3D Reinforced Composites for Improved Impact Resistance in Spacesuits

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Overview

- Background and Innovation
- 3D Reinforced Materials Fabricated
- Property Characterization Tests
- Material Property Comparison
- Impact Model Approach and Validation
- Impact Drop Test Design Exploration
- Comparison of 3D Reinforced Materials to 2D Laminate at 280 J Impact
- Future Work

Background

NASA Phase I SBIR Solicitation:

At a high level, this subtopic and scope is soliciting development of advanced material solutions for EVA suits on the Martian and lunar surface. It seeks to address deficits with previous developments as it relates to impact resistance (damage tolerance), strength, environmental resistance, mass, and feasibility for use in a spacesuit application. Specific components of concern include the HUT, hard brief, and mobility elements such as bearings, disconnects, and other hard mobility joints. For this development, there are several characteristics of concern:

- Operating range -170°F to +170°F, considerations for thermal cycling and CTE of composite materials
- Impact resistance for structures: <0.5 LPM leakage after impact of 300 J (Goal: 600 J) at 4.3 psi
- Tensile strength

Expected TRL Range at Completion of the Project: 1 to 5

Desired Deliverables of Phase I and II:

- Research
- Analysis
- Prototype

a) Small Composite HUT

b) Small Aluminum HUT

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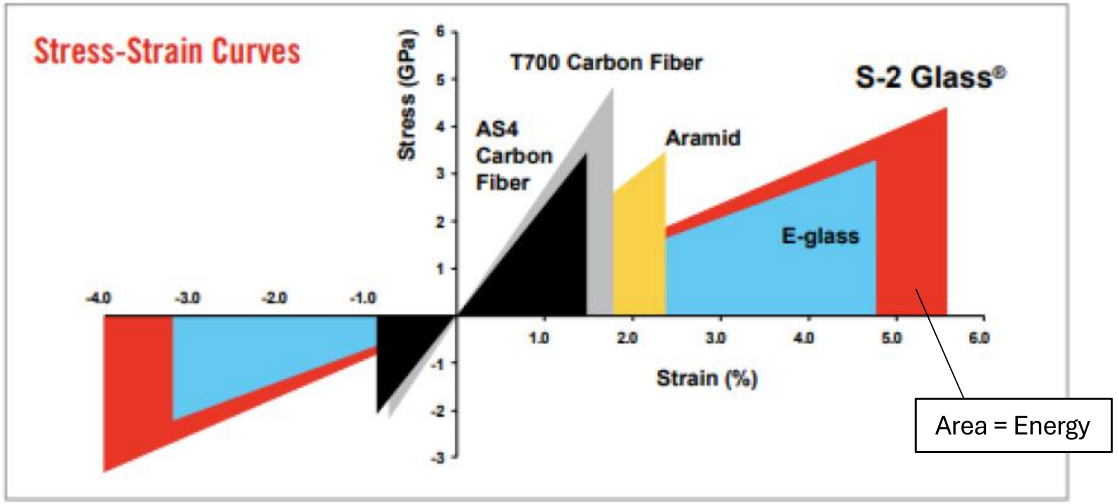
1. S. Yarlagadda et al, "Exploration Extra-Vehicular Mobility Unit (xEMU): Composite Hard Upper Torso (CHUT) Development", 52nd International Conference on Environmental Systems, July 2023.

Innovation

- Current CHUT state-of-the-art is a 2D laminate of S-2 glass with epoxy resin matrix without through-thickness reinforcement.
- This program investigated the capabilities of both 3D woven and 3D braided materials for improved impact strength and mass reduction.
- In-plane stiffnesses, strengths, and interlaminar shear strength used in Phase I to assess the ability to resist impact.
- Fiber: S-2 Glass, enhanced ability to absorb energy before failure (see plot to the right) compared to other reinforcement materials.

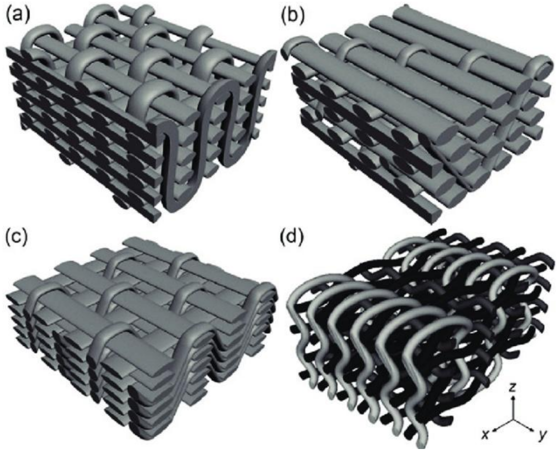
S-2 Glass Strain Energy



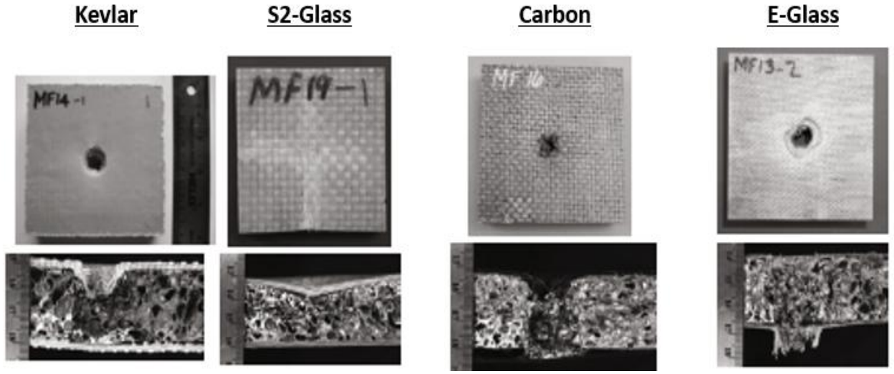
Area = Energy

S-2 Glass Composite Vehicle Armor Systems.pdf

3D Weave Example



2. Karaduman, Nesrin Şahbaz, et al. (2017). "Textile Reinforced Structural Composites for Advanced Applications." In Textiles for Advanced Applications, IntechOpen.



3. S. Abrate, Impact Engineering of Composite Structures, CSIM Courses and Lectures, Vol. 526. 2011.

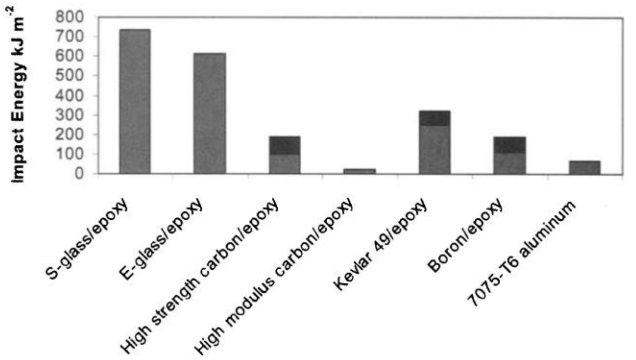


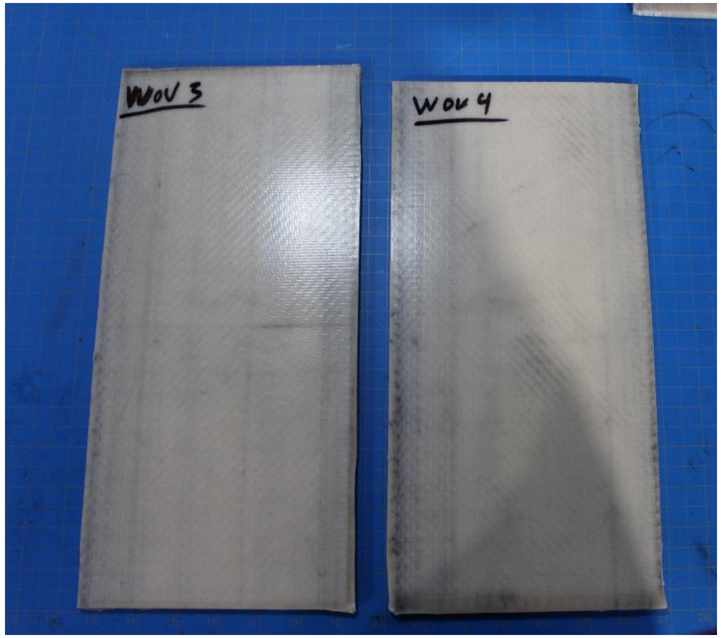
Fig 8.6 Charpy impact energy absorption of some composite and, for comparison, non-composite materials, as indicated.

4. A. Baker, S. Dutton, and D. Kelly, *Composite Materials for Aircraft Structures*, 2nd ed., Reston, VA: AIAA, 2004.

Materials Fabricated

- FMI Textiles provided MR&D with panels of multiple architectures
- Two panels (14 in x 6.75 in) of modified-layer-to-layer weave
- Two panels (14 in x 6.75 in) of 3D triaxial braid with a single layer (0.067 in thick)
- Two panels (14 in x 6.75 in) of 3D triaxial braid with four layers (0.27 in thick)
- All preforms densified with SC-15 epoxy via RTM
- SC-15 was recommended by FMI based on legacy use in composite armor applications

Woven Material



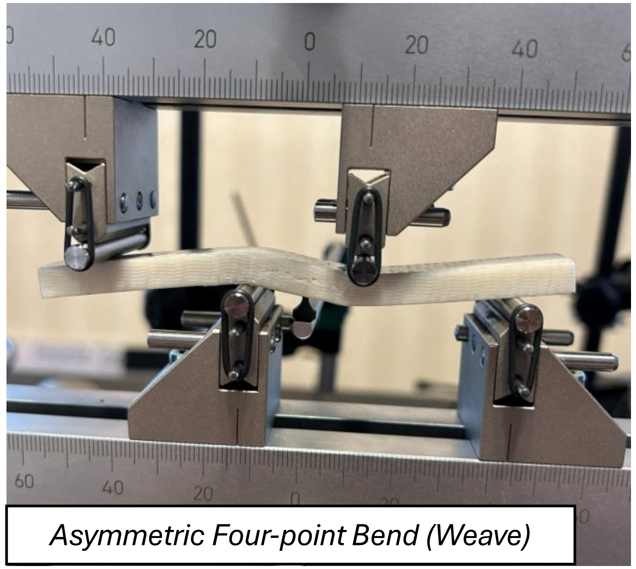
Braided Material

Material Property Characterization

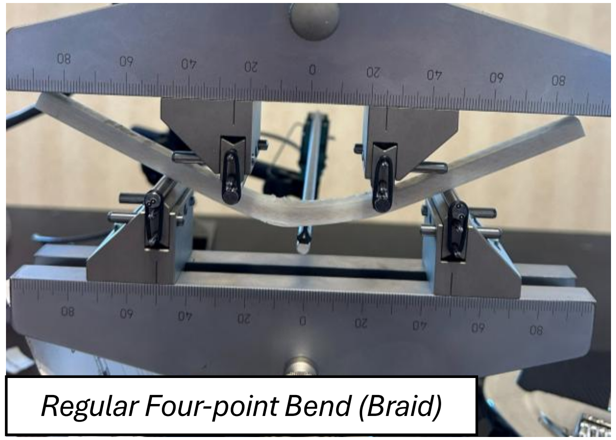
Test	Material	Thickness	Properties	Specimen #
In-Plane Tension	Weave	0.27”	σ_{11}, E_{11}	8
In-Plane Tension	Weave	0.27”	σ_{22}, E_{22}	8
Short-Beam Shear	Weave	0.27”	ILSS	8
Asymmetric Four-Point Bend	Weave	0.27”	ILSS	8
In-Plane Tension	Braid	0.27”	σ_{11}, E_{11}	4
In-Plane Tension	Braid	0.27”	σ_{22}, E_{22}	4
In-Plane Tension	Braid	0.07”	σ_{11}, E_{11}	4
In-Plane Tension	Braid	0.07”	σ_{22}, E_{22}	4
Four-Point Bend	Braid	0.27”	σ_{11}(Compression)	6
Short-Beam Shear	Braid	0.27”	ILSS	4
Short-Beam Shear	Braid	0.07”	ILSS	4
Asymmetric Four-Point Bend	Braid	0.27”	ILSS	4

**11-direction is warp direction in weave, axial direction in braid. 22-direction is fill direction in weave, in-plane transverse direction in braid*

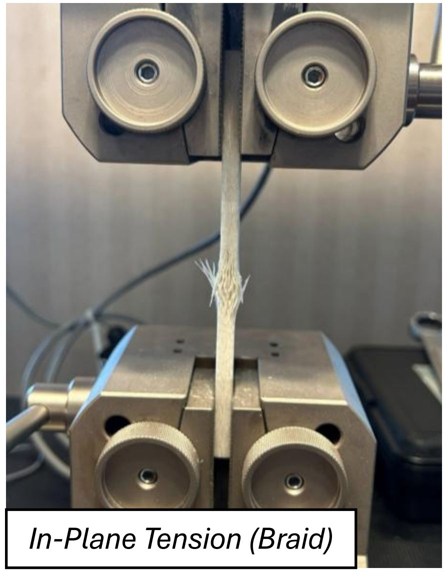
Material property characterization performed at MR&D



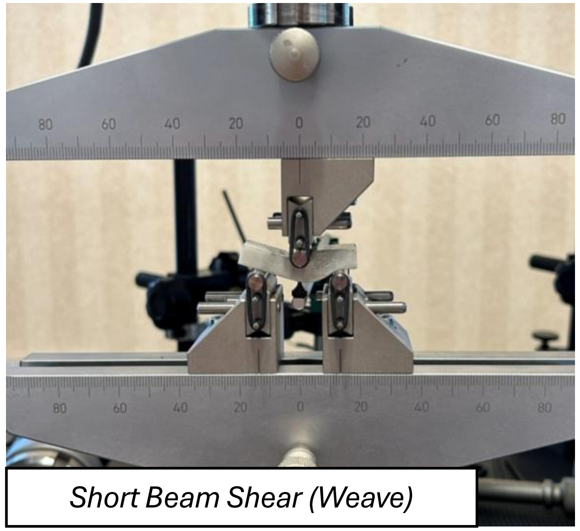
Asymmetric Four-point Bend (Weave)



Regular Four-point Bend (Braid)



In-Plane Tension (Braid)



Short Beam Shear (Weave)

MR&D

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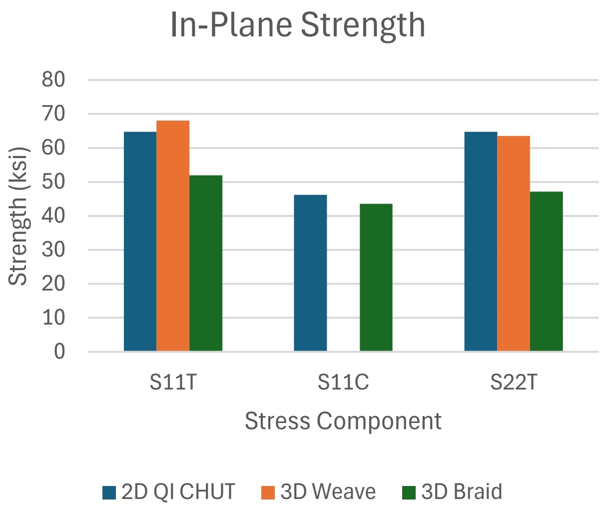
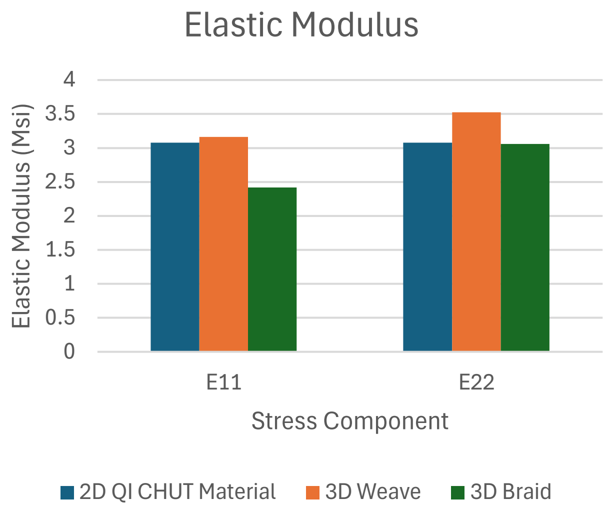
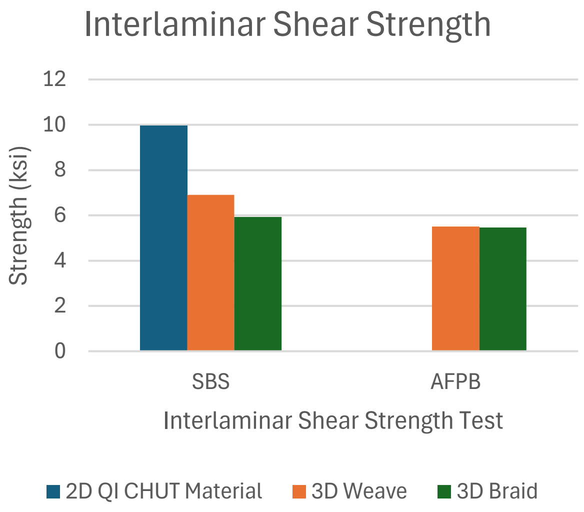
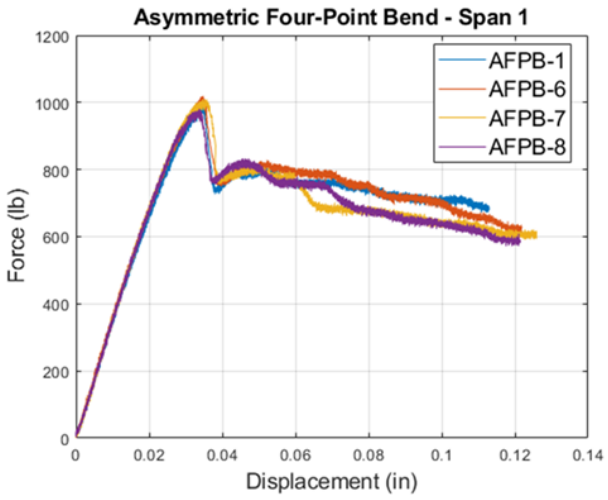
Material Comparison

- Shown to the right are comparisons of the measured material properties of the weave and the braid compared to the incumbent CHUT material.
- All properties are representative of the bulk composite properties in the CHUT (QI45 properties in the incumbent material).
- Woven material has comparable strength and stiffnesses to the 2D material. Braid has lower in-plane stiffness and strength.
- Neither material reached an ultimate ILS strength as high as the 2D material in short-beam shear. However, the woven material demonstrated the ability to continue to carry load without absolute failure occurring.
- The woven and braided material properties are used to model impact loading and compared to a 2D laminate of the same constituent materials to demonstrate the effect of the 3D reinforcement on impact resistance.


In-Plane Strength


Elastic Modulus

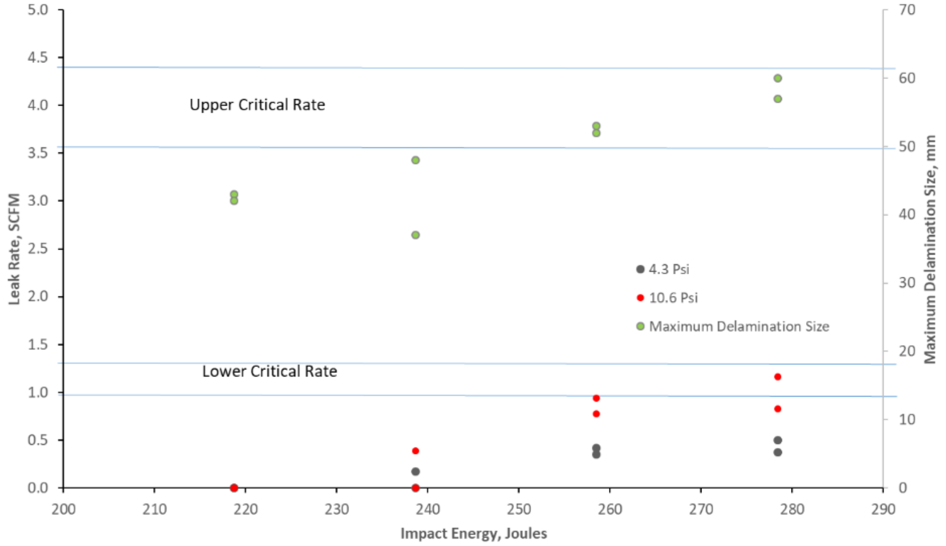

Interlaminar Shear Strength


Asymmetric Four-Point Bend - Span 1

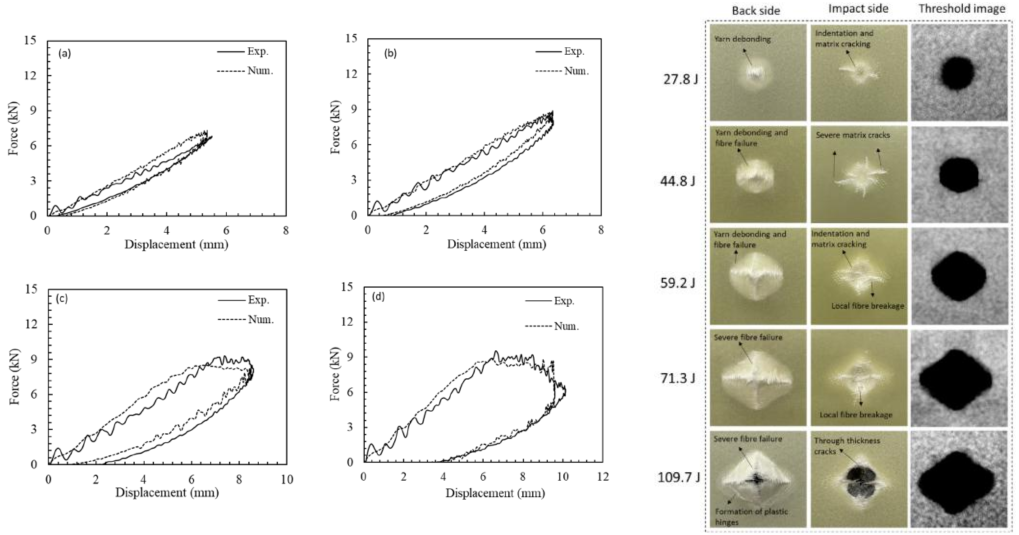
Impact Model Approach and Objectives

- MR&D did not possess detailed reports on the impact tests that produced the results for the incumbent material (S2-Glass / PMT-F4A).
- In lieu of this information, MR&D analytically demonstrated the benefits of across-ply reinforcement for low velocity impacts (LVI).
- The objectives were as follows:
    - Aggregate material properties from the open literature
    - Validate LVI model's response to experimental data (load-deflection, absorbed energy, etc.)
    - Extend the model to look at other impact configurations and higher energies
    - Modify the material model to represent 3D reinforced composites
    - Compare the analytical performances between 2D and 3D materials

ICES Paper from 2023[1]



Open Literature Example



5. Rezazefat, M., Kumar, Y., da Silva, A. A. X., Amico, S. C., Hogan, J. D., & Manes, A. (2023). "Dynamic Behavior and Permanent Indentation in S2-Glass Woven Fabric Reinforced Polymer Composites under Impact: Experimentation and High-Fidelity Modeling." Journal of Composites Science, 7(10), 430.

S-2 Glass / SC-15 Material Properties

- MR&D possesses an in-house developed User material (VUMAT) to simulate the dynamic behavior of composite materials for use in commercial finite element code Abaqus
- MR&D sourced material properties from the open literature to inform the LVI model
- Elastic constants and strengths were measured on QI45 laminates under quasi-static loading conditions[6]
- Rate dependent strengths were measured via Split-Hopkinson Pressure Bar testing[7]
- Damage progression terms are detailed in work performed by University of Delaware[8]

Rate Dependent Strength

$$\sigma_f = \sigma_0 \left(1 + A\, ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right)$$

Damage Progression

$$\omega = 1 - e^{\frac{1}{M}\left(1-\left(\frac{\varepsilon}{\varepsilon_f}\right)^{M}\right)}$$

QI45 S2/SC15 Elastic Constants[6]

E11	E22	E33	v12	v13	v23	G12	G13	G23
(Msi)	(Msi)	(Msi)	(-)	(-)	(-)	(Msi)	(Msi)	(Msi)
2.17	2.17	1.43	0.279	0.167	0.167	1.43	0.75	0.75

QI45 S2/SC15 Strengths[6]

S11T	S11C	S22T	S22C	S33T	S33C	S12	S13	S23
(ksi)	(ksi)	(ksi)	(ksi)	(ksi)	(ksi)	(ksi)	(ksi)	(ksi)
47.57	36.02	47.57	36.02	3.26	82.96	30.41	3.97	3.97

QI45 S2/SC15 Rate Dependent Strength Coefficients[7]

A11T	A11C	A22T	A22C	A33T	A33C	A12	A13	A23
(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
0.20	0.20	0.20	0.20	0.13	0.13	0.20	0.13	0.13

QI45 S2/SC15 Damage Progression Coefficients[8]

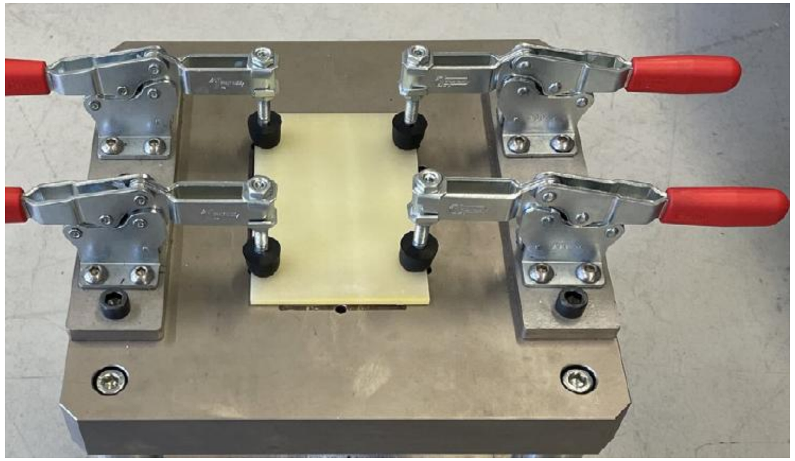
M11T	M11C	M22T	M22C	M33T	M33C	M12	M13	M23
(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
2.00	2.00	2.00	2.00	0.35	0.35	2.00	0.35	0.35

6. Kowalkowski, K. J., Grace, N. F., & Hodges, S. E. (2013). “Three-Dimensional Material Properties of Composites with S2-Glass Fibers or Ductile Hybrid Fabric.” Proceedings of the International SAMPE Technical Conference and Exhibition, Long Beach, CA, May 7, 2013.
7. Kumar, Y., Rezasefat, M., Amico, S. C., Manes, A., Dolez, P. I., & Hogan, J. D. (2024). “Comparison of two progressive damage models for predicting low-velocity impact behavior of woven composites.” Thin-Walled Structures, 197, 111611.
8. Haque, B. Z. (Gama), & Gillespie, J. W., Jr. (2014). “Rate Dependent Progressive Composite Damage Modeling using MAT162 in LS-DYNA.” Proceedings of the 13th International LS-DYNA Users Conference, Dearborn, MI, USA.

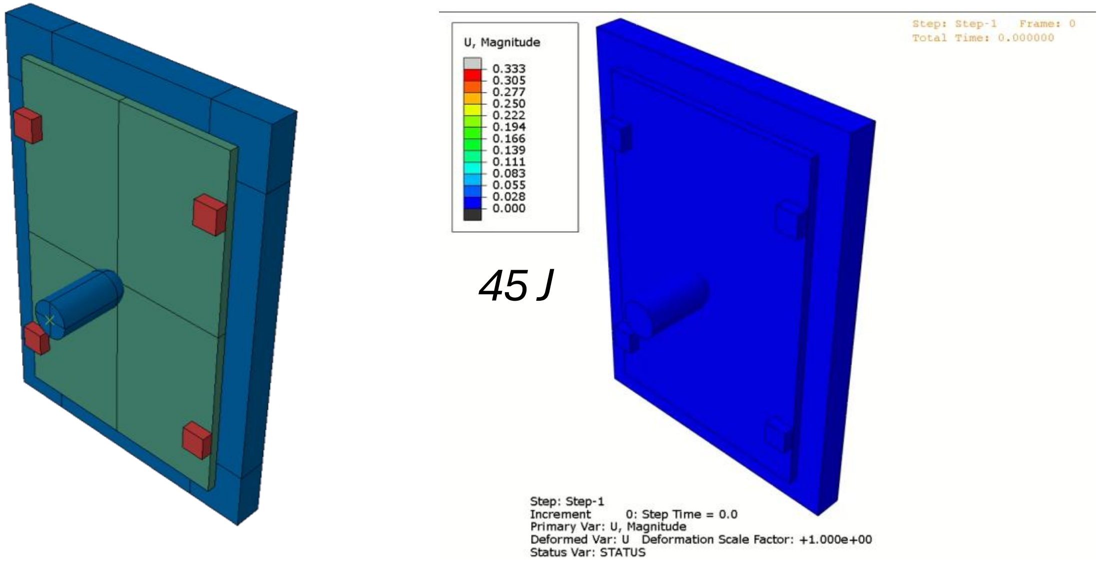
LVI Model Details

- The test configuration reported in Kumar reference follows ASTM D7136 standard[9]
- Specimen Size
  - Inplane: 150 mm x 100 mm (5.9 in x 3.9 in)
  - Thru-Thick: 4 mm (0.157 in)
- Hemispherical Impactor
  - Tup diameter: 16 mm (0.63 in)
- Hole in Support Plate
  - 125 mm x 75 mm (4.92 in x 2.95 in)
- Four Clamps with Rubber Dampers

Test Configuration in Kumar Paper[5]

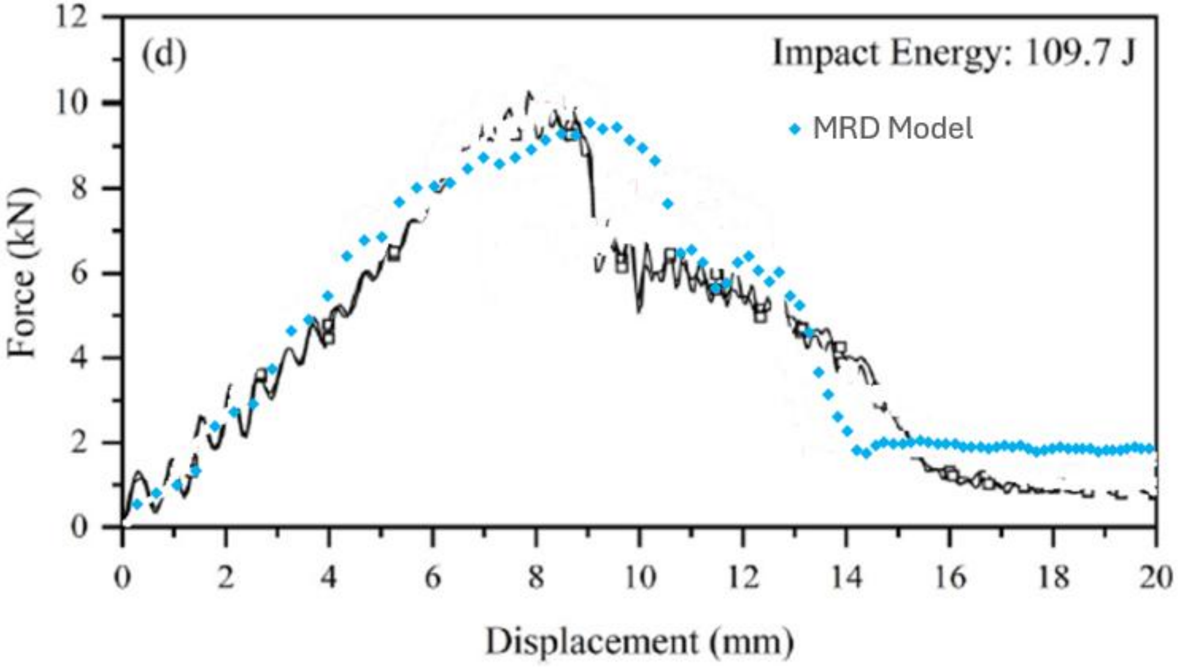


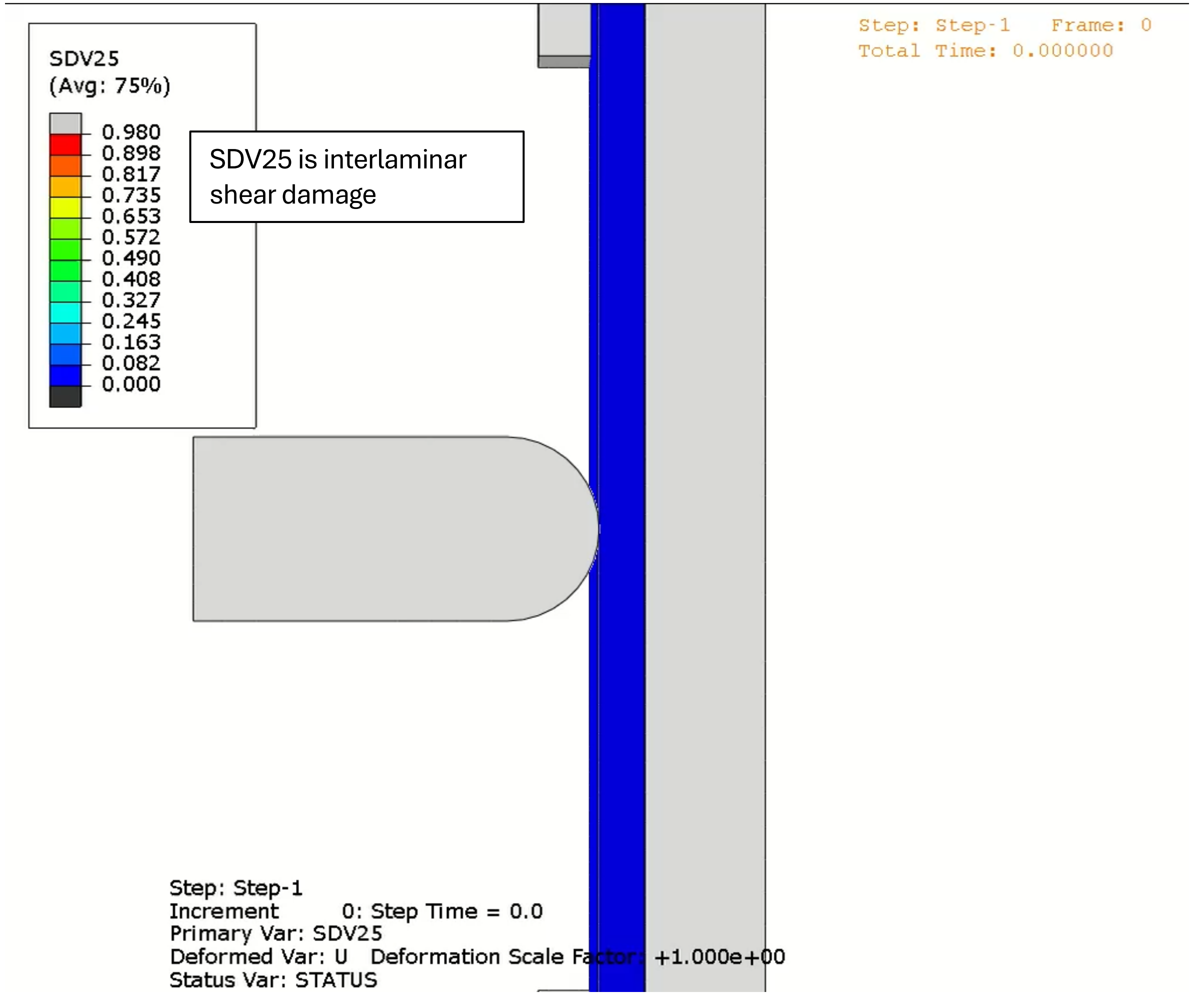
Test Configuration in LVI Model



9. ASTM International. *ASTM D7136/D7136M-20: Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event*. West Conshohocken, PA: ASTM International, 2020.

LVI Model Results, 109.7 J





SDV25 is interlaminar shear damage

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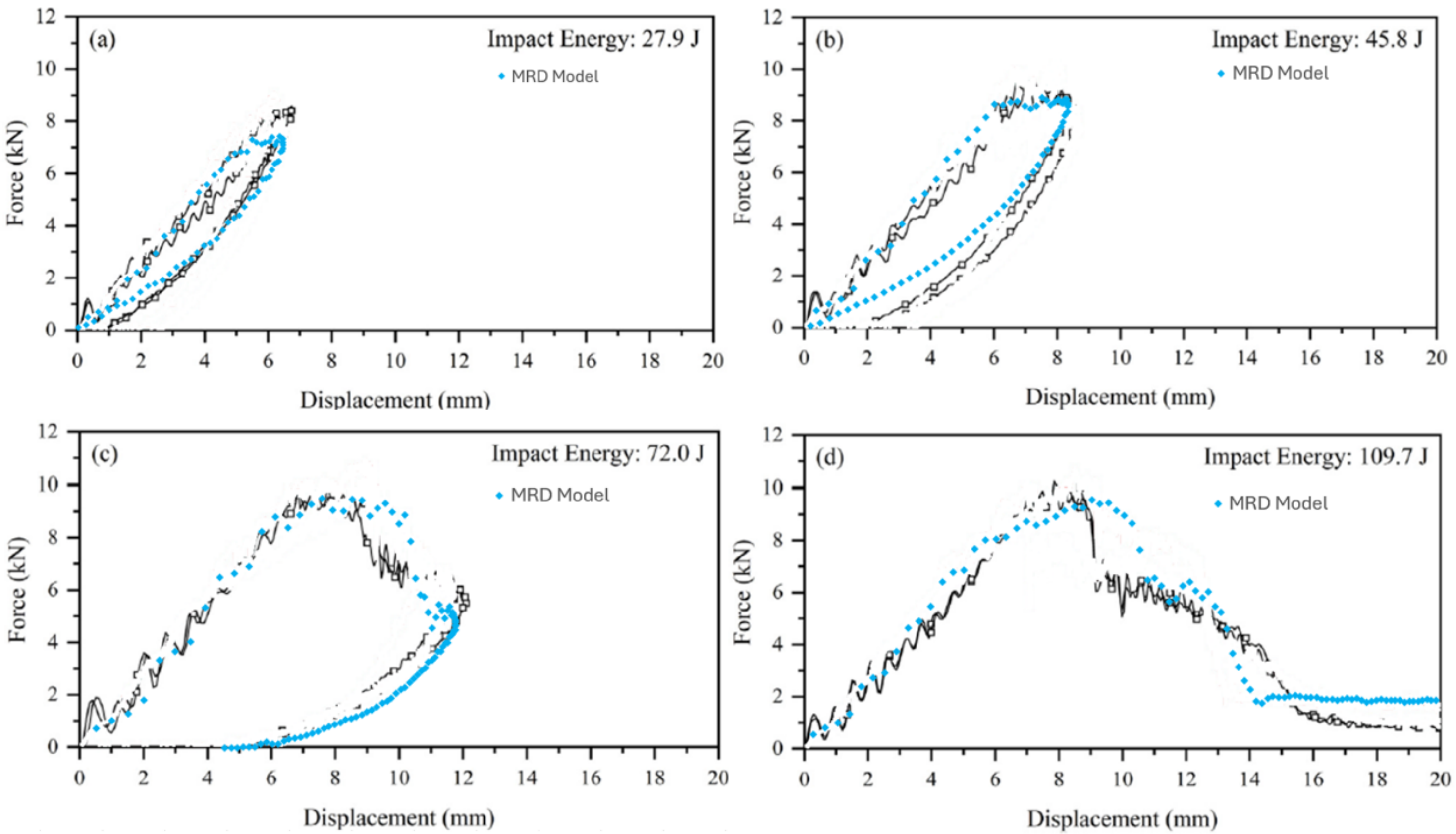
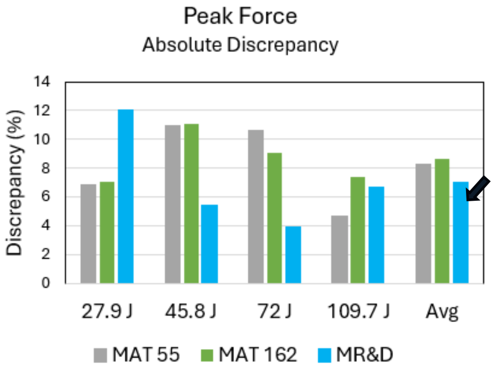
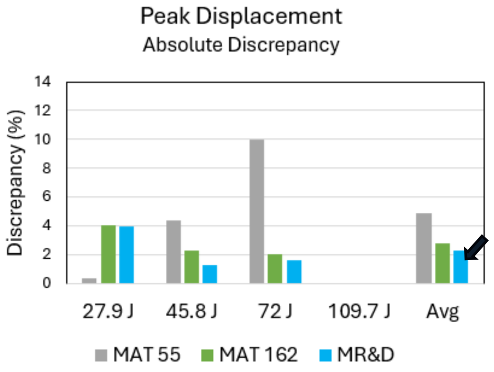
Step: Step-1
Increment      0: Step Time = 0.0
Primary Var: SDV25
Deformed Var: U   Deformation Scale Factor: +1.000e+00
Status Var: STATUS
```

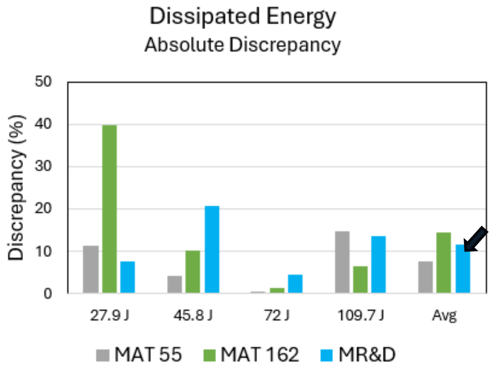
LVI Model Validation

- Overall, there is good agreement for load-deflection data and dissipated energy across all impact energies.
- In the Kumar reference[5], the authors report the accuracy of two material models available in LS-DYNA, MAT 55 and MAT 162.
- On average, the MR&D model performed better than the LS-DYNA models.
- Based on this acceptable level of agreement, MR&D concluded the validation effort and proceeded to look at other LVI scenarios.









Design Space

- Below is a comparison between the Kumar experimental setup and what is known about the impact testing performed on the current CHUT material

Kumar[5]

- Energies: 28 J, 46 J, 72 J and 110 J
- Tup Diameter: 0.63 in
- Specimen Size: 5.9 in x 3.9 in x 0.16 in
- Supports: Rubber dampers (front) and support plate (back)
- Support Hole Size: 4.92 in x 2.95 in

CHUT Testing

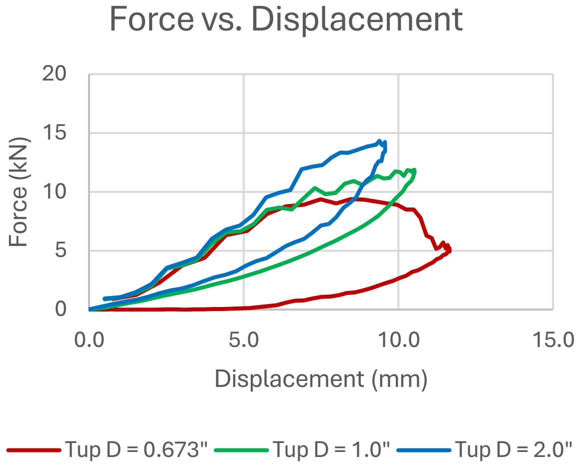
- Maximum Energy: 280 J
- Tup Diameter: 2.0 in
- Specimen Size: 8.0 in x 8.0 x 0.16 in
- Supports: Metal plate (front and back)
- Support Hole Size: 6 in diameter (circular)

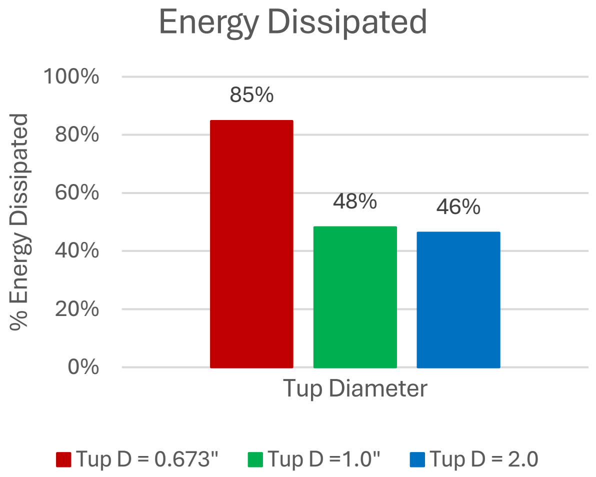
- *The following slides detail the incremental steps to build the model from the ASTM Method used in Kumar to the set-up used on the CHUT material to capture the effect of each change on the damage incurred by the material*

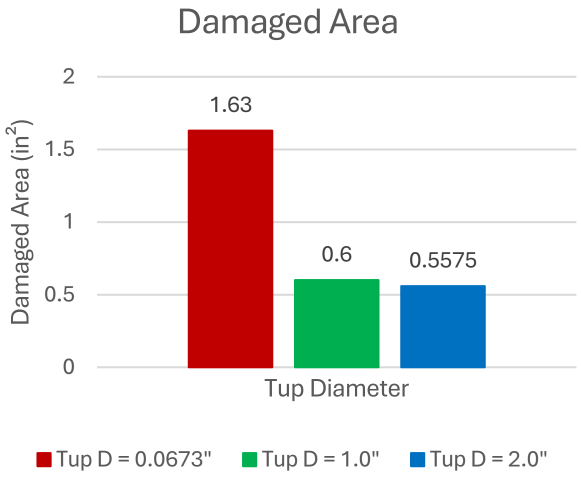
Effect of Tup Diameter

- Shown to the right are comparisons between FEA models with different tup diameters and how this effects force/displacement, total energy dissipated, and damage area in the specimen.
- Damaged area is the area of elements that are deleted by the VUMAT after reaching a maximum strain limit of 0.275.
- *Increasing the tup diameter from 0.673” to 1” leads to a large decrease in energy dissipated and the damage incurred by the specimen.*

__Consistent Parameters__
Energy: 72 J
Setup: ASTM Standard D7136
Material: QI45 S2-glass/SC-15
Element size: 0.05” x 0.05” x 0.02”

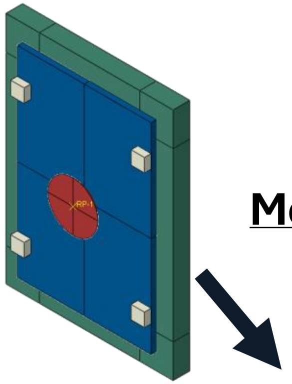




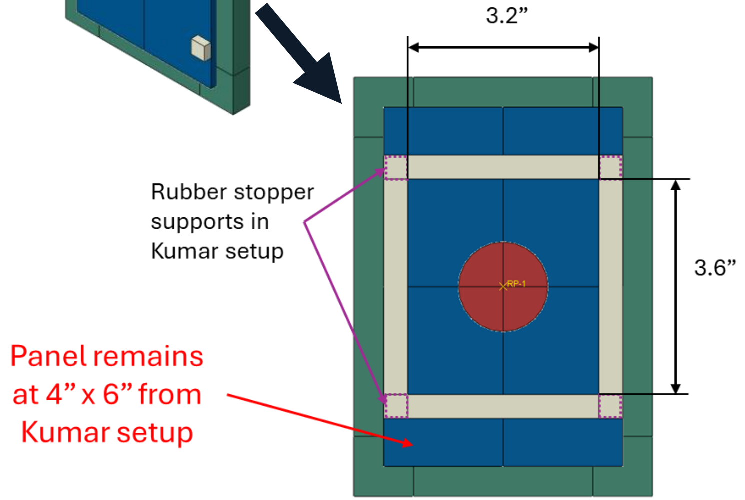


Additional Parameter Changes

- The additional parameter changes were not as significant as changing the tup diameter, and are summarized below:

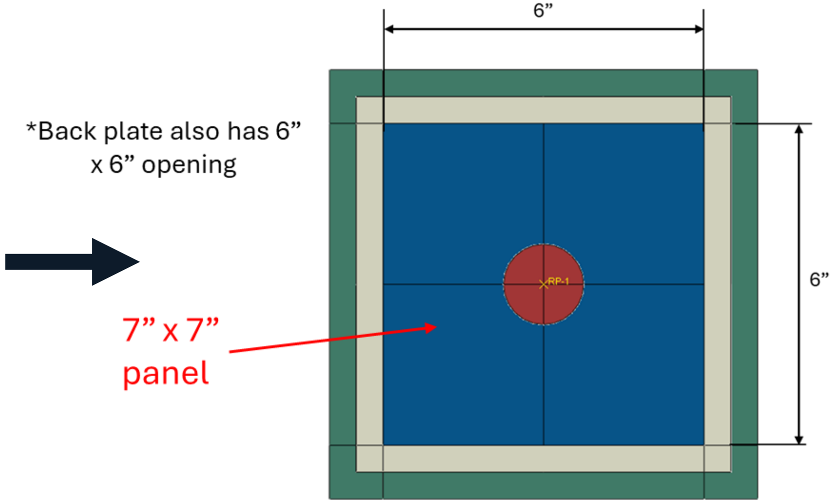


Metal Front Support



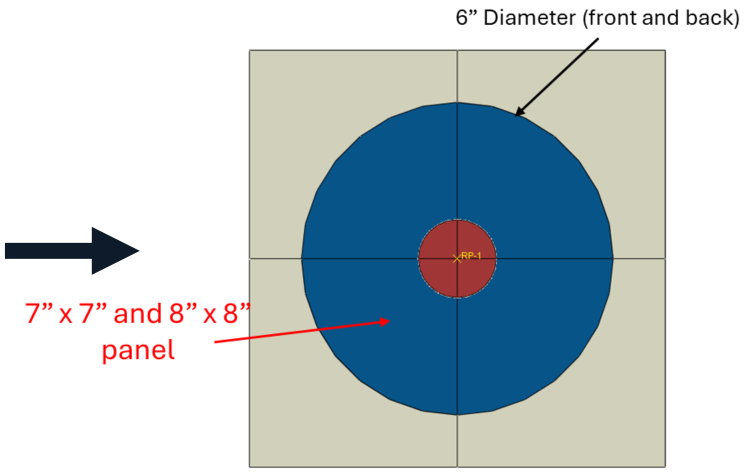
Damaged Area ↓ *7.2%*

Square, Larger Panel



Damaged Area ↑ *25%*

Circular Support Hole



Damaged Area ↑ *18%*

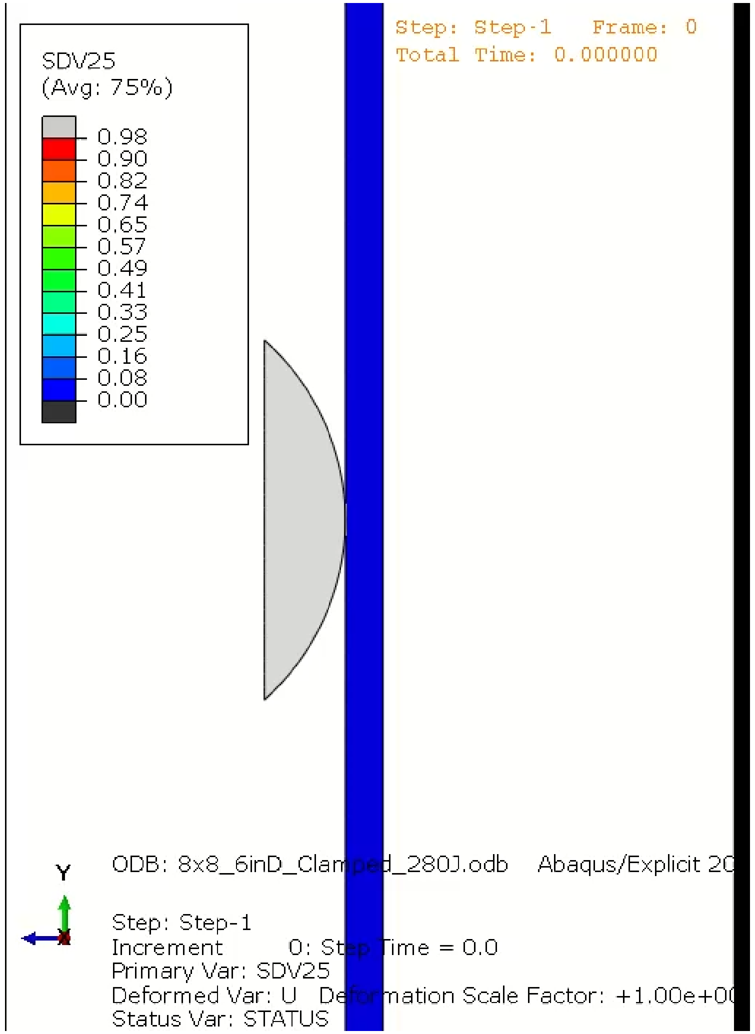
Design Space Summary

- The size of the tup had the greatest effect on impact performance.
  - Increasing the tup diameter led to an increase in peak force, while decreasing energy dissipated and the damage incurred by the specimen.
- Switching from rubber dampers to a metal plate results in less displacement, slightly more energy dissipated, and less damage incurred.
- Going from the ASTM-size specimen to a 7” x 7” panel with a 6” x 6” square support hole results in higher displacements, slightly lower energy dissipation, and more damage incurred.
- Changing the shape of the support hole from a square to a circle results in an increase in energy dissipated and damage incurred.

- *Next, the energy level was increased to 280 Joules, keeping the 8” x 8” specimen size and 6” diameter circular support hole. The QI45, 3D weave, and 3D braid materials for S2-glass / SC-15 were all simulated in this setup.*

Impact Animations – 280 J

2D QI45 S2/SC-15



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Step: Step-1    Frame: 0
Total Time: 0.000000
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```
ODB: 8x8_6inD_Clamped_280J.odb    Abaqus/Explicit 20

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Primary Var: SDV25
Deformed Var: U   Deformation Scale Factor: +1.00e+00
Status Var: STATUS
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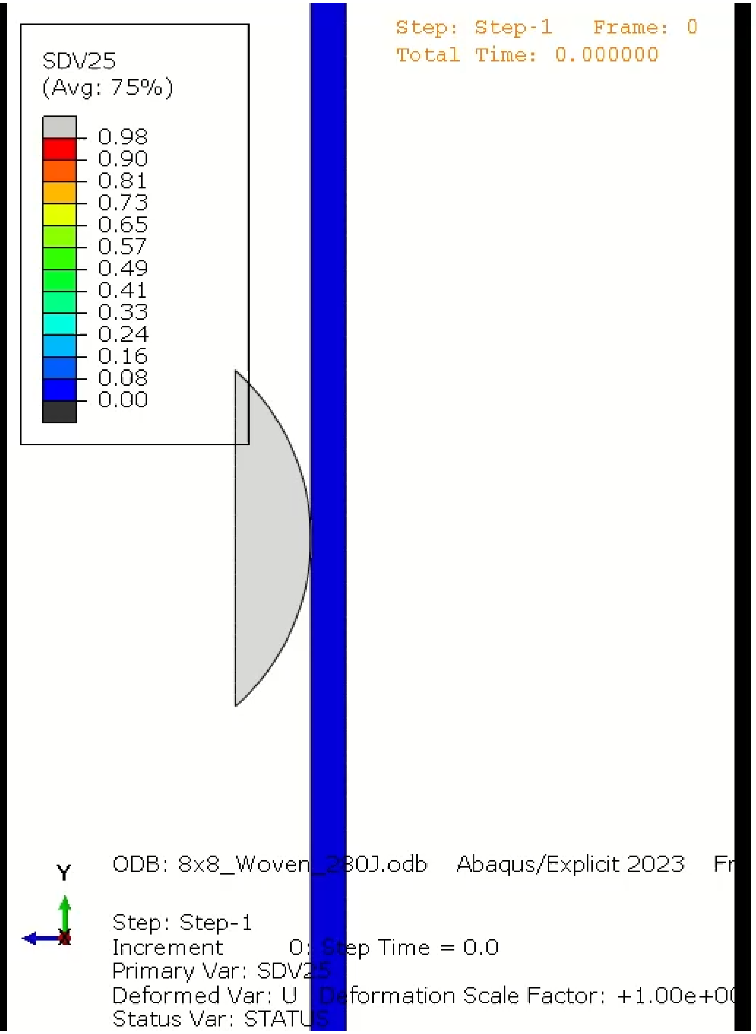
3D Woven S2/SC-15



```
Step: Step-1    Frame: 0
Total Time: 0.000000
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ODB: 8x8_Woven_280J.odb    Abaqus/Explicit 2023    Fr

Step: Step-1
Increment         0: Step Time = 0.0
Primary Var: SDV25
Deformed Var: U   Deformation Scale Factor: +1.00e+00
Status Var: STATUS
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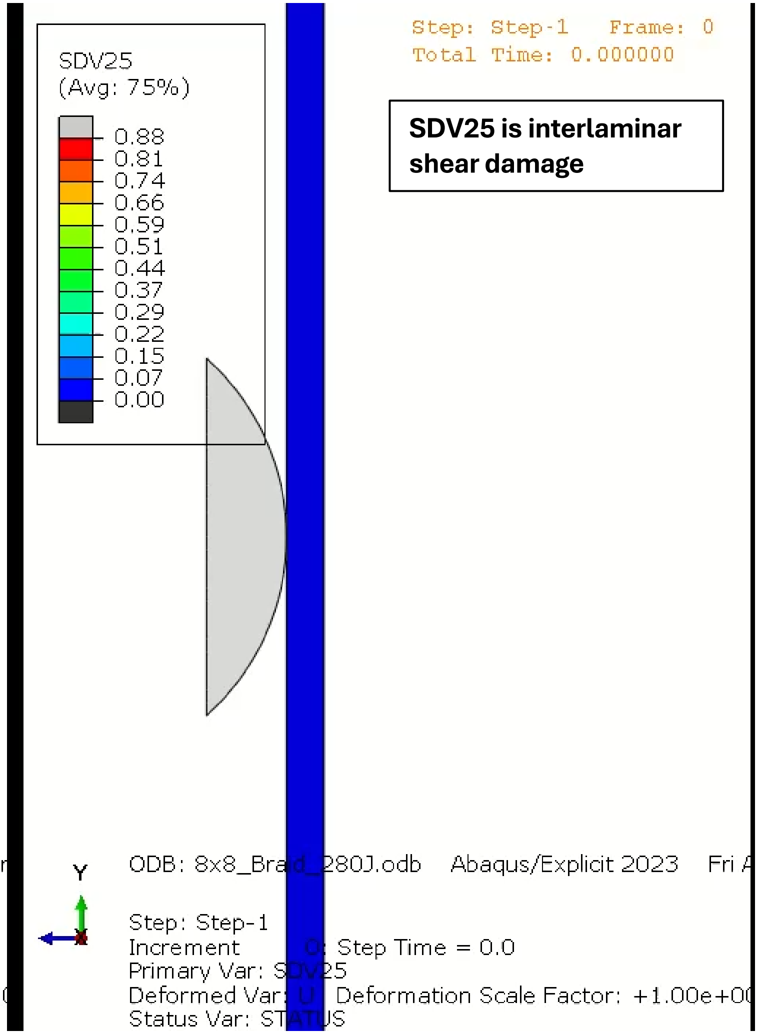
3D Braided S2/SC-15



```
Step: Step-1    Frame: 0
Total Time: 0.000000
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SDV25 is interlaminar shear damage

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ODB: 8x8_Braid_280J.odb    Abaqus/Explicit 2023    Fri A

Step: Step-1
Increment         0: Step Time = 0.0
Primary Var: SDV25
Deformed Var: U   Deformation Scale Factor: +1.00e+00
Status Var: STATUS
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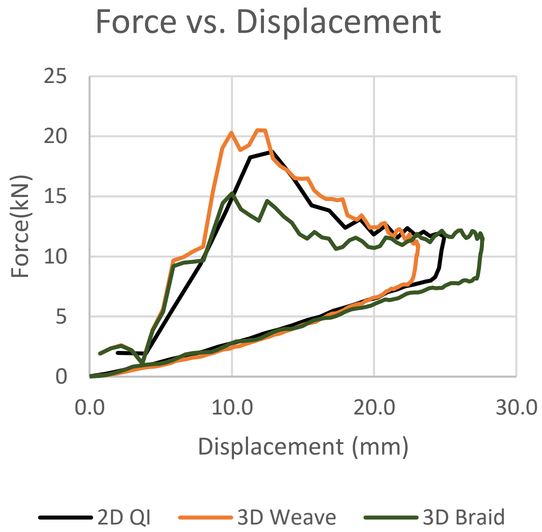
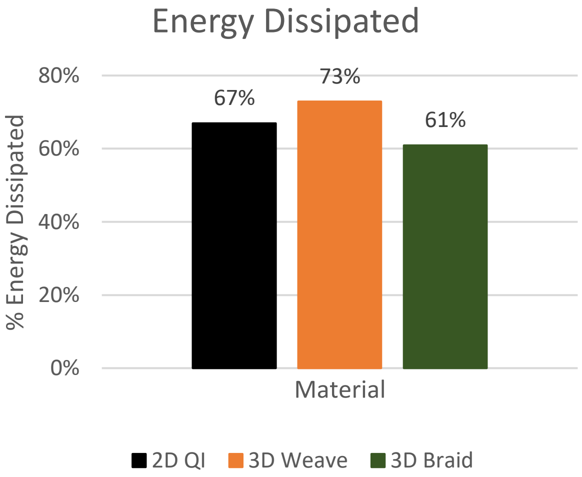
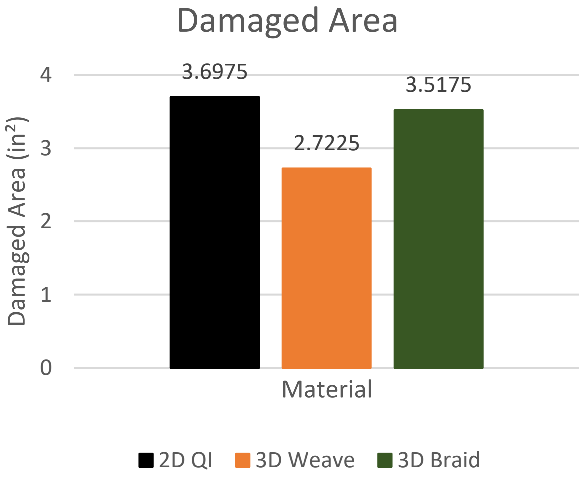
Material Impact Results – 280 J

- At a 280 Joule impact energy, the QI45 2D material, 3D woven material, and 3D braided material were simulated under impact testing conditions.
- Shown on the previous slide, interlaminar shear damage improves in the two 3D reinforced materials compared to the 2D material.
- The braided material experiences the highest displacement (lowest in-plane elastic moduli) and lowest peak load, while the woven material experiences the highest load but the lowest displacement (highest in-plane elastic moduli).
- The woven material dissipates the most energy and results in the lowest area of damaged material.
- The braided material also results in a decrease in the amount of area damaged by the impact, compared to the 2D material.

__Consistent Parameters__
Energy: 280 J
Mass: 5.66 kg
Tup Diameter: 2.0”
Material: S2-glass/SC-15
Panel Size: 8” x 8” x 0.16”
Support: 6” diameter hole
Element size: 0.05” x 0.05” x 0.02”







Summary of Phase I Technical Effort

- FMI fabricated both a 3D woven material and a 3D braided material consisting of SC-15 epoxy reinforced with S2-glass fibers.
- In-plane stiffnesses and strengths, as well as interlaminar shear strengths, of both materials were characterized by MR&D.
- Material properties are comparable between the measured properties and the incumbent material. The incumbent material had a higher ultimate shear stress in short beam shear, but the 3D reinforced material demonstrated a greater ability to deform while continuing to carry load than a 2D material.
- MR&D analytically recreated damage progression under impact testing of S2-glass / SC-15 materials using published experimental results.
- Analysis results comparing the 3D reinforced materials to a 2D laminate of the same constituents indicate superior performance in the 3D woven and braided materials, with the woven material being the most impact resistant.

Future Work

- Proposed Phase II Effort
- Continue to consider both woven and braided materials in Phase II effort
- Impact testing and subsequent pressure leakage testing to be performed early in Phase II
- Impact testing results will inform refinement of damage progression parameters for the 3D reinforced materials
- Additional material property characterization
- Full-article analysis and design
- Down-selection of material for full-article fabrication
- Phase II will culminate in the fabrication and non-destructive evaluation of one prototype full-scale article

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Questions?

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MR&D