An Overview of NASA ACC High Energy Dynamic Impact Methodology for Prediction of Ballistic Limit

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Outline

- **Provide an Executive Overview of this Session**
- **Brief Overview of the Advanced Composites Project**
- **Summary of the High Energy Dynamic Impact Program Element**
  - Advanced Composites Consortium Effort
  - Impact Testing programs at NASA Glenn
  - MAT213 Development at NASA Glenn
- **Progressive Damage Analysis Methods**
  - LS-DYNA MAT162
  - LS-DYNA MAT261
  - Peridynamics EMU
- **Future Work**

Consortium Research Team

Advanced Composites Consortium

NASA

United Technologies

BOEING

Sandia National Laboratories

Phase I Partners

GE Aviation

Phase II Partners

UNIVERSITY OF SOUTH CAROLINA

McNAIR Center

NIAR

WICHITA STATE UNIVERSITY

NATIONAL INSTITUTE FOR AVIATION RESEARCH

NASA ACC Technical Challenge Areas

1) Predictive Capabilities

- Robust analysis for smarter testing
- Better prelim design, fewer redesigns

2) Rapid Inspection

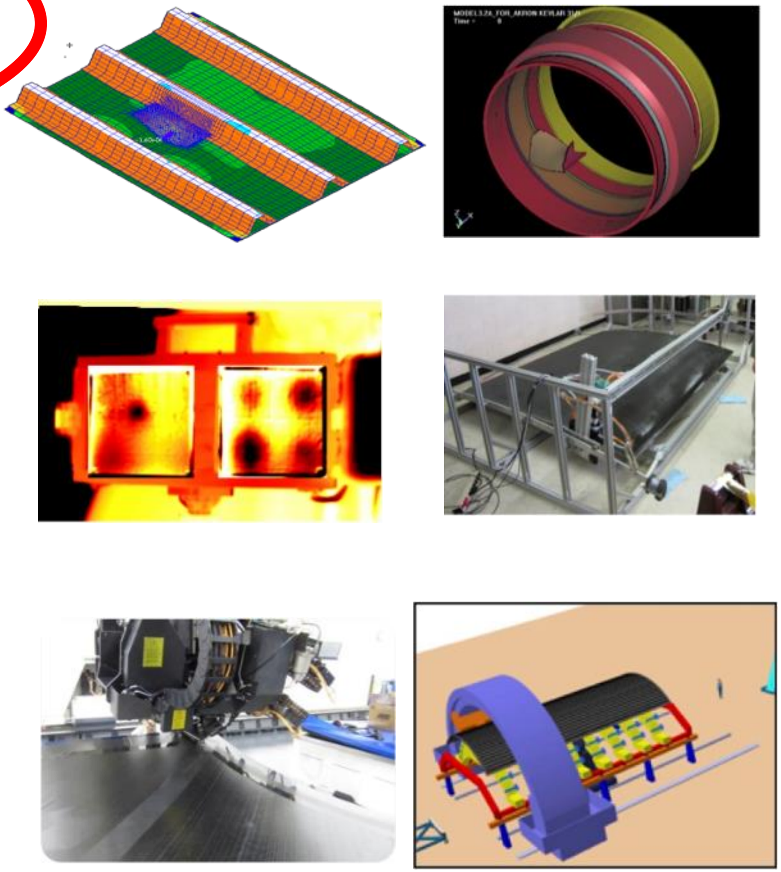
- Increase inspection throughput
- Quantitative characterization of defects
- Automated inspection

3) Manufacturing Process Simulation

- Reduce manufacture development time
- Improve quality control
- Fiber placement and cure process models

Verification & Validation

- Tie Technical Challenge work together
- Validate program benefits



High Energy Dynamic Impact Program Element

Objective

- Evaluate & develop impact analysis tools to predict performance of safety-critical engine/airframe structures dominated by high-energy impact events.
- Benchmark methods and tools for reducing development to certification timeline.

Five Year Project Duration

Phase 1 :
- Assess state of the art
- Identify deficiencies and technologies to be advanced
- Fundamental and small scale testing
- Validate methods against tests

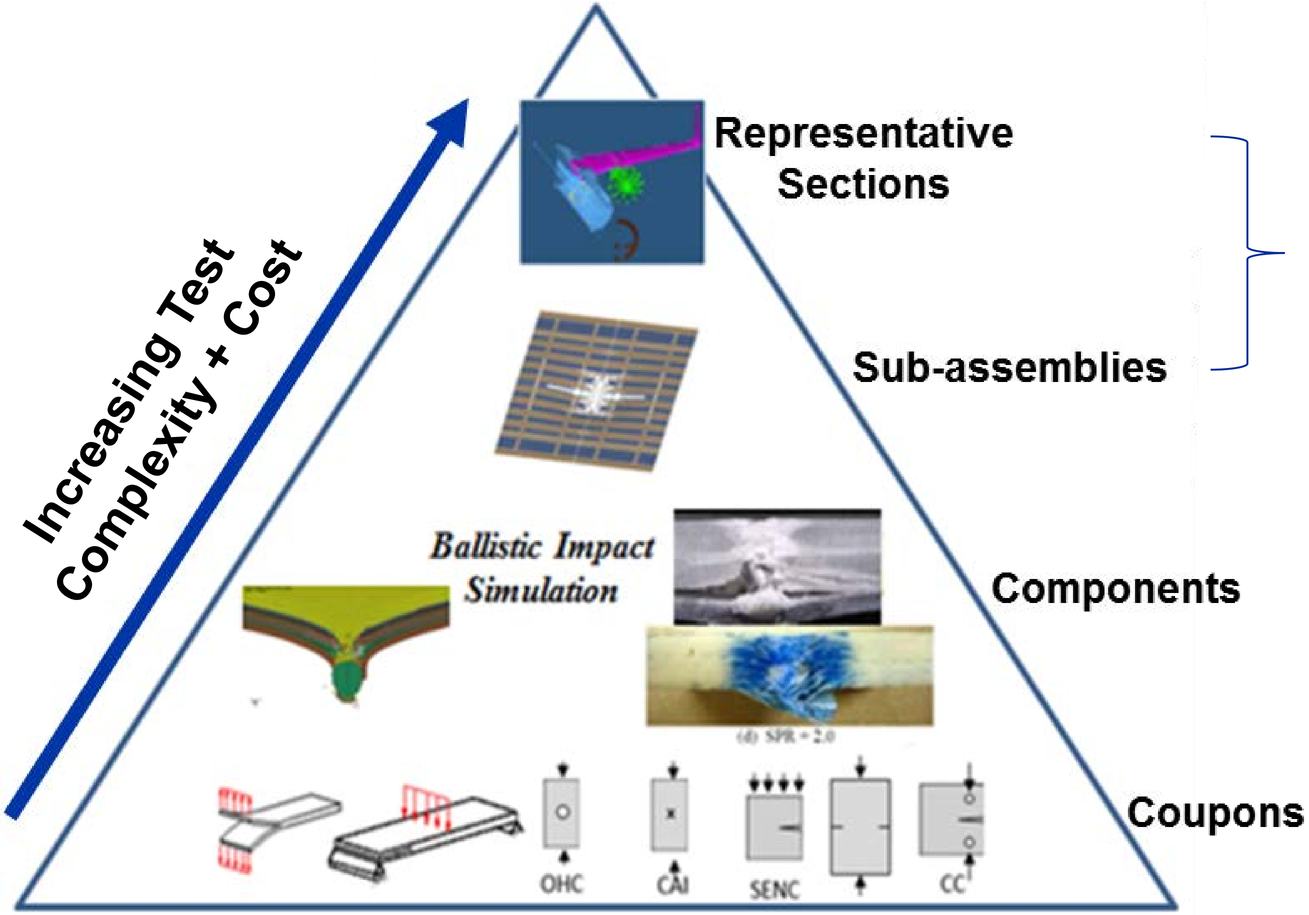
Phase 2 :
- Continue more focused technology maturation on selected methods
- Sub-component and component testing
- Continue validation with higher level tests
- Establish best practices and guidance

Predominant focus on LS DYNA with smaller effort on Peridynamics

Existing LS DYNA models utilized in this study are MAT162, MAT261 and SPG along with a new model under development at NASA Glenn called MAT213

Analytical Method – Building Block Approach

Use Building Block Approach to validate PDFA material model:



Increasing Test Complexity + Cost

Representative Sections

Sub-assemblies

Components

Coupons

Inform/Reduce Testing

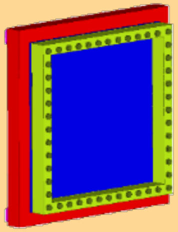
Calibration & Validation

Once validated, a PDFA model can serve to inform higher complexity test configurations and reduce scope of expensive testing

Overview of NASA ACC HEDI Testing

Phase 1

- Sub-element ballistic panel impact testing
- Non-configured flat panels

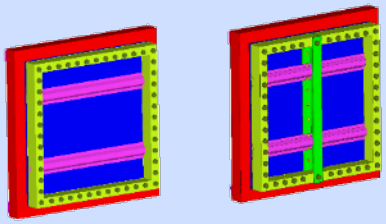


✓ *Completed*

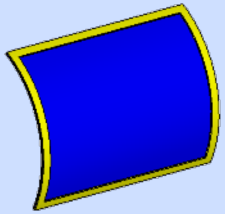
Phase 2

Build on Phase 1 testing adding:

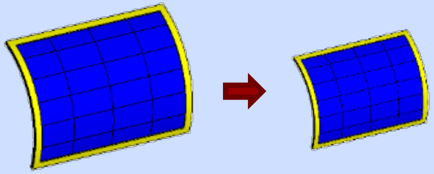
- **Configuration (fastener, stringer, frame)**



- **Curvature**

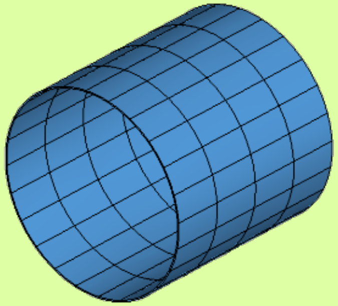


- **Scale**



Planned

Aircraft Structure



Projected Demo

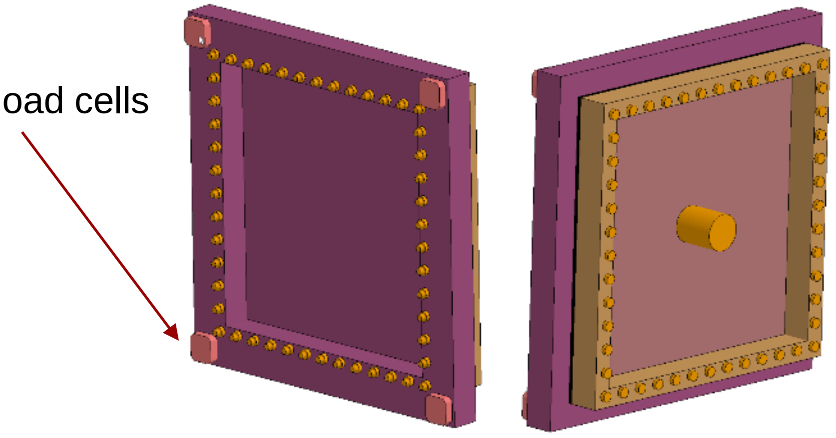
Phase I Program Flow

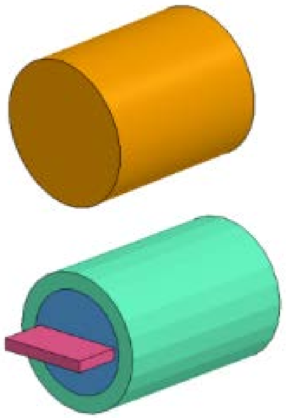
- Examine Applicable material models
- Develop a test matrix
- Expert FEM users develop blind predictions
- Perform testing
- Calibrate model response
- Assess technical gaps and End User needs

Simulation Approach

Four (4) material models:

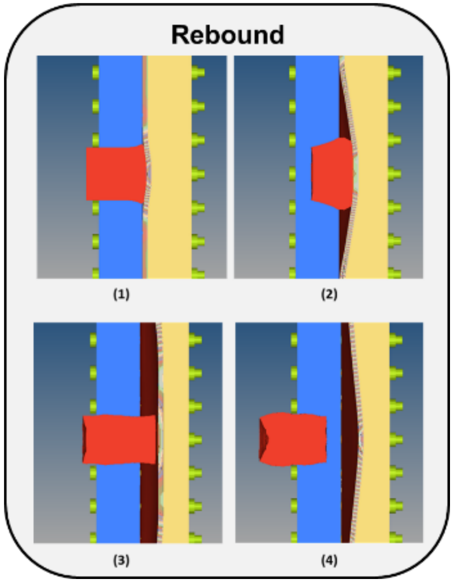
- LS-DYNA MAT162
- LS-DYNA MAT261
- Smoothed Particle Galerkin (SPG)
- EMU Peridynamics

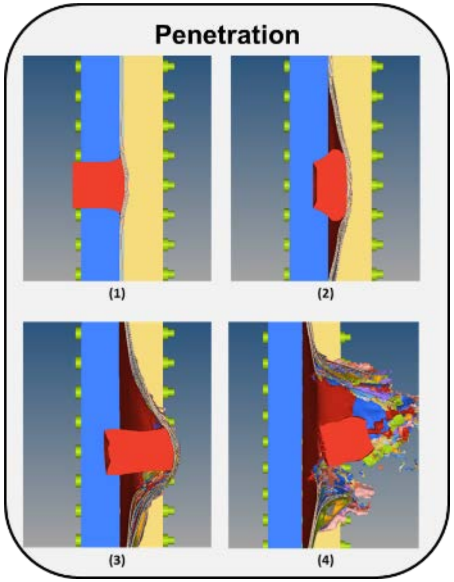




<u>Phase 1</u>

- ✓ Model of panel and frame only
- ✓ Ply thickness of 1 element
- ✓ Cohesive contact between ply layers





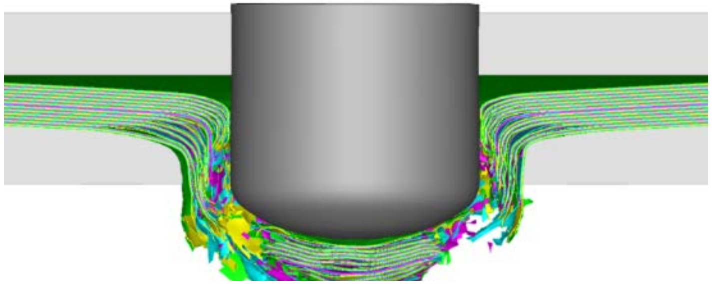
Why use MAT162 for HEDI?

MAT162 General Overview:

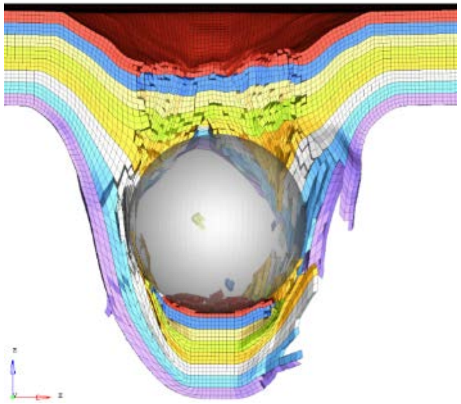
- Intended for use in high energy impact events exhibiting penetration and perforation of thick-section tape and woven composite materials
- Incorporates higher order failure modes using 11 parameters only observed at elevated loading rates, specifically:
- In-plane → 2 compression, 2 tension, 1 shear
- Out-of-plane → 1 tension, 2 transverse shear
- Coulomb friction angle for shear band formation
  - Fiber Crush stress limit (SFC)
  - Fiber Shear stress limit (SFS)

Standard test methods exist (in-plane, out-of-plane and Coulomb friction angle)

Unique to MAT162 (SFC and SFS)



Aluminum hollow projectile impact



Steel bearing impact

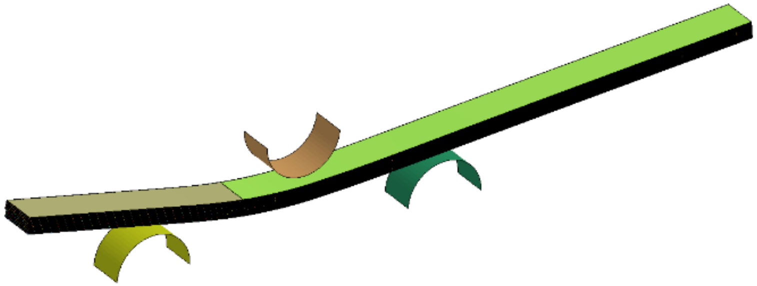
Incorporation of SFC and SFS offer a unique capability to represent material failure immediately in front of the projectile in HEDI events

Why use MAT261 for HEDI?

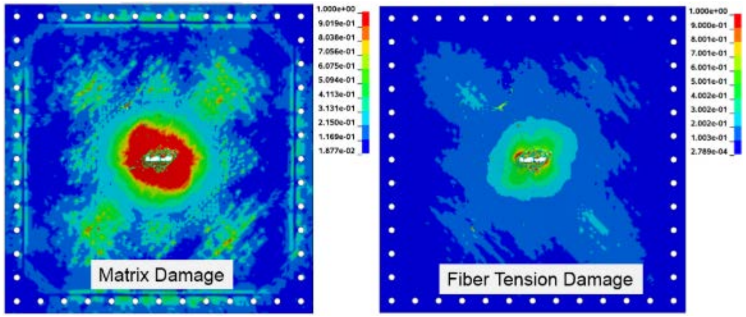
MAT261 General Overview:

- Includes five damage failure modes to capture not only in-plane and out-of-plane failure, but also mechanics of failure/damage observed in high energy dynamic impact
- Input of fracture toughness helps to determine damage progression:
  - ENKINK – Fiber compression fracture toughness
  - ENA – Fiber tension fracture toughness
  - ENB – Intra-laminar matrix tension fracture toughness
  - ENT – Intra-laminar matrix transverse shear fracture toughness
  - ENL – Intra-laminar matrix longitudinal shear fracture toughness

Determine with testing



ENF simulation for ENT and ENL



Damage after impact

Strain rate capability and through-thickness damage model offer a unique capability to represent material failure in HEDI events

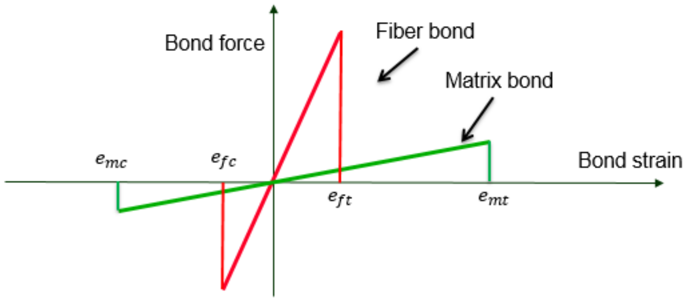
Why use Peridynamics for HEDI?

Peridynamics General Overview:

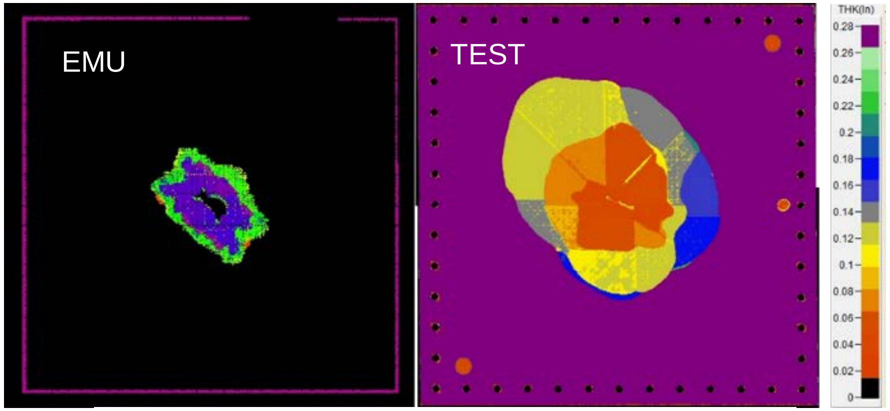
- Formulation models bond-based damage propagation in composite materials without limitations of crack initiation and crack growth law
- Constitutive model consists of 14 total inputs to characterize material, regardless of discontinuities:
  - 6 Elastic constants
  - 4 Fiber / matrix failure strains in tension / compression
  - 1 Matrix shear failure strain
  - 2 Energy release rates
  - 1 Density

$$\rho\ddot{\mathbf{y}}(\mathbf{x},t) = \int_{\mathcal{H}} \mathbf{f}(\mathbf{x}',\mathbf{x},t)\, dV_{\mathbf{x}'} + \mathbf{b}(\mathbf{x},t)$$

Peridynamics theory of motion



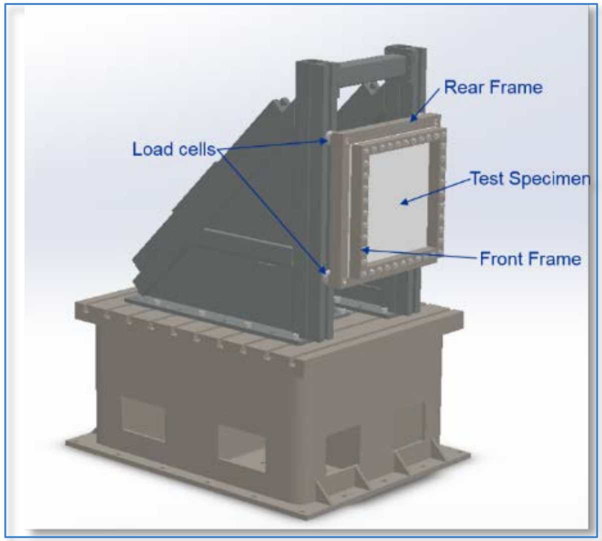
Lamina level failure model



In-plane damage and delamination

Peridynamics theory offers a unique capability to represent material failure without influence of relations for crack initiation and propagation

Impact Testing at NASA Glenn (25” x 25” Panels)

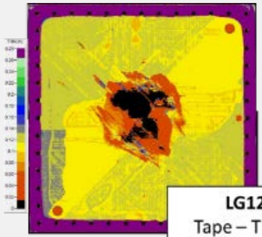



Gas Gun Facility

Multiple material systems and projectiles are tested to expand an experimental database for which to validate impact predictive models

Ballistic Impact Testing

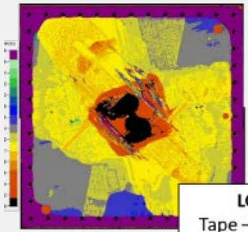
LG1206 Back
Tape – TL (40p)
667 ft/s
204 ft/s (Penetrate)



LG1206
Tape – TL (40p)
667 ft/s
204 ft/s (Penetrate)

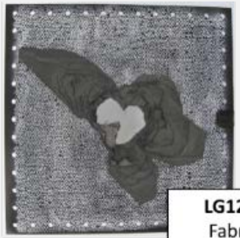
UD Tape only
Quasi-isotropic

LG1242 Back
Tape – NTL (40p)
660 ft/s
240 ft/s (Penetrate)

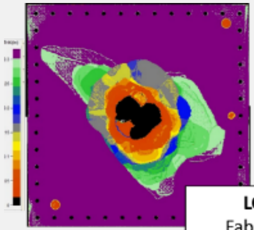


LG1242
Tape – NTL (40p)
660 ft/s
240 ft/s (Penetrate)

UD Tape only
Non-Traditional

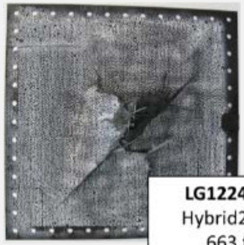


LG1214 Back
Fabric (40p)
663 ft/s
397 ft/s (Penetrate)

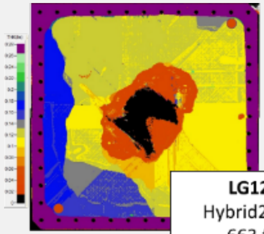


LG1214
Fabric (40p)
663 ft/s
397 ft/s (Penetrate)

PW Fabric only

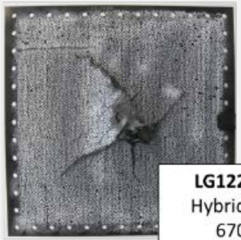


LG1224 Back
Hybrid2 (40p)
663 ft/s
223 ft/s (Penetrate)

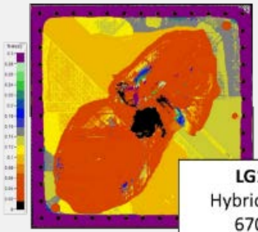


LG1224
Hybrid2 (40p)
663 ft/s
223 ft/s (Penetrate)

UD Tape /
PW Fabric (2)



LG1229 Back
Hybrid3 (40p)
670 ft/s
140 ft/s (Penetrate)

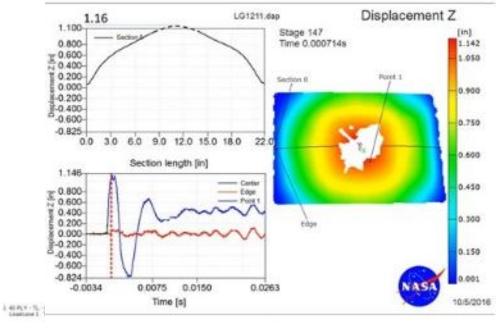


LG1229
Hybrid3 (40p)
670 ft/s
140 ft/s (Penetrate)

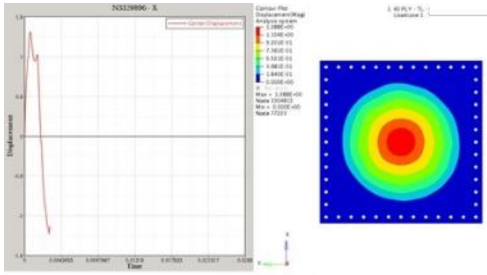
UD Tape /
PW Fabric (3)

Test-Analysis Comparison

Displacement



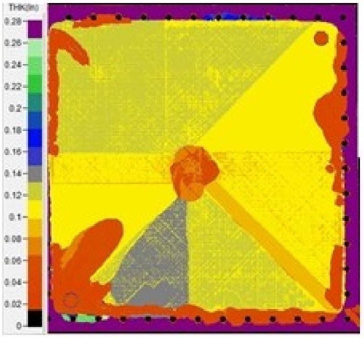
Test



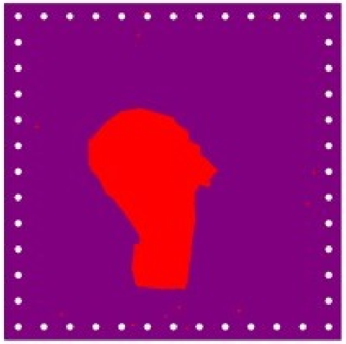
MAT 162 Simulation

- ➢ *40p-TL w/ blunt projectile*
- ➢ *MAT162 results*

Delamination

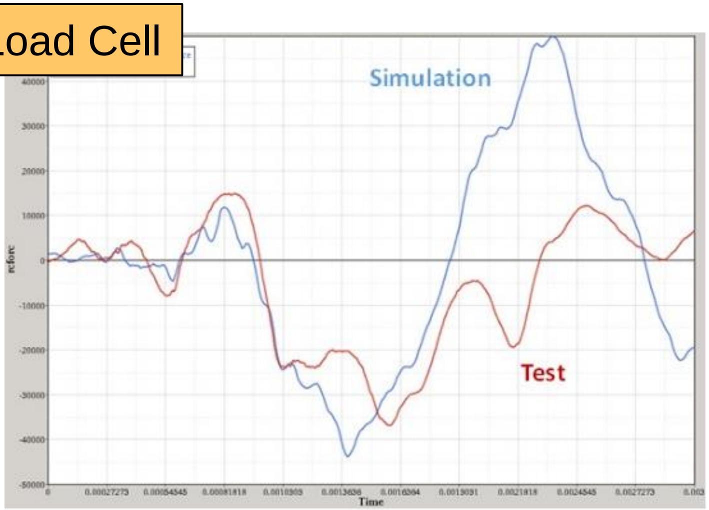


Panel NDE

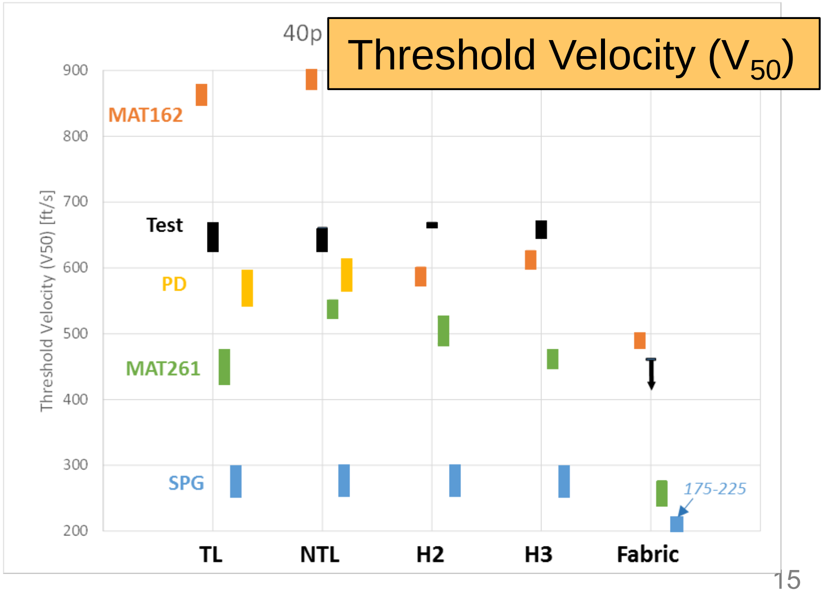


Simulation

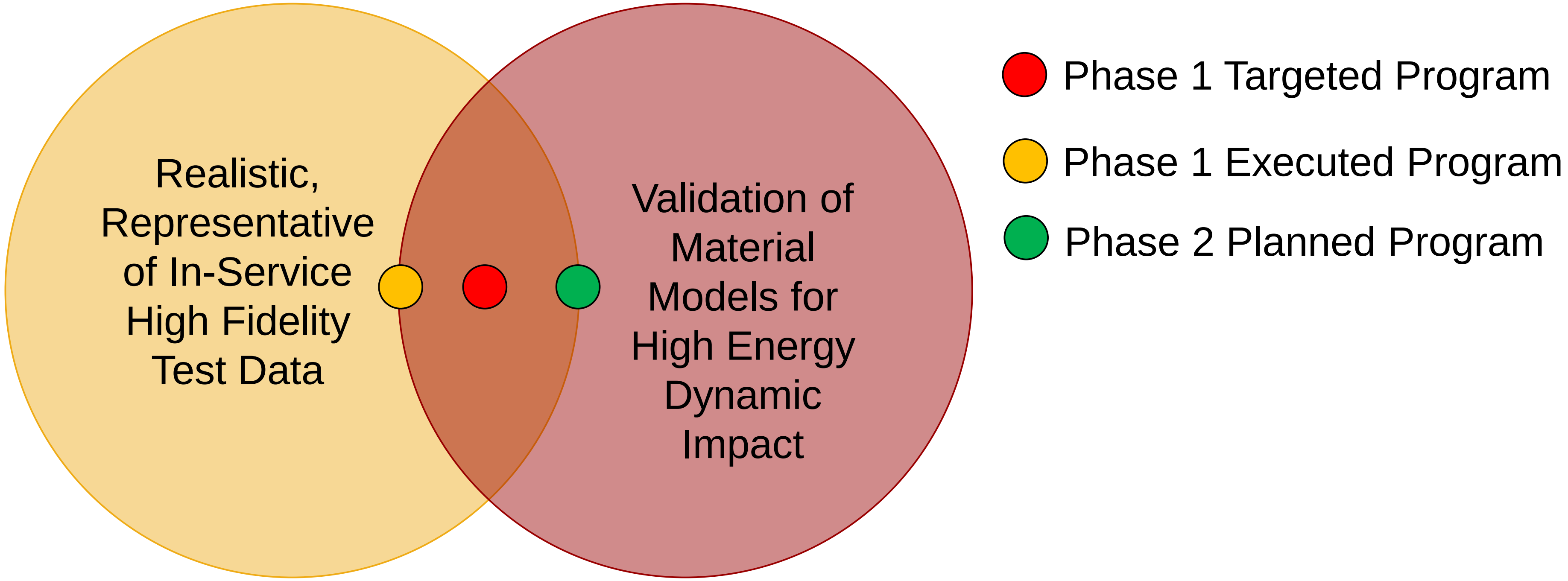
Load Cell



Threshold Velocity (V_{50})



Transitioning Phase 1 to Phase 2



🔴 Phase 1 Targeted Program

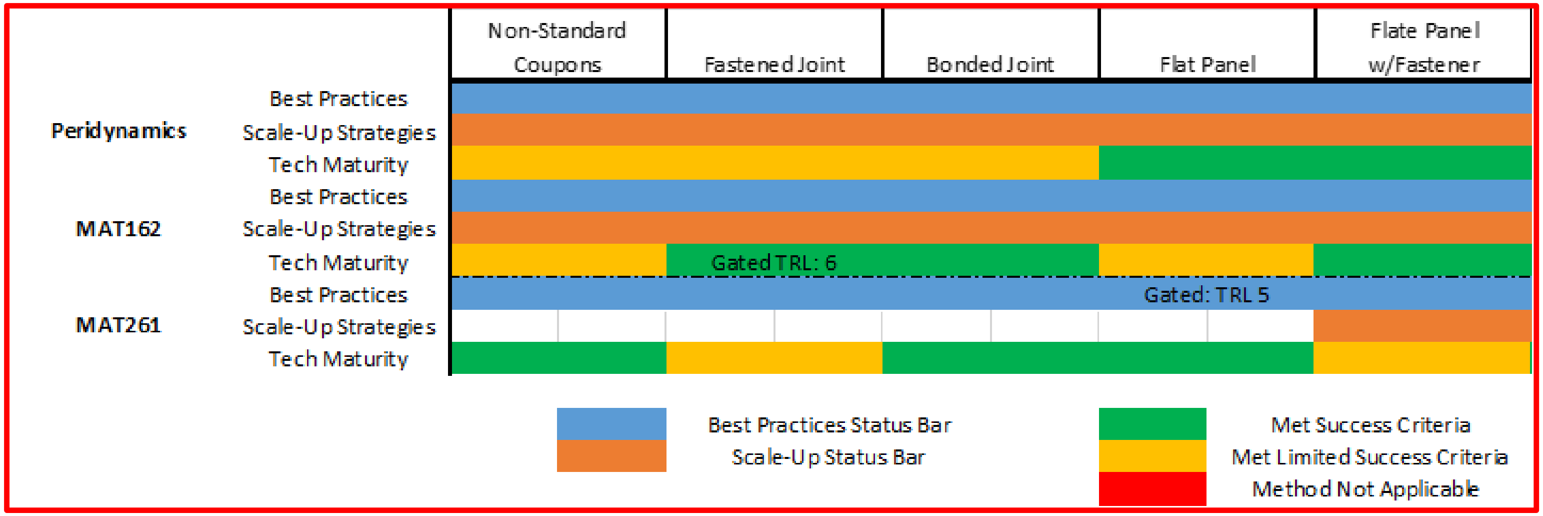
🟡 Phase 1 Executed Program

🟢 Phase 2 Planned Program

- **Lessons learned led to a Phase 2 effort focused on validation of material models**
  - Updated projectile to minimize uncertainty of impact
  - Developing MAT213
  - Developing MAT162 sub-laminate modeling approach
  - Creating best practices for MAT261
  - Developing a non-linear, strain rate dependent stretch model for PD

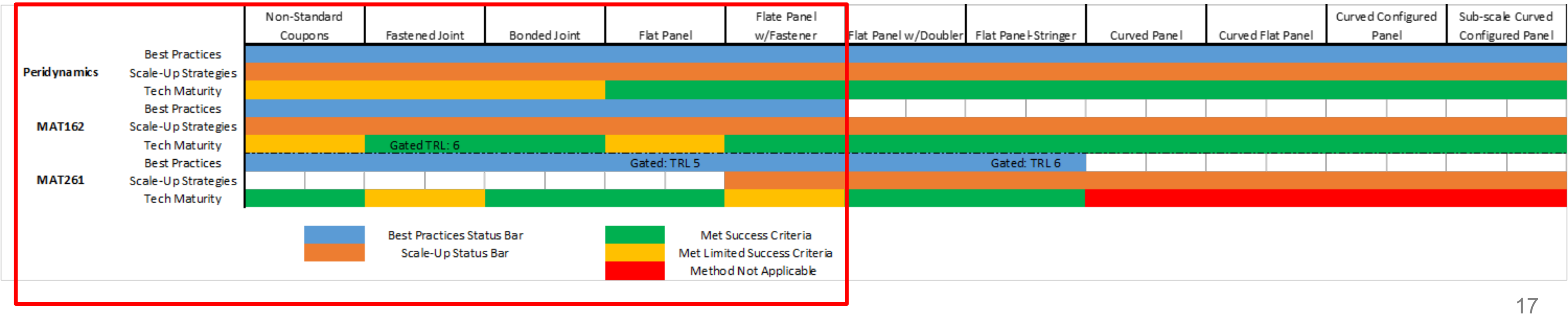
Phase 2: "HEDI Playbook"

- **Envisioned Final HEDI Deliverable is "The HEDI Playbook"**
  - Chart allows end users to quickly assess what are the modeling needs for the length scale of interest, which tool is recommended, and what the expected success will be
    - This chart will be accompanied with CRT CDRLs including benchmarking/verification report, best practices report, and scale-up strategies



		Non-Standard Coupons	Fastened Joint	Bonded Joint	Flat Panel	Flate Panel w/Fastener
Peridynamics	Best Practices	🟦	🟦	🟦	🟦	🟦
	Scale-Up Strategies	🟧	🟧	🟧	🟧	🟧
	Tech Maturity	🟨	🟨	🟨	🟩	🟩
MAT162	Best Practices	🟦	🟦	🟦	🟦	🟦
	Scale-Up Strategies	🟧	🟧	🟧	🟧	🟧
	Tech Maturity	🟨	🟩 Gated TRL: 6	🟩	🟨	🟩
MAT261	Best Practices	🟦	🟦	🟦	🟦 Gated: TRL 5	🟦
	Scale-Up Strategies					🟧
	Tech Maturity	🟩	🟨	🟩	🟩	🟨

🟦 Best Practices Status Bar
🟧 Scale-Up Status Bar
🟩 Met Success Criteria
🟨 Met Limited Success Criteria
🟥 Method Not Applicable

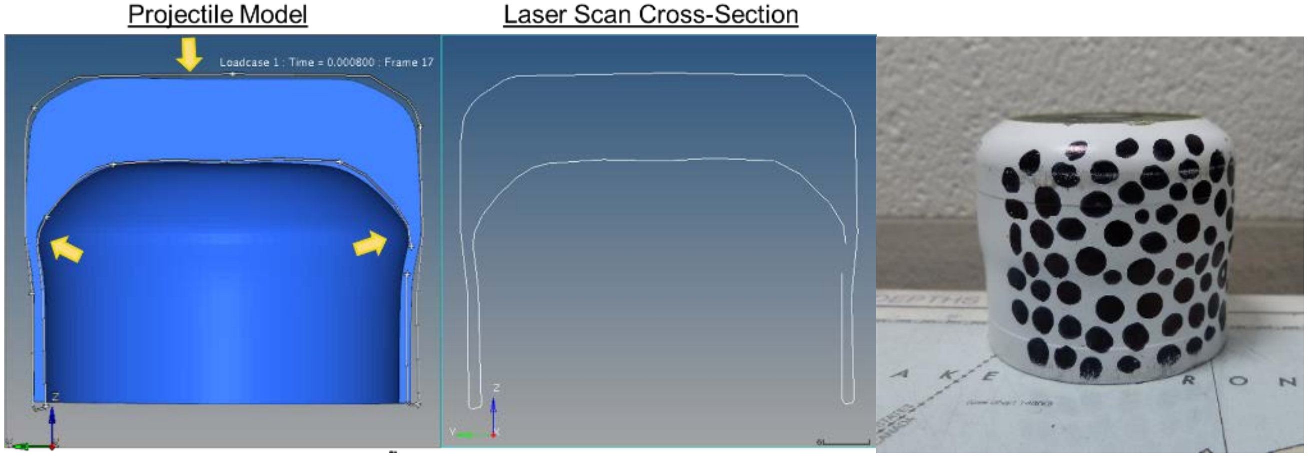


		Non-Standard Coupons	Fastened Joint	Bonded Joint	Flat Panel	Flate Panel w/Fastener	Flat Panel w/Doubler	Flat Panel-Stringer	Curved Panel	Curved Flat Panel	Curved Configured Panel	Sub-scale Curved Configured Panel
Peridynamics	Best Practices	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Scale-Up Strategies	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	Tech Maturity	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
MAT162	Best Practices	🟦	🟦	🟦	🟦	🟦						
	Scale-Up Strategies	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	Tech Maturity	🟨	🟩 Gated TRL: 6	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩
MAT261	Best Practices	🟦	🟦	🟦	🟦 Gated: TRL 5	🟦	🟦	🟦 Gated: TRL 6				
	Scale-Up Strategies					🟧	🟧	🟧	🟧	🟧	🟧	🟧
	Tech Maturity	🟩	🟨	🟩	🟩	🟨	🟩	🟩	🟥	🟥	🟥	🟥

🟦 Best Practices Status Bar
🟧 Scale-Up Status Bar
🟩 Met Success Criteria
🟨 Met Limited Success Criteria
🟥 Method Not Applicable

Phase 2: Validation of Projectile

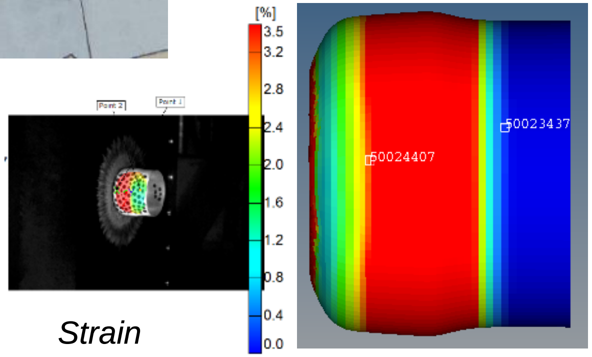
- **Modified ASTM D8101 projectile (91g vs. 50 g)**
  - Al-6061 → *concerns about strain-rate sensitivity*
- **Johnson-Cook material model validated for analysis use**
  - Test of projectile against rigid plate
  - Captures strain sensitivity and deformation


Projectile Model

Laser Scan Cross-Section

Deformation


Projectile (Pristine)

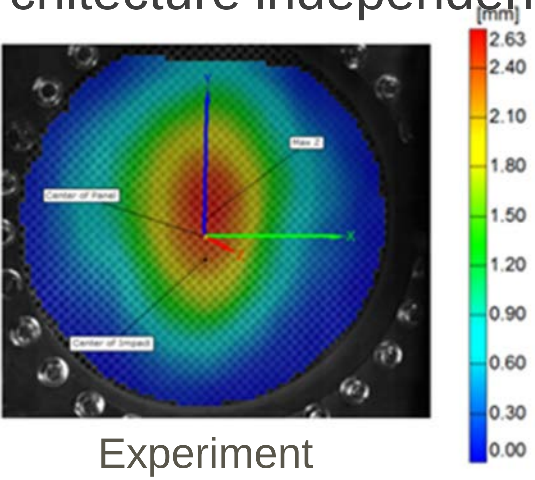


Strain

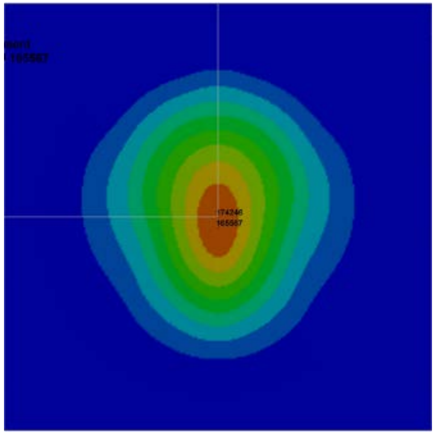
MAT213 Development

MAT213 General Overview:

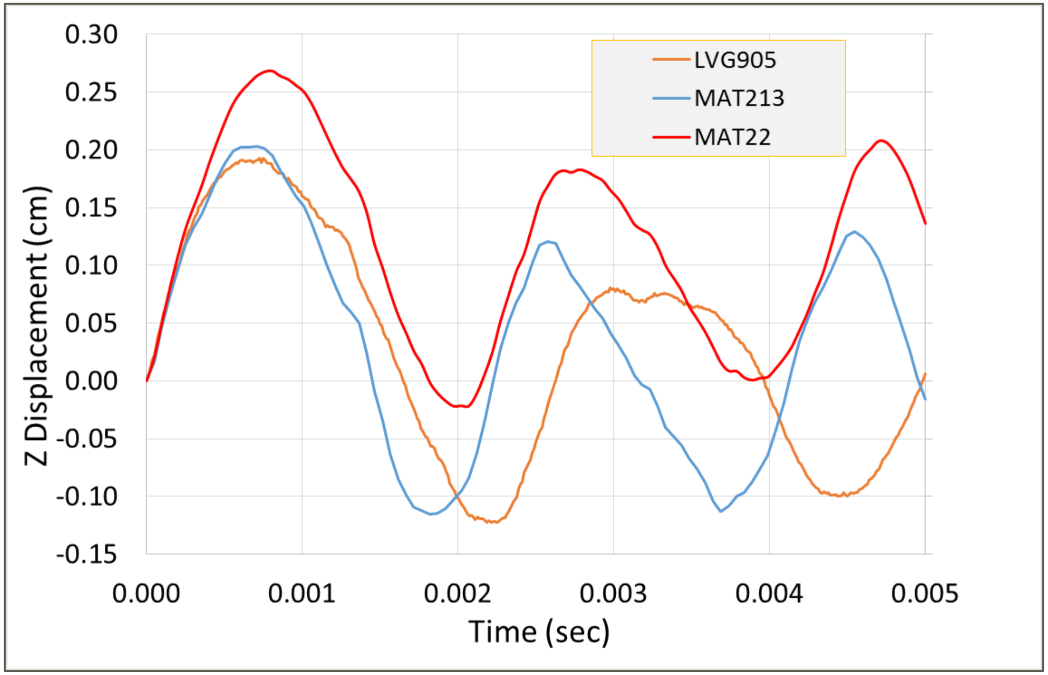
- Incorporates plasticity, damage, and failure
- Architecture independent



Experiment



Simulation



Displacement: Test vs. Simulation

Summary

- **Phase I**
  - Material models developed with promising results from MAT162, MAT261, and peridynamics
    - MAT 261 showed reasonable results with limited calibration
    - Identified areas for SPG improvements; continuing SPG development in other fields
  - Identification of tech gaps
    - Calibration of MAT162 parameters for parts idealized at the sublaminate length scale
    - Analysis of bolted joint failure at high loading rates
- **Phase II**
  - Performing analysis of impact on structural assemblies, including fasteners, bonded joints, doublers, and stiffeners
  - Developed validation framework of PDA models
  - Validated Johnson-Cook projectile model for subsequent analysis
  - Developing Best Practices & Benchmarking for HEDI modeling
  - Continuing rigorous verification and validation of MAT213 with multiple material architectures and constituents
  - Improved PD material modeling capability to include nonlinearity and strain rate effects

Significant strides have been made towards the goal of using simulation of composites in impact applications

Acknowledgements

- Special thanks to the HEDI team:
  - Alan Byar, Fernando Cuenca, Jeff Iqbal, Matt Molitor, Rick Rosman, Steve Slaughter, Olaf Weckner (Boeing)
  - Robert Goldberg (NASA Glenn)
  - HEDI Partners: UTC, GE Aviation

- This effort was performed under the support of the NASA Advanced Composites Project and Consortium
  - Industry wide effort to develop and transition technology that will enable validated strength and life prediction tools for complex composite structures and standardize procedures for their reliable use
  - Study was a product of the research involving development of PDFA tools for high energy dynamic impact

- 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 the National Aeronautics and Space Administration.

Questions?

Backup

Ballistic Impact Testing Overview

Phase 1

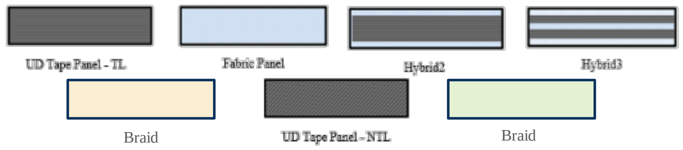

Ti Projectile


Blunt Projectile


Sharp Projectile

Realistic, Representative of In-Service, High Fidelity Test Data

- Four (4) material systems
  - IM7/8552 UD tape & PW fabric; T700/5208 and T800/AMD-825 triaxial braid
- Multiple laminate types and thicknesses



Phase 2

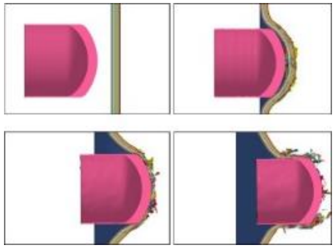

Ti Projectile


Phase II Projectile

Validation of Material Models for High Energy Dynamic Impact

- Three (3) material systems
  - IM7/8552 UD tape & PW fabric; T800/AMD-825 triaxial braid
- Multiple laminate types and thicknesses

Phase I Technical Development



Model Evaluation with Case Studies

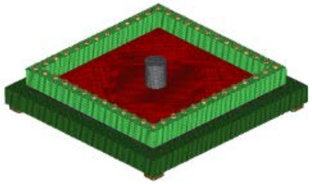
Blind Predictions

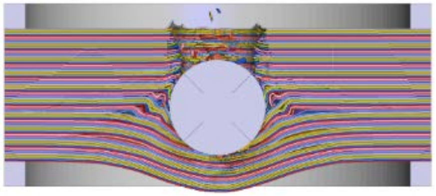
Material Model Calibration

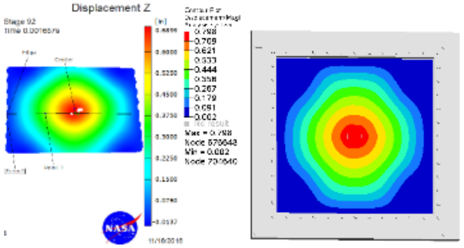
Test-Analysis Correlation

Material Characterization Testing

Ballistic Impact Testing

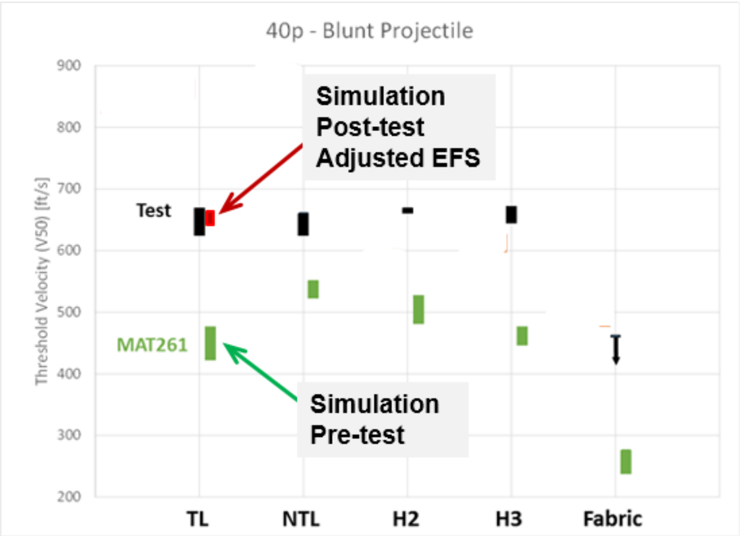






MAT261 Results

- Adjusting EFS (Effective Failure Strain) leads to significant improvement in correlation with test

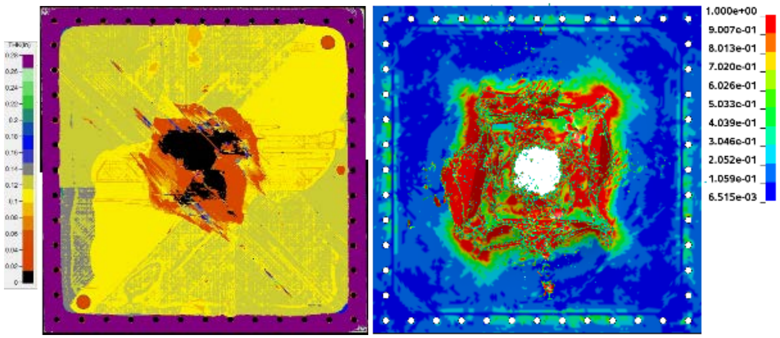


Ballistic Limit

V = 628 ft/s

Penetration
EFS = 0.04

Rebound
EFS = 0.05



Comparison of matrix damage