

# **Continuum Damage Mechanics Based Explicit 3D Progressive Failure Analysis of Composite Laminates**

**(Development and Preliminary Results)**

**John T. Wang**  
**NASA Langley Research Center**

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# Outline

- Motivation
- Objective
- Approach
- CDM Based PFA
  - Failure criteria
  - Damage evolution modeling using crack band theory
  - 3D stress-strain relations for damaged lamina
- Validation of Analysis Results
- Concluding Remarks

# Motivation

- Many progressive failure analysis (PFA) tools have been developed and used; however, predicting the failure load of composite structures is still a challenging problem
- Since damage initiation in composite laminates often involves out-of-plane stresses such as the familiar cases of edge delamination and low velocity impact damage, 3D progressive failure analysis tools are highly desired
- Recent studies<sup>1</sup> show that lamina property degradations after damage initiation can be modeled by the crack band theory<sup>2</sup> that can also alleviate mesh dependency issues
- Crack band theory provides the key ingredient for establishing the continuum damage mechanics (CDM) based progressive failure tool

1. Pineda and Waas, Int J Fract (2013)

2. Bazant and Oh, Mater Struct (1983)

# Objective

- Develop a CDM based 3D PFA tool that can be linked to commercial finite element analysis (FEA) software for laminated composite structures

# Approach

- Develop CDM model based 3D constitutive equations for damaged lamina, utilizing only standard unidirectional material properties
- Implement the CDM model as a user defined material model (VUMAT) to link with Abaqus/Explicit code for performing PFA of laminated composite structures
- Validate the PFA tool with available experimental data

# CDM Based PFA

- Strain based failure criteria for damage initiation
- Damage evolution modeling<sup>1,2</sup>
  - Crack-band strain in damaged element
  - Crack band theory for material property degradations
- Matzenmiller type 3D stress-strain relations<sup>3</sup> for damaged lamina

1. Pineda and Waas, Int J Fract (2013)

2. Bazant and Oh, Mater Struct (1983)

3. Matzenmiller, Lubliner, and Taylor, Mech Mater(1995)

# Strain Based Failure Criteria for Damage Initiation

- Hashin-Rotem Failure Criteria

Fiber Failure

$$\left( \frac{\varepsilon_{11}}{X_1} \right)^2 = 1$$

Matrix Failure

$$\left( \frac{\varepsilon_{22}}{X_2} \right)^2 + \left( \frac{\gamma_{23}}{X_4} \right)^2 + \left( \frac{\gamma_{12}}{X_6} \right)^2 = 1$$

$$\left( \frac{\varepsilon_{33}}{X_3} \right)^2 + \left( \frac{\gamma_{23}}{X_4} \right)^2 + \left( \frac{\gamma_{13}}{X_5} \right)^2 = 1$$

$$X_i = \frac{\textit{Strength}_i}{\textit{Modulus}_i}$$

# Crack-Band Strains in Damaged Element<sup>1,2</sup>

- Smearing the crack opening displacements to increase the element strains, namely, the crack-band strains

$$l_e \varepsilon_{11} = l_e \varepsilon_{11}^C + \delta_I^f$$

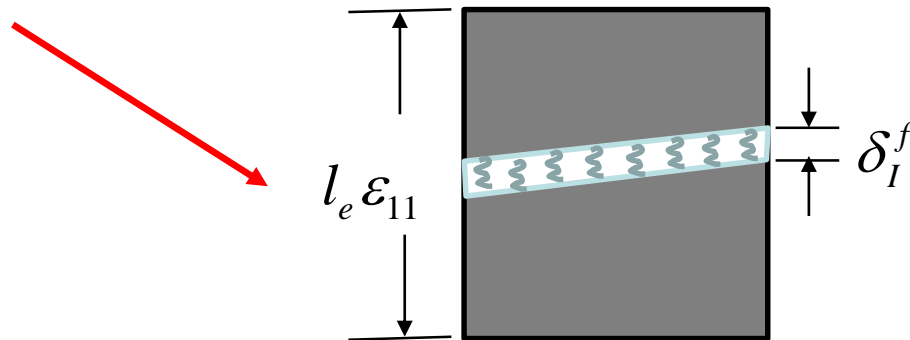
$$l_e \varepsilon_{22} = l_e \varepsilon_{22}^C + \delta_I^m$$

$$l_e^t \varepsilon_{33} = l_e^t \varepsilon_{33}^C + \delta_I^m$$

$$l_e \gamma_{12} = l_e \gamma_{12}^C + 2\delta_{II}^m$$

$$l_e^t \gamma_{13} = l_e^t \gamma_{13}^C + 2\delta_{II}^m$$

$$l_e^t \gamma_{23} = l_e^t \gamma_{23}^C + 2\delta_{II}^m$$



Damaged element with cohesive opening

$l_e$  = length scale for ply in – plane strains

$l_e^t$  = length scale for ply transverse strains

- Crack-band strains combined with the traction-separation laws for determining material property degradations

1. Pineda and Waas, Int J Fract (2013)

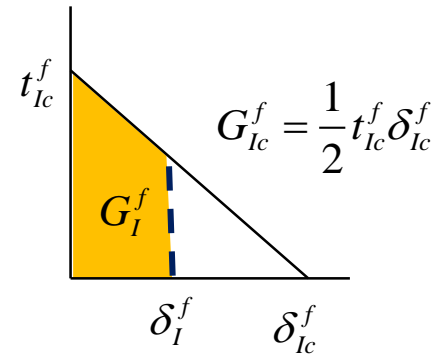
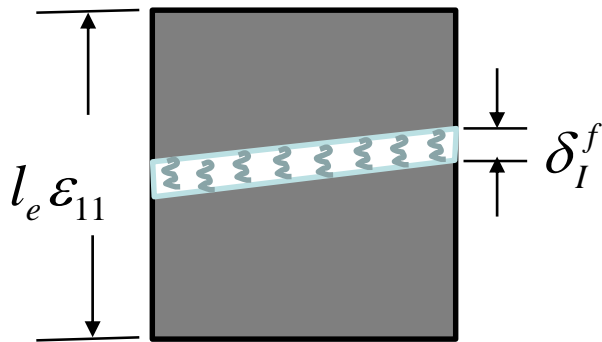
2. Bazant and Oh, Mater Struct (1983)



# Crack Band Theory for Fiber Direction Modulus Degradation

Linear elastic modulus      Damage evolution

$$E_{11} = \left\{ \frac{1}{E_{110}} + \frac{\varepsilon_{11} - \varepsilon_{11}^C}{t_{IC}^f \left[ 1 - \frac{l_e t_{IC}^f (\varepsilon_{11} - \varepsilon_{11}^C)}{2G_{IC}^f} \right]} \right\}^{-1}$$



$$l_e \varepsilon_{11} = l_e \varepsilon_{11}^C + \delta_I^f$$

Crack-band strain      +      Traction-separation law

# Material Moduli Degradations

$$E_{11} = \left\{ \frac{1}{E_{110}} + \frac{\varepsilon_{11} - \varepsilon_{11}^C}{t_{IC}^f \left[ 1 - \frac{l_e t_{IC}^f (\varepsilon_{11} - \varepsilon_{11}^C)}{2G_{IC}^f} \right]} \right\}^{-1}$$

$$G_{12} = \left\{ \frac{1}{G_{120}} + \frac{\gamma_{12} - \gamma_{12}^C}{2t_{IIC}^m \left[ 1 - \frac{l_e t_{IIC}^m (\gamma_{12} - \gamma_{12}^C)}{4G_{IIC}^m} \right]} \right\}^{-1}$$

$$E_{22} = \left\{ \frac{1}{E_{220}} + \frac{\varepsilon_{22} - \varepsilon_{22}^C}{t_{IC}^m \left[ 1 - \frac{l_e t_{IC}^m (\varepsilon_{22} - \varepsilon_{22}^C)}{2G_{IC}^m} \right]} \right\}^{-1}$$

$$G_{13} = \left\{ \frac{1}{G_{130}} + \frac{\gamma_{13} - \gamma_{13}^C}{2t_{IIC}^m \left[ 1 - \frac{l_e t_{IIC}^m (\gamma_{13} - \gamma_{13}^C)}{4G_{IIC}^m} \right]} \right\}^{-1}$$

$$E_{33} = \left\{ \frac{1}{E_{330}} + \frac{\varepsilon_{33} - \varepsilon_{33}^C}{t_{IC}^m \left[ 1 - \frac{l_e t_{IC}^m (\varepsilon_{33} - \varepsilon_{33}^C)}{2G_{IC}^m} \right]} \right\}^{-1}$$

$$G_{23} = \left\{ \frac{1}{G_{230}} + \frac{\gamma_{23} - \gamma_{23}^C}{2t_{IIC}^m \left[ 1 - \frac{l_e t_{IIC}^m (\gamma_{23} - \gamma_{23}^C)}{4G_{IIC}^m} \right]} \right\}^{-1}$$

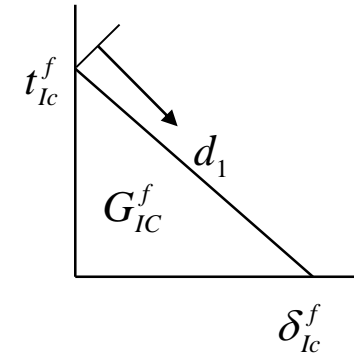
# Damage Indices (Internal State Variables)

- Definition of damage index (Internal state Variable)

$$d_1 = 1 - E_{11} / E_{110} \quad ds_{12} = 1 - G_{12} / G_{120}$$

$$d_2 = 1 - E_{22} / E_{220} \quad ds_{13} = 1 - G_{13} / G_{130}$$

$$d_3 = 1 - E_{33} / E_{330} \quad ds_{23} = 1 - G_{23} / G_{230}$$



$E_{11}, E_{22}, E_{33}, G_{12}, G_{13},$  and  $G_{23}$  are degraded material moduli

$E_{110}, E_{220}, E_{330}, G_{120}, G_{130},$  and  $G_{230}$  are linear elastic material moduli

- Note that *damage index* = 0 is at undamaged state (fully elastic)  
*damage index* = 1 is at fully failed state
- Continuum damage mechanics model using these damage indices to establish the material stiffness degradations

# Stress-Strain Relations for Damaged Lamina

$$\boldsymbol{\sigma} = C(d)\boldsymbol{\varepsilon} \quad \text{where} \quad C(d) = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ & C_{22} & C_{23} & 0 & 0 & 0 \\ & & C_{33} & 0 & 0 & 0 \\ & & & C_{44} & 0 & 0 \\ & \text{Symmetry} & & & C_{55} & 0 \\ & & & & & C_{66} \end{bmatrix}$$

$$C_{11} = (1-d_1)E_1[1-(1-d_2)(1-d_3)\mathbf{v}_{32}\mathbf{v}_{23}]/\Delta$$

$$C_{22} = (1-d_2)E_2[1-(1-d_1)(1-d_3)\mathbf{v}_{13}\mathbf{v}_{31}]/\Delta$$

$$C_{33} = (1-d_3)E_3[1-(1-d_1)(1-d_2)\mathbf{v}_{12}\mathbf{v}_{21}]/\Delta$$

$$C_{12} = (1-d_1)(1-d_2)E_1[(1-d_3)\mathbf{v}_{31}\mathbf{v}_{23} + \mathbf{v}_{21}]/\Delta$$

$$C_{13} = (1-d_1)(1-d_3)E_1[(1-d_2)\mathbf{v}_{21}\mathbf{v}_{32} + \mathbf{v}_{31}]/\Delta$$

$$C_{23} = (1-d_2)(1-d_3)E_2[(1-d_1)\mathbf{v}_{12}\mathbf{v}_{31} + \mathbf{v}_{32}]/\Delta$$

$$C_{44} = 2d_4G_{12}/\Delta \quad C_{55} = 2d_5G_{31}/\Delta$$

$$C_{66} = 2d_6G_{23}/\Delta$$

$d_4$ ,  $d_5$ , and  $d_6$  can be expressed as the following phenomenological equations

$$d_4 = (1-d_1)(1-\alpha d_2)(1-\beta ds_{12})$$

$$d_5 = (1-d_1)(1-\alpha d_3)(1-\beta ds_{13})$$

$$d_6 = (1-d_1)(1-\alpha d_2)(1-\alpha d_3)(1-\beta ds_{23})$$

$$\Delta = 1 - (1-d_2)(1-d_3)\mathbf{v}_{32}\mathbf{v}_{23} - (1-d_1)(1-d_3)\mathbf{v}_{31}\mathbf{v}_{13} - (1-d_1)(1-d_2)\mathbf{v}_{21}\mathbf{v}_{12} \\ - 2(1-d_1)(1-d_2)(1-d_3)\mathbf{v}_{13}\mathbf{v}_{21}\mathbf{v}_{32}$$

# VUMAT for Abaqus/Explicit Analysis

- Implementing the CDM based 3D PFA equations developed as a user defined material model (VUMAT) in Abaqus/Explicit Code
- Implemented for the reduced integration 3D element, C3D8R
- Applicable for geometrically nonlinear analysis
- Using mass scaling to shorten the analysis time while controlling the proper time incrementation for obtaining stable accurate solutions

# Validation of Analysis Results

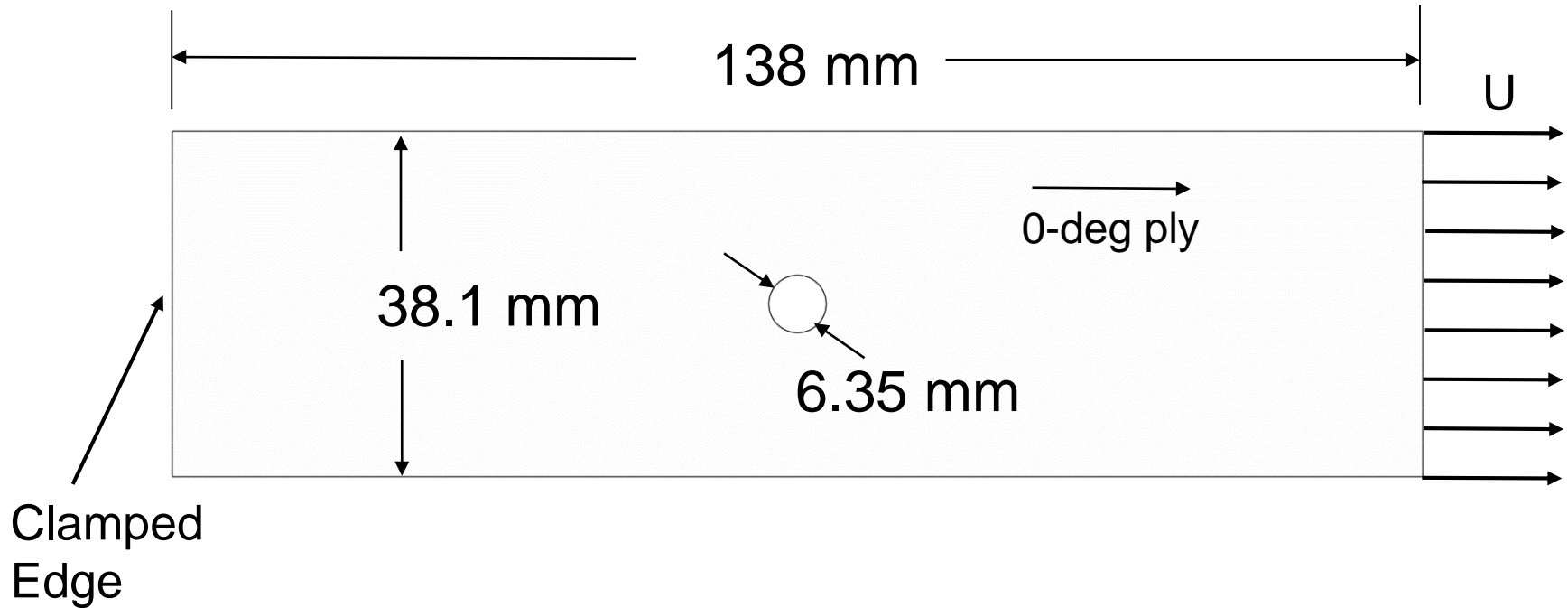
## AFRL open hole specimens test data

- From publications<sup>1-7</sup> related to AFRL program entitled “Damage Tolerance Design Principles (DTDP)”

AIAA SciTech 2015 (56<sup>th</sup> SDM conference)

1. Clay and Holzwarth
2. Engelstad, Action, Clay, Holzwarth, Robbins, and Dalgarno
3. Zhang, Patel, and Waas
4. Joseph, Waas, Ji, Pineda, Liguore and Wanthal
5. larve, Hoos, Braginsky, Zhou, and Mollenhauer
6. Fang, Cui, and Luya
7. Abdi, Codines, DorMohammadi, and Minnetyan

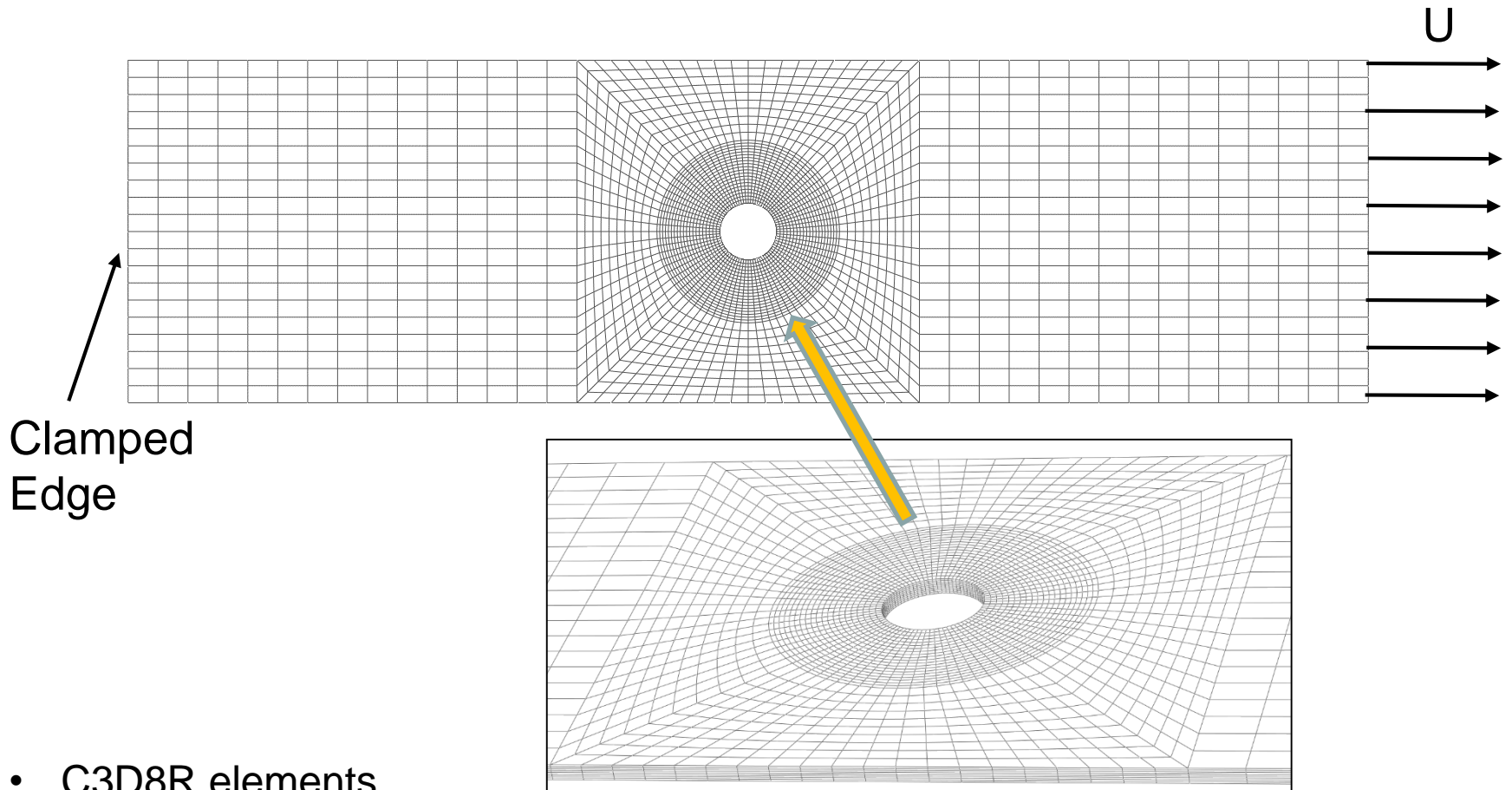
# IM7/977-3 OHT and OHC Specimen



Three different layups

1.  $[0/45/90/-45]_{2S}$
2.  $[60/0/-60]_{3S}$
3.  $[30/60/90/-60/-30]_{2S}$

# 3D Finite Element Mesh of Open Hole Specimen



- C3D8R elements
- One element per ply thickness
- Only top half of the laminate modeled (symmetry boundary conditions employed)



# IM7/977-3 Material Properties<sup>1,2</sup>

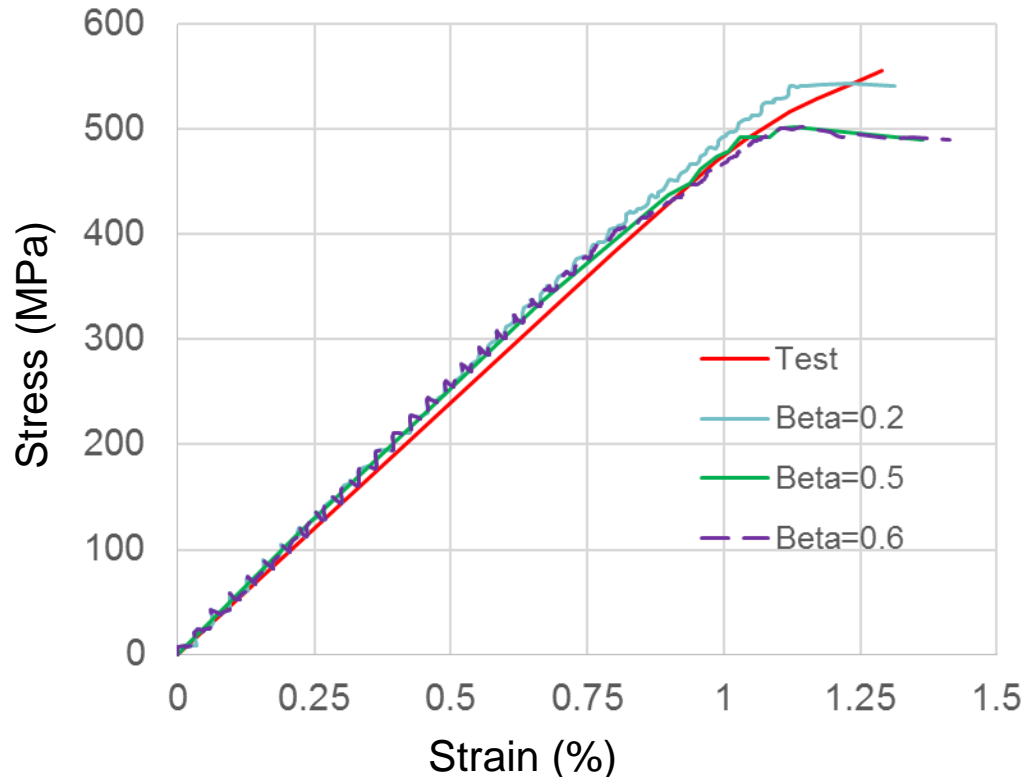
Material Property	
$E_{11}$ (GPa)	164/137.4
$E_{22}, E_{33}$ (GPa)	8.977
$G_{12}, G_{13}$ (GPa)	5.02
$G_{23}$ (GPa)	3.00
$\nu_{12}, \nu_{13}$	0.32
$\nu_{23}$	0.496
$G_{IC}, G_{IIC}$ (N / mm)	0.256, 1.156
$Y_T, Y_C$ (MPa)	100.0, 247.0
$S$ (MPa)	80.0
$X_T, X_C$ (GPa)	2.9, 1.68
$G_{FT}, G_{FC}$ (N / mm)	81.534, 24.533
$G_{MT}, G_{MC}$ (N / mm)	0.256, 1.156

1.  $G_{FT}, G_{FC}$  : Fiber tension and compression toughness parameters
2.  $G_{MT}, G_{MC}$  : Matrix tension and compression toughness parameters

1. AIAA SciTech 2015 Papers:
  - a) Clay and Holzwarth
  - b) larve, Hoos, Braginsky, and Zhou
  - c) Zhang, Patel, and Waas

2. Camanho, Mami, Davila, Compos Sci Technol, (2007)

# Stress-Strain Curves for Various Beta Values ([0/45/90/-45]<sub>2S</sub> OHT)



- Same initial stiffness for all cases
- As  $\beta$  increases, predicted failure stress decreases
- All predicted failure stresses exceed 90% of the test maximum stress

Using the distance of extensometer knife edges, located half an inch (along the length direction) below and above the center of the hole for computing strain

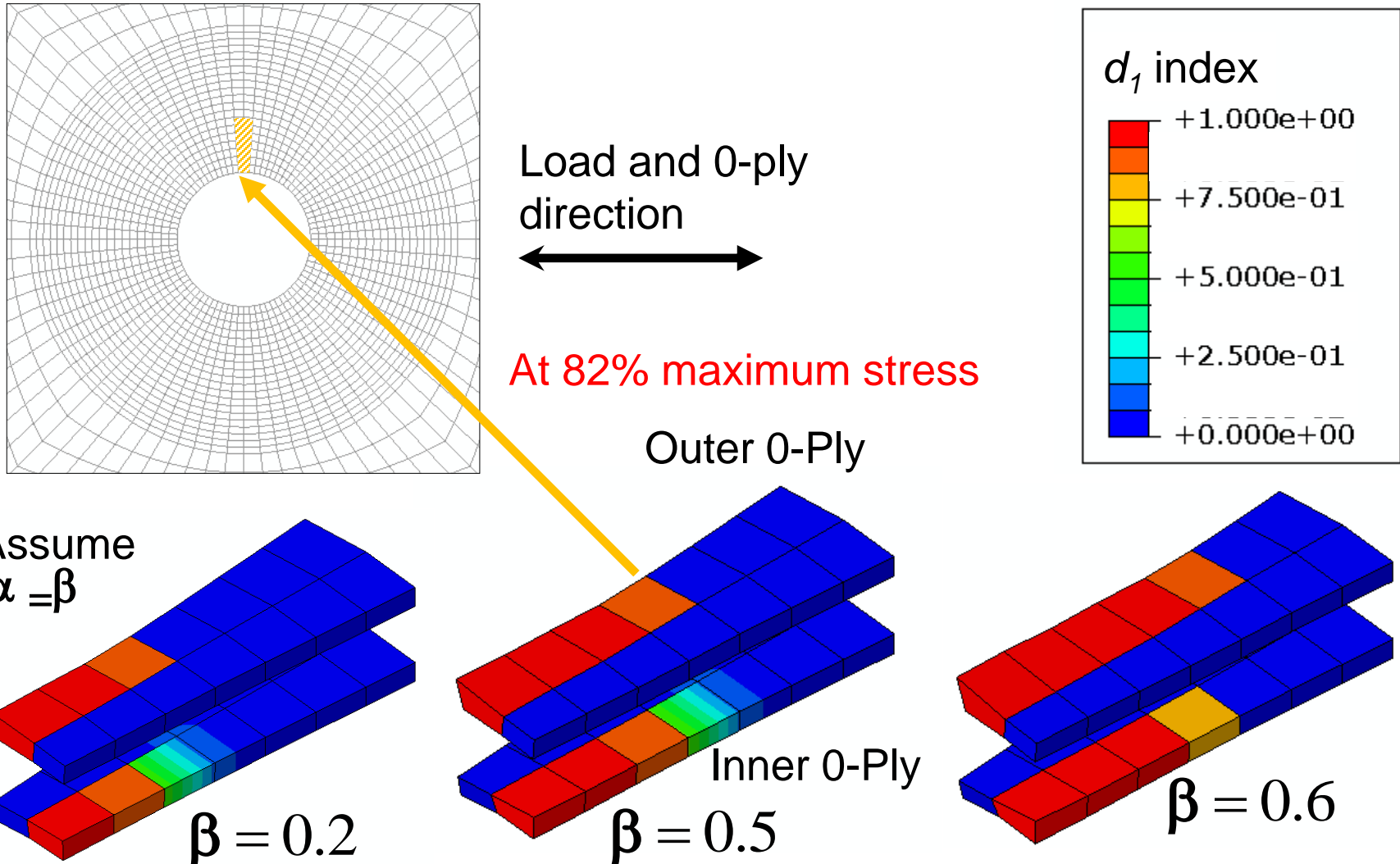
# Test and Analysis Correlation of Maximum Applied Stress

- Performed many parametric studies with various values of  $\alpha$  and  $\beta$  and selected  $\alpha = \beta = 0.5$  for shear stiffness degradations for all OHT and OHC cases analyzed

Lay-Ups	OHT	OHC
[0/45/90/-45] <sub>2S</sub>	-8.82%	-6.94%
[60/0/-60] <sub>3S</sub>	-2.52%	-18.3%
[30/60/90/-60/-30] <sub>2S</sub>	6.03%	8.32%

- Reasonable good correlations obtained; however, further development or adoption of more accurate PFA tool needed

# Influence of Beta on Damage Evolution in 0-Plies ([0/45/90/-45]<sub>2s</sub>)



- As  $\beta$  increases, damage progression increases for same load level

# Concluding Remarks

- Developed and implemented a CDM based explicit 3D PFA tool as a VUMAT subroutine to work with 3D elements in a commercial FEM code
- Key features implemented in the VUMAT including:
  - Simple failure criteria used for failure initiation
  - Lamina material properties obtained from standard test procedures
  - Technique for alleviating mesh dependency implemented
  - Damage due to 3D stress fields considered
  - Matzenmiller type stress-strain relations for damaged lamina used in which the stiffness degradations expressed as functions of the fiber, matrix, and shear damage indices
- Preliminary predicted failure stresses having reasonably good agreement with test data of OHT and OHC specimens with various layups