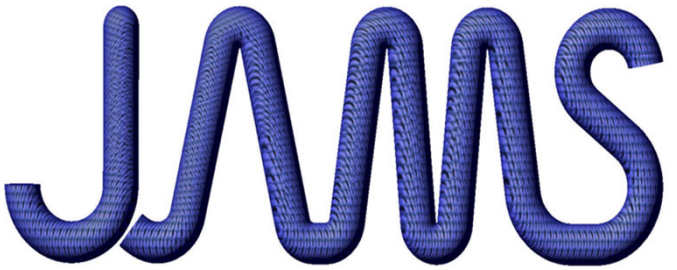
Effects of Defects in Composite Materials at Elevated Strain Rates

Federal Aviation Administration

Presented by:

Akhil Bhasin

NIAR-AVET



Joint Centers of Excellence for Advanced Materials

JAMS Technical Review

May 23rd, 2024

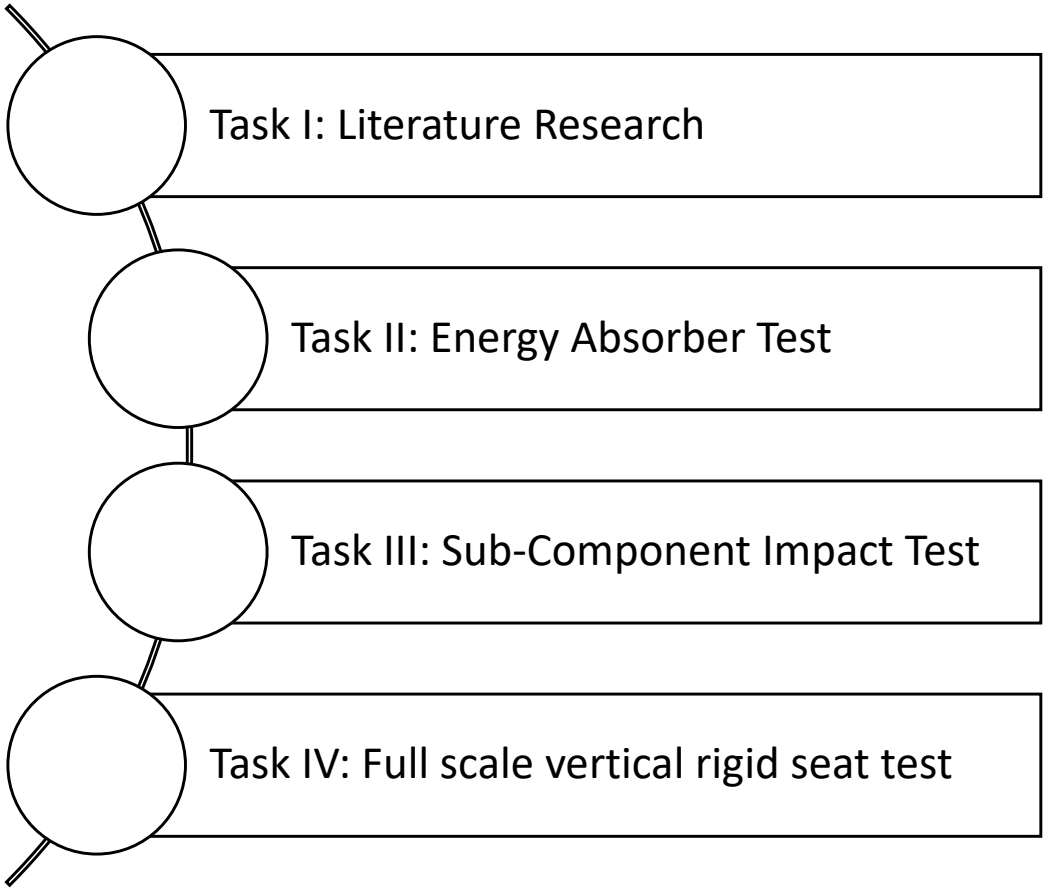
Research Team and Project Sponsors

- **Project Participants**
  - PI: Gerardo Olivares , Suresh Raju Keshavanarayana
  - Primary Researchers: Akhil Bhasin, Luis Gomez, Tanat Maichan
  - Additional Researchers: Parth Sejpal, Joseph Hagerott, Javier Martinez, Alejandro Fernandez
- **FAA Technical Monitor:** Dave Stanley
- **FAA Program Manager:** Ahmet Oztekin
- **FAA Program Sponsors:** Cindy Ashforth, Joseph Pelletier, Jeff Gardlin
- **Industry Partnerships/Other Collaborations:** Hexcel, CMH-17 Crashworthiness group

Project Motivation

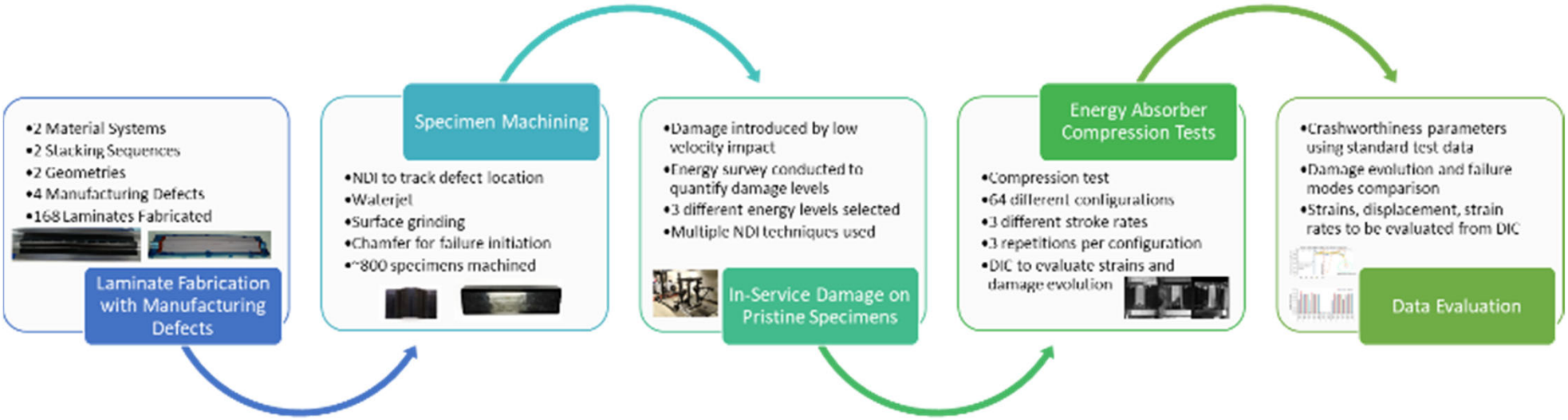
- **Motivation & Key Issues**
  - Composite energy absorbers improve the crashworthiness performance of modern commercial aircraft by dissipating energy through failure. **The load carrying capabilities of these targeted energy absorbers could be undermined due to the presence of defects**. During a survivable crash event, these energy absorbers would experience elevated strain rates and loading rates. **Thus, there is a need to investigate the performance of these crash absorbers with presence of defects at dynamic loading rates**.
  - For aircraft seats, manufacturing defects and in-service damage are substantiated only during static test but not included in dynamic test. **During the definition of SAE ARP 6337 [1], there were concerns that these defects/damage might improve or enhance the behavior of the seats in a dynamic test**. Thus, to balance the lack of Category 1 damage in dynamic test, Category 1 and some extension into Category 2 damage in the static test has been defined. The rationale is that with adequate margins in the static test, robustness of the seat system can be demonstrated for both static and dynamic tests. However, there is a need to assess the effect of defects on the performance of different seat components. **Current investigation will benefit the development of guidance material in support of ARP 6337.**

Project Task Breakdown & Approach



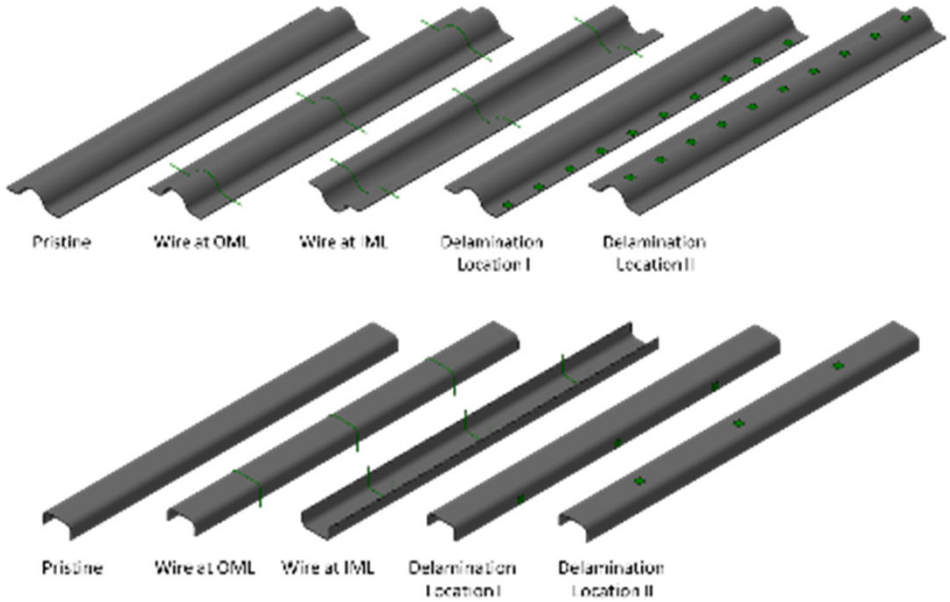
- **Task II:** Introduce prefabricated manufacturing defects and in-service damage on composite energy absorbers. Evaluate their crush performance and damage modes at multiple loading rates and compare them against their pristine counterparts.
- **Task III:** Introduce prefabricated manufacturing defect and in-service damage on representative flat composite seat pans. Conduct sub-component level impact tests at multiple loading rates and compare them against their pristine counterparts.
- **Task IV:** Introduce in-service damage on representative flat composite seat pans. Conduct full-scale vertical (rigid seat) tests to compare the performance of seat pans with damage against their pristine counterpart.

Task II: Workflow



Laminate Fabrication Overview

Panel Type	Configuration	Laminates Fabricated
Pristine	C-Channel Stanchion	64
Wire placed at OML		16
Wire placed at IML		16
Delamination Location I		16
Delamination Location II		16
Pristine	Corrugated Beam (Semi-Sine)	8
Wire placed at OML		12
Wire placed at IML		12
Delamination Location I		4
Delamination Location II		4



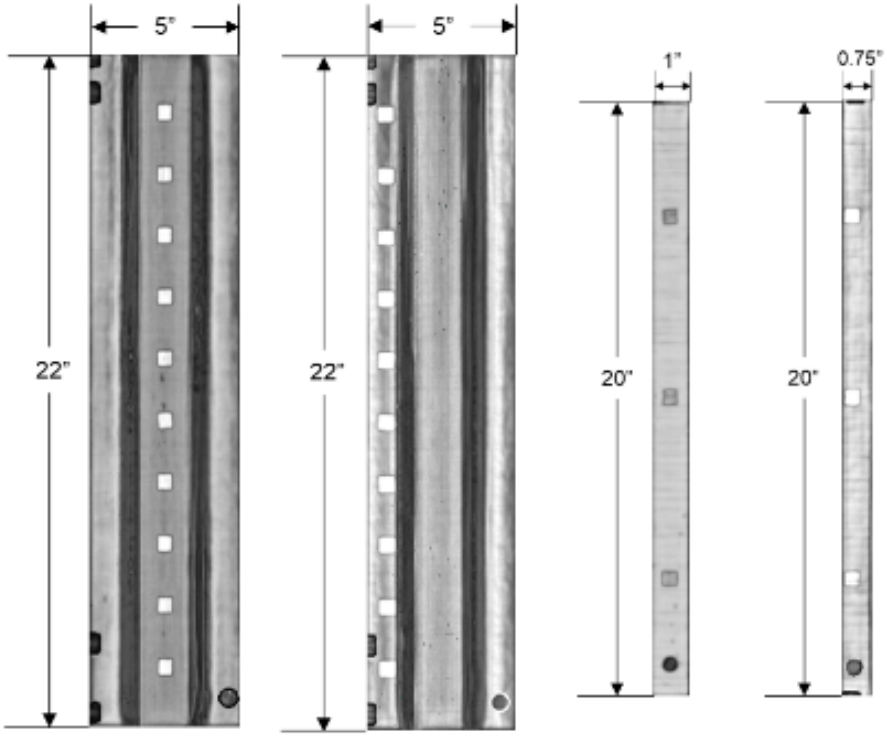
- **Material Systems: IM7/8552 (Tape); AS4 PW/8552 (Fabric)**
- **Stacking Sequence: $[90^o/0^o]_{2s}$ (Cross-Ply); $[45^o/90^o/-45^o/0^o]$s (Quasi-Isotropic)**
- **Out-of-plane fiber waviness introduced by placing a flexible stainless-steel wire of diameter 0.051" at two different locations:**
- **Delamination introduced by placing PTFE tape of thickness 0.0005" between plies**
- **168 laminates were manufactured using 24 autoclave cure cycles**

Non-Destructive Inspection

- Equipment Details:
  - Manufacturer: TecScan
  - Nozzle diameter: 0.25”
  - Scan speed: 6 in/s
  - Transducer Type: Flat
- For each cure cycle, atleast 2 laminates were inspected

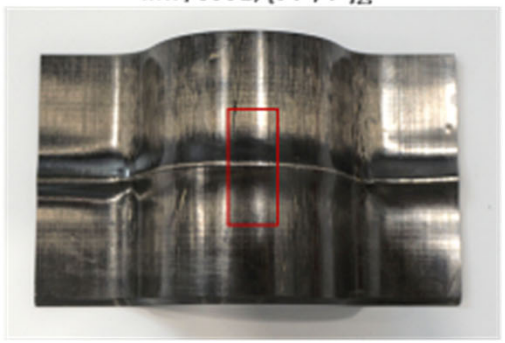
Corrugated Beam

C-Channel Stanchion



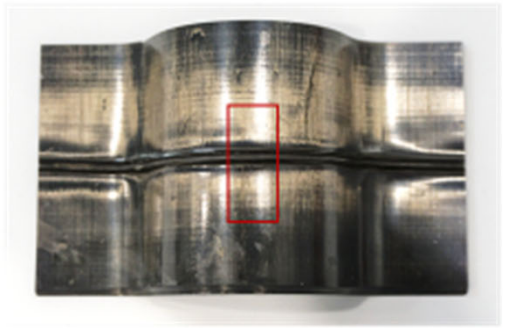
Microscopic Analysis: Fiber Waviness

IM7/8552; $[90°/0°]_{2s}$



Waviness due to the wire placed at IML

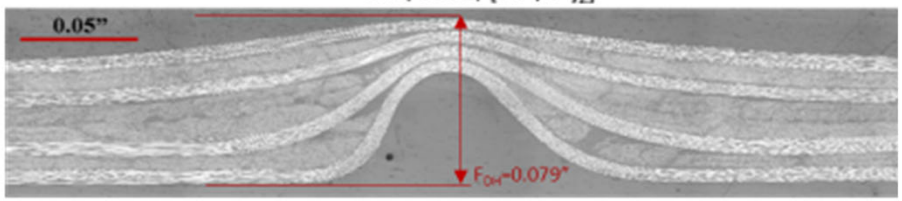
IM7/8552; $[90°/0°]_{2s}$



Waviness due to the wire placed at OML

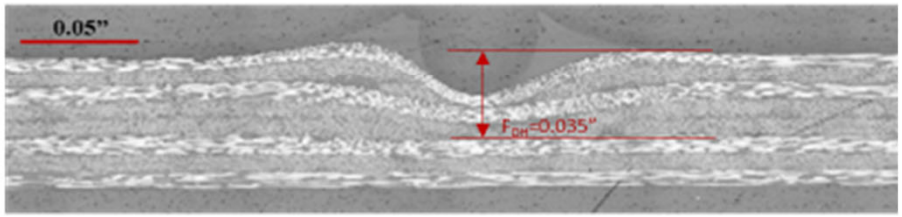
Potted specimen in clear epoxy

IM7/8552; $[90°/0°]_{2s}$



Waviness due to the wire placed at IML

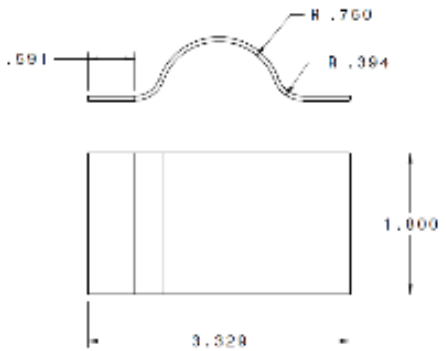
IM7/8552; $[90°/0°]_{2s}$



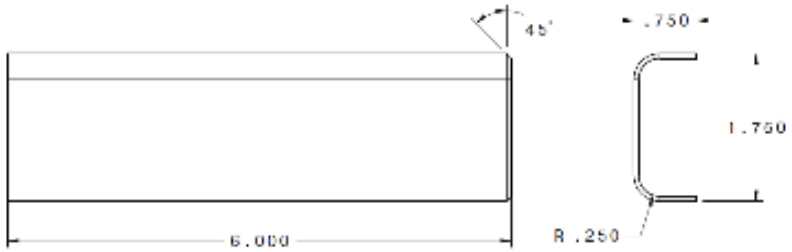
Waviness due to the wire placed at OML

Specimen Machining

- Post laminate fabrication and NDI inspection, specimens were extracted from the laminates.
  - 3 from c-channel laminate and 10 from corrugated beam laminate
- Specimens were first cut using waterjet and then surface grinded to achieve nominal length and width
- One edge of the specimen was chamfered 45° to initiate failure during compression loading

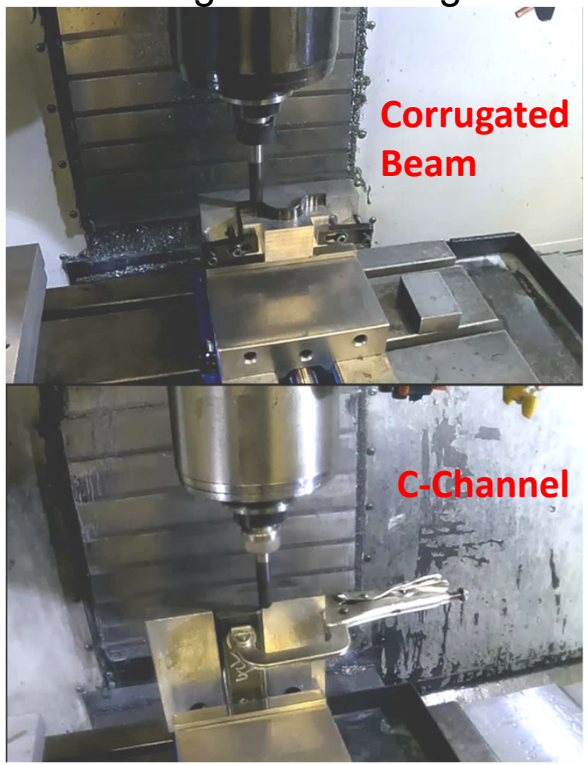


Corrugated Beam Specimen
(dimensions in inches)



C-Channel Specimen
(dimensions in inches)

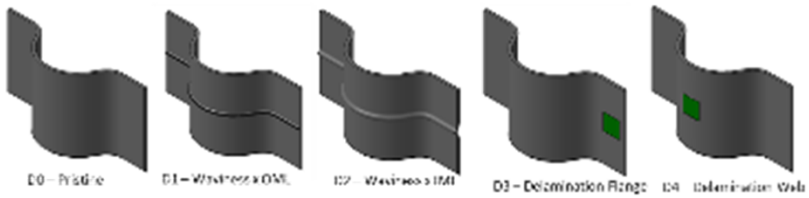
Edge Chamfering



Test Matrix: Manufacturing Defects

Test Matrix					
Energy Absorber: Corrugated Beam					
Material System	Stacking Sequence	Manufacturing Defect	Stroke Rate		
			0.01 in/s	1 in/s	100 in/s
IM7/8552	$[90°/0°]_{2s}$	D0	x3	x3	x3
		D1	x3	x3	x3
		D2	x3	x3	x3
		D3	x3	x3	x3
		D4	x3	x3	x3
	[45°/90°/-45°/0°]s	D0	x3	x3	x3
		D1	x3	x3	x3
		D2	x3	x3	x3
		D3	x3	x3	x3
		D4	x3	x3	x3

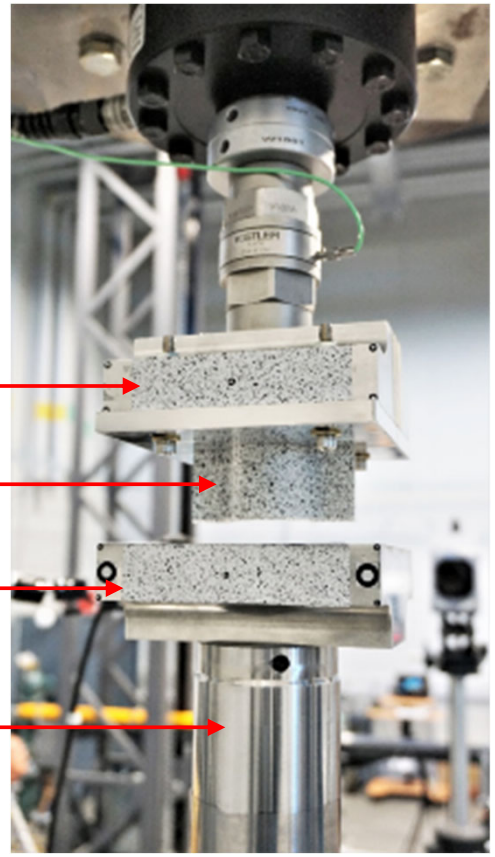
Test Matrix Continued					
Energy Absorber: Corrugated Beam					
Material System	Stacking Sequence	Manufacturing Defect	Stroke Rate		
			0.01 in/s	1 in/s	100 in/s
AS4 PW/8552	$[90°/0°]_{2s}$	D0	x3	x3	x3
		D1	x3	x3	x3
		D2	x3	x3	x3
		D3	x3	x3	x3
		D4	x3	x3	x3
	[45°/90°/-45°/0°]s	D0	x3	x3	x3
		D1	x3	x3	x3
		D2	x3	x3	x3
		D3	x3	x3	x3
		D4	x3	x3	x3

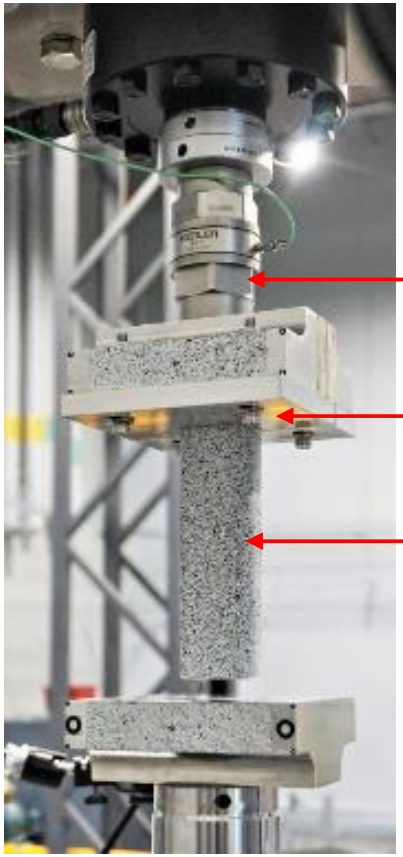


Same Test Matrix for C-Channel

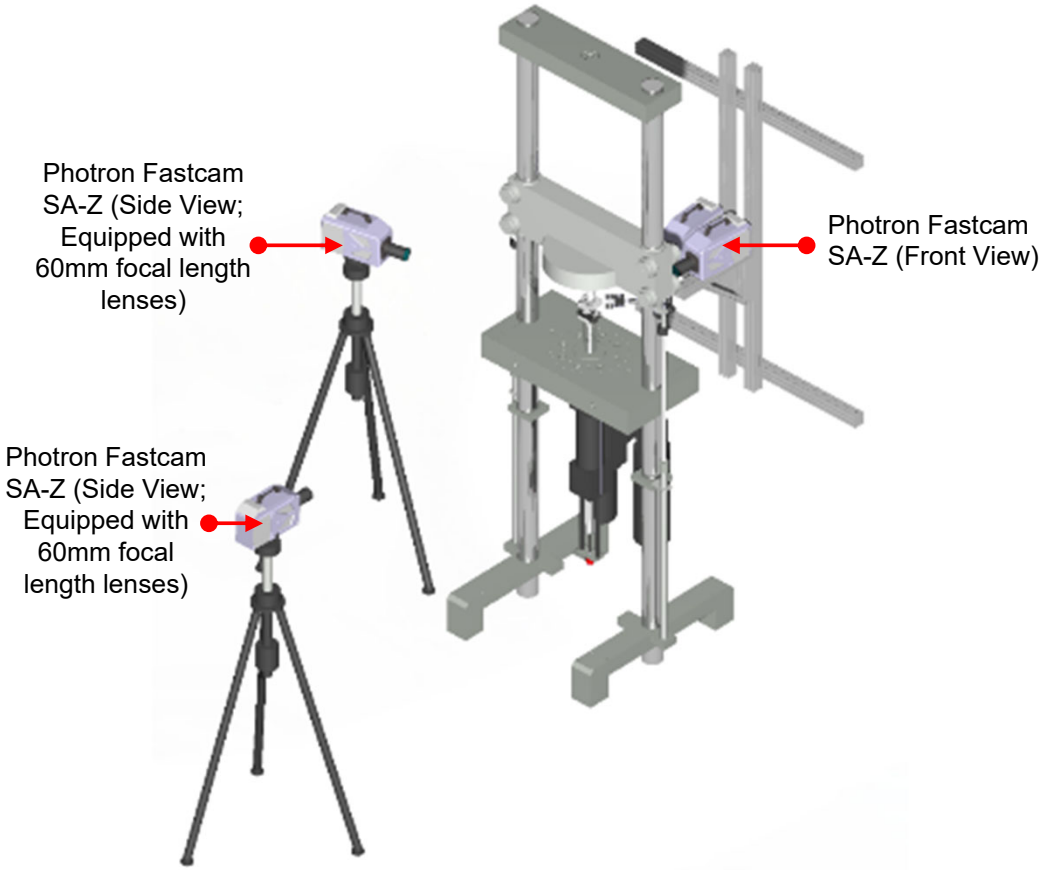
Total Specimens: 360

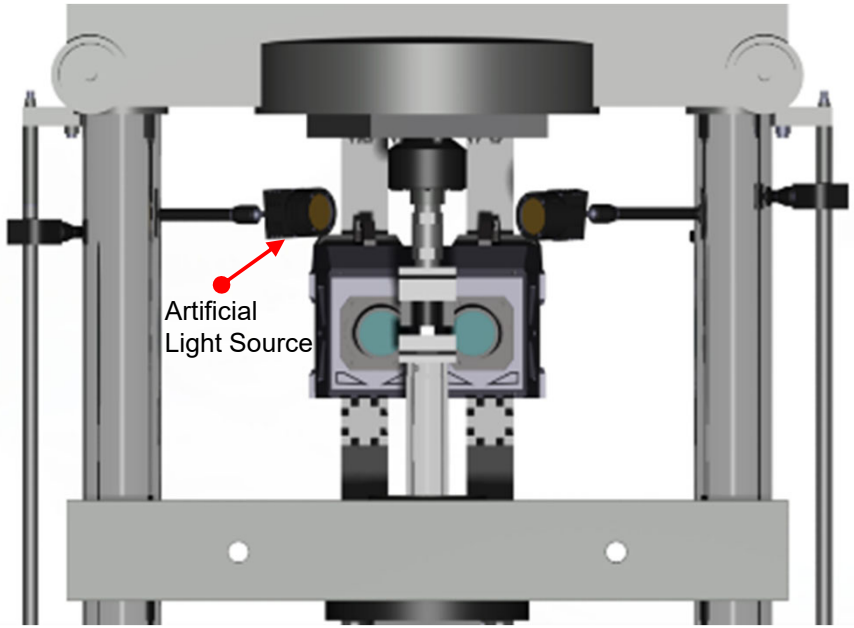
Test Apparatus



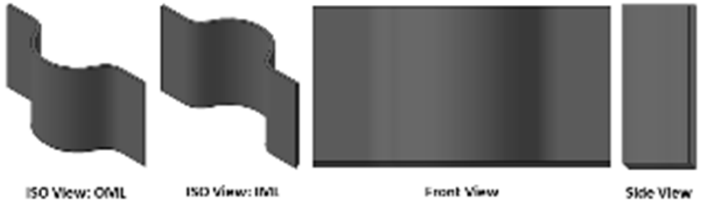


High Speed DIC: Test Schematic

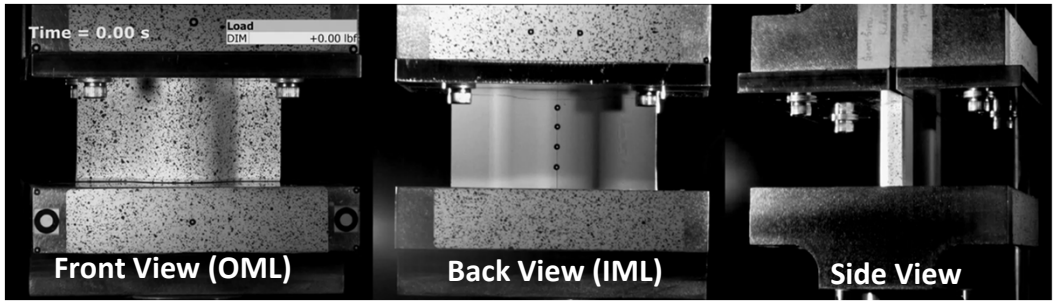


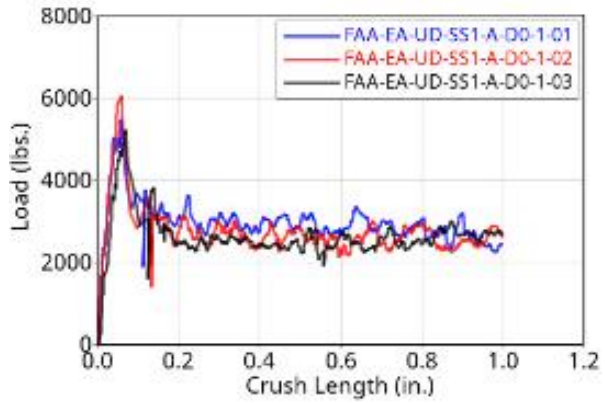


Corrugated Beam (Pristine)



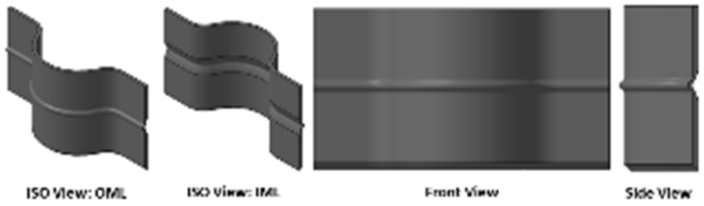
Defect Type: Pristine
Material System: IM7/8552**; Stacking Sequence:** $[90^o/0^o]_{2s}$; **Stroke Rate**: 1 in/s



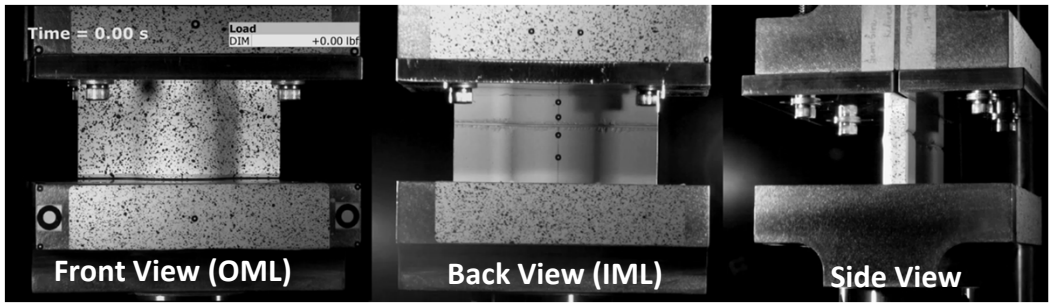


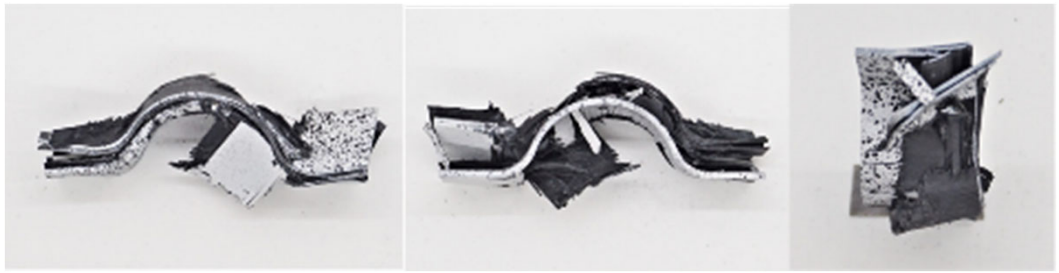
Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb/lb]	Total CFE
01	5,488.19	2,974.20	208,107.90	0.5419
02	6,070.71	2,749.10	192,357.44	0.4528
03	5,226.68	2,643.58	184,974.41	0.5058
COV	7.72%	6.06%	6.06%	8.96%

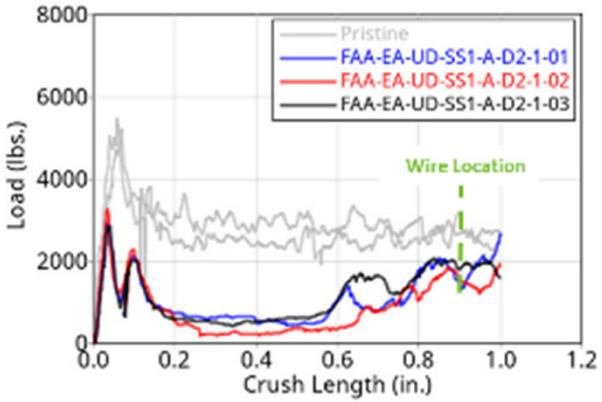
Corrugated Beam (Waviness IML)



Defect Type: Waviness/Wrinkle (wire at IML)
Material System: IM7/8552**; Stacking Sequence:** $[90^o/0^o]_{2s}$; **Stroke Rate**: 1 in/s

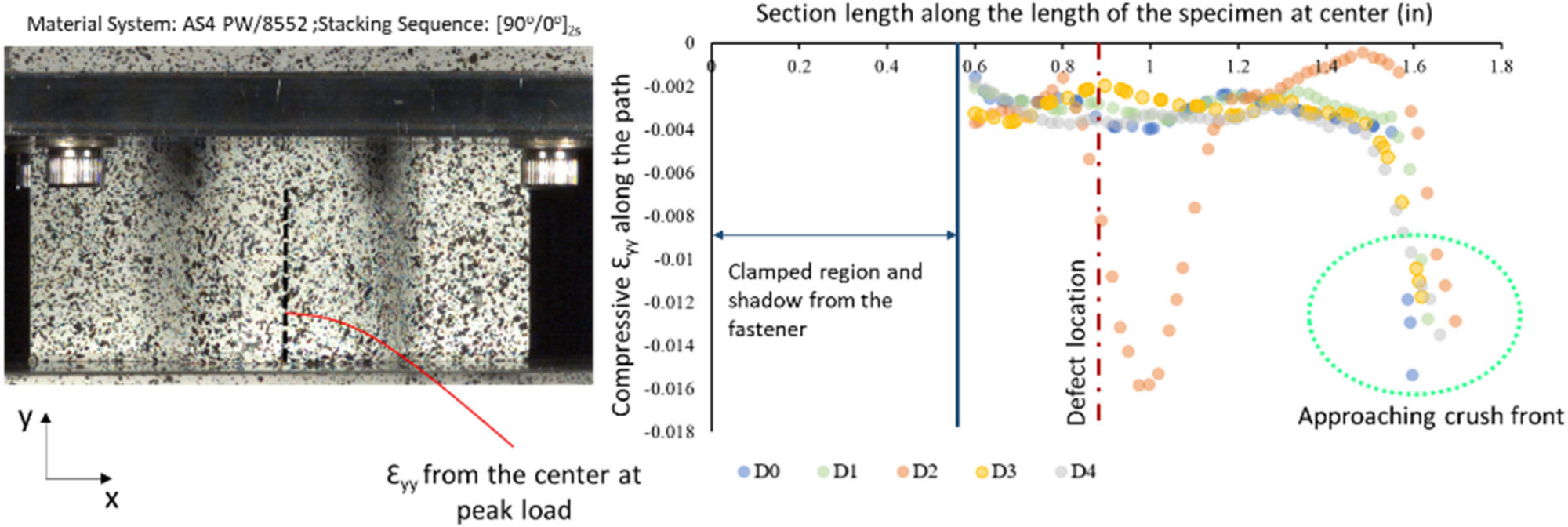






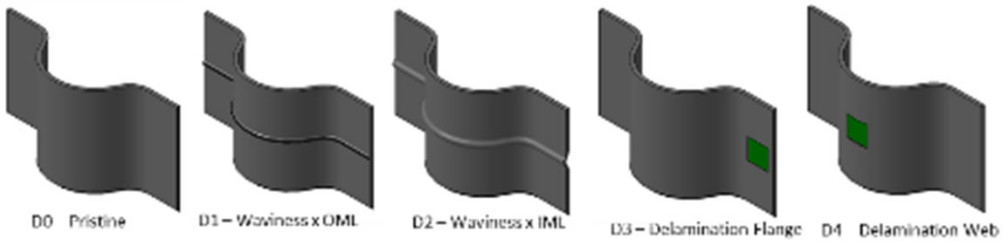
Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb/lb]	Total CFE
01	2,944.70	455.20	31,851.16	0.1546
02	3,284.10	377.49	26,413.45	0.1149
03	2,851.00	423.78	29,652.48	0.1486
COV	7.53%	9.33%	9.33%	15.34%

Strain Path Plot: DIC

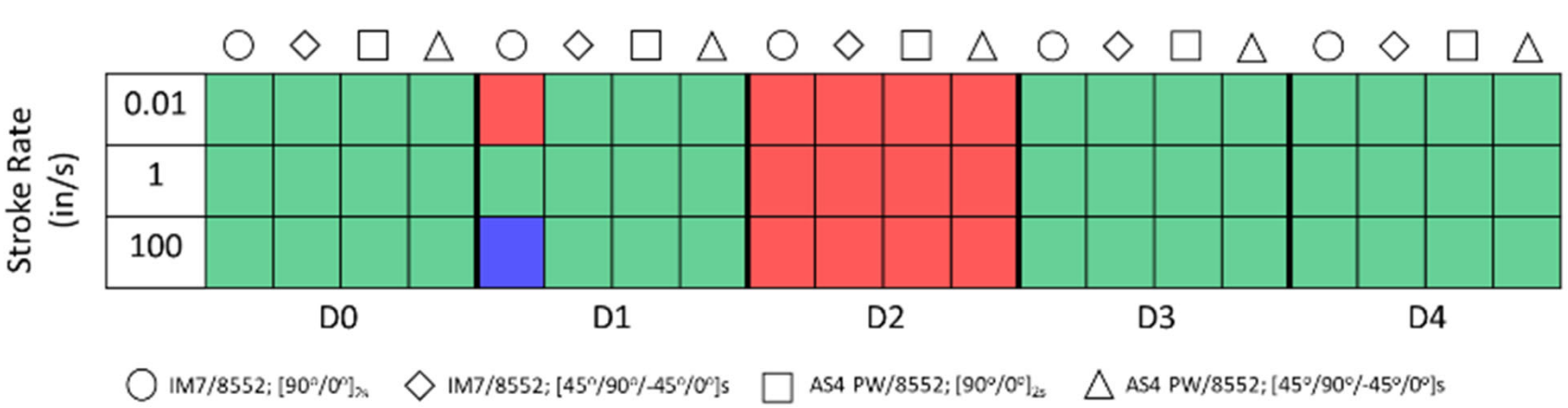


D0 – Pristine; D1 – Waviness x OML; D2 – Waviness x IML; D3 – Delamination Flange; D4 – Delamination Web

Summary: Failure Modes



Effects of strain rates & manufacturing defects on crushing behavior of corrugated beam energy absorbers



All specimens for this configuration have stable crushing

All specimens for this configuration have unstable crushing

Some specimens for this configuration have stable crushing and some specimens have unstable crushing

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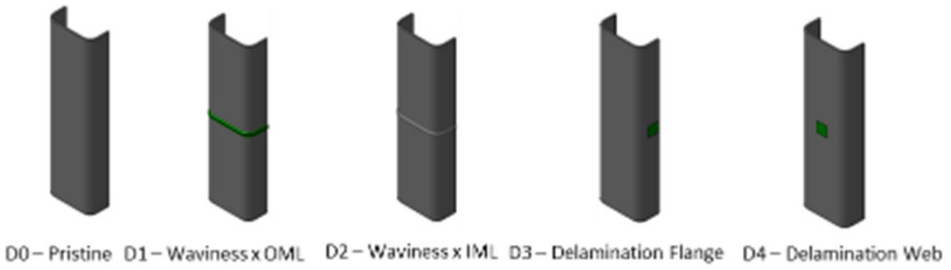
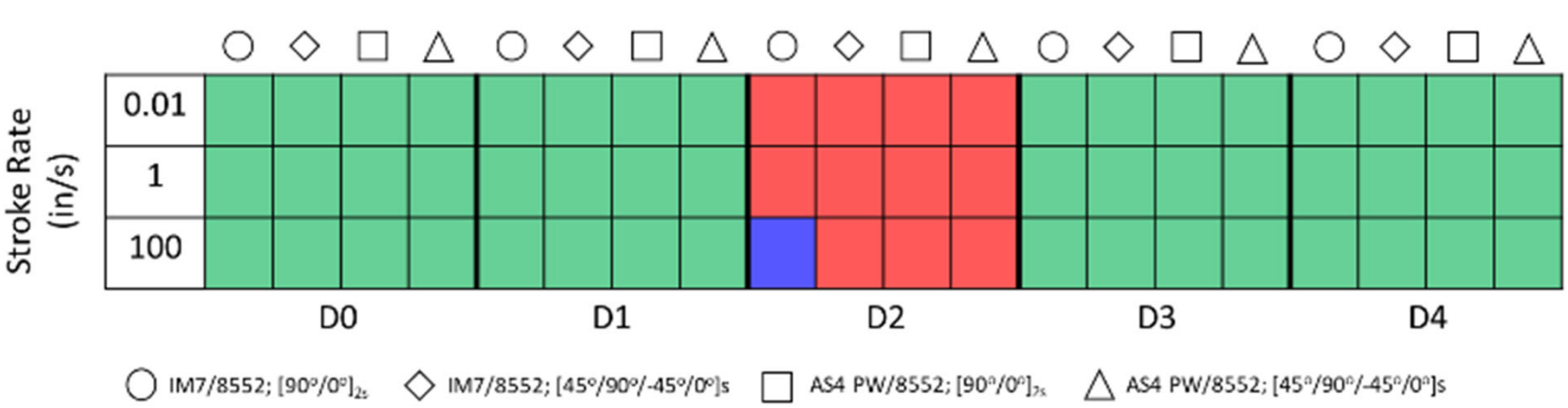
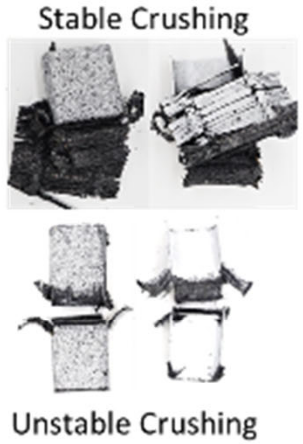
Summary: Failure Modes



Effects of strain rates & manufacturing defects on crushing behavior of c-channel stanchion energy absorbers





All specimens for this configuration have stable crushing

All specimens for this configuration have unstable crushing

Some specimens for this configuration have stable crushing and some specimens have unstable crushing

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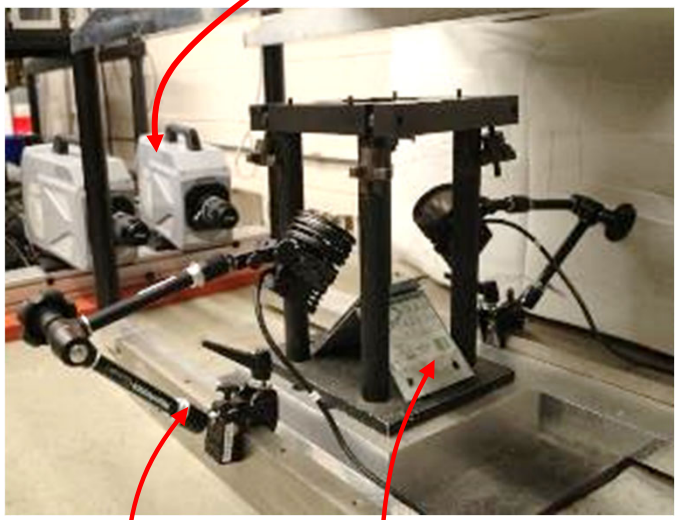
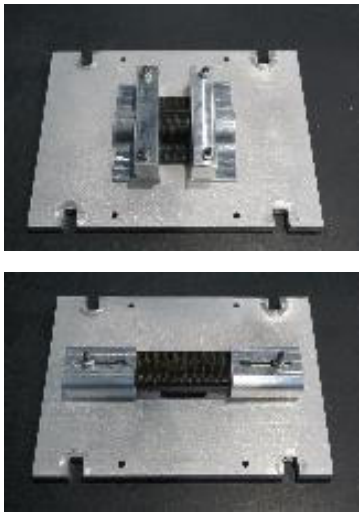
In-Service Impact Damage: LVI

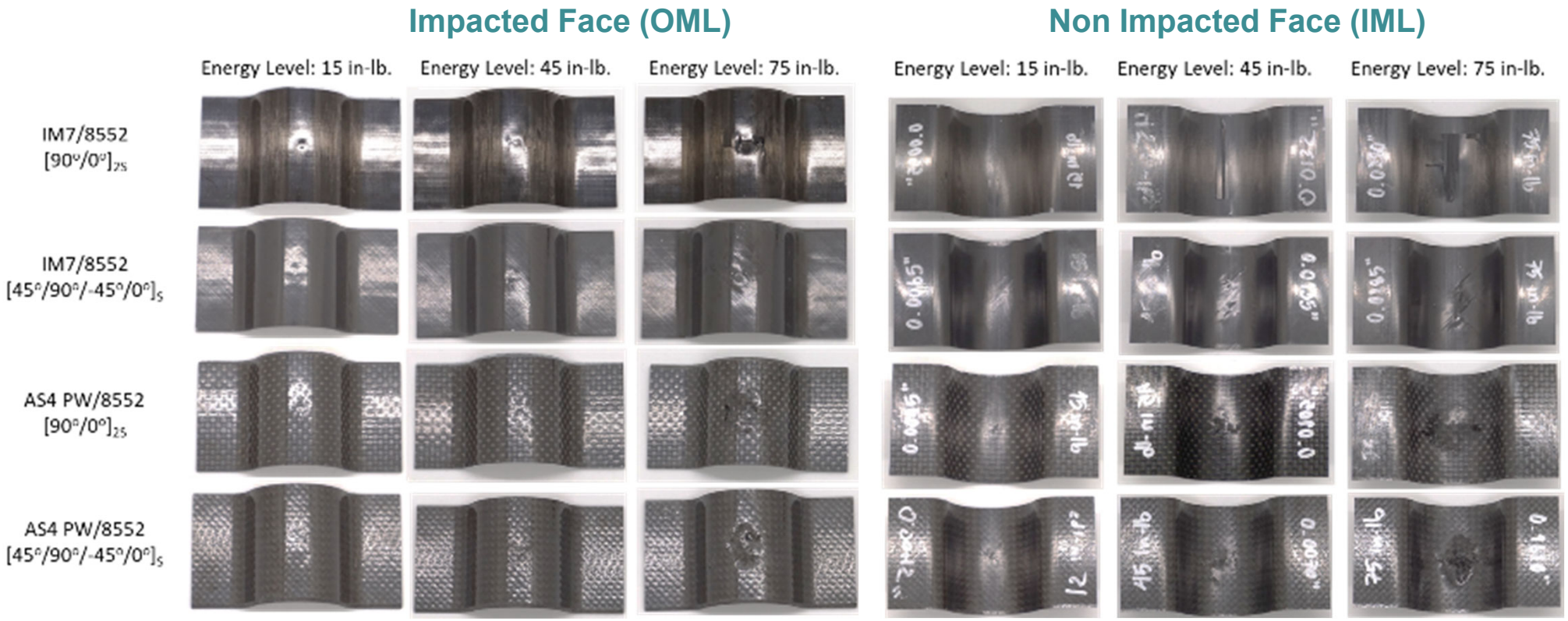




Test Setup Information	
Test Frame	Dynatup 8250
Impactor Diameter	0.5”
Drop weight	6 lbs.
Drop Height	~ Energy Level

High Speed Camera Information	
Camera Type	Photron Fastcam SA-Z
Resolution	1024 x 840 pixels
Frame Rate	25,000 fps
Lens Focal Length	105 mm

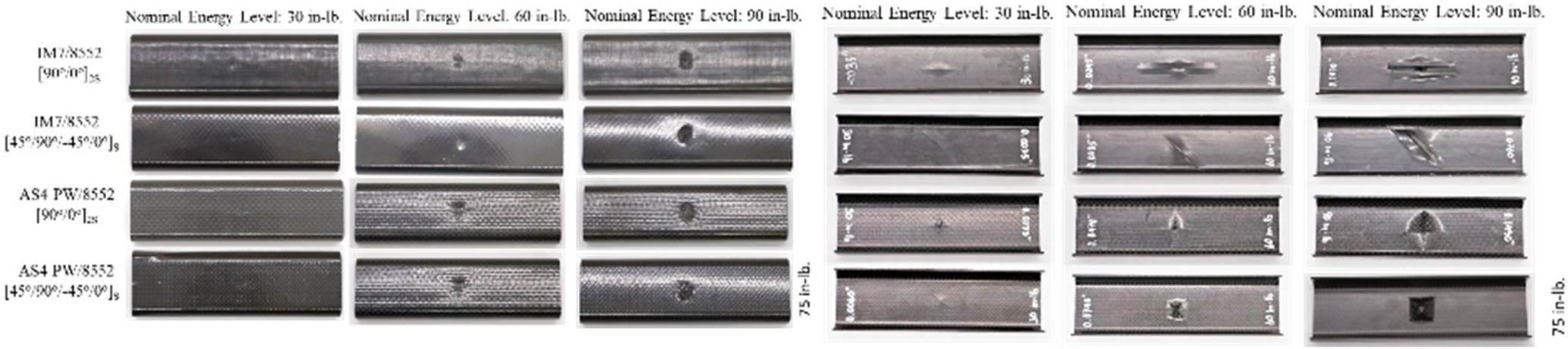
Damage Level – Corrugated Beam



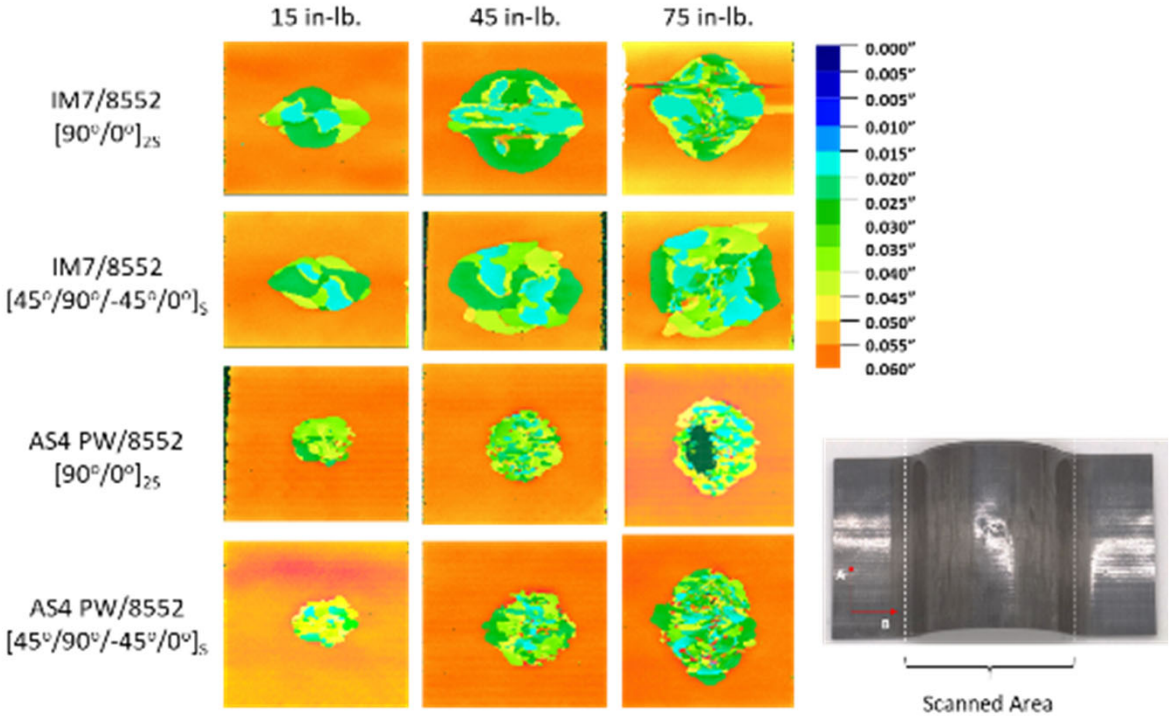
Damage Level – C-Channel

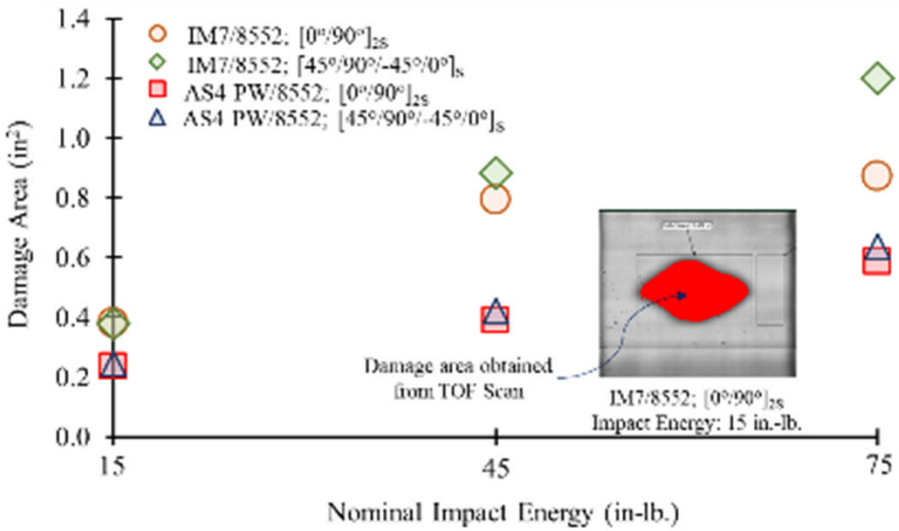
Impacted Face (OML)

Non Impacted Face (IML)



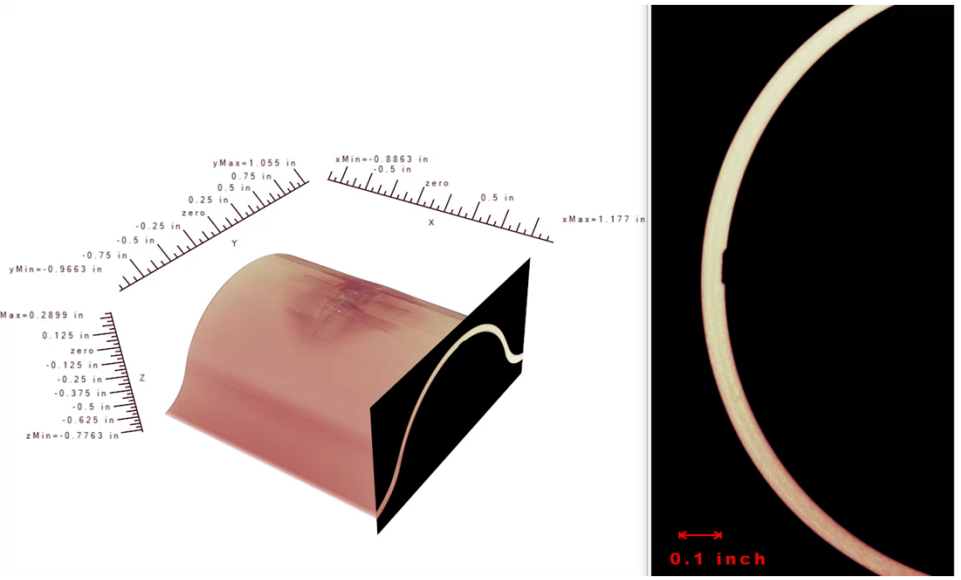
Damage Area: Corrugated Beam



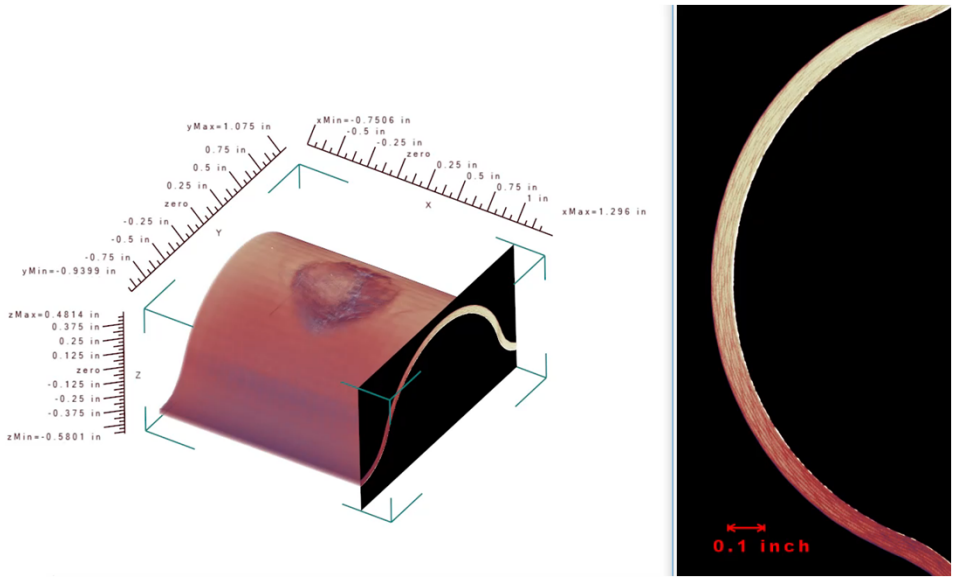


X-Ray Ct: Corrugated Beam

Nominal Impact Energy: 75 in-lb.



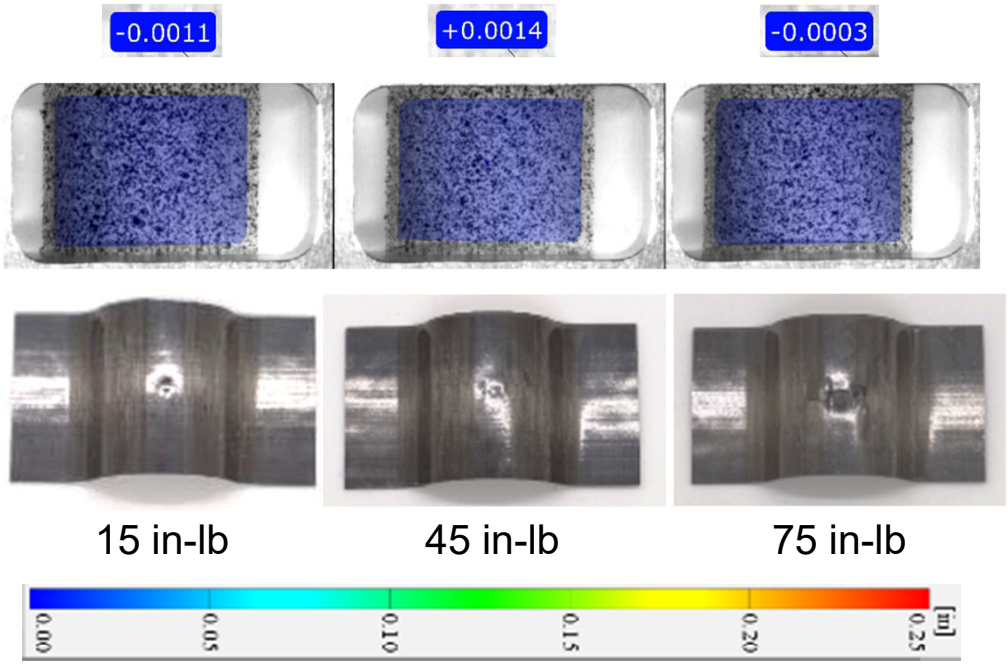
IM7/8552; $[90^o/0^o]_{2S}$

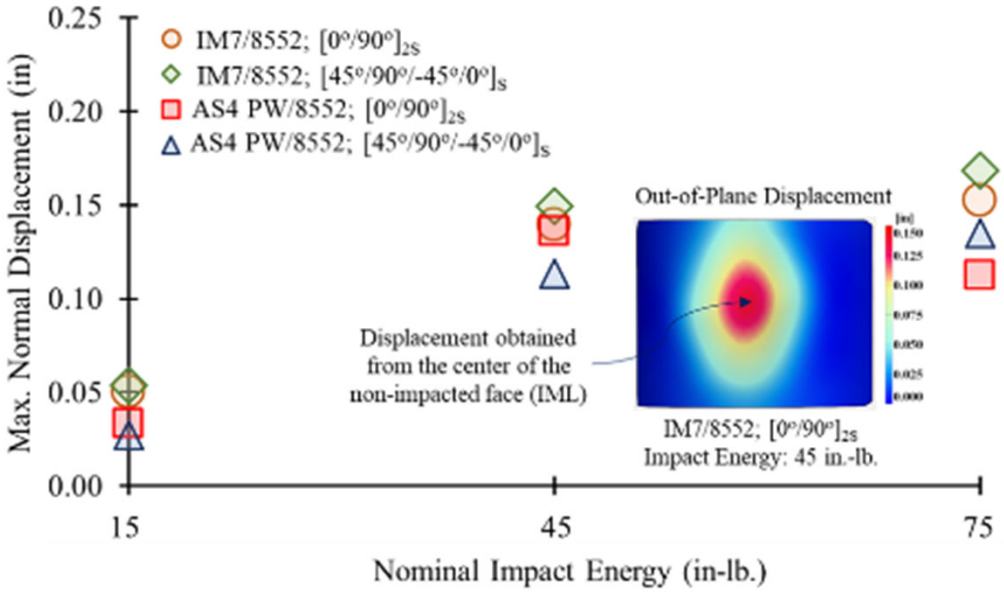


AS4 PW/8552; $[90^o/0^o]_{2S}$

High Speed DIC: Corrugated Beam

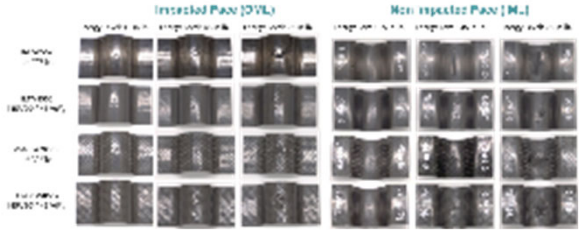
IM7/8552; $[90^o/0^o]_{2S}$



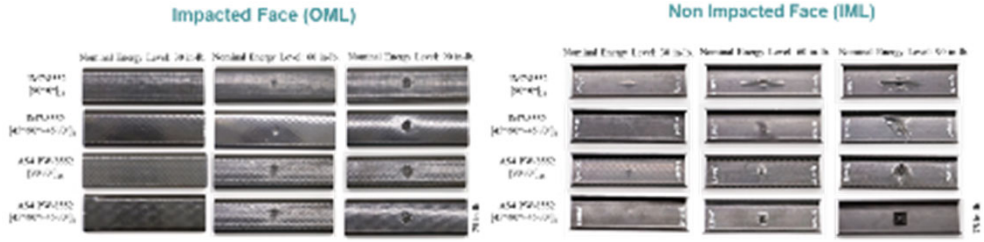


Test Matrix: In-Service Damage

Test Matrix					
Energy Absorber: Corrugated Beam					
Material System	Stacking Sequence	Impact Energy Level (in.-lb.)	Stroke Rate		
			0.01 in/s	1 in/s	100 in/s
IM7/8552	$[90°/0°]_{2s}$	15 (BVID)	x3	x3	x3
		45 (VID #1)	x3	x3	x3
		75 (VID #2)	x3	x3	x3
	[45°/90°/-45°/0°]s	15 (BVID)	x3	x3	x3
		45 (VID #1)	x3	x3	x3
		75 (VID #2)	x3	x3	x3
AS4 PW/8552	$[90°/0°]_{2s}$	15 (BVID)	x3	x3	x3
		45 (VID #1)	x3	x3	x3
		75 (VID #2)	x3	x3	x3
	[45°/90°/-45°/0°]s	15 (BVID)	x3	x3	x3
		45 (VID #1)	x3	x3	x3
		75 (VID #2)	x3	x3	x3

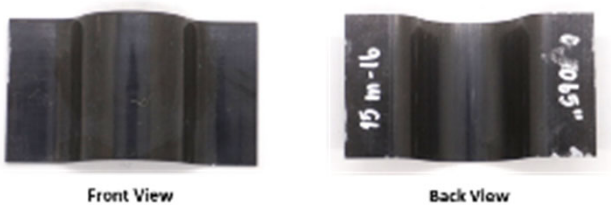


Test Matrix					
Energy Absorber: C-Channel Stanchion					
Material System	Stacking Sequence	Impact Energy Level (in.-lb.)	Stroke Rate		
			0.01 in/s	1 in/s	100 in/s
IM7/8552	$[90°/0°]_{2s}$	30 (BVID)	x3	x3	x3
		60 (VID #1)	x3	x3	x3
		90 (VID #2)	x3	x3	x3
	[45°/90°/-45°/0°]s	30 (BVID)	x3	x3	x3
		60 (VID #1)	x3	x3	x3
		90 (VID #2)	x3	x3	x3
AS4 PW/8552	$[90°/0°]_{2s}$	30 (BVID)	x3	x3	x3
		60 (VID #1)	x3	x3	x3
		90 (VID #2)	x3	x3	x3
	[45°/90°/-45°/0°]s	30 (BVID)	x3	x3	x3
		60 (VID #1)	x3	x3	x3
		75 (VID #2)	x3	x3	x3

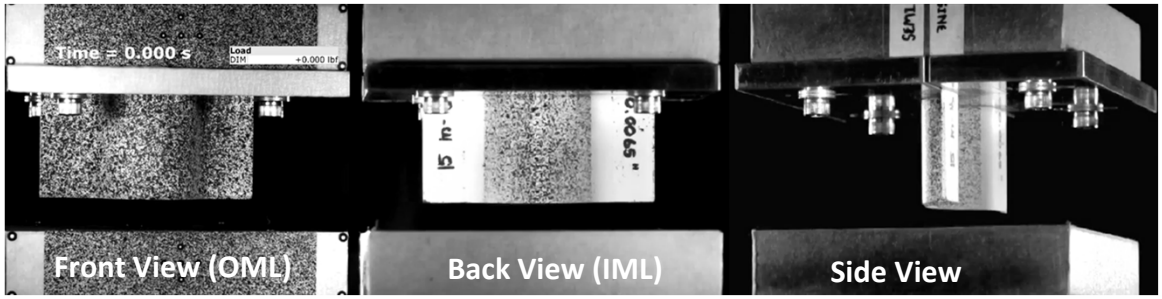


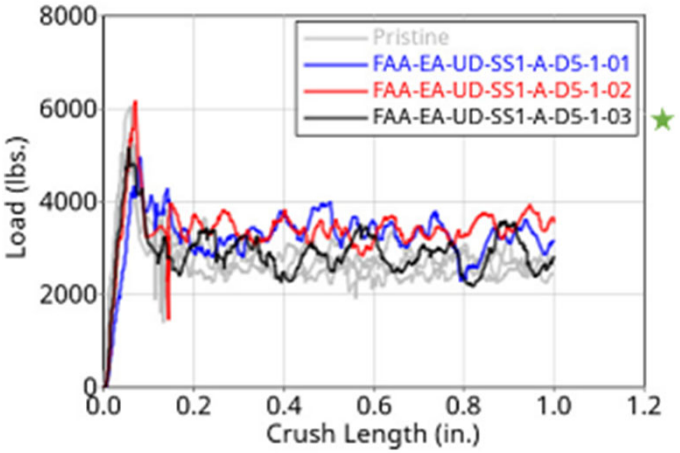
Total Specimens: 216

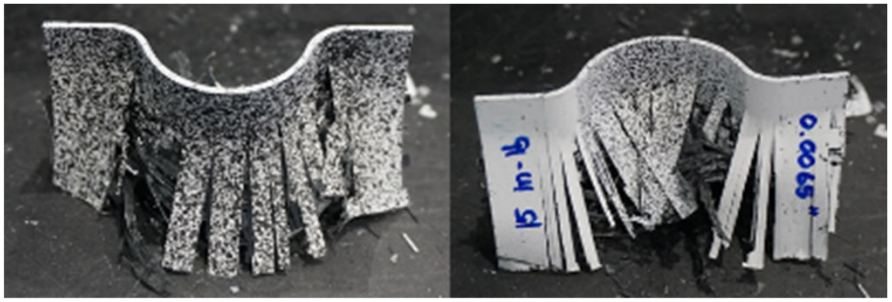
Corrugated Beam (BVID)



Defect Type: Impact Energy 15 in-lb. (BVID)
Material System: IM7/8552**; Stacking Sequence:** $[90^o/0^o]_{2s}$; **Stroke Rate**: 1 in/s



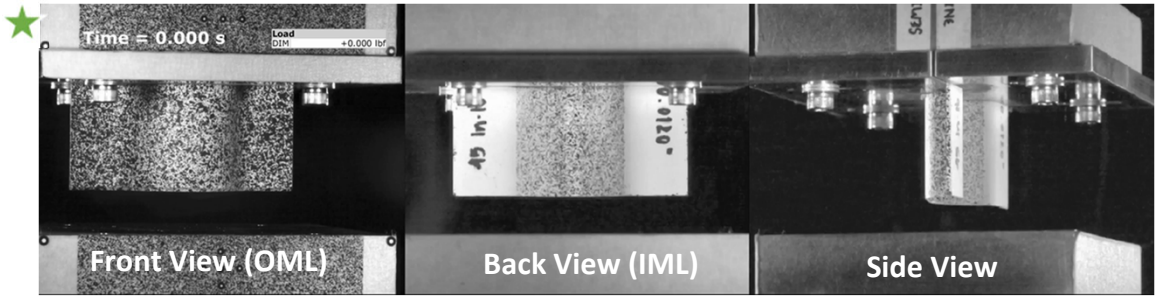


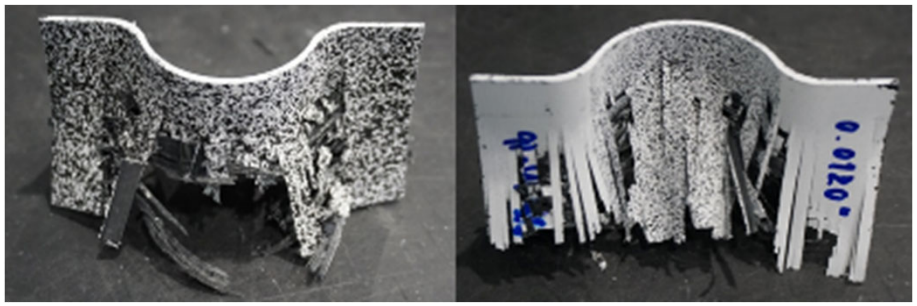


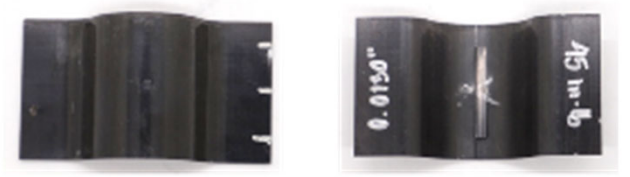
Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb./lb.]	Total CFE
01	4,964.94	3,244.74	227,038.17	0.6535
02	6,184.21	3,408.42	238,490.60	0.5511
03	5,179.72	2,896.72	202,686.60	0.5592
COV	11.96%	8.21%	8.21%	9.68%

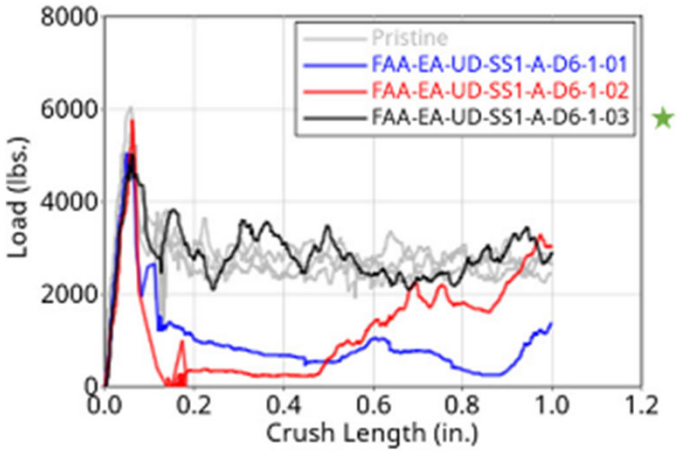
Corrugated Beam (VID #1)

Defect Type: Impact Energy 45 in-lb. (VID#1)
Material System: IM7/8552**; Stacking Sequence:** $[90^o/0^o]_{2s}$; **Stroke Rate**: 1 in/s



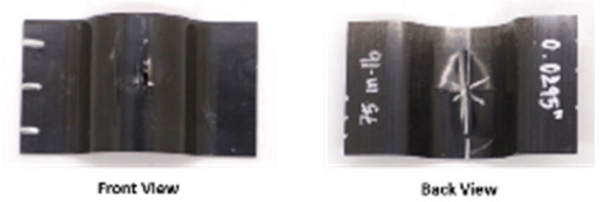




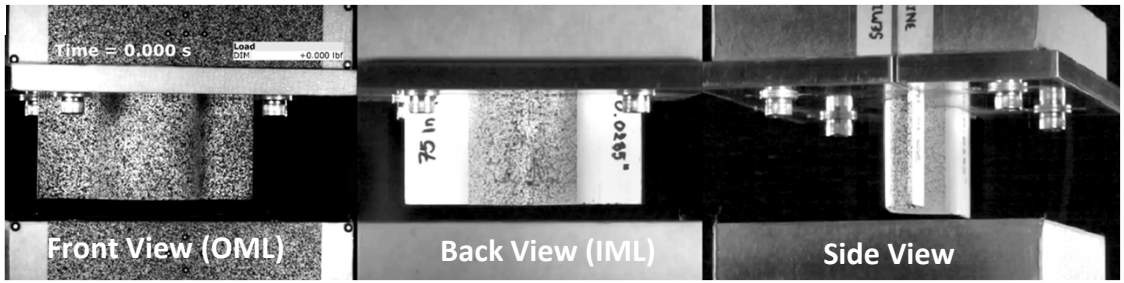


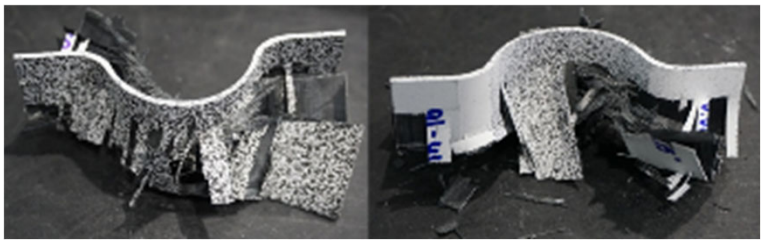
Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb./lb.]	Total CFE
01	5,062.84	997.14	69,770.95	0.1970
02	5,771.56	1,295.50	90,647.29	0.2245
03	5,015.18	2,870.14	200,826.63	0.5723
COV	8.02%	58.48%	58.48%	63.16%

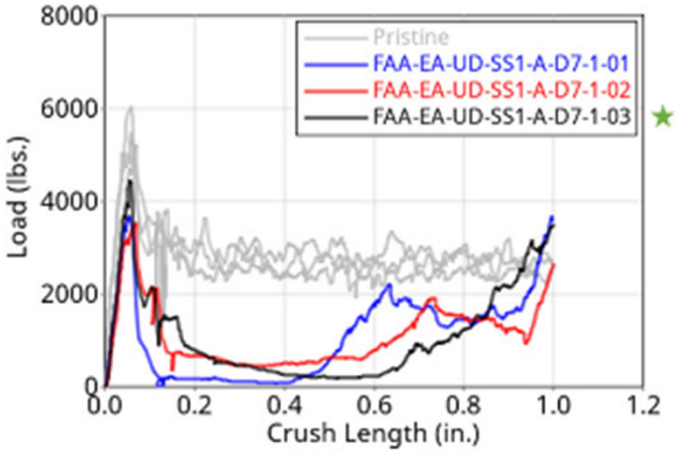
Corrugated Beam (VID #2)



Defect Type: Impact Energy 75 in-lb. (VID#2)
Material System: IM7/8552**; Stacking Sequence:** $[90^o/0^o]_{2s}$; **Stroke Rate**: 1 in/s

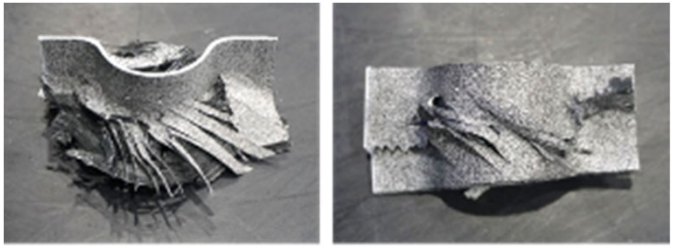




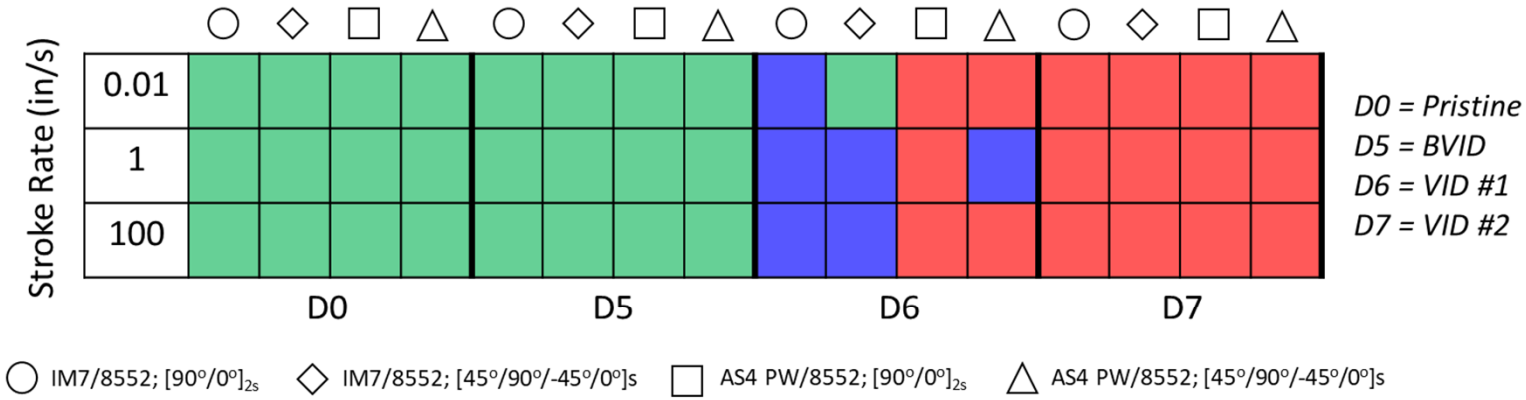


Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb./lb.]	Total CFE
01	3,682.41	106.97	7,484.57	0.0290
02	3,533.29	144.62	10,118.88	0.0409
03	4,443.94	116.79	8,171.85	0.0263
COV	12.57%	15.90%	15.90%	24.26%

Summary :Failure Modes Corrugated Beams



Effects of strain rates & impact damage on crushing behavior of corrugated beam energy absorbers



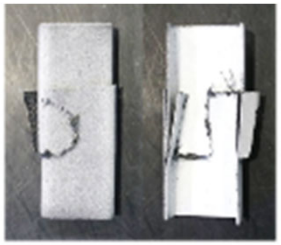
All specimens for this configuration have stable crushing

All specimens for this configuration have unstable crushing

Some specimens for this configuration have stable crushing and some specimens have unstable crushing

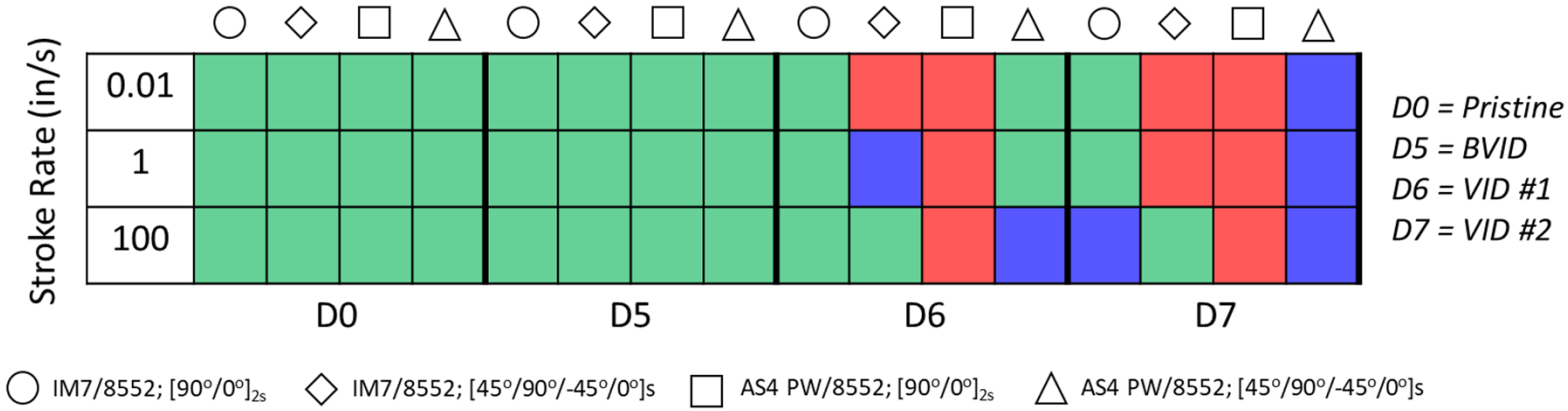
Summary :Failure Modes C-Channel Stanchions

Stable Crushing



Unstable Crushing

Effects of strain rates & impact damage on crushing behavior of c-channel stanchion energy absorbers

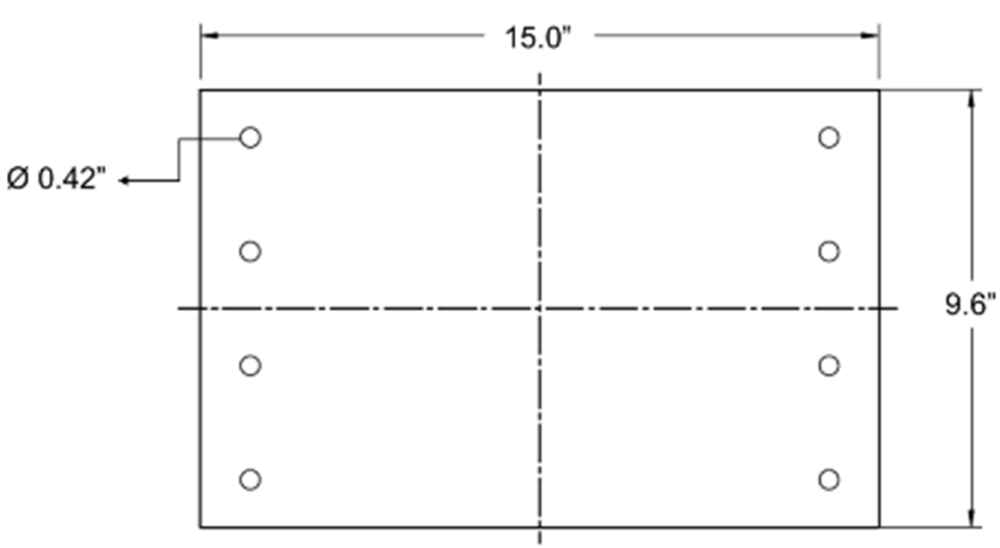


All specimens for this configuration have stable crushing

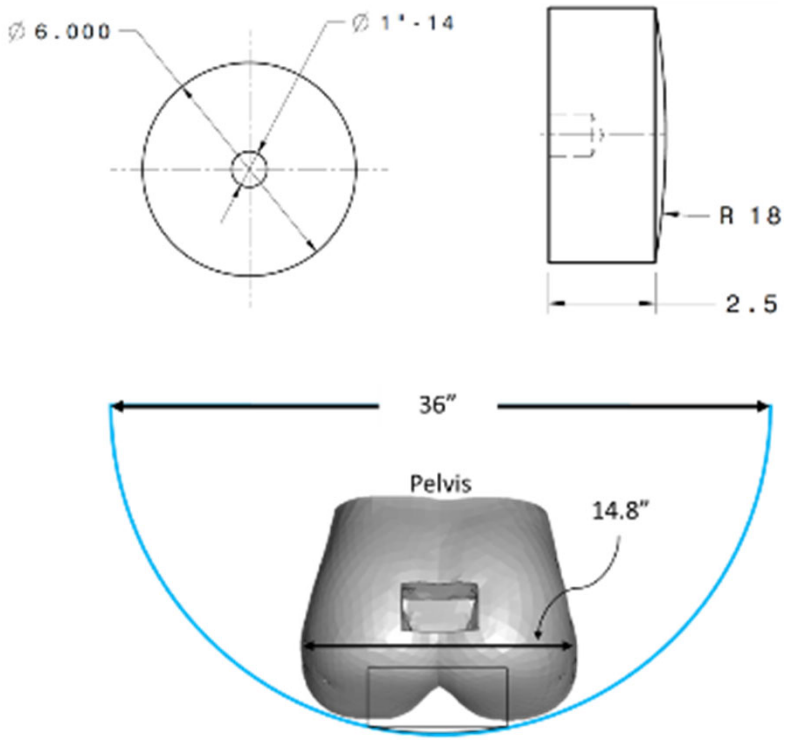
All specimens for this configuration have unstable crushing

Some specimens for this configuration have stable crushing and some specimens have unstable crushing

Task III: Specimen and Impactor Dimension



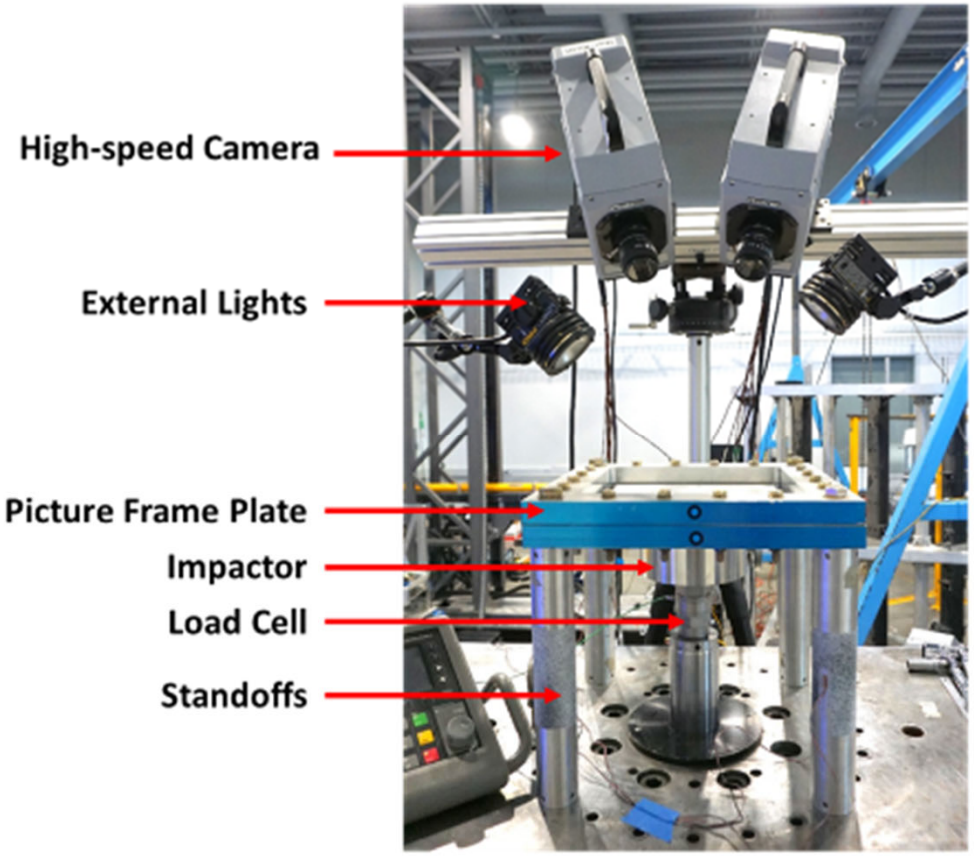
Material System: AS4 PW/8552 (CFRP)
Stacking Sequence: $[0°]_4$



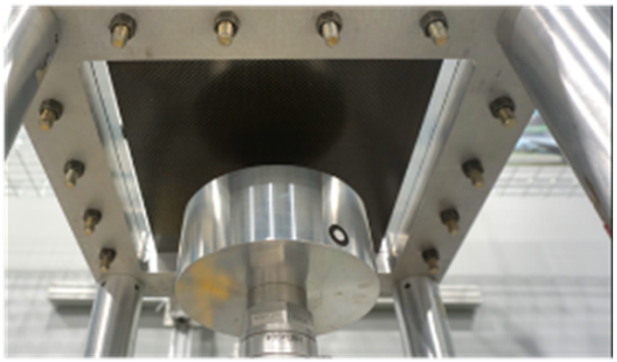
Task III: Test Matrix (Previously Approved)

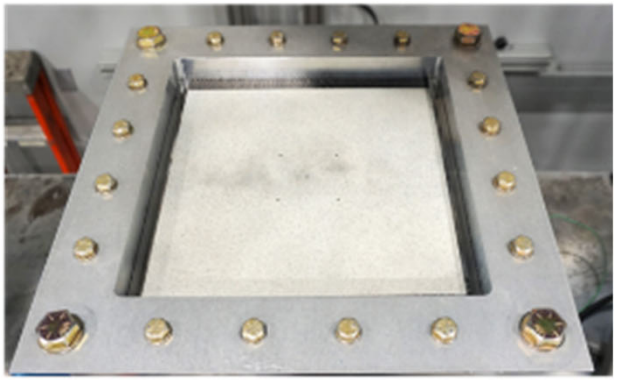
Sub-Component Impact Testing			
Defect Type	Impact Velocity		
	0.01 in/s	1 in/s	100 in/s
Pristine	x3	x3	x3
Wrinkle (IML)	x3	x3	x3
Impact Damage (BVID)	x1	x1	x1
Impact Damage (VID)	x1	x1	x1

Task III Test Setup (Previously Approved)



Impacted Face





Non-Impacted Face

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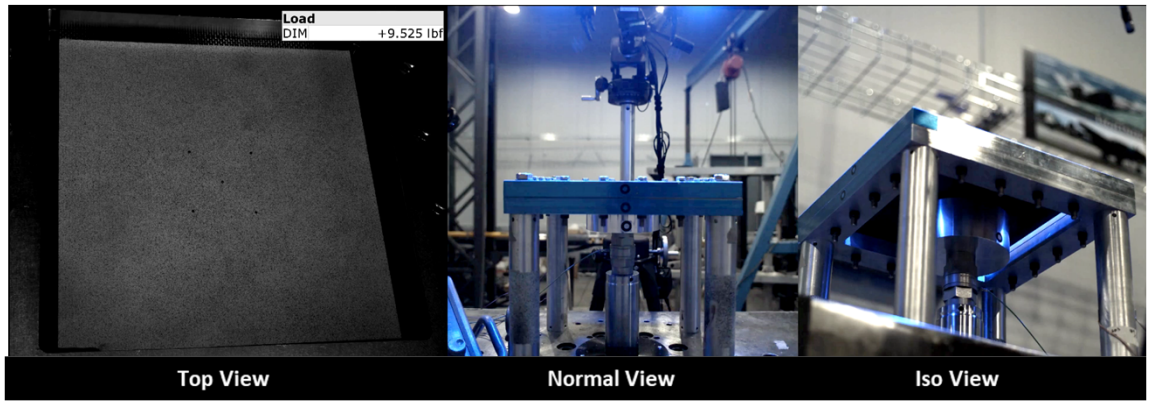
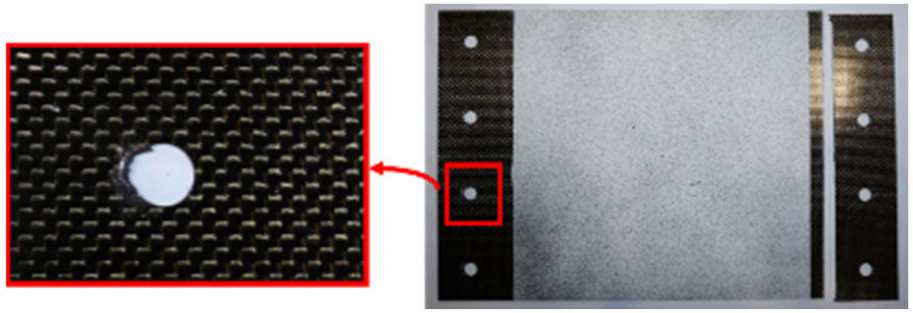
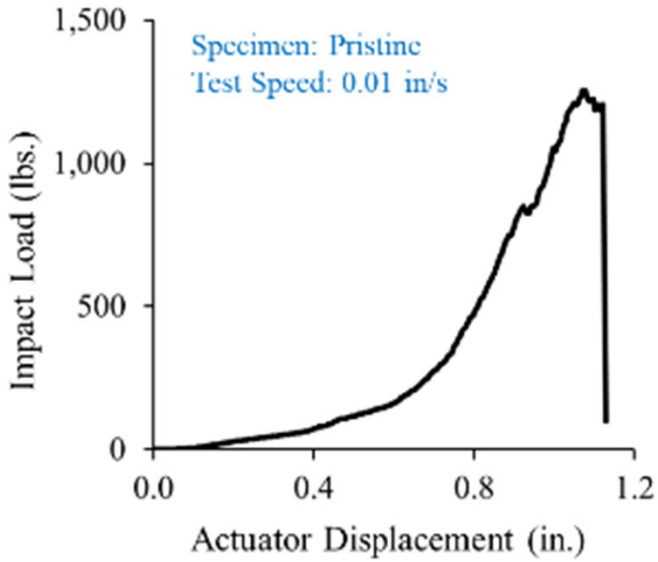
Pristine Configuration



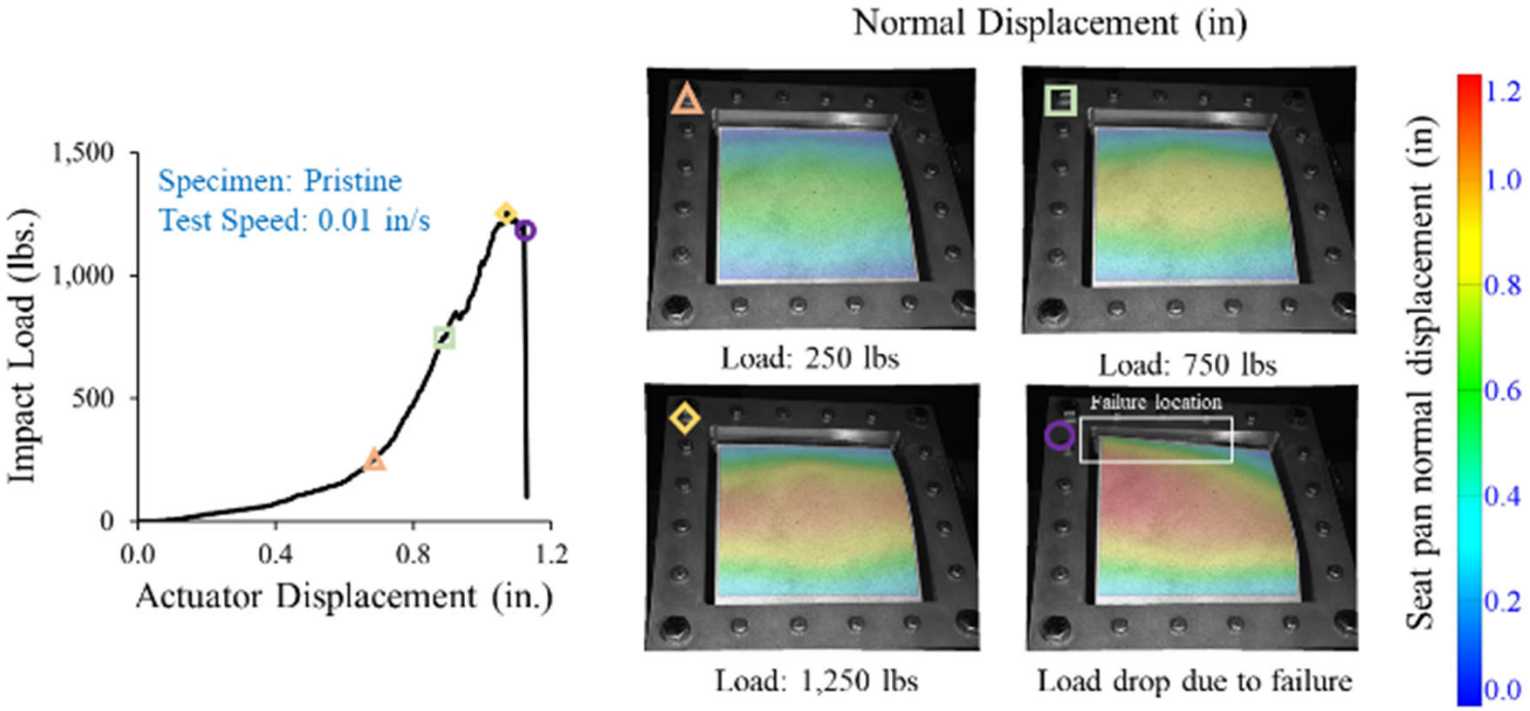
Defect Type: Pristine

Material System: AS4 PW/8552 **Stacking Sequence: $[0^o]_4$**



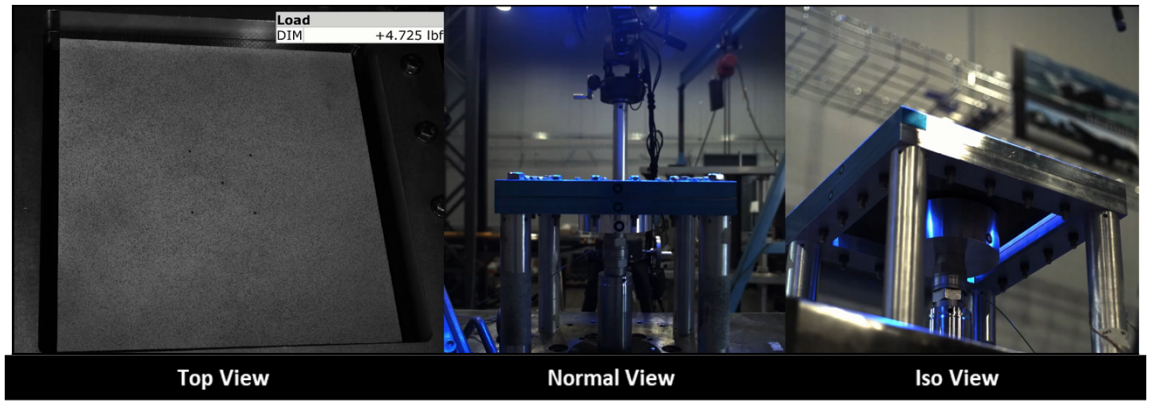


Normal Displacements: Pristine



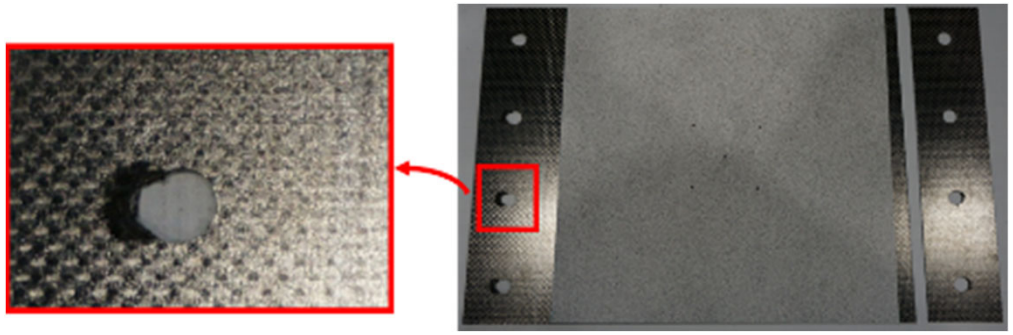
Configuration: Pristine; Test Speed: 0.01 in/s

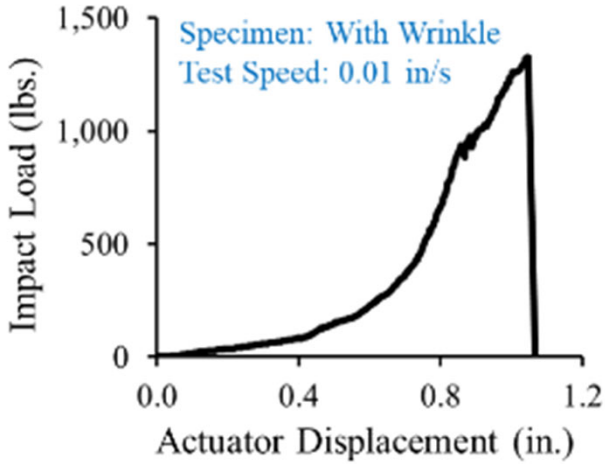
Wrinkle Manufacturing Defect



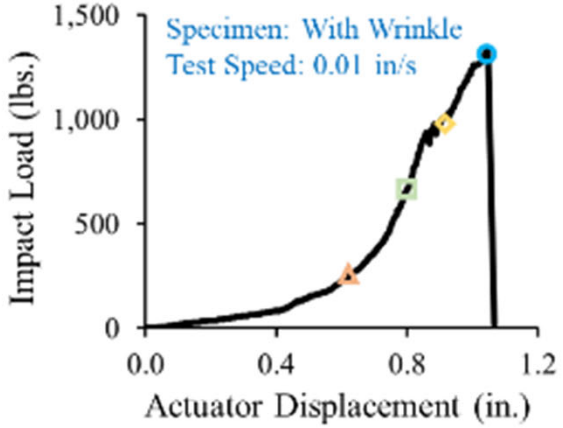
Defect Type: Wrinkle

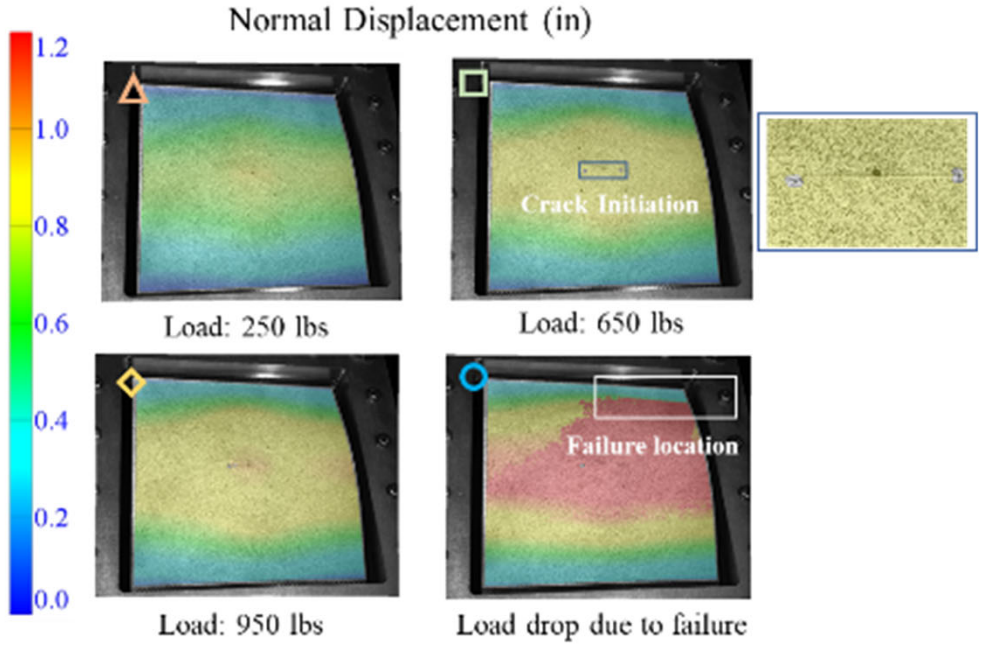
Material System: AS4 PW/8552 **Stacking Sequence: $[0^o]_4$**





Normal Displacements: Wrinkle





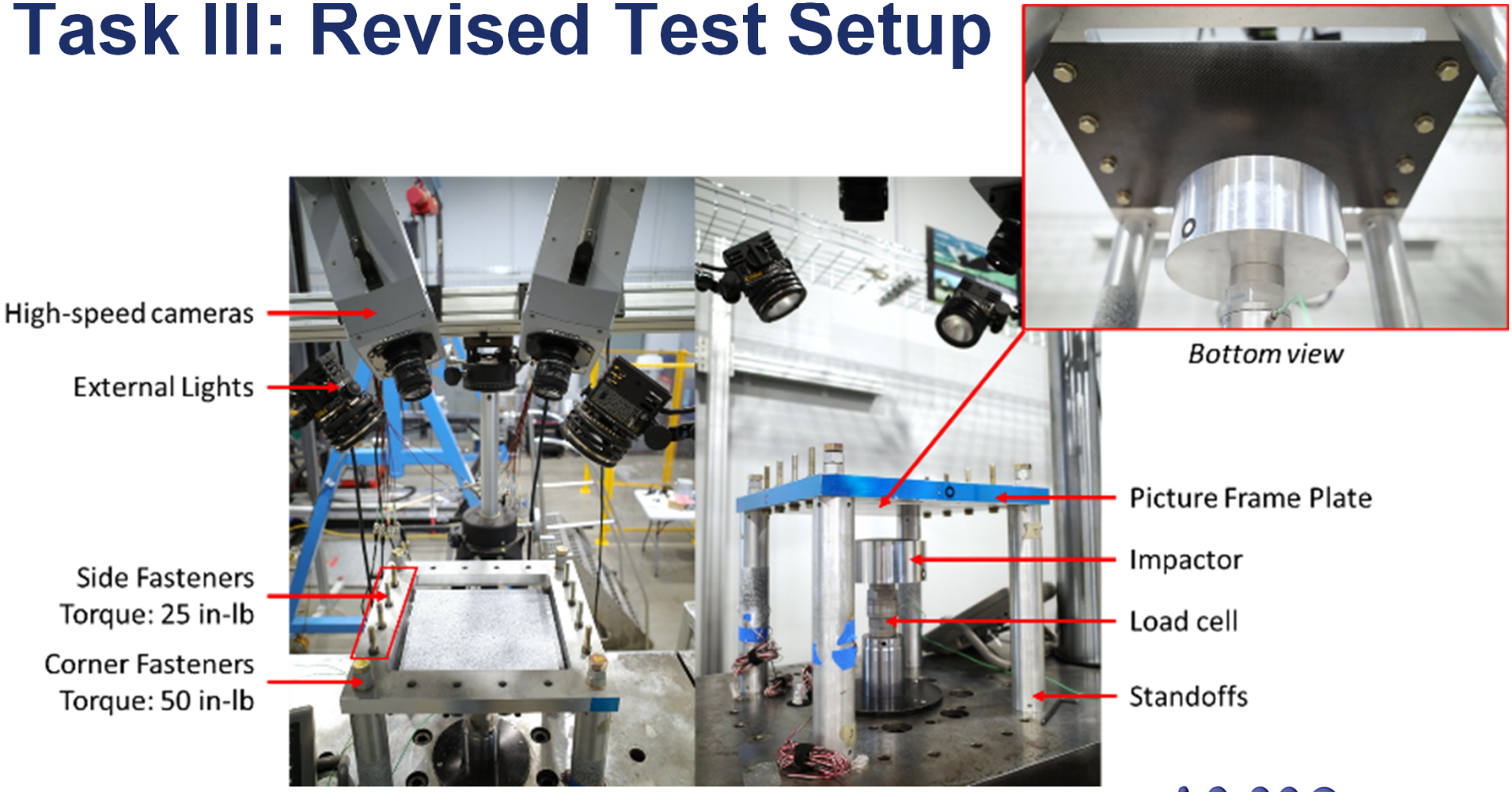
Configuration: Wrinkle Defect; Test Speed: 0.01 in/s

Test Data Comparison: Task III

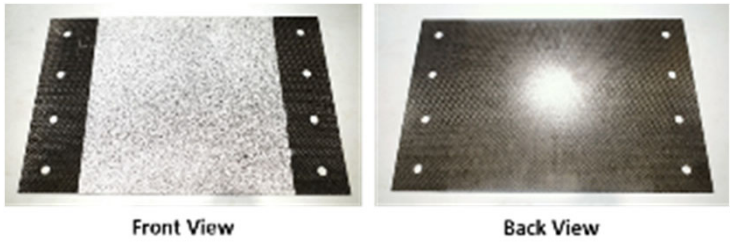
Stroke Rate [in/s]	Seatpan Configuration	Avg. Load at failure [lbs.]	Avg. ω_z at failure [in]	Avg. Ɛyy at failure [micro strain]	Average $\dot{\varepsilon}_{yy}$ [1/s]
0.01	Pristine	1,202	1.10	3,720	2.7E-05
	Wrinkle	1,166	1.07	7,886	9.5E-05
1	Pristine	1,206	0.96	3,290	4.4E-03
	Wrinkle	1,219	1.02	8,175	9.1E-03
100	Pristine	1,290	0.94	3,364	6.4E-01
	Wrinkle	1,371	0.95	9,683	1.02

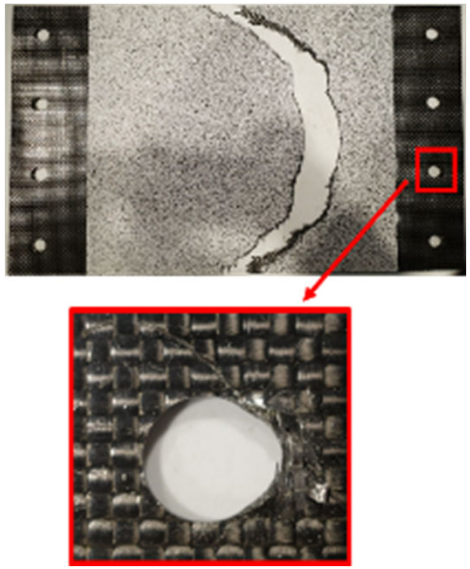
- As the final failure occurs at the clamped edge, no significant difference was observed in failure load and normal displacement for both the configurations
- Due to the crack initiation at the vicinity of the wrinkle, the in-plane normal strains (and thus the strain rates) obtained at the center of the seatpan are higher in comparison to the pristine configuration

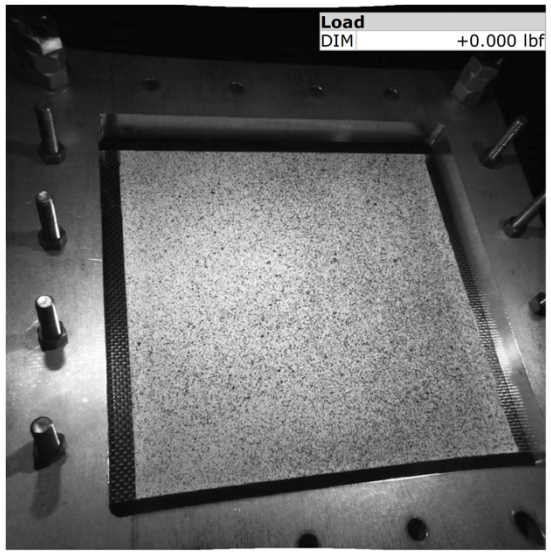
Task III: Revised Test Setup



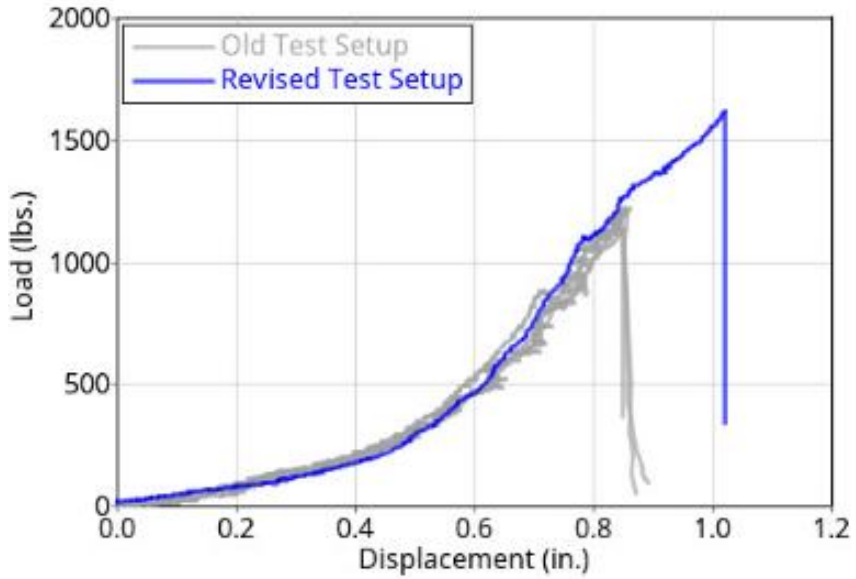
Pristine Configuration







Test speed: 1 in/s



Defect Type: Pristine

Material System: AS4 PW/8552 **Stacking Sequence: $[0^o]_4$**

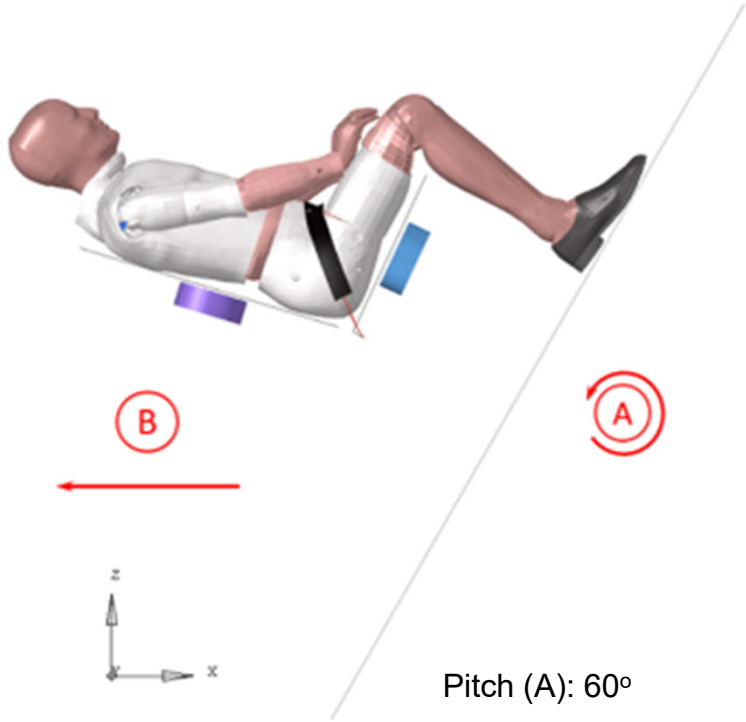
Task III: Updated Test Matrix (Revised Setup)

Sub-Component Impact Testing (Updated Boundary Condition)			
Defect Type	Impact Velocity		
	0.01 in/s	1 in/s	100 in/s
Pristine	x3	x3	x3
Wrinkle (IML)	x3	x3	x3
Delamination (size TBD)	x3	x3	x3
Impact Damage (BVID)	x3	x3	x3
Impact Damage (VID)	x3	x3	x3

Based on discussion with the FAA, it was determined that there is a need to conduct the tests for Task III with the new boundary conditions.

Task IV: Overview

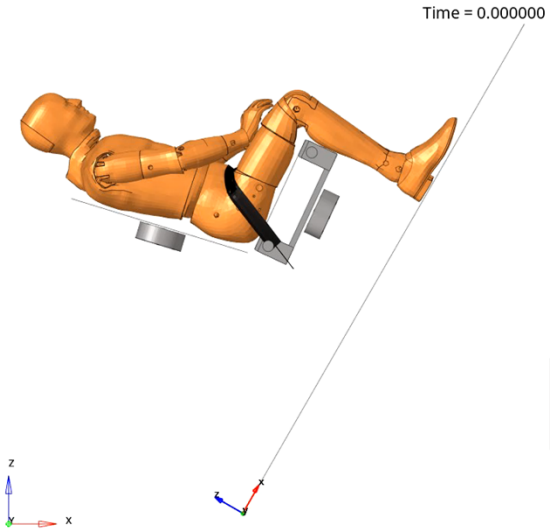
Full Scale Vertical Test – Rigid Seat with Composite Seatpan	
Defect Type	**Acceleration Pulse: 14g**
Pristine	x1
Wrinkle (IML)	x1
Delamination (size TBD)	x1
Impact Damage (BVID)	x1
Impact Damage (VID)	x1

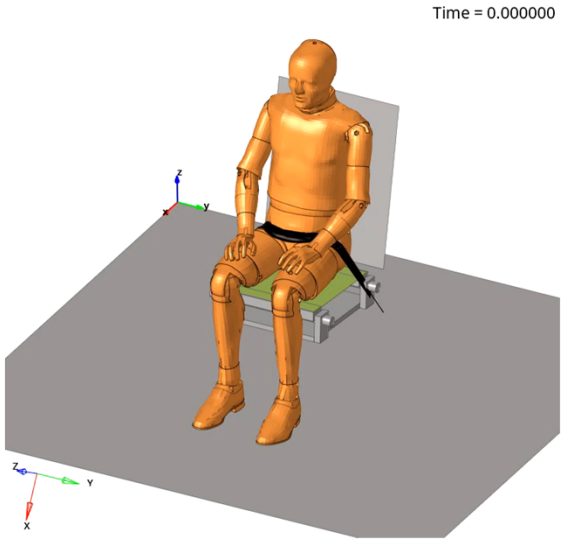


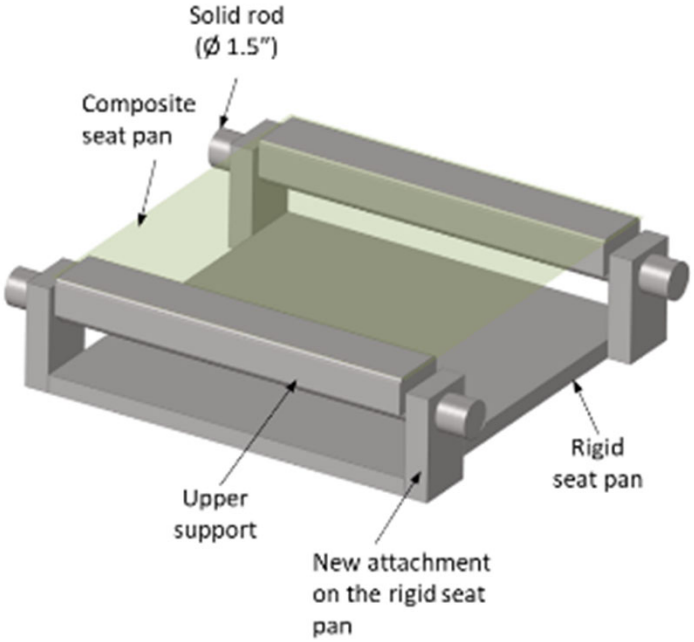
Pitch (A): 60°

Acceleration Ideal Pulse (B): 14g

Task IV: Ongoing Work

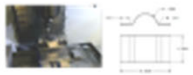






Designing fixture to attach deformable composite seat to rigid seat

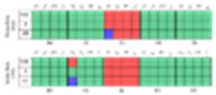
Current Progress Summary



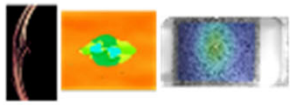
Specimen machining:
*Specimens waterjet
*Surface grinded
*One edge chamfered 45°
*~ 800 specimens machined

Testing Status:
*Manufacturing defects finished
*Damage evolution captured
*Post-test images

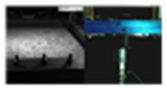
Effects of strain rates observed on manufacturing defect for tape material with cross-ply stacking sequence



In-service damage evaluation:
*TTU C-Scan, Pulse-Echo
*Micro x-ray ct
*DIC on non-impacted face



Sub-component test:
*Preliminary tests to determine strain rates has been finished
*In service damage introduction: ongoing

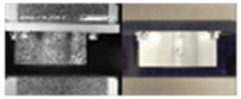


Energy absorber laminate fabrication:
*2 material systems
*2 stacking sequences
*4 manufacturing defects
*168 laminates
*24 autoclave cure cycles

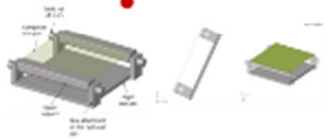
Test Setup:
*Compression loading condition
*Custom fixture
*High speed camera setup
*DIC conducted on the OML side

Major Observations:
*Reduction in energy absorption found with fiber wrinkling
*Delamination did not have significant effect on energy absorption capabilities

In-service damage introduction:
*Single IVI with custom fixture
*Survey to identify energy levels
*3 energies selected per config.
*Supported with DIC



Energy absorber testing with in-service damage:
* Testing finished
* VID causes significant reduction in EA
* Data evaluation ongoing



Full-scale test:
*Test article fabrication finished
*Conducting simulations to design custom test fixture to install on rigid seat

Potential Future Work

- **Evaluate scalability of defects to sub-component level energy absorbers**
  - Use a combination of analytical and testing methods to reduce the cost and timeline of the program.
- **Evaluate effects of defects on other main load path seat components: cross-tubes, seat spreaders, seat legs, seatbacks, etc.**
- **Full scale analysis to understand how defects change the load path in aircraft seats structures.**

Published Technical Papers

- **“Effects of Manufacturing Defects on Composite Seat Pans at Static and Dynamic Strain Rates”**
  - http://dx.doi.org/10.2514/6.2024-1404
- **“Effects of Impact Damage on the Energy Absorption Capabilities of Composite Materials”**
  - http://dx.doi.org/10.12783/asc38/36577
- **“Low Velocity Impact on Composite Energy Absorbers: Experimental Analysis”**
  - https://arc.aiaa.org/doi/10.2514/6.2023-1262
- **“Effect Of Manufacturing Defects On Composite Energy Absorbers: Experimental Analysis”**
  - https://dpi-proceedings.com/index.php/asc37/article/view/36389

Questions?