Simulating High Energy Dynamic Impact of IM7/PEKK Continuous Fiber Laminated Thermoplastic Composite using Open Hole Coupon Experiments

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American Society for Composites 39th Technical Conference
20th US-Japan Conference on Composite Materials
October 21st -24th San Diego, California

High Energy Dynamic Impact (HEDI)

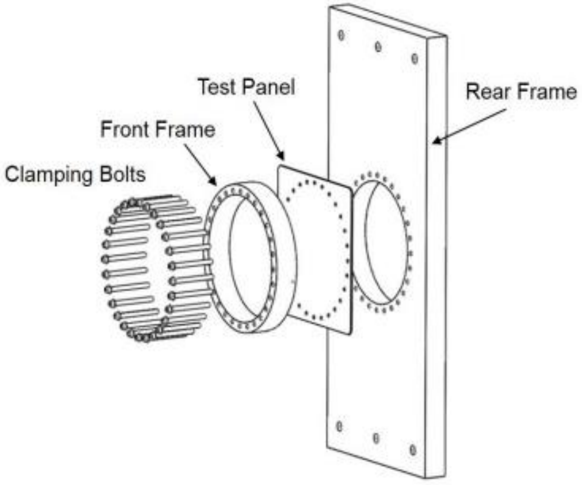
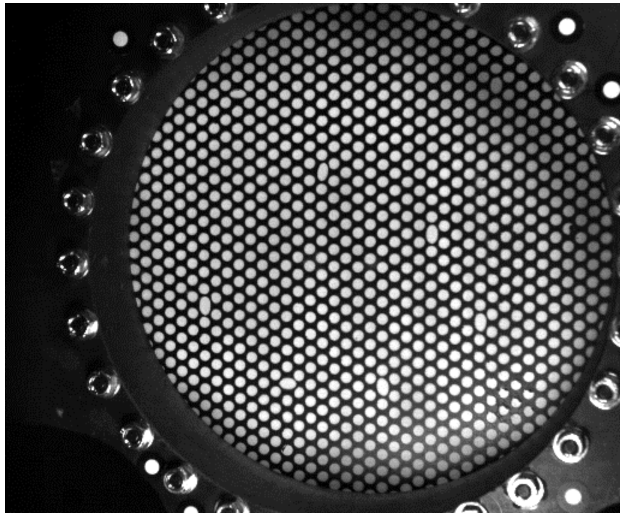


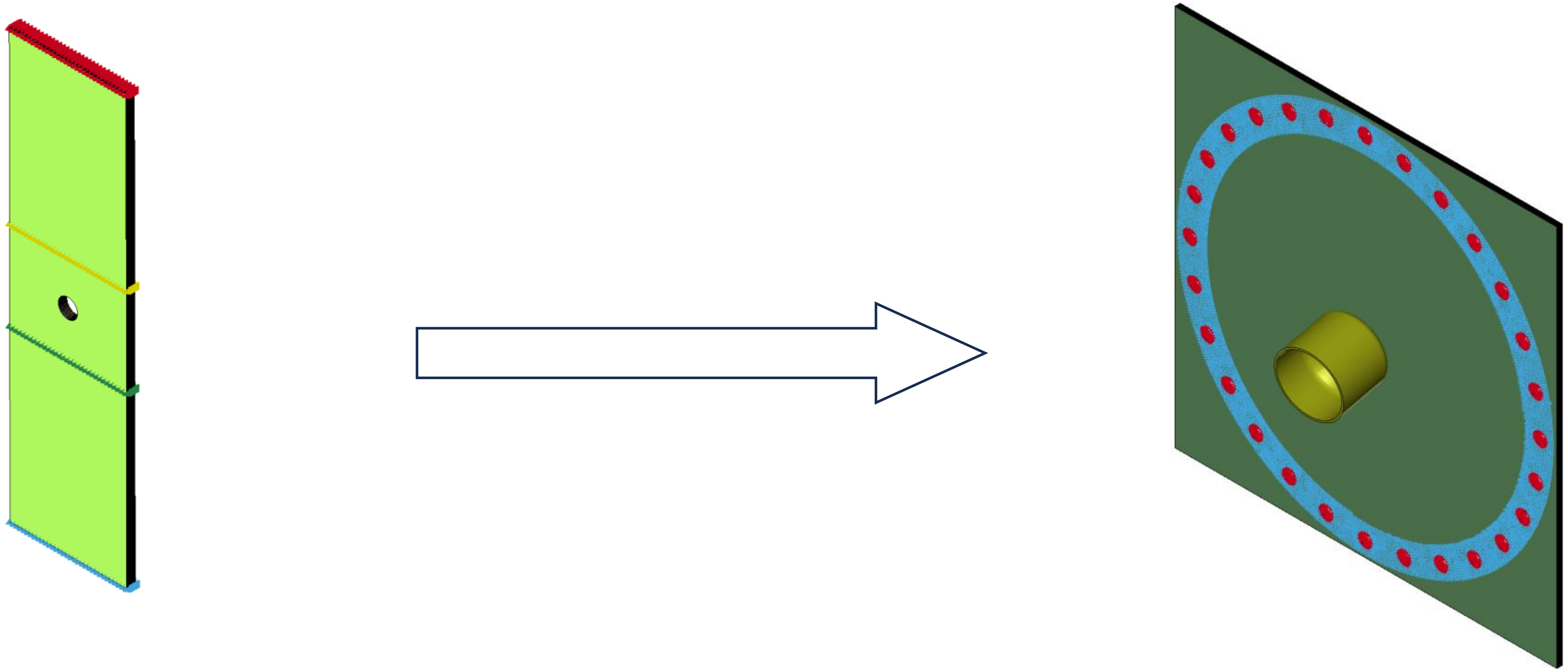
Figure 1. Test Fixture for 12" x 12" flat panels



High Energy Dynamic Impact Response is crucial for aircraft safety and certification.

Verification

Validation



Objectives

- Improved predictions and validation at panel level
- Verification at laminate notched coupon level

Composite Material Modeling Challenges

- Anisotropy and complex failure modes [1,2].

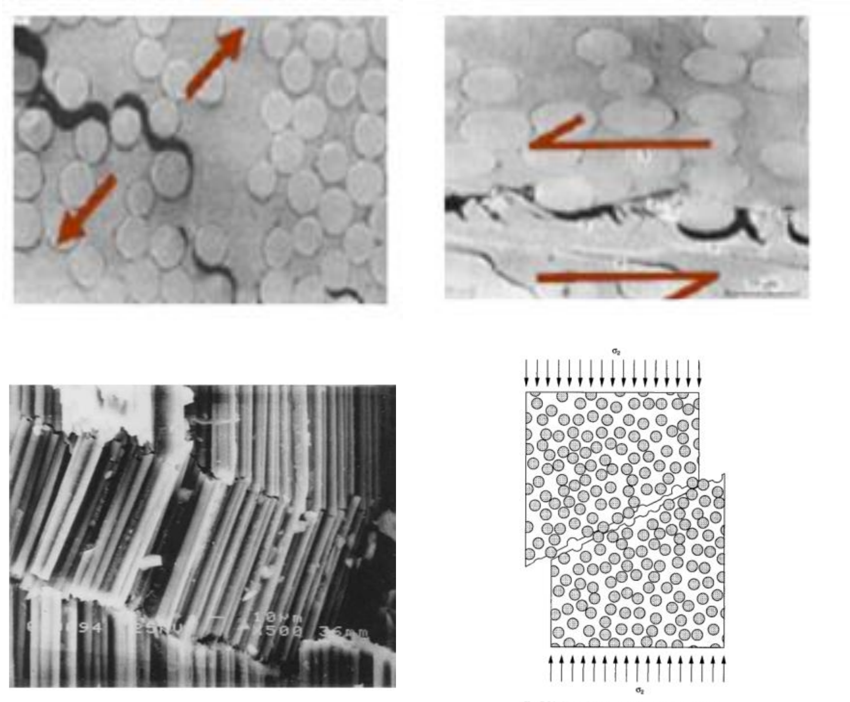
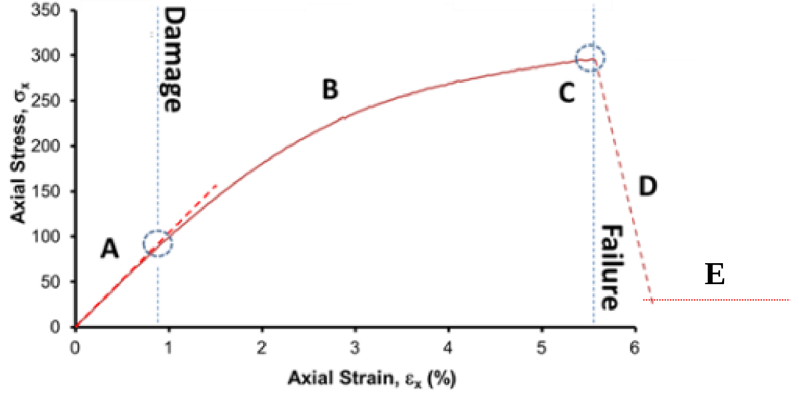
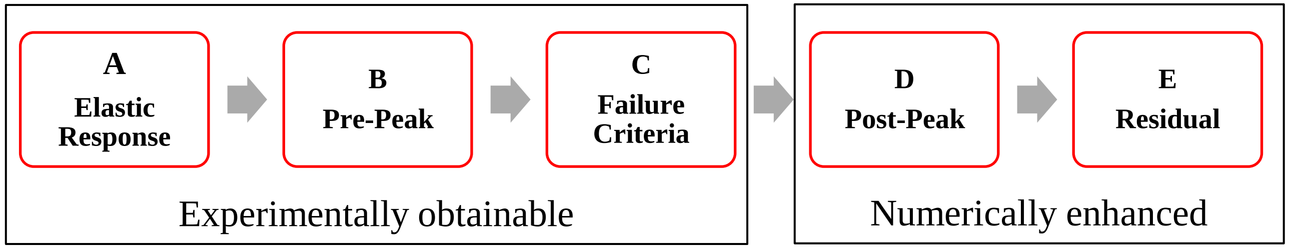


Fig. 5.26 Shear failure mode in unidirectional composite under transverse compression.





A
Elastic Response

B
Pre-Peak

C
Failure Criteria

D
Post-Peak

E
Residual

Experimentally obtainable

Numerically enhanced

Figure. Advanced Composite Material Stress-Strain Response. Modified from [3] to include residual in MAT213.

[1] Rabiee, A., & Ghasemnejad, H. (2017). Progressive crushing of polymer matrix composite tubular structures.
[2] Daniel, I. M., & Ishai, O. (2006). Engineering Mechanics of Composite Materials.
[3] Wanthal, Steven, et al. "Verification and validation process for progressive damage and failure analysis methods in the NASA Advanced Composites Consortium." American Society for Composites (ASC) Technical Conference. No. NF1676L-26362. 2017.

Outline

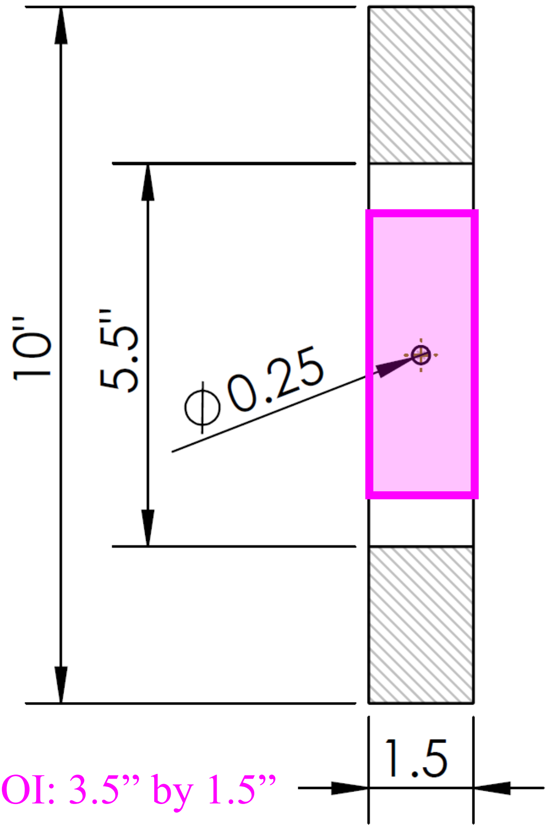
- **Open Hole Tension (OHT) Experiments**
- **Composite Material Modeling Inputs**
- **Numerical Results**
  - **OHT**
  - **HEDI**
- **Conclusions and future work**

Open Hole Tension Experimental Setup

- Material: IM7/PEKK continuous fiber tape
- Testing using Instron load frames at quasi-static room temperature (QSRT) loading.
- ASTM D5766
  - Specimen width to hole ratio = 6
- Digital Image Correlation (DIC)
  - Vic3D

Table 1. Thermoplastic notched composite test matrix

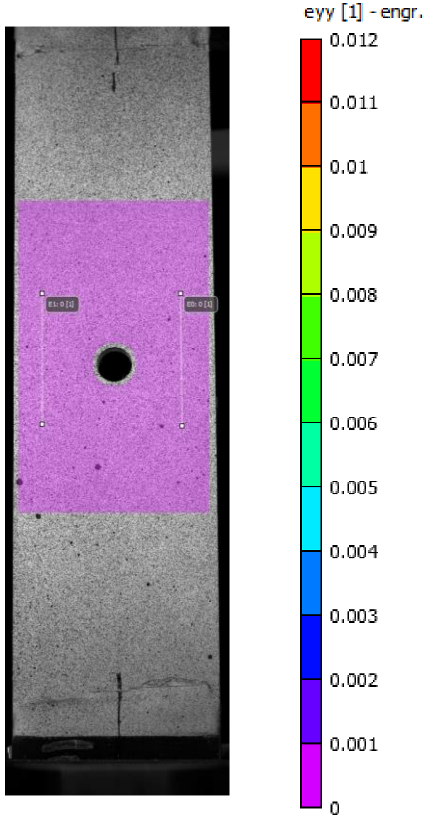
Material	Layup	Specimens
IM7/PEKK	$[0]_{16}$	4
	$[90/0]_{3s}$	5
	$[+45/0/-45/90]_{2s}$	5

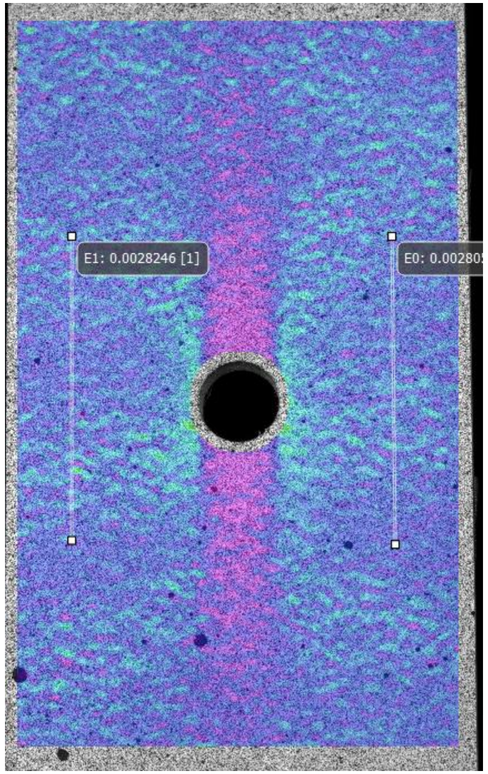


3D DIC AOI: 3.5” by 1.5”

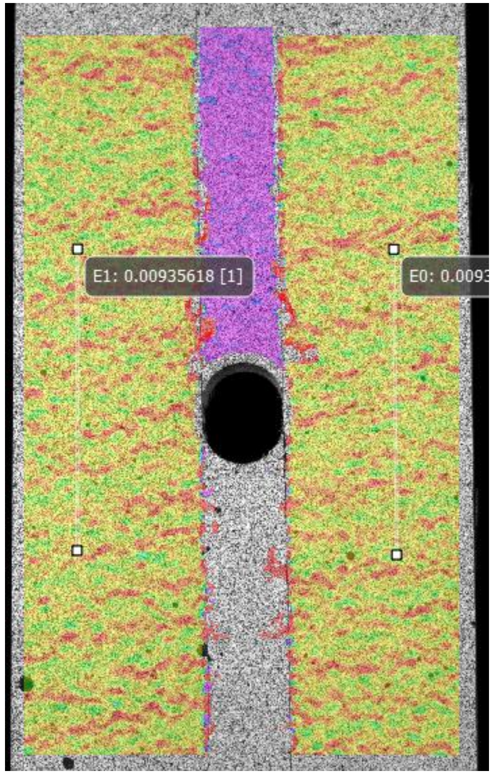
Figure. Open Hole Tension Specimen Geometry where the hatched area shows gripping area and maroon area shows DIC area of interest.

Open Hole Tension Experimental Results

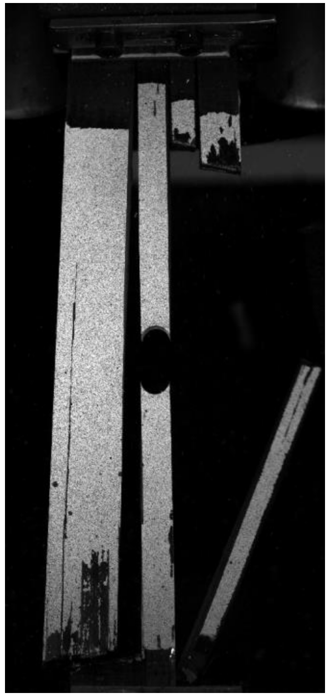




Axial Stain 25% peak load



Axial Stain 75% peak load

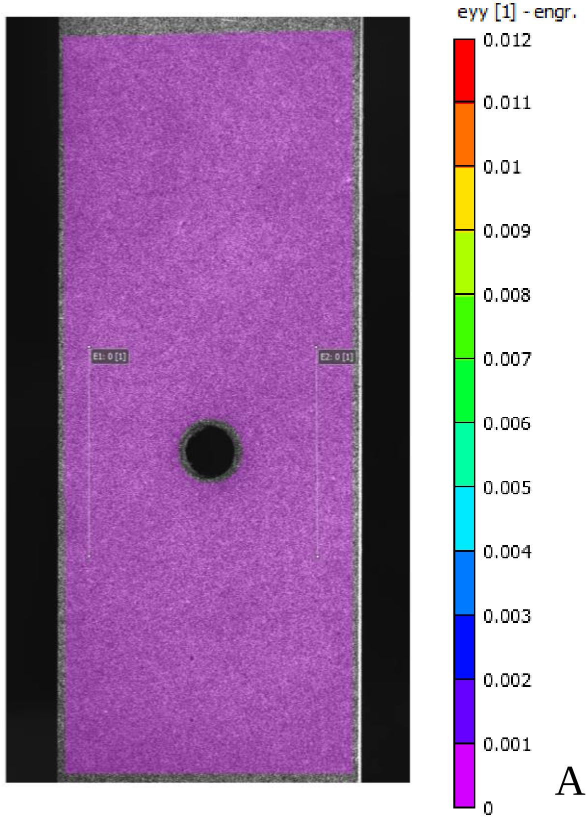


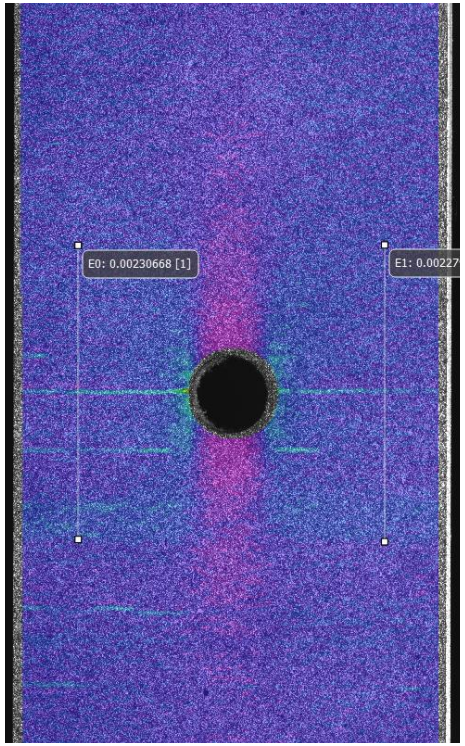
Post-test images

Layup	σ_0, Un-notched Strength	σ_N, Notched Strength	σ_0/σ_N
$[0]_{16}$	400.17+/- 5.60 ksi	255.60 +/- 3.21	0.6387

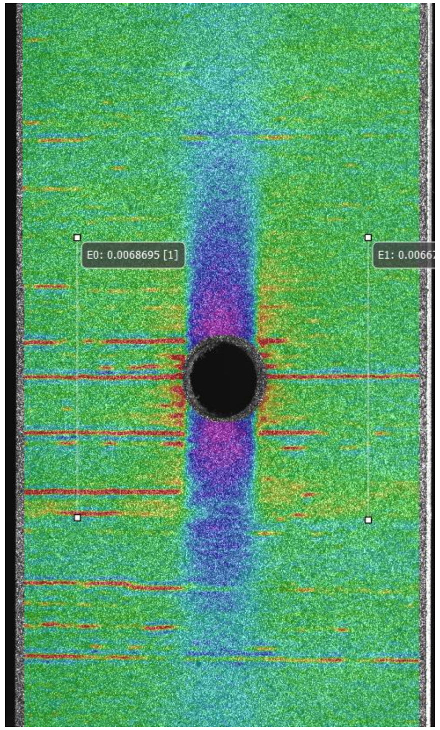
Open Hole Tension Experimental Results

Loading Direction

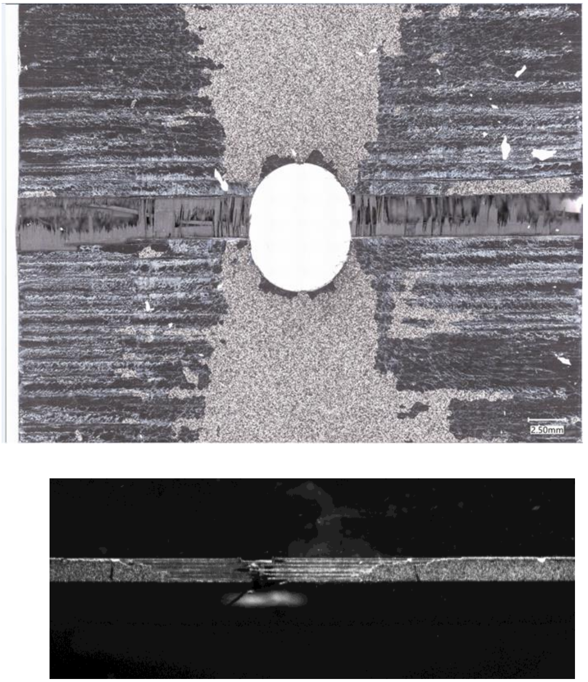




Axial Stain 25% peak load



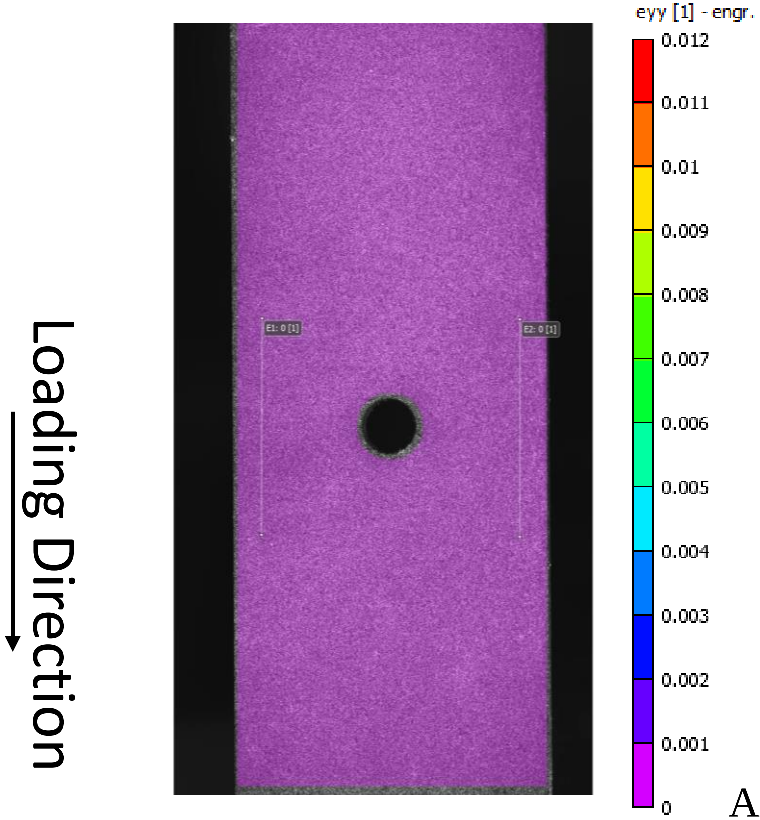
Axial Stain 75% peak load

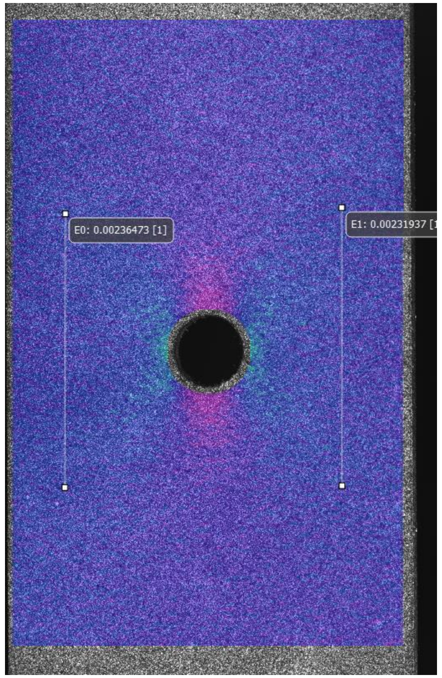


Post-test images

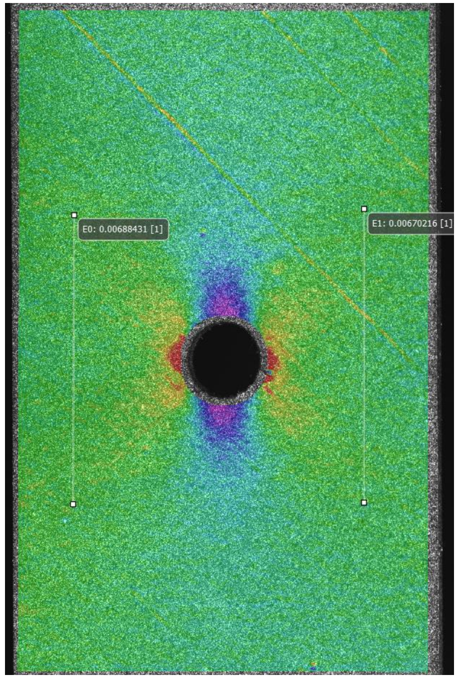
Layup	σ_0, Un-notched Strength	σ_N, Notched Strength	σ_0/σ_N
$[90/0]_{3s}$	N/A	143.06 +/- 5.70	N/A

Open Hole Tension Experimental Results

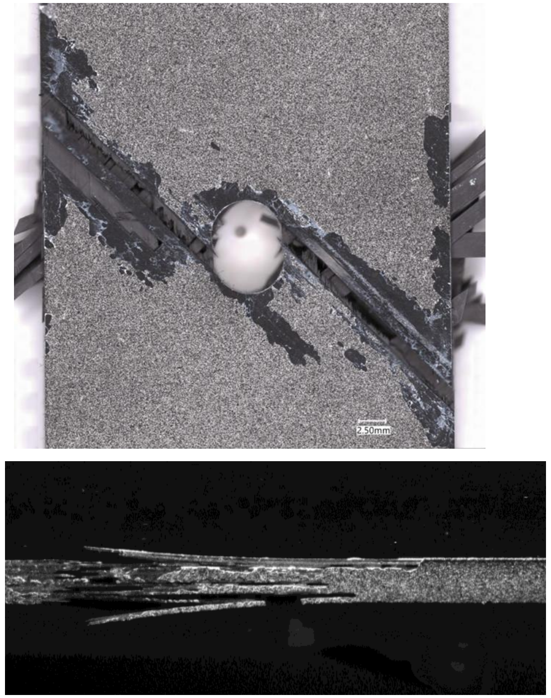




Axial Stain 25% peak load



Axial Stain 75% peak load



Post-test images

Layup	σ_0, Un-notched Strength	σ_N, Notched Strength	σ_0/σ_N
$[+45/0/-45/90]_{2s}$	105.68 +/- 4.51	70.15 +/ 2.33	0.667

OHT Experiments | Composite Material Modeling Inputs | OHT Simulations | HEDI Simulations

Finite Element Modeling Approach

- Ply-by-ply modeling approach using LS-DYNA
  - Fully integrated “thin” shells with 3 integration pts. through the thickness per ply.
- Inter-ply behavior for delamination (cohesive zone contact)
  - Peak tractions calculate following Turon et. al 2008. [5]
- Intra-ply behavior MAT_213
  - Tabular input orthotropic plasticity material model
    - Tension 1-direction and 2-direction, Compression 1-direction and 2-direction, Shear 12-plane

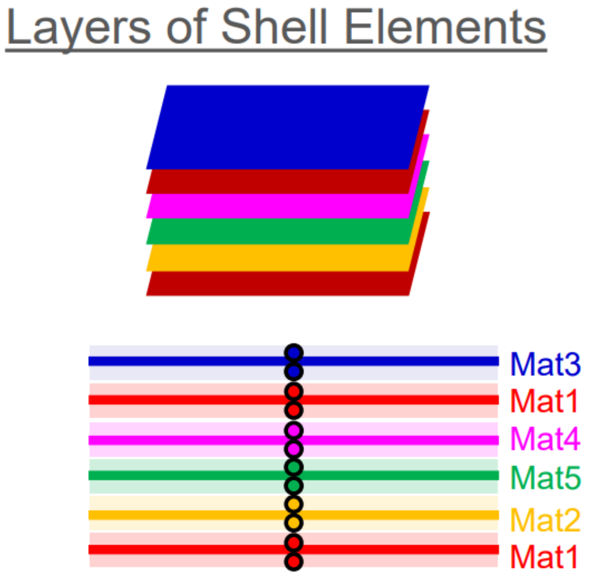


Figure. Illustration of ply-by-ply composite modeling using layers of thin shell elements [4].

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[4] Introduction to Composites Modelling in LS-DYNA Slide 20. https://www.oasys-software.com/dyna/wp-content/uploads/2019/03/6_Composites_Modelling_LS-DYNA_Galal-Mohamed-IN.pdf

[5] Turon, A., Davila, C. G., Camanho, P. P., & Costa, J.: An engineering solution for mesh size effects in the simulation of delamination using cohesive zone models. Engineering fracture mechanics, 74(10), 1665-1682 (2007).

Composite Material Mechanical

- Quasi-static room temperature (QSRT) testing using 2D DIC [6,7].
  - Tension: ASTM D3039
  - Compression: ASTM D6641
  - Shear: ASTM D5379
- Interlaminar fracture tests following ASTM D5528 and D7905 for Mode I and II, respectively.

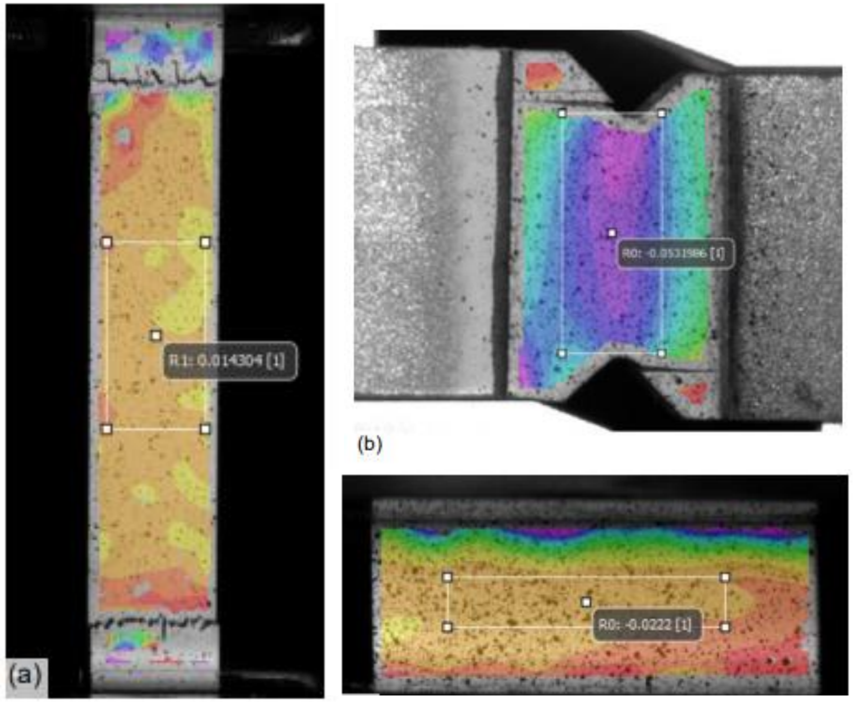


Figure. Typical (a) tension specimens, (b) shear specimens, (c) compression specimens [6].

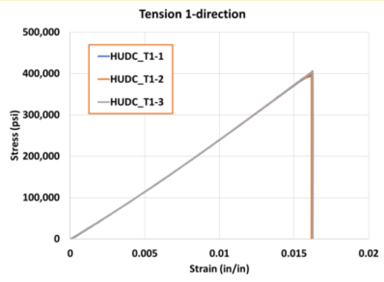
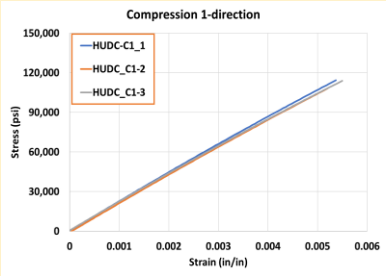
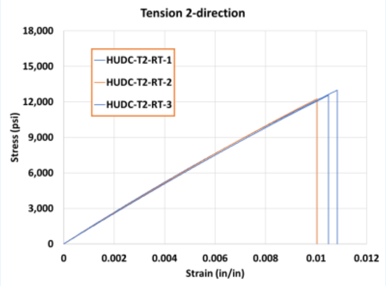
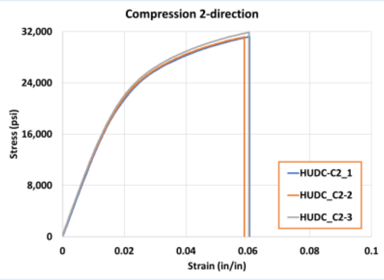
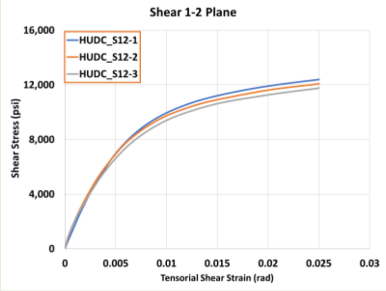
Table . Experimental Fracture Coupon Mechanical Properties Summary

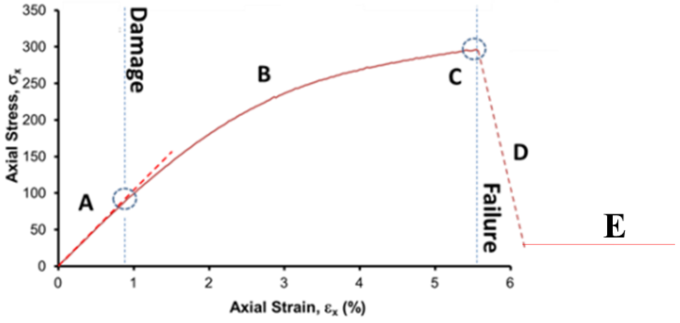
Fracture	Layup	a_0 (mm)	P_c (kN)	G (kJ/m^2)
DCB	$[0]_{16}$	48	0.177	0.777
ENF	$[0]_{16}$	30	1.490	1.745

[6] Khaled, Bilal. "Experimental Characterization and Finite Element Modeling of Composites to Support a Generalized Orthotropic Elasto-Plastic Damage Material Model for Impact Analysis." PhD diss., Arizona State University, 2019.

[7] Maurya, Ashutosh, Seetha Pavan Tanneru, Subramaniam Rajan, J. Michael Pereira, and Sandi G. Miller. *Experimental Tests to Characterize the Behavior and Properties of IM7-8552 Composite*. No. E-20097. 2023.

Composite Material Modeling Inputs

Curve ID	T1	C1	T2	C2	S12
Experimental Curve					

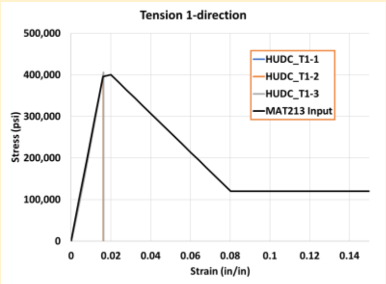
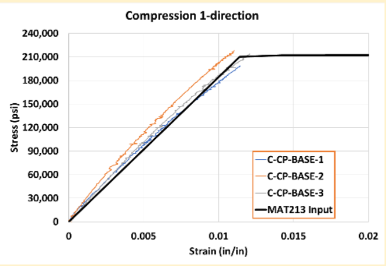
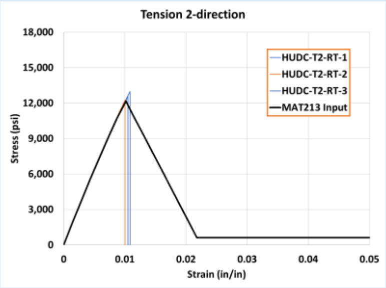
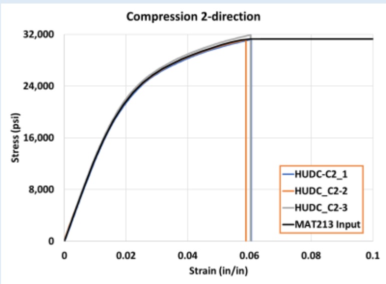
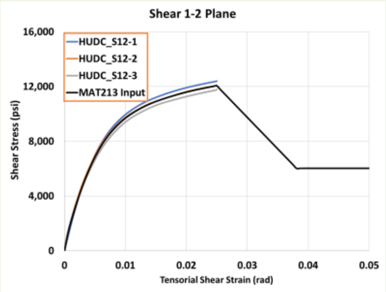


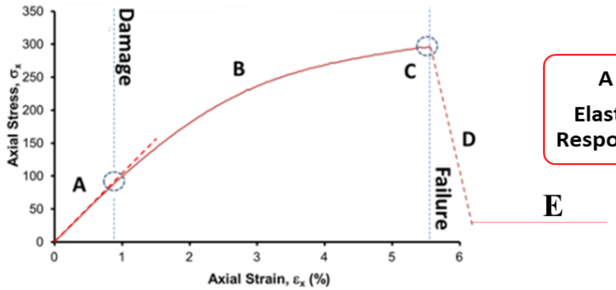
A **Elastic Response** → **B** **Pre-Peak** → **C** **Failure Criteria** → **D** **Post-Peak** → **E** **Residual**

Experimentally obtainable

Fiber Dominant
Matrix Dominant
Shear Dominant

Composite Material Modeling Inputs

Curve ID	T1	C1	T2	C2	S12
Model Curve					
Energy, Γ	**CT [9]**	**-**	**DCB**	**-**	**ENF**
Residual	**0.7**	**-**	**0.95**	**-**	**0.5**



A **Elastic Response** → **B** **Pre-Peak** → **C** **Failure Criteria** → **D** **Post-Peak** → **E** **Residual**

Numerically enhanced

Failure (linear post peak slope) using energy-based degradation [8,9].

$$\varepsilon^f = \varepsilon^0 + \frac{2\Gamma}{\sigma^0 L}$$

[8] Shyamsunder, L., Khaled, B., Rajan, S. D., & Blankenhorn, G.: Improving failure sub-models in an orthotropic plasticity-based material model. Journal of Composite Materials, 55(15), 2025-2042 (2021).

[9] Ricks, T.M., Goldberg, R.K. And Pereira, J.M.: High-Energy Dynamic Impact Modeling of an AS4D/PEKK-FC Composite Using LS-DYNA MAT_213. In: Proceedings of the American Society for Composites-Thirty-Eighth Technical Conference (2023).

OHT Simulation Background

- Element size (0.06”) kept consistent for coupon and impact simulations

- A fiber aligned mesh in which the finite element mesh is aligned along the fiber direction of the material which has been seen to improve the accuracy of predicting damage in unidirectional fiber reinforced composites.

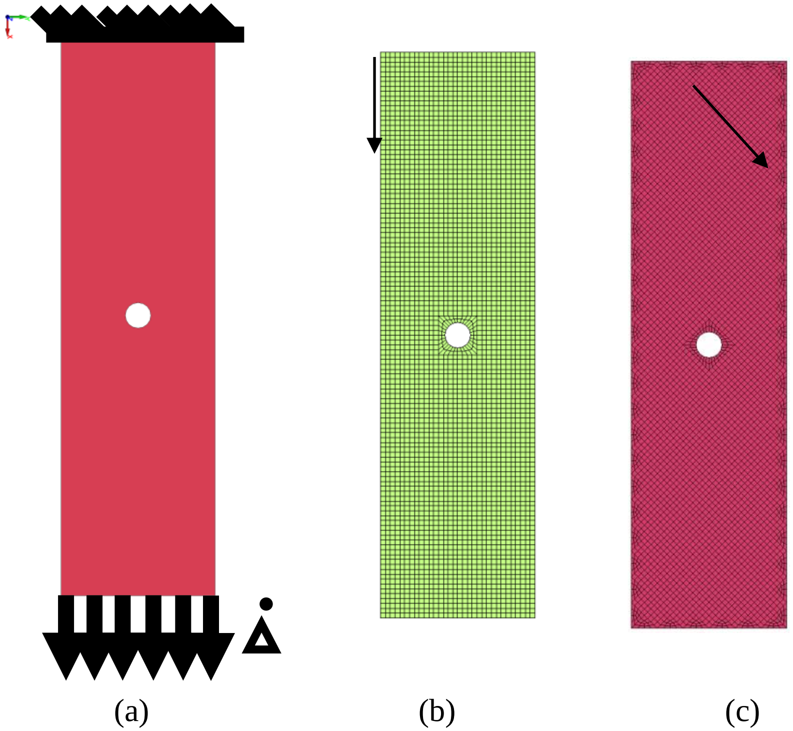
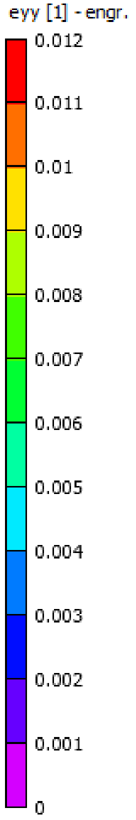


Figure. Open Hole Tension illustration showing (a) boundary conditions and (b) mesh for 0 degree and 90 degree plies and (c) mesh for +45 degree ply and -45 degree ply

OHT Simulation Results



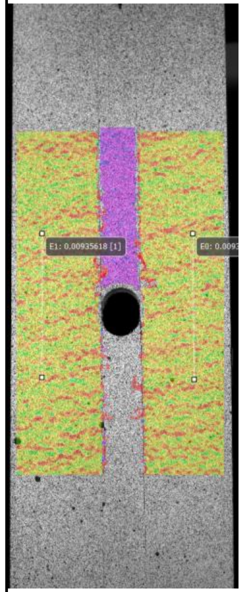
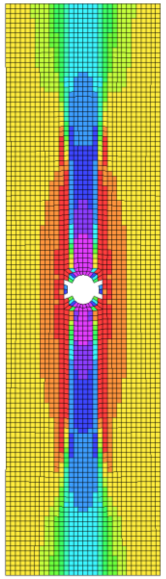
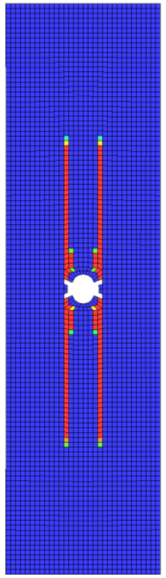
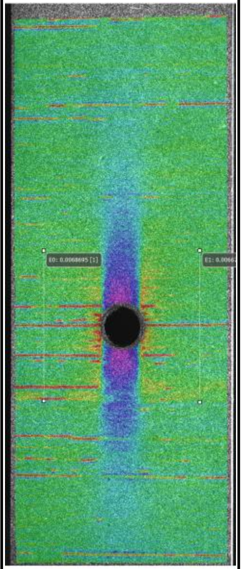
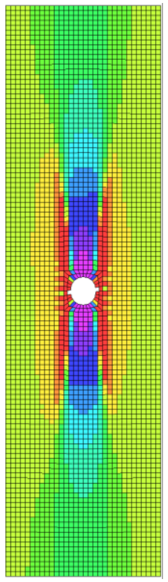
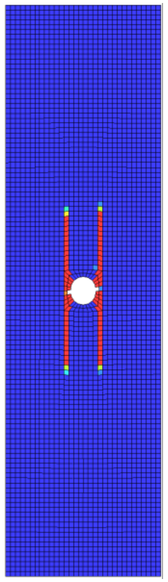
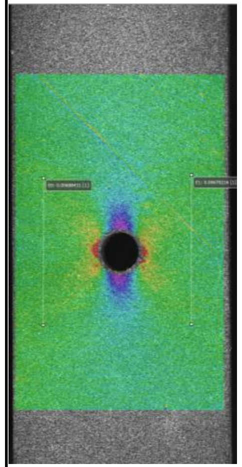
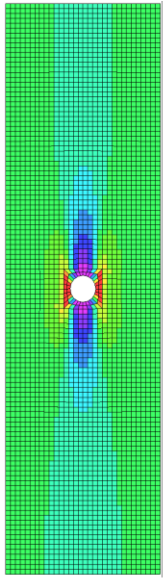
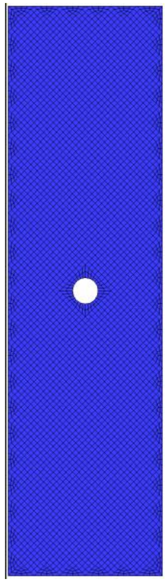
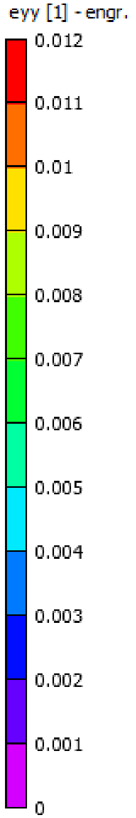
	$[0]_{16}$			$[90/0]_{3s}$			$[+45/0/-45/90]_{2s}$		
	Experimental Strain	Simulation Strain	Simulation HV#18	Experimental Strain	Simulation Strain	Simulation HV#18	Experimental Strain	Simulation Strain	Simulation HV#18
75% Peak Strength									

Figure. Failure pattern comparison of DIC axial strain contours of the continuous fiber IM7/PEKK open hole coupons experiments with simulation failure at 75% peak force. HV#18 represents shear damage with blue showing no damage, green showing post-peak and red showing fully failed.

OHT Simulation Results



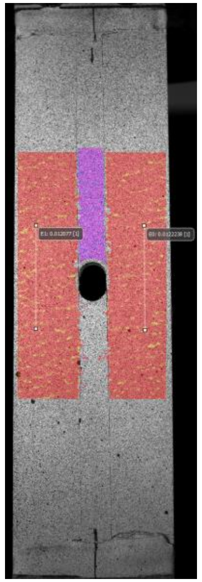
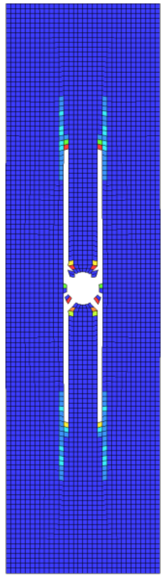
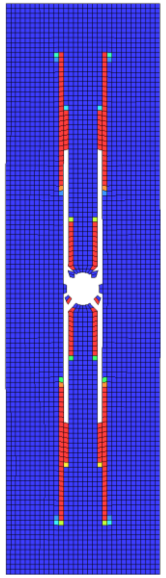
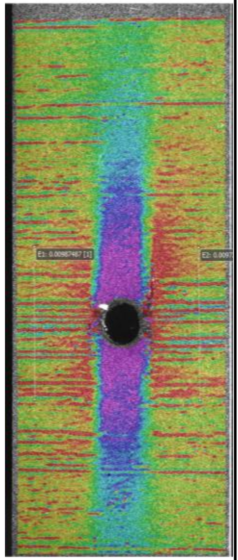
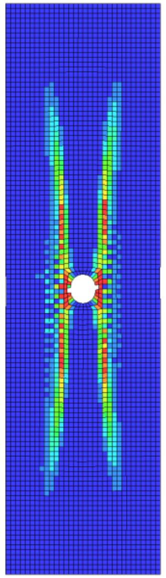
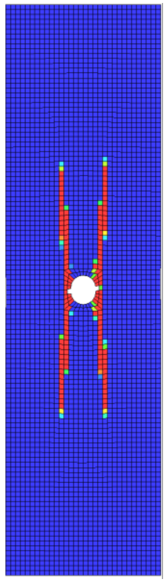
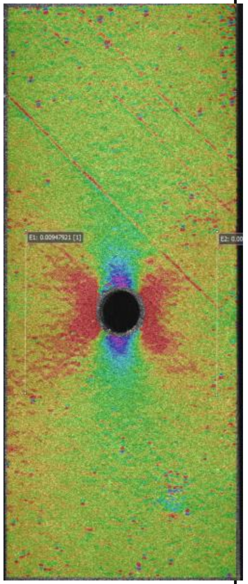
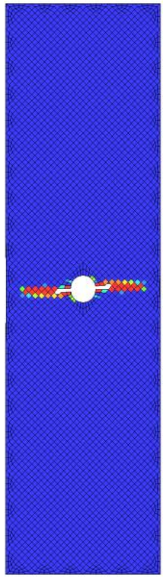
	$[0]_{16}$			$[90/0]_{3s}$			$[+45/0/-45/90]_{2s}$		
	Experimental Strain	Simulation HV#15	Simulation HV#18	Experimental Strain	Simulation HV#15	Simulation HV#18	Experimental Strain	Simulation HV#15	Simulation HV#18
Peak Strength									

Figure. Failure pattern comparison of DIC axial strain contours of the continuous fiber IM7/PEKK open hole coupons experiments with simulation failure at peak force. HV#15 is represents matrix tension damage and HV#18 represents shear damage with blue showing no damage, green showing post-peak and red showing fully failed.

OHT Simulation Results

- In-plane shear stress-strain curve
  - ASTM D3518: +/-45 off-axis shear
  - ASTM D5379: v-notch beam
- Better correlation using v-notch
  - Reduced +/- 45 ply response
  - Shear damage observed in $[0]_{16}$ experiments.

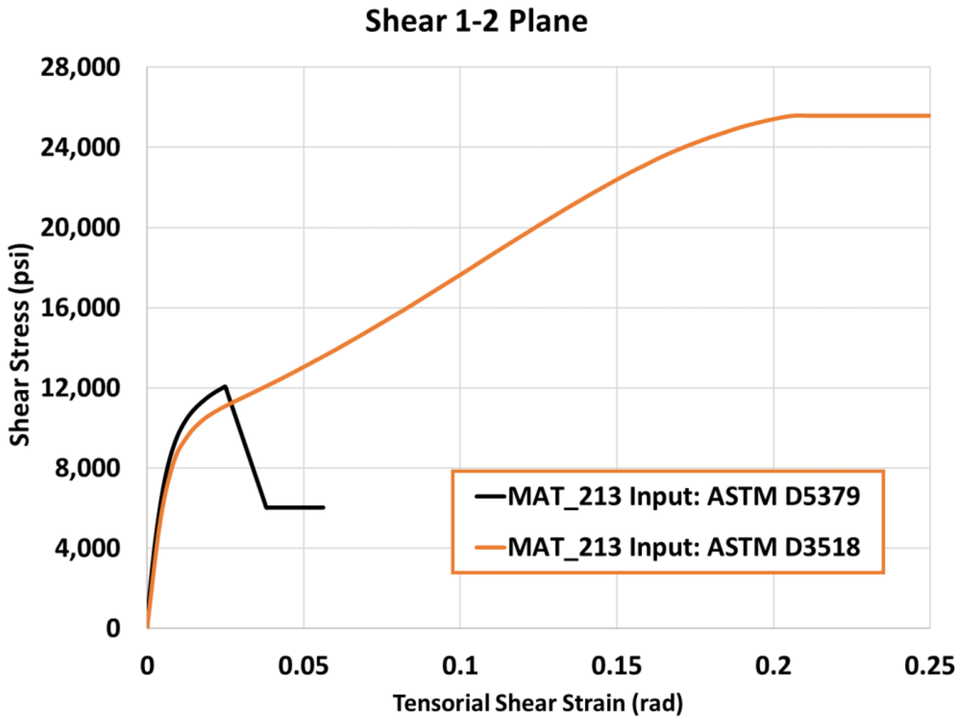
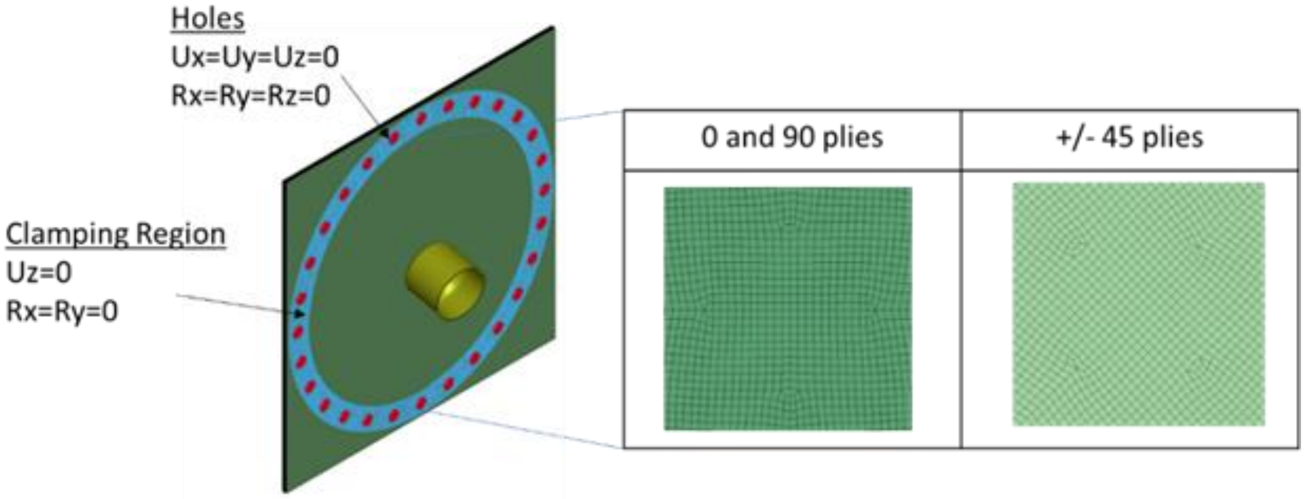


Table. Comparison of experimental and simulated open hole tension coupons

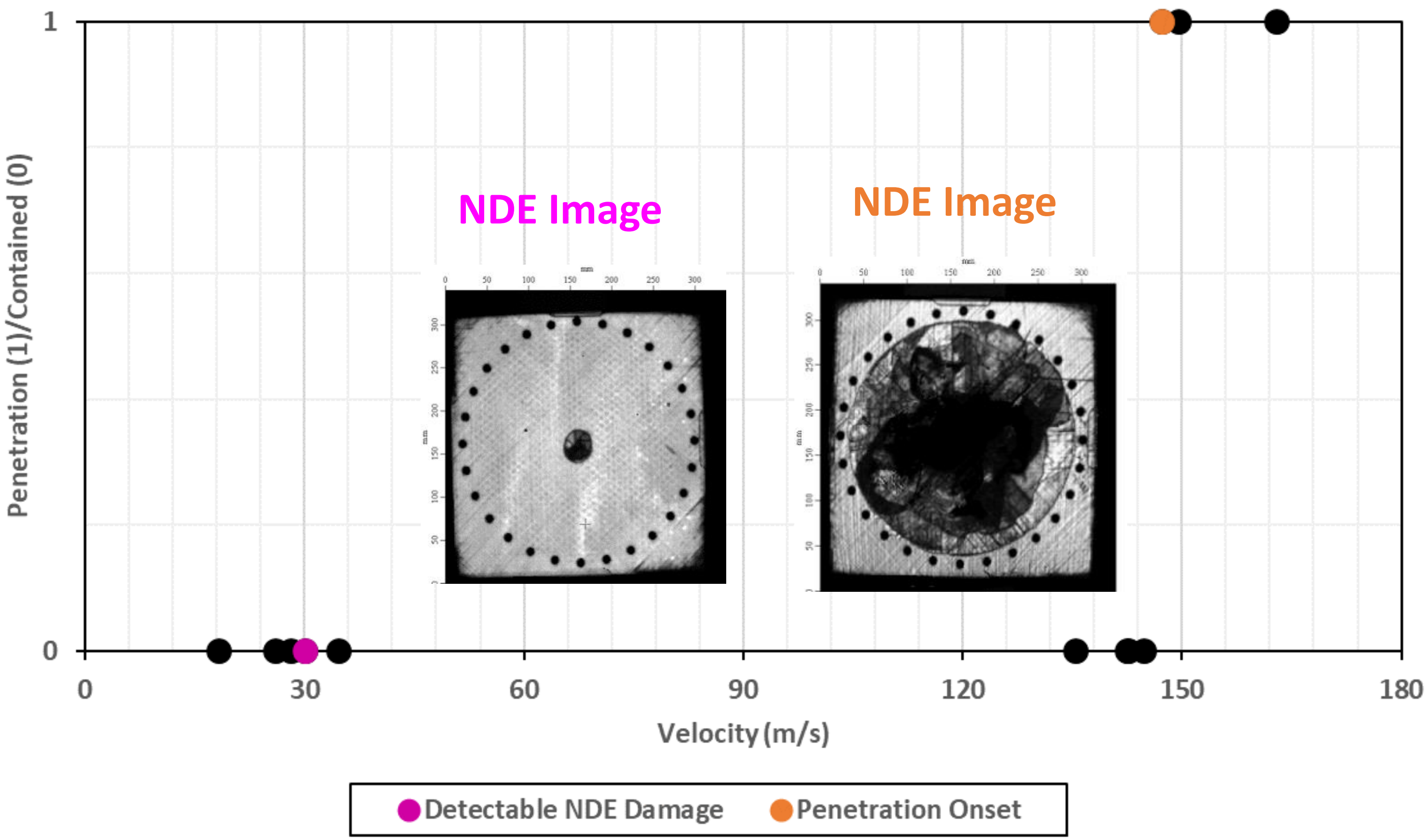
Layup	Notched Strength, (MPa)	Simulation Shell- ASC paper	Simulation Shell-update
$[0]_{16}$	1762 ± 22	1642	1720
$[90/0]_{3s}$	658 ± 26	779	764
$[+45/0/-45/90]_{2s}$	484 ± 16	543	476

HEDI Simulation Background

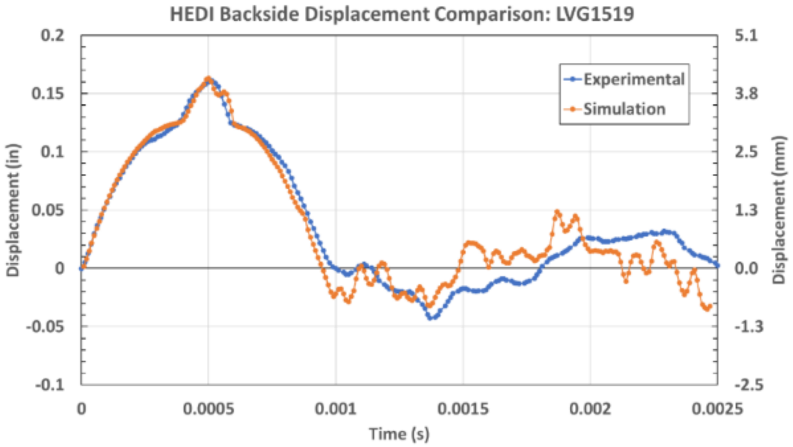
- Element size (~0.06”) kept consistent for coupon and impact simulations
- Layup: $[+45/0/-45/90]_{3s}$

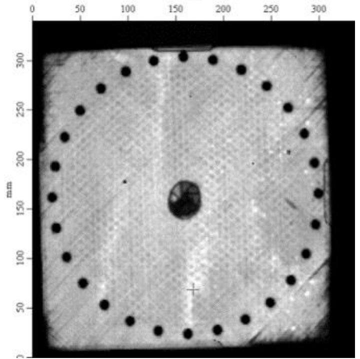
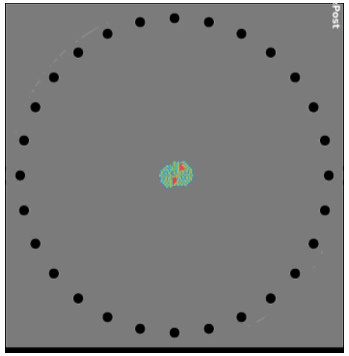


HEDI Experimental Results Summary for IM7/PEKK following ASTM D8101/D8101M



HEDI Simulation Results: Low Velocity



LVG1523: 30 m/s	
Experiment	Simulation
	

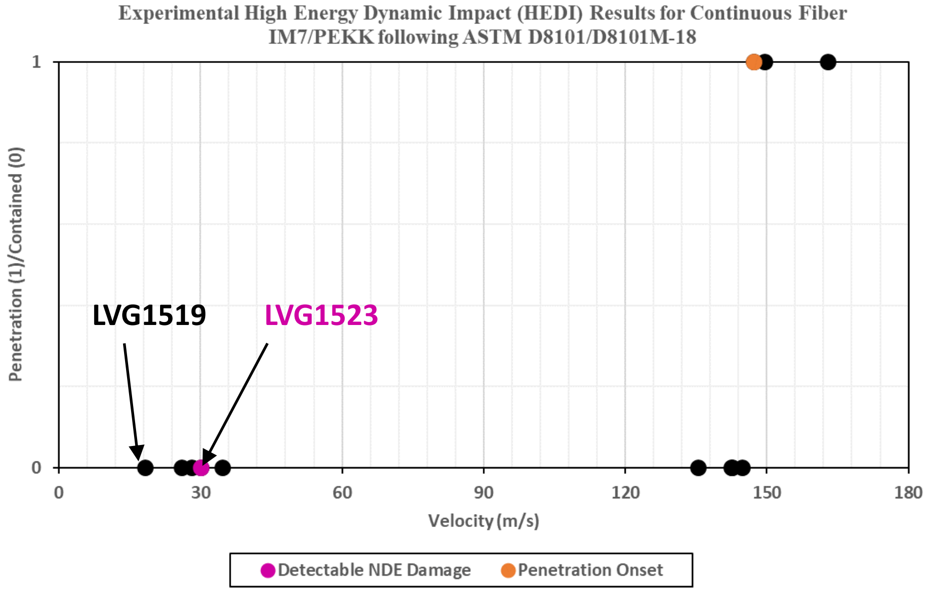
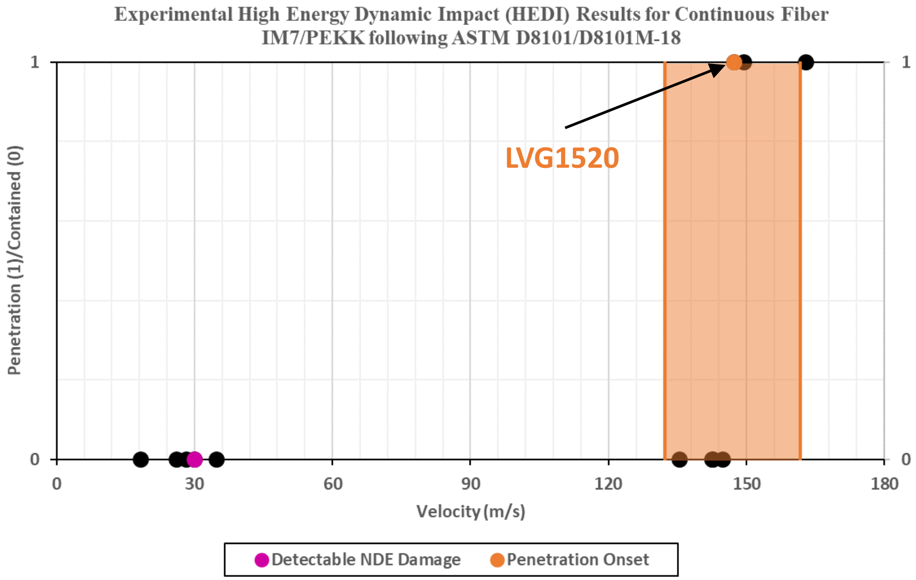


Table. Comparison of experimental and simulated HEDI rebound Velocity

Label	Experimental (m/s)	Simulation (m/s)
LVG1519	-14.3	-16.6
LVG1523	-23.3	-26.4

HEDI Simulation Results: High Velocity

- Penetration threshold found to be sensitive to erosion value.
- Calibration shows good correlate experiments within 10% of penetration threshold.
- Delamination in simulation underpredicted



Shaded area Penetration Threshold: ± 10%

<table>
<tr><th colspan="2">LVG1520: 147 m/s</th></tr>
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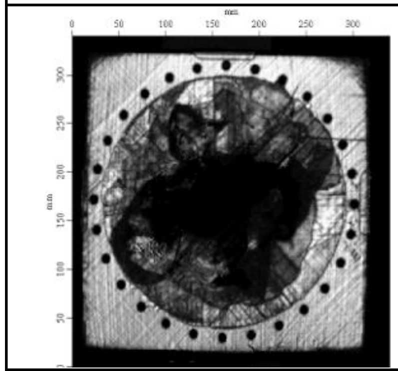
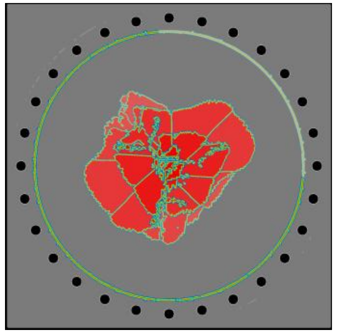
<tr><td></td><td></td></tr>
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Table. Comparison of experimental and simulated HEDI exit velocity

Label	Experimental (m/s)	Simulation (m/s) Erode = 0.24	Simulation (m/s) Erode = 0.27
LVG 1520	+11.2	+48.6	+17.4
10% Below	N/A	+16.3	-9.5

Conclusions

- OHT simulations using MAT_213 matched experimental strengths within 5% for $[0]_{16}$ and $[+45/0/-45/90]_{2s}$. Simulation of $[90/0]_{3s}$ overpredicted response 16%.
- In-plane shear curve using v-notched stress-strain improved simulation strengths.
- Impact simulations at lower velocities showed good correlation between experimental displacement and rebound velocity with no calibration needed.
- Higher velocity impacts required calibration of erosion strain to correlate penetration threshold and rebound velocity. Delamination and damage underpredicted compared to experiment.
- Future work, includes applying methodology on other material systems (TuFF) and improve simulations using 3D solid or thick shell elements.

Acknowledgements

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The End!

Thank you!

Questions?