

A numerical and experimental study of damage growth in a CFRP composite honeycomb sandwich

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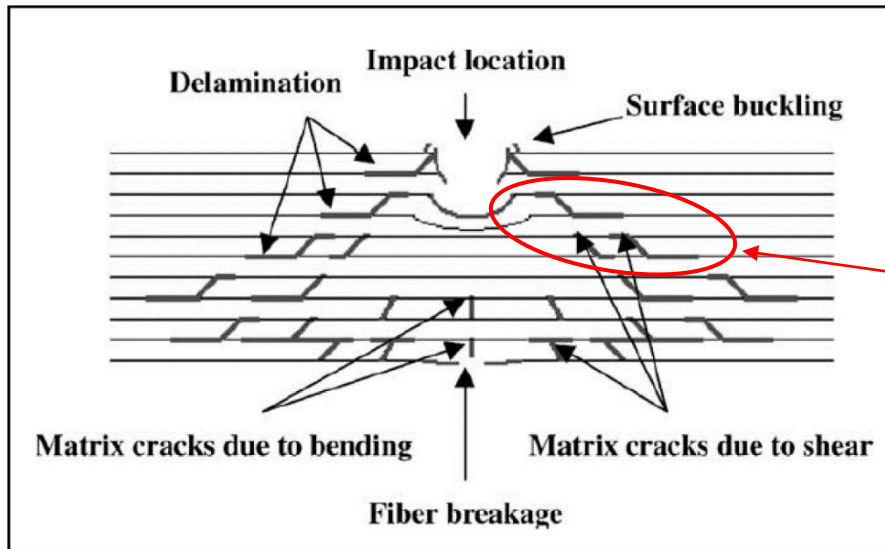
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Introduction

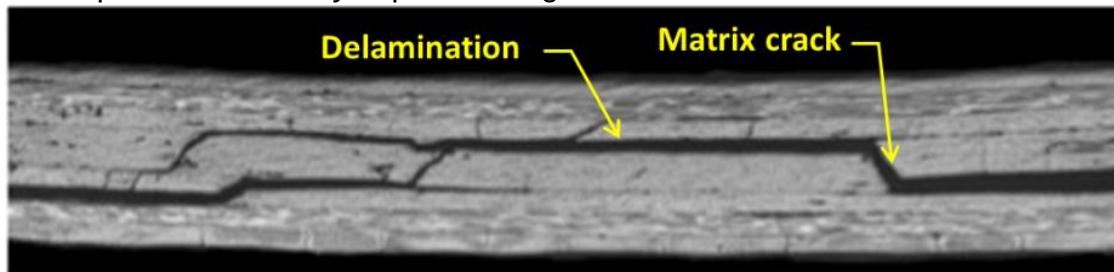
Motivation: Predict internal damage resulting from low velocity impact



- Visible damage: Fiber breakage, indentation
- Internal damage: Delamination and matrix cracks (low velocity impact)

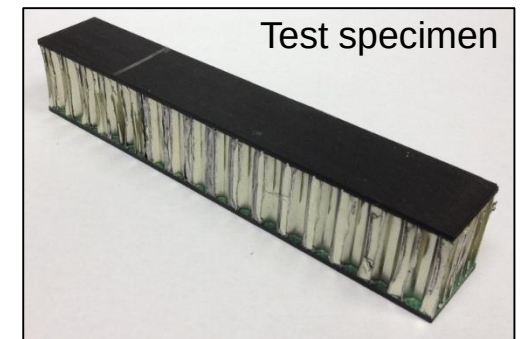
Maier, A., R. Schmidt, B. Oswald-Tranta, R. Scheljewski. "Non-destructive thermography analysis of impact damage on large scale CFRP automotive parts." *Materials* 2014, 7(1) 413-429.

Example of low-velocity impact damage in a laminate

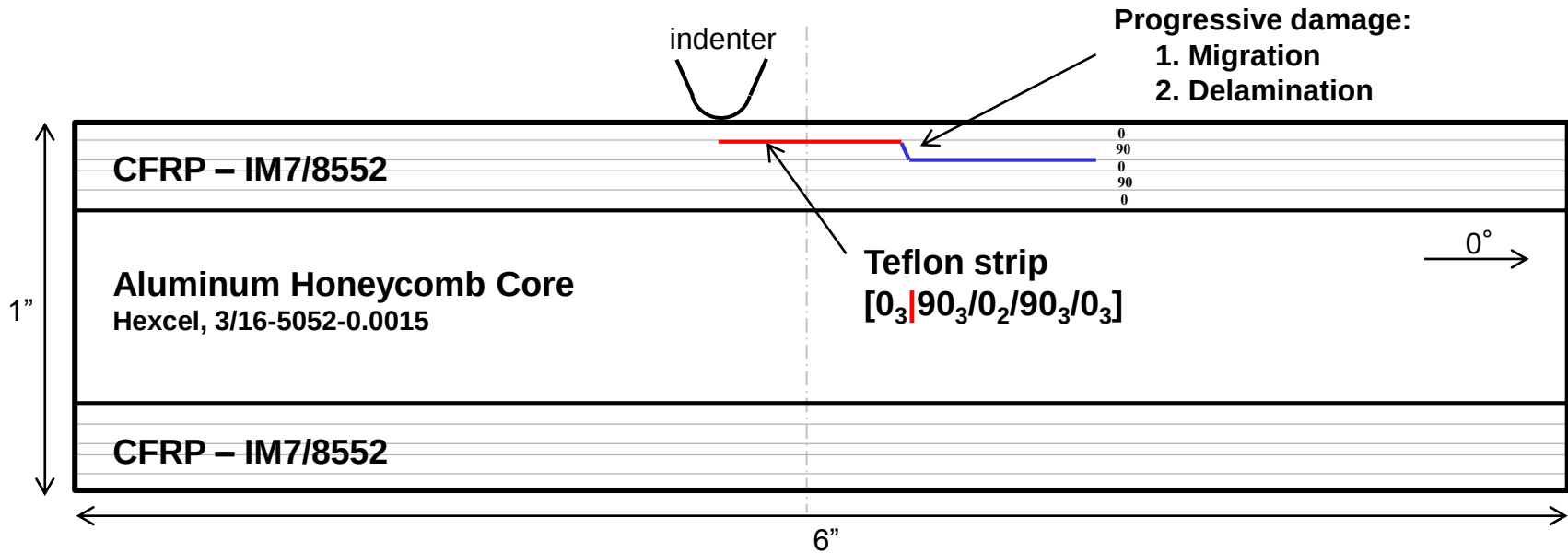


Introduction

- Objective: Use a numerical model to simulate damage progression in a laminate subjected to low-velocity impact
- Approach: Study an isolated internal delamination migration damage process
 - Perform quasi-static indentation test of composite sandwich specimens
 - Design specimens to exhibit delamination migration damage mechanism
 - Sandwich core used to stabilize damage process in facesheet
 - Perform numerical simulation of test
 - Develop core crush damage modeling technique
 - Compare cohesive and continuum type damage modelling techniques in the facesheet
 - Investigate details of migration crack



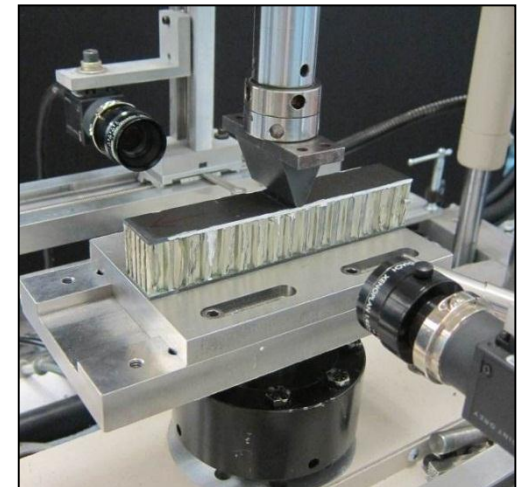
Experimentation: Specimen & Test Configuration



Facesheet damage characterized in real time

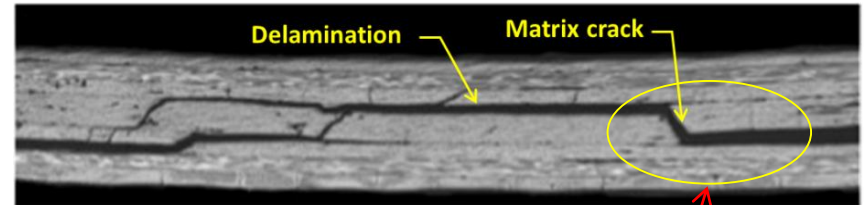
- Visual inspection
- Digital Image Correlation
- Test stand force displacement data
- Microscopy
- UT Scan
- X-Ray CT Scan

3-kip servo hydraulic test stand

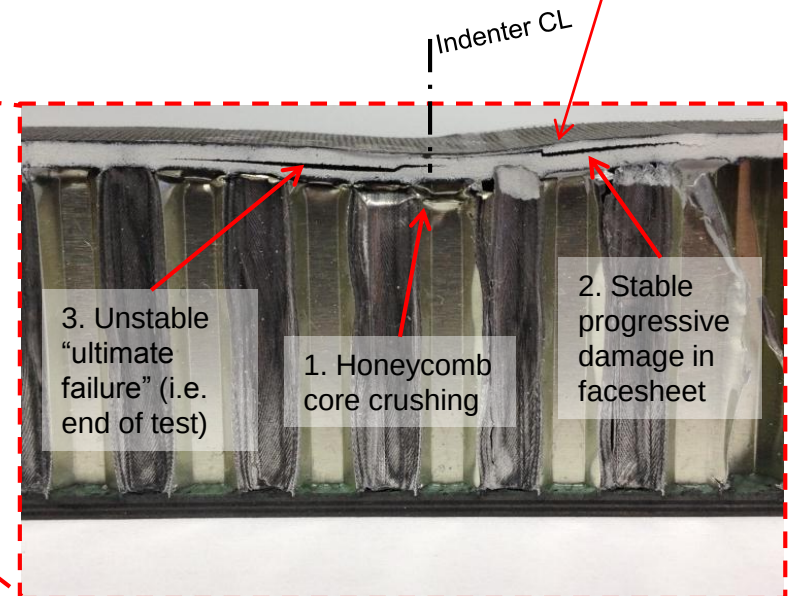
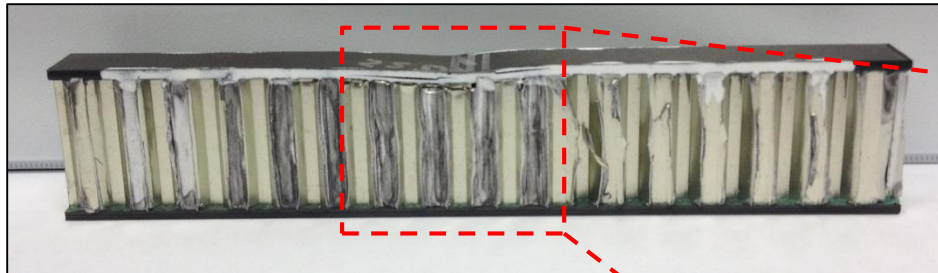


Experimentation

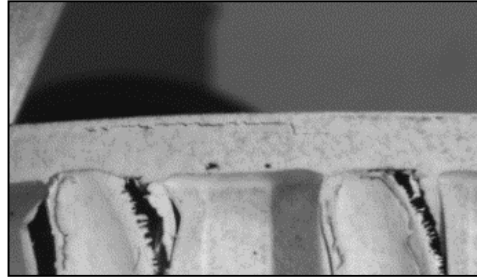
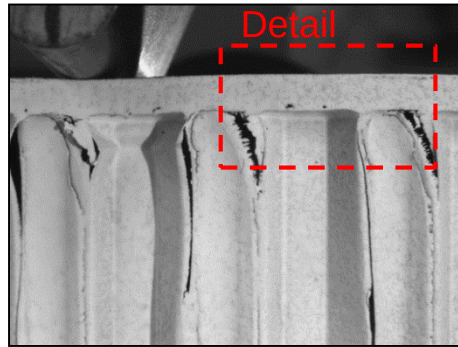
Goal of experiment is to create and observe in detail a delamination migration via a matrix crack



Typical damage observed in testing



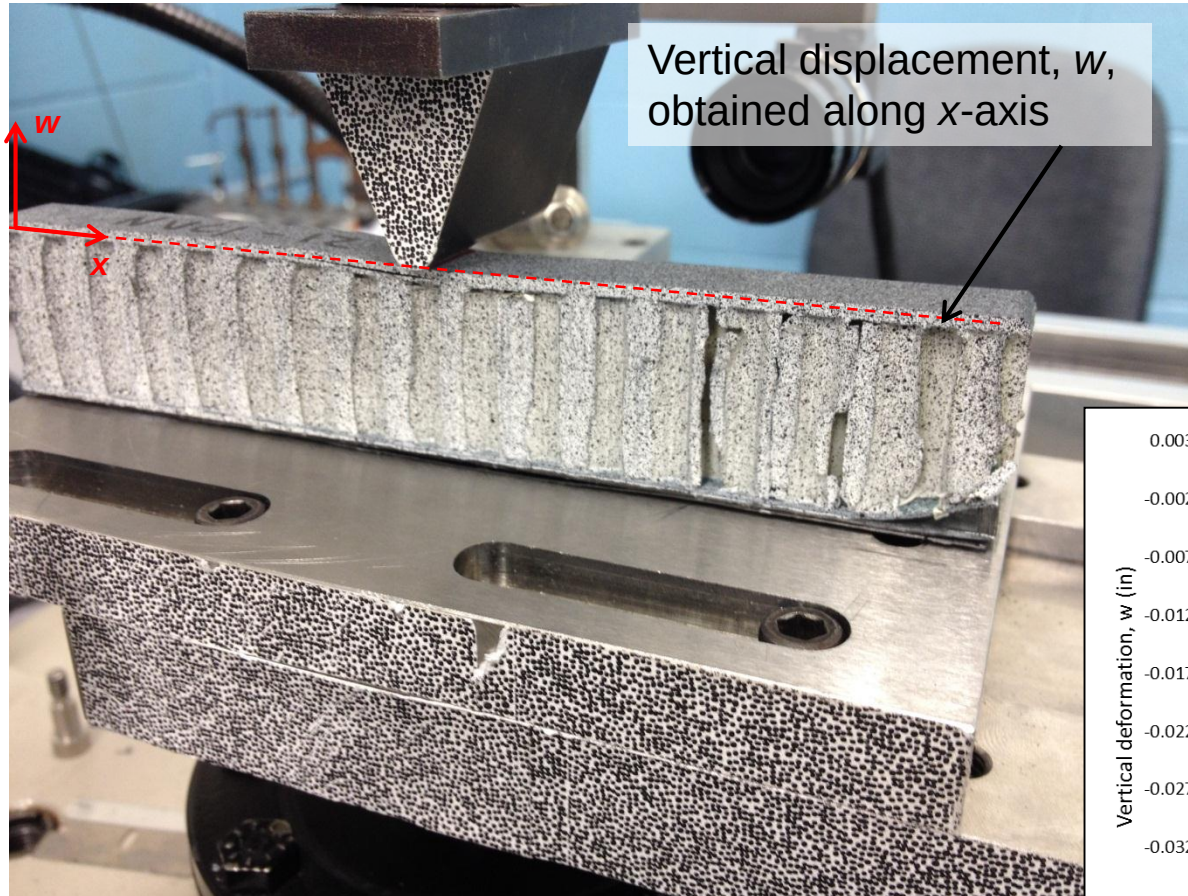
Experimentation: Damage Characterization - Visual



Use to observe delamination length as a function of time or as a function of indenter force & displacement

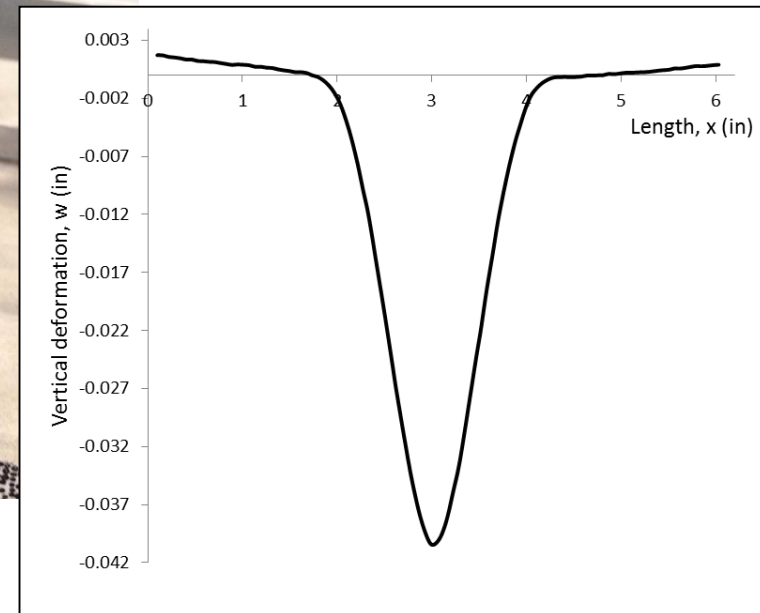
Experimentation: Damage Characterization - Digital Image Correlation

Digital Image Correlation*



Use to observe top facesheet deformed shape along specimen length

Top facesheet deformed shape



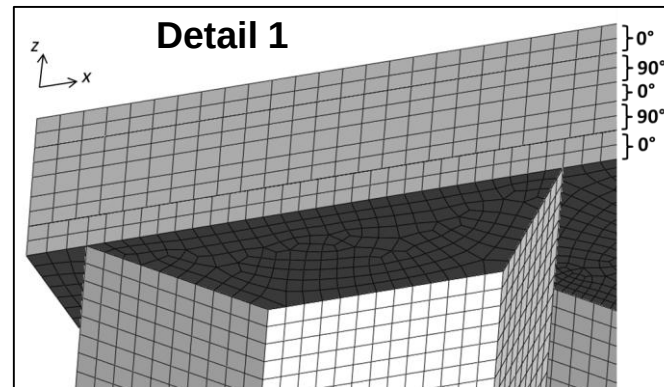
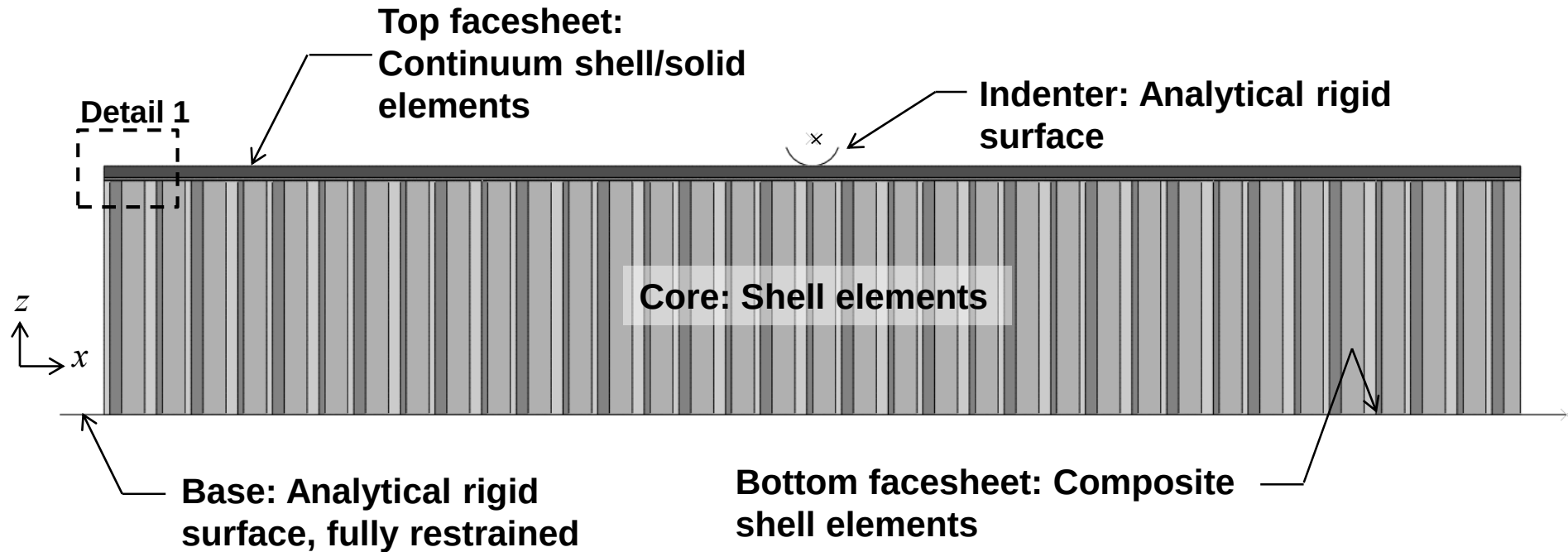
*Correlated Solutions. 2010. "Vic-3d Reference Manual."

Analysis: Outline

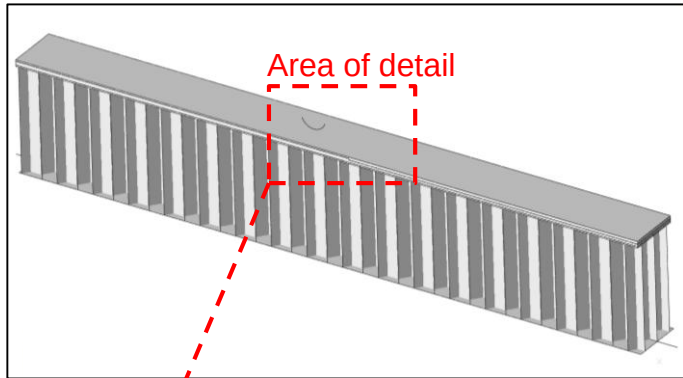
- I. Finite Element Model Description
- II. Pristine Facesheet Model (PFM): No facesheet damage, used to validate core crushing simulation
- III. Cohesive Zone Model (CZM): Predefined crack path for migration and delamination
- IV. Continuum Damage Model (CDM): Predefined crack path for delamination only
- V. Migration crack study: Use CZM to study migration parameters

All finite element models created and ran using ABAQUS/Explicit® 6.13

Analysis: Finite Element Model Overview

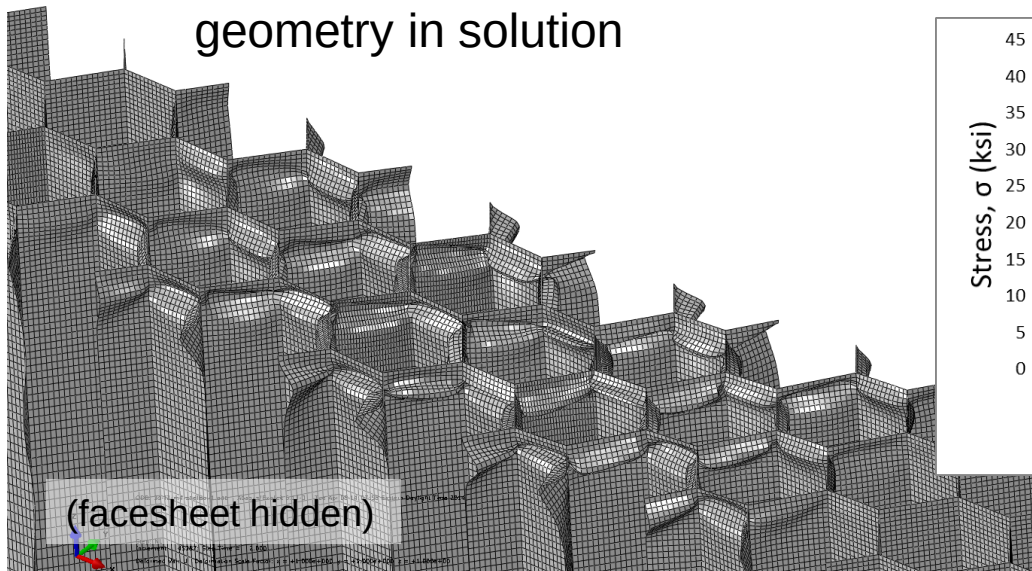


Analysis: Core Damage Model

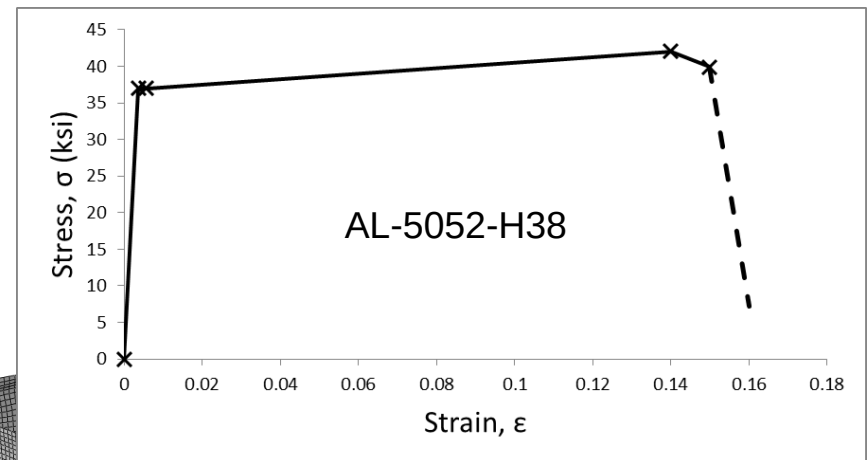


Core crushing consists of structural AND material failure

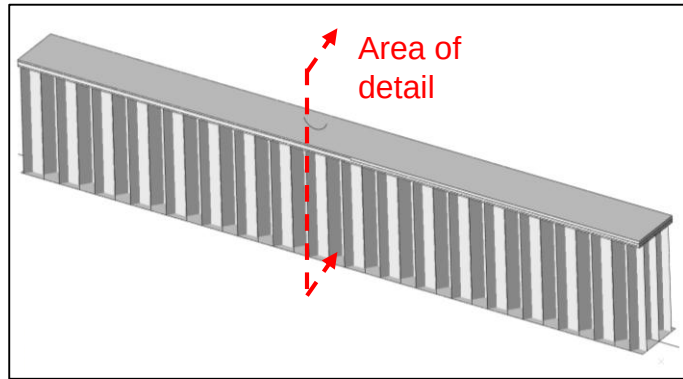
1) Structural failure, i.e. cell buckling: Enable nonlinear geometry in solution



2) Material failure, i.e. yielding: Use nonlinear material in plasticity model



Analysis: Facesheet Damage Models

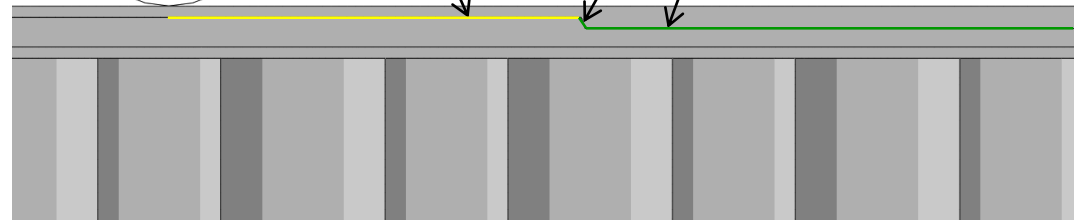


Cohesive Zone Model

C3D8R elements @ 0.01 in

Contact definition on
embedded crack

Predefined CZ
along entire
damage path

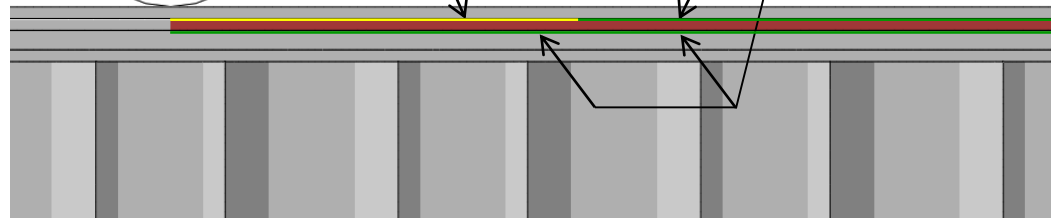


Continuum Damage Model

SC8R elements @ 0.01 in

Contact definition on
embedded crack

CZ above and
below 2nd ply



■ = Hashin/CDM material

■ = Cohesive zone

■ = Contact

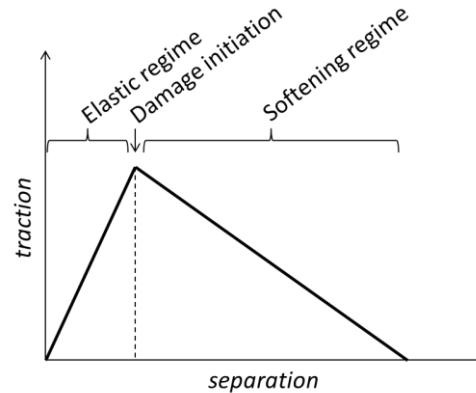
Analysis: Facesheet Damage Models

Cohesive Zone Model

- Quadratic traction initiation criterion: $\left\{ \frac{\langle t_n \rangle}{t_n^o} \right\}^2 + \left\{ \frac{t_s}{t_s^o} \right\}^2 + \left\{ \frac{t_t}{t_t^o} \right\}^2 = 1$

- Cohesive damage law:

(mode mixity captured with B-K law)



Continuum Damage Model

- Hashin initiation criterion

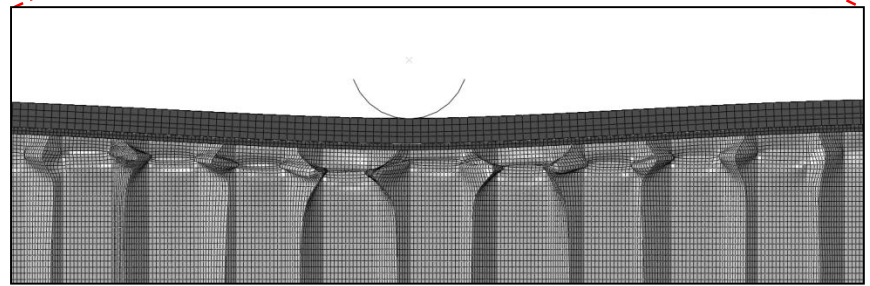
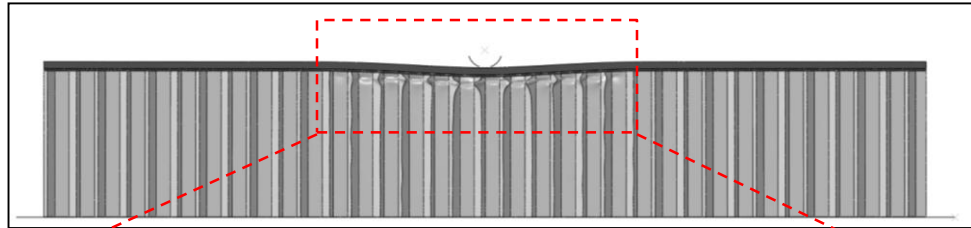
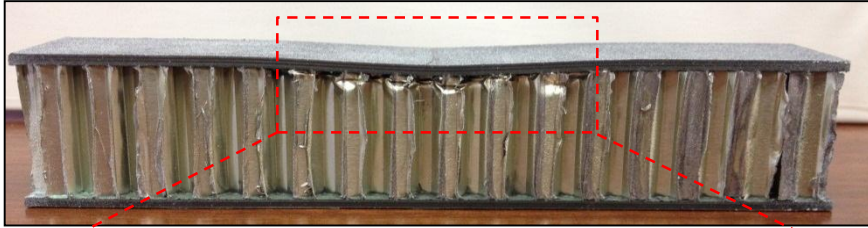
$$C = \frac{1}{D} \begin{bmatrix} (1 - d_f)E_1 & (1 - d_f)(1 - d_m)v_{12}E_1 & 0 \\ (1 - d_f)(1 - d_m)v_{12}E_1 & (1 - d_m)E_2 & 0 \\ 0 & 0 & (1 - d_s)GD \end{bmatrix}$$

- Damage evolution occurs according to a stress-displacement relation

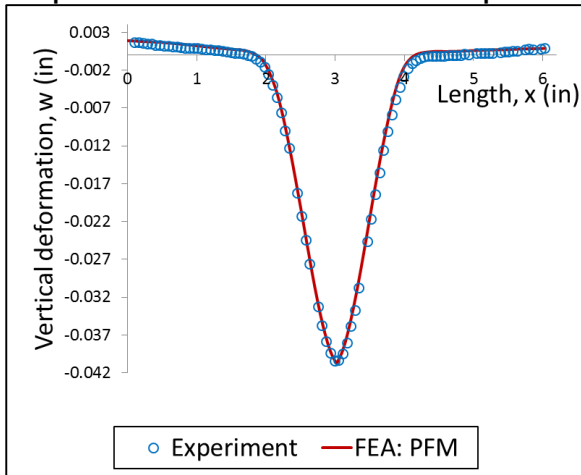
$$D = 1 - (1 - d_f)(1 - d_m)v_{12}v_{21}$$

Analysis: Pristine Facesheet Model (PFM)

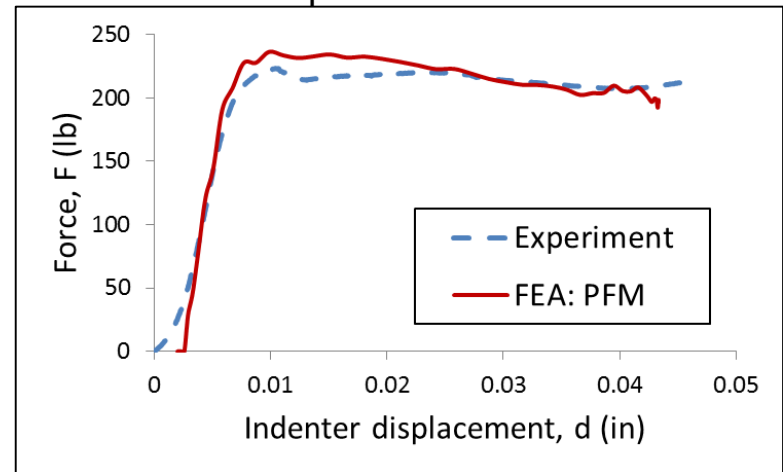
Visual correlation



Top facesheet deformed shape

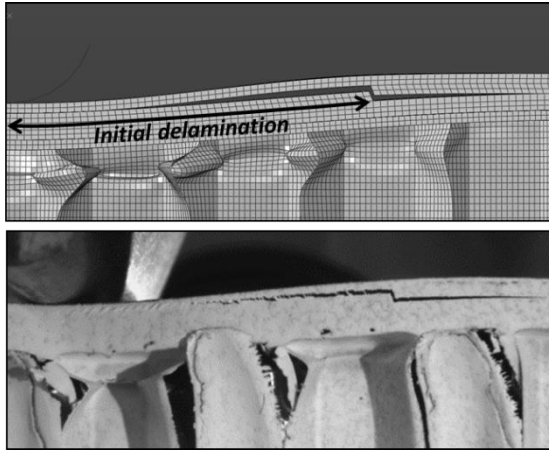


Indenter force displacement

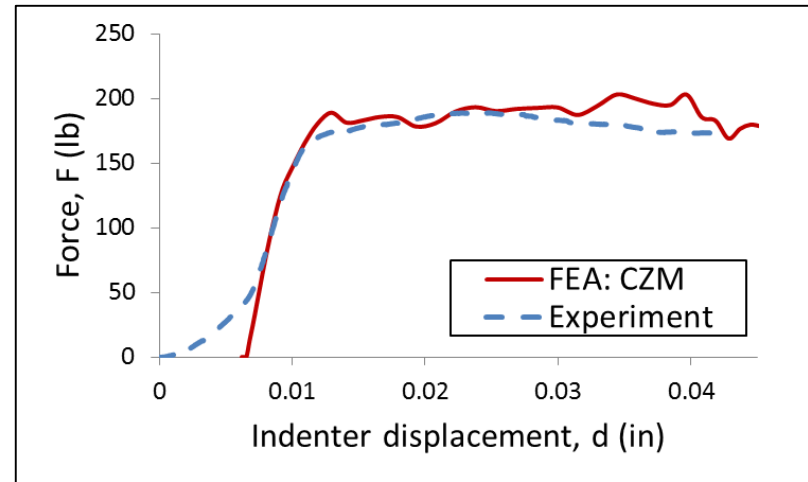


Analysis: Cohesive Zone Model (CZM)

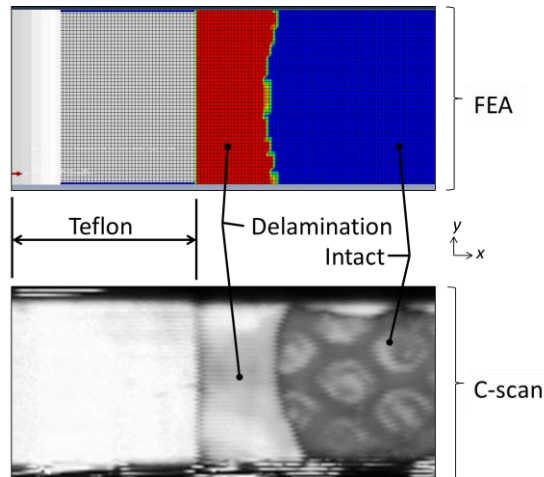
Visual correlation



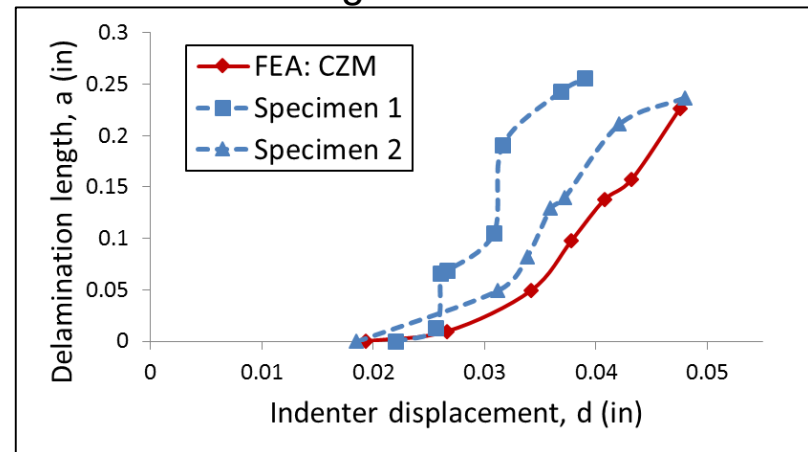
Indenter force displacement



UT correlation (plan view)

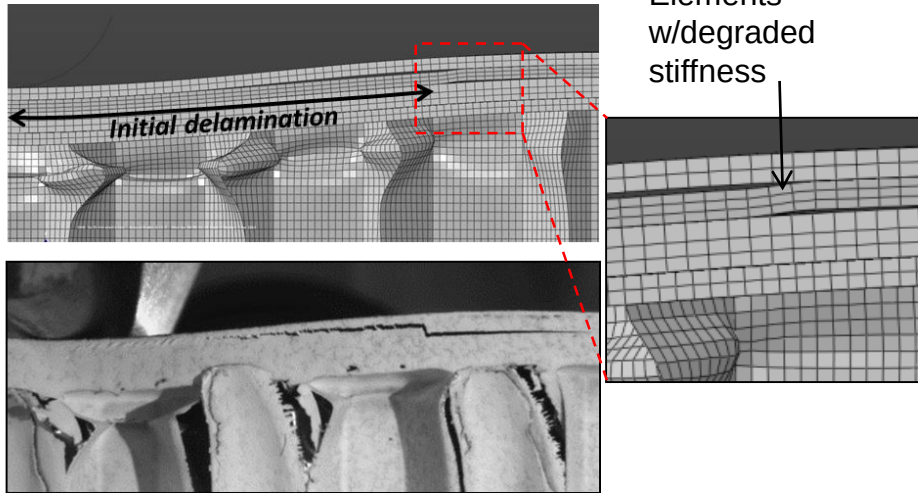


Delamination length

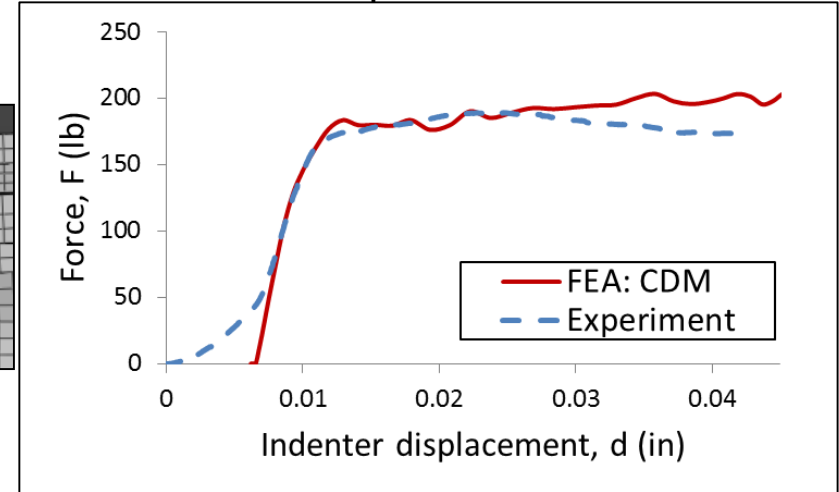


Analysis: Continuum Damage Model (CDM)

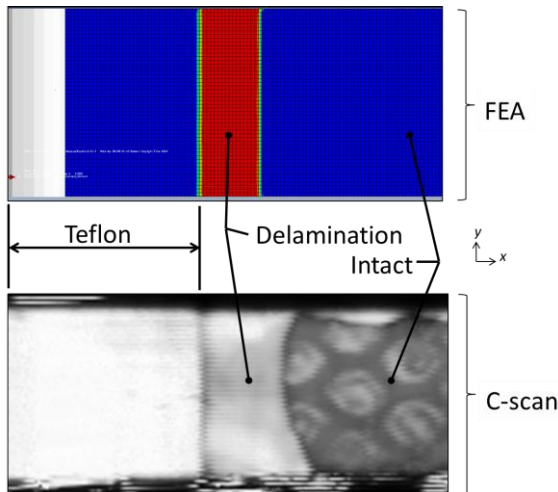
Visual correlation



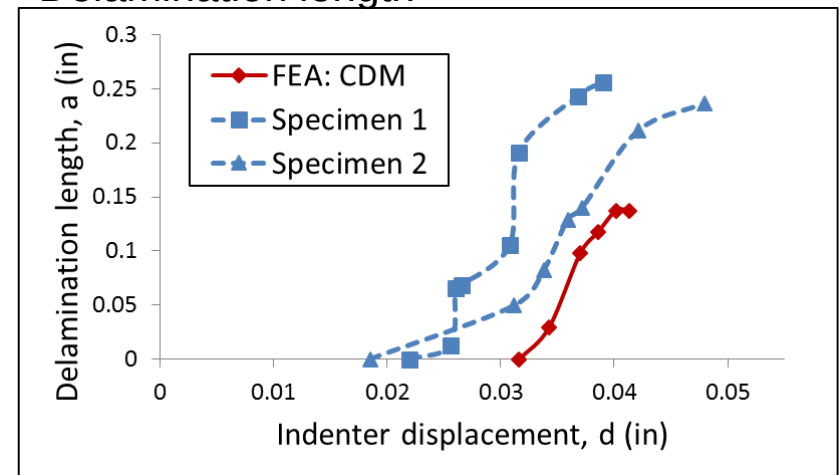
Indenter force displacement



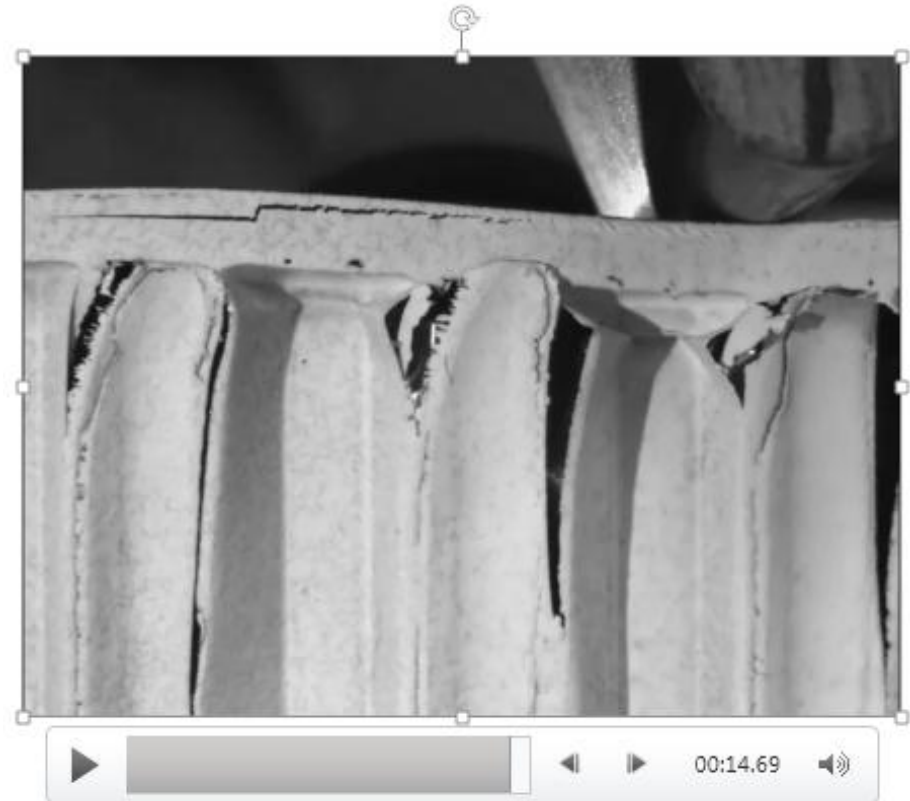
UT correlation (plan view)



Delamination length



Analysis



PLAY

Analysis: Migration Crack Study

How relevant is the migration angle and associated energy dissipation?

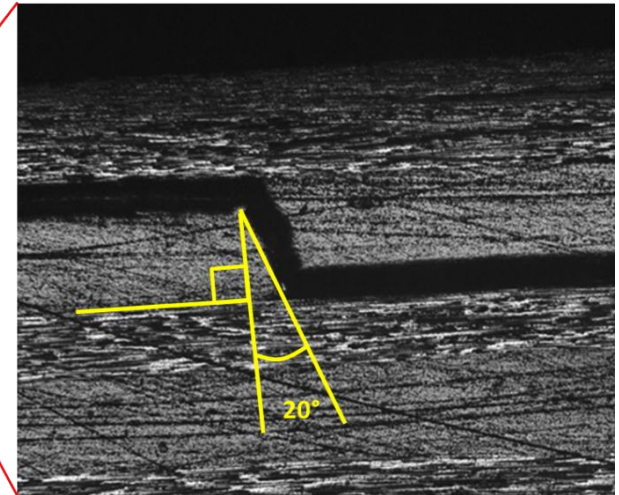
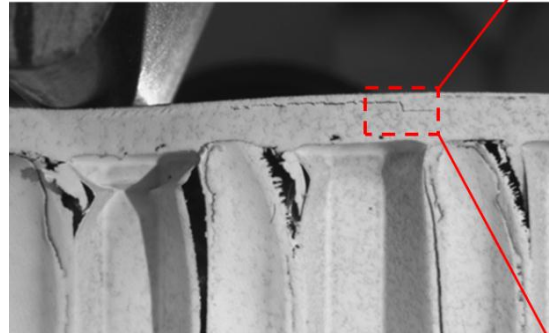
Conservation of energy

$$dW = dU + E_{dam}$$

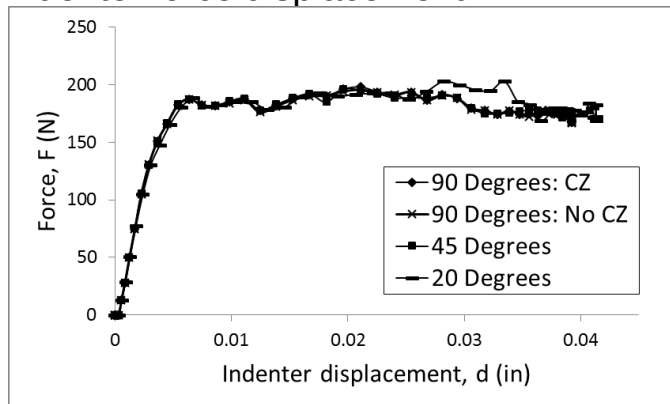
↑
Δ External Work

↑
Δ Internal Strain Energy

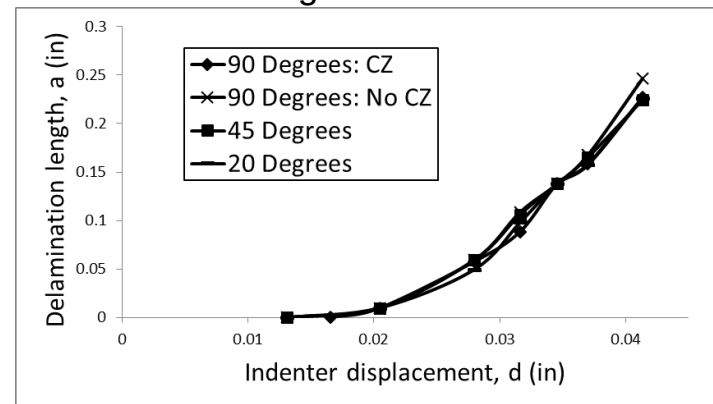
↑
Energy Dissipated Due to Damage



Indenter force displacement



Delamination length



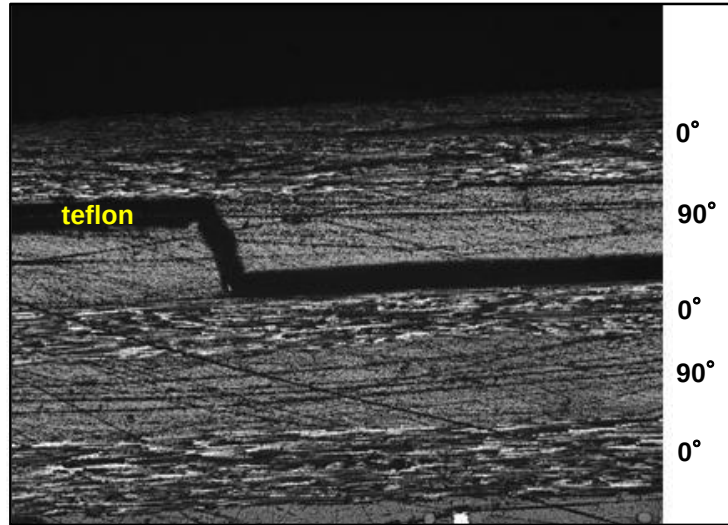
Conclusions

- Experiment devised that allows detailed characterization of a simple delamination migration damage process
- Pristine facesheet model
 - Matches data well
 - Core crushing modeling technique is validated
- Cohesive zone model
 - Matches data reasonably well
 - Offers little predictive capability
- Continuum damage model
 - Does not correlate well with delamination growth, migration location is predicted well
 - Can likely be improved with an enhanced continuum damage formulation
- Migration study
 - Matrix crack angle in migration can be assumed vertical in a numerical simulation
 - Energy dissipation in migration is negligible
- Future work
 - Use of a 3-D implemented continuum damage model
 - Use of Extended Finite Element Method or similar

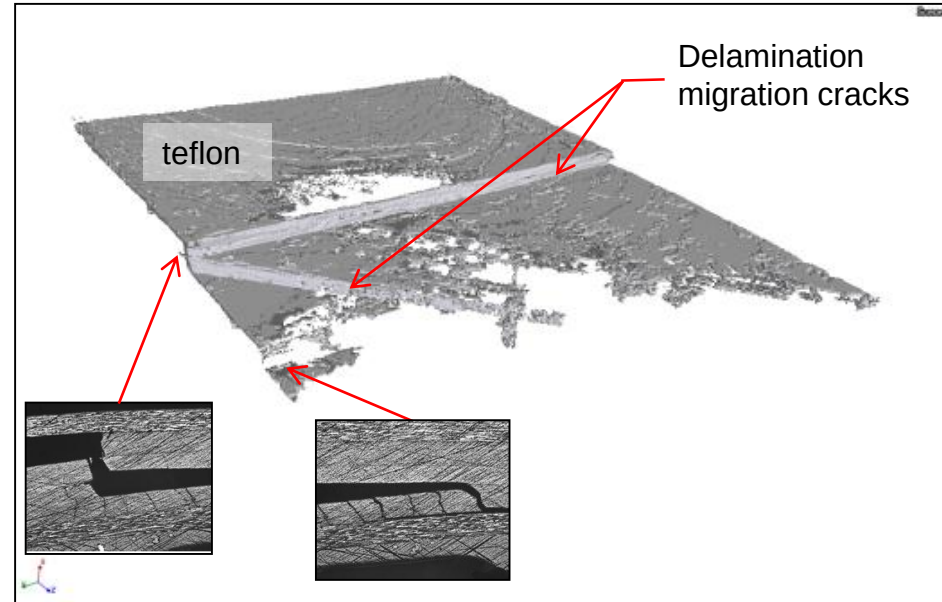
Questions?

Experimentation: Damage Characterization - Microscopy, UT, & CT

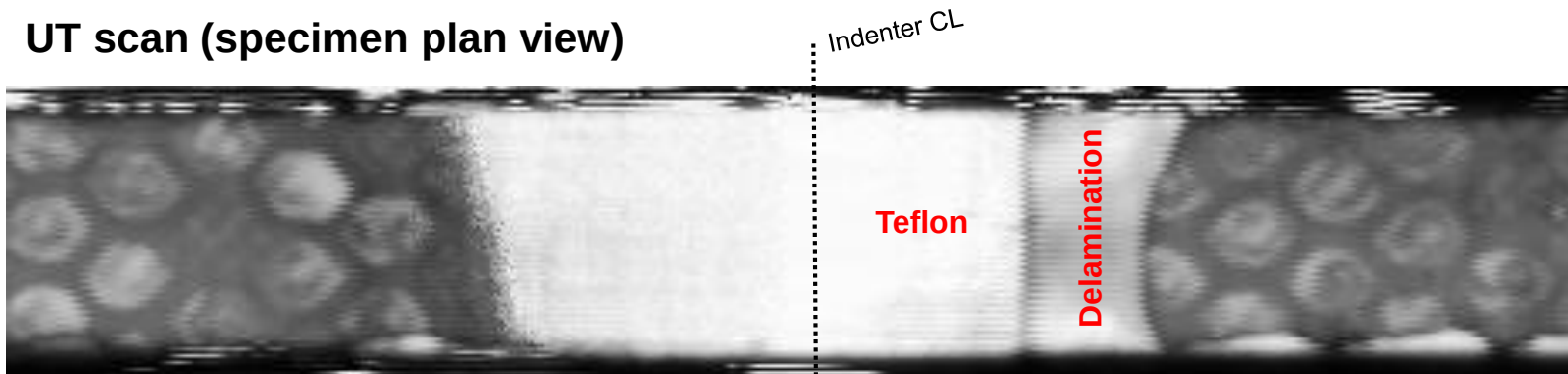
Microscopy



X-ray CT scan

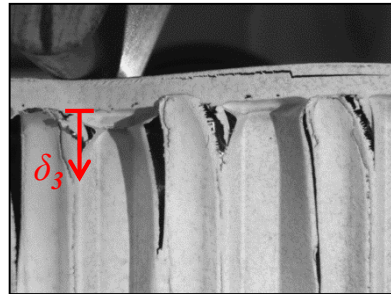
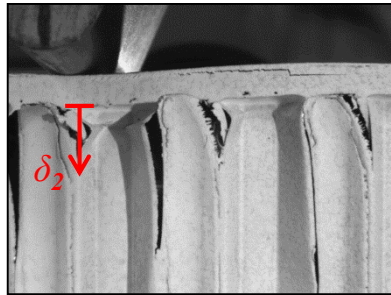
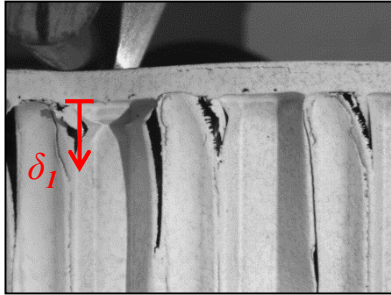


UT scan (specimen plan view)

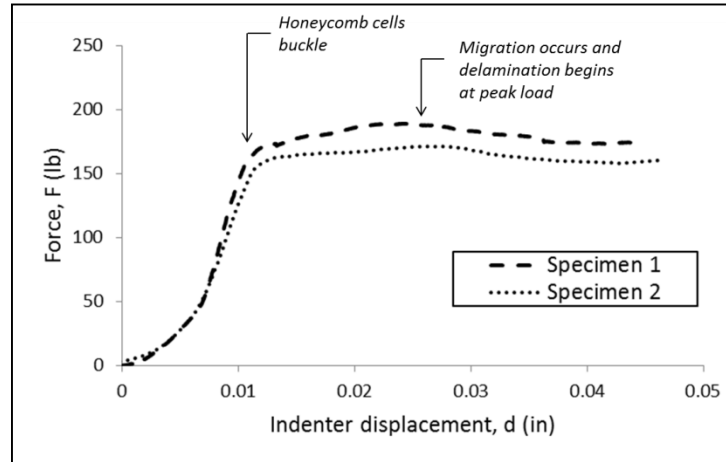


Experimentation: Initial nonlinearity

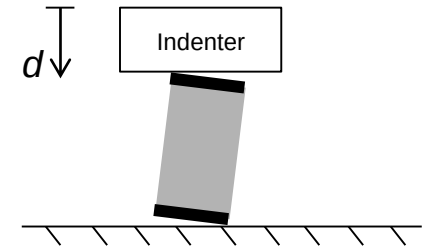
Compare vertical deformation, δ , on both sides of specimen as a function of indenter displacement, d



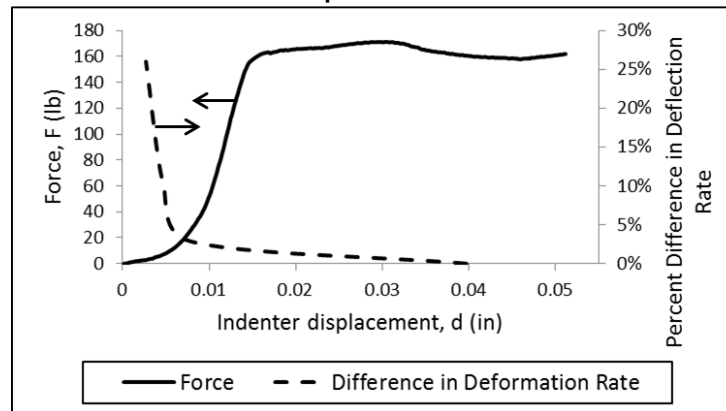
Indenter force displacement



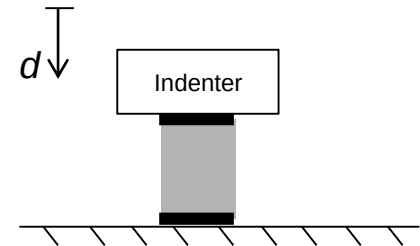
Initial condition, $d < \sim 0.01$ in



F-d correlation w/specimen rotation



“Settled” condition, $d > \sim 0.01$ in



Analysis: Continuum Damage Model (CDM) continued

Damage contour plots

