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

(Development and Preliminary Results)

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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[1] show that lamina property degradations after damage initiation can be modeled by the crack band theory[2] 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[1,2]
  - Crack-band strain in damaged element
  - Crack band theory for material property degradations

- Matzenmiller type 3D stress-strain relations[3]
  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

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

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

$$X_i = \frac{Strength_i}{Modulus_i}$$

Crack-Band Strains in Damaged Element[1,2]

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

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

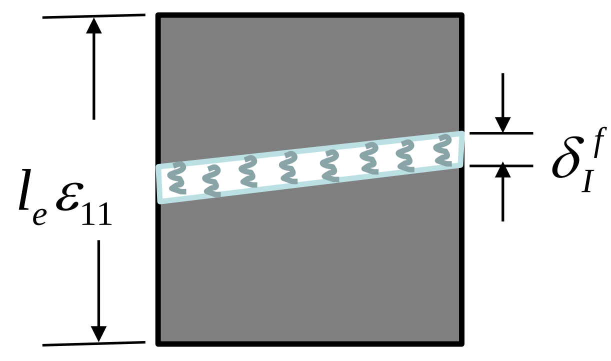
$$l_e \varepsilon_{22} = l_e \varepsilon_{22}^{C} + \delta_I^m$$

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

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

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

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



Damaged element with cohesive opening

$$l_e = \mathit{length\ scale\ \ for\ \ ply\ in-plane\ strains}$$

$$l_e^t = \mathit{length\ scale\ \ for\ \ ply\ transverse\ strains}$$

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

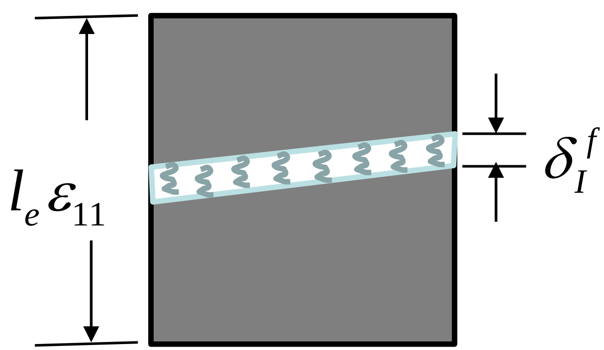
1. Pineda and Waas, Int J Fract (2013)
2. Bazant and Oh, Mater Struct (1983)

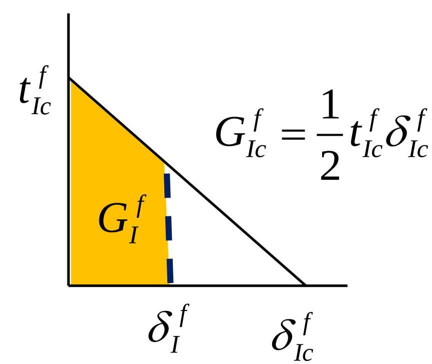
Crack Band Theory for Fiber Direction Modulus Degradation

Linear elastic modulus

Damage evolution

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





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

Crack-band strain + Traction-separation law

Material Moduli Degradations

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

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

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

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

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

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

Pineda and Waas, Int J Fract (2013)

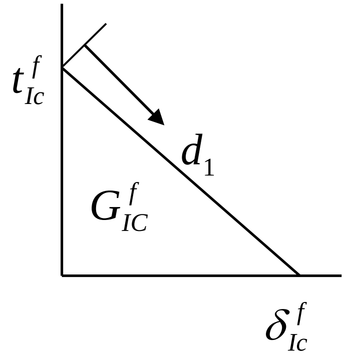
Damage Indices (Internal State Variables)

- Definition of damage index (Internal state Variable)

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

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

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



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

$E_{110}, E_{220}, E_{330}, G_{120}, G_{130}, \text{ and } G_{230}$ *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

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

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

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

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

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

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

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

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

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

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

$$d_4 = (1-d_1)(1-\alpha d_2)(1-\beta\, \mathrm{ds}_{12})$$

$$d_5 = (1-d_1)(1-\alpha\, \mathrm{d}_3)(1-\beta\, \mathrm{ds}_{13})$$

$$d_6 = (1-d_1)(1-\alpha d_2)(1-\alpha\, \mathrm{d}_3)(1-\beta\, \mathrm{ds}_{23})$$

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

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

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

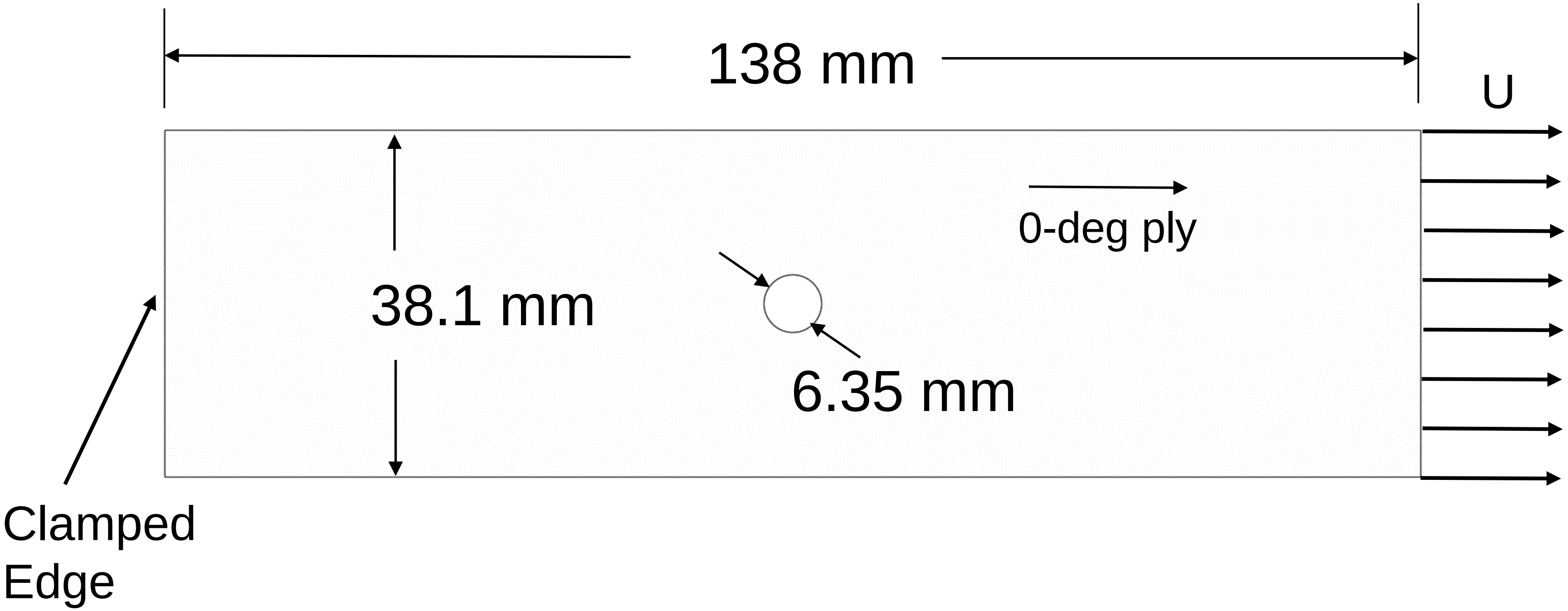
AFRL open hole specimens test data

- From publications[1-7] related to AFRL program entitled "Damage Tolerance Design Principles (DTDP)"

AIAA SciTech 2015 (56th 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. Iarve, Hoos, Braginsky, Zhou, and Mollenhauer
6. Fang, Cui, and Luya
7. Abdi, Codines, DorMohammadi, and Minnetyan

IM7/977-3 OHT and OHC Specimen

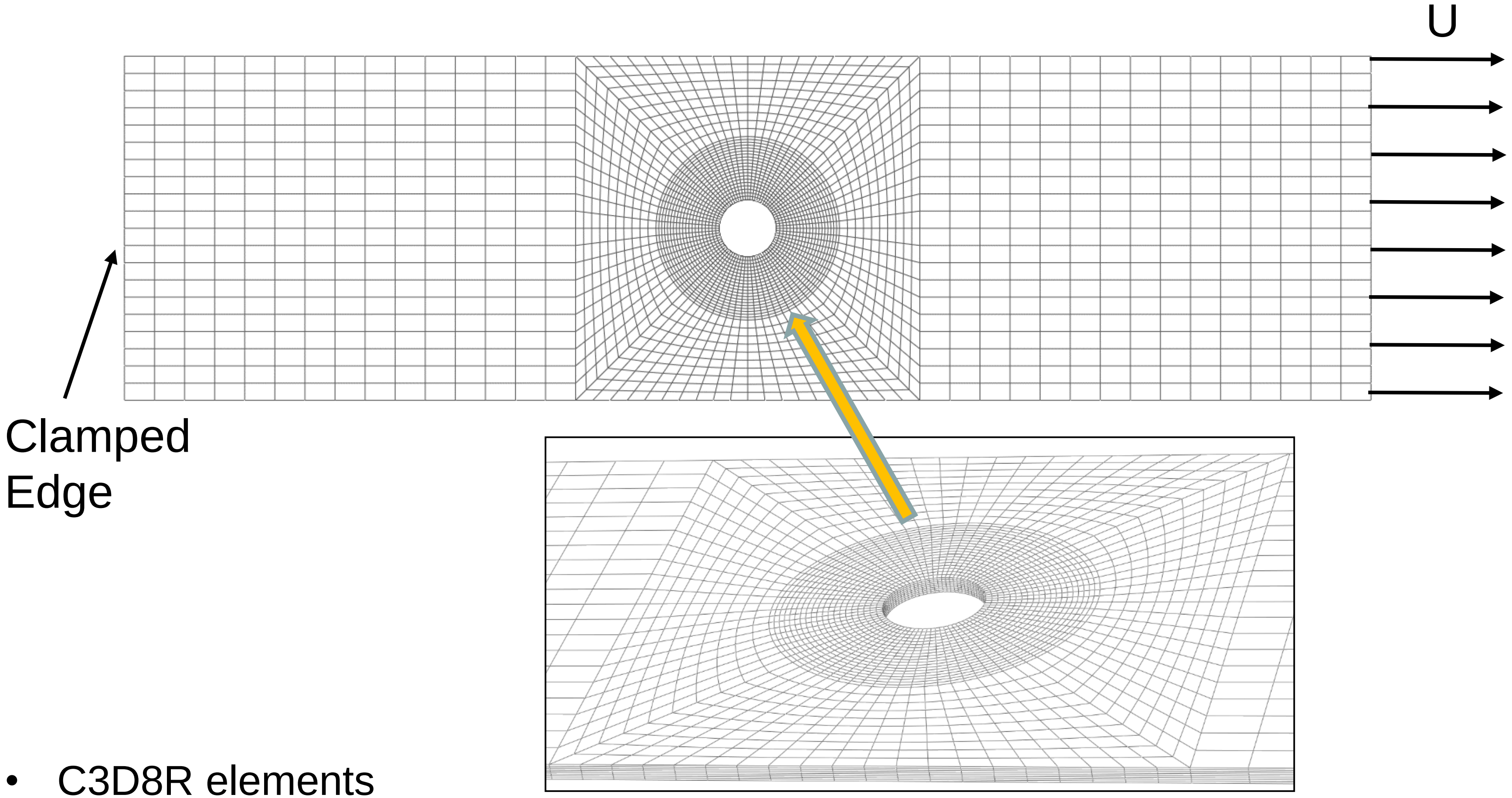


Three different layups

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

Clay and Holzwarth, AIAA SciTech Conference 2015

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[1,2]

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
ν_{12}, ν_{13}	0.32
ν_{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

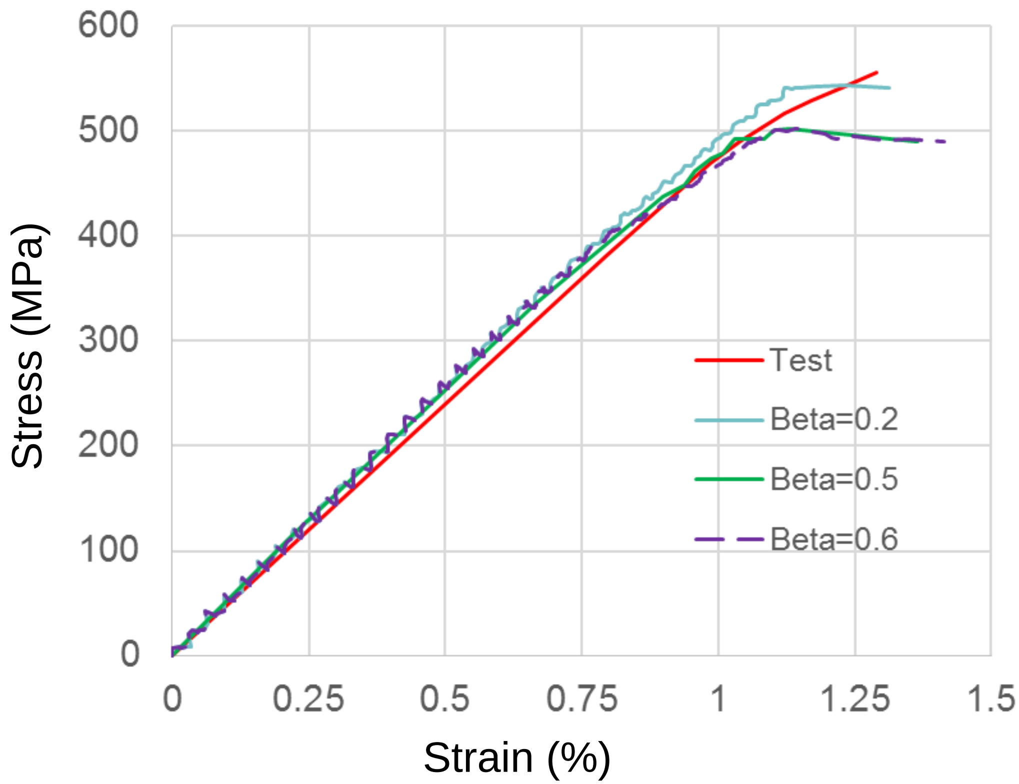
1. G_{FT}, G_{FC} : Fiber tension and compression toughness parameters

2. G_{MT}, G_{MC} : Matrix tension and compression toughness parameters

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

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

Stress-Strain Curves for Various Beta Values ($[0/45/90/-45]_{2S}$ OHT)



- Same initial stiffness for all cases
- As β 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

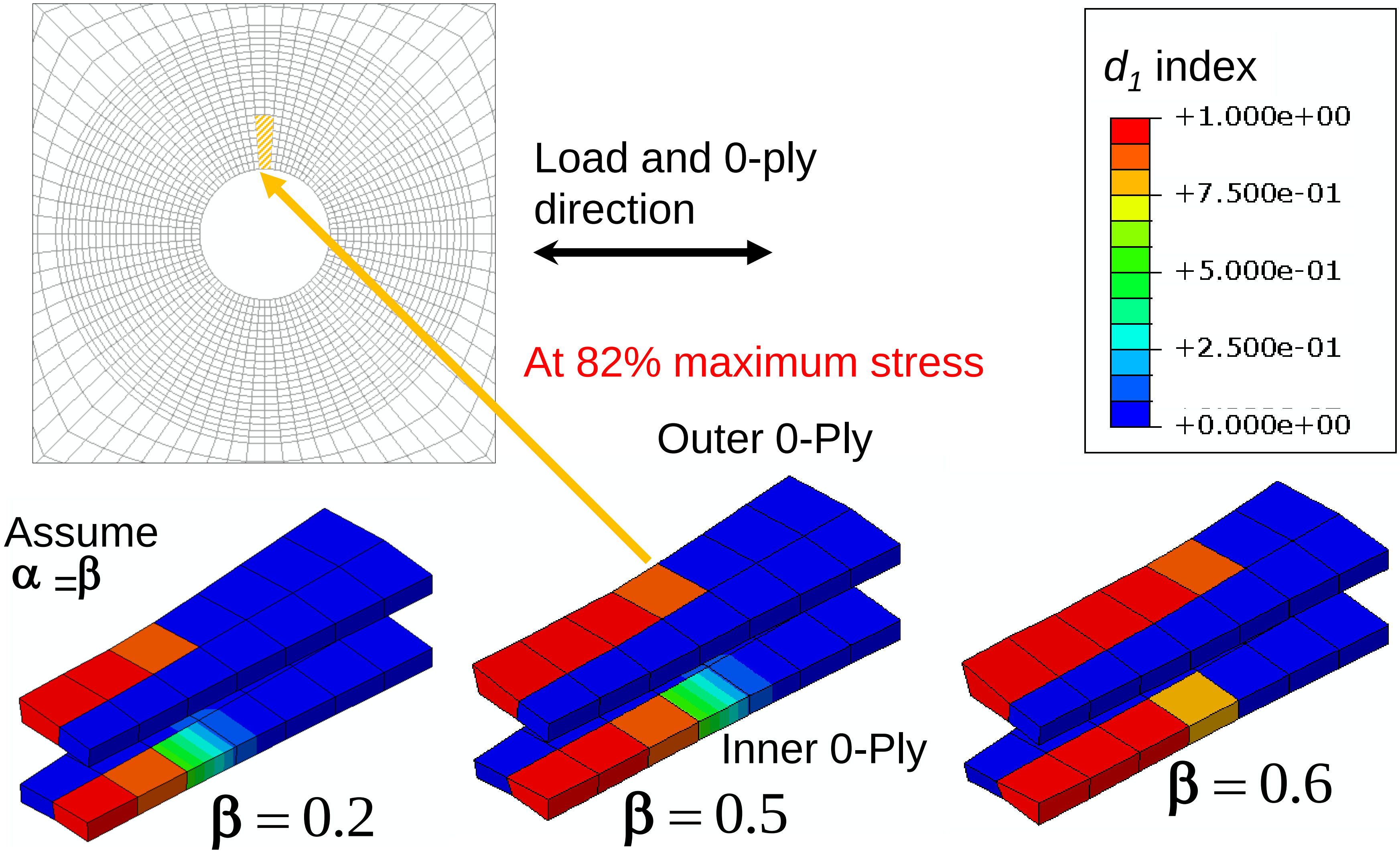
Test and Analysis Correlation of Maximum Applied Stress

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

Lay-Ups	**OHT**	**OHC**
$[0/45/90/-45]_{2S}$	-8.82%	-6.94%
$[60/0/-60]_{3S}$	-2.52%	-18.3%
$[30/60/90/-60/-30]_{2S}$	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 ($[0/45/90/-45]_{2S}$)



- As β 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