Finite Element Capabilities for Conventional and Advanced Analyses of Composite Materials

Nov 04, 2015
Composites Simulation Workshop
CDMHub, Purdue University

Deepak Goyal, PhD
Sr. Technical Specialist, DS SIMULIA

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Abaqus

Isight

Tosca

fe-safe

Products for Composites FEA

- 3D Experience Platform
  - V2015x
- CATIA CPD
- Abaqus/CAE, Abaqus/Standard & Abaqus/Explicit
- Composite Modeler For Abaqus (CMA)
- iSight, ATOM

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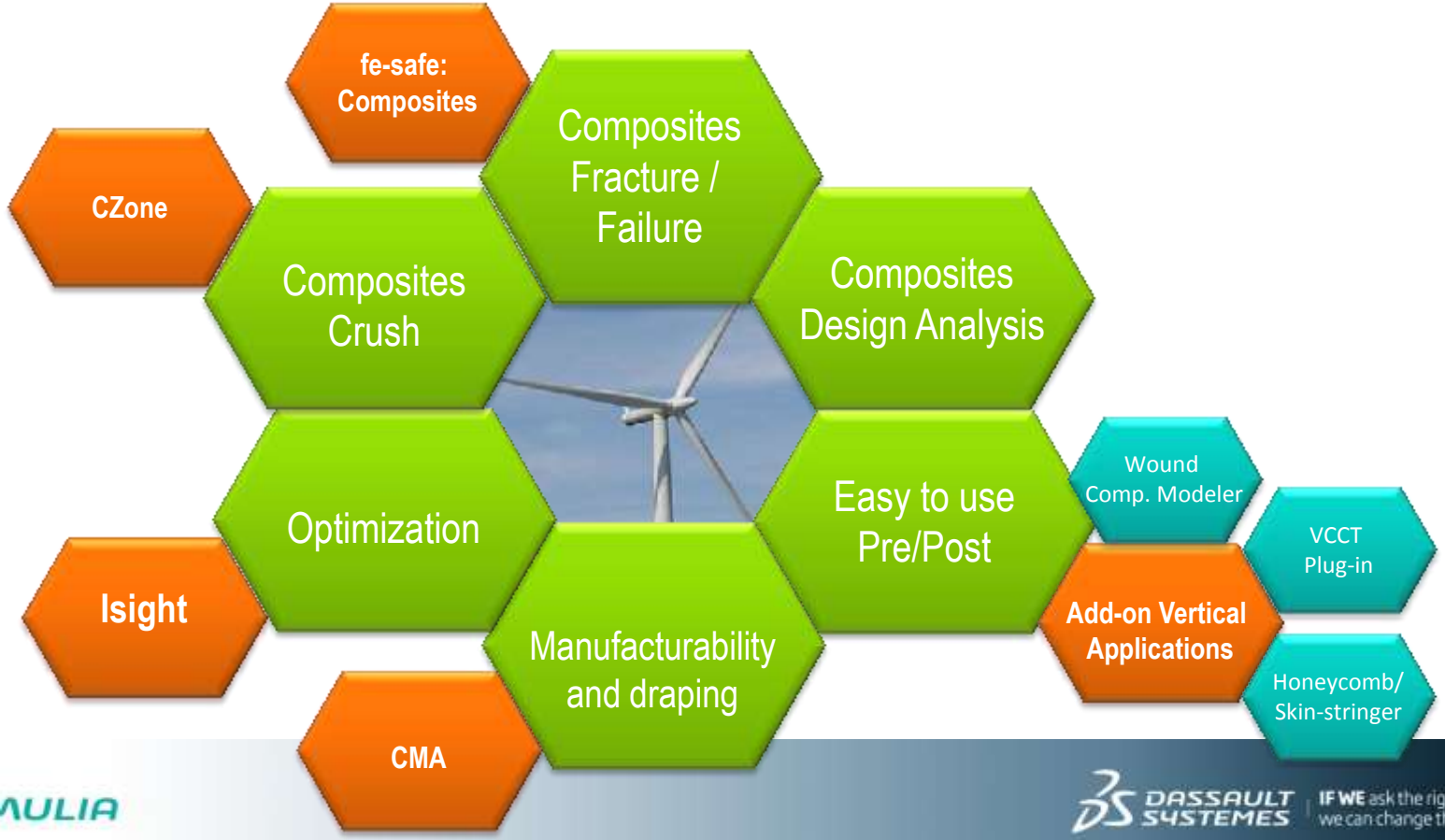
Conventional & Advanced Composites Analyses



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Collaborative FEA

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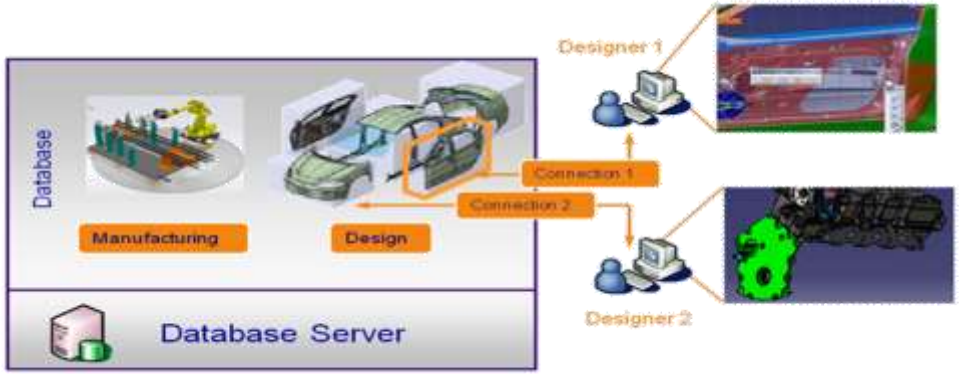
What is the 3DEXPERIENCE Platform?

- **3D**EXPERIENCE Platform is a *new interface* and a *new way* to:
  - Store and secure data
  - Search for data
  - Explore data
  - Author data
    - SIMULIA applications, among other applications.

- The **3D**EXPERIENCE Platform provides
  - a platform for global collaboration
  - the ability to capture business processes across an organization
  - a single PLM platform for IP management

- The **3D**EXPERIENCE Platform is available on-premise and on-the-cloud (public or private)



V6 Database Connection

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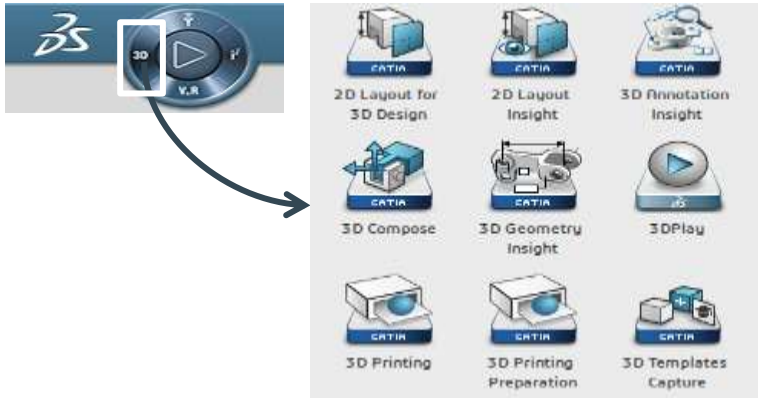
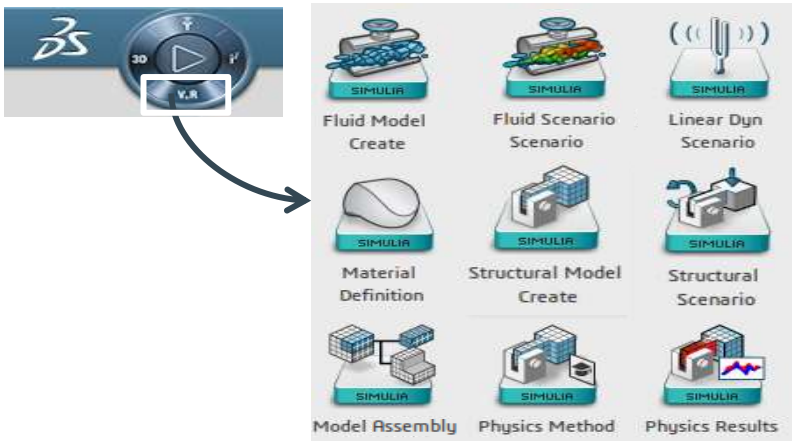
Authoring

- You create or modify (author) objects with apps
- All apps can be accessed using the **3D**EXPERIENCE Platform compass.





"Codes coming together—Exciting time for Composites Community" – Dr. Byron Pipes Director, Composites Design and Manufacturing HUB, Purdue University

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Conventional FEA Analyses

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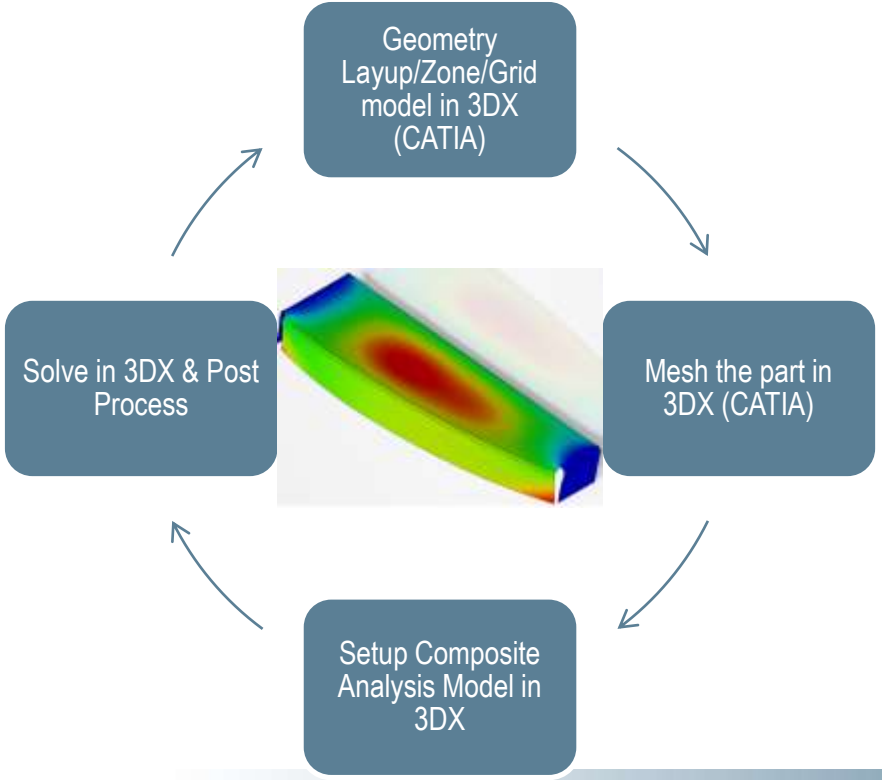
A Conventional FEA Analyses Workflow: 3DX



- Elements
- Define layup
- Material orientations
- Material properties
- Loads/BC
- Post-process-ply based

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Anisotropic Elasticity

All anisotropic models have the general form

$$\sigma_{ij} = D_{ijkl}\left(\varepsilon_{kl} - \varepsilon_{kl}^{th}\right) \quad \text{or} \quad \boldsymbol{\sigma} = \boldsymbol{D} : \left(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{th}\right).$$

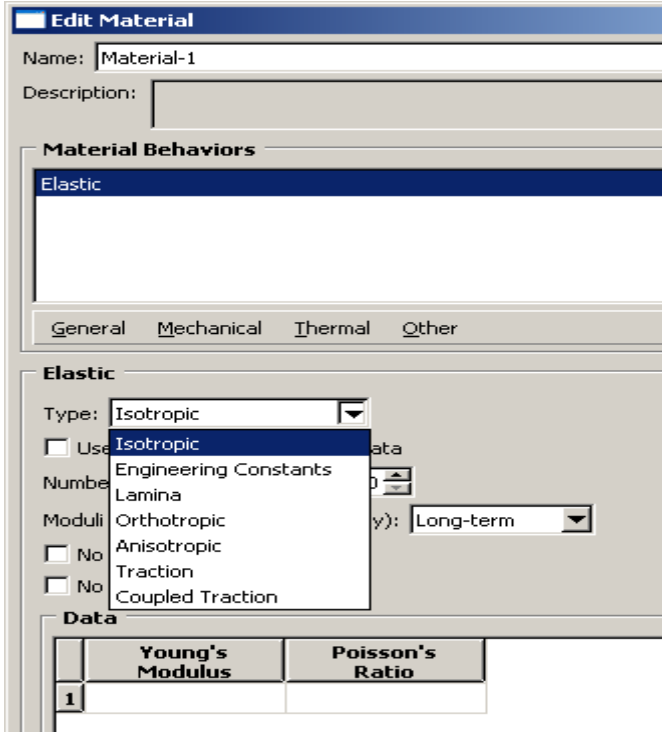
where

$\boldsymbol{D} = \boldsymbol{D}(\theta, f_i)$ is a symmetric matrix with a maximum dimension of 6×6,

θ = temperature,

f_i = predefined field variables, and

$\boldsymbol{\varepsilon}^{th} = \boldsymbol{\varepsilon}^{th}(\theta)$ is the strain due to thermal expansion.



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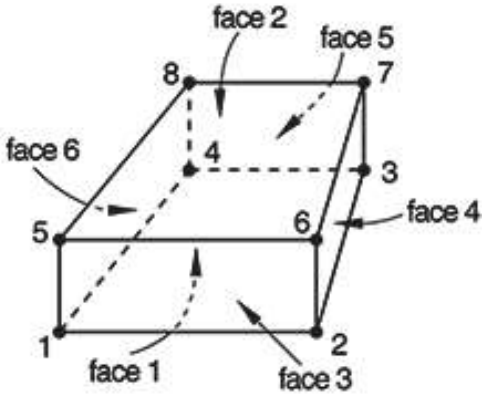
Solid element

- **Full three-dimensional**



8 - node element

$$
\begin{aligned}
u = {} & \frac{1}{8}(1-g)(1-h)(1-r)u_1 + \frac{1}{8}(1+g)(1-h)(1-r)u_2 \\
& + \frac{1}{8}(1+g)(1+h)(1-r)u_3 + \frac{1}{8}(1-g)(1+h)(1-r)u_4 \\
& + \frac{1}{8}(1-g)(1-h)(1+r)u_5 + \frac{1}{8}(1+g)(1-h)(1+r)u_6 \\
& + \frac{1}{8}(1+g)(1+h)(1+r)u_7 + \frac{1}{8}(1-g)(1+h)(1+r)u_8
\end{aligned}
$$

Interpolation function

$$
B_i^I = \frac{1}{V_{e\ell}} \int_{V_{e\ell}} N_i^I(g,h,r)\, dV_{e\ell},
$$

$$
N_i^I(g,h,r) = \frac{\partial N^I}{\partial x_i},
$$

Integration

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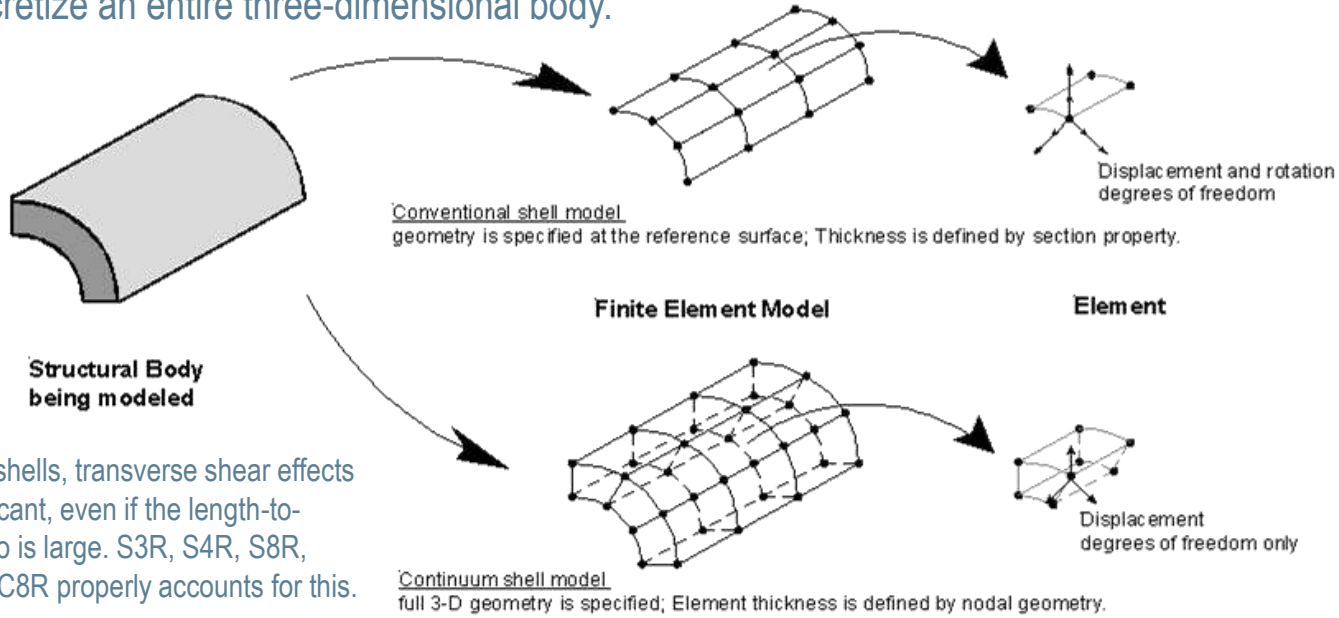
Shell element

- Conventional shell elements discretize a reference surface by defining the element's planar dimensions, its surface normal, and its initial curvature.
- Continuum shell elements, on the other hand, resemble three-dimensional solid elements in that they discretize an entire three-dimensional body.



In laminated shells, transverse shear effects can be significant, even if the length-to-thickness ratio is large. S3R, S4R, S8R, SC6R, and SC8R properly accounts for this.

Sandwich Composites w/ Skins

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Defining a Composite Layup (1/2)

Plies | Offset | Shell Parameters | Display

Make calculated sections symmetric

		Ply Name	Region	Material	Thickness	CSYS	Rotation Angle	Integration Points
1	✓	Ply-1	(Picked)	Material-1	0.5	<Layup>		3
2	✓	Ply-2	(Picked)	Material-1	0.3			
3	✓	Ply-3	(Picked)	Material-1	0.3			

Edit Material...	Alt+E
Copy Plies Before	Alt+B
Copy Plies After	Alt+A
Insert Rows Before	Ctl+B
Insert Rows After	Ctl+A
Delete Plies	Ctl+D
Pattern Plies...	Alt+P
Invert Plies...	Alt+I
Read From File...	Alt+R
Write To File...	Alt+W

Select Material

For Plies: Ply-1, Ply-2, Ply-3

Material: Material-1

OK | Cancel

Edit Material

Name: Material-1

Description:

Material Behaviors

Elastic

General | Mechanical | Thermal | Other

Elastic

Type: Lamina

Suboptions

Use temperature-dependent data

Number of field variables: 0

Moduli time scale (for viscoelasticity): Long-term

No compression

No tension

	E1	E2	Nu12	G12	G13	G23
1	50000	50000	0.35	10000	10000	5000

Note: All plies have the same material properties.

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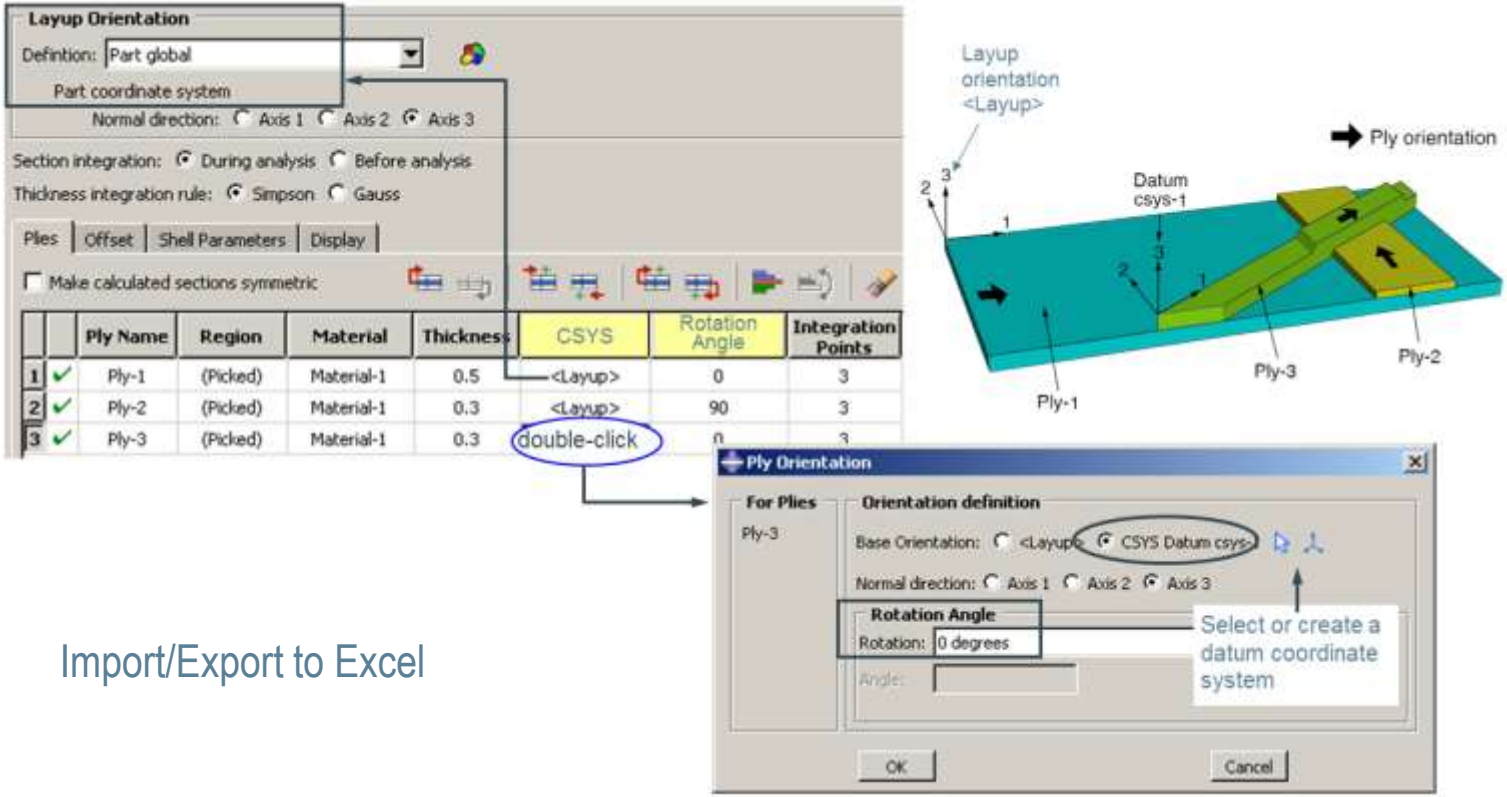
Defining a Composite Layup (2/2)



Import/Export to Excel

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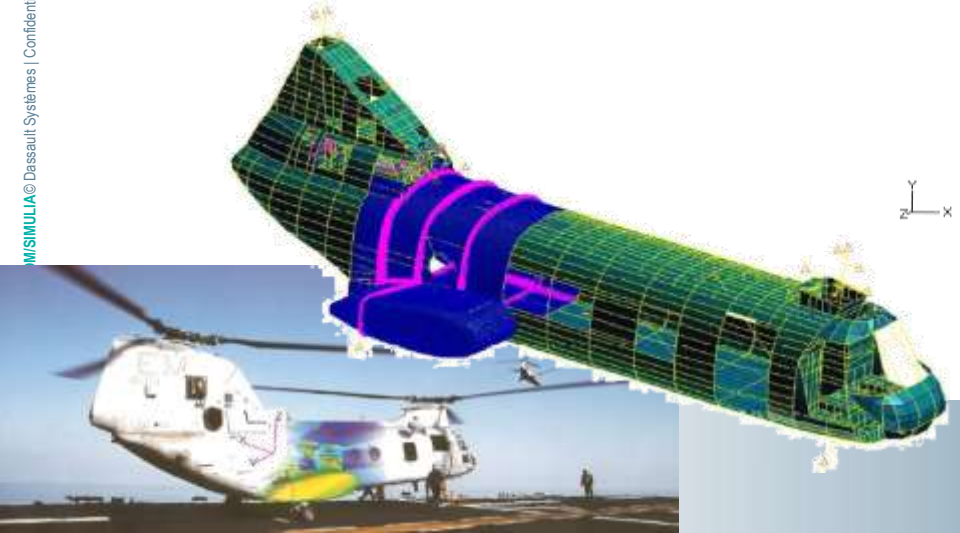
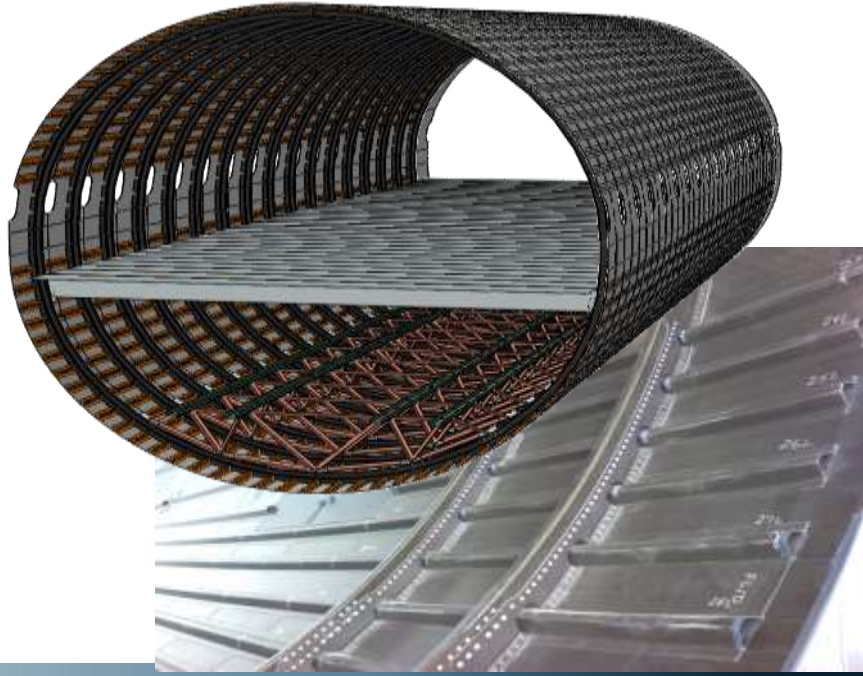
Full Vehicle Nonlinear Analysis

- Full vehicle nonlinear analysis using Abaqus
  - Boeing CH-47 Chinook Helicopter
- Large scale nonlinear analysis
  - Detailed full vehicle models for fuselage and wings
    - 10-20 Million dof





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Failure Criteria in Laminates

1. The ply failure can occur due to following failure modes: Fiber tension and fiber compression failure modes, Matrix tension and matrix compression failure modes
2. Ply failure modes can occur sequentially and initial failure envelopes can be generated

- **Stress-based failure theories**
  - Maximum stress failure criterion

$$I_F = \max\left(\frac{\sigma_{11}}{X}, \frac{\sigma_{22}}{Y}, \left|\frac{\sigma_{12}}{S}\right|\right) < 1.0.$$

  - Tsai-Hill failure criterion

$$I_F = \frac{\sigma_{11}^2}{X^2} - \frac{\sigma_{11}\sigma_{22}}{X^2} + \frac{\sigma_{22}^2}{Y^2} + \frac{\sigma_{12}^2}{S^2} < 1.0.$$

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Failure Criteria in Laminates

- **Stress-based failure theories (cont.)**
  - Tsai-Wu failure theory

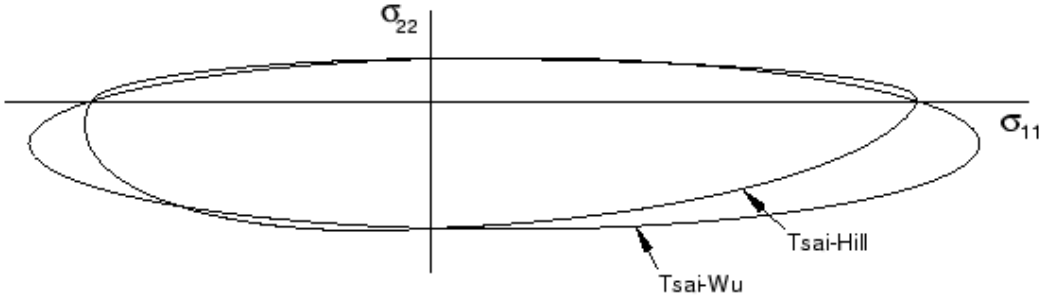
$$I_F = F_1\sigma_{11} + F_2\sigma_{22} + F_{11}\sigma_{11}^2 + F_{22}\sigma_{22}^2 + F_{66}\sigma_{12}^2 + 2F_{12}\sigma_{11}\sigma_{22} < 1.0.$$

  - Azzi-Tsai-Hill failure theory

$$I_F = \frac{\sigma_{11}^2}{X^2} - \frac{|\sigma_{11}\sigma_{22}|}{X^2} + \frac{\sigma_{22}^2}{Y^2} + \frac{\sigma_{12}^2}{S^2} < 1.0.$$

- **Strain-based failure theory**
  - Maximum strain failure theory

$$I_F = \max\left(\frac{\varepsilon_{11}}{X_\varepsilon}, \frac{\varepsilon_{22}}{Y_\varepsilon}, \left|\frac{\gamma_{12}}{S_\varepsilon}\right|\right) < 1.0.$$



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Linking Design/Manufacturing & Simulation Worlds

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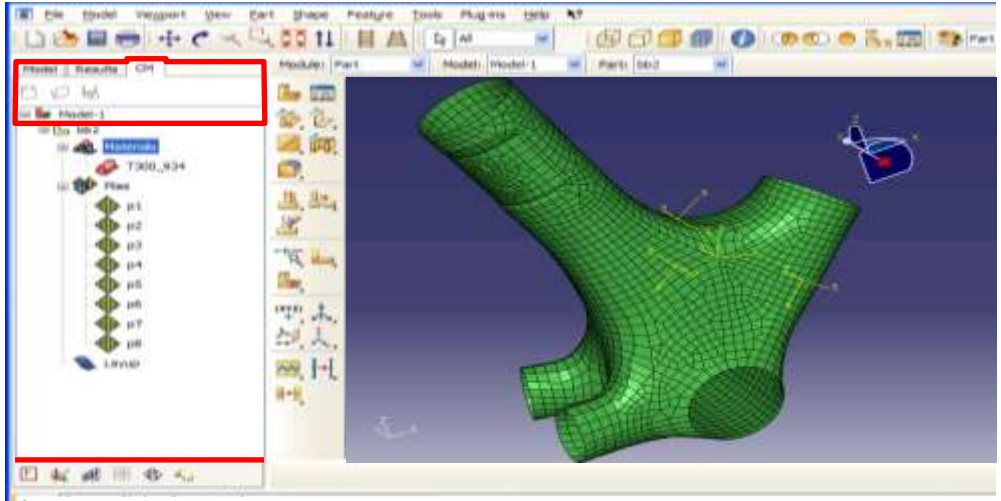
Composite Modeler for Abaqus: **CMA**

- Abaqus offers advanced fiber simulation capabilities and modeling tools via the Composites Modeler for Abaqus/CAE (CMA) add-on product.
- Draping simulations
- Generate Shell Properties
- Solid Element Support
  - Extrude to create solids from a layup based on shells
  - Fill the existing solids with ply based properties



GUI interface: Composites Modeler for Abaqus/CAE

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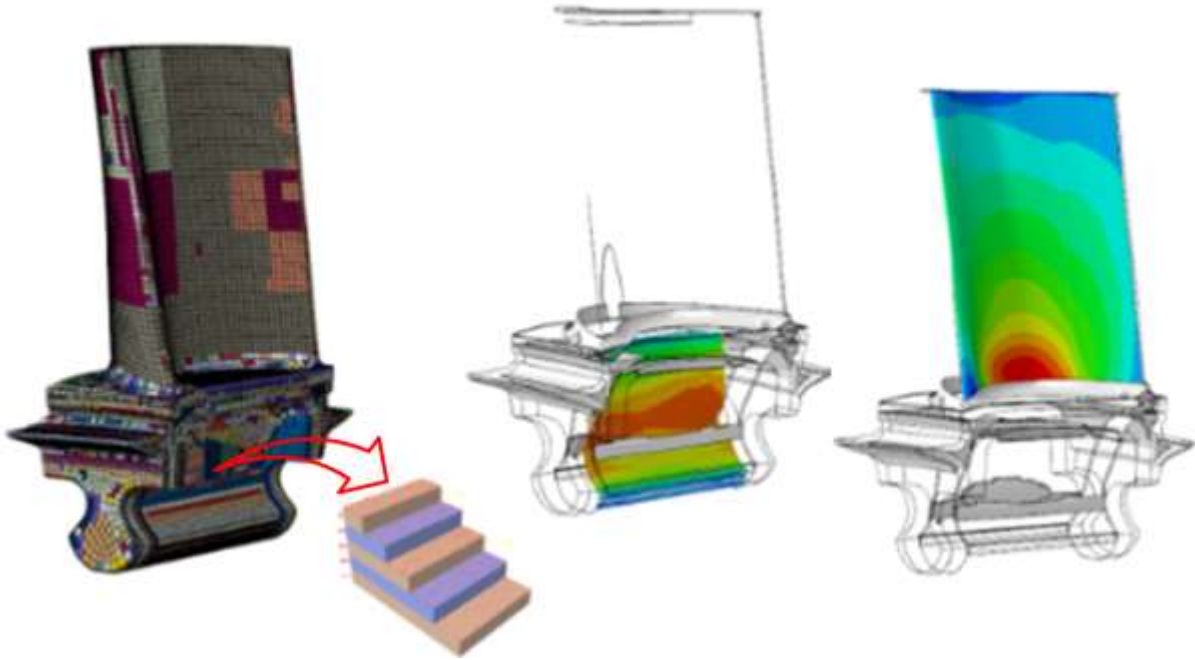
Composite Turbine Blade FEA model using Solid-Fill method

- Step 1. Prepare a clean and partitioned CAD model.
- Step 2. Use CATIA composite Slicing method to generate plies and define the lamina, this layup file is associated with the solid in CATIA.
- Step 3. Generate constant number layers of elements.
- Step 4. Import CATIA/HYPERMESH mesh to ABAQUS.
- Step 5. Fill the solid mesh with layup properties and information.
- Step 6. Assemble the meshes together in ABAQUS.



Zhang et. al., "Integrated Workflow for Analyzing Composite Gas Turbine Components", SIMULIA Community Conference, Providence, RI, May 20-22, 2014

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Draping & Effect of Seed Point, Achieve a Robust & Manufacturable Composite Design with iSight

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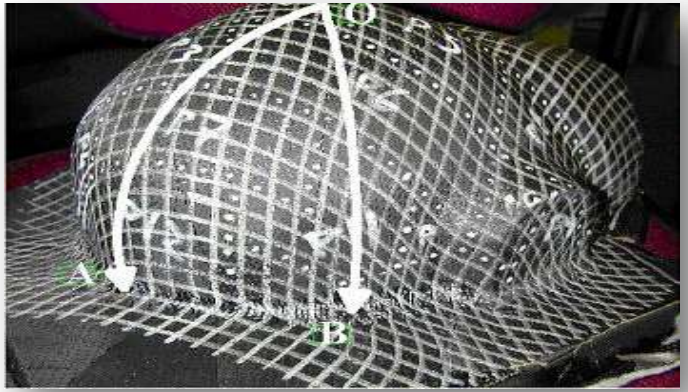
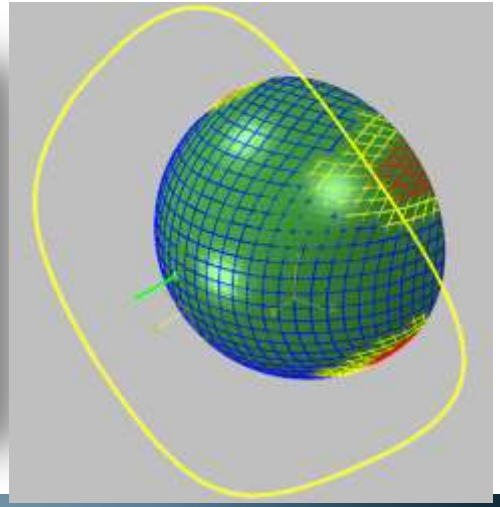
Draping & Seed Point

- **Draping** – the process of applying a flat sheet material to a mould surface.
  - The material must “shear” or “scissor” to conform to a non-developable surface and this needs to be simulated to determine as-manufactured fiber orientations.
  - Flat and draped patterns are output to aid manufacture
  - Local fiber orientations are transferred into the analysis model for realistic simulation

Seed Point: The point of first application point for a composite ply



Courtesy of Google images



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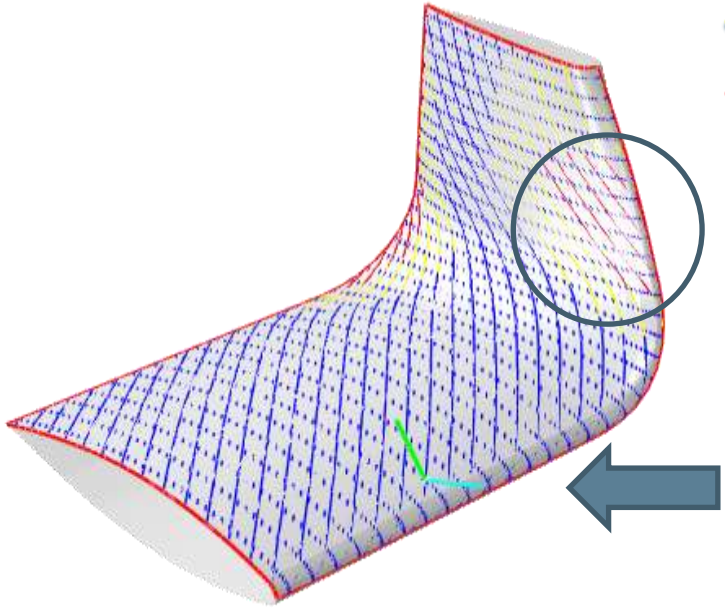
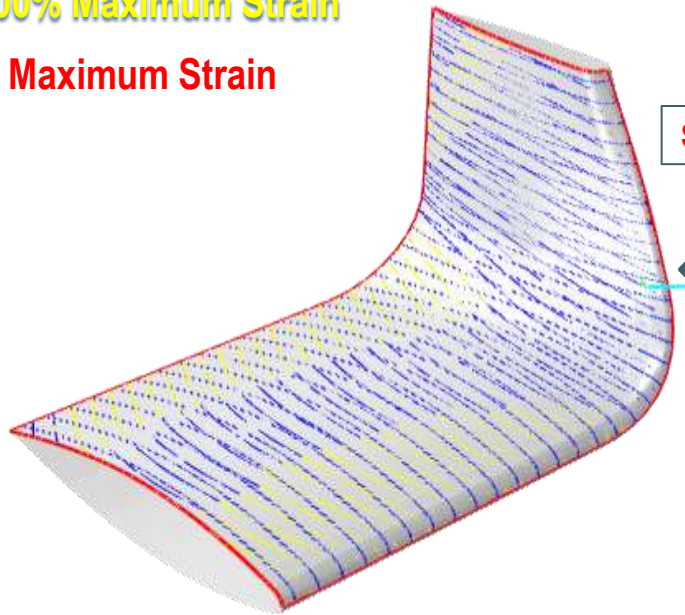
Seed Point and Draping

- Blue: < 50% Maximum Strain
- Yellow: 50-100% Maximum Strain
- Red: > 100% Maximum Strain



Seed point 1



Seed point 2

Demo

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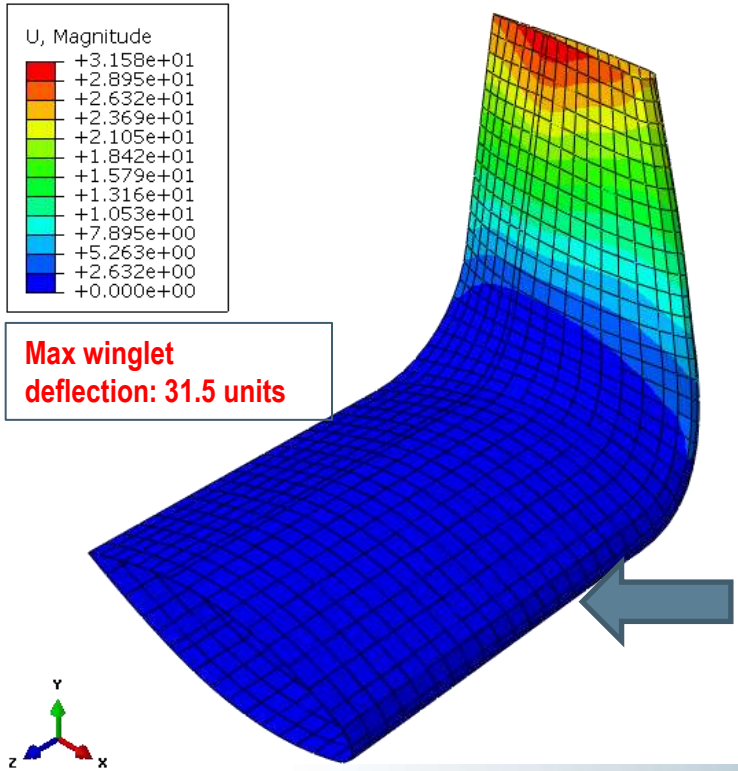
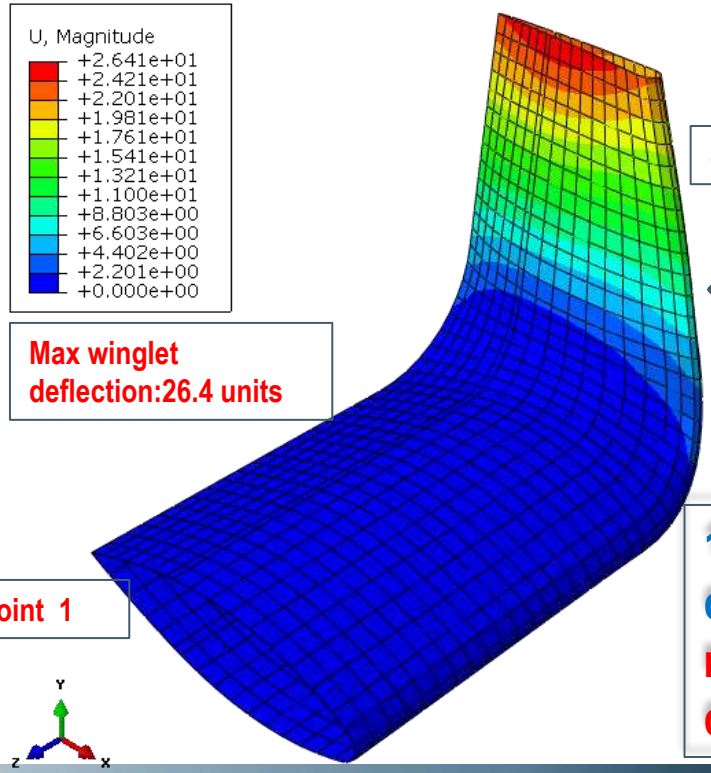
Seed Point Effect on Ply Material Properties



Seed point 1



Seed point 2

16 % difference in max deflection

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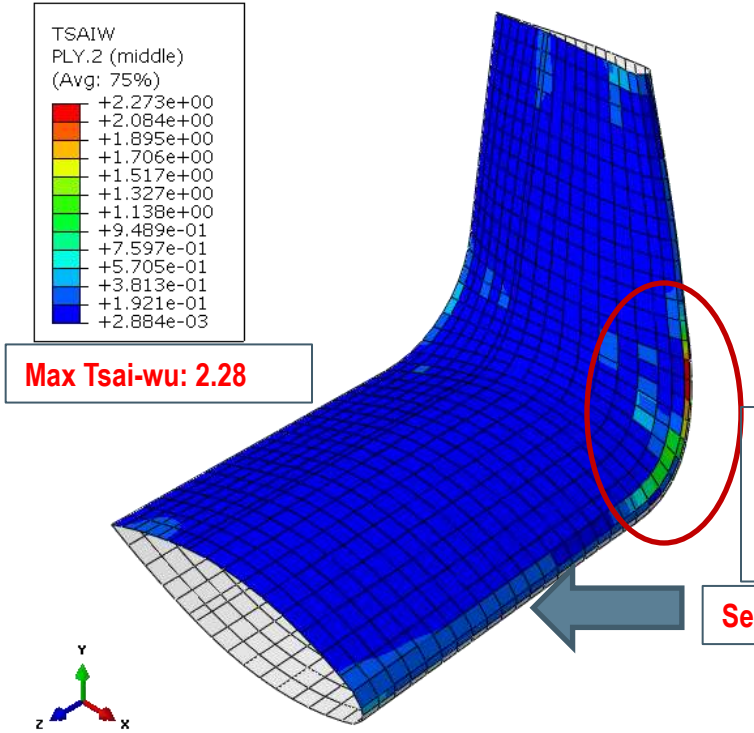
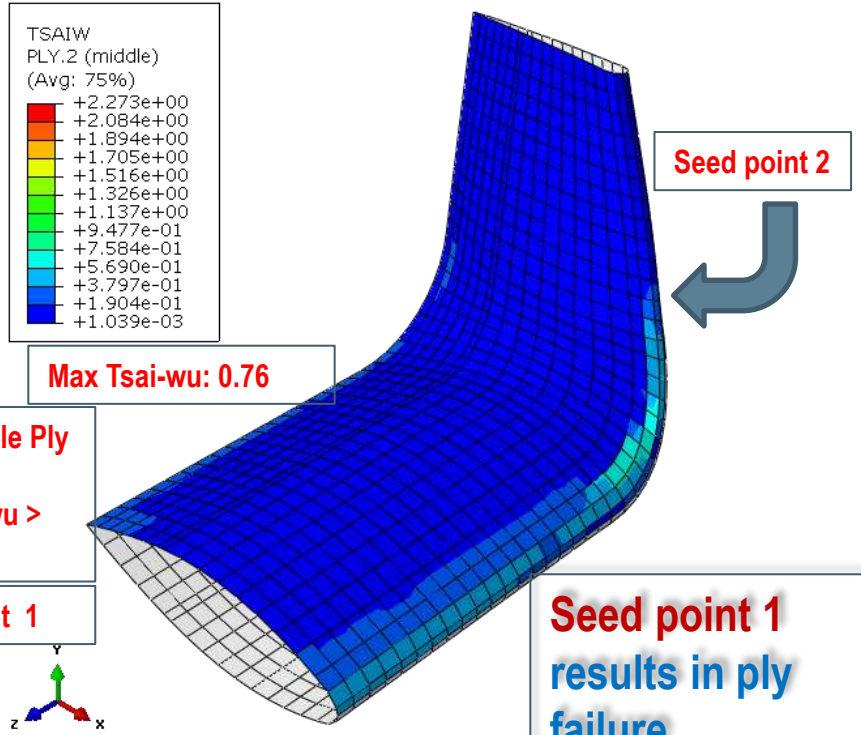
Seed Point Effect on Ply Failure



Possible Ply Failure (Tsai-wu > 1.0)

Seed point 1



Seed point 1 results in ply failure

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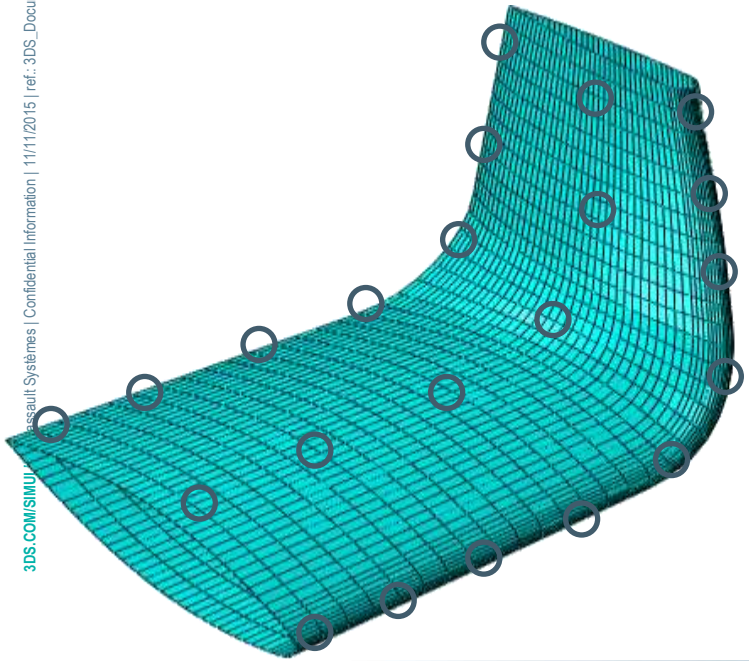
Seed Point Variation



Base Design	• 16 plies, [0,90,45,-45]2s
Constraints	• Draping Strain < 30 deg
Variables	• Seed Points ~ 31

Number of Plys*: [8-16]
Ply Angles: [0,+45,-45,-90,+90]
Seed Points: 31
CATIA V5, Excel, Abaqus, etc

Constraint: TSAIW < 1.0
Objective: Cost, Weight

> 74,613 possibilities

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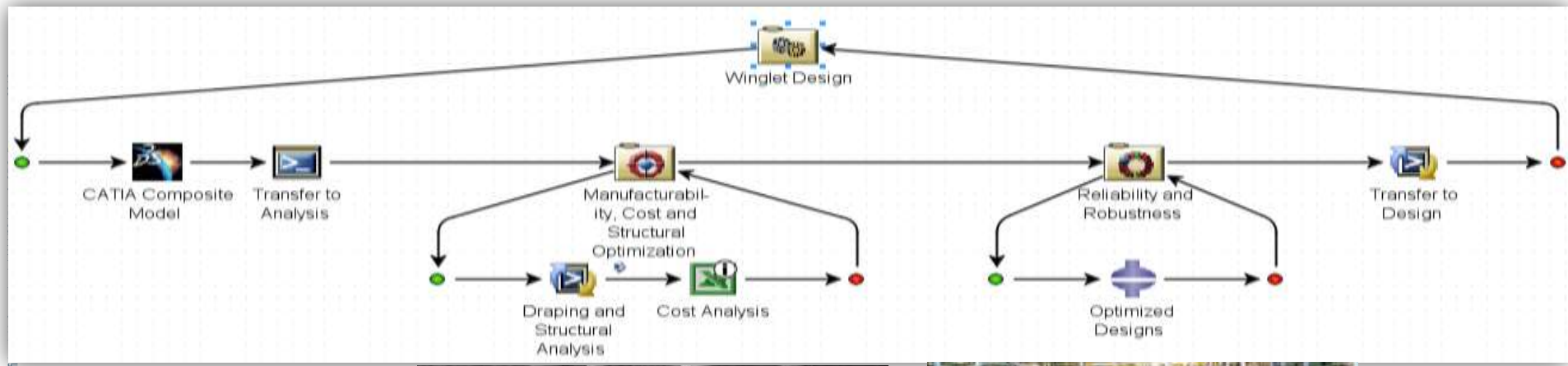
iSight Workflow



Isight:
A Software Robot

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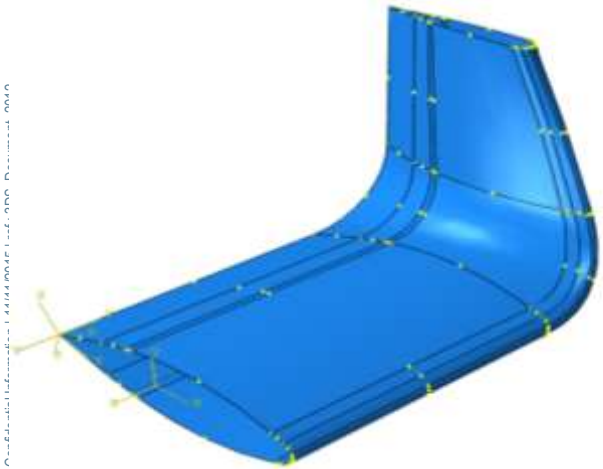
The Result



	Base	Optimized
Layup	[0/90/45/-45]2s	[0/90/90/30/-30]s
No of plies	16	10

	Original	Optimized
Deflection (< 5)	5.9	4.1
Max strain (< 30)	30.9	26.8
Tsai Wu (< 1.0)	0.74	0.34

	% savings
Weight	37

You may have more than one good design

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Units: in, lb, deg

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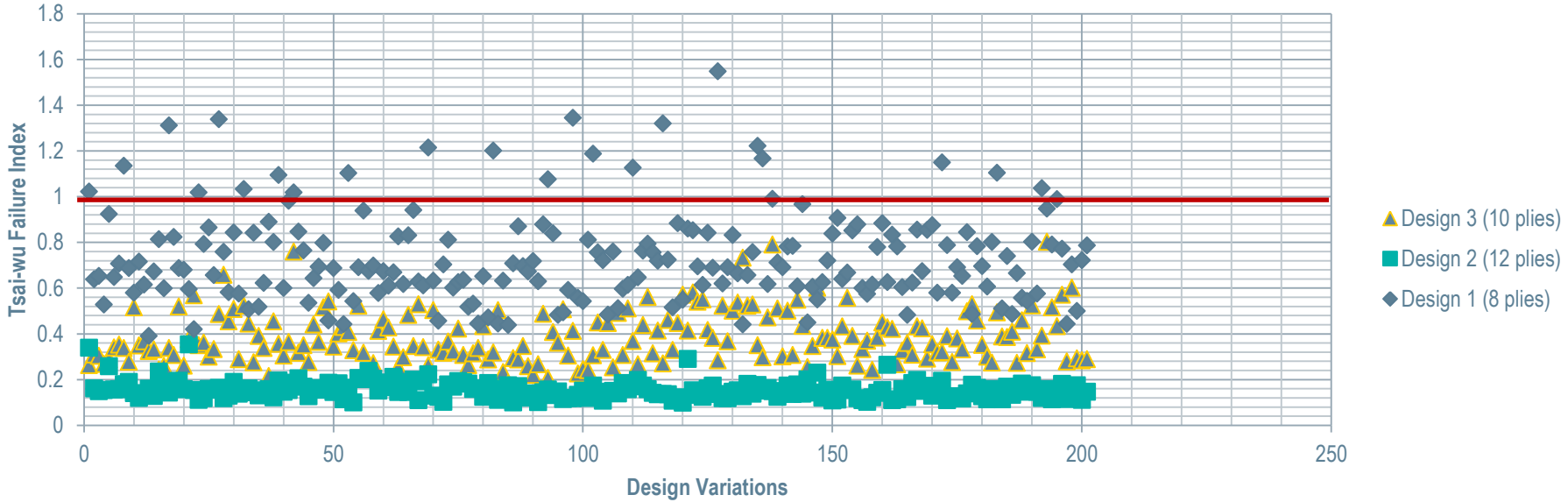
Winglet Design – Manufacturable, Reliable and Robust



Design	Lay-up	No of plies	Seed Pt
Base	[0/90/45/-45]2s	16	5
Optimized Design 1	[0/90/30/-30]s	8	16
Optimized Design 2	[0/90/90/45/45/-45/]s	12	6
Optimized Design 3	[0/90/90/30/-30]s	10	16

Initial Best

Reliable, Robust

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Machining for Simulations

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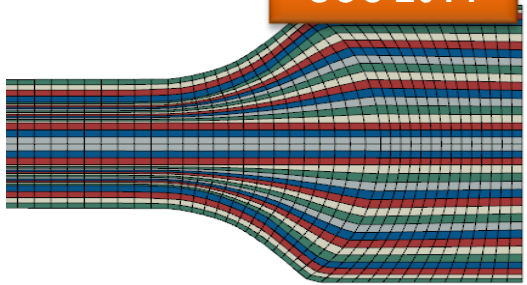
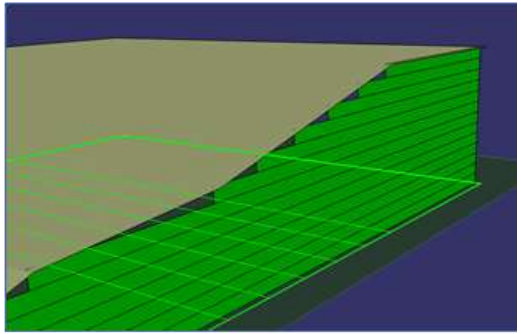
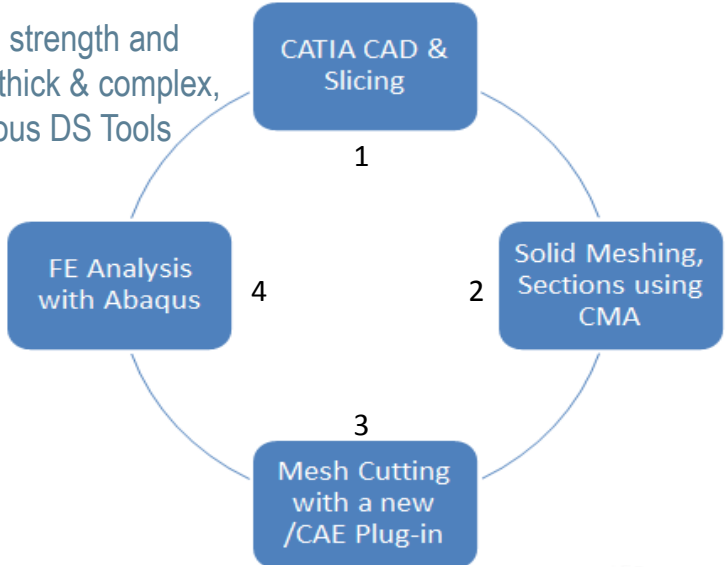
Simulation of As-Manufactured Dovetail Model with New Mesh-Cutting Tool

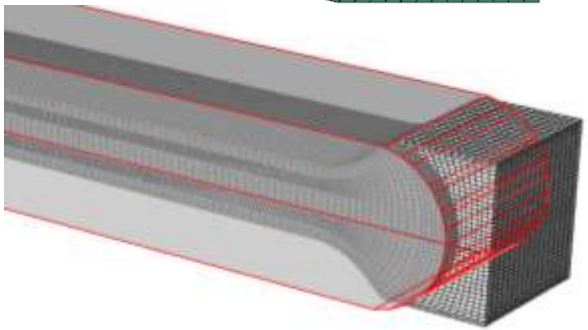
SCC 2014

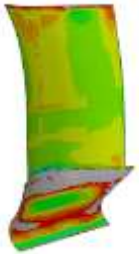
Gas turbine engines-Low density, high strength and fatigue resistance, high temperature , thick & complex, specialized modeling techniques, Various DS Tools

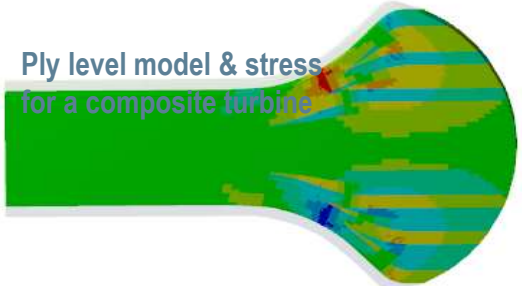




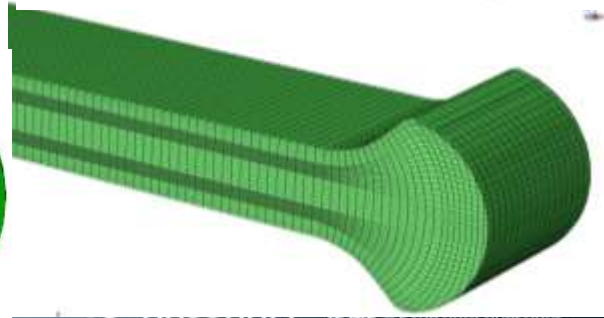








Ply level model & stress for a composite turbine



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New Plug-in: Matt Rees, R&D CATIA: Etienne Ardouin Coordination: Mahesh Turaga

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Damage Modeling

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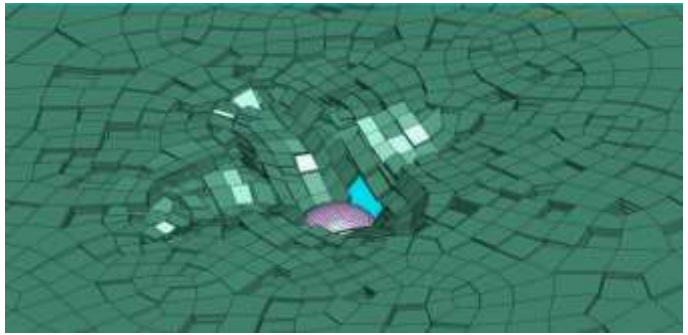
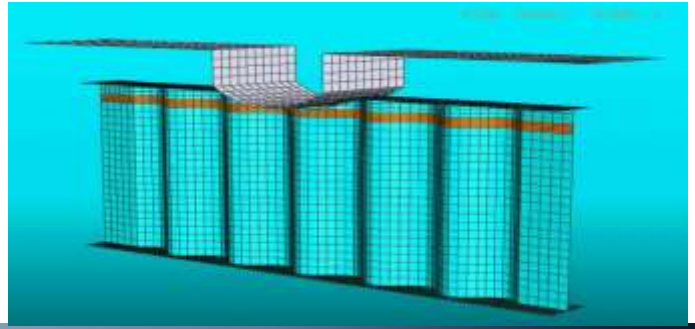
Damage

- Progressive Damage and Failure—Prediction of failure modes for both fiber and matrix materials
    - Hashin Criteria
    - UMAT (Abaqus/Standard)
    - VUMAT (Abaqus/Explicit)
- Delamination—Separation of adhesively bonded sections of laminated composites
    - Virtual Crack Closure Technique (VCCT)
    - Cohesive Elements
    - Cohesive Contact





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Damage Modeling: BVID

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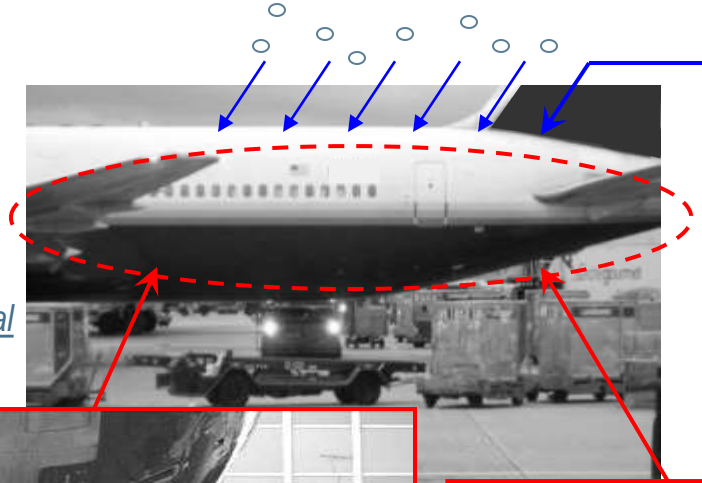
BVID (Barely Visible Impact Damage)

Blunt Impacts

- blunt impact damage (BID) can exist with *little or no exterior visibility*
- sources of interest are those that affect *wide area* or *multiple structural elements*



Research by UCSD

Hail Ice Impact

- upward & forward facing surfaces
- low mass, high velocity

Ground Vehicles & Service Equipment

- side & lower facing surfaces
- high mass, low velocity
- wide area contact
- damage possible at locations away from impact

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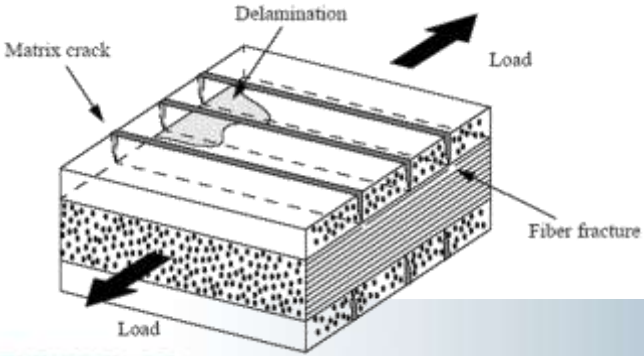
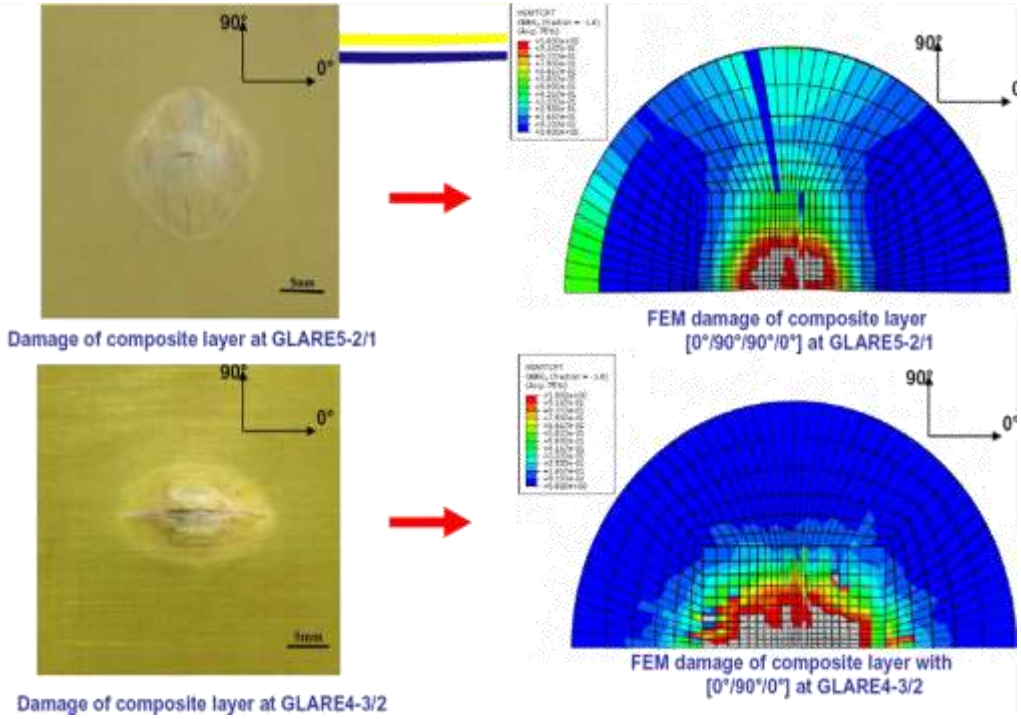
Technologies for Advanced Composites Simulation: **BVID**

- Abaqus offers a general capability for modeling progressive damage and failure in fiber-reinforced composites.
- **Four different modes of failure are considered:**
  - fiber rupture in tension;
  - fiber buckling and kinking in compression;
  - matrix cracking under transverse tension and shearing; and
  - matrix crushing under transverse compression and shearing.





BVID using Hashin's criteria

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Progressive Damage of Fiber-Reinforced Composites

- Components of material definition
  - Undamaged constitutive behavior
  - Damage initiation (point A)
  - Damage evolution (path A–B)
  - Choice of element removal (point B)
- Hashin's damage initiation criteria

Mode I: Fiber Tension $(\hat{\sigma}_{11} \geq 0)$

$$F_{ft} = \left(\frac{\hat{\sigma}_{11}}{X^T}\right)^2 + \alpha\left(\frac{\hat{\sigma}_{12}}{S^L}\right)^2 = 1, \text{ where } 0 \leq \alpha \leq 1$$

Mode II: Fiber Compression $(\hat{\sigma}_{11} < 0)$

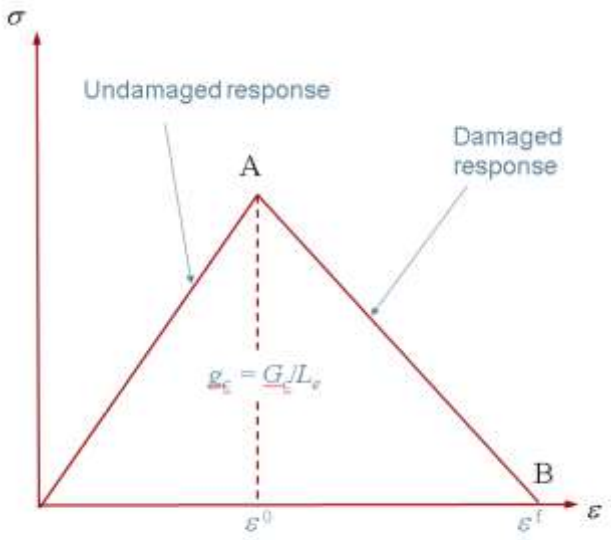
$$F_{fc} = \left(\frac{\hat{\sigma}_{11}}{X^C}\right)^2 = 1$$

Mode III: Matrix Tension $(\hat{\sigma}_{22} \geq 0)$

$$F_{mt} = \left(\frac{\hat{\sigma}_{22}}{Y^T}\right)^2 + \left(\frac{\hat{\sigma}_{12}}{S^L}\right)^2 = 1$$

Mode IV: Matrix Compression $(\hat{\sigma}_{22} < 0)$

$$F_{mc} = \left(\frac{\hat{\sigma}_{22}}{2S^T}\right)^2 + \left[\left(\frac{Y^C}{2S^T}\right)^2 - 1\right]\frac{\hat{\sigma}_{22}}{Y^C} + \left(\frac{\hat{\sigma}_{12}}{S^L}\right)^2 = 1$$



Typical material response showing progressive damage

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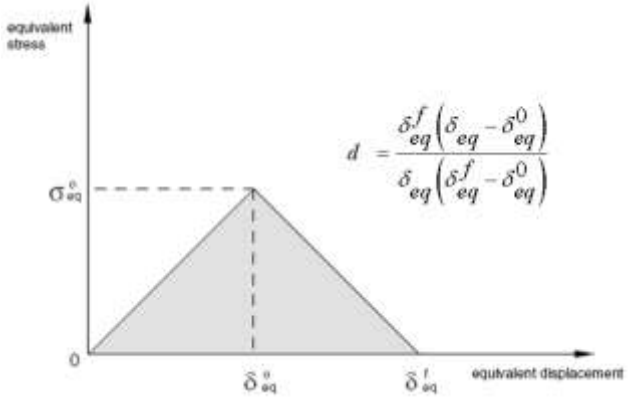
Progressive damage of Fiber-Reinforce Composites

- Damage evolution
  - Damage evolution defines the post damage-initiation material behavior, which describes the rate of degradation of the material stiffness once the initiation criterion is satisfied.
  - Response of the material after damage initiation is of the form $\sigma = \boldsymbol{C}(d):\varepsilon$, where $\boldsymbol{C}(d)$ is the damaged elasticity matrix

$$\boldsymbol{C}(d) = \frac{1}{D}\begin{bmatrix} (1-d_f)E_1 & (1-d_f)(1-d_m)\nu_{21}E_1 & 0 \\ (1-d_f)(1-d_m)\nu_{12}E_2 & (1-d_m)E_2 & 0 \\ 0 & 0 & D(1-d_s)G \end{bmatrix}$$

  - Linear material softening is assumed



$$d = \frac{\delta^f_{eq}\left(\delta_{eq} - \delta^0_{eq}\right)}{\delta_{eq}\left(\delta^f_{eq} - \delta^0_{eq}\right)}$$

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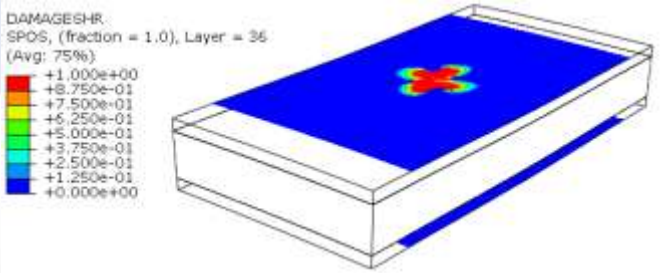
Barely Visible Impact Damage (BVID)

Abaqus allows the import of the damage model for fiber-reinforced composites from Abaqus/Explicit to Abaqus/Standard to model the analysis of Barely Visible Impact Damage (BVID) in composite structures.

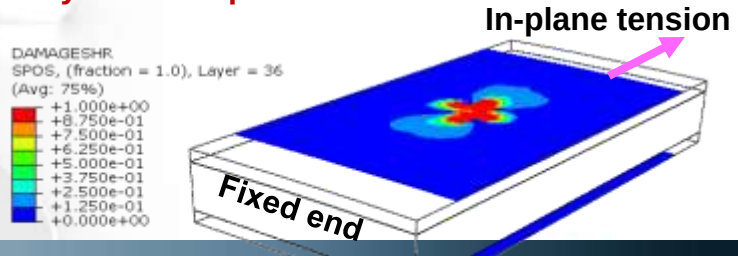
1 ABAQUS/Explicit is used to model low speed impact which results in damage.

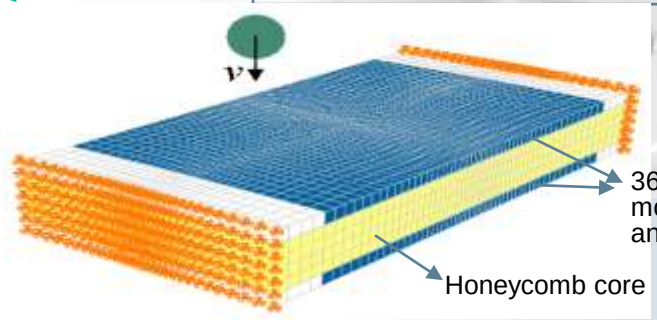
2 Further analysis of the damaged plate is conducted in Abaqus/Standard.

Impact Analysis – Abaqus/Explicit



Tensile Analysis – Abaqus/Standard





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Damage Modeling: VCCT

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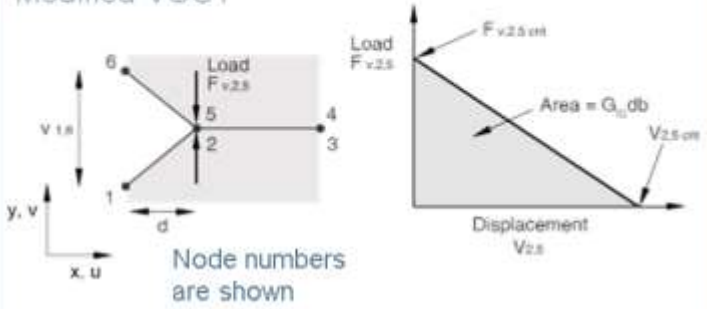
VCCT: introduction

- Useful for delaminations predictions.
- Preexisting crack
- VCCT uses LEFM concepts
  - Based on computing the energy release rates for normal and shear crack-tip deformation modes.
  - Compare energy release rates to interlaminar fracture toughness.
  - See Rybicki, E. F., and Kanninen, M. F., "A Finite Element Calculation of Stress Intensity Factors by a Modified Crack Closure Integral," *Engineering Fracture Mechanics*, Vol. 9, pp. 931-938, 1977.

Pure Mode I

Modified VCCT



Node numbers are shown

Nodes 2 and 5 will start to release when:

$$\frac{1}{2}\frac{v_{1,6}F_{v,2,5}}{bd} = G_I \geq G_{IC}$$

Mode II treated similarly

where

G_I = mode I energy release rate

G_{IC} = critical mode I energy release rate

b = width

$F_{v,2,5}$ = vertical force between nodes 2 and 5

$v_{1,6}$ = vertical displacement between nodes 1 and 6

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VCCT: criterion

- **BK law**

$$G_{equivC} = G_{IC} + \left(G_{IIC} - G_{IC}\right)\left(\frac{G_{II} + G_{III}}{G_I + G_{II} + G_{III}}\right)^{\eta}$$

Crack propagation analysis is carried out on a nodal basis. The crack-tip node debonds when the fracture criterion $f=1$

$$f = \frac{G_{equiv}}{G_{equivC}},$$

where: G_{equiv} is the equivalent strain energy release rate, and

G_{equivC} is the critical equivalent strain energy release rate calculated based on the user-specified mode-mix criterion and the bond strength of the interface.

Power law, Reeder Law Criteria also available

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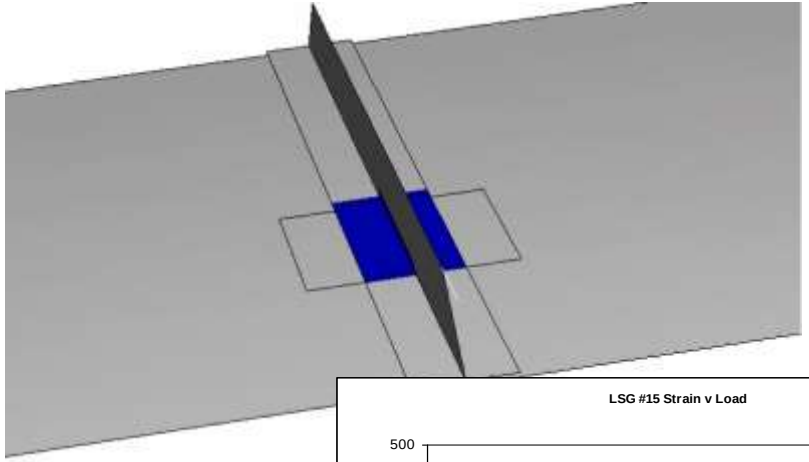
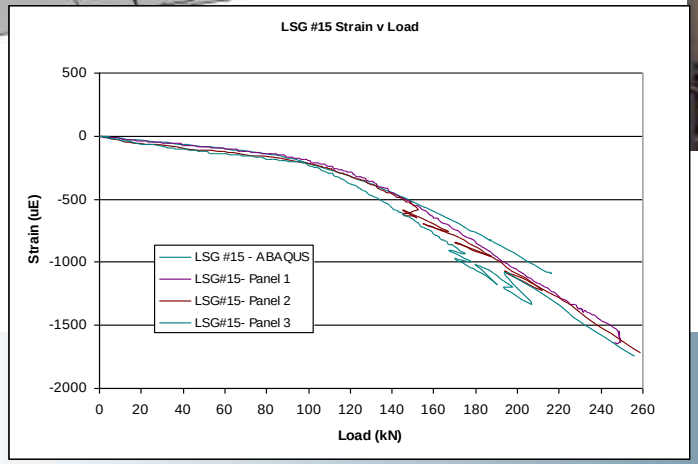
Composites Crack Propagation (VCCT)

VCCT predicts the crack growth rate and path to determine the global strength and failure modes for typical aerospace composite structures like this skin/stringer panel





Courtesy Boeing

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Damage Modeling: Cohesive Zone

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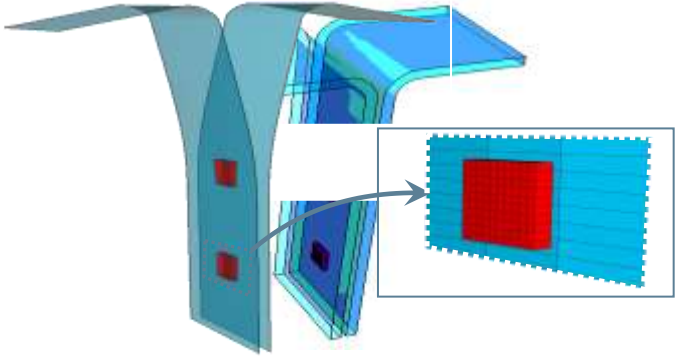
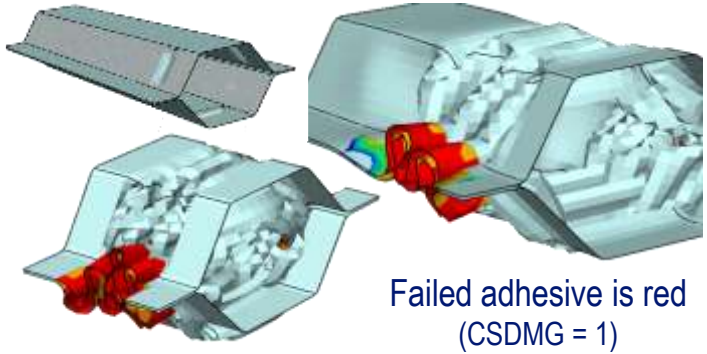
Cohesive Behavior

- **Cohesive behavior is useful Delamination in composites**
- **Idealize complex fracture mechanisms with a macroscopic "cohesive law," which relates the traction across the interface to the separation.**
- The cohesive behavior can be:
  - Element-based
    - Modeled with cohesive elements
  - Surface-based
    - Modeled with contact pairs in Abaqus/Standard and general contact in Abaqus/Explicit



T-peel analysis: Cohesive elements are used for modeling adhesive patches



Failed adhesive is red
(CSDMG = 1)

Rail crush: Cohesive surfaces

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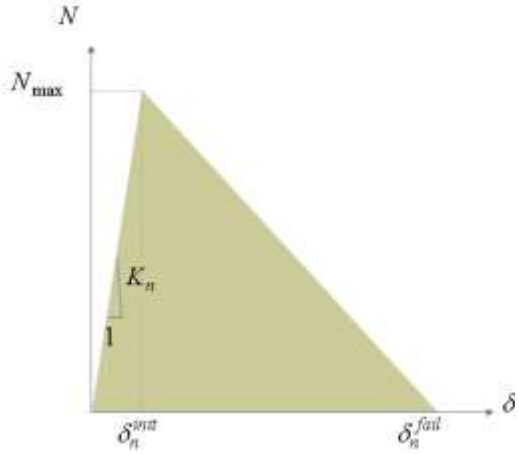
Cohesive element

1. **Specification of elastic modulus**
2. **Damage initiation**
3. **Damage evolution**

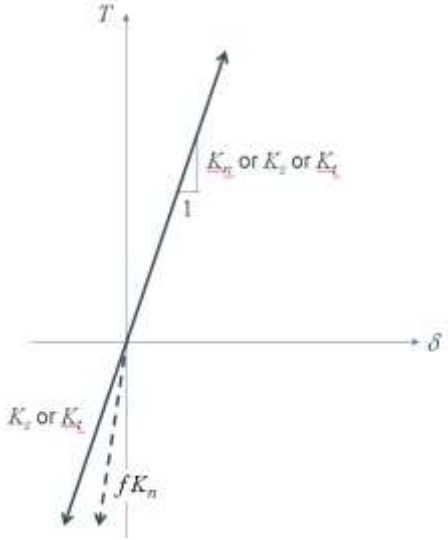


▶ Specification of elastic modulus

- ▷ The elastic modulus for the traction separation law should be interpreted as a penalty stiffness. For example, for the opening mode:

$$K_n = N_{\max} / \delta_n^{init}$$

- ▷ Elastic response for the normal component may be different in compression than in tension (it can be scaled by a factor f ; by default f =1):



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Cohesive element: damage initiation

- **Damage initiation**
  - Stress or strain based criterion
  - Mixed mode conditions

Summary of damage initiation criteria:

Maximum nominal stress criterion

$$MAX\left\{\frac{\langle\sigma_n\rangle}{N_{max}},\frac{\sigma_s}{S_{max}},\frac{\sigma_t}{T_{max}}\right\}=1$$

*DAMAGE INITIATION, CRITERION=MAXS

N_{max}, S_{max}, T_{max}

Maximum nominal strain criterion

$$MAX\left\{\frac{\langle\varepsilon_n\rangle}{\varepsilon_n^{max}},\frac{\varepsilon_s}{\varepsilon_s^{max}},\frac{\varepsilon_t}{\varepsilon_t^{max}}\right\}=1$$

*DAMAGE INITIATION, CRITERION=MAXE

ε_n^{max}, ε_s^{max}, ε_t^{max}

Quadratic nominal stress criterion

$$\left(\frac{\langle\sigma_n\rangle}{N_{max}}\right)^2+\left(\frac{\sigma_s}{S_{max}}\right)^2+\left(\frac{\sigma_t}{T_{max}}\right)^2=1$$

*DAMAGE INITIATION, CRITERION=QUADS

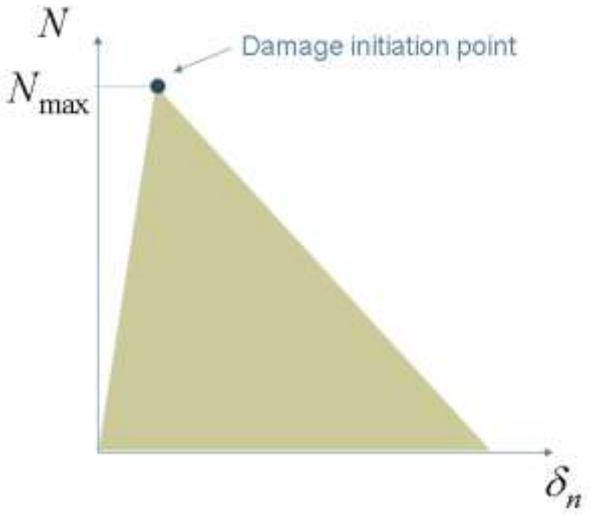
N_{max}, S_{max}, T_{max}

Quadratic nominal strain criterion

$$\left(\frac{\langle\varepsilon_n\rangle}{\varepsilon_n^{max}}\right)^2+\left(\frac{\varepsilon_s}{\varepsilon_s^{max}}\right)^2+\left(\frac{\varepsilon_t}{\varepsilon_t^{max}}\right)^2=1$$

*DAMAGE INITIATION, CRITERION=QUADE

ε_n^{max}, ε_s^{max}, ε_t^{max}



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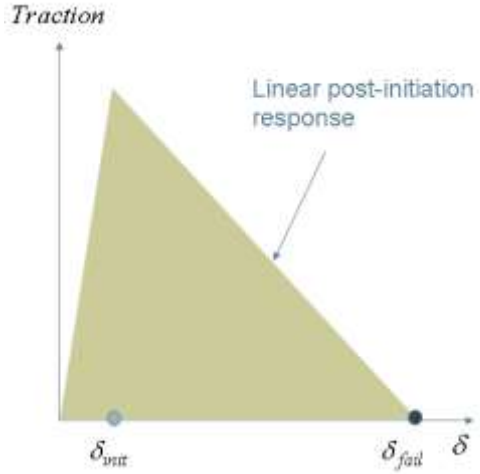
Cohesive element: damage evolution

- Damage evolution is based on energy or displacement
  - Specify either the total fracture energy or the post damage-initiation effective displacement at failure
  - May depend on mode mix
  - Mode mix may be defined in terms of energy or traction
- Displacement-based damage evolution
  - Damage is a function of an effective displacement:

$$\delta = \sqrt{\langle \delta_n \rangle^2 + \delta_s^2 + \delta_t^2}$$

  - The post damage-initiation softening response can be either:

    Linear, Exponential, Tabular



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Cohesive element: damage evolution

- Energy-based damage evolution
  - The fracture energy can be defined as a function of mode mix using either a tabular form or one of two analytical forms:
    - Power law

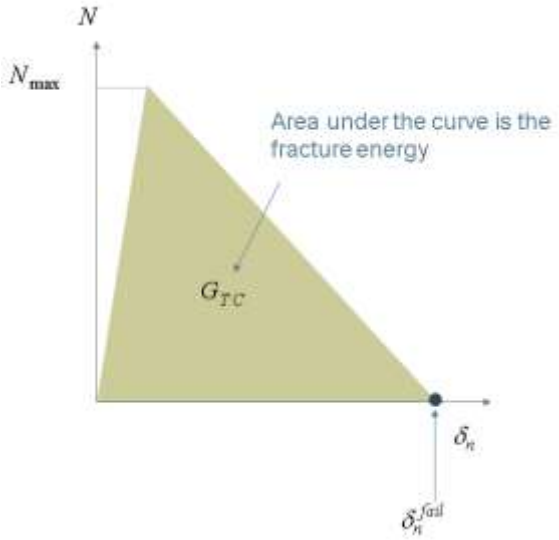
$$\left(\frac{G_I}{G_{IC}}\right)^{\alpha}+\left(\frac{G_{II}}{G_{IIC}}\right)^{\alpha}+\left(\frac{G_{III}}{G_{IIIC}}\right)^{\alpha}=1$$

    - BK (Benzeggagh-Kenane)

$$G_{IC}+\left(G_{IIC}-G_{IC}\right)\left(\frac{G_{shear}}{G_T}\right)^{\eta}=G_{TC}$$

where $G_{shear}=G_{II}+G_{III}$

$G_T=G_I+G_{shear}$



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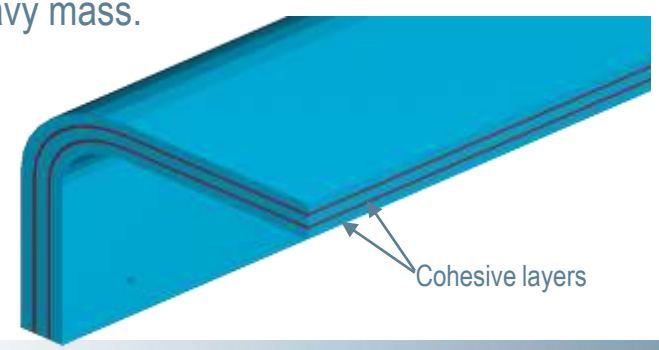
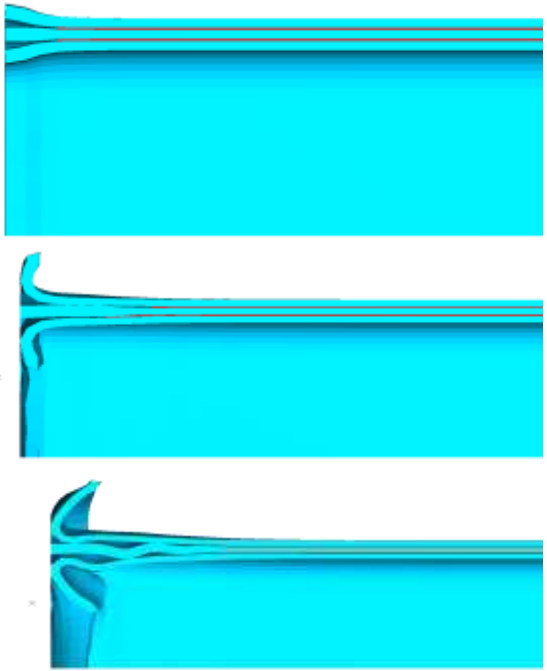
Cohesive Element Example

- Delamination of a metallic sandwich
  - This model illustrates delamination in a metallic sandwich structure.
    - It comprises 3 layers of material with adhesive layers applied between the layers.
    - The structure delaminates under the impact of a heavy mass.





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Damage Modeling: High Speed Ballistic Impact

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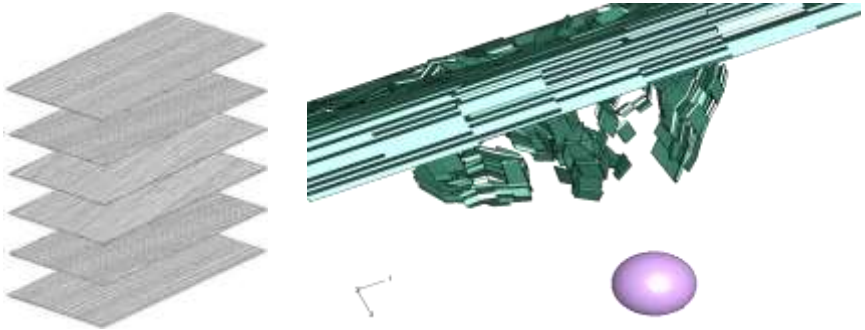
High Speed Ballistic Impact

Unidirectional Composite VUMAT

- Ballistic impact is a concern in many application areas, including road and runway debris, bird strike, armor design, and many others
- Abaqus has developed a unidirectional fiber composite damage and failure VUMAT for Abaqus/Explicit specifically for high speed impact problems
- This specific example will consider ballistic impact onto unidirectional fiber composite plate



- Geometry, material properties and experimental results are taken from Kasano, H. *Impact perforation of orthotropic and quasi-isotropic CFRP laminates by a steel ball projectile*, *Adv. Composite Mater.*, Vol. 10, No. 4, pp. 309-318, 2001

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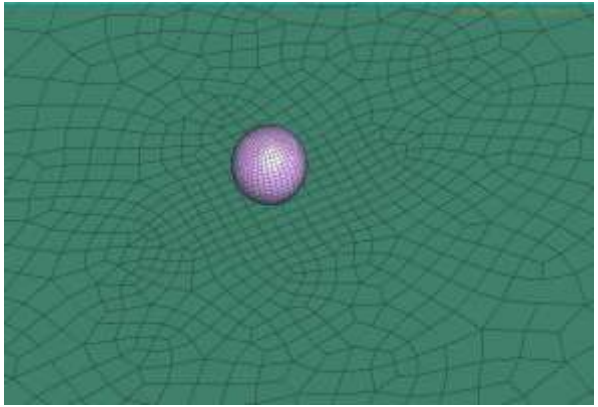
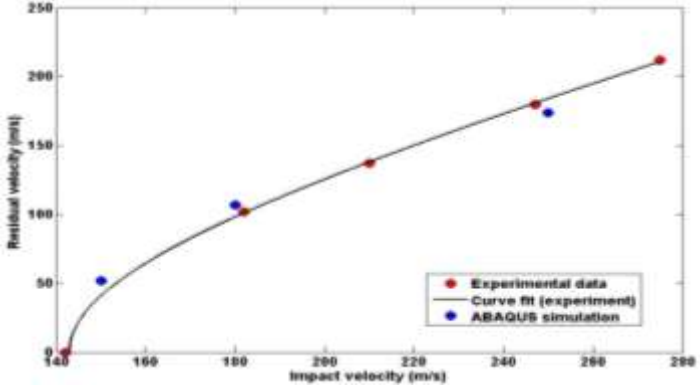
High Speed Ballistic Impact

- Damage and failure modeling in Abaqus/Explicit can be used to assess ballistic limit velocities and composite fiber and matrix damage
- Damage modeling can be combined with cohesive elements to predict delamination as well





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