Effects of Defects in Composite Materials at Elevated Strain Rates

Federal Aviation Administration

Presented by:

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JAMS

Joint Centers of Excellence for Advanced Materials

JAMS Technical Review

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Agenda

- Research Team
- Project Motivation
- Project Breakdown and Approach
- Task II
    - Laminate Fabrication
    - In-Service Damage Introduction
    - Compression Test Results at 1 in/s
- Task III Overview
- Task IV Overview
- Current Project Status Summary
- Ongoing Work

Research Team

- **Project Participants (NIAR AVET/WSU)**
  - PI: Gerardo Olivares, Suresh Raju Keshavanarayana
  - Primary Researchers: Akhil Bhasin, Luis Gomez, Tanat Maichan
  - Additional Researchers: Parth Sejpal, Alejandro Fernandez
- **FAA Technical Monitor**:
  - Dave Stanley
- **FAA Sponsors**:
  - Cindy Ashforth, Joseph Pellettiere
- **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.

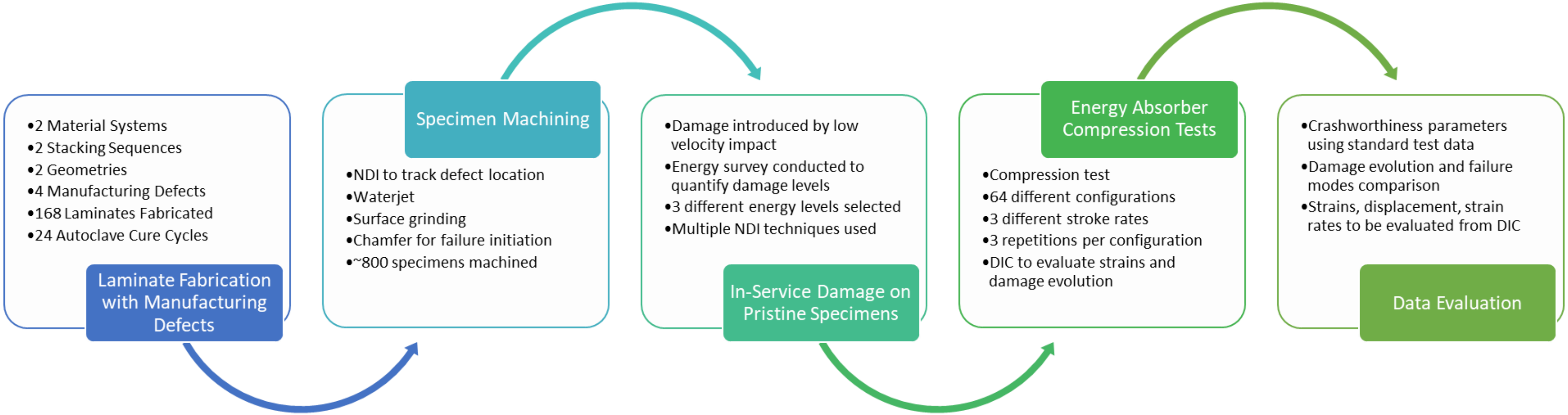
[1] SAE ARP 6337, Design, Manufacturing and Performance standard for Composite Materials used on Aircraft Seat Structures

Project Task Breakdown & Approach

- Task I: Literature Research
- Task II: Energy Absorber Test
- Task III: Sub-Component Impact Test
- Task IV: Full scale vertical rigid seat test

- **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 with Manufacturing Defects

- 2 Material Systems
- 2 Stacking Sequences
- 2 Geometries
- 4 Manufacturing Defects
- 168 Laminates Fabricated
- 24 Autoclave Cure Cycles

Specimen Machining

- NDI to track defect location
- Waterjet
- Surface grinding
- Chamfer for failure initiation
- ~800 specimens machined

In-Service Damage on Pristine Specimens

- Damage introduced by low velocity impact
- Energy survey conducted to quantify damage levels
- 3 different energy levels selected
- Multiple NDI techniques used

Energy Absorber Compression Tests

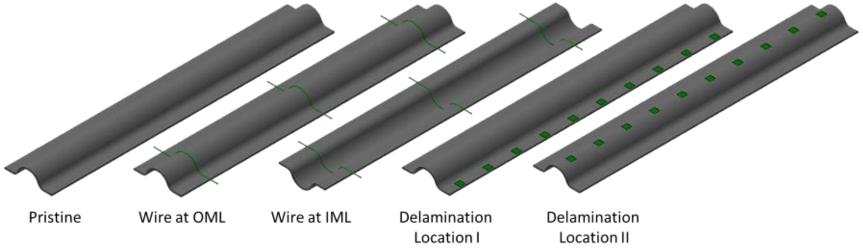
- Compression test
- 64 different configurations
- 3 different stroke rates
- 3 repetitions per configuration
- DIC to evaluate strains and damage evolution

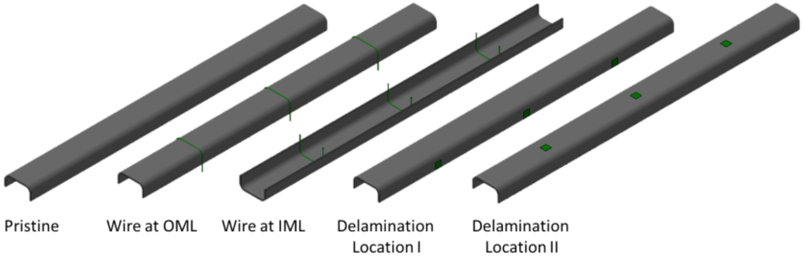
Data Evaluation

- Crashworthiness parameters using standard test data
- Damage evolution and failure modes comparison
- Strains, displacement, strain rates to be evaluated from DIC

Laminate Fabrication Overview

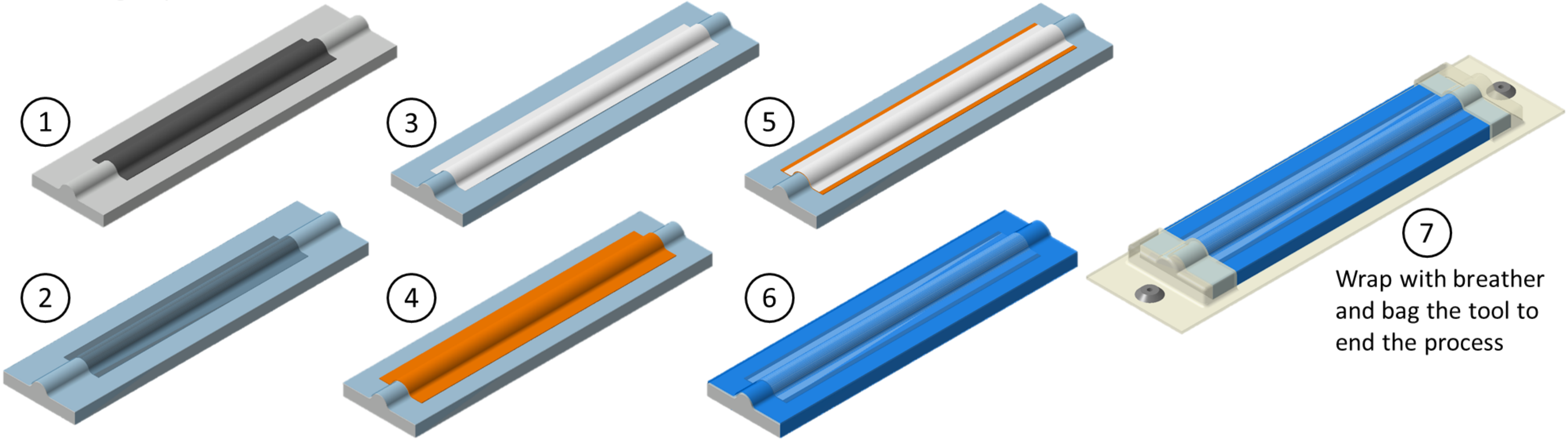
Panel Type	Configuration	Laminates Fabricated
Pristine	C-Channel Stanchion	64
Wire placed at OML		16
Wire placed at IML		16
Delamination Location I		16
Delamination Location II		16
Pristine	Corrugated Beam (Semi-Sine)	8
Wire placed at OML		12
Wire placed at IML		12
Delamination Location I		4
Delamination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

Corrugated Beam: Bagging Scheme



① Layup each ply according to stacking sequence on the tool

② Cover the plies and tooling with release film

③ Place a layer of Teflon on top

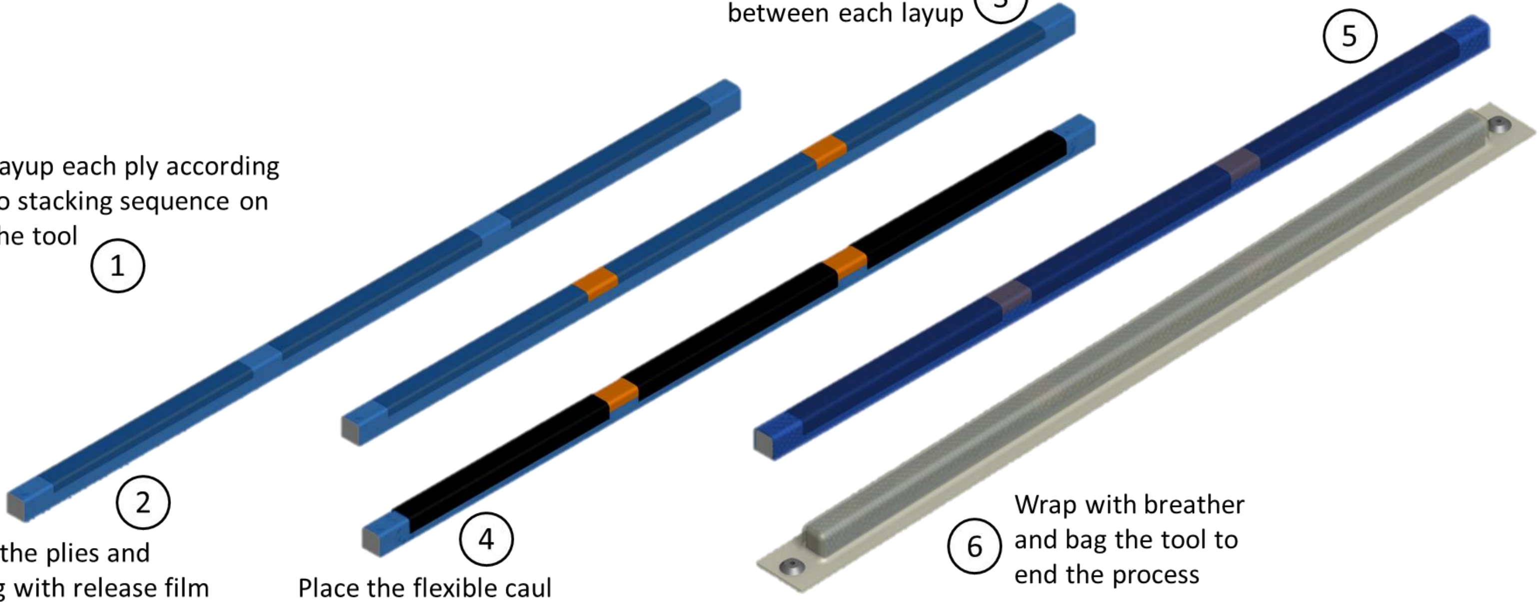
④ Place a silicon layer on top of the first Teflon layer

⑤ Place another layer of Teflon on top of the silicon

⑥ Cover the tool with peel ply

⑦ Wrap with breather and bag the tool to end the process

Laminate Bagging Scheme



① Layup each ply according to stacking sequence on the tool

② Cover the plies and tooling with release film

③ Place silicon damp between each layup

④ Place the flexible caul plate on top of layups

⑤ Cover the caul plate and tool with release film

⑥ Wrap with breather and bag the tool to end the process

Manufactured Laminate: IM7/8552


Configuration: C-Channel; Material System: IM7/8552; Pristine


Configuration: C-Channel; Material System: IM7/8552; Wire x IML


Configuration: C-Channel; Material System: IM7/8552; Wire x OML


Configuration: C-Channel; Material System: IM7/8552; Delamn. A


Configuration: C-Channel; Material System: IM7/8552; Delamn. B


Configuration: Semi-Sine; Material System: IM7/8552; Pristine


Configuration: Semi-Sine; Material System: IM7/8552; Wire x IML


Configuration: Semi-Sine; Material System: IM7/8552; Wire x OML


Configuration: Semi-Sine; Material System: IM7/8552; Delamn. A


Configuration: Semi-Sine; Material System: IM7/8552; Delamn. B

Manufactured Laminate: AS4 PW/8552


Configuration: C-Channel; Material System: AS4 PW/8552; Pristine


Configuration: C-Channel; Material System: AS4 PW/8552; Wire x IML


Configuration: C-Channel; Material System: AS4 PW/8552; Wire x OML


Configuration: C-Channel; Material System: AS4 PW/8552; Delamn. A


Configuration: C-Channel; Material System: AS4 PW/8552; Delamn. B


Configuration: Semi-Sine; Material System: AS4 PW/8552; Wire x IML

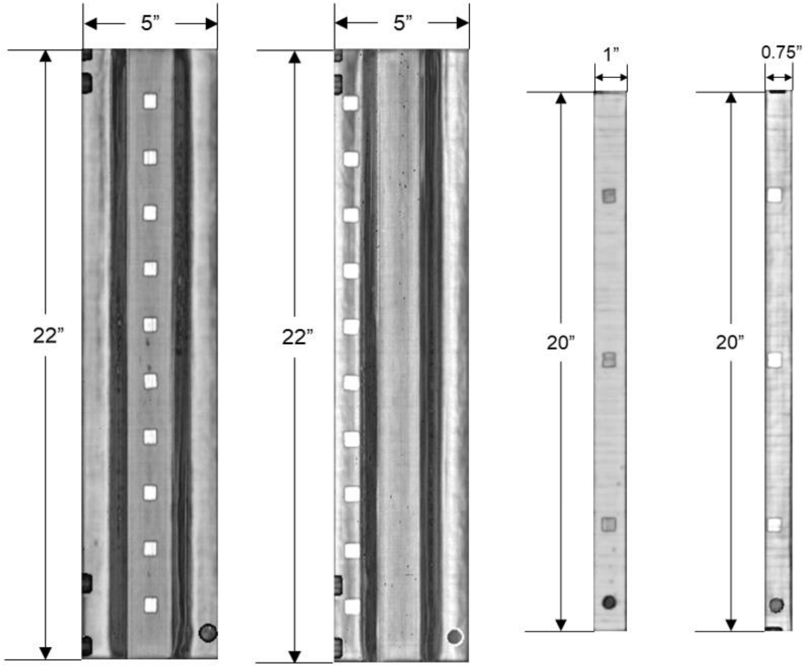

Configuration: Semi-Sine; Material System: AS4 PW/8552; Wire x OML


Configuration: Semi-Sine; Material System: AS4 PW/8552; Delamn. A


Configuration: Semi-Sine; Material System: AS4 PW/8552; Delamn. B

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

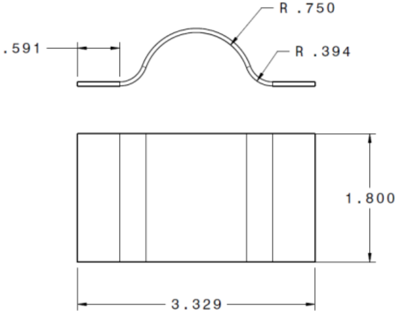


Corrugated Beam

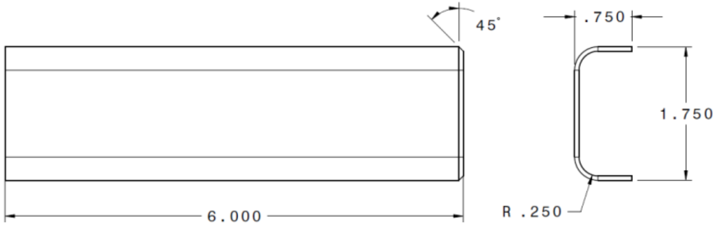
C-Channel Stanchion

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)

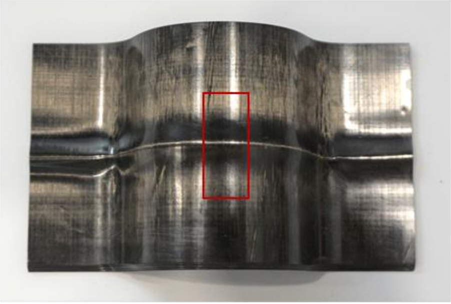


C-Channel Specimen
(dimensions in inches)

Edge Chamfering

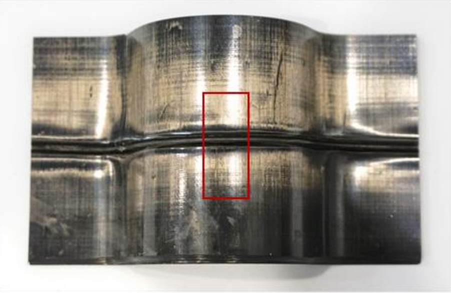
Microscopic Analysis: Fiber Waviness

IM7/8552; $[90^\circ/0^\circ]_{2s}$



Waviness due to the wire placed at IML

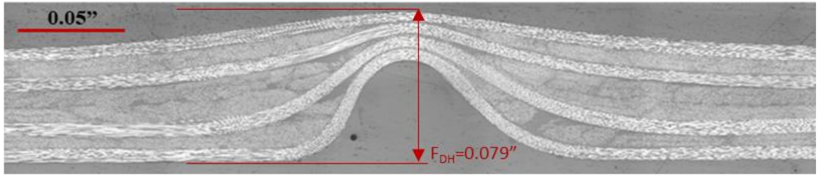
IM7/8552; $[90^\circ/0^\circ]_{2s}$



Waviness due to the wire placed at OML

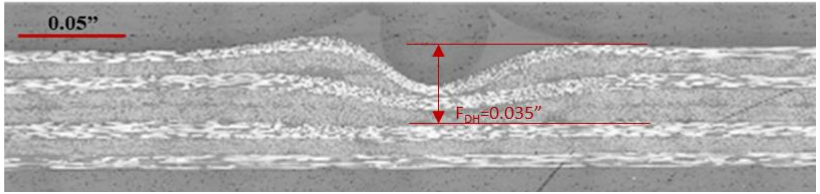
Potted specimen in clear epoxy

IM7/8552; $[90^\circ/0^\circ]_{2s}$



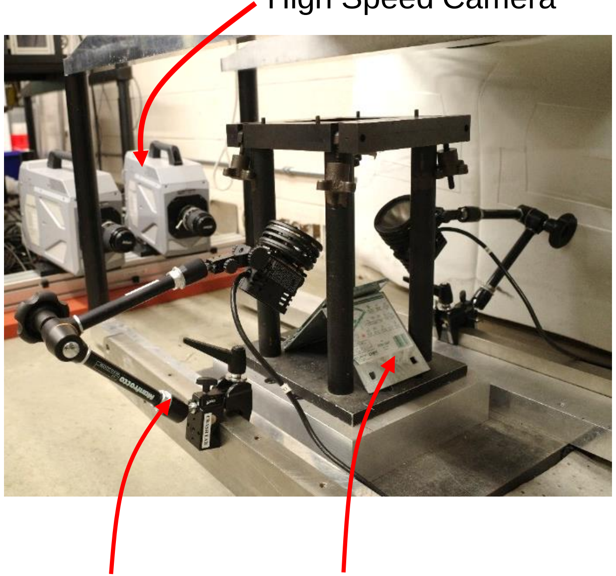
Waviness due to the wire placed at IML

IM7/8552; $[90^\circ/0^\circ]_{2s}$



Waviness due to the wire placed at OML

In-Service Impact Damage: LVI

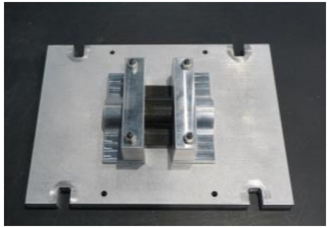


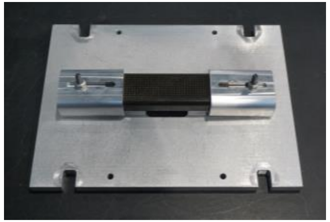
High Speed Camera

External Lights

First Surface Mirror

Corrugated Beam





C-Channel

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

IM7/8552 $[90^\circ/0^\circ]_{2S}$

IM7/8552 $[45^\circ/90^\circ/-45^\circ/0^\circ]_S$

AS4 PW/8552 $[90^\circ/0^\circ]_{2S}$

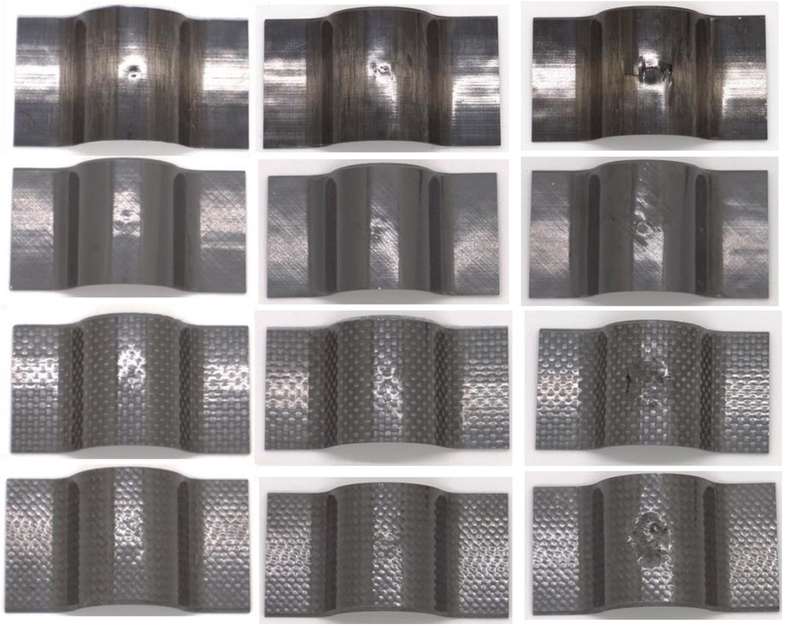
AS4 PW/8552 $[45^\circ/90^\circ/-45^\circ/0^\circ]_S$

Impacted Face (OML)

Energy Level: 15 in-lb.

Energy Level: 45 in-lb.

Energy Level: 75 in-lb.



Non Impacted Face (IML)

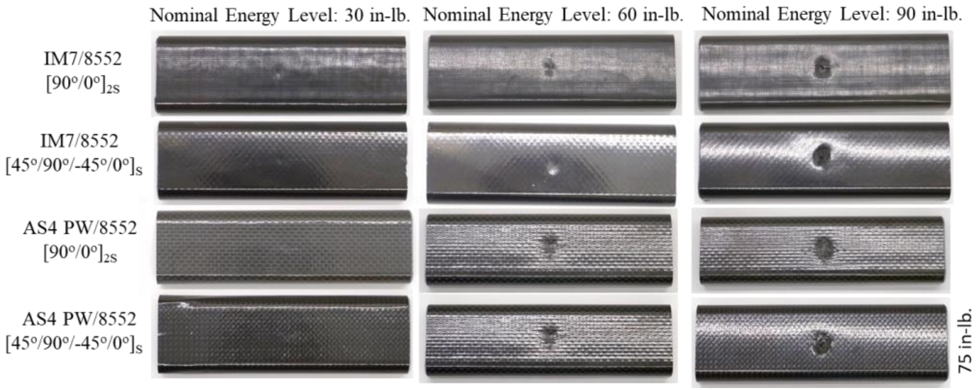
Energy Level: 15 in-lb.

Energy Level: 45 in-lb.

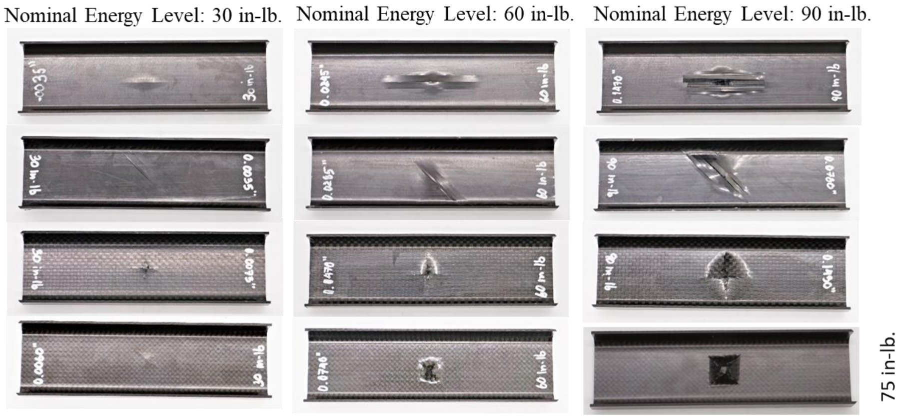
Energy Level: 75 in-lb.

Damage Level – C-Channel

Impacted Face (OML)

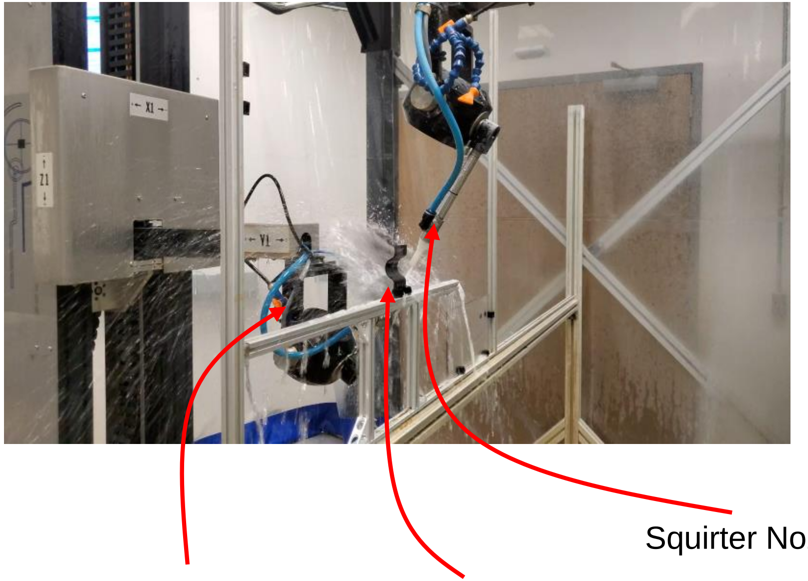


Non Impacted Face (IML)



TTU C-Scan and Pulse Echo Details

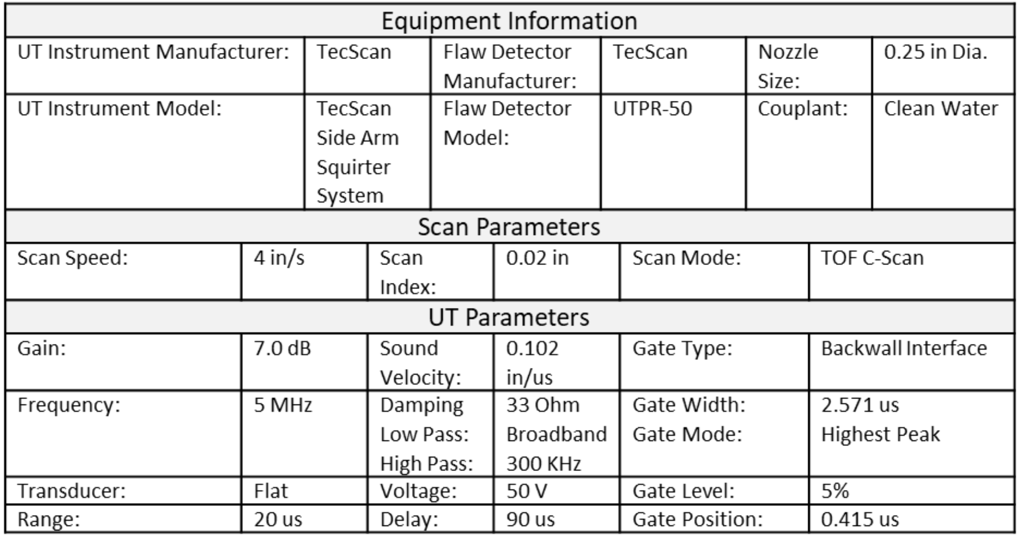
TTU C-Scan Setup for Corrugated Beam



Squirter Nozzle

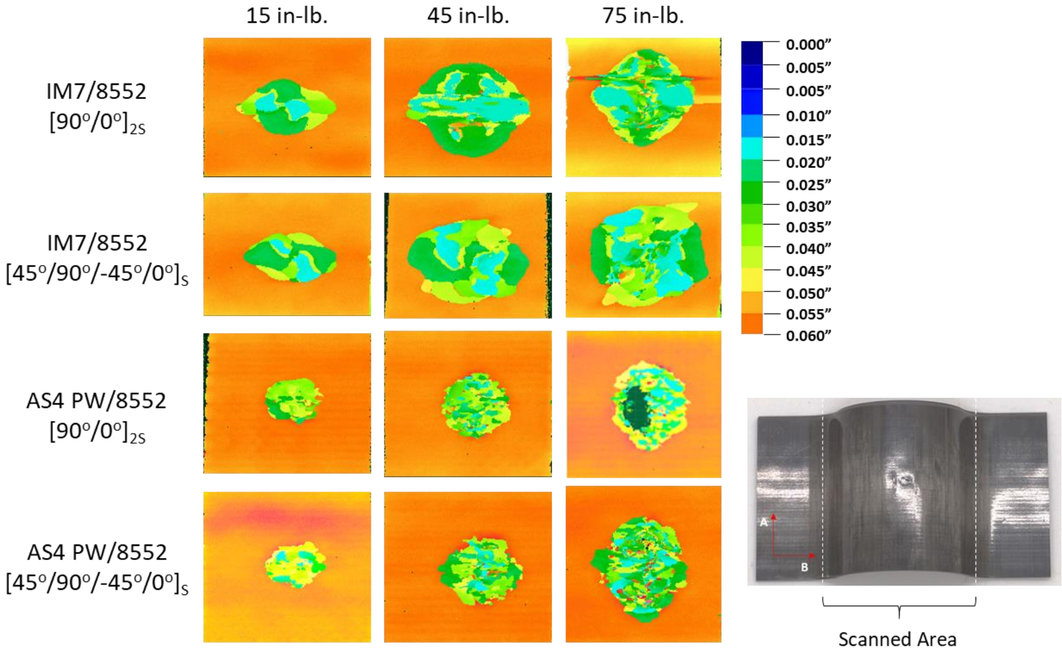
X-axis tower, Y-axis carriages and Z-Axis Swivel assembly

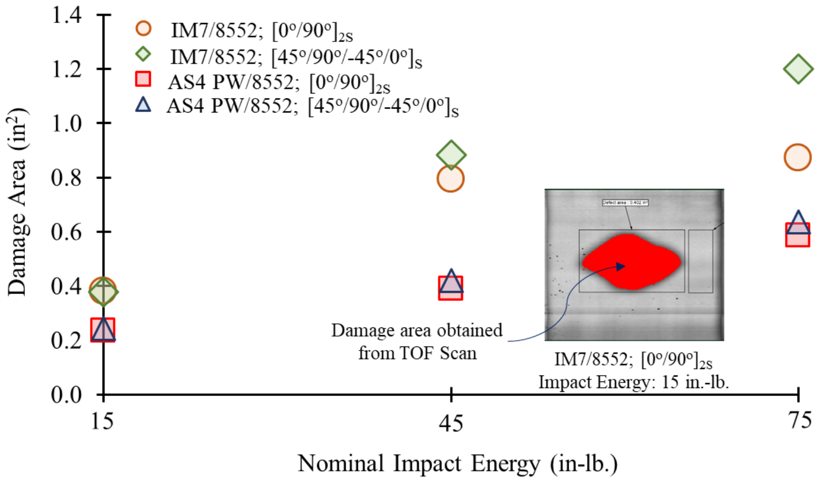
Specimen



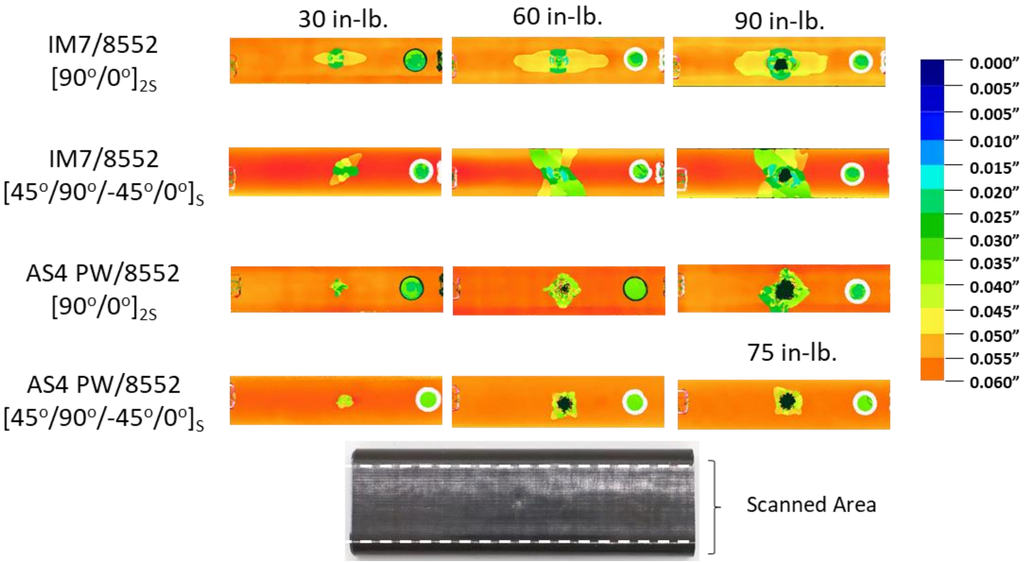
Equipment Information					
UT Instrument Manufacturer:	TecScan	Flaw Detector Manufacturer:	TecScan	Nozzle Size:	0.25 in Dia.
UT Instrument Model:	TecScan Side Arm Squirter System	Flaw Detector Model:	UTPR-50	Couplant:	Clean Water
Scan Parameters					
Scan Speed:	4 in/s	Scan Index:	0.02 in	Scan Mode:	TOF C-Scan
UT Parameters					
Gain:	7.0 dB	Sound Velocity:	0.102 in/us	Gate Type:	Backwall Interface
Frequency:	5 MHz	Damping Low Pass: High Pass:	33 Ohm Broadband 300 KHz	Gate Width: Gate Mode:	2.571 us Highest Peak
Transducer:	Flat	Voltage:	50 V	Gate Level:	5%
Range:	20 us	Delay:	90 us	Gate Position:	0.415 us

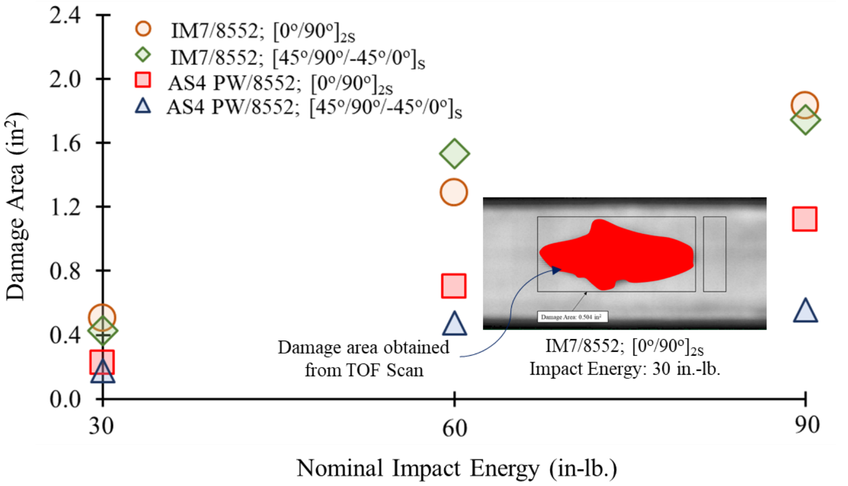
Damage Area: Corrugated Beam





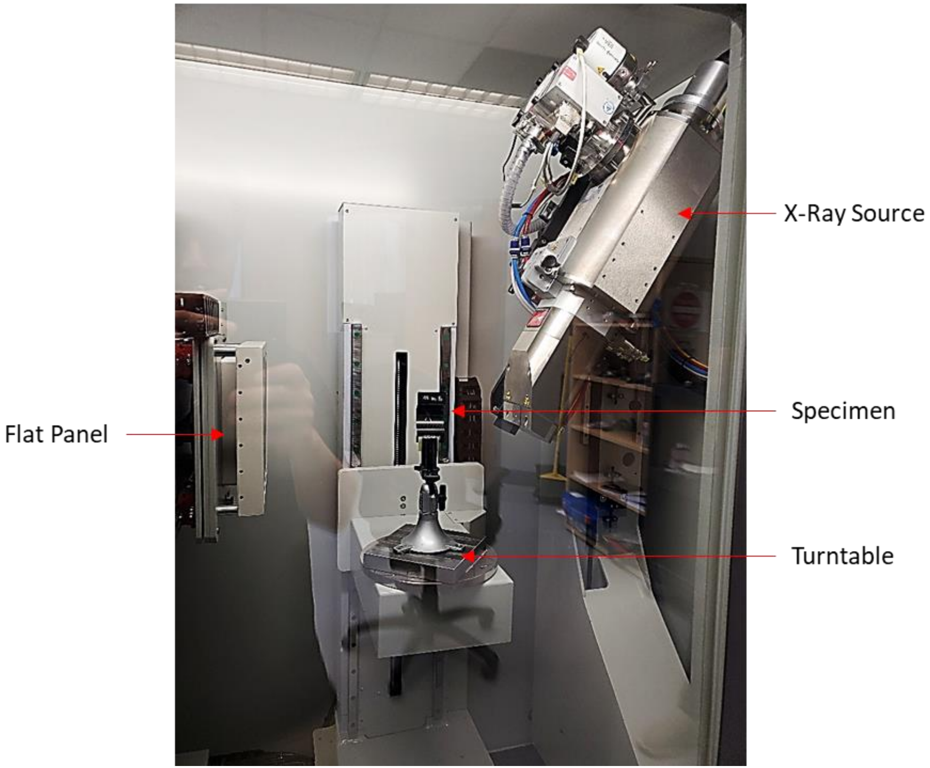
Damage Area: C-Channel

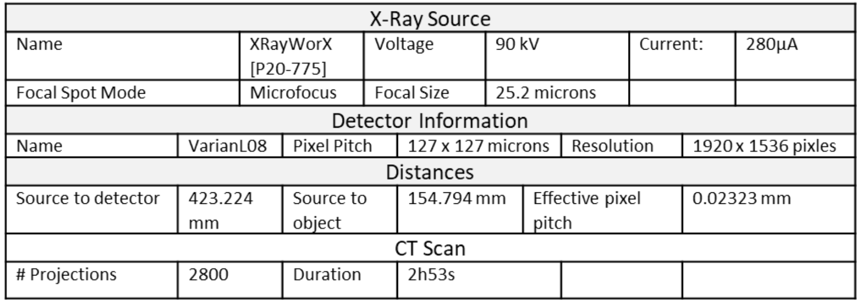




X-Ray Ct Details

NSI X3000

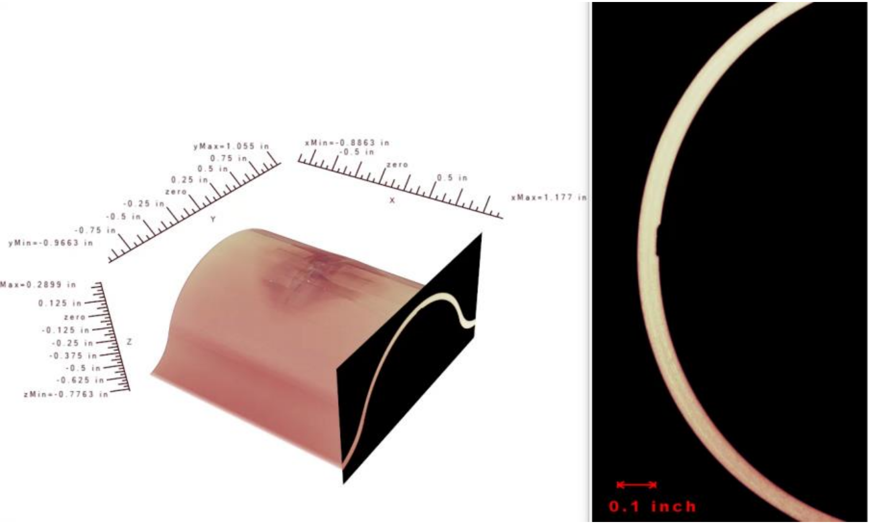


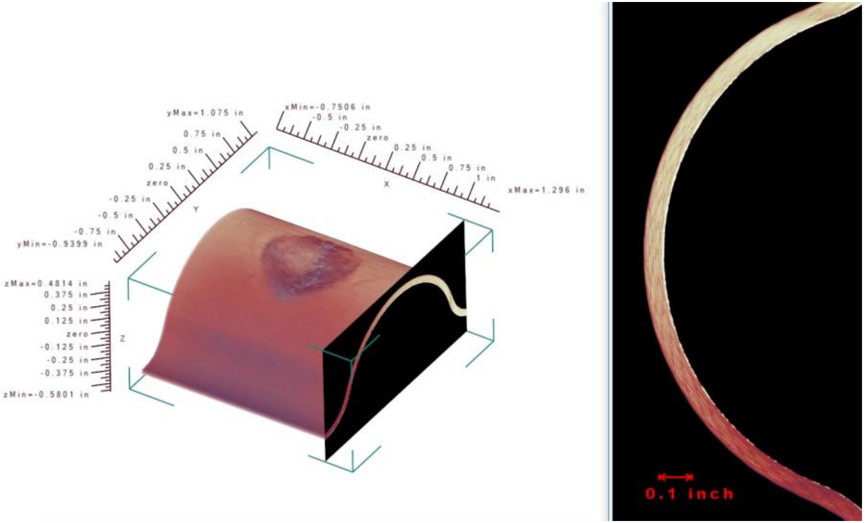


X-Ray Source					
Name	XRayWorX [P20-775]	Voltage	90 kV	Current:	280µA
Focal Spot Mode	Microfocus	Focal Size	25.2 microns		
Detector Information					
Name	VarianL08	Pixel Pitch	127 x 127 microns	Resolution	1920 x 1536 pixles
Distances					
Source to detector	423.224 mm	Source to object	154.794 mm	Effective pixel pitch	0.02323 mm
CT Scan					
# Projections	2800	Duration	2h53s		

X-Ray Ct: Corrugated Beam

Nominal Impact Energy: 75 in-lb.



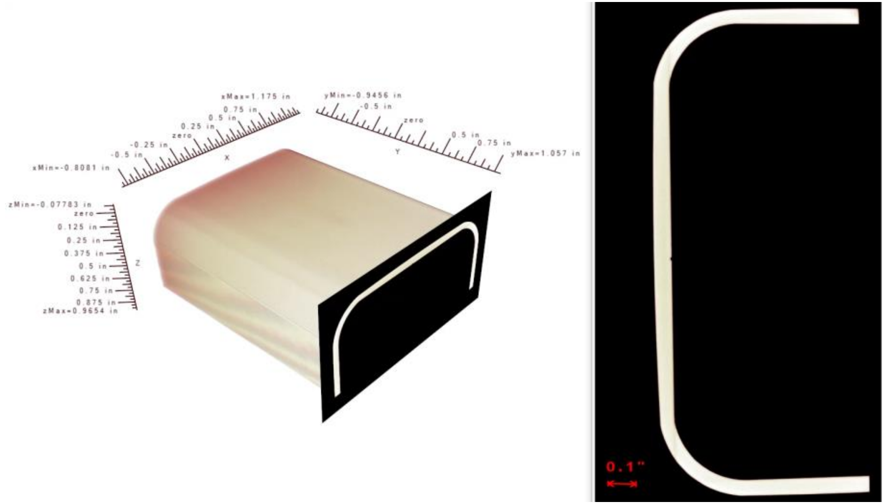


IM7/8552; [90º/0º]$_{2S}$

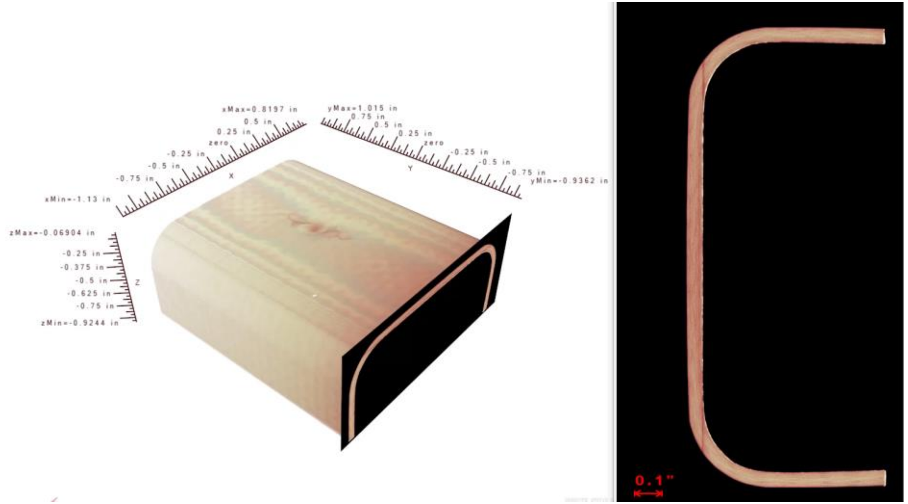
AS4 PW/8552; [90º/0º]$_{2S}$

X-Ray Ct: C-Channel

Nominal Impact Energy: 30 in-lb.



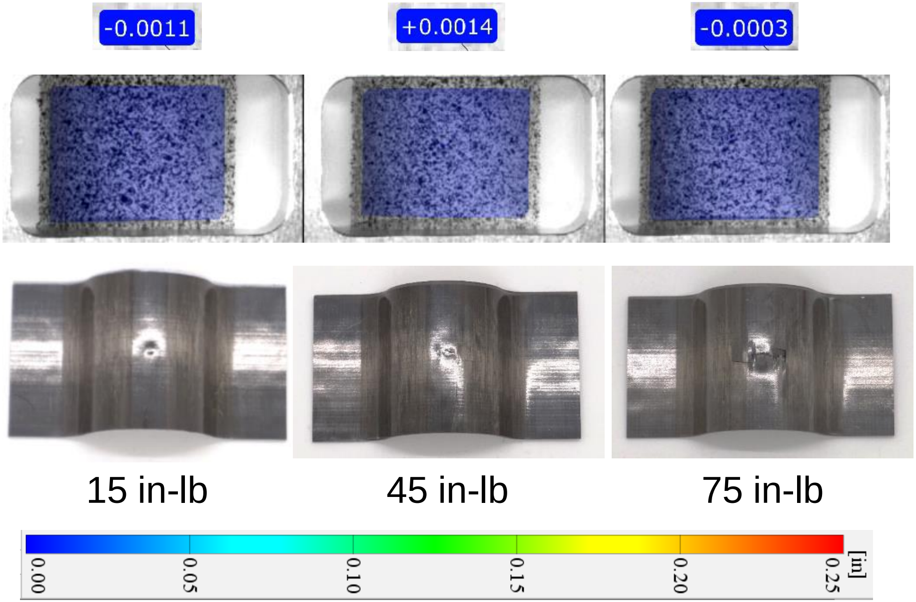
IM7/8552; [45º/90º/-45º/0º]$_S$

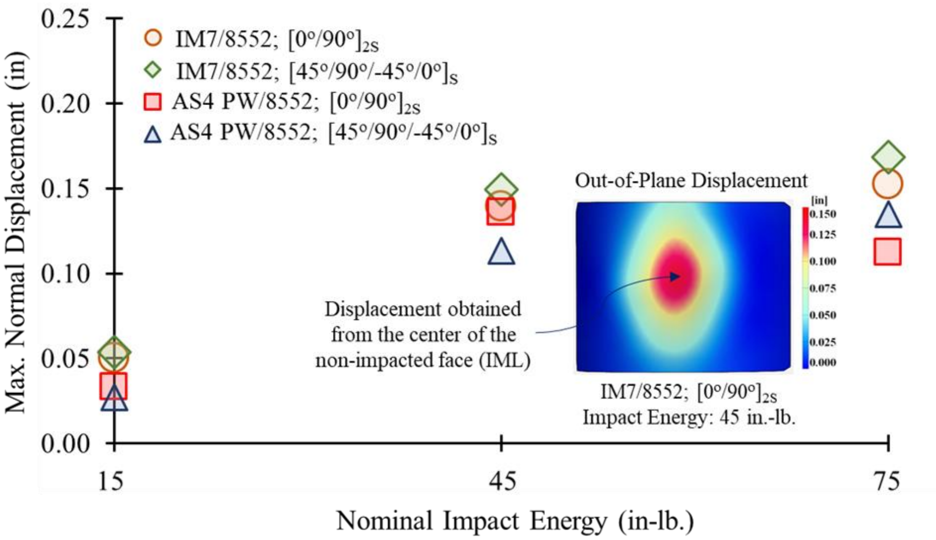


AS4 PW/8552; [45º/90º/-45º/0º]$_S$

High Speed DIC: Corrugated Beam

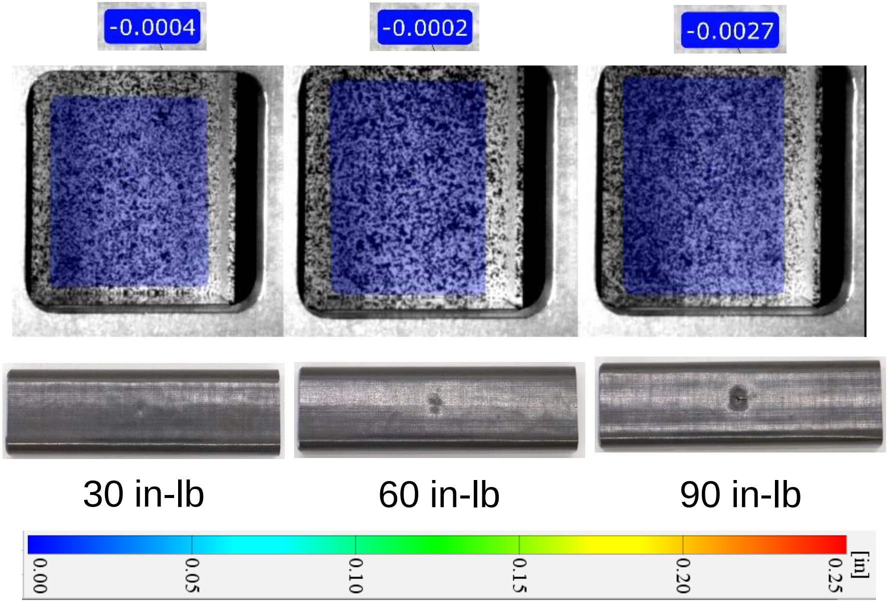
IM7/8552; [$90^o/0^o]_{2S}$

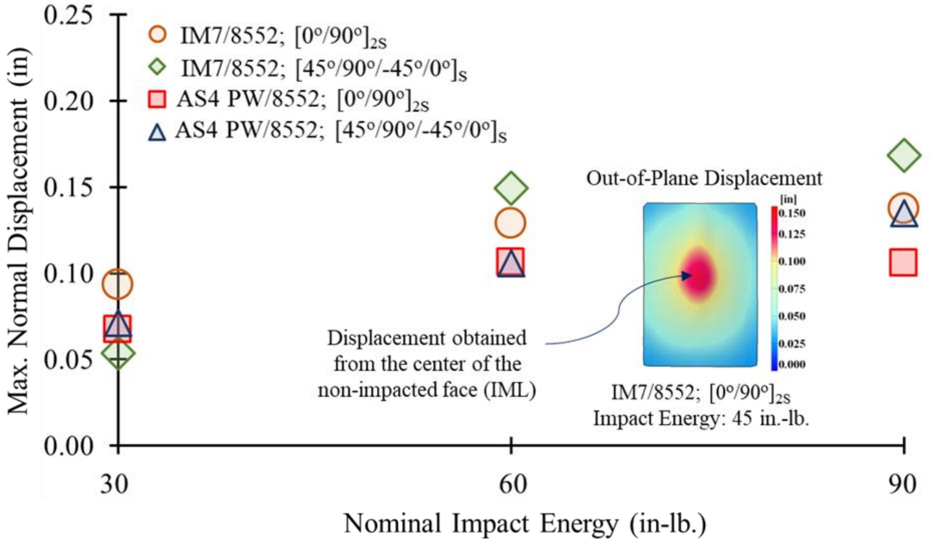




High Speed DIC: C-Channel

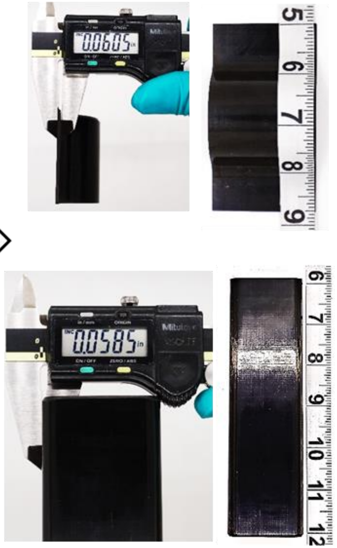
IM7/8552; $[90^{o}/0^{o}]_{2S}$





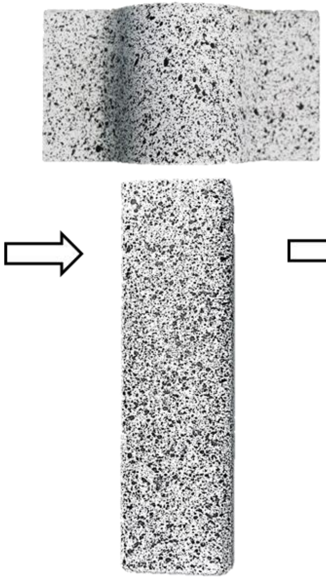
Specimen Traceability

Machined Specimens



Dimensions

Weight Measurement



Stochastic Speckle Pattern

Specimen placed in bags

Specimen Nomenclature

Client ID | Test Method ID | Material Type | Stacking Sequence | Energy Absorber Type | Defect Type | Stroke Rate | Specimen ID

FAA-EA-PW-SS2-A-D1-1-02

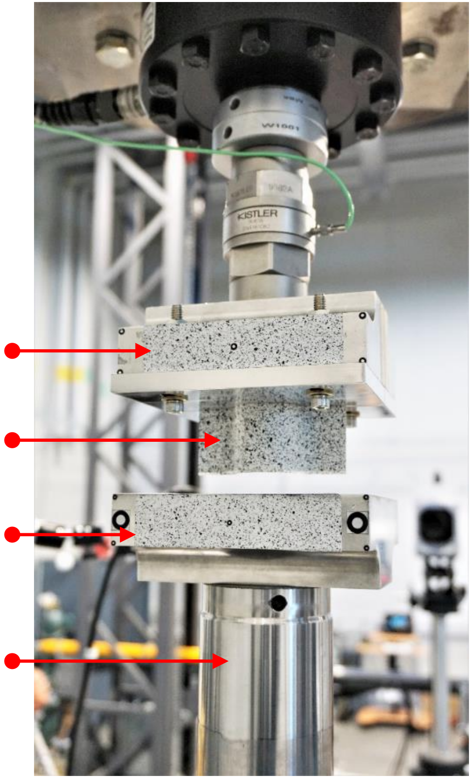
Specimen Nomenclature		
Client ID	FAA	FAA
Test Method ID	Energy Absorber	EA
Material Type	Hexcel IM7/8552	UD
	Hexcel AS4 PW/8552	PW
Stacking Sequence	$[90^{o}/0^{o}]_{2s}$	SS1
	$[45^{o}/90^{o}/-45^{o}/0^{o}]s$	SS2
Defect Type	Pristine	D0
	Fiber Waviness: OML	D1
	Fiber Waviness: IML	D2
	Delamination: Flange	D3
	Delamination: Web	D4
	Impact Energy Level I	D5
	Impact Energy Level II	D6
	Impact Energy Level III	D7
Energy Absorber Type	Corrugated Beam	A
	C-Channel Stanchion	B
Stroke Rate	0.01 in/s	0.01
	1 in/s	1
	100 in/s	100

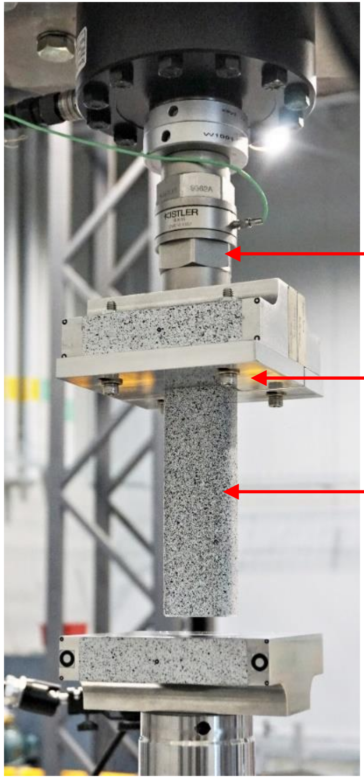
Energy Absorbers: Test Matrix

<table>
<tr><th colspan="4">Test Matrix</th></tr>
<tr><td colspan="4">Material Systems: IM7/8552 ; AS4 PW/8552;
Stacking Sequences: $[90^{o}/0^{o}]_{2s}$ and $[45^{o}/90^{o}/-45^{o}/0^{o}]s$
Defect Type: Pristine, Out-of-plane fiber waviness: IML, Out-of-plane fiber waviness: OML, Delamination: Web, Delamination: Flange, In-Service Damage</td></tr>
<tr><td rowspan="2">Energy Absorber Type</td><td colspan="3">Stroke Rate</td></tr>
<tr><td>0.01 in/s</td><td>1 in/s</td><td>100 in/s</td></tr>
<tr><td>Corrugated Beam</td><td>x3</td><td>x3</td><td>x3</td></tr>
<tr><td>C-Channel Stanchion</td><td>x3</td><td>x3</td><td>x3</td></tr>
</table>

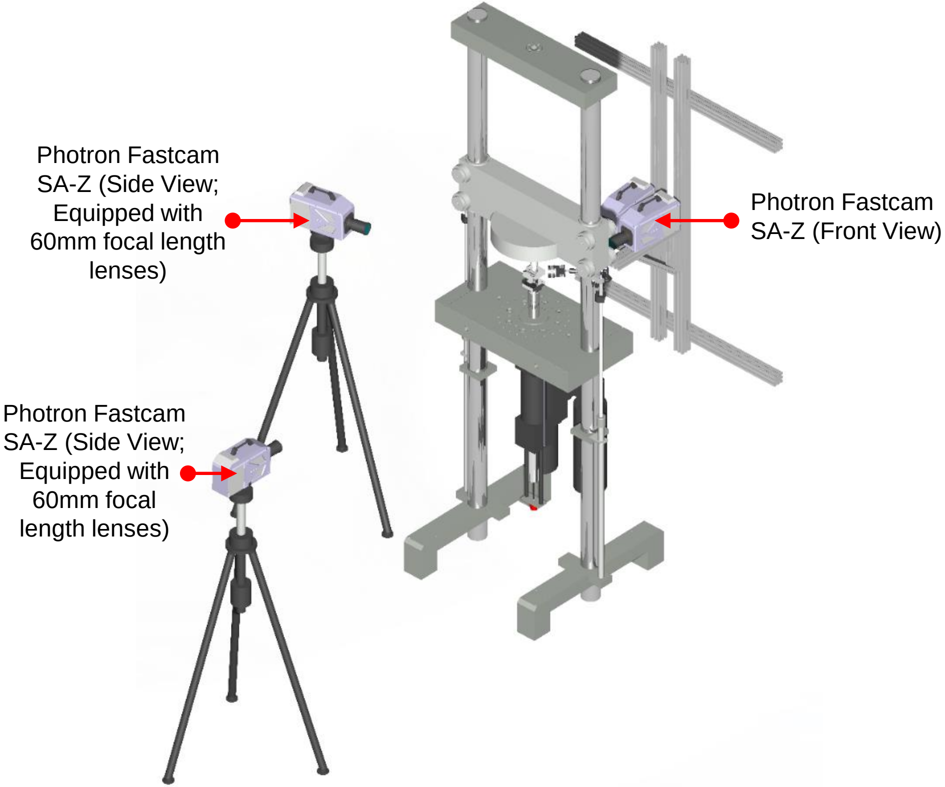
*Minimum specimens to be tested: 576

Test Apparatus



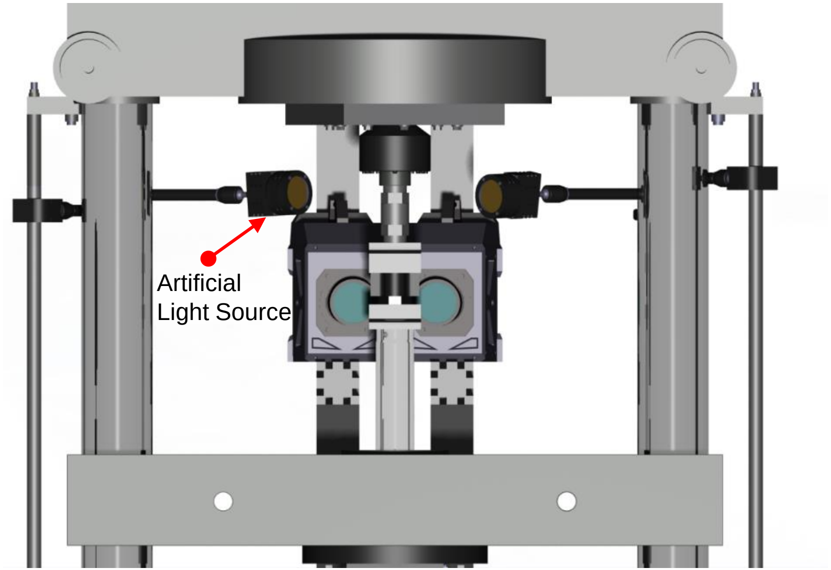


High Speed DIC: Test Schematic

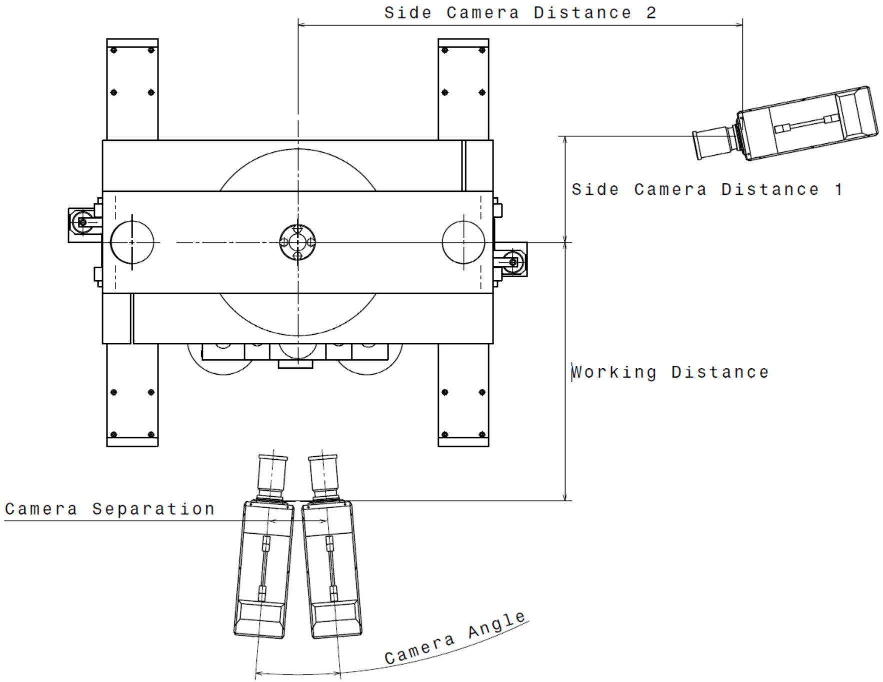

Photron Fastcam SA-Z (Side View; Equipped with 60mm focal length lenses)

Photron Fastcam SA-Z (Front View)

Photron Fastcam SA-Z (Side View; Equipped with 60mm focal length lenses)


Artificial Light Source

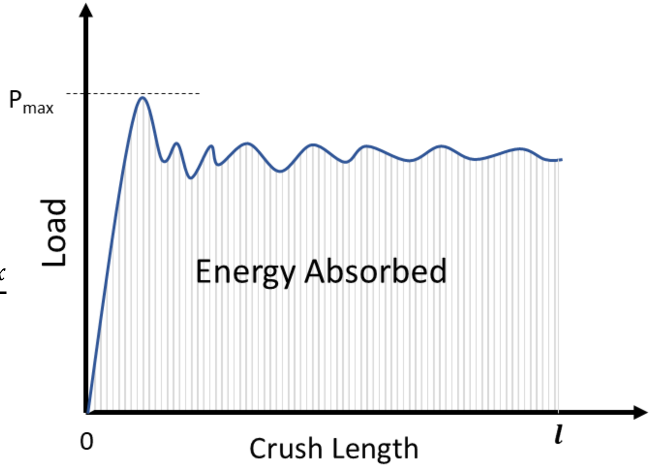
3D DIC Camera Setup Details



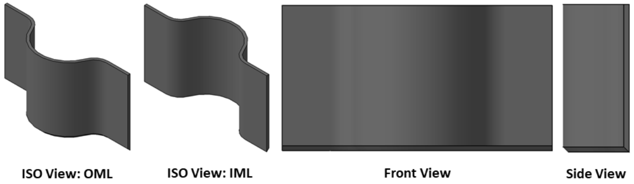
Digital Image Correlation Camera Setup		
Parameter Information	Corrugated Beam	C-Channel Stanchion
Lenses Focal Length	105mm	60mm
Camera Angle	18.5°	20.5°
Working Distance	36”	29.5”
Camera Separation	12”	11”
Field of View	6.3” x 6.3”	9.3” x 9.3”

Crashworthiness Parameters

- **Peak Load (P_{max})**: Initial peak load recorded as crushing initiates
- **Crush length ($\boldsymbol{l}$)**: Length of the specimen crushed
- **Energy Absorbed (EA)**: Area under the load-displacement graph; $\int_o^l F(x)dx$
- **Sustained load**: Energy absorbed/crush length; $\frac{\int_o^l F(x)dx}{l}$
- **Specific Energy Absorber (SEA)**: Energy absorber per unit mass of crushed length; $\frac{\int_o^l F(x)dx}{\rho \times A \times l}$
- **Crush force Efficiency (CFE)**: Sustained load/Peak Load

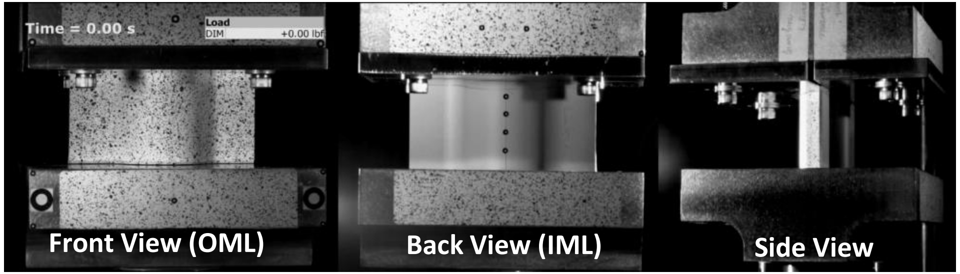


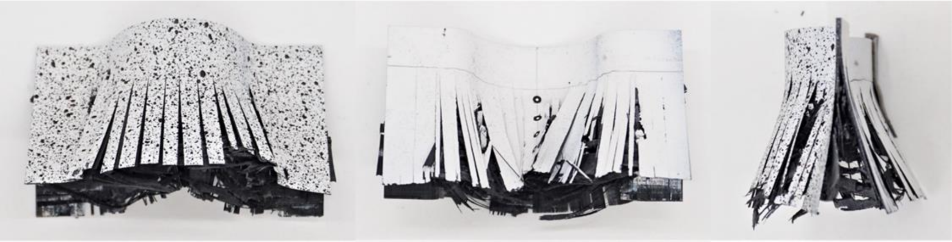
Corrugated Beam (Pristine)

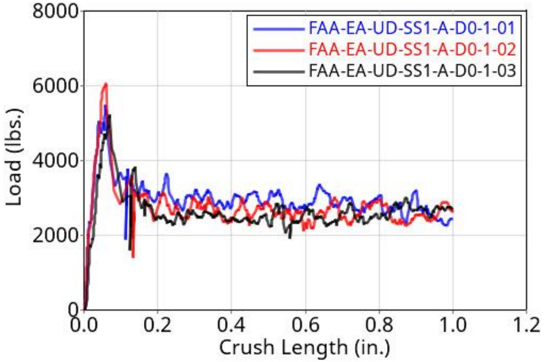


Defect Type: Pristine

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

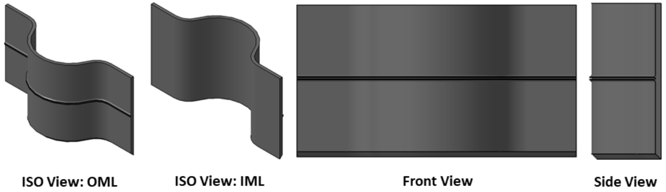






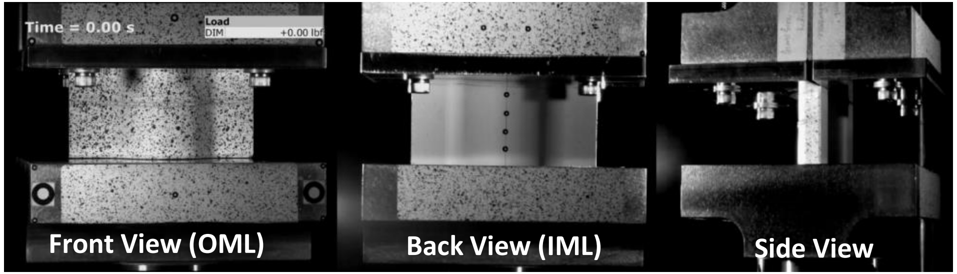
Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb/lb]	Total CFE
01	5,488.19	2,974.20	208,107.90	0.5419
02	6,070.71	2,749.10	192,357.44	0.4528
03	5,226.68	2,643.58	184,974.41	0.5058
COV	7.72%	6.06%	6.06%	8.96%

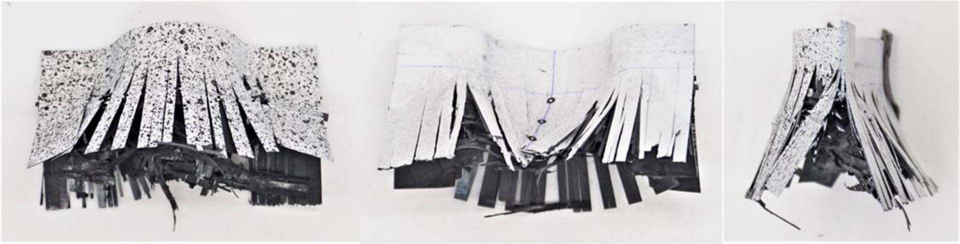
Corrugated Beam (Waviness OML)

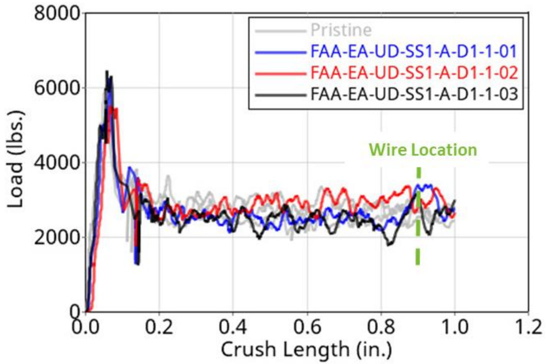


Defect Type: Waviness/Wrinkle (wire at OML)

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

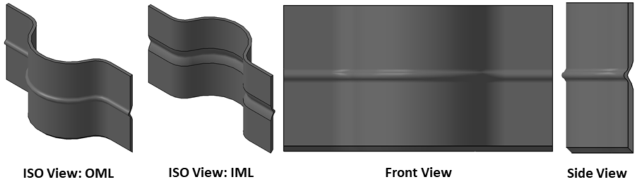






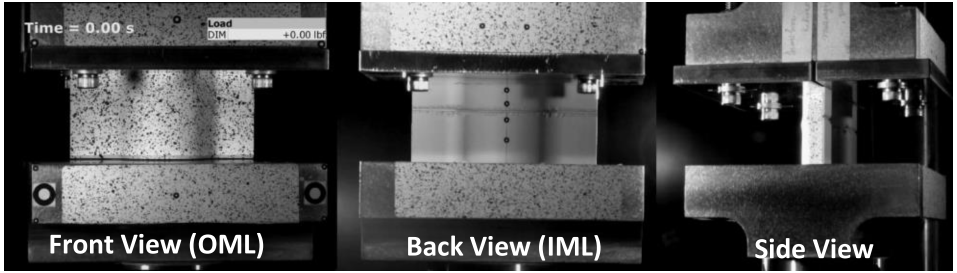
Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb/lb]	Total CFE
01	6,269.39	2,714.05	189,905.29	0.4329
02	5,523.62	2,918.13	204,184.98	0.5283
03	6,470.32	2,622.94	183,530.13	0.4054
COV	8.19%	5.49%	5.49%	14.16%

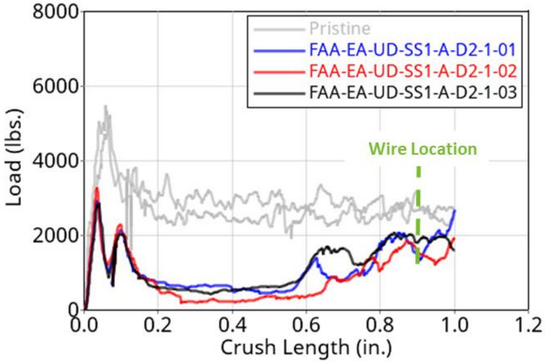
Corrugated Beam (Waviness IML)



Defect Type: Waviness/Wrinkle (wire at IML)

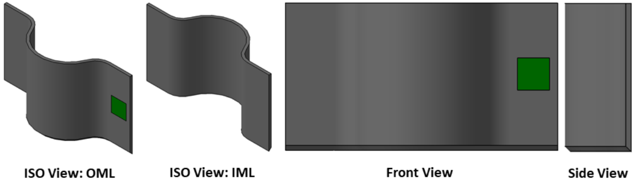
Material System: IM7/8552**; Stacking Sequence:** $[90^o/0^o]_{2s}$; **Stroke Rate**: 1 in/s



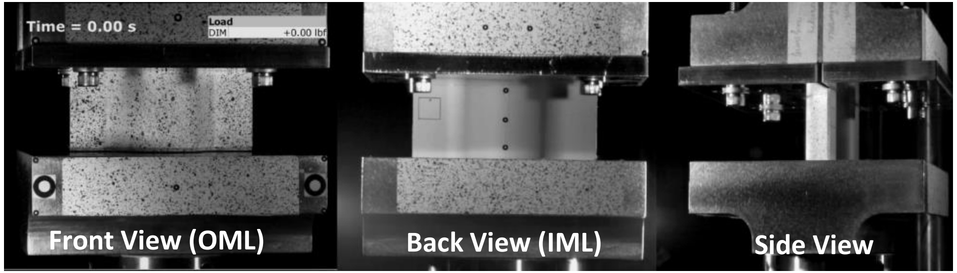


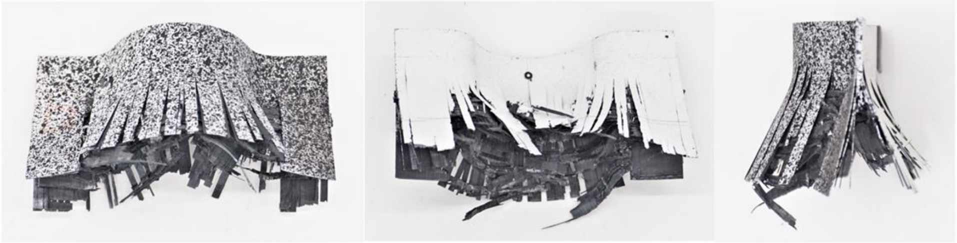
Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb/lb]	Total CFE
01	2,944.70	455.20	31,851.16	0.1546
02	3,284.10	377.49	26,413.45	0.1149
03	2,851.00	423.78	29,652.48	0.1486
COV	7.53%	9.33%	9.33%	15.34%

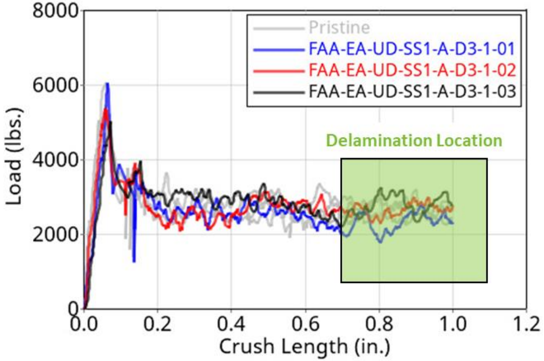
Corrugated Beam (Delam. Flange)



Defect Type: Delamination (PTFE at Flange)
Material System: IM7/8552; **Stroke Rate**: 1 in/s
Stacking Sequence: [90º /0º/Delamn/90º/0º/0º/90º/0º/90º]

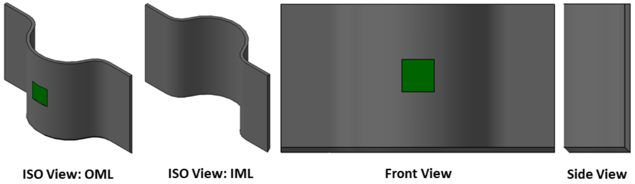




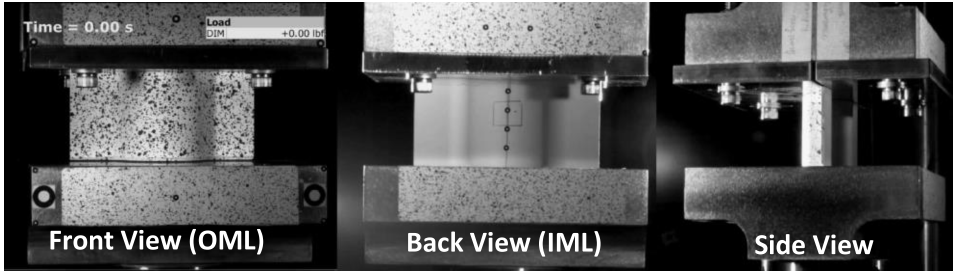


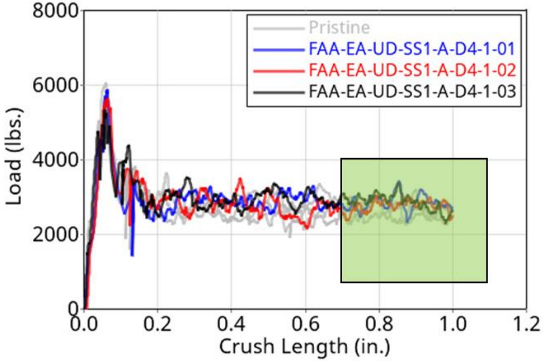
Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb/lb]	Total CFE
01	6,047.53	2,591.82	181,352.18	0.4286
02	5,373.25	2,765.89	193,532.14	0.5148
03	5,016.90	2,885.73	201,917.60	0.5752
COV	9.55%	5.38%	5.38%	14.56%

Corrugated Beam (Delam. Web)



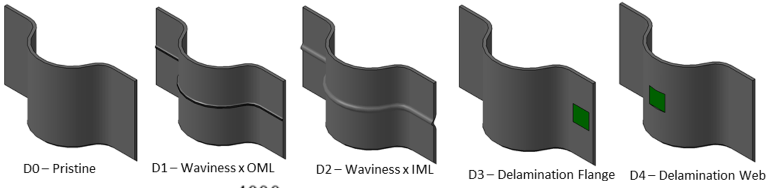
Defect Type: Delamination (PTFE at Web)
Material System: IM7/8552**; Stroke Rate**: 1 in/s
Stacking Sequence: [90º /0º/Delamn/90º/0º/0º/90º/0º/90º]

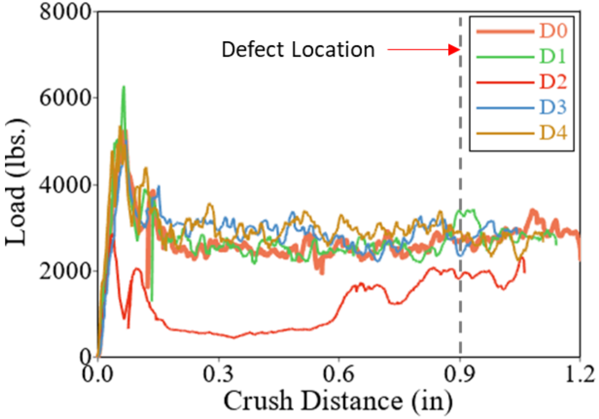


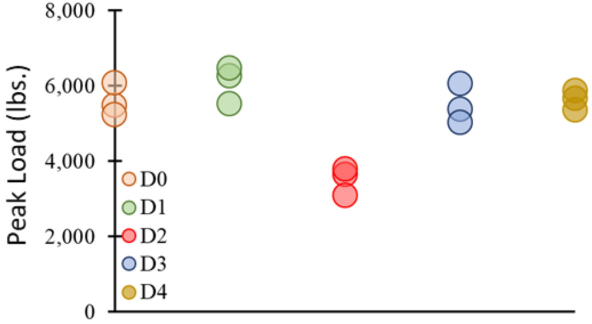


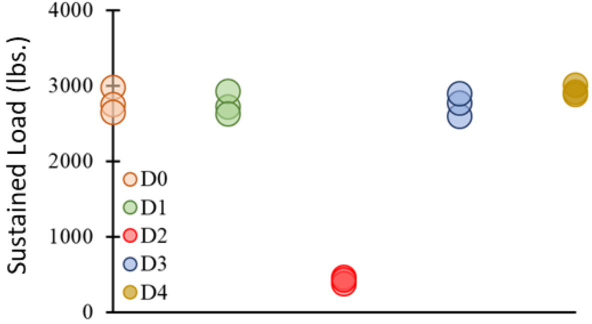
Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb/lb]	Total CFE
01	5,874.24	2,907.16	203,416.85	0.4949
02	5,657.58	2,874.41	201,125.48	0.5081
03	5,347.13	3,004.81	210,249.50	0.5619
COV	4.71%	2.32%	2.32%	6.81%

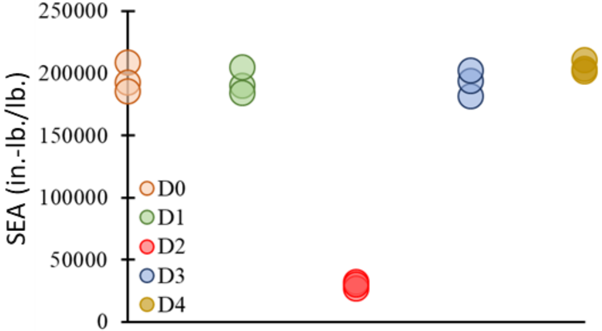
Comparison: Corrugated Beam IM7/8552; $[90^{o}/0^{o}]_{2s}$







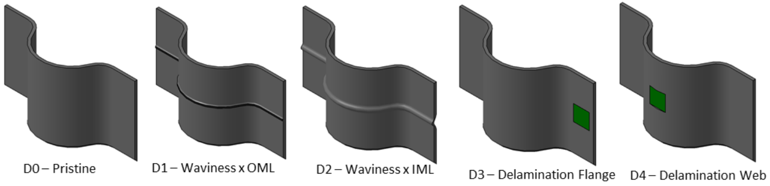


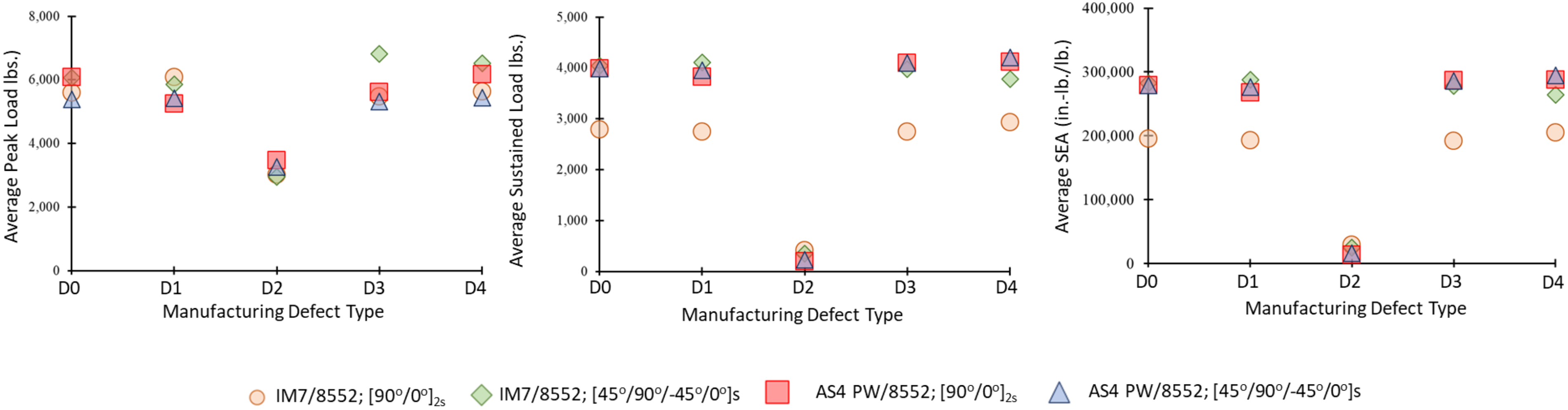


% change in comparison to D0 (Pristine)		
Defect Type	Avg. Peak Load	Avg. Total SEA
D1	+8.80%	-1.34%
D2	-45.91%	-84.98%
D3	-2.07%	-1.48%
D4	+0.56%	+5.01%

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

Comparison: Corrugated Beam All Configurations

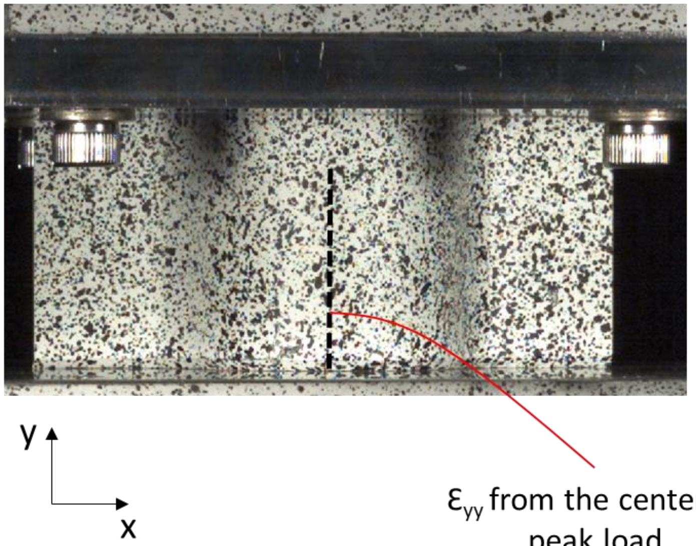




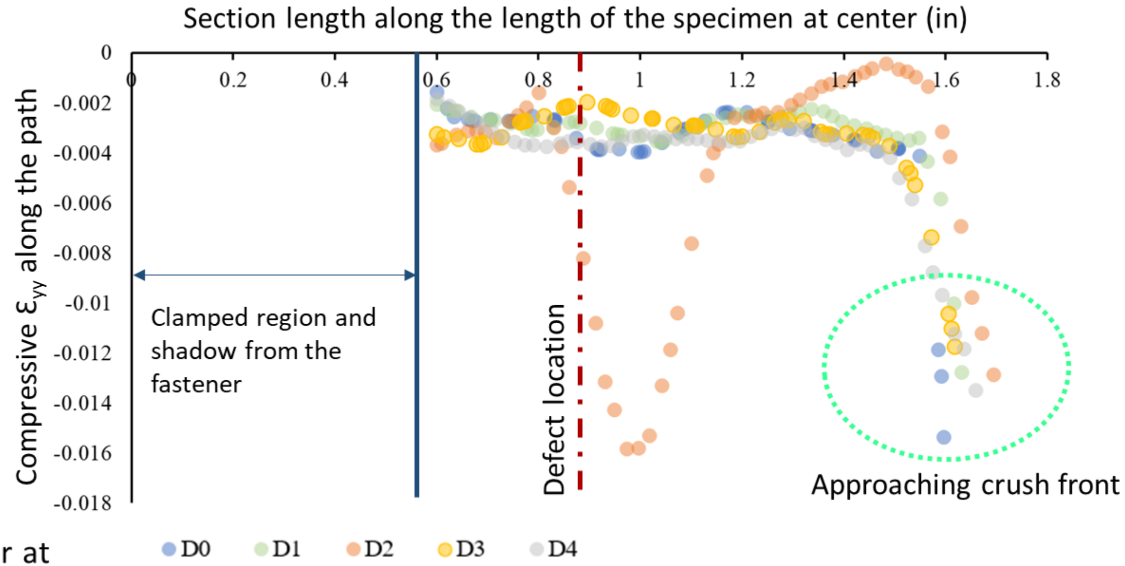
D0 – Pristine; D1 – Waviness x OML; D2 – Waviness x IML; D3 – Delamination Flange; D4 – Delamination Web

Strain Path Plot: DIC

Material System: AS4 PW/8552 ;Stacking Sequence: [90°/0°]$_{2s}$



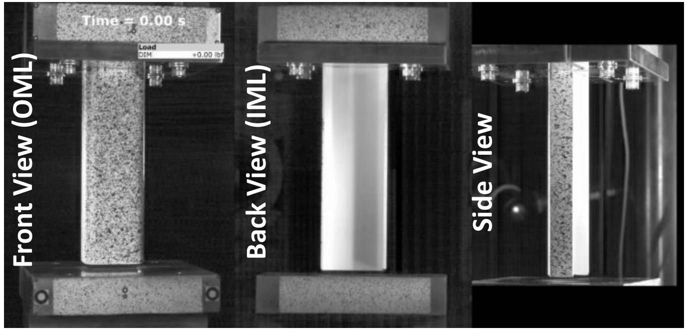
ε_{yy} from the center at peak load

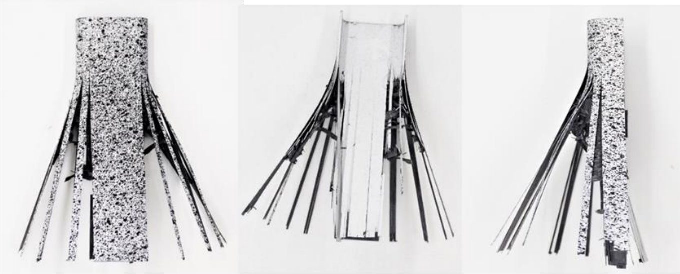


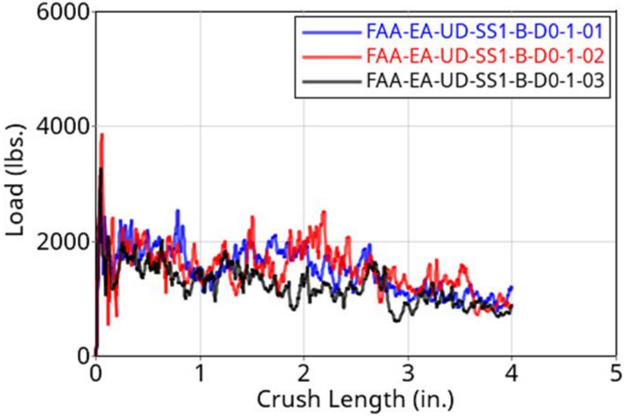
D0 – Pristine; D1 – Waviness x OML; D2 – Waviness x IML; D3 – Delamination Flange; D4 – Delamination Web

C-Channel (Pristine)

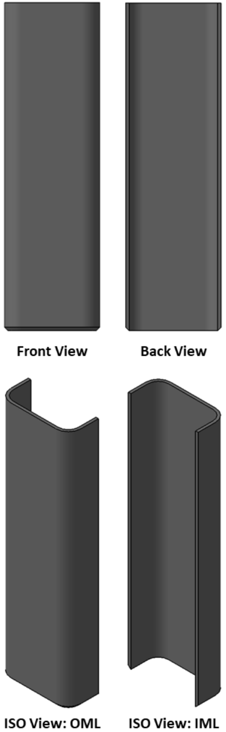
Defect Type: Pristine
Material System: IM7/8552**;**
Stacking Sequence: $[90^o/0^o]_{2s}$;
Stroke Rate: 1 in/s





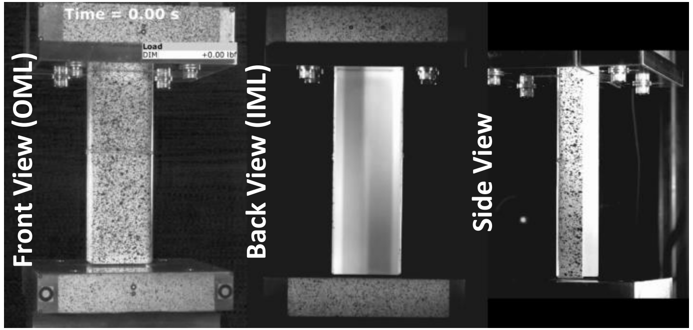


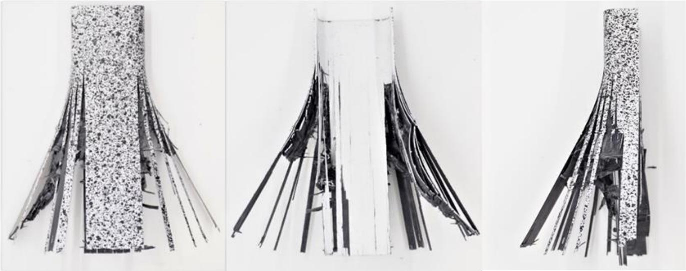
Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb/lb]	Total CFE
01	2,856.33	1,501.55	136,448.08	0.5257
02	3,878.96	1,528.38	138,886.38	0.3940
03	3,273.86	1,220.49	110,907.48	0.3728
COV	15.41%	12.04%	12.04%	19.23%

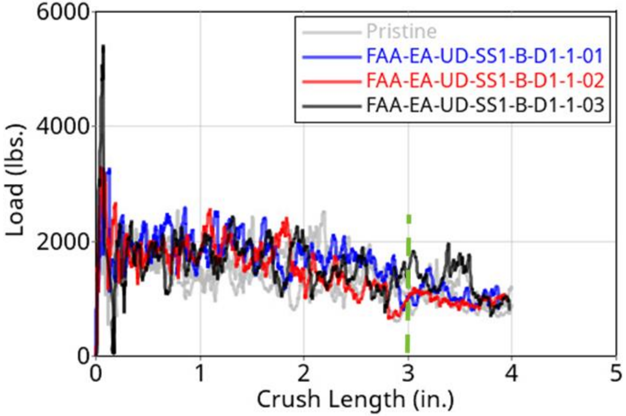


C-Channel (Waviness OML)

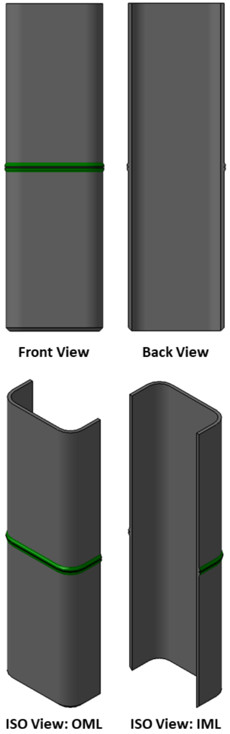
Defect Type: Waviness/Wrinkle (wire at OML)
Material System: IM7/8552**;**
Stacking Sequence: $[90^{o}/0^{o}]_{2s}$;
Stroke Rate: 1 in/s





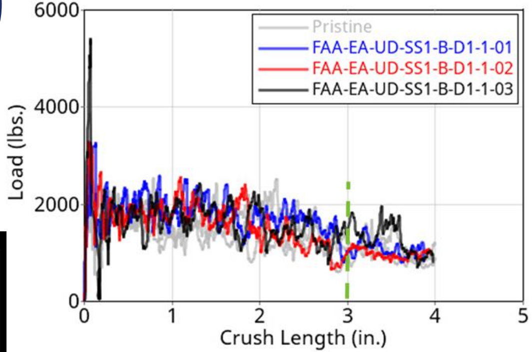


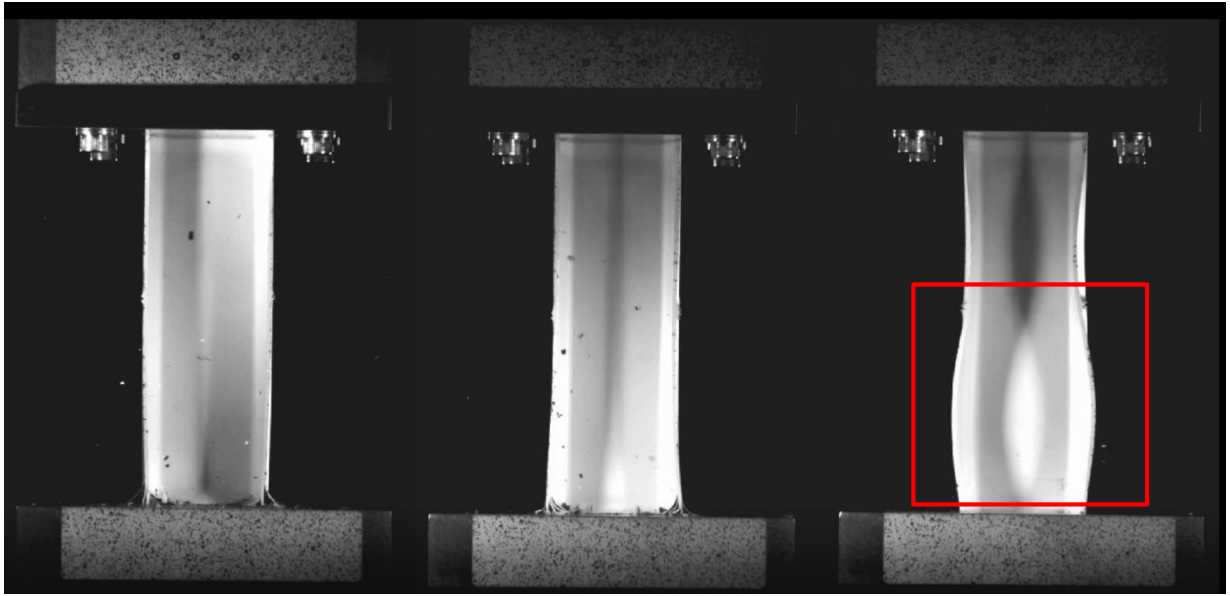
Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb/lb]	Total CFE
01	3,287.96	1,595.05	144,945.01	0.4851
02	3,296.32	1,469.06	133,495.92	0.4457
03	5,426.51	1,563.85	142,109.25	0.2882
COV	30.78%	4.25%	4.25%	25.64%



C-Channel (Waviness OML)

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

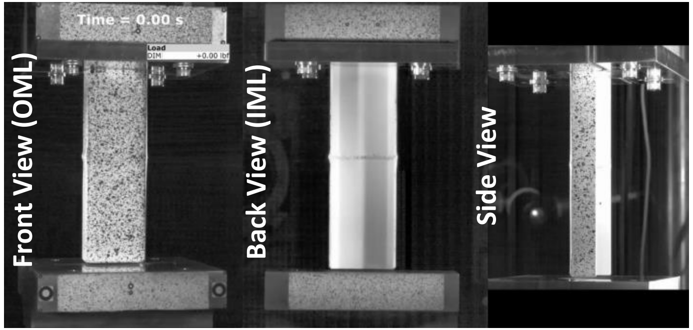


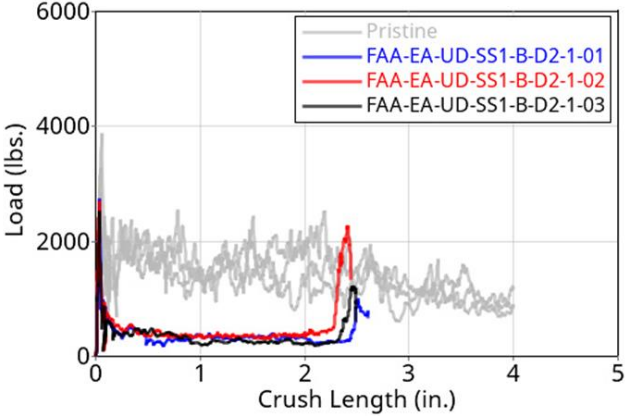


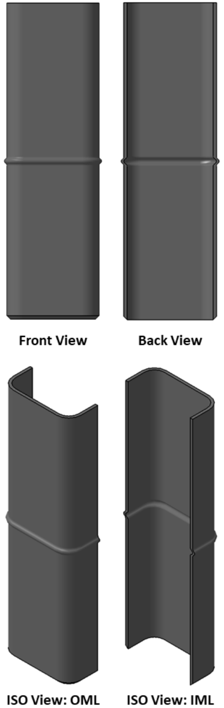
FAA-EA-UD-SS1-B-D1-1-01 FAA-EA-UD-SS1-B-D1-1-02 FAA-EA-UD-SS1-B-D1-1-03

C-Channel (Waviness IML)

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



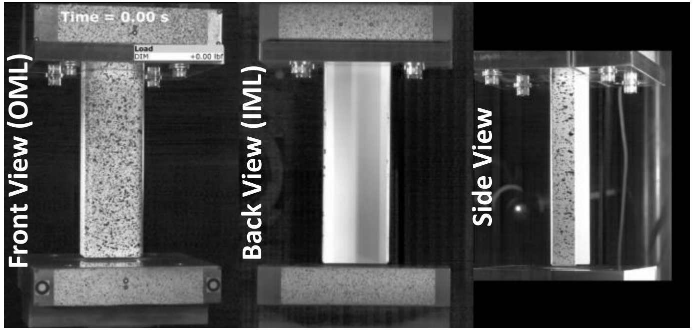


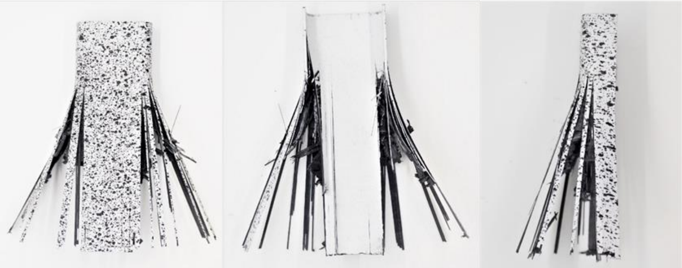


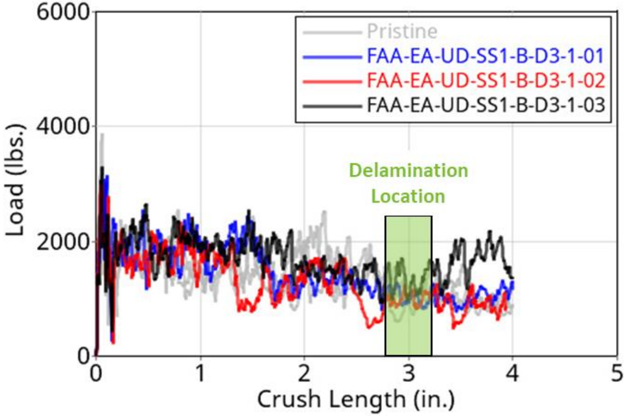
Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb/lb]	Total CFE
01	2,735.72	380.49	34,575.94	0.1391
02	2,701.59	427.22	38,822.21	0.1581
03	2,527.71	350.07	31,811.21	0.1385
COV	4.20%	10.07%	10.07%	7.69%

C-Channel (Delamination Flange)

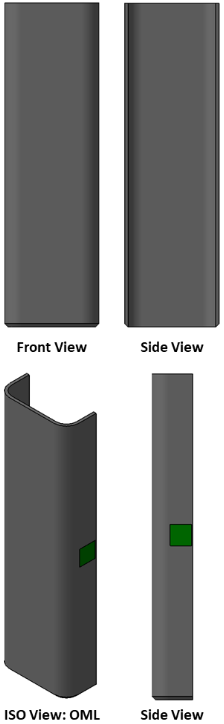
Defect Type: Waviness/Wrinkle (PTFE at Flange)
Material System: IM7/8552**;**
Stacking Sequence: [90° /0°/Delamn/90°/0°/0°/90°/0°/90°]
Stroke Rate: 1 in/s





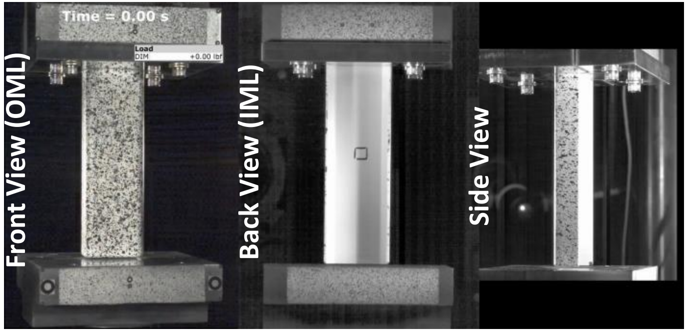


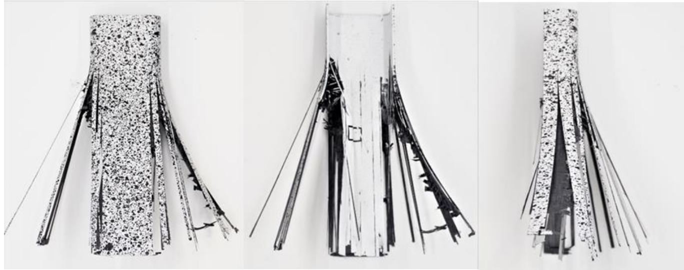
Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb/lb]	Total CFE
01	3,205.84	1,456.07	132,315.52	0.4635
02	3,002.99	1,270.85	115,484.33	0.4306
03	3,346.24	1,698.79	154,371.47	0.5143
COV	5.42%	14.55%	14.55%	8.98%

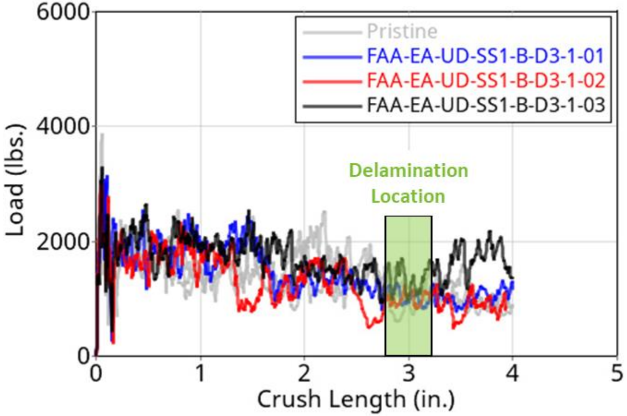


C-Channel (Delamination Web)

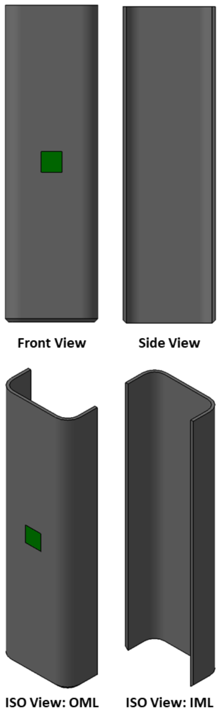
Defect Type: Waviness/Wrinkle (PTFE at Web)
Material System: IM7/8552**;**
Stacking Sequence: [90º /0º/Delamn/90º/0º/0º/90º/0º/90º]
Stroke Rate: 1 in/s



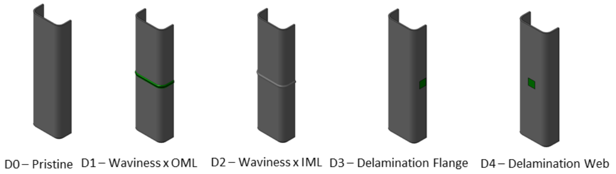


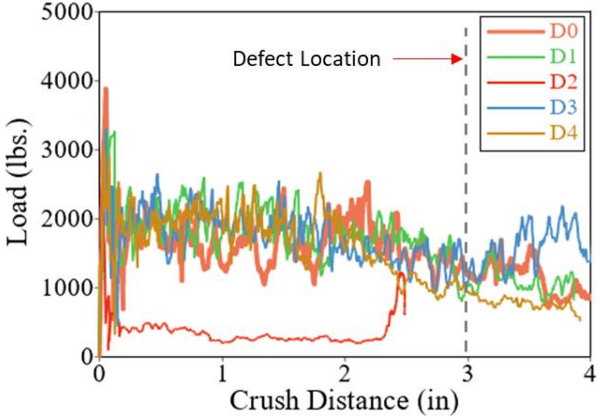


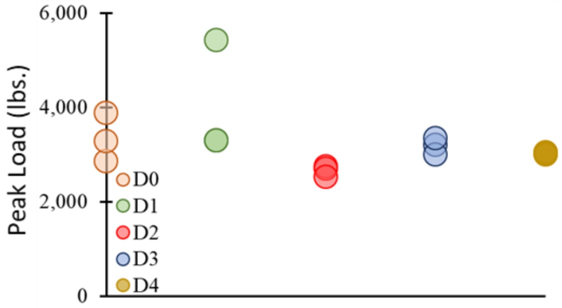
Specimen #	Peak Load [lbs.]	Sustained Load [lbs.]	Total SEA [in-lb/lb]	Total CFE
01	3,027.76	1,581.26	143,691.93	0.5087
02	3,001.62	1,531.86	139,202.09	0.4829
03	3,039.58	1,441.16	130,960.76	0.4661
COV	0.64%	4.68%	4.68%	4.42%

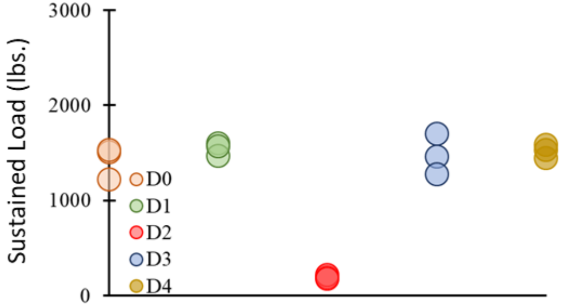


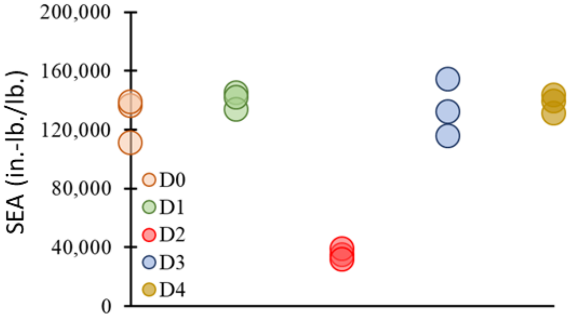
Comparison: C-Channel IM7/8552; $[90^o/0^o]_{2s}$









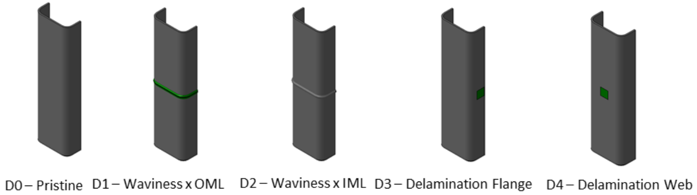


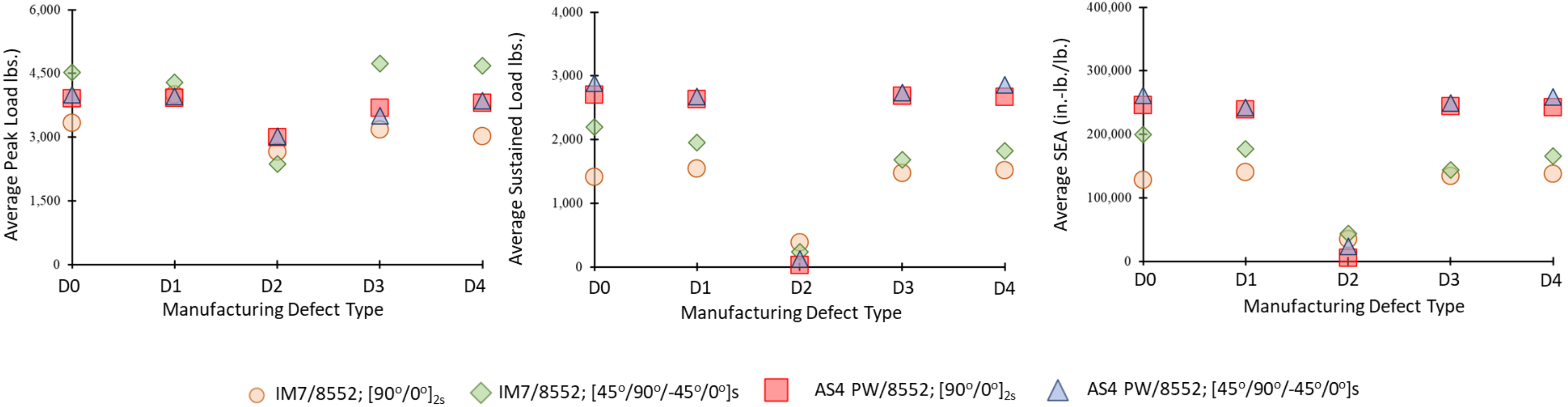
% change in comparison to D0 (Pristine)

Defect Type	Avg. Peak Load	Avg. Total SEA
D1	+20.00%	+8.88%
D2	-20.42%	-72.76%
D3	-4.54%	+4.12%
D4	-9.39%	+7.15%

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

Comparison: C-Channel All Configurations

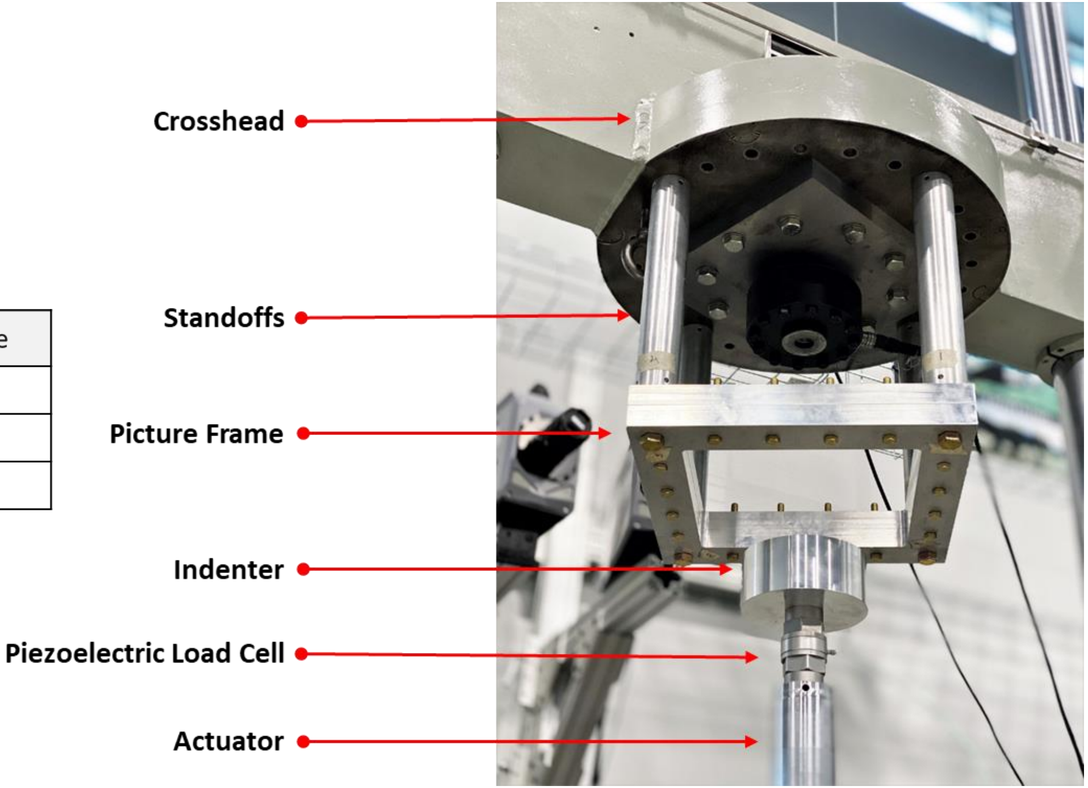




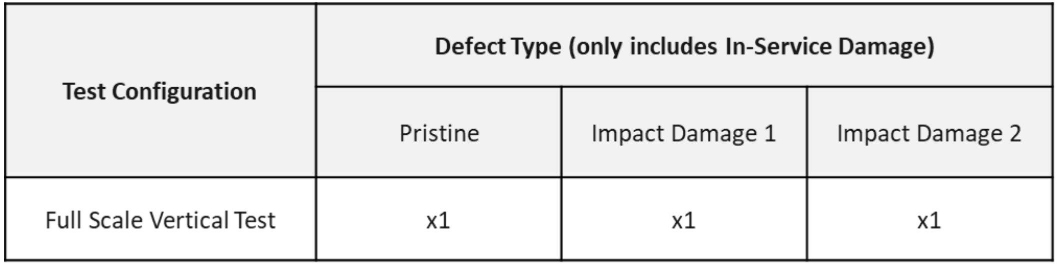
D0 – Pristine; D1 – Waviness x OML; D2 – Waviness x IML; D3 – Delamination Flange; D4 – Delamination Web

Task III: Overview

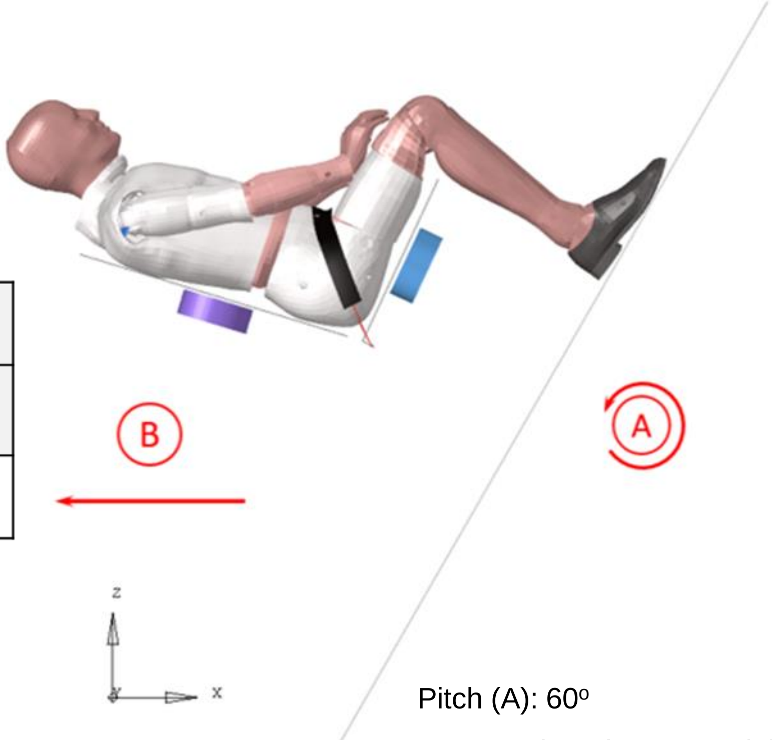
Defect Type: Pristine, Fiber Waviness (IML), In-Service Damage			
Loading Condition	Stroke Rate (in/s)		
	SR1	SR2	SR3
Impact Test	x3	x3	x3



Task IV: Overview



Test Configuration	Defect Type (only includes In-Service Damage)		
	Pristine	Impact Damage 1	Impact Damage 2
Full Scale Vertical Test	x1	x1	x1



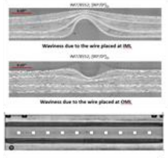
Pitch (A): 60°

Acceleration Ideal Pulse (B): 14g

Current Progress Summary

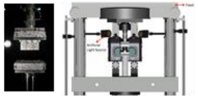
Energy absorber laminate fabrication:
- *2 material systems
- *2 stacking sequences
- *4 manufacturing defects
- *168 laminates
- *24 autoclave cure cycles

*NDI to track location of specimen defects
*Microscopic analysis to compare fiber waviness



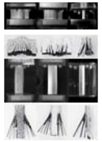
Specimen machining:
- *Specimens waterjet
- *Surface grinded
- *One edge chamfered 45°
- *~ 800 specimens machined

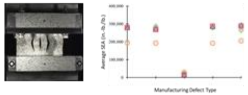
Specimen preparation:
- *Dimensioning and weight
- *Speckle painting for DIC
- *Take pretest pictures



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

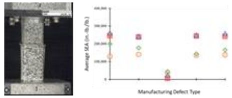
Testing Status:
- *1 in/s finished (Manf. Defects)
- *Damage evolution captured
- *Post-test images

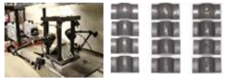




Corrugated beam results:
- *Significant reduction in SEA when waviness introduced due to wire at IML
- *IM7/8552 cross-ply stacking sequence has lower SEA in comparison to other config.

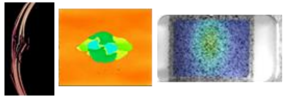
C-Channel stanchion results:
- *Significant reduction in SEA when waviness introduced due to wire at IML
- *Lower SEA for IM7/8552





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

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



Sub-component test:
- *Pristine flat laminates and laminates with waviness defect has been manufactured
- *Picture frame fixture has been machined

Ongoing Work

- **Task II: Energy Absorber Test**
    - Manufacturing defects testing: finished
    - In-service damage introduction: finished
    - In-service damage testing: finished
    - Data evaluation: ongoing
- **Task III: Sub-Component Impact Test**
    - Laminate fabrication: finished
    - Fixture machining: finished
    - Specimen machining: ongoing
    - Testing: ongoing
- **Task IV: Full Scale Vertical Rigid Seat Test**
    - Laminate fabrication: finished
    - Rigid seat modification to install composite seat pan: ongoing
    - Testing: not started

Potential Future Work

- Currently the defects were introduced away from the chamfered edge, at the center of specimen, to have stable crush initiation. Would the response vary if the defect location were to be changed along the length of the specimen?
- Effect of manufacturing defects could change based on energy absorber geometries. Effect of critical manufacturing defect/in-service impact damage, can be evaluated on tubes, tension joints etc.
- Current research effort focuses on composite seat pans and would help assess if in-service damage yields significant different results during a dynamic test in comparison to their pristine counterparts. Future work could focus aircraft seatbacks, cross tubes and seat legs. The research will help development of SAE ARP 6337 document.
- Full scale analysis supported by element level tests could be developed to further understand if the manufacturing defects/in-service damage changes the load-path in aircraft seats during emergency landing conditions

Published Technical Papers

- **“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?

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