AE 737 - MECHANICS OF DAMAGE TOLERANCE

Lecture 25

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Last Updated: May 3, 2016 at 12:59am

Wichita State University, Department of Aerospace Engineering

- 3 May - Finite Elements, Damage in Composites
- 5 May - Repair
- 10 May - Final Project Due by 5:00 pm

SKUNK WORKS TALK

- Friday, May 6
- 12:00 - 1:00 pm
- Shocker Hall Multipurpose Room - Honors College
- Pizza (first-come first-served)

Figure 1: LASRE on top of SR-71 Blackbird

1. finite elements
2. damage in composites

FINITE ELEMENTS

FINITE ELEMENT METHODS IN FRACTURE

- Direct method (use near-tip stress field)
  - Requires very fine mesh near the tip to be accurate
  - Can be made feasible with specialty elements
- Crack closure method
  - An energy based method
  - Calculate energy to close crack one element away from crack tip
  - Can have a courser mesh than direct method
- Cohesive elements
  - Specialty elements act like an adhesive between two materials
  - Used to model crack propagation when crack path (and material behavior) are known
- XFEM
  - eXtended Finite Element Method
  - Can predict crack growth in any direction
  - Adds ”phantom” cracks in all elements

- We can calculate the strain energy release rate (G_I and G_{II}) by calculating the work done at the crack tip
- We calculate the force acting on the node at the crack tip
- We then allow the crack to progress one node farther and calculate the displacement at that node
- G_I is calculated as

$$G_I = \frac{1}{2\Delta a} F_y^{(c)} \left(u_y^{(c)} - u_y^{(d)} \right) \tag{25.1}$$

- and K_I is

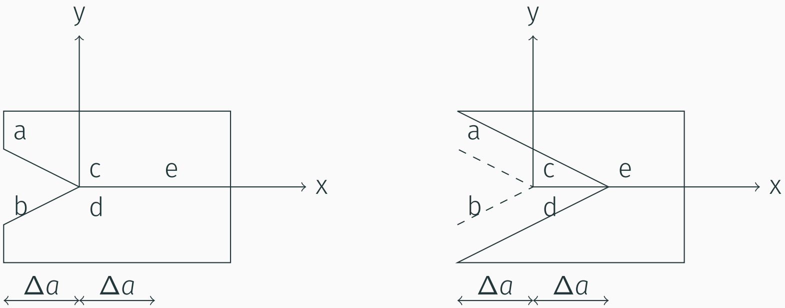
$$G_I = \frac{\kappa + 1}{8\nu} K_I^2 \tag{25.2}$$

where

$$\kappa = 3 - 4\nu \qquad \text{(plane strain)}$$

$$\kappa = \frac{3 - \nu}{1 + \nu} \qquad \text{(plane stress)}$$

CRACK CLOSURE

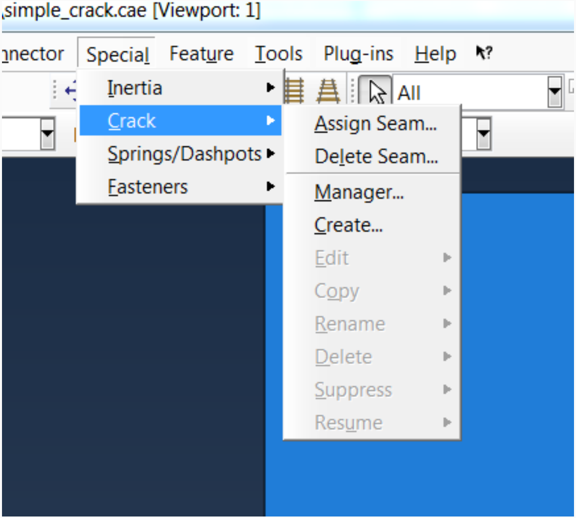


- If we assume the mesh size is small relative to the crack length, and the distance between nodes are evenly spaced in the crack tip region, we can use the displacement at nodes (a) and (b) instead
- This requires only one simulation
- $\Delta a/a \leq 0.05$

$$G_I = \frac{1}{2\Delta a} F_y^{(c)} \left(u_y^{(a)} - u_y^{(b)} \right) \tag{25.3}$$

- Most of these methods will apply in some fashion to other FE software tools
- First draw the net shape (taking symmetry into account)
- In this example, I am drawing 1/4 of a middle-cracked plate
- Partition the edge so that you can easily separate the crack tip from the plate
- It is helpful to add some partitions now for meshing purposes later, a box or circle/semi-circle around the crack tip

MODELING IN ABAQUS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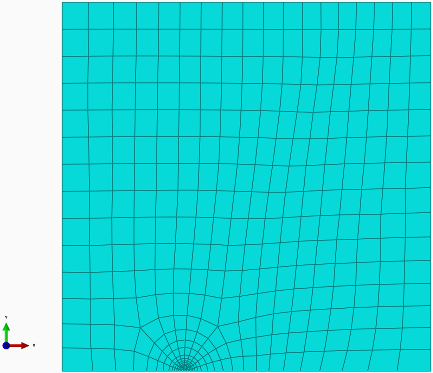
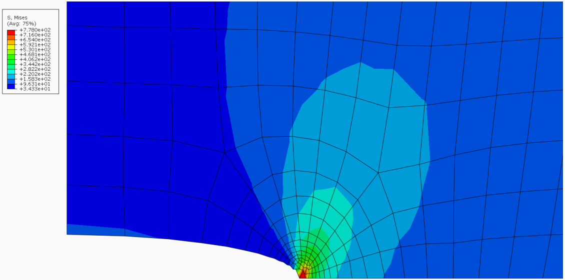
Suppress
Resume

- If you are modeling a symmetric part, make sure to impose the appropriate symmetric boundary conditions
- In my case, I use XSYMM (U1 = UR2 = UR3 = 0) on the left edge
- On the bottom edge, I use YSYMM (U2 = UR1 = UR3 = 0) on the portion of the bottom edge which is not cracked
- To mesh, be sure to seed the edges, this is where partitioning comes in handy

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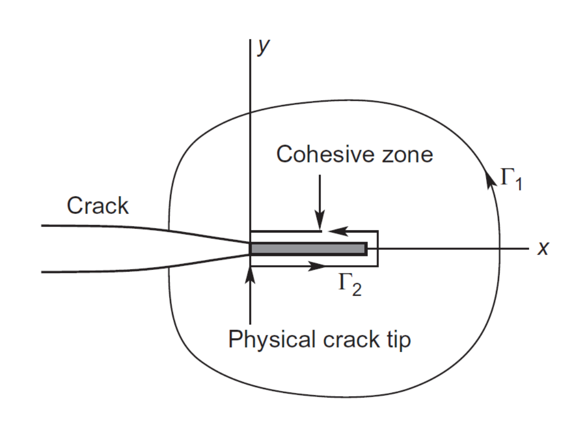
- To post-process results, we need the force acting on the crack tip and the displacement one node away
- In this case, we assume, due to symmetry, that $u_y^{(a)} - u_y^{(b)} = 2u_Y^{(a)}$
- To get nodal values in ABAQUS, from the Visualization module we use Tools -> Query -> Node -> Probe Values
- The variable corresponding to F_y in ABAQUS is RF2
- We also probe the nodal value of displacement one node away, u_y in ABAQUS is U2

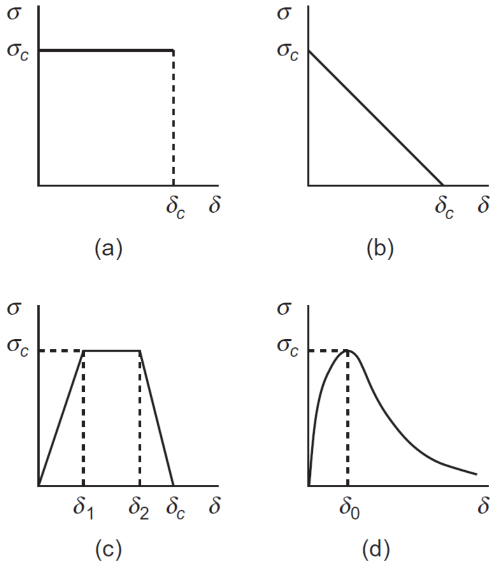
- When using the direct method, we need to get values of either displacement or stress along a path
- In ABAQUS this is done in two steps, first Tools -> Path -> Create -> Node List
- Next do Tools -> XY Data -> Create -> Path
- Choose the path you created, the variable you need (either u_y or σ_{yy}) and hit Plot
- Next export the data for processing in Excel (Report -> XY -> Choose file name, de-select ”Append to file”)
- You can now paste this data into Excel for processing

COHESIVE ELEMENTS

- Cohesive elements are one way to model crack propagation
- We need to know the crack path in advance, we model the the crack growth using a traction-separation law
- The cohesive zone theory assumes stress can never reach infinity, the maximum allowable stress in a material is the stress required to separate atoms
- The stress required to separate the atoms changes as a function based on their Traction-Separation law, until the atomic bond is broken

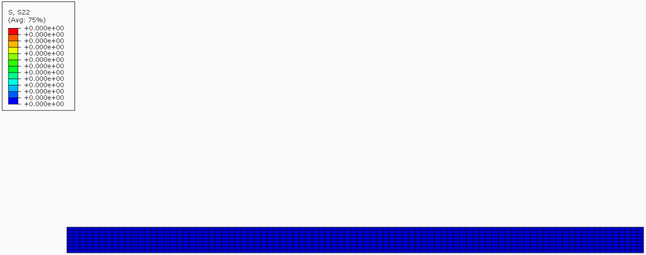

y
Cohesive zone
Γ_1
Crack
x
Γ_2
Physical crack tip

TRACTION SEPARATION



- In practice, the cohesive zone can be used to model crack growth
- It is most often used to model de-bonding of adhesives
- Also commonly used to model delamination in composites

DCB



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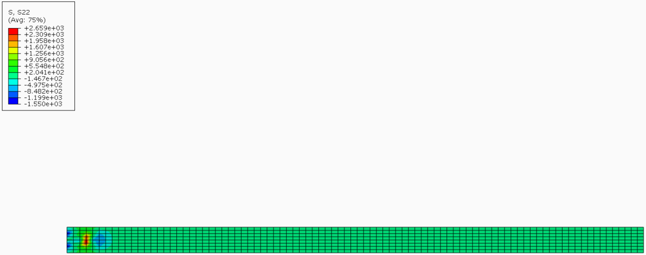
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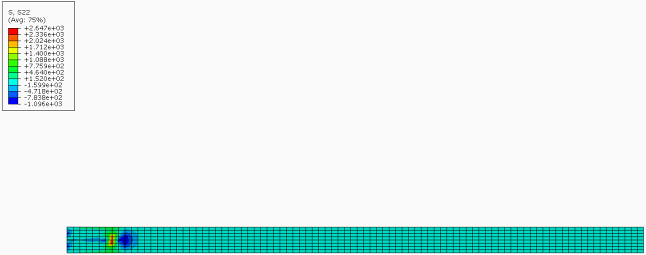
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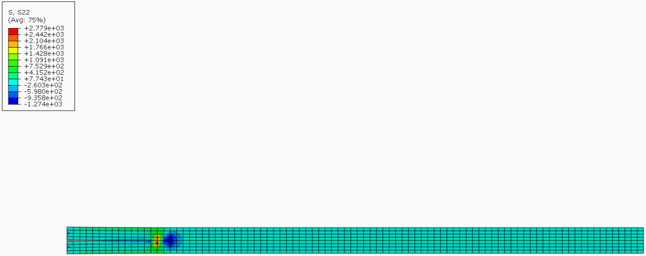
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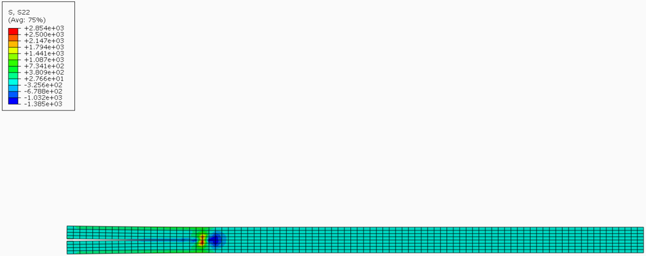

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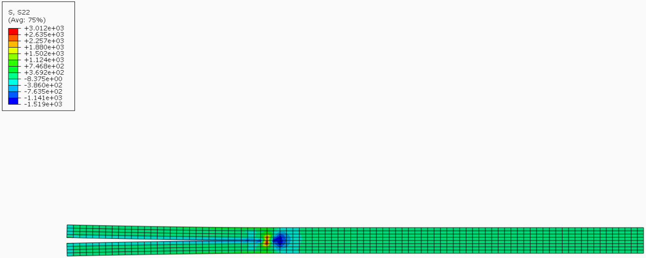

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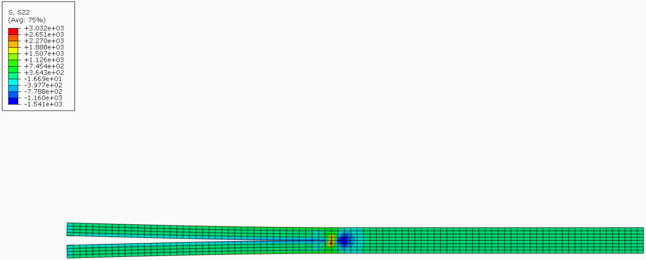
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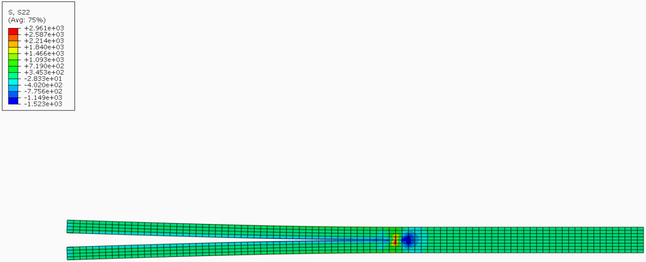
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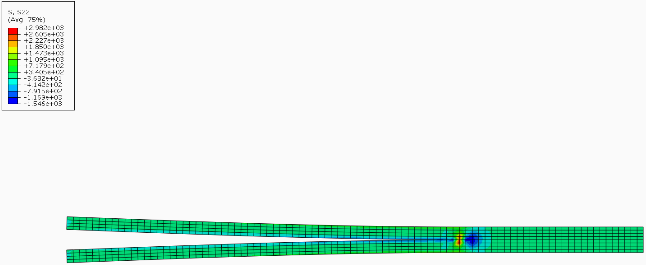

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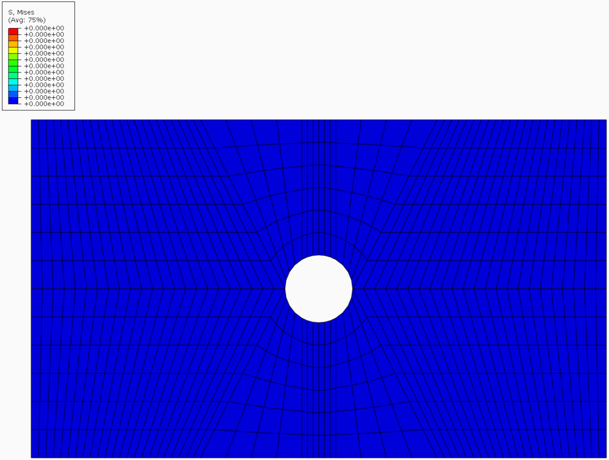
EXTENDED FINITE ELEMENT METHOD

- Traditional methods need the mesh to conform to a discontinuity (crack) to model it
- XFEM treats the discontinuity as an additional degree of freedom within an element
- A key advantage of this method is that the mesh does not need to conform to the discontinuity
- This is done using nodal enrichment functions, which model the singularity near the crack tip

XFEM



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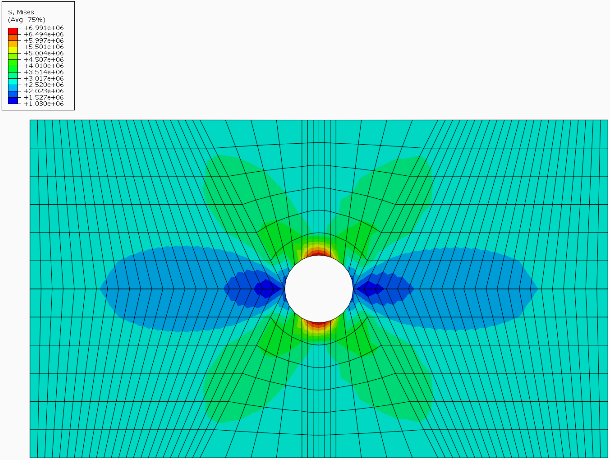
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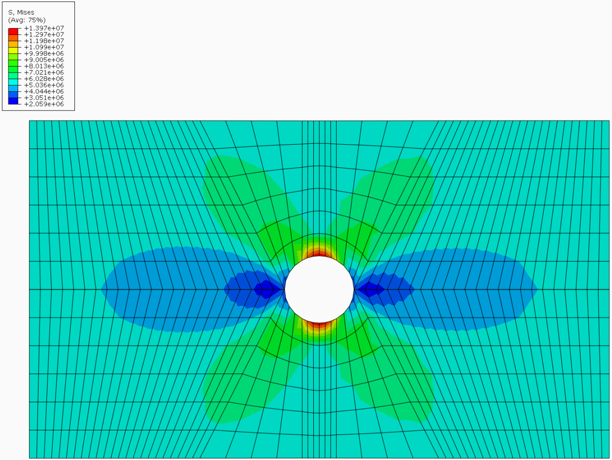
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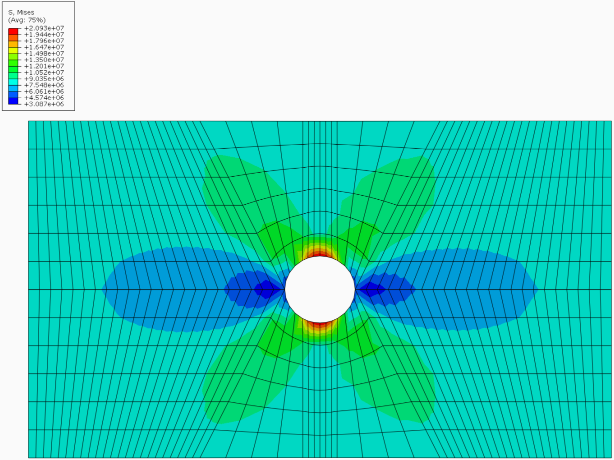
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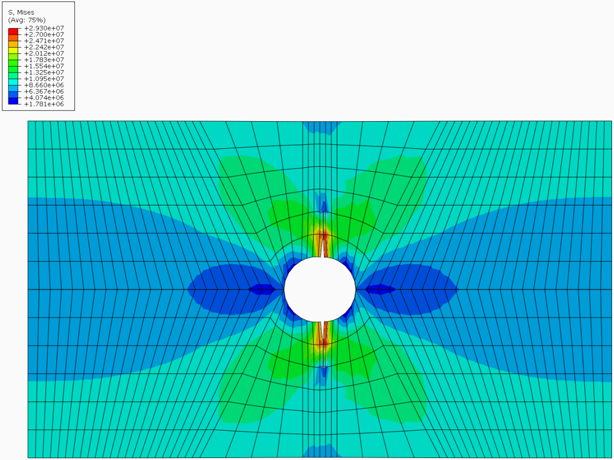
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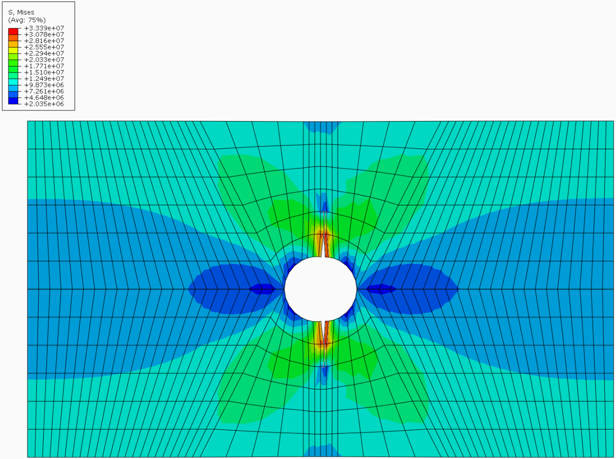
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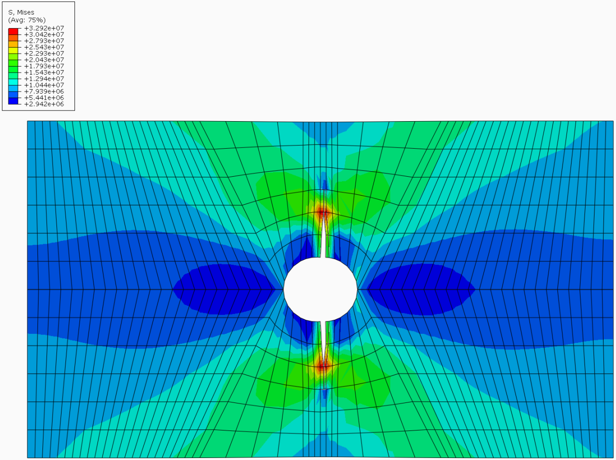
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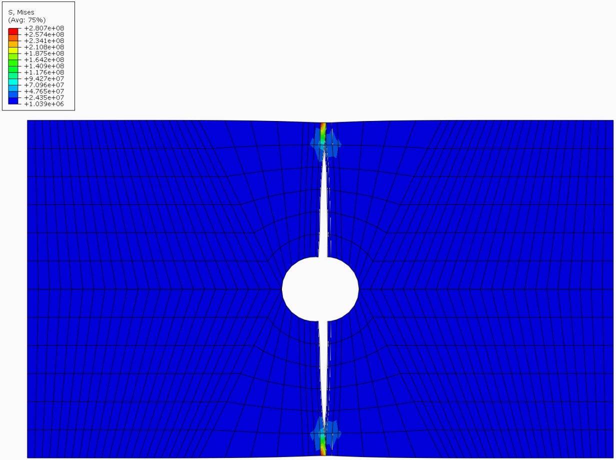
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DAMAGE IN COMPOSITES

- One challenge in dealing with fatigue in composites is that there are different mechanisms
- For low-cycle fatigue (high loads), failure can occur directly in fibers, each successive load will cause more fibers to fail
- For intermediate loads, matrix cracking and crack growth can occur
- For low loads, crack propagation will not occur in a lamina
- Composite laminae have a relatively high fatigue limit, leading many to neglect fatigue in composites

- In laminates the same mechanisms apply as in a lamina, with one additional consideration
- In laminates, cracks can also develop (or propagate to) the boundary between layers
- Delamination can then occur, while individual laminae remain intact, the strength of the structure is compromised as the layers are no longer bound together

- In laminate theory, the assumption is made that the shear stress τ_{xz} is zero
- This is a good assumption away from the edges of a part, however this stress term sharply increases near the free edge
- This stress term can initiate cracks between layers at the edge
- In this region, the assumptions of a perfectly bonded laminate no longer hold, and unexpected damage propagation can occur

- In general, composites are much stronger in-plane
- This leads to poor impact damage behavior, as an impact can generate significant out-of-plane damage
- This is another challenge for composites in aircraft

OTHER ISSUES

- Analysis for fracture in composites is much more complicated than for a homogeneous material
- How does matrix crack interact with fibers when it approaches them?
- Cracks also behave differently in an anisotropic material
- Fiber-matrix interface can cause mixed-mode conditions even when remote load is not
- Ply boundaries behave differently than interior
- Fiber concentration is not uniform
- Work force is not trained in anisotropic/heterogeneous analysis

ADVANTAGES

- Damage tolerant failure (weak fibers fail first, strong fibers remain)
- Material properties can be tailored to specific use cases
- Different composites can be designed for different use cases (high temperature ceramic-matrix composites)
- Can improve the damage tolerance of a material (SiC-SiC composites allows use of a brittle ceramic in many advanced aircraft)
- Self-healing
- Out-of-autoclave (on-site) repair
- Adhesive joining (reduce holes, fastener count)