack insertion into an uncracked model*
    - *Fracture analysis by three-dimensional enriched finite elements*
- Applications:
    - *Mode-I surface crack insertion into an uncracked finite-thickness plate*
    - *Inclined and deflected surface crack insertion into an uncracked finite-thickness plate*
    - *Fracture solutions by enriched finite elements*
    - *Fatigue crack growth analysis of Mode-I surface crack in a plate under cyclic bending load*
- Summary/Conclusions

Applications: Crack Insertion (Mode-I Surface Crack)

Uncracked Plate Finite Element Model



An Elliptical Crack Shape to be Inserted into Plate Model

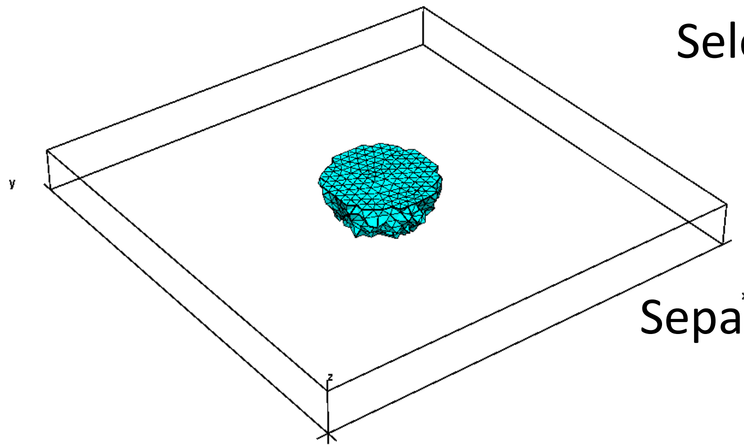


Info for …

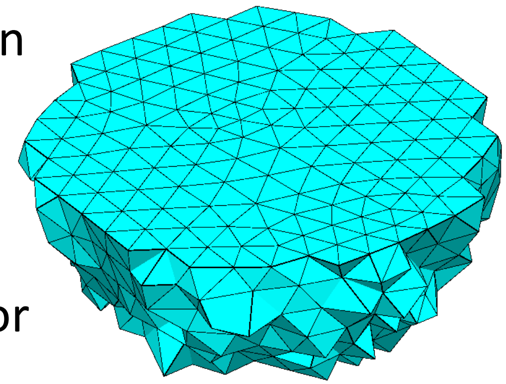
Location, Size and Orientation

of the crack are needed !

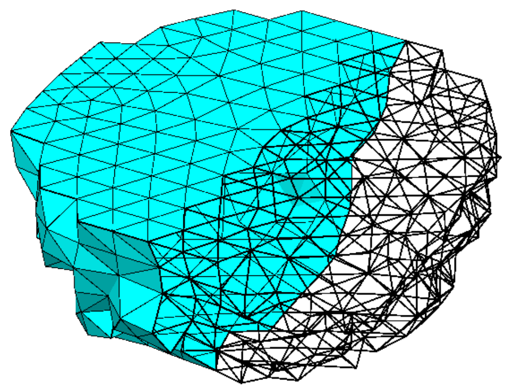
Applications: Crack Insertion (Mode-I Surface Crack)



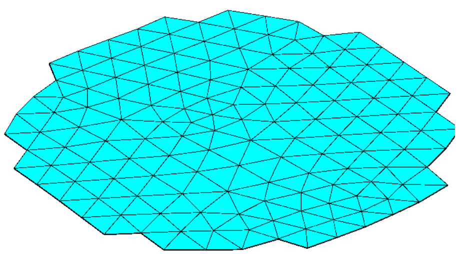
Select A Chunk Region



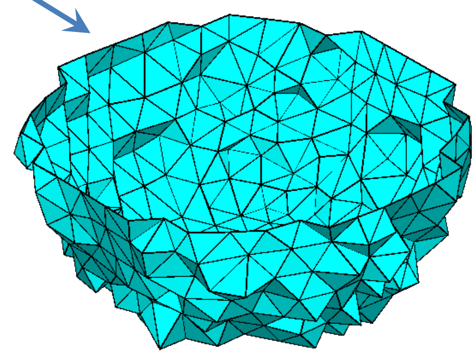
Separate Chunk Exterior Mesh Facets

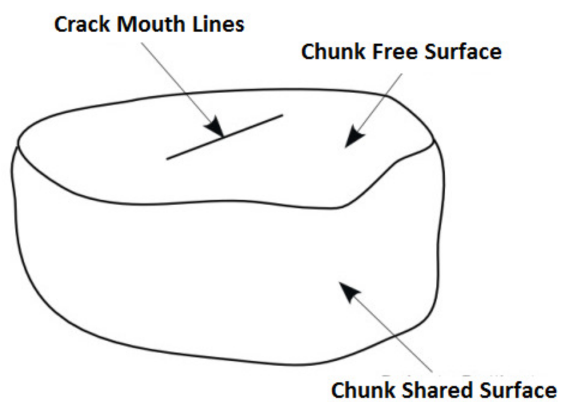


Chunk Outer Free Surface



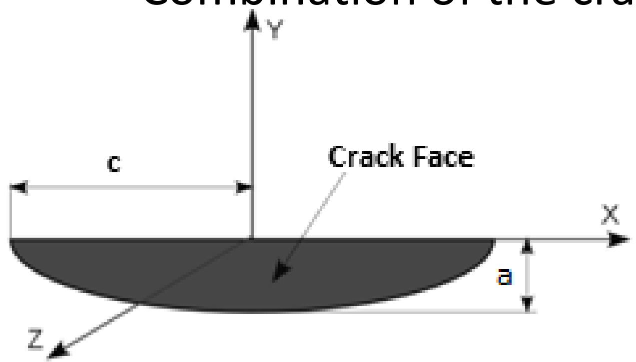
Chunk outer shared-surface

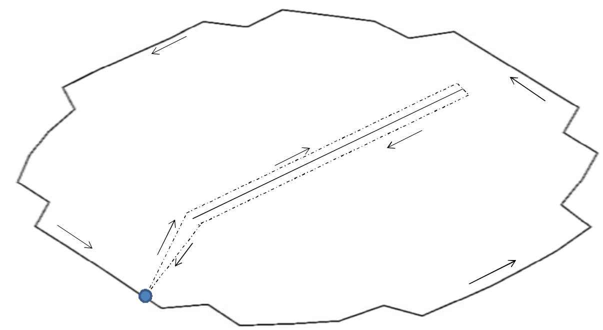




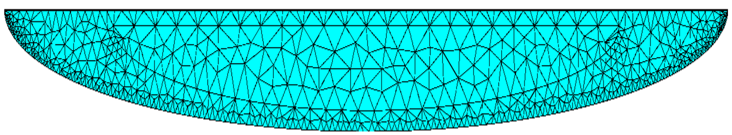
Applications: Crack Insertion (Mode-I Surface Crack)

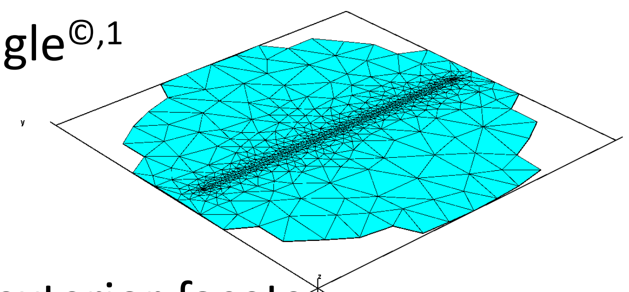
Combination of the crack mouth line and crack front line



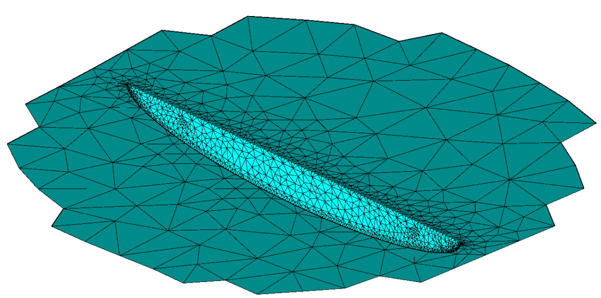


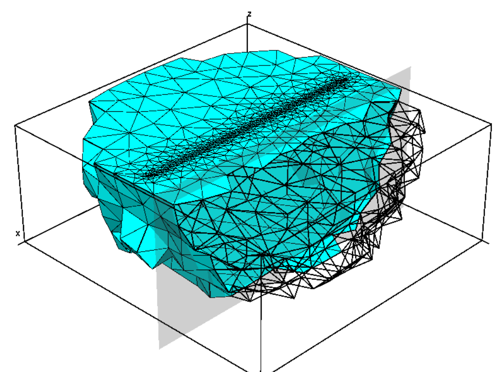
2D meshing by Triangle©,1

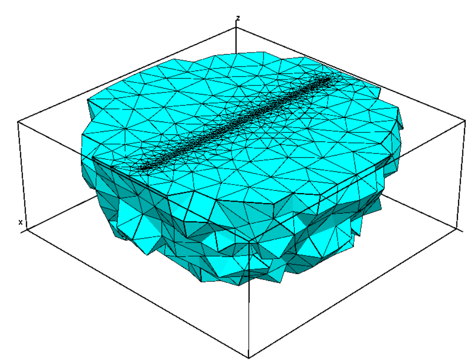




Combine the modified chunk exterior facets



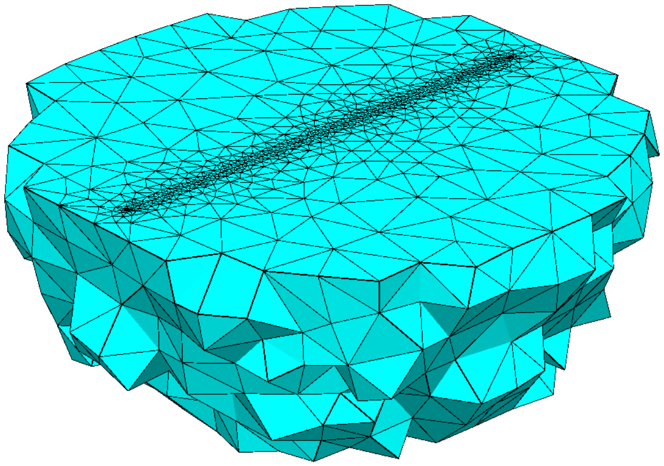


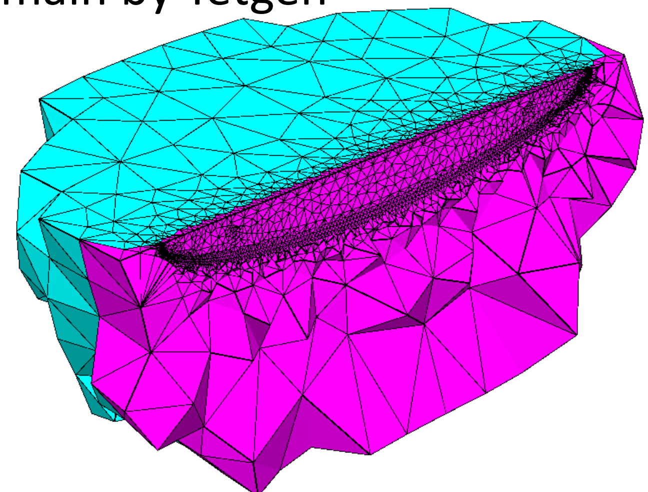


©,1 Shewchuk, J.R., 1996. Triangle: engineering a 2D quality mesh generator and Delaunay triangulator. In: Ming C., Dinesh M, editors. Applied computational geometry: towards geometric engineering. Springer-Verlag. 1148, pp. 203-222.

Applications: Crack Insertion (Mode-I Surface Crack)

3D meshing of Chunk Domain by Tetgen[©,2]





Constrained volume meshing for keeping,

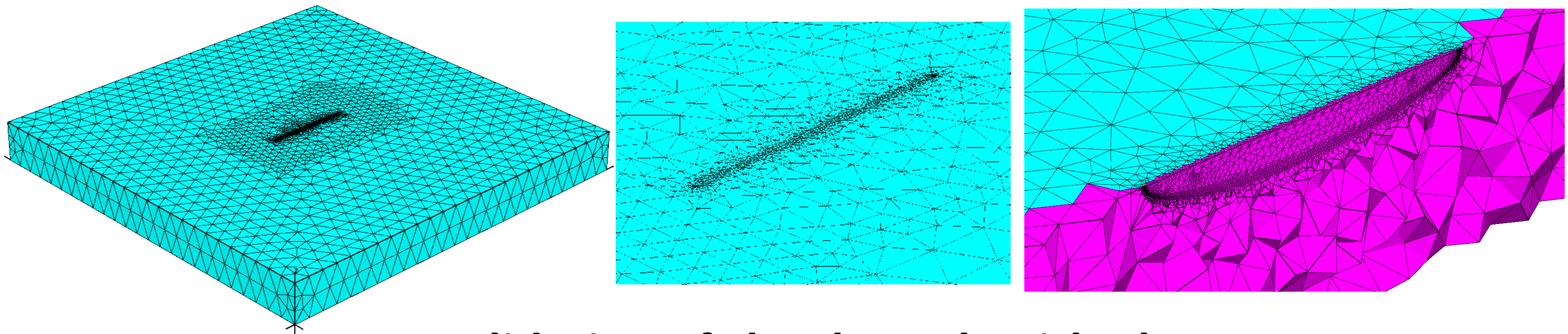
- chunk outer surface facets,
- crack surfaces meshing by Triangle ©, and
- crack mouth-line nodal points

unchanged.

©,2 Tetgen software website, http://tetgen.berlios.de/

Applications: Crack Insertion (Mode-I Surface Crack)

Consolidation of chunk volume mesh by Tetgen© with plate without the chunk



Consolidation of chunk mesh with plate,

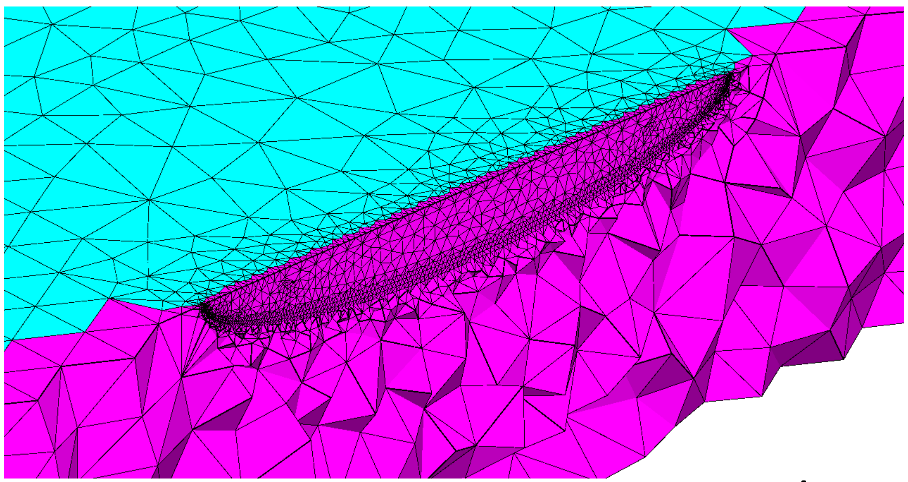
- node numbers on the shared surfaces kept the same,
- displacement and load boundary conditions outside chunk zone book kept,
- nodes on the crack surfaces duplicated and surface split,
- nodes and elements along crack front book kept to define the local crack front geometry.

The fully-unstructured finite element mesh w/ crack included (a/t=0.2, a/c=0.2)
(Next step Fracture Analysis by 3D Enriched Elements)

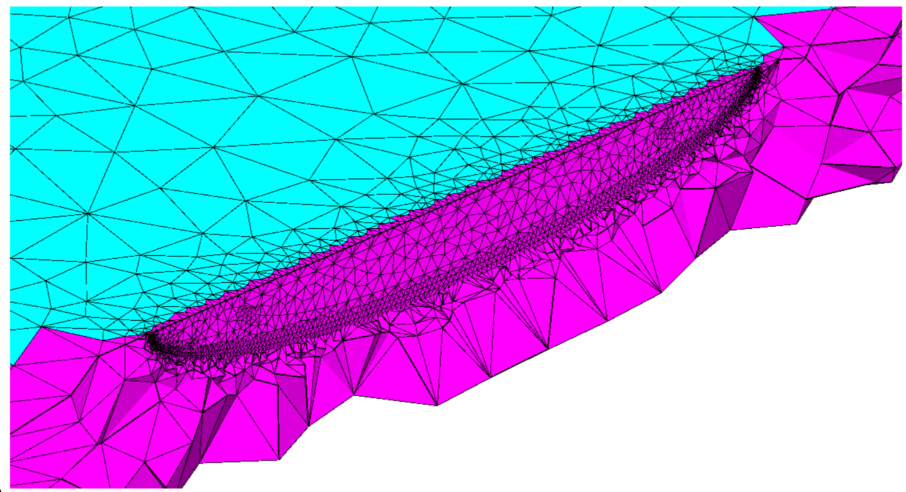
Applications: Crack Insertion (Mode-I Surface Crack)

a/c=0.2

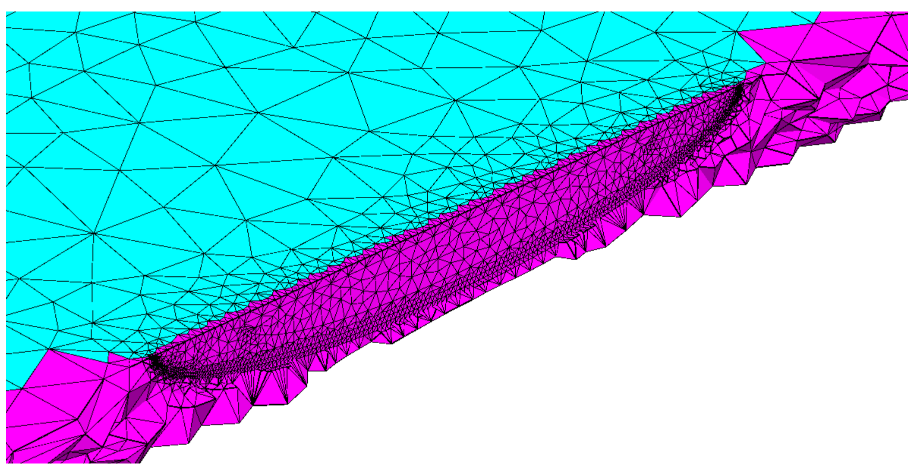
a/t=0.2



a/t=0.5



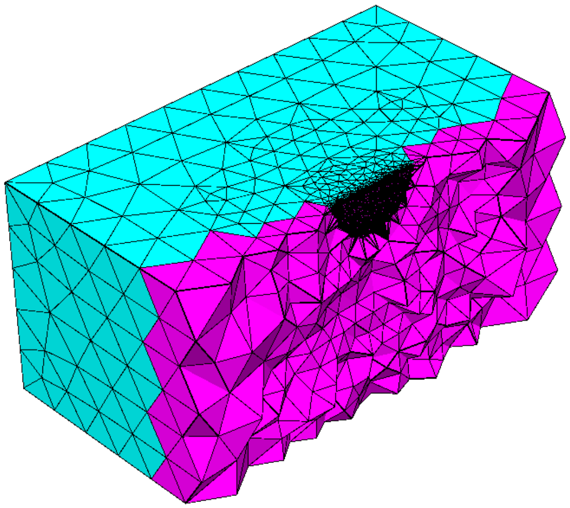
a/t=0.8



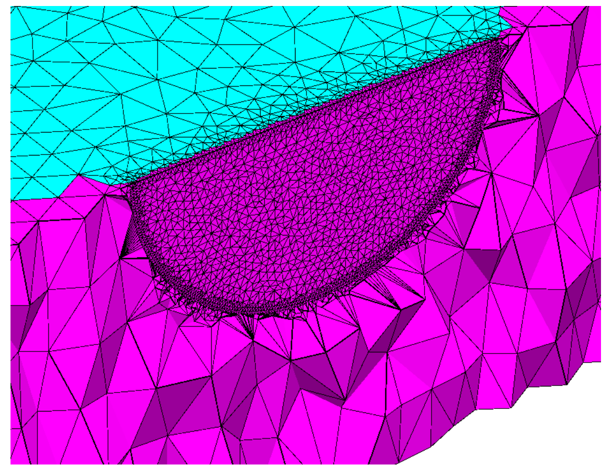
Applications: Crack Insertion (Mode-I Surface Crack)

a/c=1.0

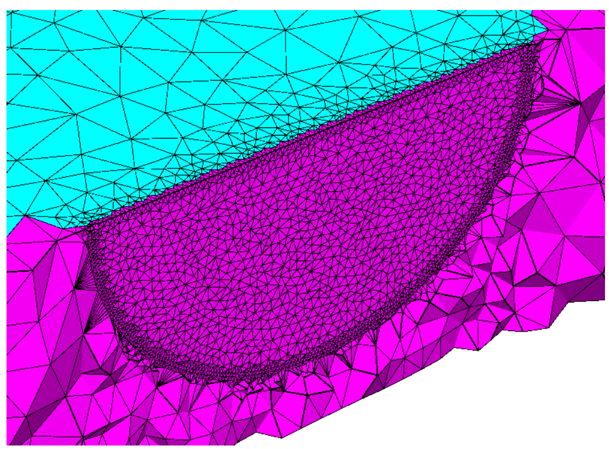
a/t=0.2



a/t=0.5



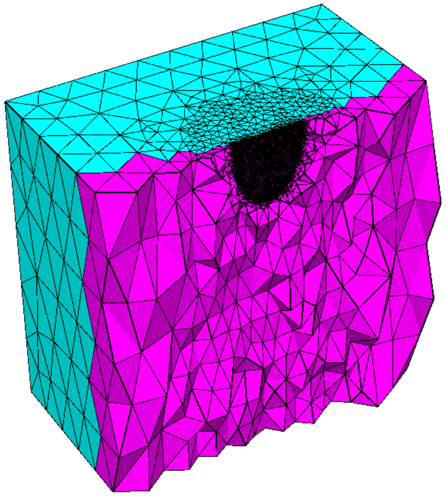
a/t=0.8



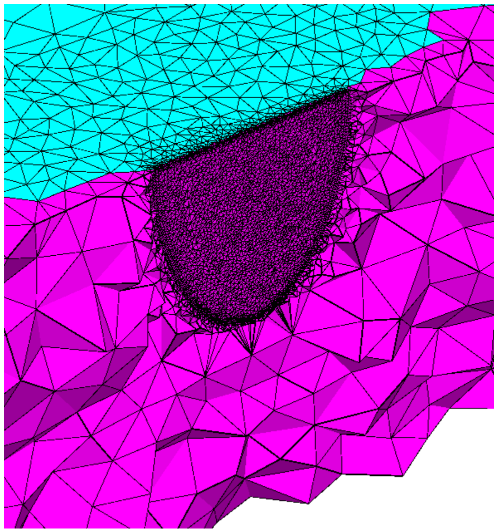
Applications: Crack Insertion (Mode-I Surface Crack)

a/c=2.0

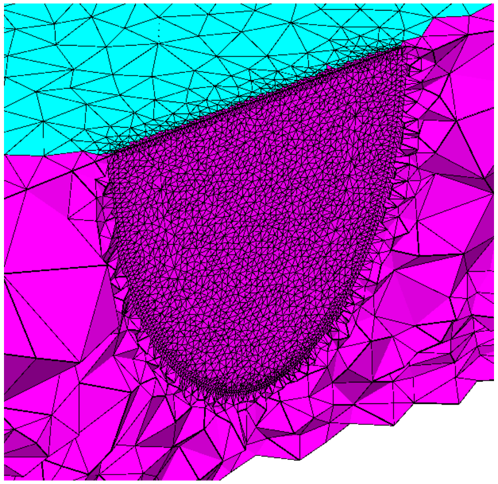
a/t=0.2



a/t=0.5

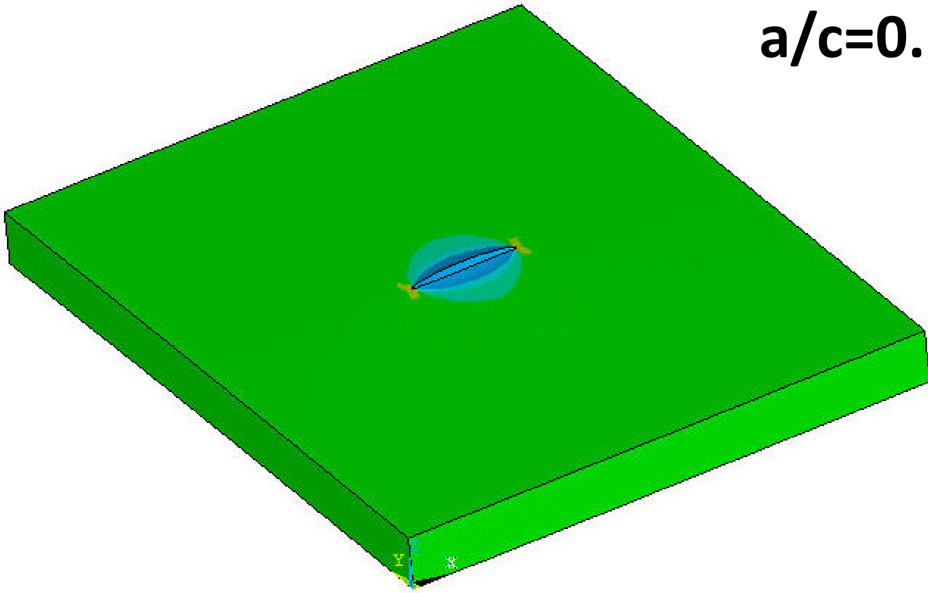


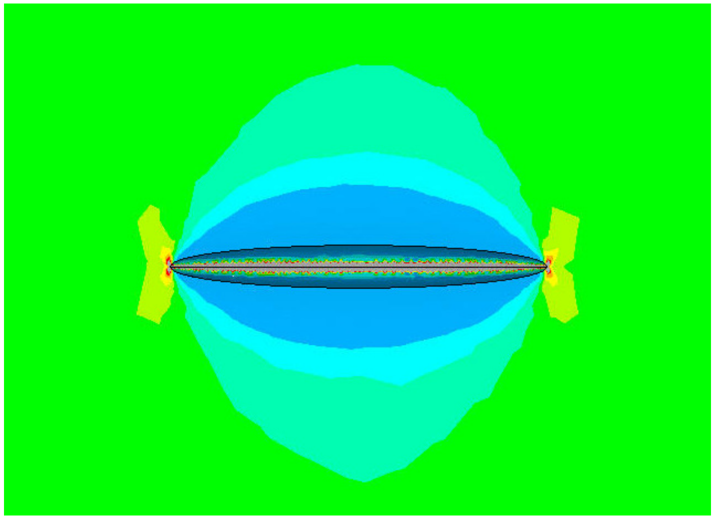
a/t=0.8

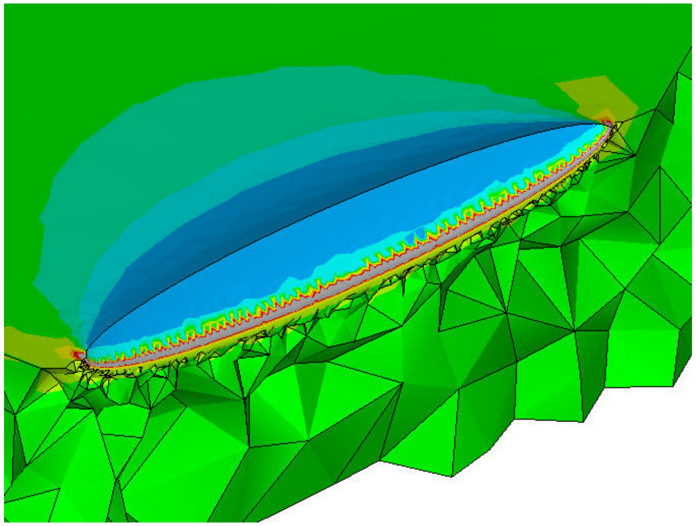


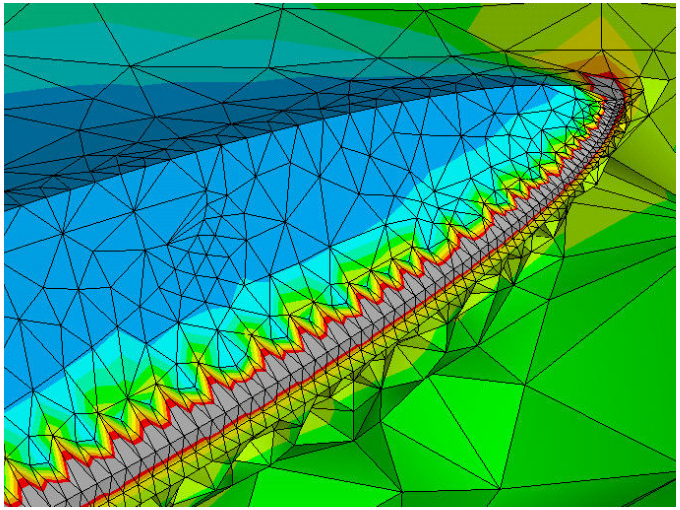
Applications: Crack Insertion (Mode-I Surface Crack)

a/c=0.2



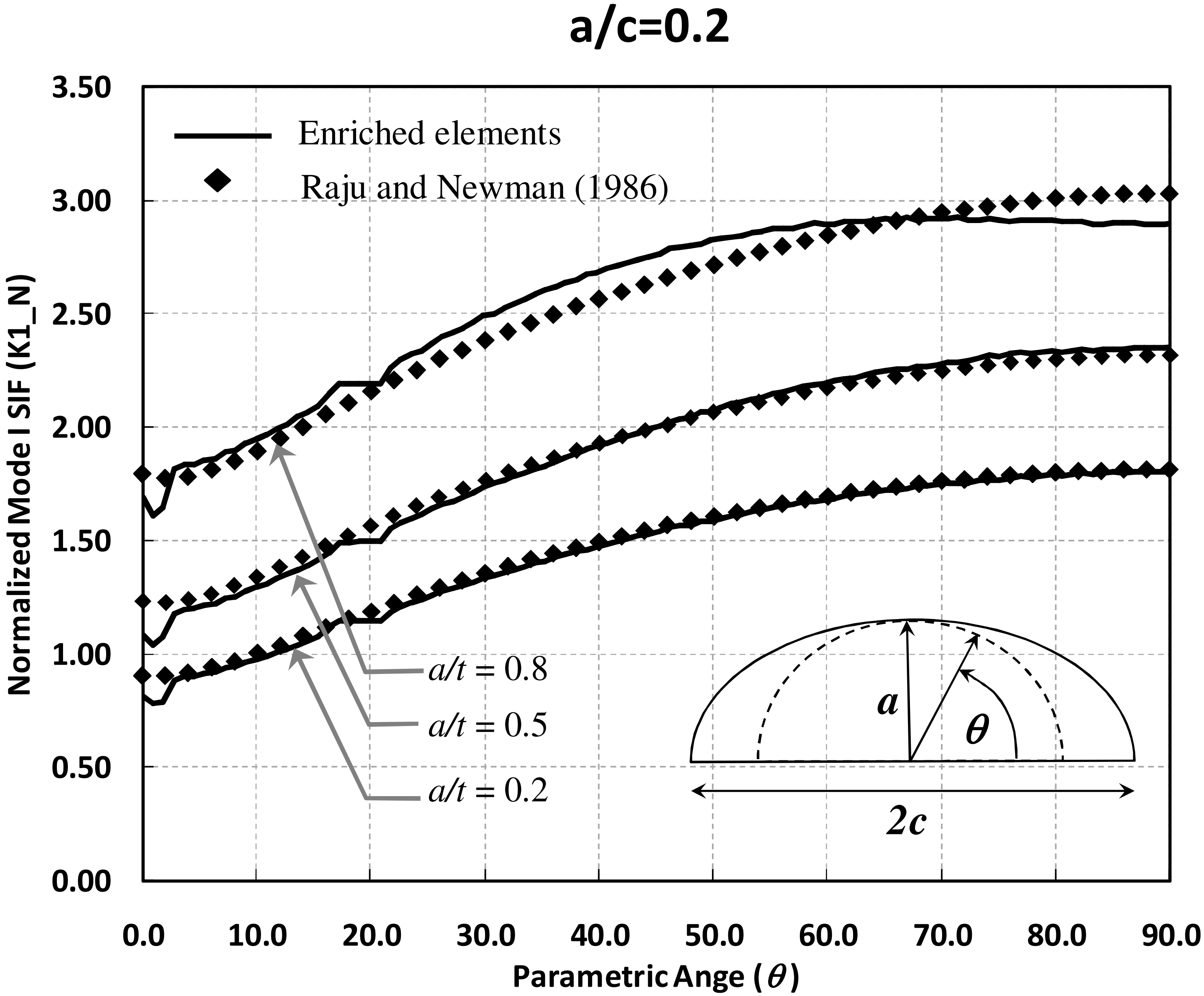




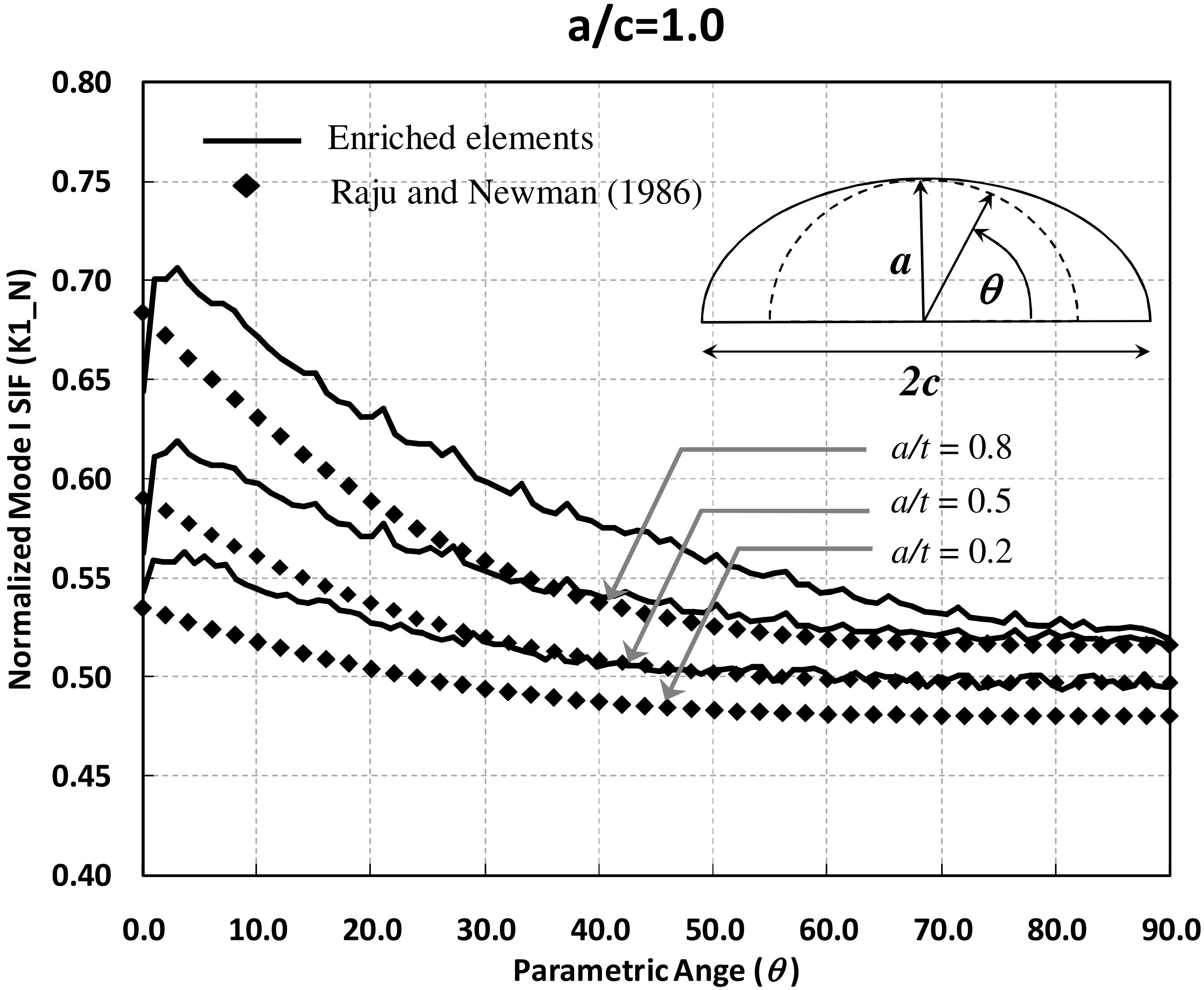


Deformed shapes as a first-step validation of the mesh

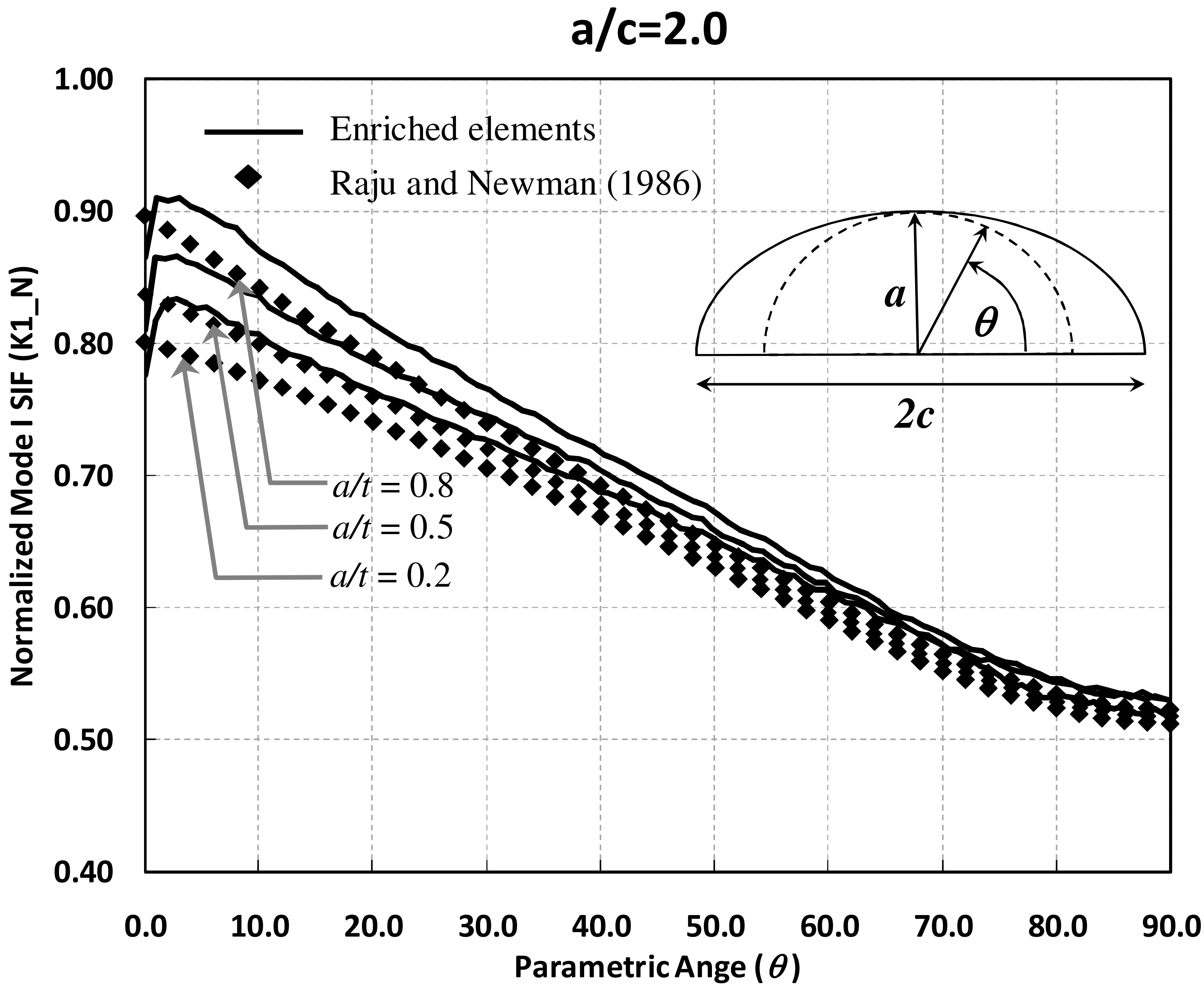
Applications: Fracture Analysis (Mode-I Surface Crack)



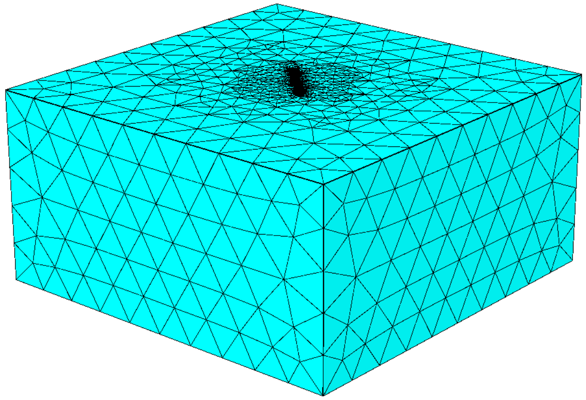
Applications: Fracture Analysis (Mode-I Surface Crack)

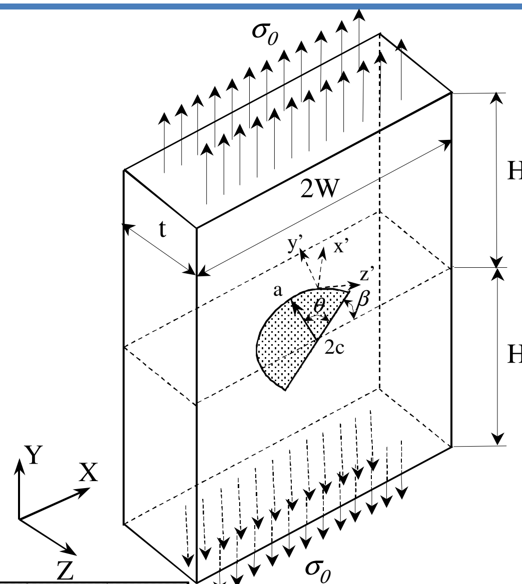


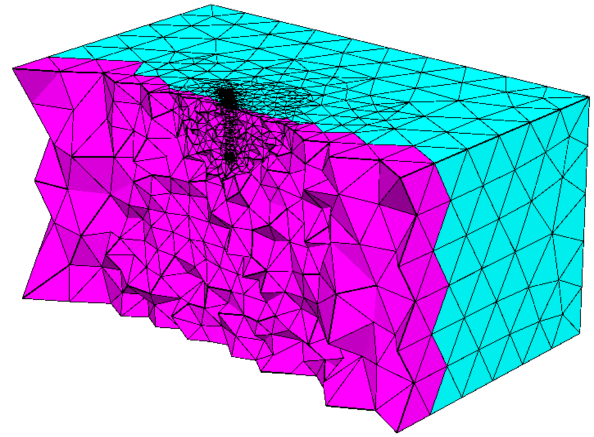
Applications: Fracture Analysis (Mode-I Surface Crack)

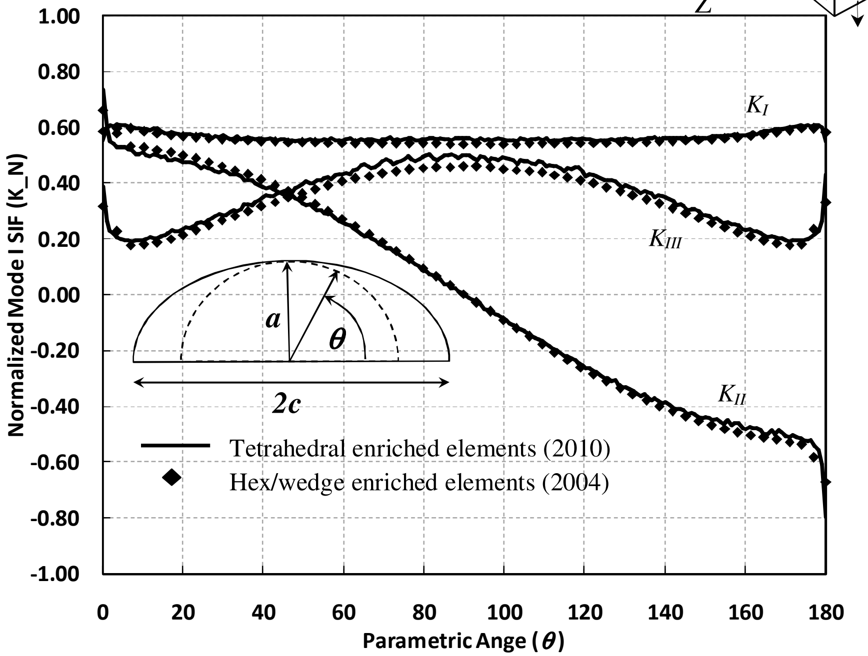


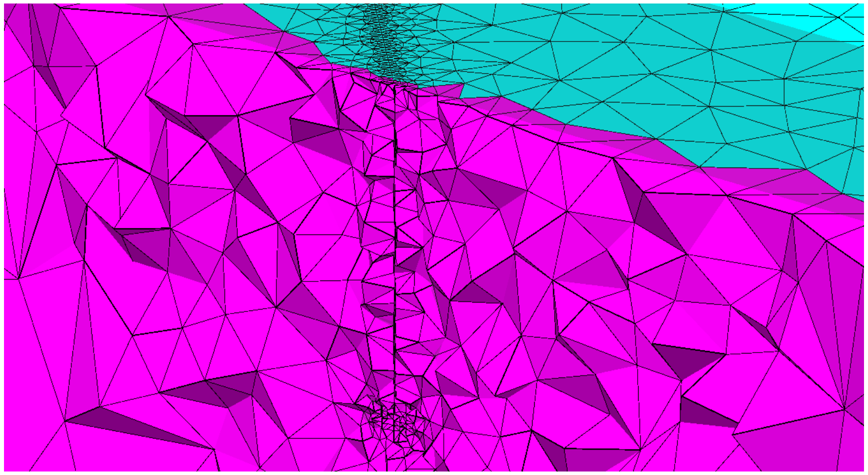
Applications: Crack Insertion (Inclined Surface Crack)





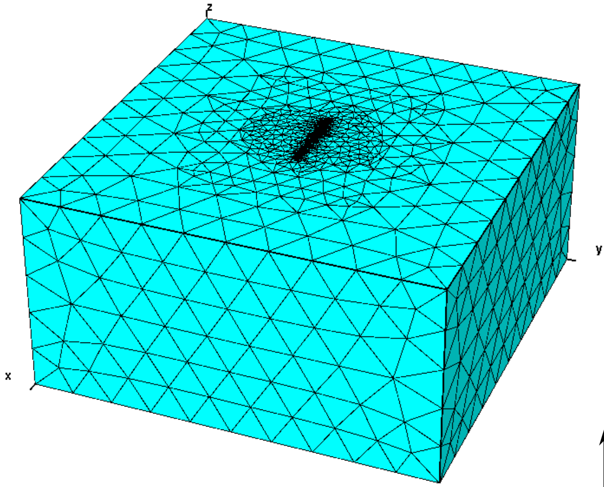


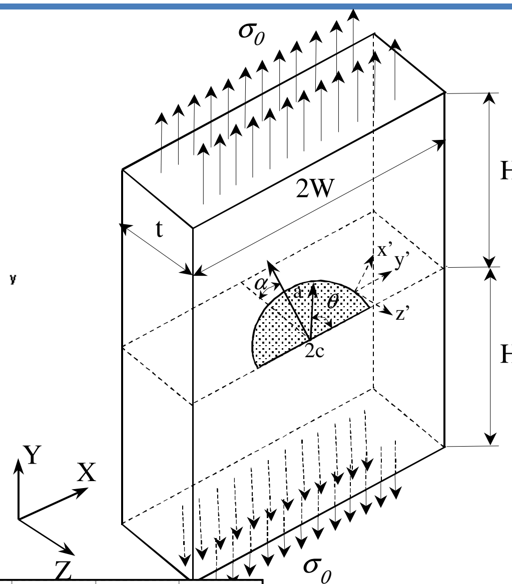


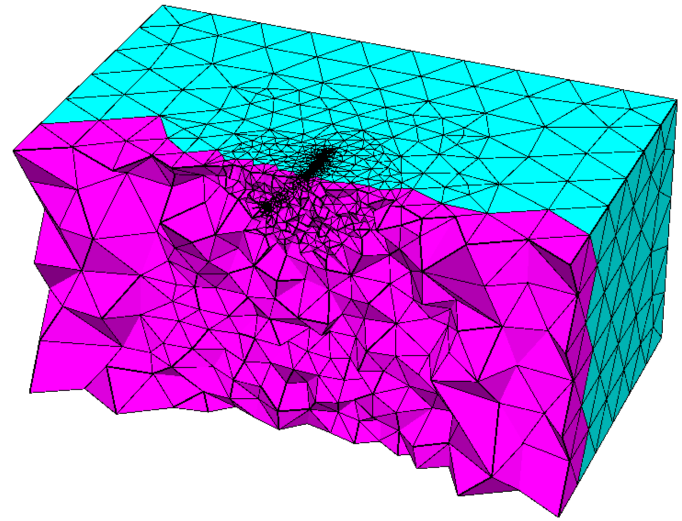


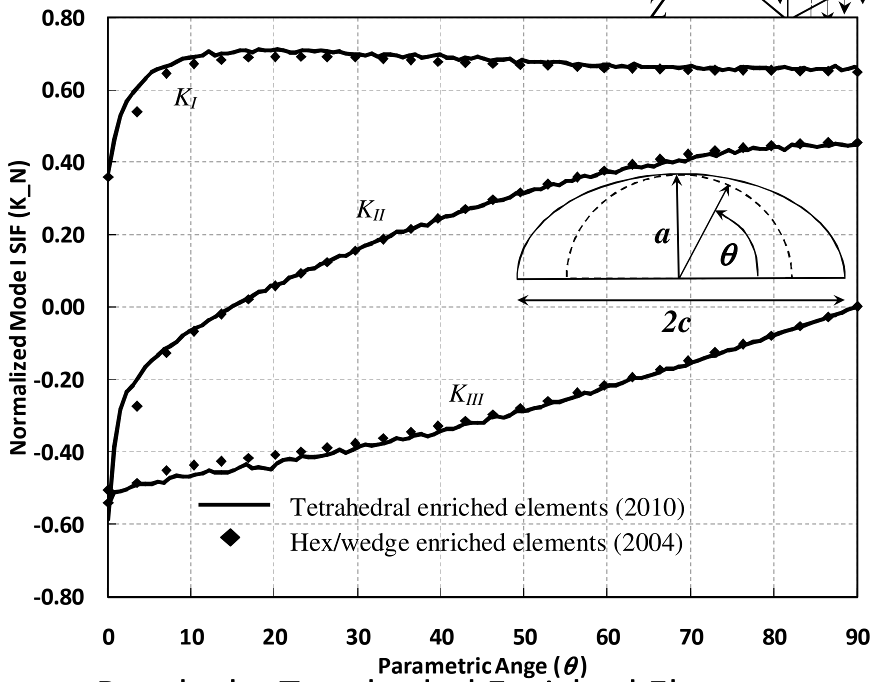
Results by Tetrahedral Enriched Elements agree with those of Hexahedral Enriched Elements (2004)

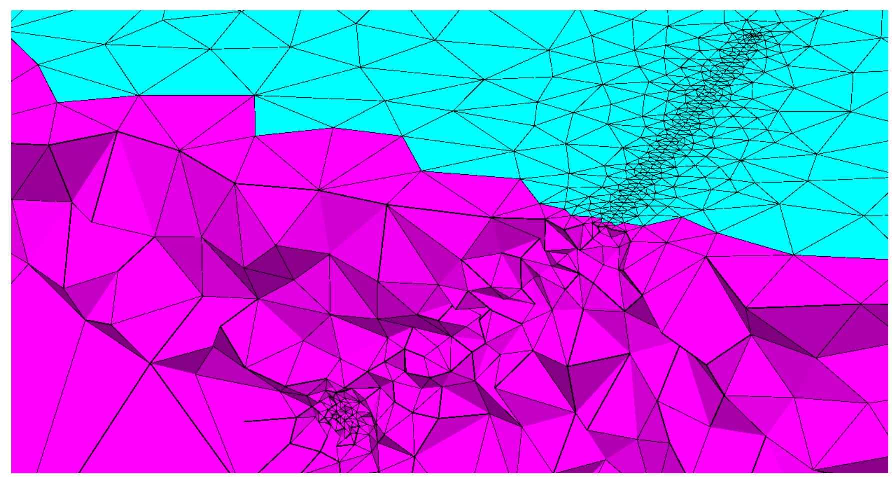
Applications: Crack Insertion (Deflected Surface Crack)





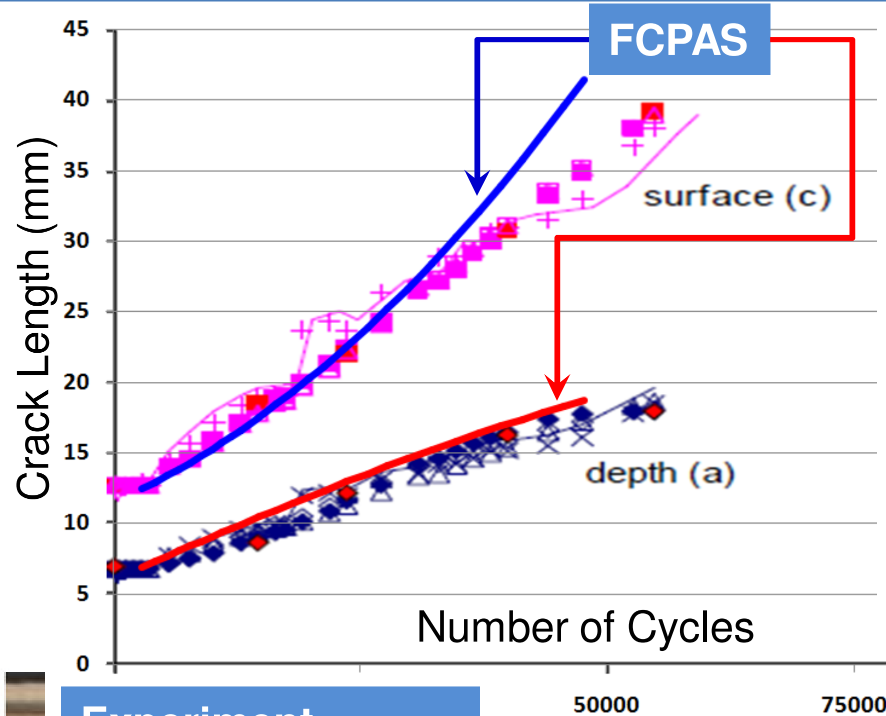




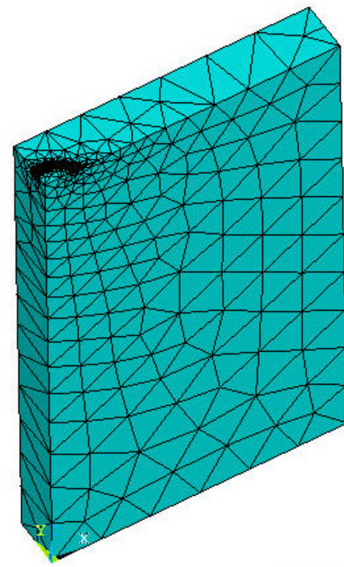


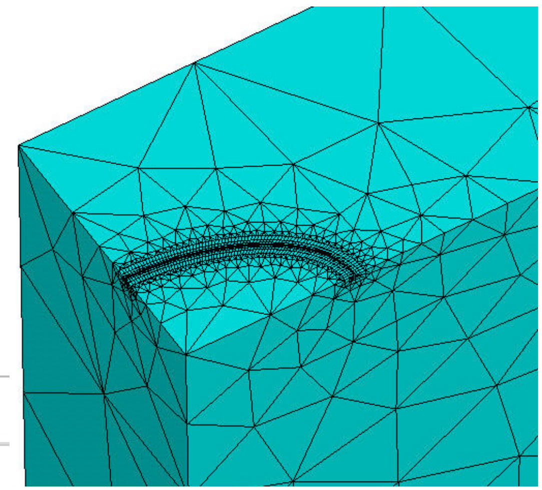
Results by Tetrahedral Enriched Elements agree with those of Hexahedral Enriched Elements (2004)

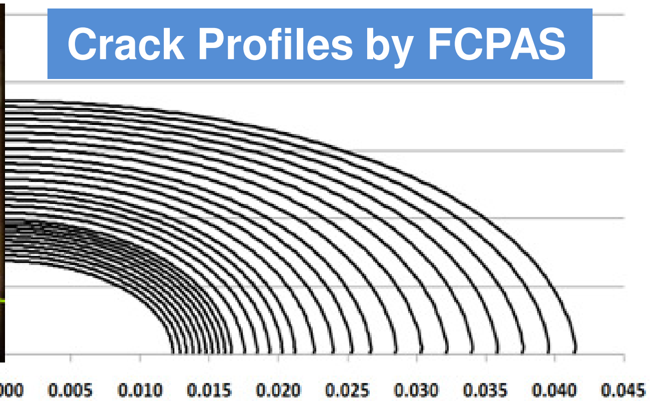
FCPAS Fatigue Crack Propagation Analysis (FE Models by ANSYS™)



Surface Crack in a Finite-Thickness Plate under Bending Load







FCPAS Simulation Results Agree Very Well with Experimental Observations

*(The permission by OMMI (Power Plant: Operation Maintenance and Materials Issues) and its publisher European Technology Development Ltd. UK, for reproducing and republishing data by Reytier, M. is gratefully acknowledged.)

Agenda

- ❑ Fracture Mechanics – Motivation and Needs
- ❑ 3D Fracture Mechanics – Available Methods/Tools
- ❑ Enriched Finite Elements for 3D Fracture Mechanics
- ❑ FCPAS – Fracture and Crack Propagation Analysis System
  - ❑ *Fracture finite element models developed using ANSYS*
  - ❑ *Fracture finite element models developed by crack insertion into an uncracked model*
  - ❑ *Fracture analysis by three-dimensional enriched finite elements*
- ❑ Applications:
  - ❑ *Mode-I surface crack insertion into an uncracked finite-thickness plate*
  - ❑ *Inclined and deflected surface crack insertion into an uncracked finite-thickness plate*
  - ❑ *Fracture solutions by enriched finite elements*
  - ❑ *Fatigue crack growth analysis of Mode-I surface crack in a plate under cyclic bending load*
- ❑ Summary/Conclusions

Summary/Conclusions

- Crack Insertion into an Uncracked Finite Element Model Using Fully Unstructured Mesh Successfully Demonstrated,
  - ✓ 2D Meshing Triangle ©, 3D Meshing by Tetgen ©
  - ✓ Crack insertion procedure presented by in-house code,
  - ✓ Output model with fully tetrahedral finite elements to be analyzed by FCPAS Solver
- Finite Element-Based Fracture Analysis Using Tetrahedral Enriched Elements,
  - ✓ Fracture finite element model from crack insertion readily available for fracture analysis (*.geo file),
  - ✓ Three-dimensional enriched finite elements for fracture calculations,
  - ✓ No special mesh requirements other than customary refinement near crack front,
  - ✓ Stress intensity factors along crack front directly calculated at the same time as nodal displacements,
  - ✓ Accurate solutions without any post-processing of finite element solution,
  - ✓ Presented method very efficient as any model can be meshed with tetrahedral elements.
- Crack insertion, meshing and fracture analyses of parts with curved outer surfaces next steps.

Acknowledgements

✓ *Authors are thankful to The Scientific and Technological Research Council of Turkey (TUBITAK) for the financial support and to the administration and personnel of Çukurova and Sakarya Universities for the organizational support.*