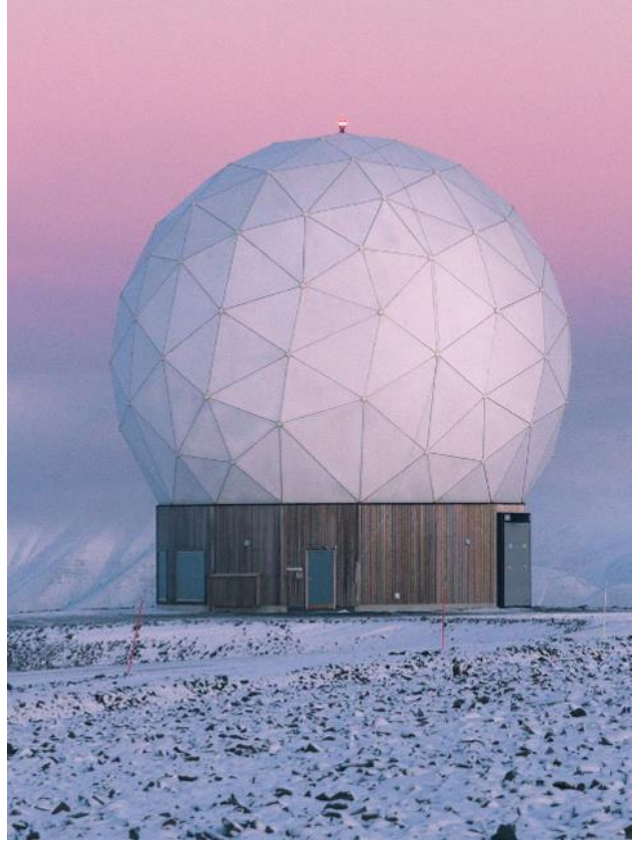





Impact of Thermoplastic Composites: Testing and Modeling

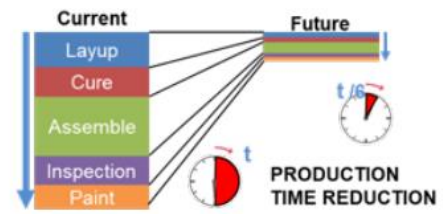
Sreenivasa R. Voleti and Prabhakar Rao
Raytheon Technologies Research Center
East Hartford, Connecticut, USA

J. Michael Pereira
NASA Glenn Research Center, Cleveland, OH

Presented at the 38th Annual Technical Conference of the American Society for Composites, September 18 – 20, 2023, Boston, MA, USA

Motivation

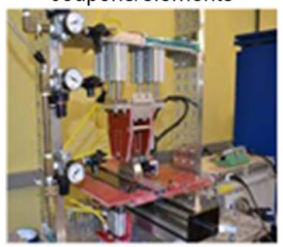
Thermoplastic Composites (TPCs) could enable 4X–6X production rate increase in Next Generation Single Aisle aircraft



The NASA Hi-Rate Composite Aircraft Manufacturing (HiCAM) program envisions enabling production rate increases across the seven identified rate drivers in a systematic manner by concurrently advancing manufacturing technologies and analysis methods/tools

7 Rate Drivers

Precursors: coupons/elements



MRL 4 – Lab scale technology demonstration

Precursor details

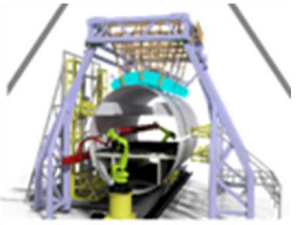


MRL 5 – Produce prototypes in production relevant environment

Capstone



MRL 6 – Produce prototype system/sub-system in production relevant environment



MRL 7 – Produce system/sub-system in production relevant environment

MRL: Manufacturing Readiness Level

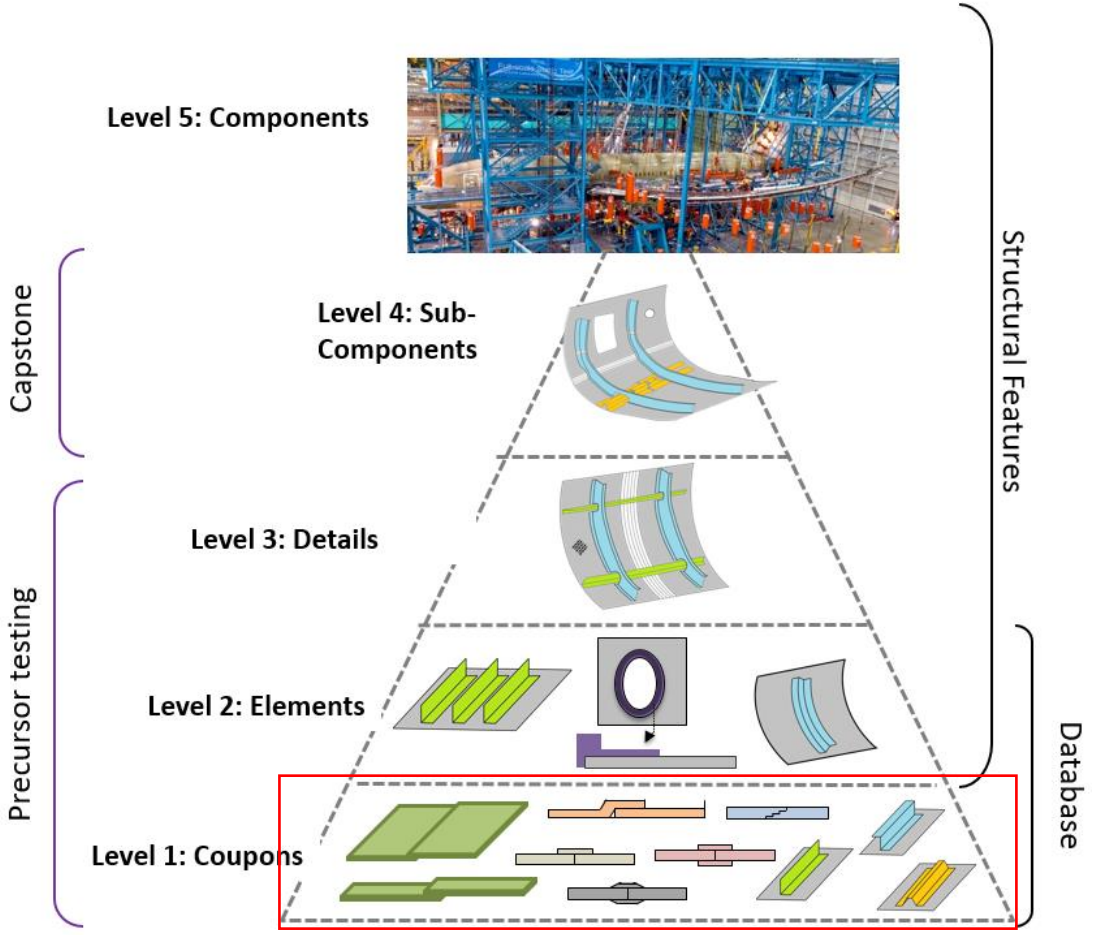
Enabling accelerated production with TPCs and advanced manufacturing technologies

Objectives – Structural Sizing Tools

Systematically validate analysis methods to enable faster incorporation of TPCs into aircraft structures

The overarching objective is to validate design and high-fidelity analysis tools suitable for the trade concepts that emerge from HiCAM studies, enabling those concepts to transition smoothly into a next generation aircraft development program

- Develop new test methods/standards for generating material property input
  - Typical properties for models only – not statistical design values
- Evaluate existing sizing tools for application to new materials and architectures
  - Thermoplastic materials and resin infused composites
- Identify analysis/modeling approaches for structural scale applications



Focus of the current study

Systematic approach for maturing manufacturing technologies and analysis tools

High Impact Energy Tests : Gas Gun Test Apparatus and Chamber

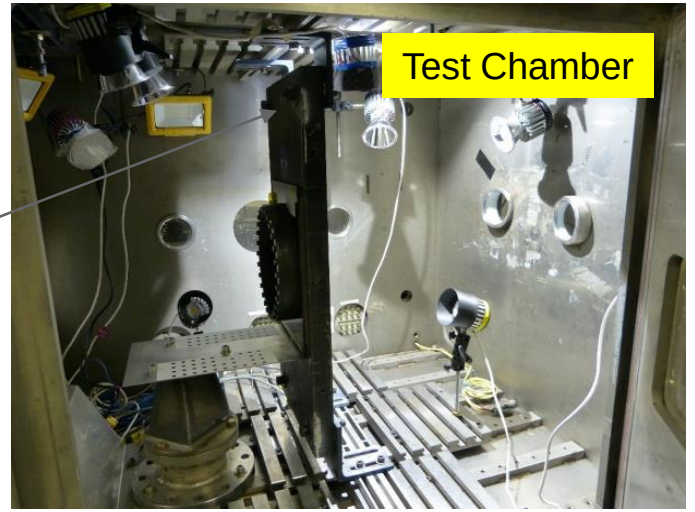
- Tests performed at NASA Glenn Research Center
- Projectile: ~~A~~ 92 gm metal cylinder with curved front end (not sharp)
- Thermoplastic Panels:
  - TC1225 T700G/LM-PAEK unidirectional tape (Toray)
  - APC AS4D/PEKK-FC unidirectional tape (Solvay)
  - Layup: $[45/0/-45/90]_{4S}$
- Thirteen impact tests on LM-PAEK panels: Rebound and punch through
- Twelve impact tests on PEKK panels
- Impact Velocity range: 39.5 m/s to 216.7 m/s (71 J to 2160 J)

Projectile



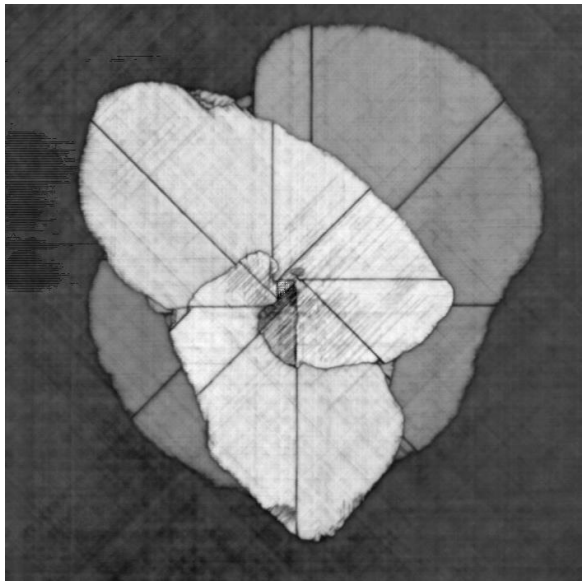


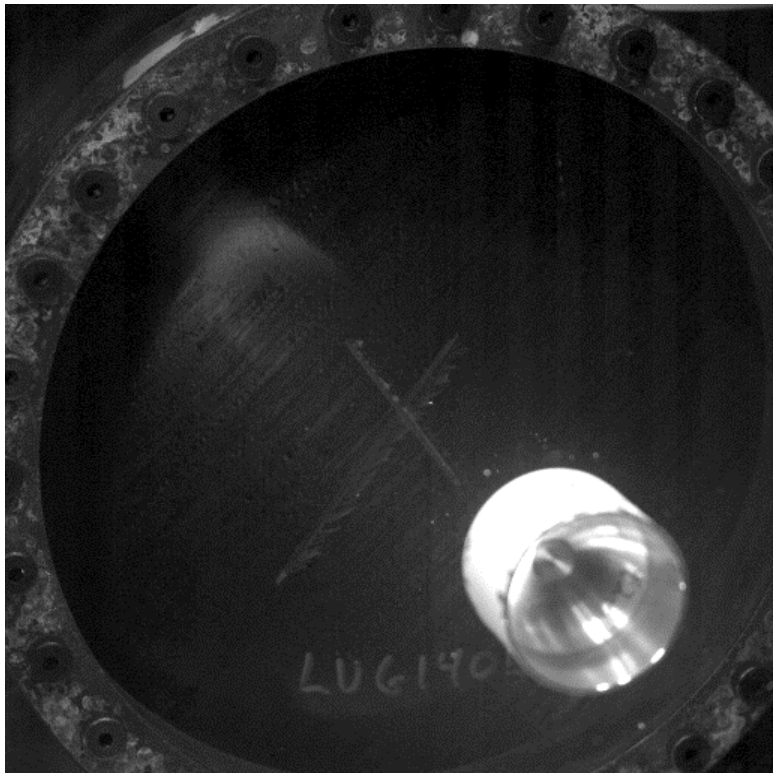
Test Panel



Impact Test: Test video and NDE Scans

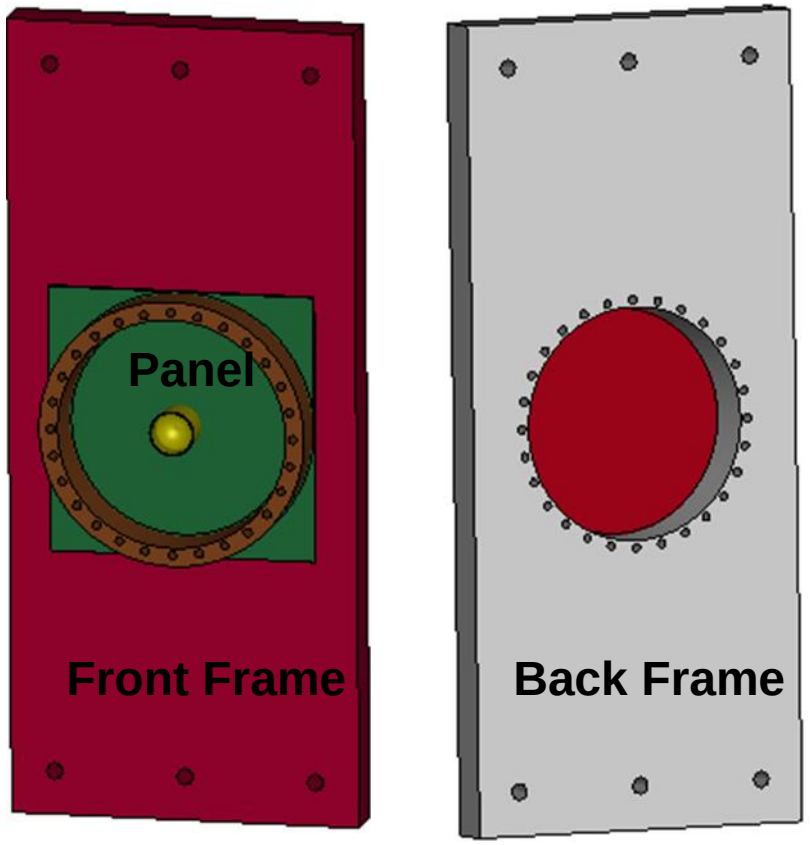
- Toray panels penetrated at 158 m/s and higher
- DIC used to measure panel deformation
- Post-test Ultrasonic C-scans for delamination assessment
- Post-test X-ray CT scans done to assess delamination and ply damage
- Test data for impact at 73.8 m/s
- Damage modes:
  - Fiber failure (not significant)
  - Matrix cracking and delaminations





Panel Impact Model

- Model set up:
  - Layup: $[45/0/-45/90]_{4S}$; 32 plies and 31 interfaces
  - T700/LM-PAEK properties sourced from NCAMP database
  - Impact velocity: 73.2 m/s (250 J)
- Modeling approach:
  - Each ply modeled with one element through the thickness
    - Reduced integration elements with hour-glass control
    - Type of mesh used – structured, not fiber aligned
    - Element edge length in damage region: 0.62 mm
  - Delamination modeled via Contact-Tiebreak
  - Parametric variations of GIc, GIIc performed (reduced by 20%)
  - Front and rear frame fixturing modeled
  - 12,227,870 nodes; 6,092,148 solid elements
- MAT299: Composite_Softening_DGD damage model
  - New material model in LS-DYNA
  - Improved damage coupling modes over MAT 261
  - Deformation Gradient Decomposition (DGD) based composite damage model
- Bilinear cohesive law, with B-K mixed mode behavior



High-fidelity impact models were developed

LS-DYNA MAT299

- Improvements made to damage evolution & coupling, over MAT 261
- LaRC-04 failure criterion in compression and Hashin criterion in tension
- Updated damage evolution modes:
  - Fiber tension and compression considered separately
  - Matrix failure mode: Damage variable (dmat) affects only in-plane matrix response (not through-thickness shear)
  - Damage variable (d3) Though-thickness matrix damage is treated separately, and applied to through-thickness shear damage modes as well
  - If fiber or matrix mode has failed, no in-plane shear resistance exists
  - Transverse ply damage a function of fiber damage (tension/compression) and through-thickness matrix damage (d3)

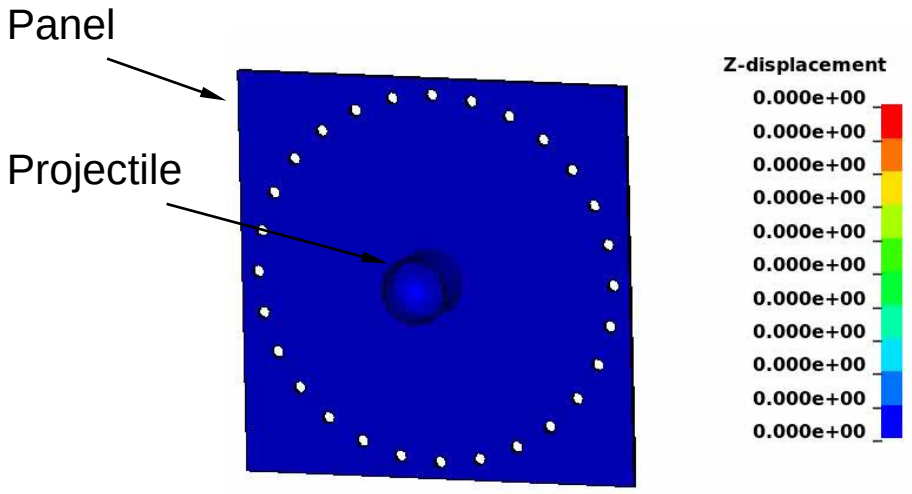
$$M = \begin{bmatrix} \frac{1}{1-d_{AF/AK}} & 0 & 0 & & & \\ 0 & \frac{1}{1-d_{MAT}} & 0 & & \cdots & \\ 0 & 0 & \frac{1}{1-d_3} & & & \\ & & & \frac{1}{1-(1-d_{AF/AK})(1-d_{MAT})(1-d_3)} & 0 & 0 \\ & \cdots & & 0 & \frac{1}{1-(1-d_{AF/AK})(1-d_3)} & 0 \\ & & & 0 & 0 & \frac{1}{1-(1-d_{AF/AK})(1-d_{MAT})} \end{bmatrix}$$

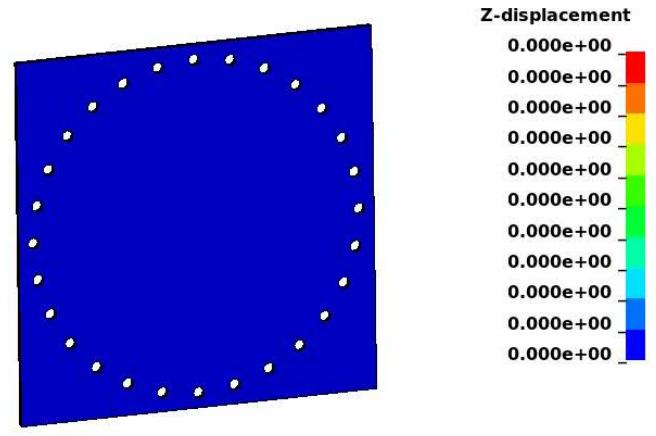
Deformation of Panel

Out-of-plane displacement profiles of the panel, due to impact

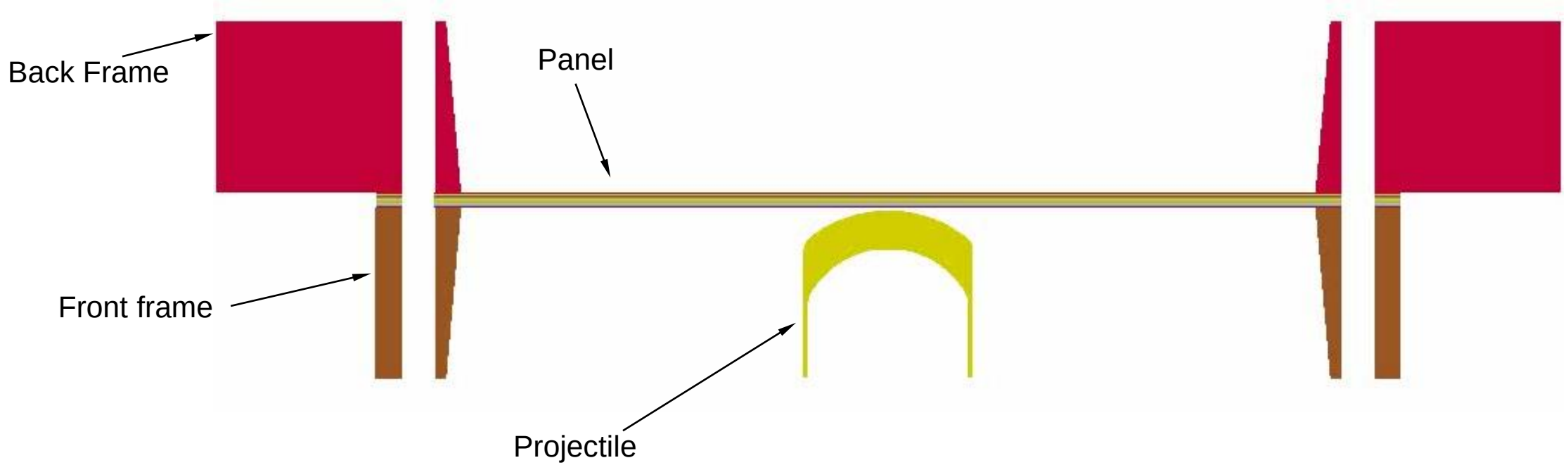
Front

Back



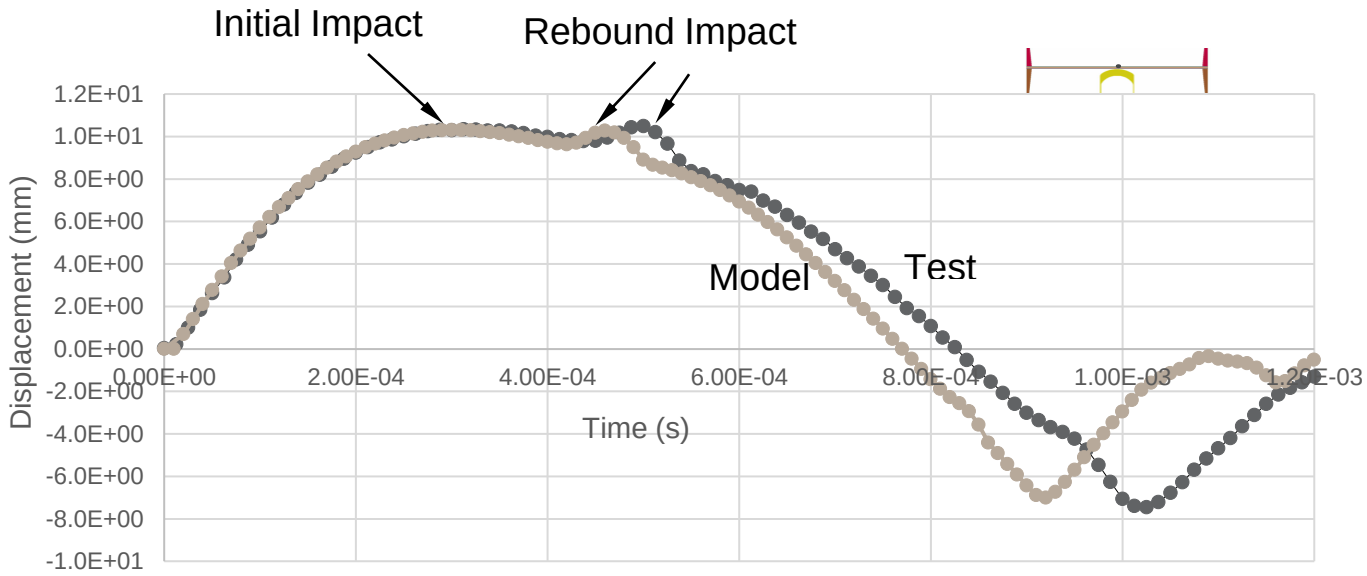


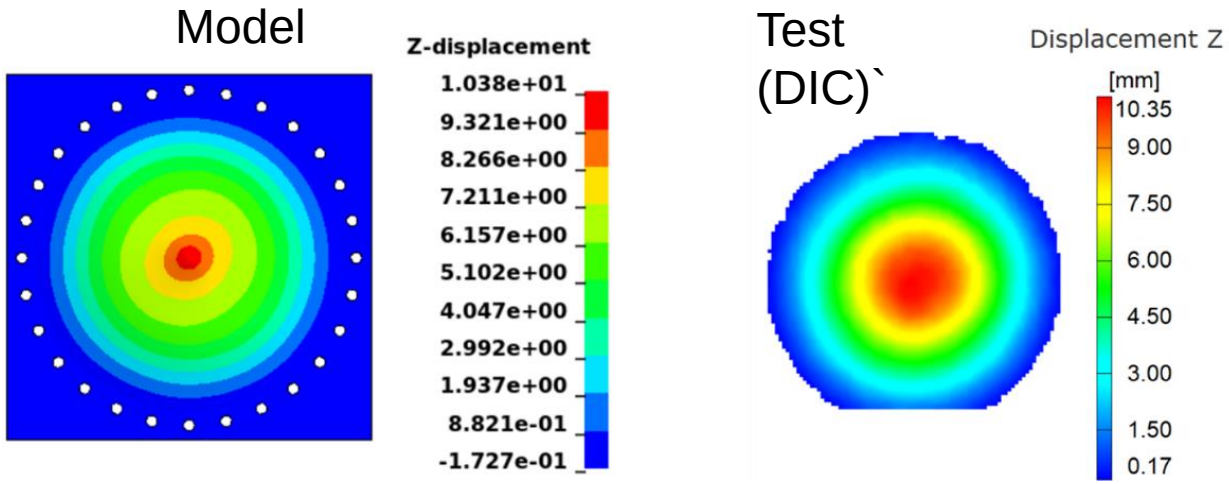
Deflection of Cross-section of panel



Correlations with Test Data

- Center Point Displacements
  - Initial Impact *(at 3.20e-4s)*
    - $d_{Model} = 10.309\ mm$; $d_{Test} = 10.304\ mm$; $Error = 0.04\%$
  - Rebound impact displacement
    - $d_{Model} = 10.10\ mm$ *(at 4.70e-4s)*
    - $d_{Test} = 10.49\ mm$ *(at 5.00e-4s)*
    - $Error = 3.7\%$
- Projectile Rebound Velocity
  - $V_{Model} = 51.3\,m/s$; $V_{Test} = 42.60\ m/s$; $Error = 20.40\%$

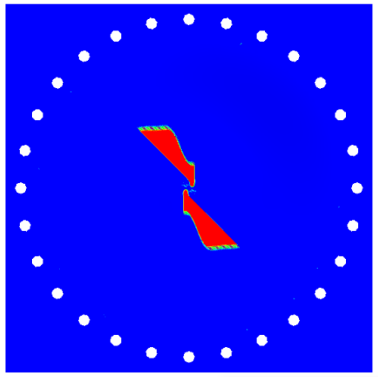




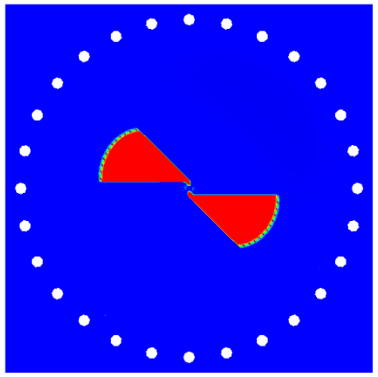
Panel Displacement Profiles

Predicted Delaminations at various interfaces

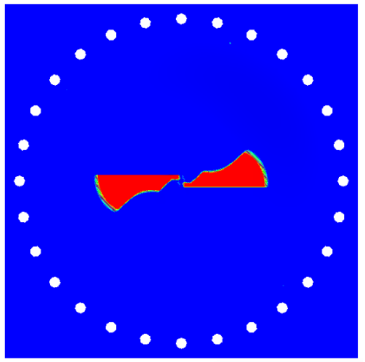
Ply layup:
$[+45/0/-45/90]_{4s}$



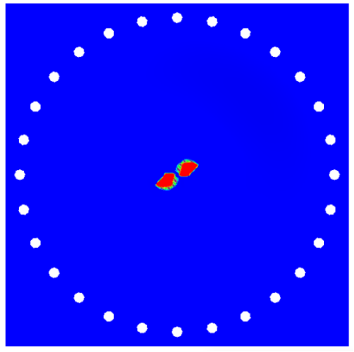
Ply interface 12-13



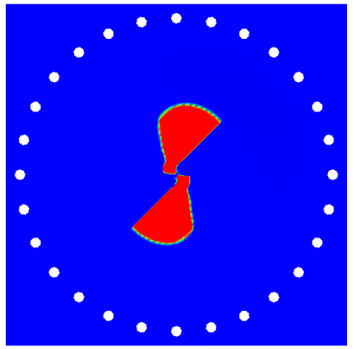
Ply interface 13-14



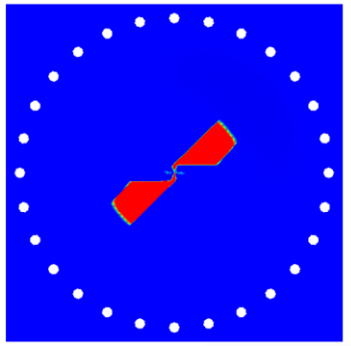
Ply interface 14-15



Ply interface 15-16



Ply interface 17-18



Ply interface 18-19

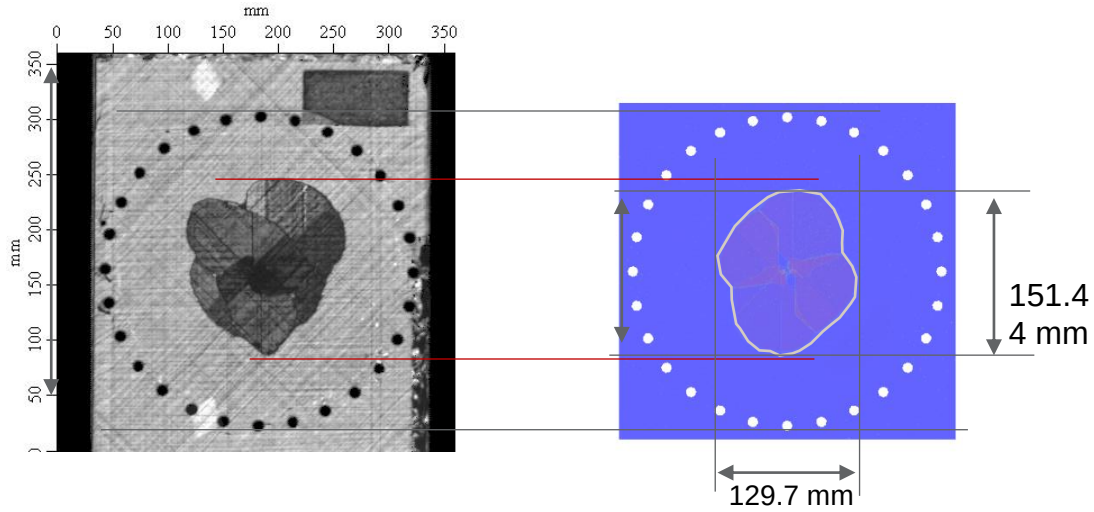
Correlations with Test Data: Delaminations

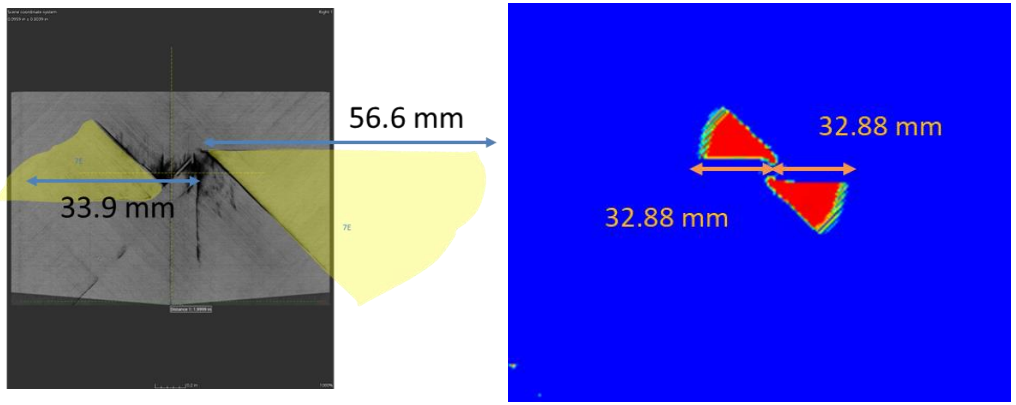
- Delamination footprint comparison
  - Ultrasonic C-scan performed on panel, compared with simulation
  - Predicted delaminations are smaller by 9.6% (width) and 6.9% (height) as marked
  - Shape prediction is similar, but clear differences observed

- Ultrasonic C-scan images superposed on X-ray CT images
- Location: Ply 7 (-45°) /Ply 8 interface (90°)
- Geometry
  - 2 petal-shaped delaminations seen in test and simulation
  - Petals unsymmetric in test, unlike in simulation
  - Non-uniform petal size in tests (simulation shows uniform size)
- Delamination Geometry
  - Test data indicates delaminations are not symmetric
  - Irregular shape; may change with repeated testing

Ultrasonic Scan

LS-Dyna Simulation

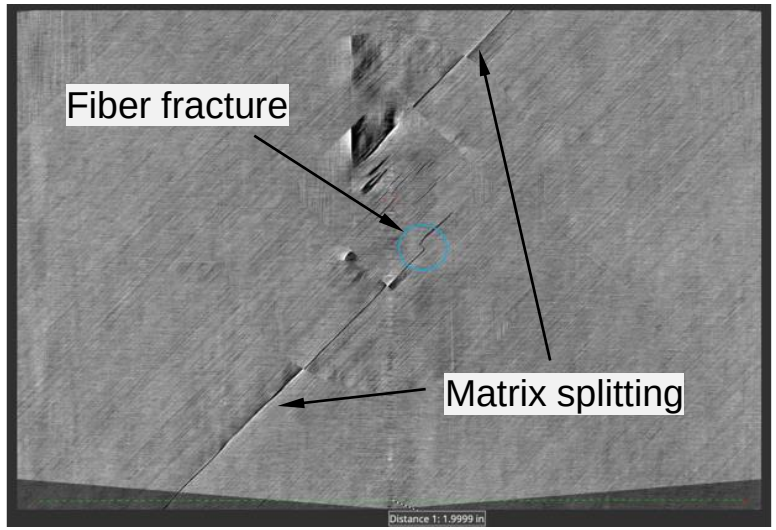




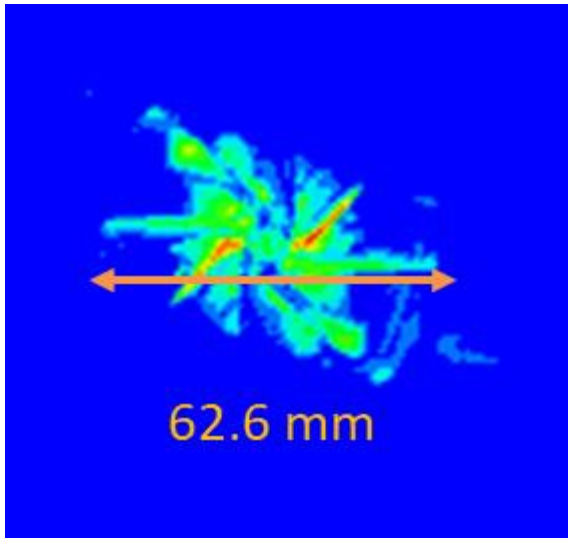
Correlations with Test Data: Damage to ply

- X-Ray CT scan of the panel performed
  - Location of ply: Ply # 9 (+45°)
- Damage modes marked:
  - Matrix splitting
  - Fiber fracture

- Model:
  - Matrix damage plotted (matrix splitting, variable # 6)
  - Fiber-aligned mesh not used
  - Matrix damage evolves in various directions (not bound by the meshing direction)
  - Fiber damage captured by model is minimal

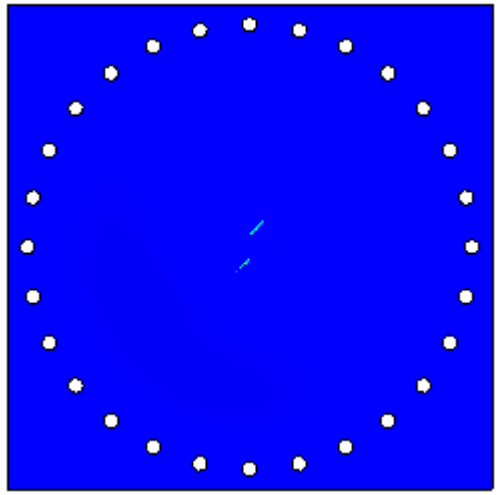


X-ray CT Scan showing ply damage



LS-DYNA result (ply # 9, var # 6)

Fiber damage minimal
(Var # 4)



Summary

- Several T700-LM-PAEK panels were impacted at various velocities
  - Test with impact velocity of 73.8 m/s simulated
  - Projectile did not penetrate panel
  - Significant delaminations seen in most interlaminar regions.
- Modeling of Panel Impact
  - Performed in LS-DYNA, using MAT 299 for intralaminar damage, tie-break for interlaminar damage
  - Panel deformation captured accurately on impact (< 1% error)
    - Rebound impact deformation reasonably accurate (error 3.7%)
    - Rebound velocity error 20.4%
  - Delamination size -under-predicted
  - Delaminations un-symmetric in test, symmetric in simulation
    - Strain rate effects not incorporated, material model is capable
- Future work:
  - Address strain rate effects
  - Simulate higher-velocity impact tests (with penetration of panels)

An impact test of a T700- LM-PAEK thermoplastic panel was performed, and simulated in LS-DYNA

Acknowledgements

This material is based upon work supported by the National Aeronautics and Space Administration (NASA) under Award No. 80NSSC22M0159.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of NASA. Additional support received from Raytheon Technologies Corporation (RTX) is gratefully acknowledged.

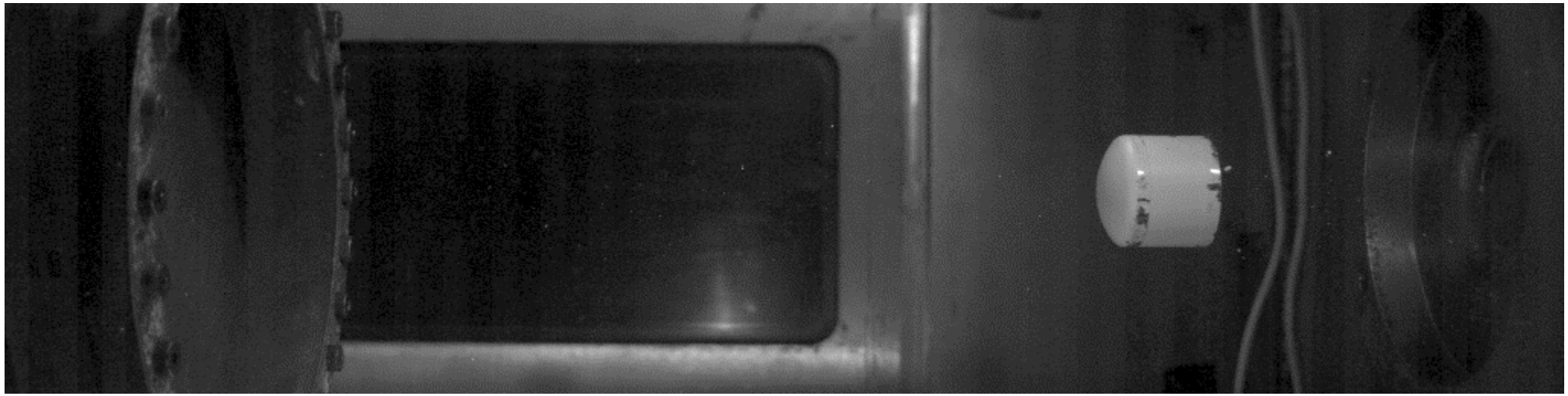
The authors appreciate NASA HiCAM team members for their insightful discussions, and Mr. Charles Ruggeri, Duane Revilock, Richard Martin and Wade Jackson for impact testing and post-test NDE support.

Thank You

Backup

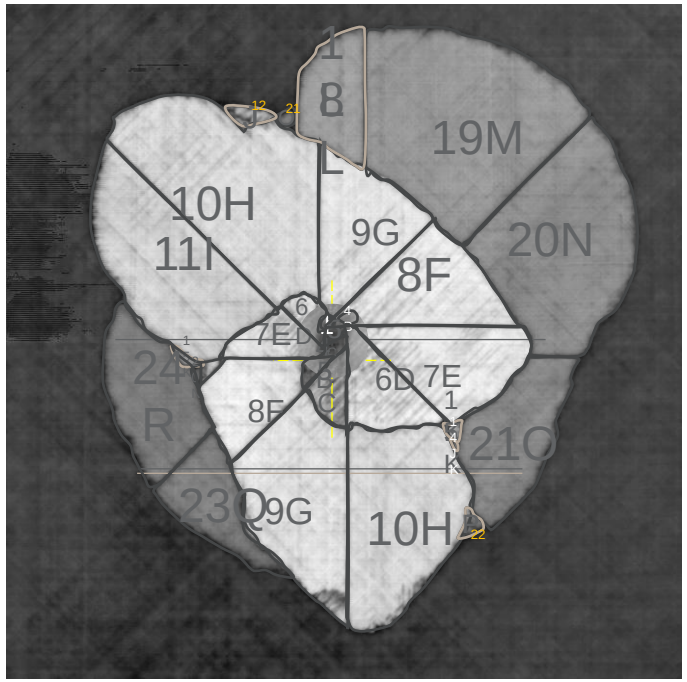
Impact Test: Side view (Test 1406)

- Sideview of Impact Test



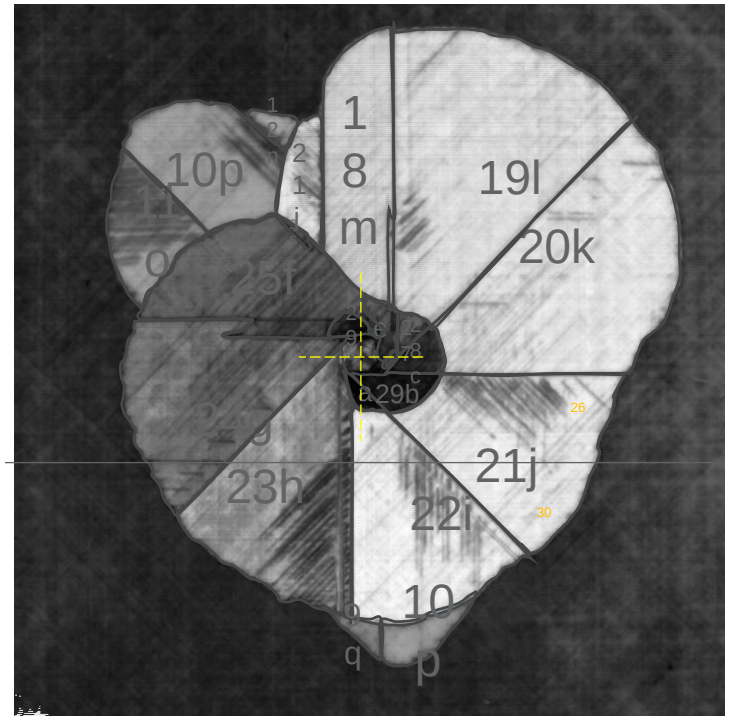
Impact Test: NDE Scan with delaminations marked

- HEDI Test 1406



Impact Side (7 “ x 7” scan)

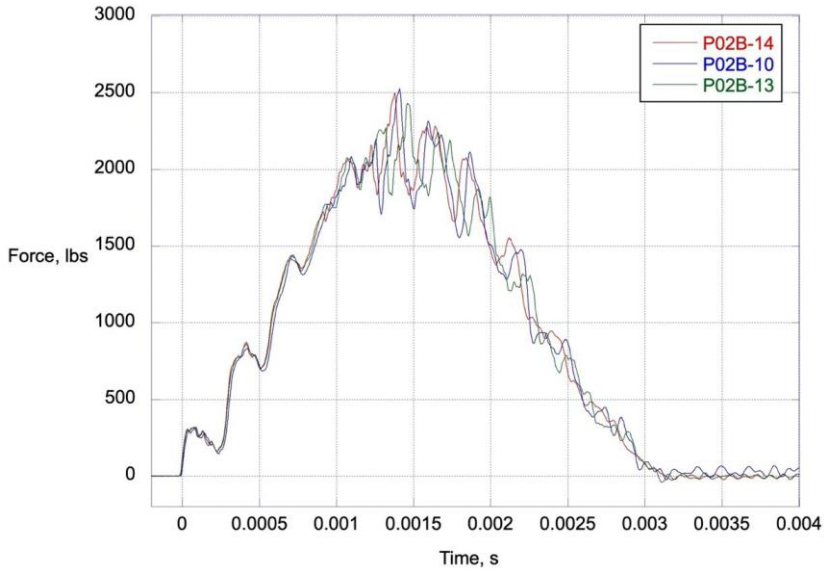
0°

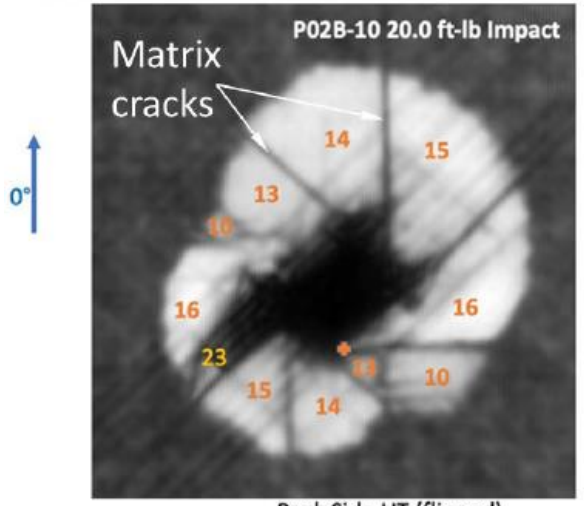


Back Side (7 “ x 7” scan)

Low Velocity Impact Testing: Sample Test Results

- Low Velocity Energy Impact (LVI): Test Scope
  - Force vs. time response measured.
  - Panels scanned for damage using ultrasound
  - Damage modes: delamination, matrix cracking
  - ‘Rotating fan’ shape of delaminations, bounded by matrix cracks





Back Side UT (flipped)


CT scan of ply damage

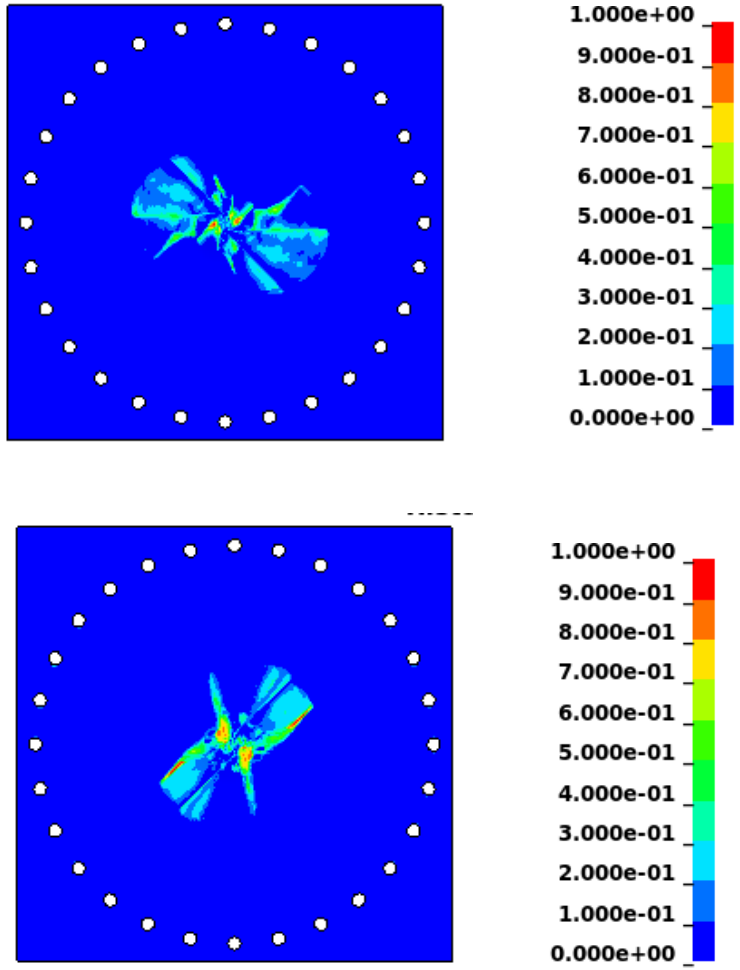
MAT 299: Capabilities

- Improved stability: Residual stiffness after failure of element (PFRF)
  - Can define it as a factor of the original stiffness

- Strain rate dependence of the following parameters:
  - Non-linear, elastic portion of the in-plane shear response
  - Matrix strength
  - Interlaminar delamination response:
    - Option 13- G_Ic, G_IIc

- Improved localization effects:
  - Ply transverse shear and ply crushing: Hashin fiber shear-tension failure criterion
  - Element erosion/deletion: fiber mode, matrix mode

Matrix Damage in Plies



Low velocity and high velocity impact tests were conducted