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Load Sequencing Effects and Damage Growth Retardation of Composites

Damage Tolerance Testing and Analysis Protocols for Full-Scale Composite Airframe Structures under Repeated Loading

2016 Technical Review

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Damage Tolerance Testing and Analysis Protocols for Full-Scale Composite Airframe Structures under Repeated Loading

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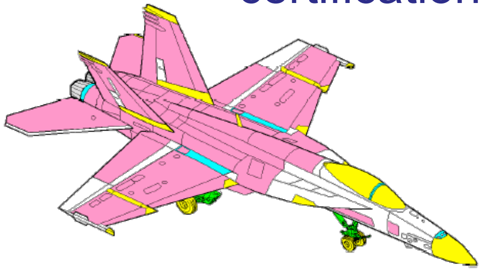
- DoD & Industry Participation
  - Air Force Research Lab (AFRL), Airbus, Boeing, Bombardier, Bell Helicopter, Textron Aviation, Honda Aircraft Co., NAVAIR, and Spirit Aerosystems

Damage Tolerance Testing and Analysis Protocols for Full-Scale Composite Airframe Structures under Repeated Loading

- **Motivation and Key Issues**
  - Damage growth mechanics, critical loading modes and load spectra for composite and metal structure have significant differences that make the certification of composite-metal hybrid structures challenging, costly and time consuming.
  - Data scatter in composites compared to metal data is significantly higher requiring large test duration to achieve a particular reliability that a metal structure would demonstrate with significantly low test duration.
  - Metal and composites have significantly different coefficient of thermal expansion (CTE)
  - Mechanical and thermal characteristics of composites are sensitive to temperature and moisture
  - Need for an efficient certification approach that weighs both the economic aspects of certification and the time frame required for certification testing, while ensuring that safety is the key priority



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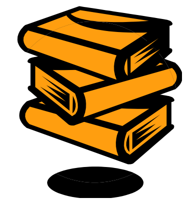
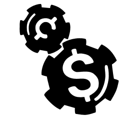
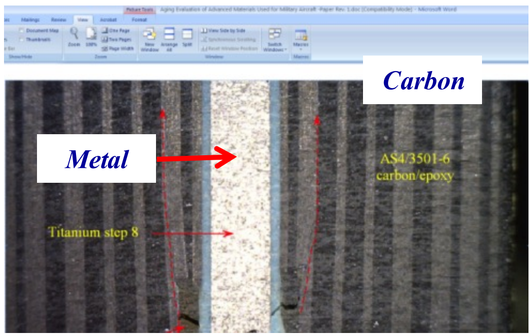
Certification of Composite-Metal Hybrid Structures

- **Primary Objective**
  - Develop guidance materials for analysis and large-scale test substantiation of composite-metal hybrid structures.

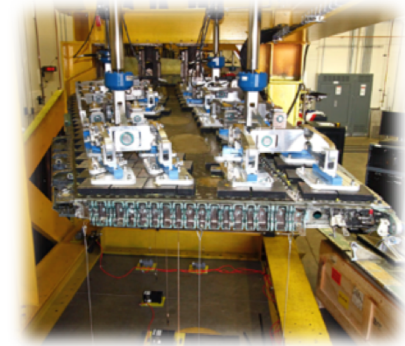


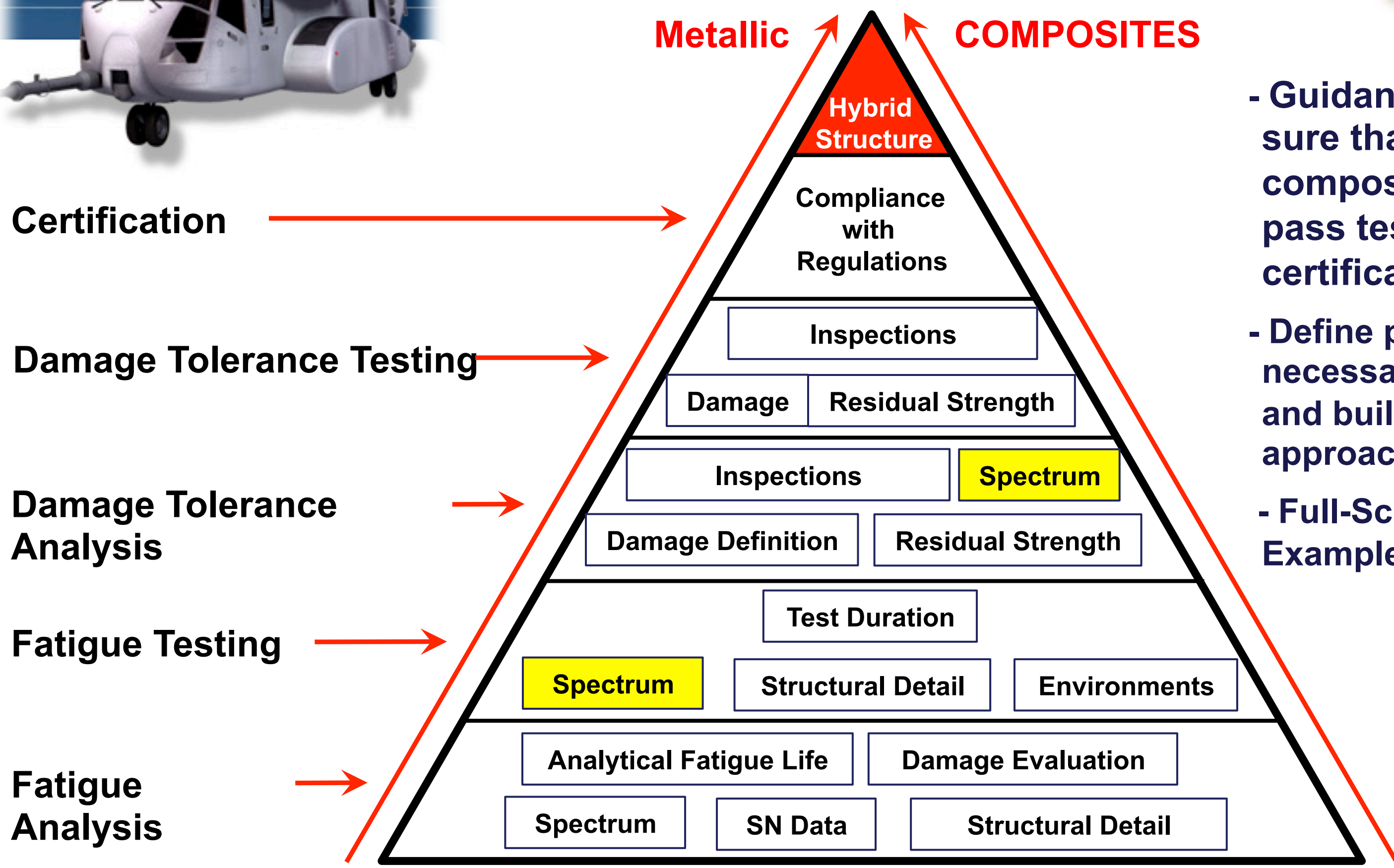


- **Secondary Objectives**
  - Evaluate the damage mechanics and competing failure modes (origination and propagation)
    - Mechanical & bonded joints
  - Data scatter and reliability analysis, i.e., LEF
  - Modifications to load spectra and application LEF
  - Address mismatched Coefficient of Thermal Expansion (CTE) and ground-air-ground (GAG) effects
  - Impact of environmental effects on hybrid structures
    - Environmental compensation factor (ECF)
    - Test environments



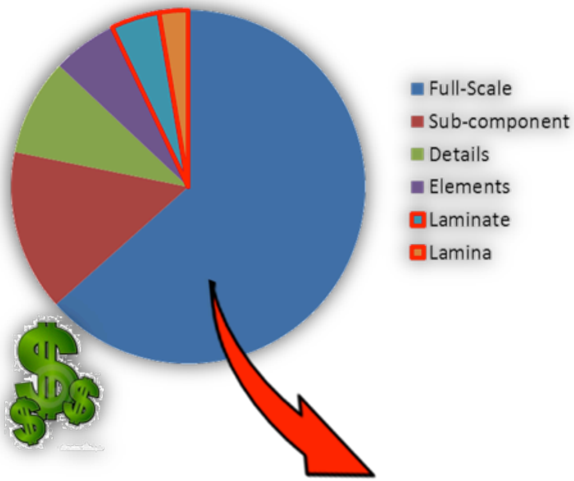
Approach

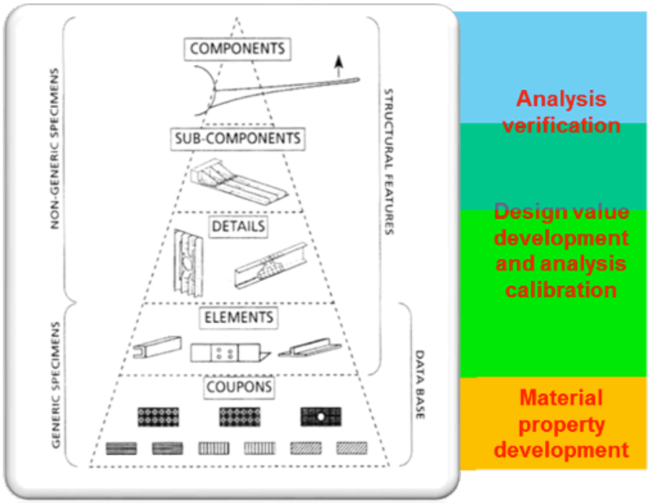


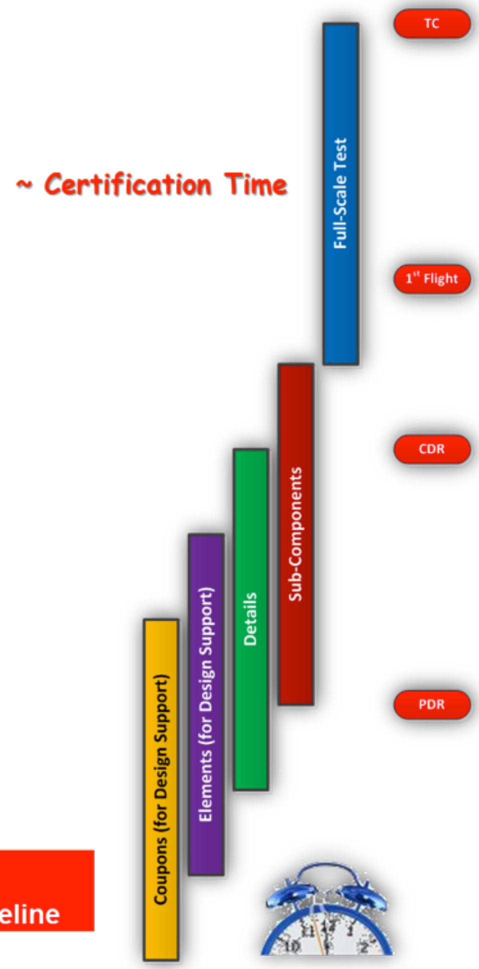


- Guidance is need to make sure that both metal and composite are designed to pass testing and certification requirement.
- Define procedures necessary to support testing and building block approaches
- Full-Scale Validation and Examples

Certification Cost & Time





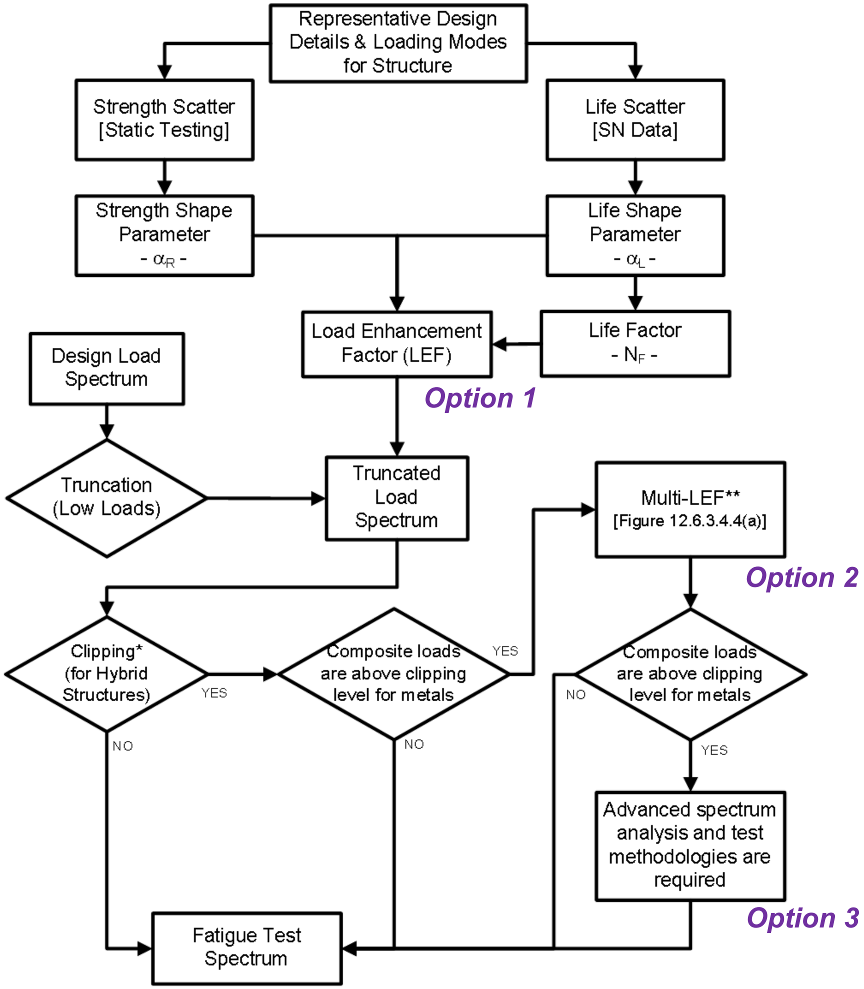


Full-scale test is a significant portion of the overall budget
Improvements to full-scale test duration → Reduction to overall test timeline

Considerations for Metal/Composite Hybrid Structure

- Current industry practice generally avoids addressing metallic and composite fatigue with the same article
- Emerging approaches that may enable addressing metallic and composite fatigue with the same article (for composite-dominant designs)
  - ***Option 1:*** Drive LEFs low enough (either via increasing the test duration and/or via thorough testing to substantiate lower values) to avoid overload concerns in metal
  - ***Option 2:*** Multi-LEF Approach
  - ***Option 3:*** Deferred Spectrum Approach

These options can be combined



NOTES:
* Clipping of high loads are only required for metals; composite loads should not be clipped.
** Further analysis and supporting experiments are required prior to applying these methods.

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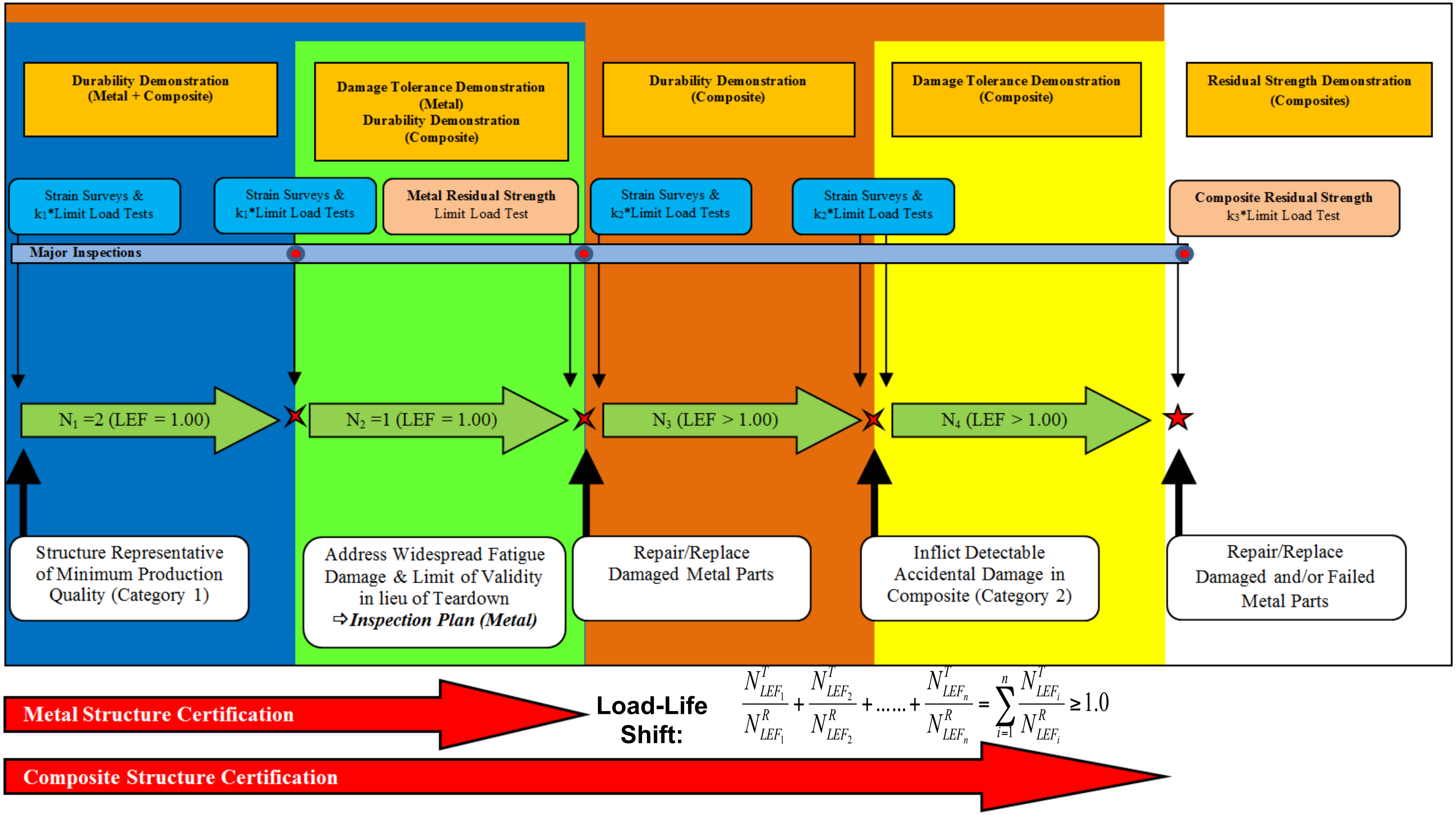
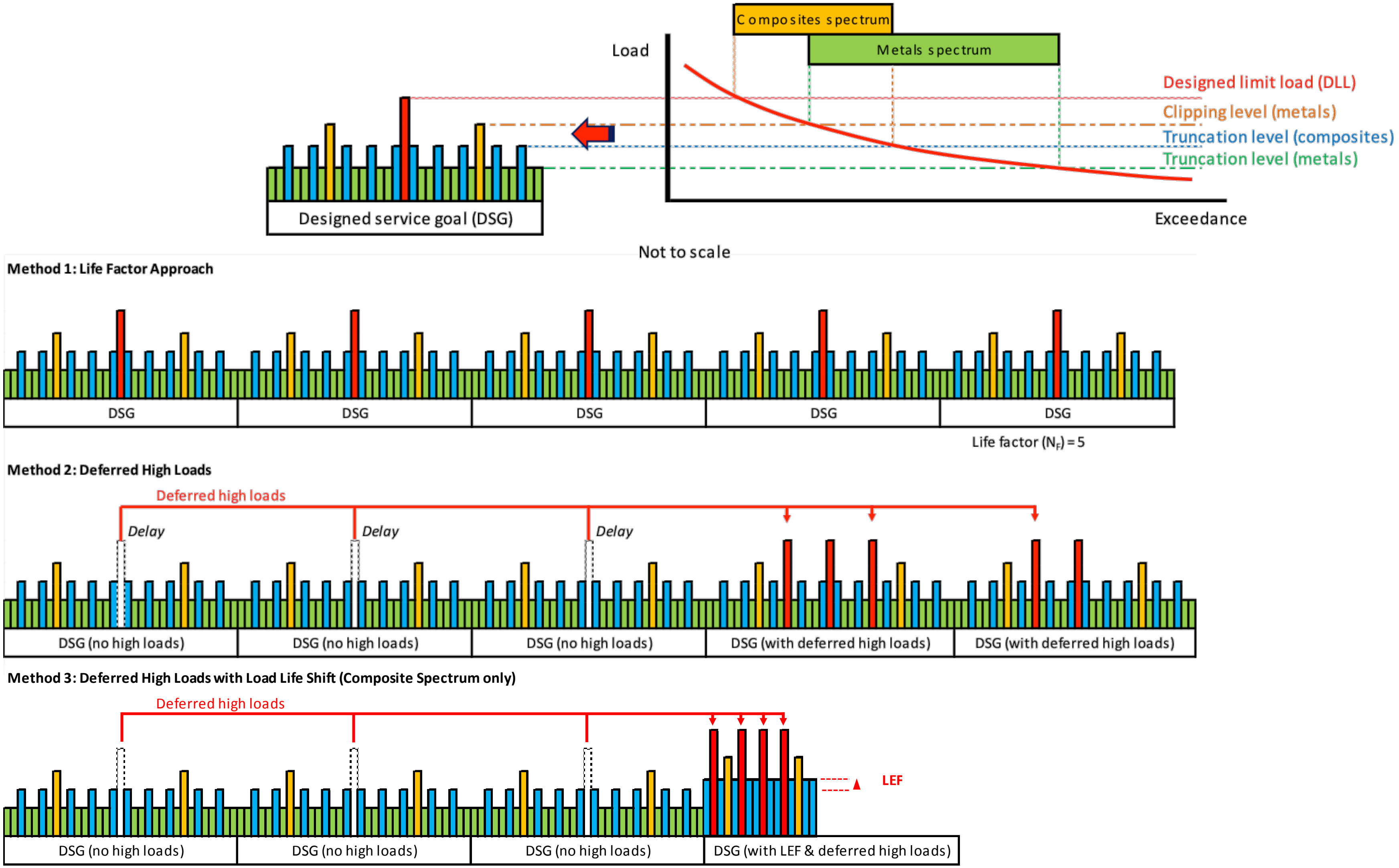
Single Article for Composite-Metal Hybrid FSFT



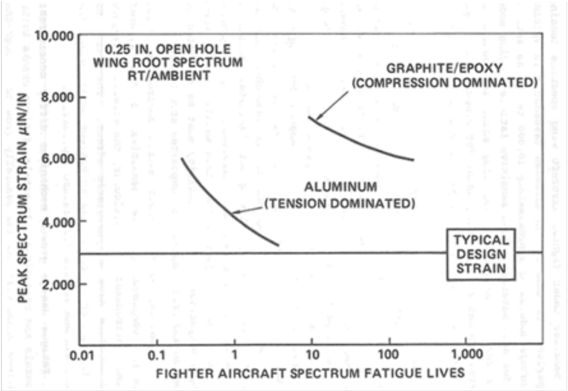
Load-Life Shift:

$$\frac{N^T_{LEF_1}}{N^R_{LEF_1}} + \frac{N^T_{LEF_2}}{N^R_{LEF_2}} + \ldots\ldots + \frac{N^T_{LEF_n}}{N^R_{LEF_n}} = \sum_{i=1}^{n} \frac{N^T_{LEF_i}}{N^R_{LEF_i}} \geq 1.0$$

Deferred Severity Spectrum for Hybrid Structures

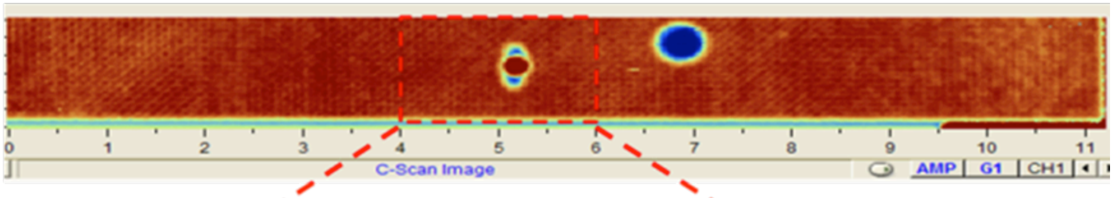


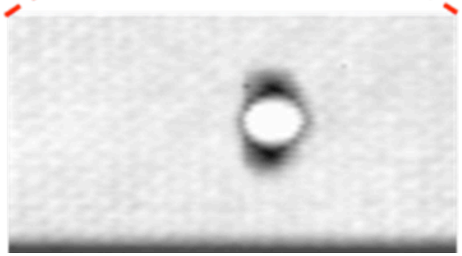
Operating Stress/Strain Levels



Ref: Whitehead, *et. al.* (1986), NADC-87042-60

Operating levels for composites are significantly low
➔ No sequencing effects





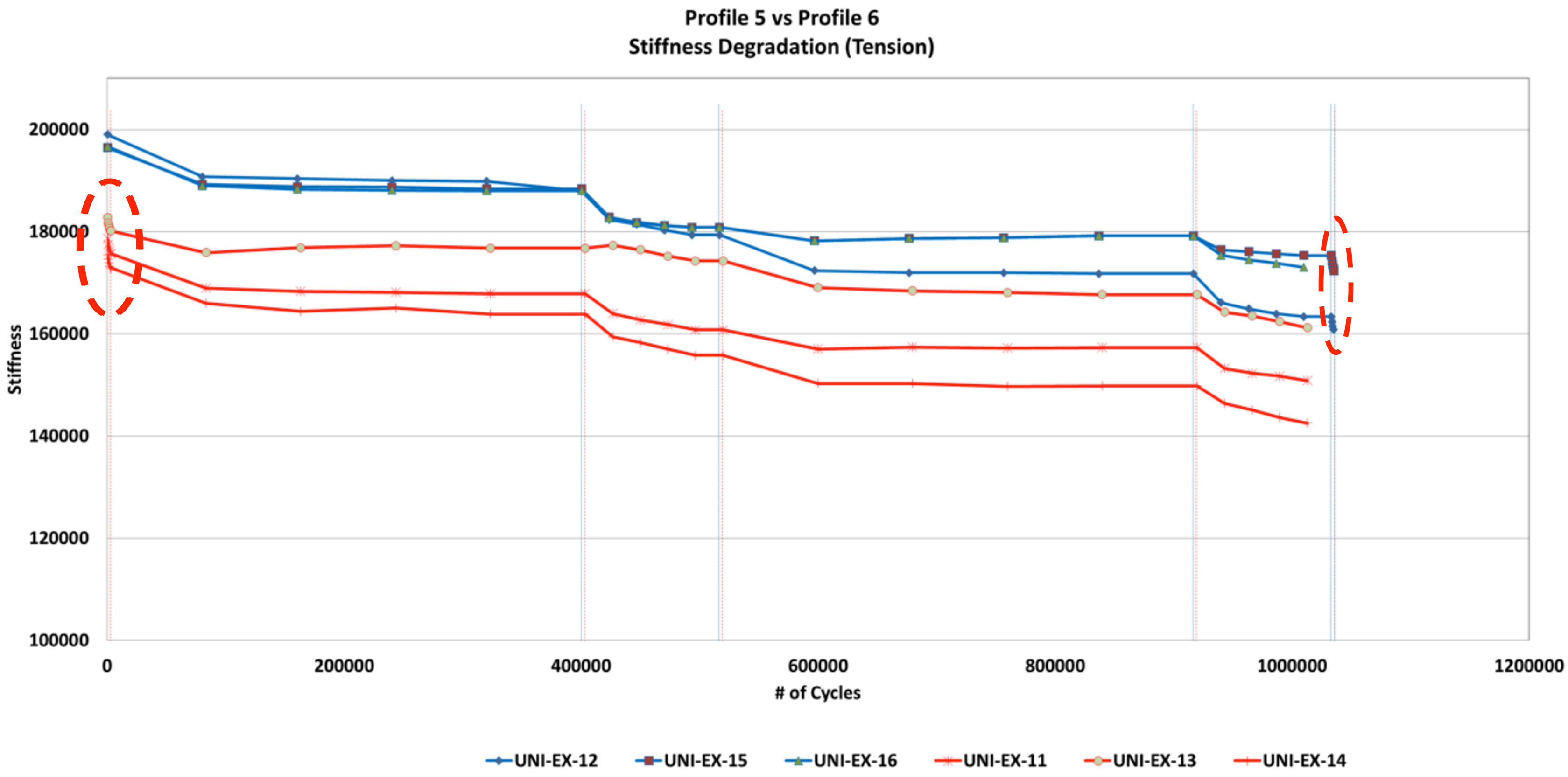
Open Hole 25/50/25 Out-of-Autoclave Material

- R=5
- Stress Level: 50% of Mean Static (~25 ksi)
- Runout: After 25 million cycles @ f=5 Hz

Load Sequencing Effects – Open Hole Tension/ Compression (UNI) – Spectrum Fatigue Results

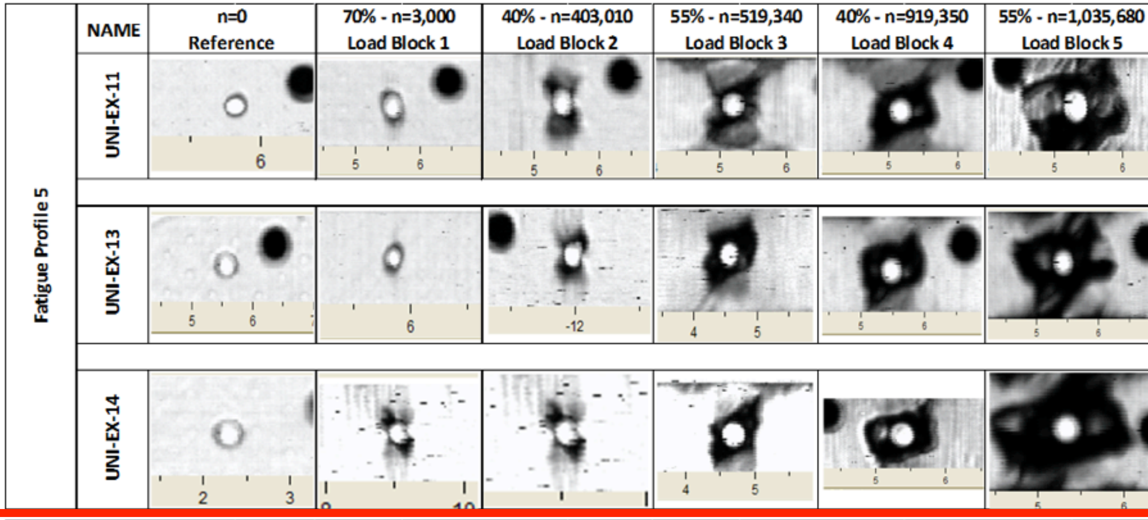
Fatigue Profile	Specimen Name	Block 1	Block 2	Block 3	Block 4	Block 5	Total # of Cycles	Comments
5	UNI-EX-11	**3000**	400010	116330	400010	116330	1035680	Survived
5	UNI-EX-13	**3000**	400010	116330	400010	116330	1035680	Survived
5	UNI-EX-14	**3000**	400010	116330	400010	116330	1035680	Survived
5	UNI-EX-17	**3000**	400010	116330	400010	116330	1035680	Survived
5	UNI-EX-19	**3000**	400010	116330	400010	116330	1035680	Survived
5	UNI-EX-21	**3000**	400010	116330	400010	116330	1035680	Survived
6	UNI-EX-12	400010	116330	400010	116330	**2775**	1035455	Failed
6	UNI-EX-15	400010	116330	400010	116330	**3000**	1035680	Survived
6	UNI-EX-16	400010	116330	400010	116330	**472**	1033152	Failed
6	UNI-EX-18	400010	116330	400010	116330	**543**	1033223	Failed
6	UNI-EX-20	400010	116330	400010	116330	**2447**	1035127	Failed
6	UNI-EX-22	400010	116330	400010	116330	**3000**	1035680	Survived

Stiffness Degradation



Load Sequencing Effects – Open Hole Tension/ Compression (UNI) - Inspections

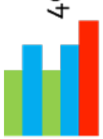
70-40-55-40-55 (High-Low)

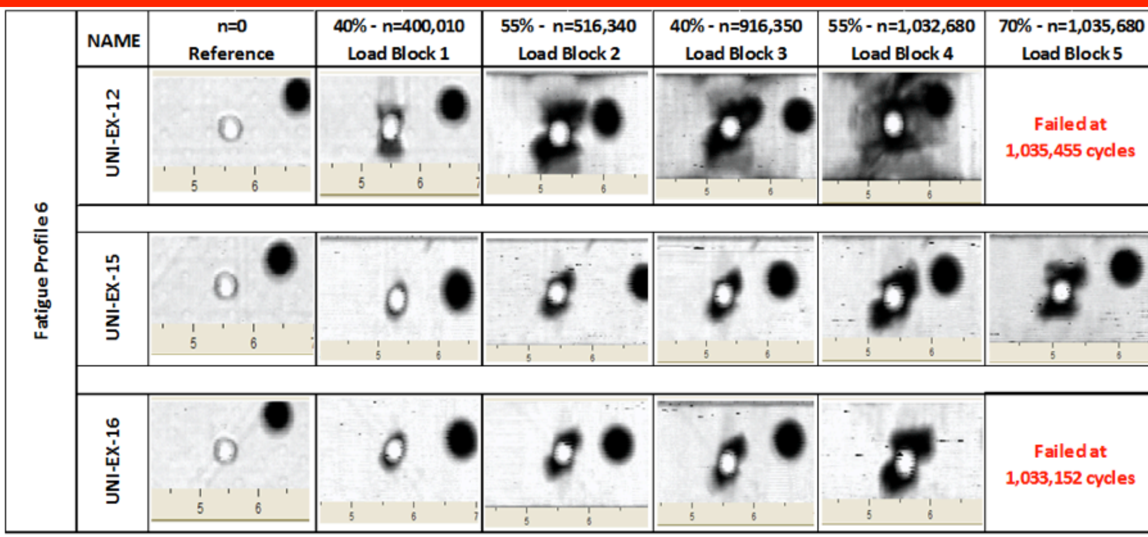


Fatigue Profile 5	
Stress Level	# of Cycle
70	3000
40	400010
55	116330
40	400010
55	116330

6 spec. survived profile 5

40-55-40-55-70 (Low-High)



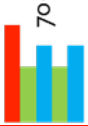


Fatigue Profile 6	
Stress Level	# of Cycle
40	400010
55	116330
40	400010
55	116330
70	3000

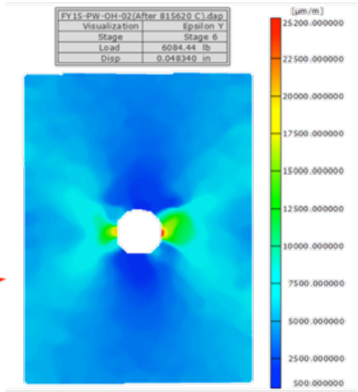
4 spec. failed and 2 spec. survived profile 6

Load Sequencing Effects – Open Hole Tension/ Compression (PW)

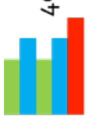
70-40-55-40-55 (High-Low)



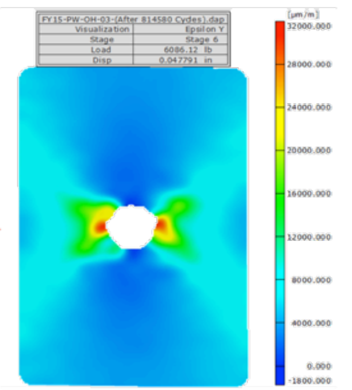
Fatigue Profile 5	NAME	n=0 Reference	70% - n=1,040 Load Block 1	40% - n=401,050 Load Block 2	55% - n=415,610 Load Block 3	40% - n=815,620 Load Block 4	55% - n=830,180 Load Block 5
	PW-OH-27						
	PW-OH-1						Failed at 823,523 cycles
	PW-OH-2						Failed at 827,830 cycles



40-55-40-55-70 (Low-High)



Fatigue Profile 6	NAME	n=0 Reference	40% - n=400,010 Load Block 1	55% - n=414,570 Load Block 2	40% - n=814,580 Load Block 3	55% - n=429,140 Load Block 4	70% - n=430180 Load Block 5
	PW-OH-3					Failed at 815,550 cycles	
	PW-OH-4					Failed at 822,849 cycles	
	PW-OH-6					Failed at 816,002 cycles	



PW Specimens failed before 70% block

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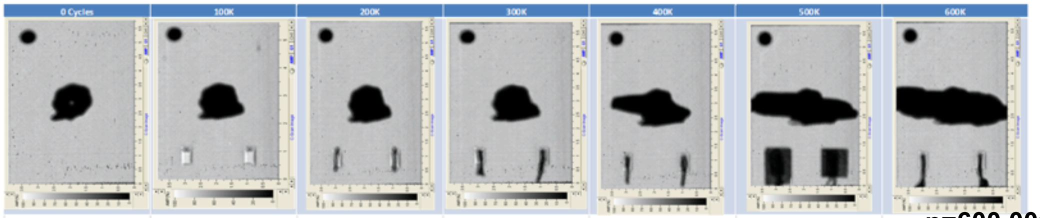
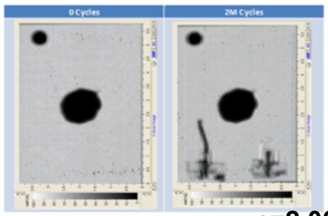
Load Sequencing Effects - Compression After Impact

Constant Amplitude (70% CAI SS)



n=600,000

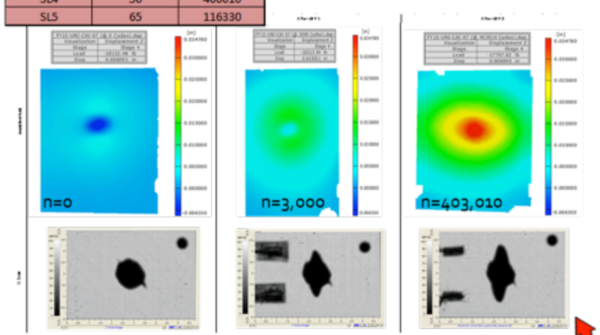
Constant Amplitude (55% CAI SS)



n=2,000,000

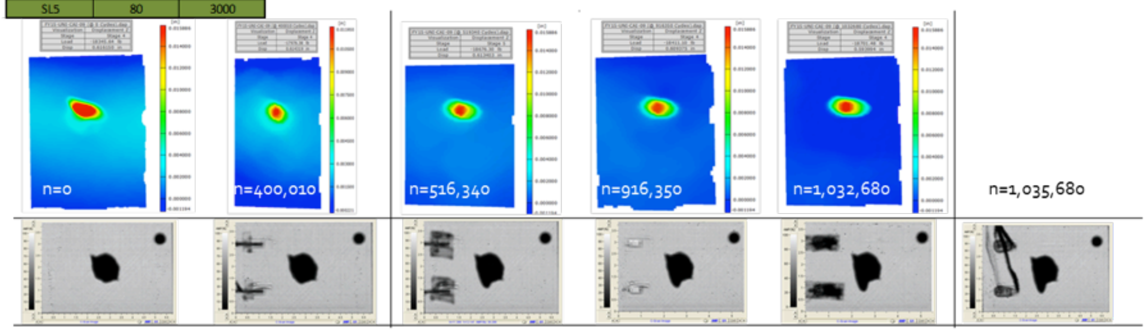
Spectrum Fatigue

Fatigue Profile 5		
Stress Level	Percentage [%]	# of Cycles
SL1	80	3000
SL2	50	400010
SL3	65	116330
SL4	50	400010
SL5	65	116330

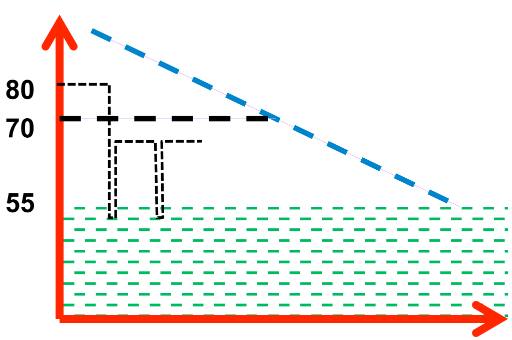


1 spec. failed at n=403,011
1 spec. survived n=1,035,680

Fatigue Profile 6		
Stress Level	Percentage [%]	# of Cycles
SL1	50	400010
SL2	65	116330
SL3	50	400010
SL4	65	116330
SL5	80	3000



3 spec. survived
n=1,035,680



Developing residual strength models based on Sendeckyj analysis

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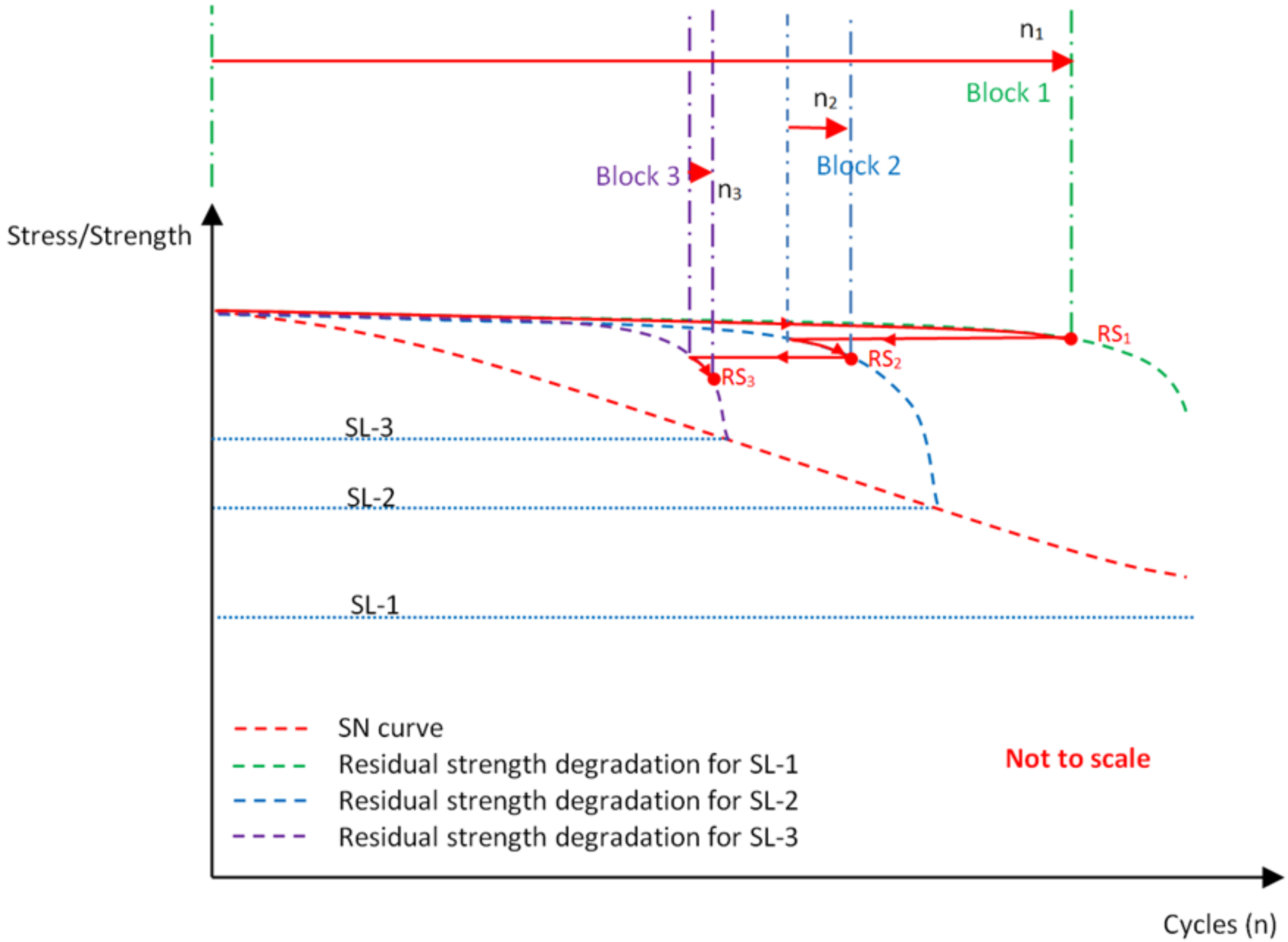
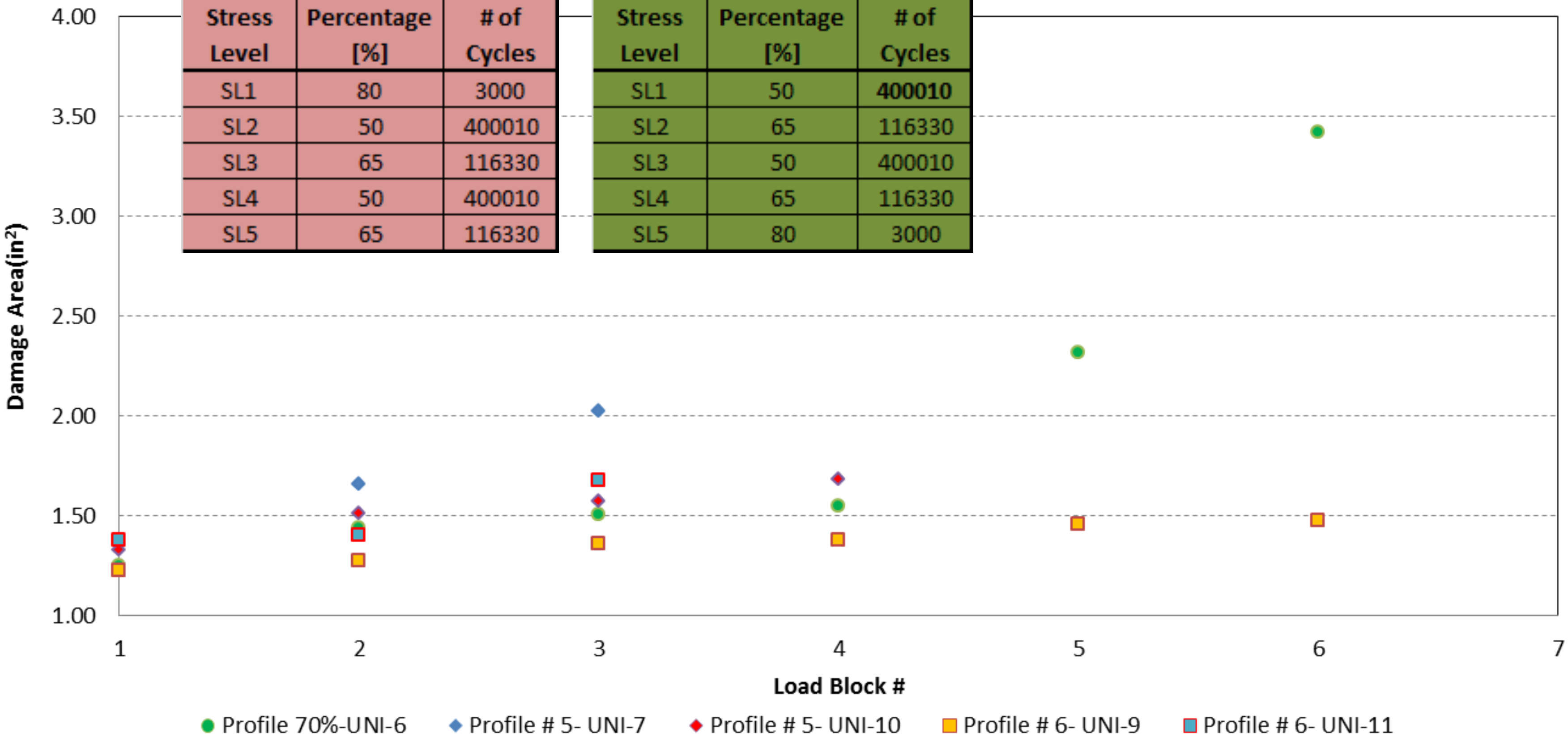
Residual Strength Degradation Models



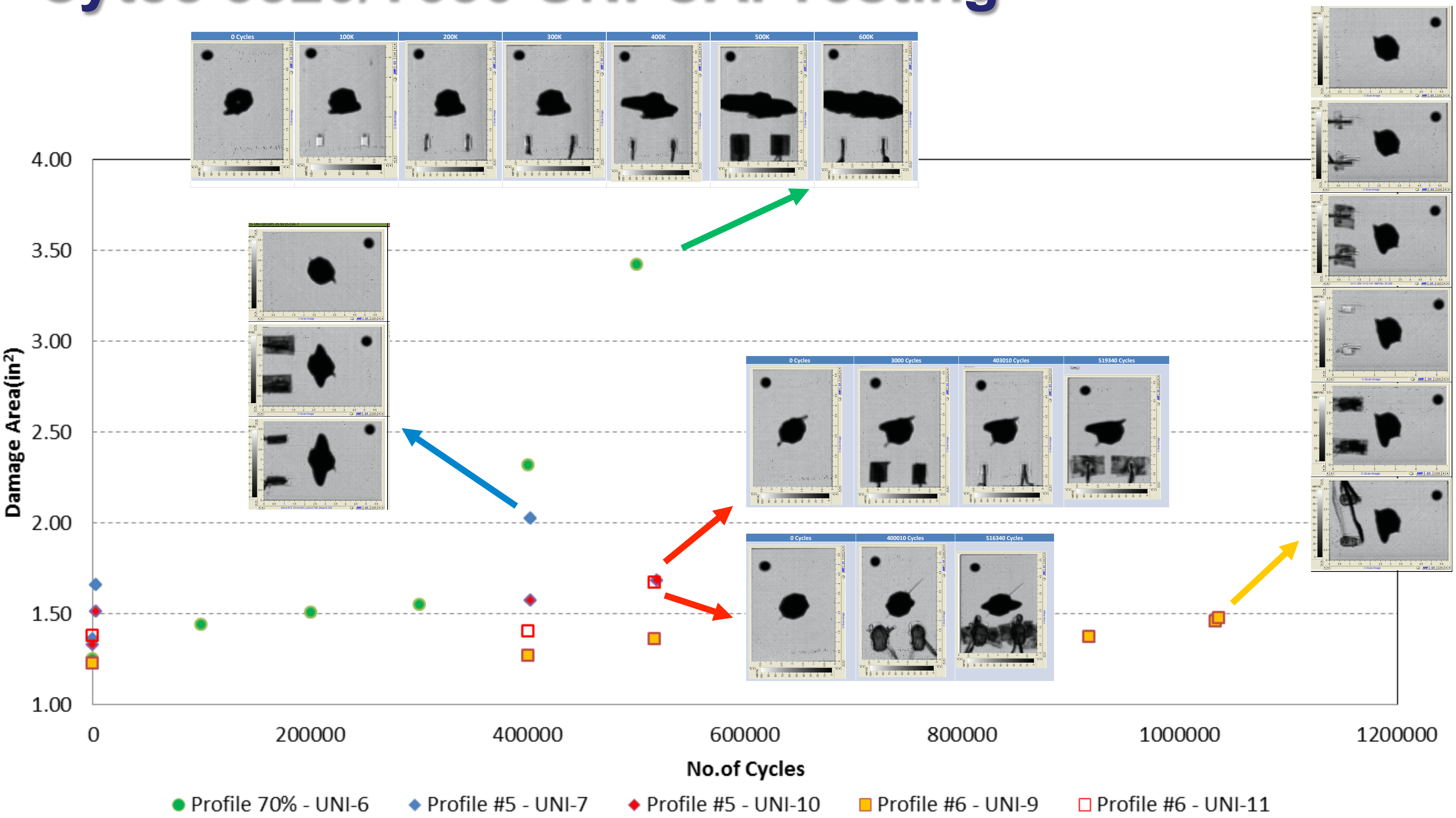
Cytec 5320/T650 UNI-CAI Testing

Fatigue Profile 5		
Stress Level	Percentage [%]	# of Cycles
SL1	80	3000
SL2	50	400010
SL3	65	116330
SL4	50	400010
SL5	65	116330

Fatigue Profile 6		
Stress Level	Percentage [%]	# of Cycles
SL1	50	**400010**
SL2	65	116330
SL3	50	400010
SL4	65	116330
SL5	80	3000



Cytec 5320/T650 UNI-CAI Testing



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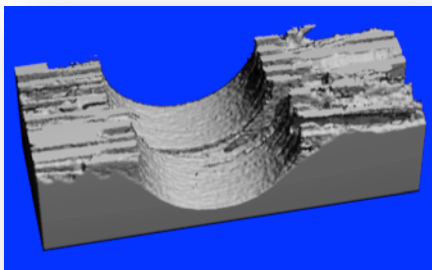
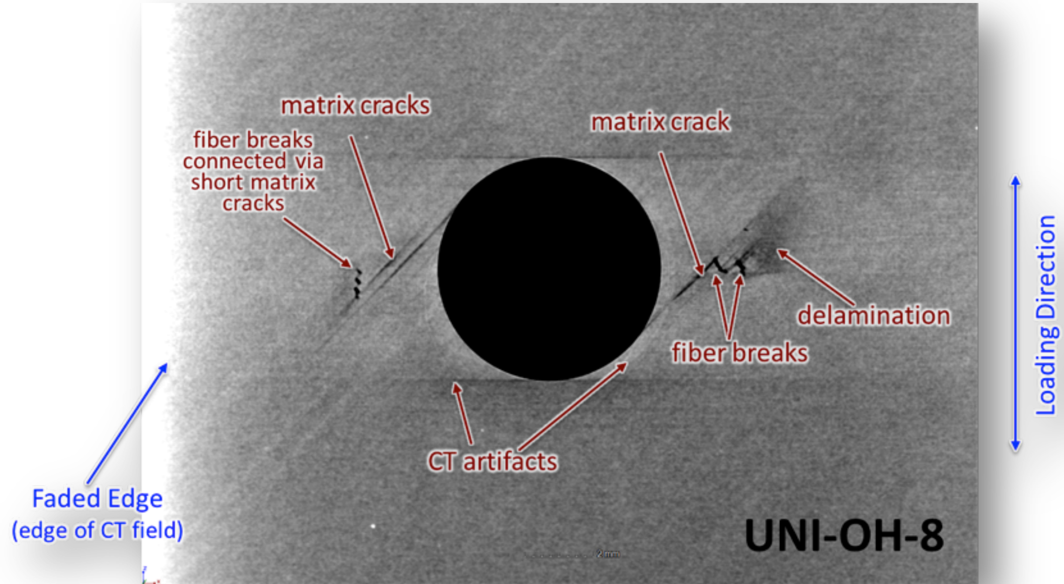
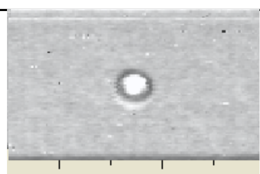
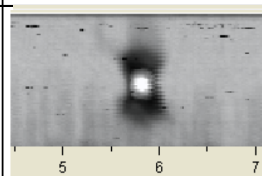
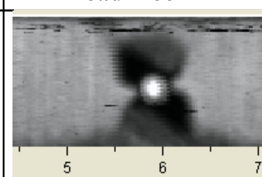
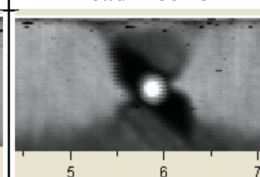
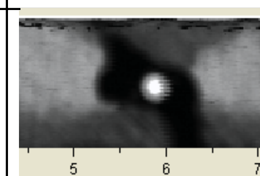
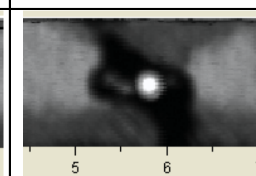
X-Ray CT-Scans

Collaboration with David Mollenhauer (AFRL)





	n=0 Reference	40% - n=400,010 Load Block 1	55% - n=516,340 Load Block 2	40% - n=916,350 Load Block 3	55% - n=1,032,680 Load Block 4	70% - n=1,035,680 Load Block 5
UNI-OH - 8						

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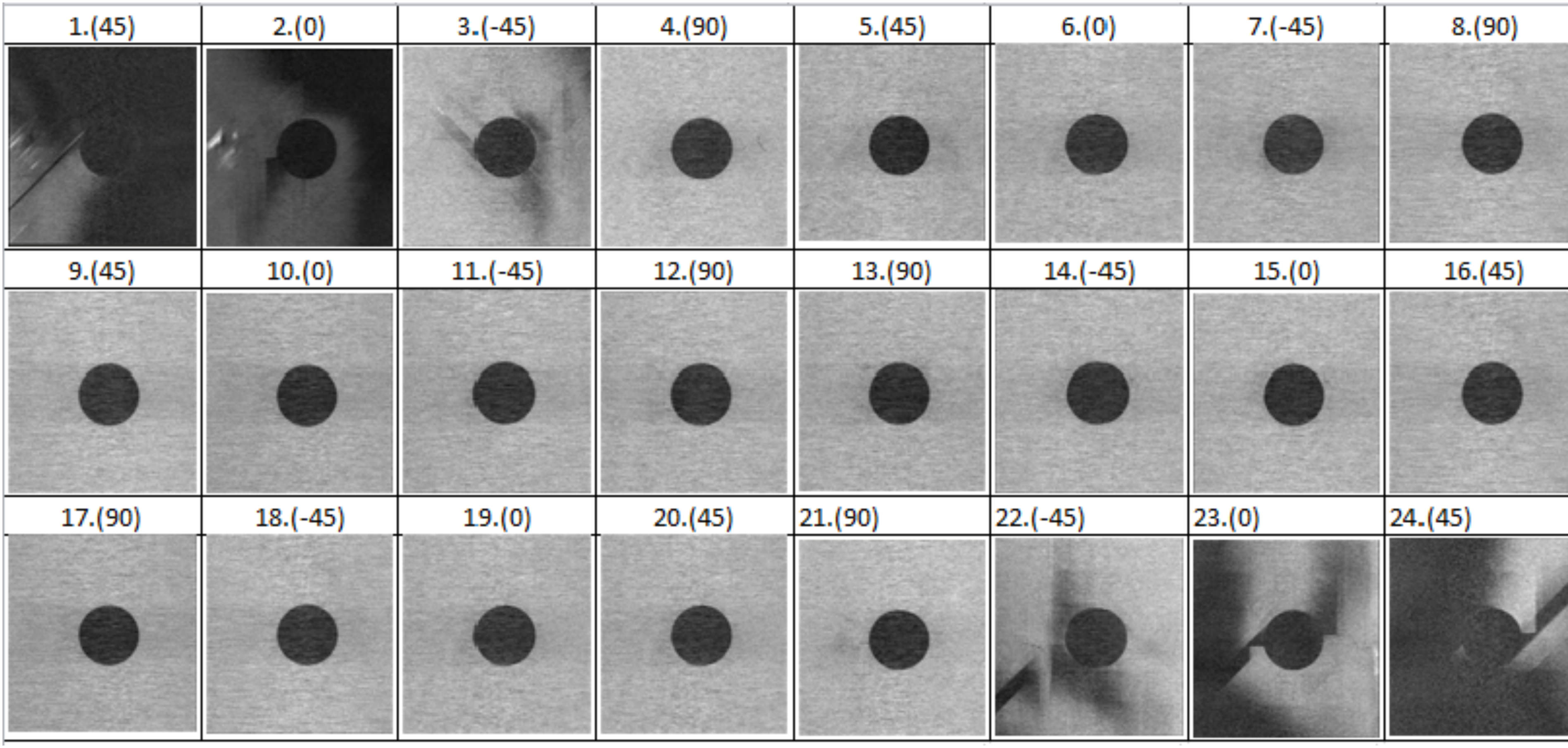
Micro CT 55kw (UNI-OH)



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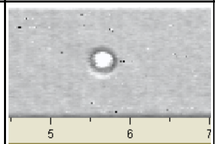
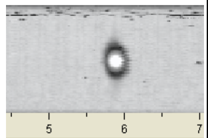
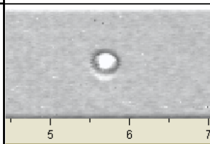
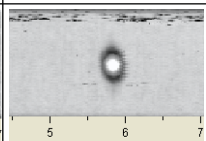
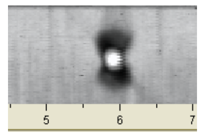
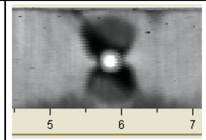
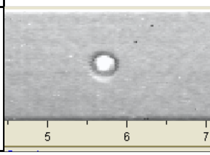
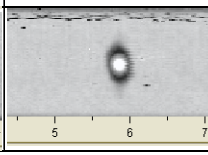
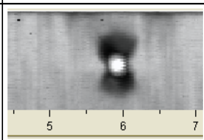
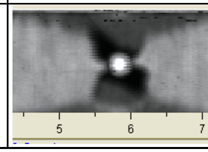
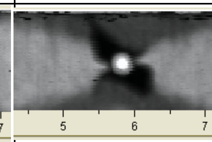
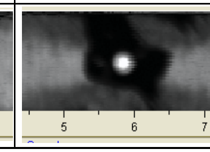
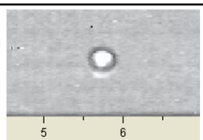
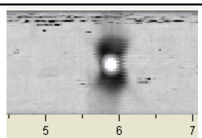
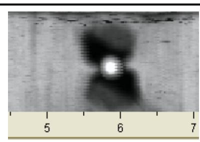
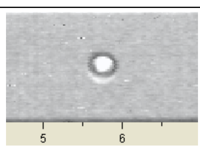
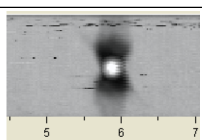
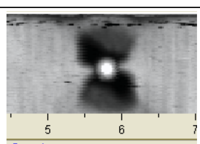
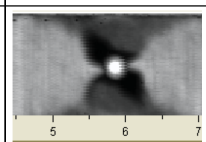
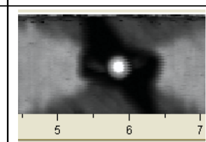
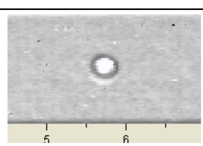
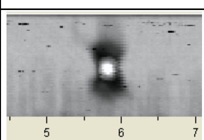
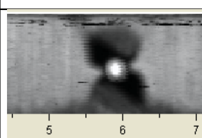
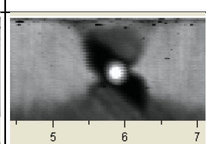
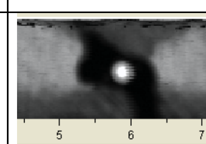
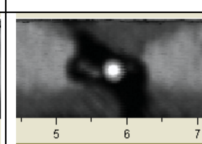
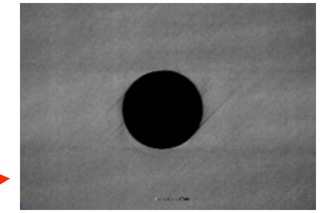
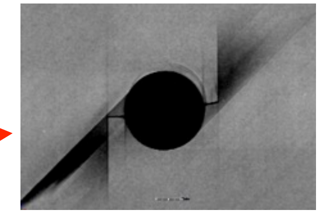
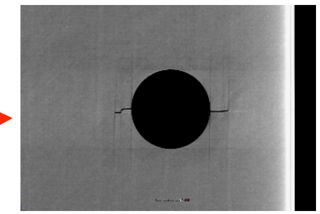
Additional CT-Scans

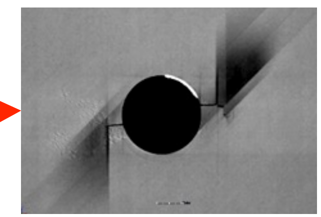
		n=0 Reference	70% - n=3,000 Load Block 1	40% - n=403,010 Load Block 2	55% - n=519,340 Load Block 3	40% - n=919,350 Load Block 4	55% - n=1,035,680 Load Block 5
Fatigue Profile - 5	UNI-OH - 3						
	UNI-OH - 4						
	UNI-OH - 9						

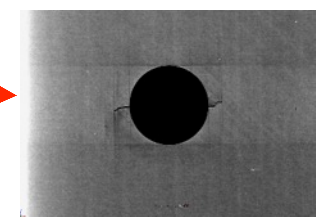
		n=0 Reference	40% - n=400,010 Load Block 1	55% - n=516,340 Load Block 2	40% - n=916,350 Load Block 3	55% - n=1,032,680 Load Block 4	70% - n=1,035,680 Load Block 5
Fatigue Profile - 6	UNI-OH - 6						
	UNI-OH - 7						
	UNI-OH - 8						

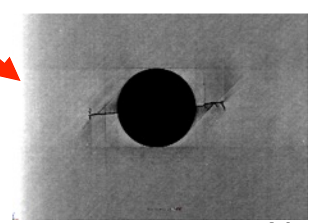




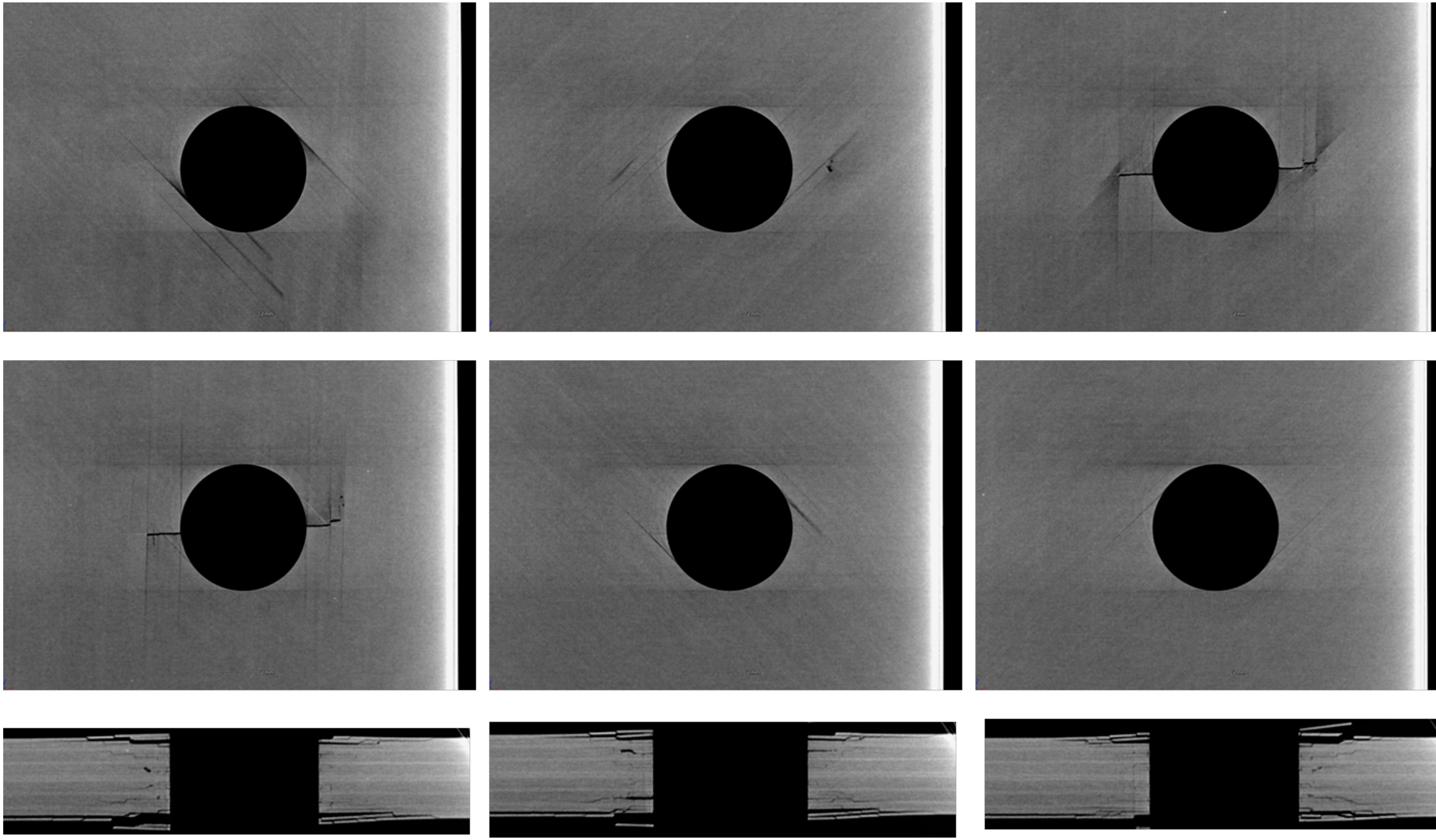








UNI-OHC-09 (Selected X-Ray CT-Scans)



Summary

- Multi-LEF and Deferred severity spectrum approaches can be applied to hybrid structures to prevent metal overloads
  - Smart Testing ➔ Significantly reduce the total test duration and cost of FSFT
  - Applicable for composite-dominant designs
  - Need analysis/tests to justify spectrum modifications
    - Sequencing effects
    - X-Ray CT-Scans
  - Effects of additional test duration on metals
    - Invalidation of metal test when high loads are applied (life extension)
- Additional considerations
  - Competing failure modes
  - Effects of CTE mismatch
  - Effects of environment

On-Going Efforts

- Complete OH-PW, CAI-UNI, and CAI-PW
- Failure analysis
  - C-scans
  - Stiffness degradation
  - X-ray CT-scans
- Hybrid Fatigue Investigation
  - Single-shear two-fastener bearing configuration
    - Failure analysis
  - Effects of CTE mismatch
    - RTA and CTA fatigue comparison
- Collaboration with AFRL (David Mollenhauer) and UTA (Prof. Endel Iarve) for progressive damage modeling of composites

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Looking Forward

- **Benefit to Aviation**
  - Efficient certification approach that weighs both the economic aspects of certification and the time frame required for certification testing, while ensuring that safety is the key priority.
    - Guidance materials for analysis and large-scale test substantiation of composite-metal hybrid structures.
    - Damage mechanics and competing failure modes (origination and propagation)
    - Guidance for hybrid load spectra and application LEF

- **Future needs**
  - Guidance on spectrum development
  - Validated fatigue and residual strength analysis methods

End of Presentation.

Thank you.

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