WICHITA STATE UNIVERSITY
NATIONAL INSTITUTE FOR AVIATION RESEARCH

Strength Tracking (ST) Method for

Determination of Composite Life under Variable-Amplitude Fatigue Loading

Waruna Seneviratne, PhD
Director NIAR ATLAS
Sr. Research Scientist (Composites & Structures)

Joint CMH-17-EASA-FAA Workshop on Damage Tolerance
Cologne, Germany
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ATLAS
ADVANCED TECHNOLOGIES LAB FOR AEROSPACE SYSTEMS

NIAR Locations

NIAR Headquarters @ Wichita State University (WSU)

- Composites & Mechanical Test, Computational Mechanics, Crash Dynamics, Environmental Test, Human Factors , Mechanical Test, Research Machine Shop, Walter H. Beech Wind Tunnel

Aircraft Structural Test & Evaluation Center (ASTEC)

(Kansas Coliseum)

- Aging Aircraft, Composites & Mechanical Test, Full-Scale Structural Test, Ballistic & Impact Dynamics

National Center for Aviation Training (NCAT)

- Advanced Coatings, CAD/CAM, Composites & Advanced Materials, Nondestructive Testing, Virtual Reality, Reverse Engineering

Electromagnetic Effects & Environmental Test Labs (ETL)

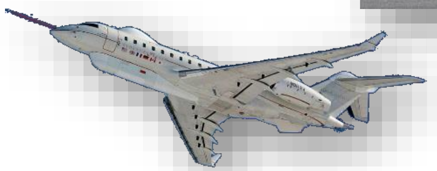
(former Boeing Military - Wichita Facility)

- Direct Effects of Lightning, Environmental Test, EMI/EMC, Vibration, Metrology

Engineering Design & Modification Team (BFTC)

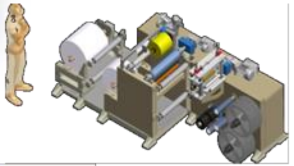
(former Bombardier Flight Test Center)

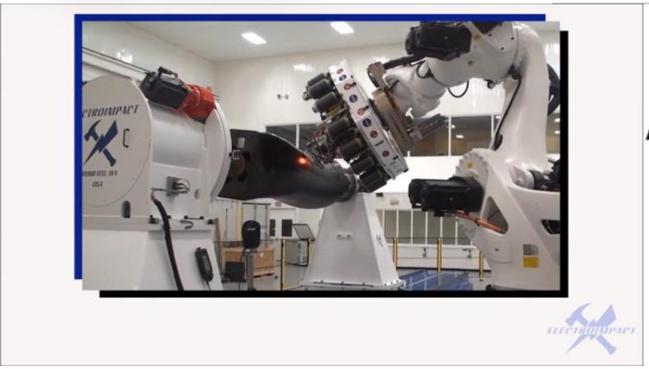
- Engineering, design, manufacturing, modification, test and certification



Innovation Campus – Master Plan

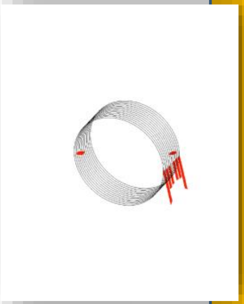
Develop a multi-disciplinary manufacturing environment and an engineering education program to prepare engineers and educators for the *Factory of the Future* and to aid the current workforce in seamlessly adapting to advancements in the workplace.





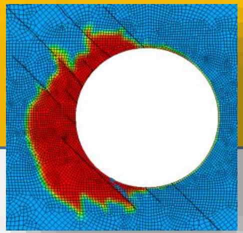
Automated Manufacturing

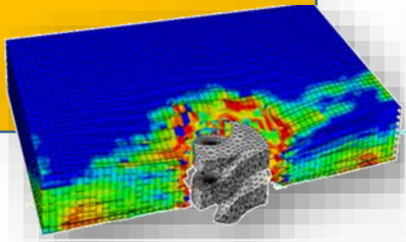
- Automated Fiber Placement
  - Thermoset
  - Thermoplastic
  - Dry Fiber
- Press Forming
  - Injection Molding
  - Over-Molding
  - Press-Molding



Computer-Aided Simulations & Analysis

- Manufacturing Simulations
- Process Modeling
- Global Stress Analysis
- Discrete Damage Modeling

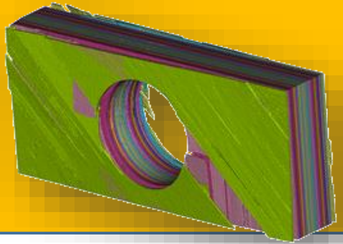




ATLAS
ADVANCED TECHNOLOGIES LAB FOR AEROSPACE SYSTEMS

High-Fidelity Inspections

- X-Ray CT (XCT)
- MAUS
- Acoustic Emission (AE)
- Digital Image Correlation (DIC)

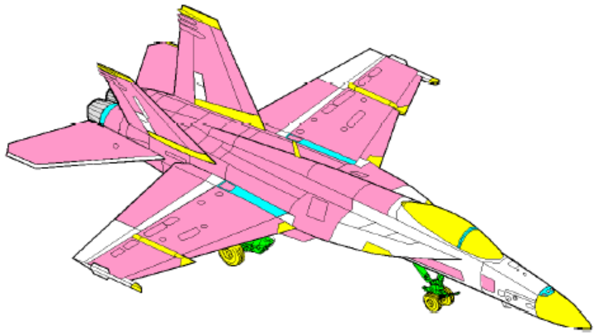


Structural Test & Evaluations

- Biaxial Axial-Torsion Testing
- Durability & Damage Tolerance
- Structural Health Monitoring
- Aging Evaluations
- Life Extension
- Repair Evaluations

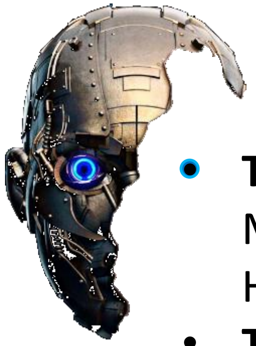
Variable Amplitude Fatigue Damage Growth (Background)

- Due to the anisotropy and heterogeneous nature of composites, fatigue damage growth characteristics of composites are complex and predictive methodologies are at their infant stages.
- Therefore, overly conservative assumptions are made for fatigue life assessment without taking full advantage of fatigue capabilities of composites.
- In order to design efficient composite structures, a greater understanding of fundamentals of fatigue damage initiation and growth characteristics of composite is needed.
- Need to understand the interaction of high-cycle (low stress) and low-cycle (high stress) fatigue on the life assessment of composite.



The primary goal of this research is to investigate the fatigue damage growth of composites under variable amplitude fatigue loading.
The secondary goal of the program is to develop tools for determining the residual strength degradation or wearout.

Modeling for Affordable Sustainable Composite (MASC)



- **Task 1:** Development of Fatigue Life Assessment Methodology of Advanced Composite Structures aided by High-Fidelity Damage Modeling
- **Task 2:** Advanced Material Characterization and Knowledge Representation
- **Task 3:** Certification Framework for Automated Fiber Placed Advanced Structures
- **Task 4:** Sustainment of Composite Structures
- **Task 5:** Sustainment Demo & Validation

Task	Task Description	Sub-Task Description	CY2019				2020				2021			
			Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
I	Fatigue Life Assessment	Strength Tracking Method	■	■	■	■	■	■	■	■				
		Spectrum Severity			■	■	■	■	■	■	■	■	■	■
	DDM Validation for Fatigue	Twining Method Validation	■	■	■	■								
		Local-Global Analysis			■	■	■	■	■	■	■	■	■	■
II	Advanced Material Characterization	Infusion Materials				■	■	■	■	■	■	■		
		Thermoset Materials		■	■	■	■	■	■	■	■	■	■	
		Adhesive Compatibility		■	■	■	■	■	■	■				
		Knowledge Representation	■	■	■	■	■	■	■	■	■	■	■	■
III	Certification Framework for AFP	Advance Materials			■	■	■	■	■	■	■	■	■	■
		Structural Development			■	■	■	■	■	■	■	■	■	■
		Lightening Strike Coating							■	■	■	■	■	■
		Certification Framework			■	■	■	■	■	■	■	■	■	■
IV	Sustainment of Composite Structure	Repair Analysis	■	■	■	■								
		Bondline Assessment		■	■	■	■	■	■	■	■	■	■	■
		NDI-Driven Modeling	■	■	■	■	■	■						
		Long-Term Aging Study	■	■	■	■	■	■	■	■	■	■	■	■
V	Sustainment Demo & Validation (Option)	Preliminary Design					■	■						
		Detailed Design							■	■				
		Manufacturing									■	■	■	
		Validation Testing										■	■	■

Building-Block Validation of ST Method

Method Development	User Subroutine	Structural Application

Fatigue Test

High-Fidelity Inspections

High-Fidelity Analysis

Fatigue Life Prediction using Residual Strength Degradation (ST Method)

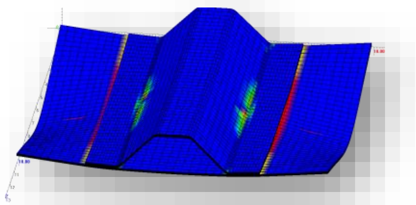
Verification & Validation

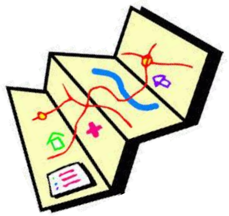
Development of User Subroutine

Structural Analysis (TBD)

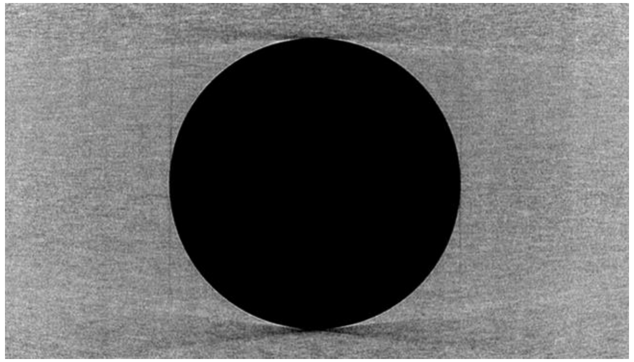
Incorporate into Hi-Fi FEA

Structural Test Validation

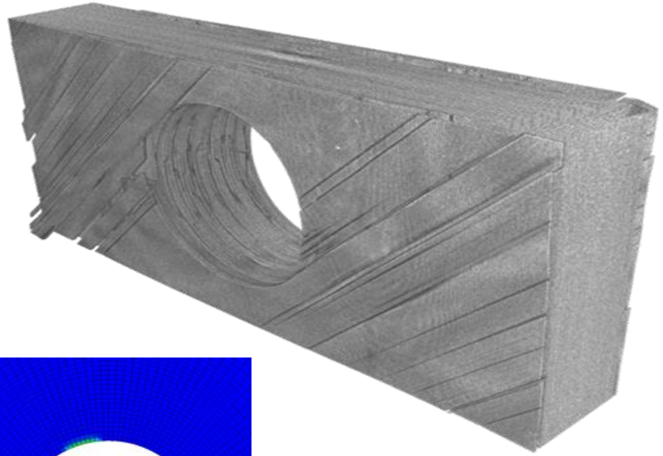




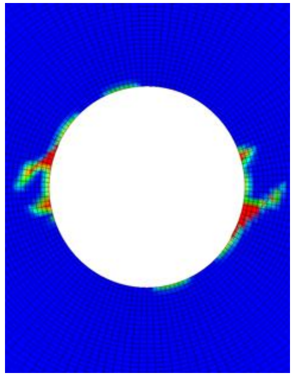
Overview of the Presentation



- Development of Strength Tracking (ST) Methodology
  - Variable Amplitude Fatigue Analysis
  - Validation
- High-Fidelity Inspections for Damage Characterization
  - X-Ray Computed Tomography (XCT)
  - High-fidelity inspection database

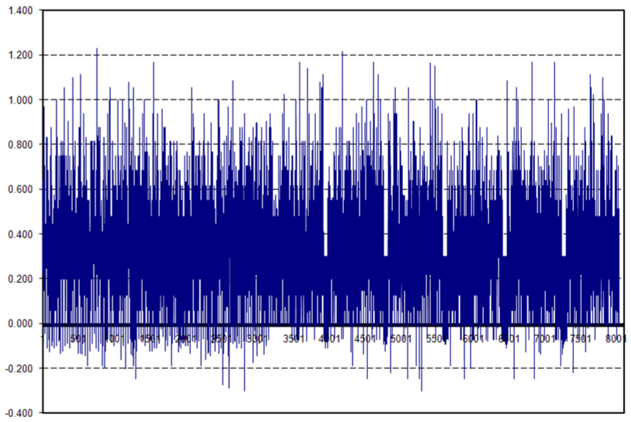


- High-Fidelity Finite Element Analysis
  - Regularized Extended Finite Element Analysis (Rx-FEM)
  - Validation with XCT and test results



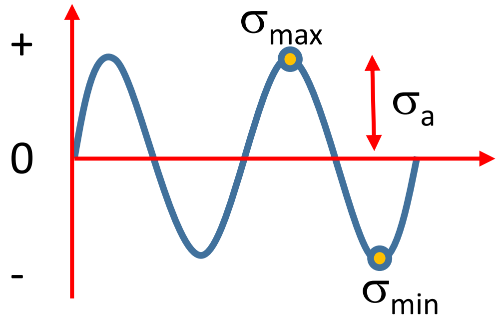
Development of Strength Tracking (ST) Methodology

Variable Amplitude Fatigue Testing & Analysis



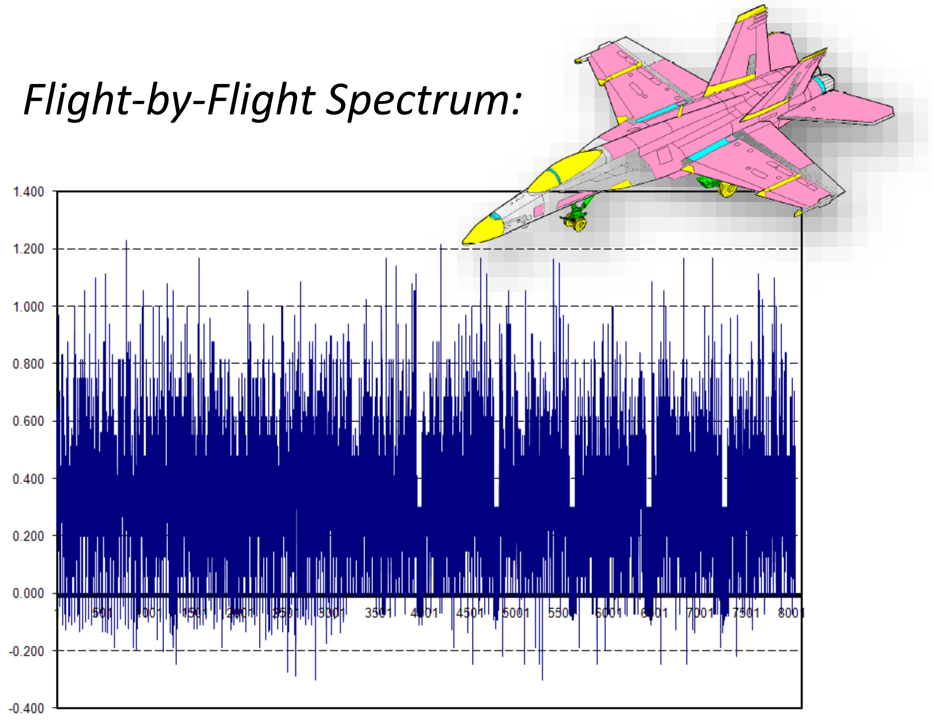
Constant Amplitude vs. Variable Amplitude (Spectrum)

Constant amplitude:



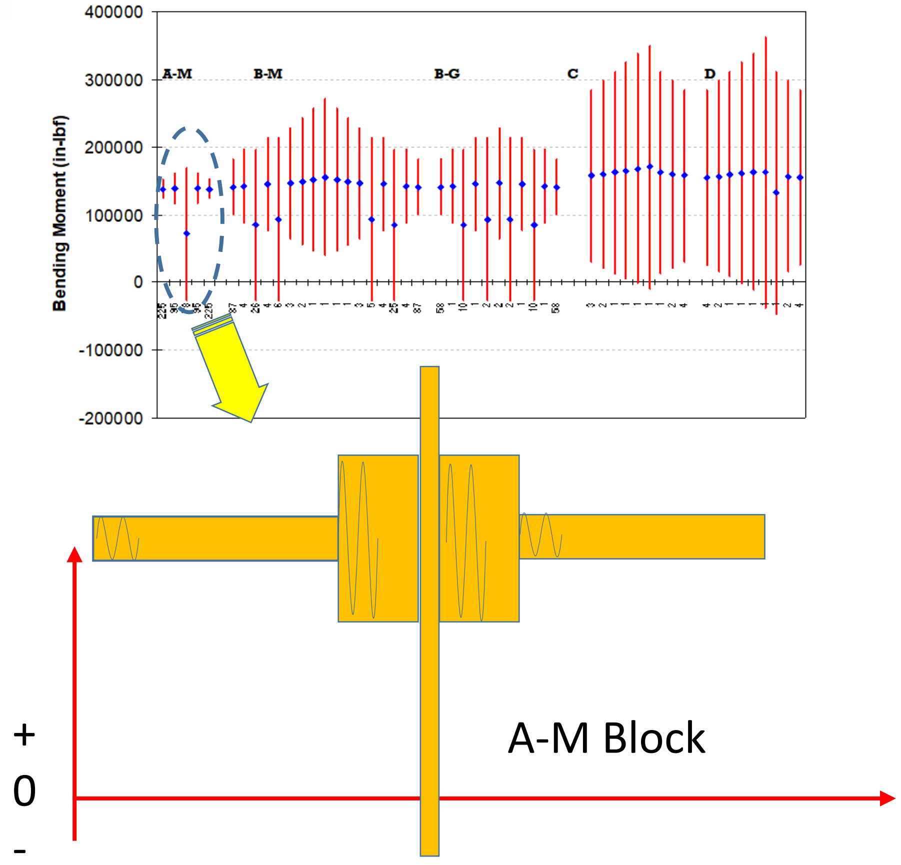
$A = (\sigma_{max} + \sigma_{max})/2$

Flight-by-Flight Spectrum:



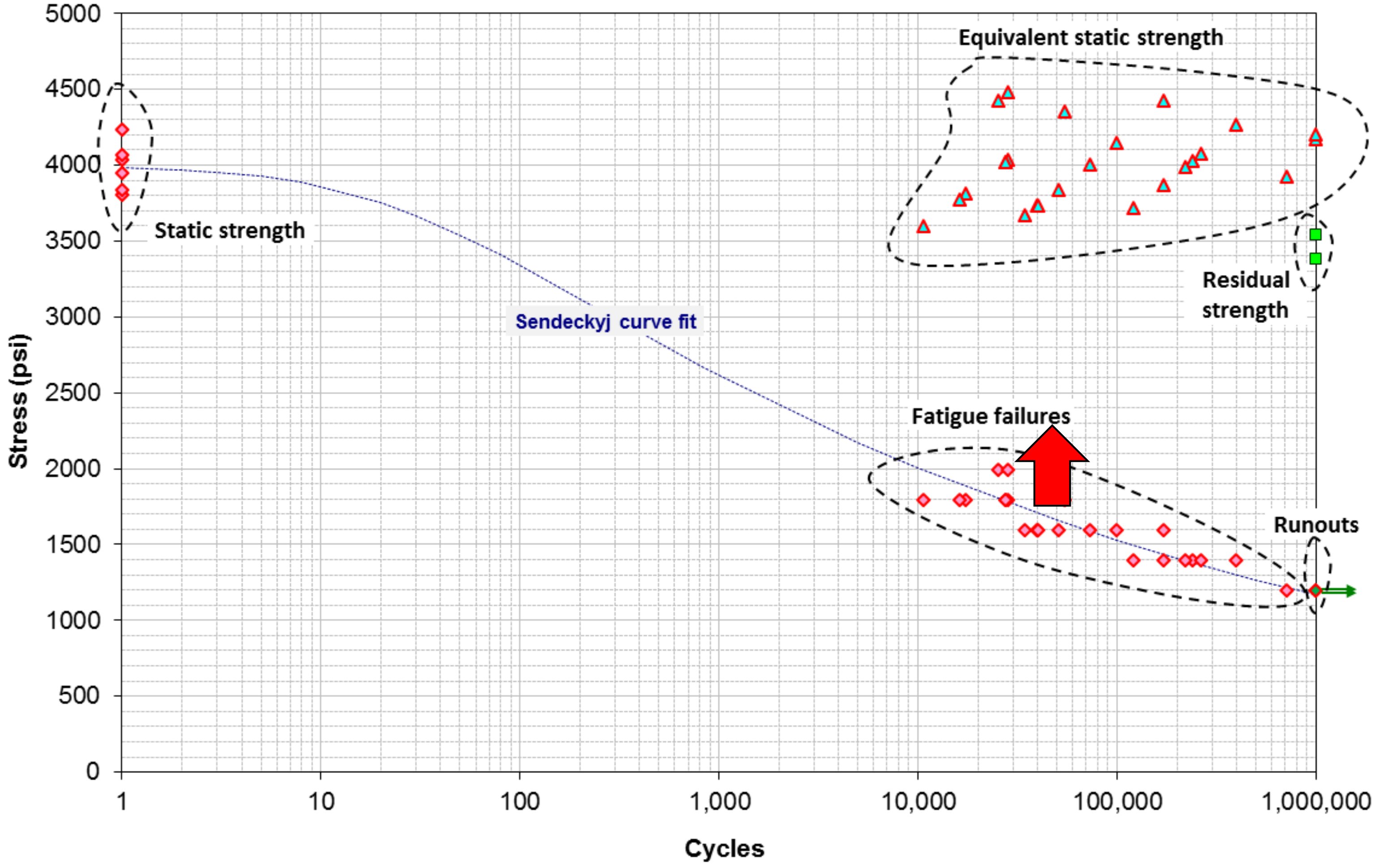
REF: Seneviratne, W., *et.al.*, "Durability and Residual Strength Assessment of F/A-18 A-D Wing-Root Stepped-Lap Joint," 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and the Centennial of Naval Aviation Forum, September 2011.

Block Spectrum:



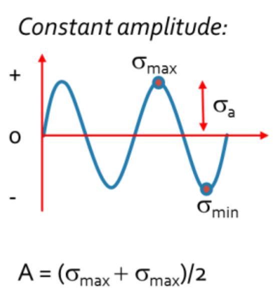
REF: Seneviratne, W. , "Fatigue Life Determination of a Damage-Tolerant Composite Airframe," Wichita State University, December 2008.

Sendeckyj Equivalent Static Strength Model

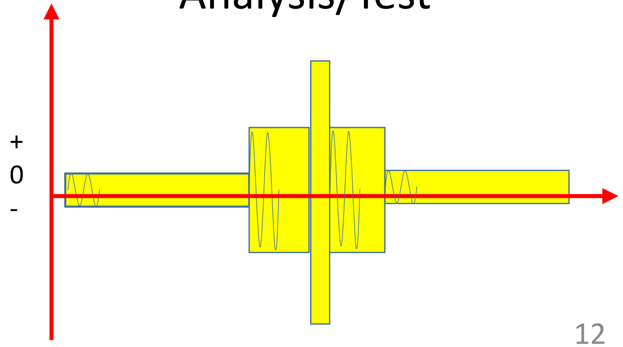


$$\sigma_r = \sigma_a \left[\left(\frac{\sigma_e}{\sigma_a} \right)^{1/S} - C(n_f - 1) \right]^S$$

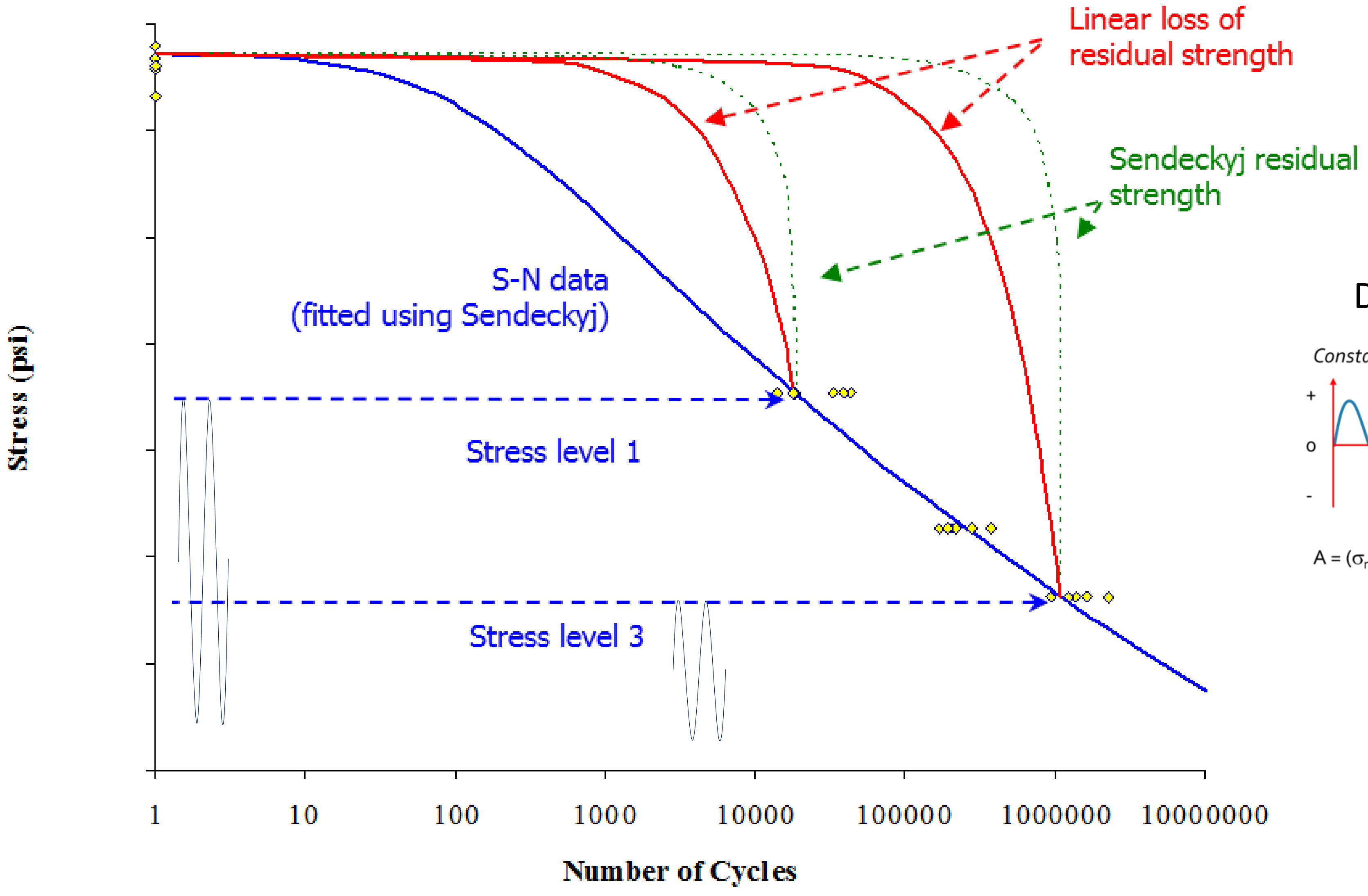
Data



Analysis/Test



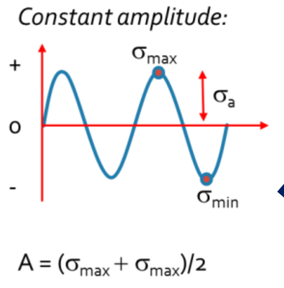
Wearout under Constant Amplitude Fatigue



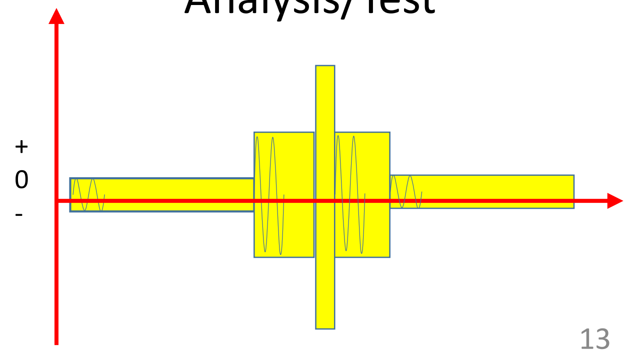
$$\sigma_r = \sigma_e + \left(\frac{\sigma_a - \sigma_e}{N_f(\sigma_a)} \right) \cdot n_f$$

$$\sigma_r = \sigma_a \left[\left(\frac{\sigma_e}{\sigma_a} \right)^{1/S} - C(n_f - 1) \right]^S$$

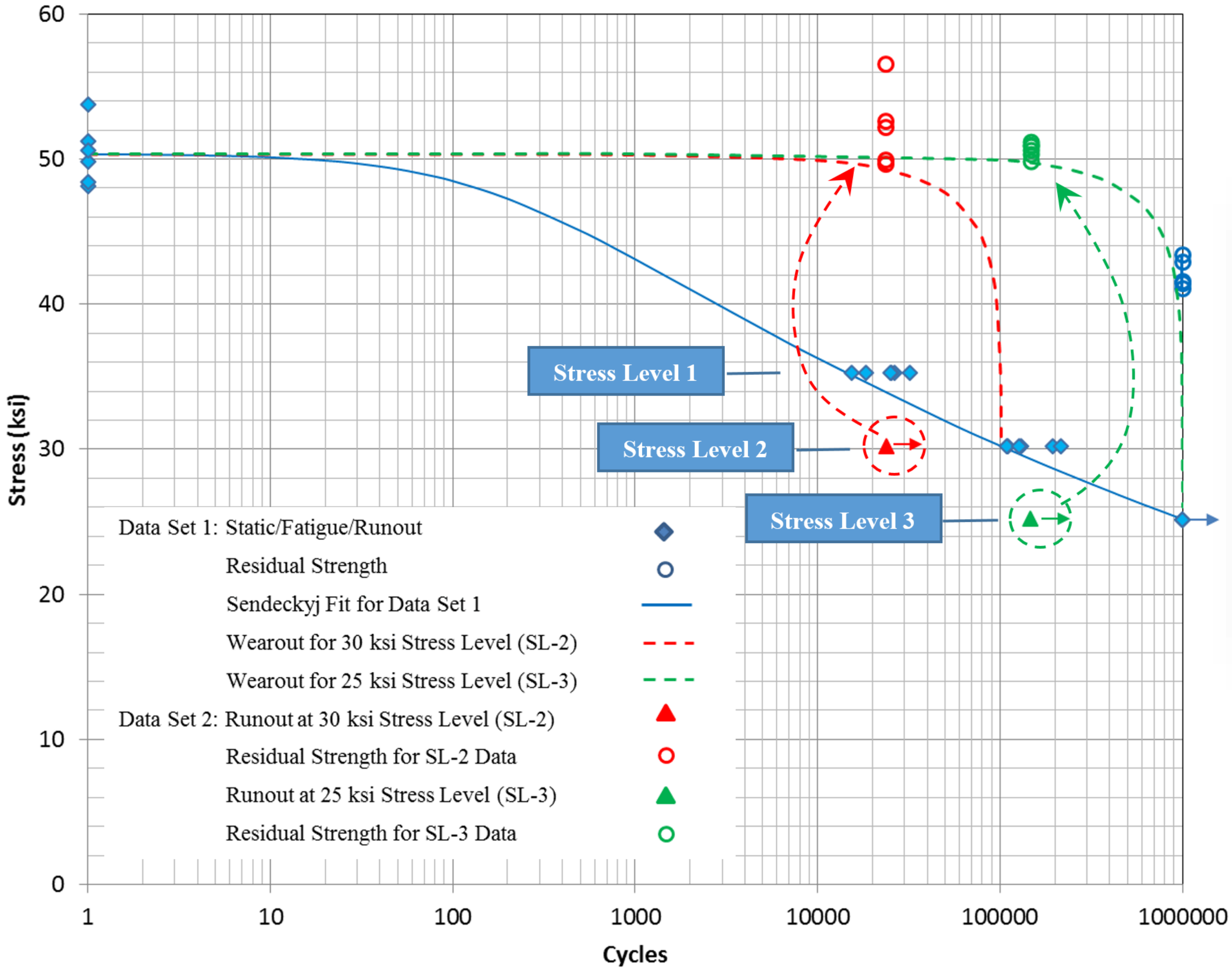
Data



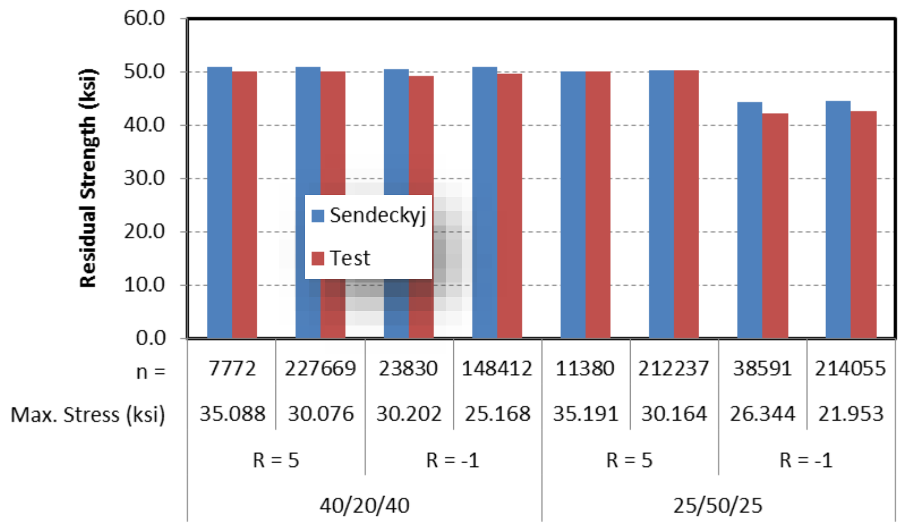
Analysis/Test



Sendeckyj Residual Strength Degradation



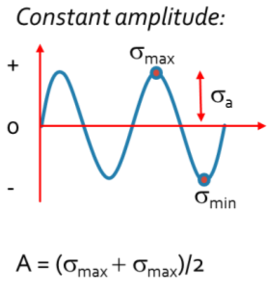
$$\sigma_r = \sigma_a \left[\left(\frac{\sigma_e}{\sigma_a} \right)^{1/S} - C(n_f - 1) \right]^S$$



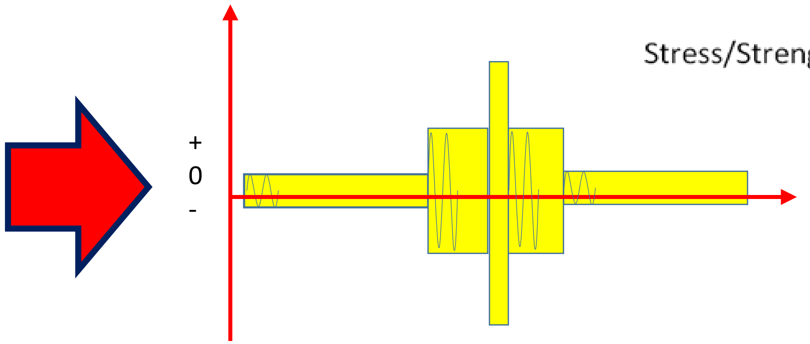
REF: Seneviratne, W. P., Tomblin, J. S., and Palliyaguru, U. **"Fatigue and Residual Strength Analysis of Out-of-Autoclave T650/5320 Plain Weave Fabric Composite Material,"** *CAMX 2014*.

Strength Tracking (ST) Method

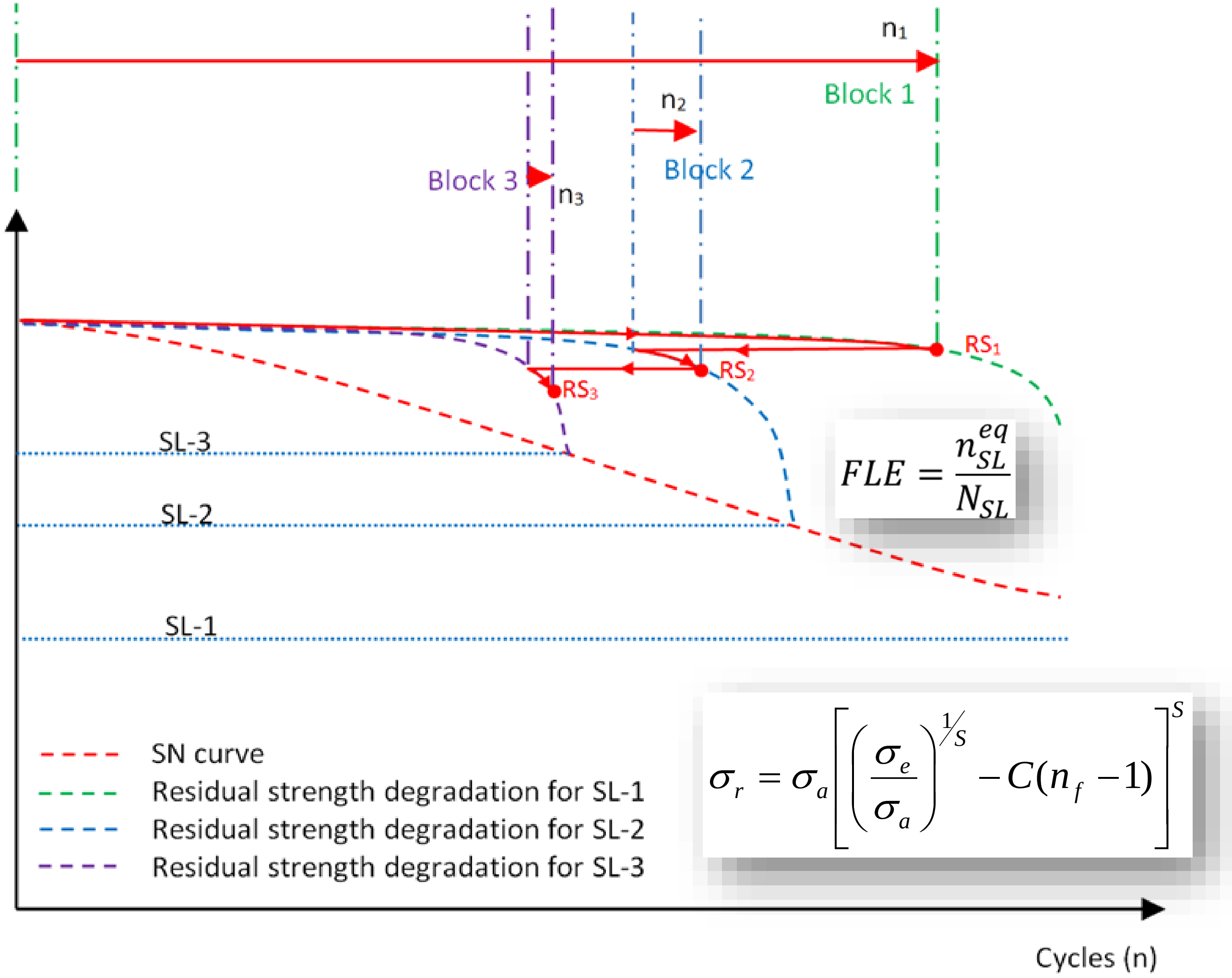
Fatigue Model Based on Residual Strength Degradation (Wearout)



Data



Analysis/Test



$$FLE = \frac{n_{SL}^{eq}}{N_{SL}}$$

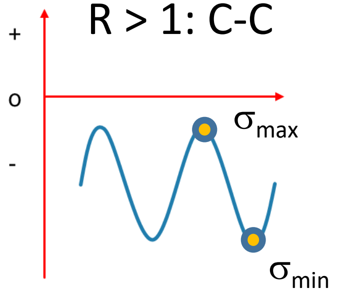
$$\sigma_r = \sigma_a\left[\left(\frac{\sigma_e}{\sigma_a}\right)^{1/S} - C(n_f - 1)\right]^S$$

Block No.	Stress Ratio	Stress Level	Number of Cycles in Block	Cumulative Cycles	Residual Strength
1	R = -1	SL-1	n_1	n_1	RS_1
2	R = -1	SL-2	n_2	$n_1 + n_2$	RS_2
3	R = -1	SL-3	n_3	$n_1 + n_2 + n_3$	RS_3

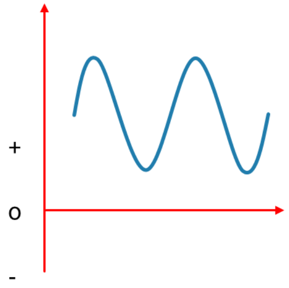
Stress Ratio (R) Effects

R = min / max stress

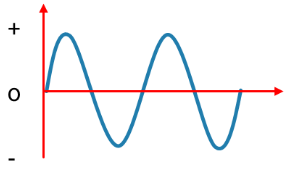
R > 1: C-C

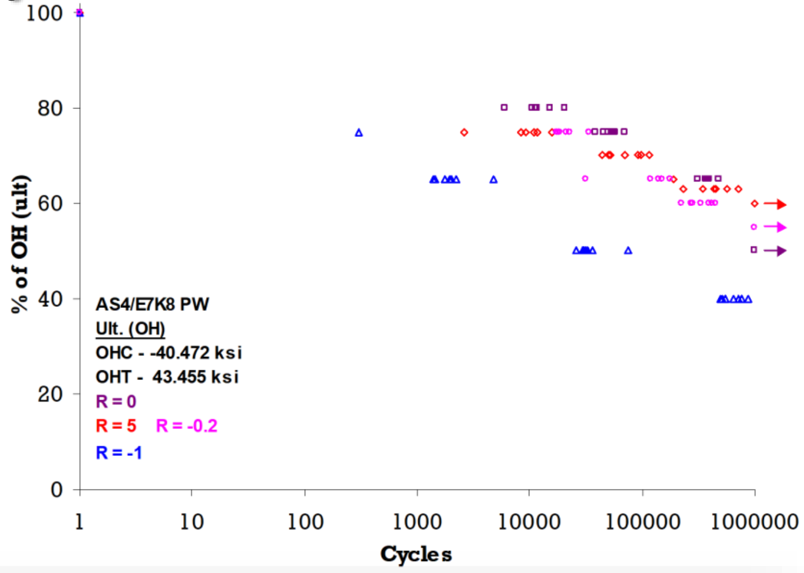


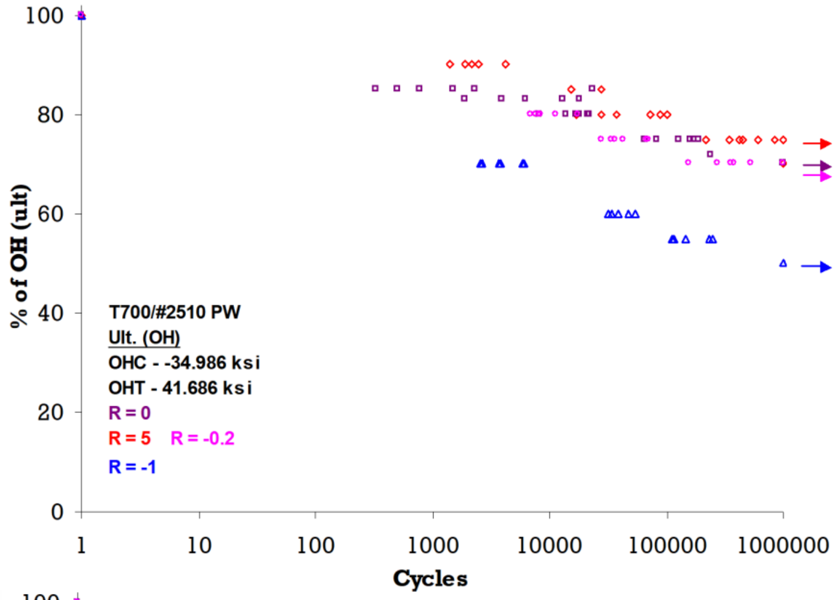
1 > R > 0: T-T

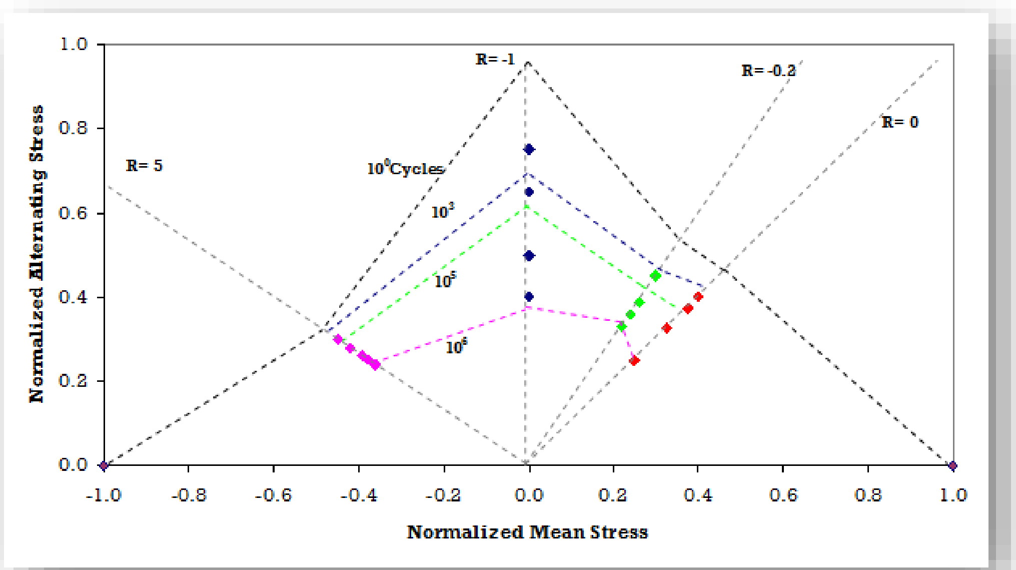


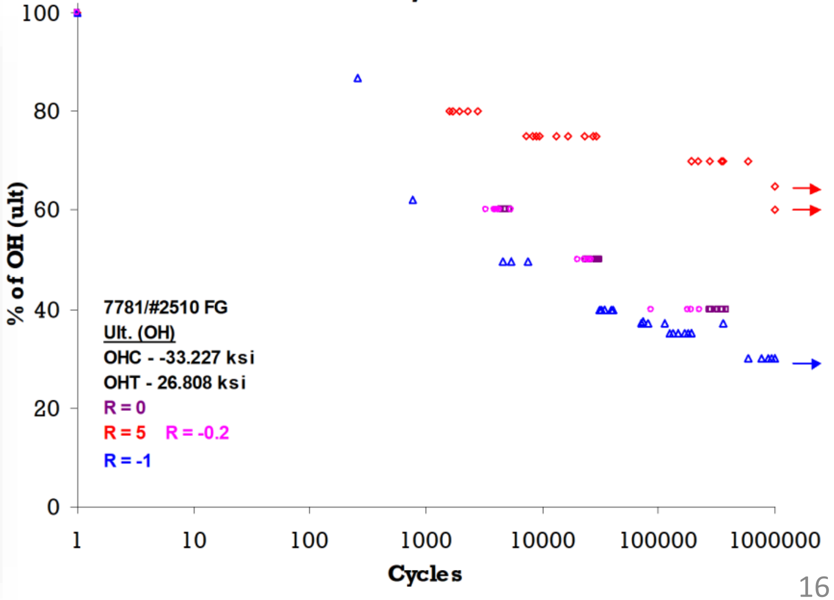
R < 0: C-T





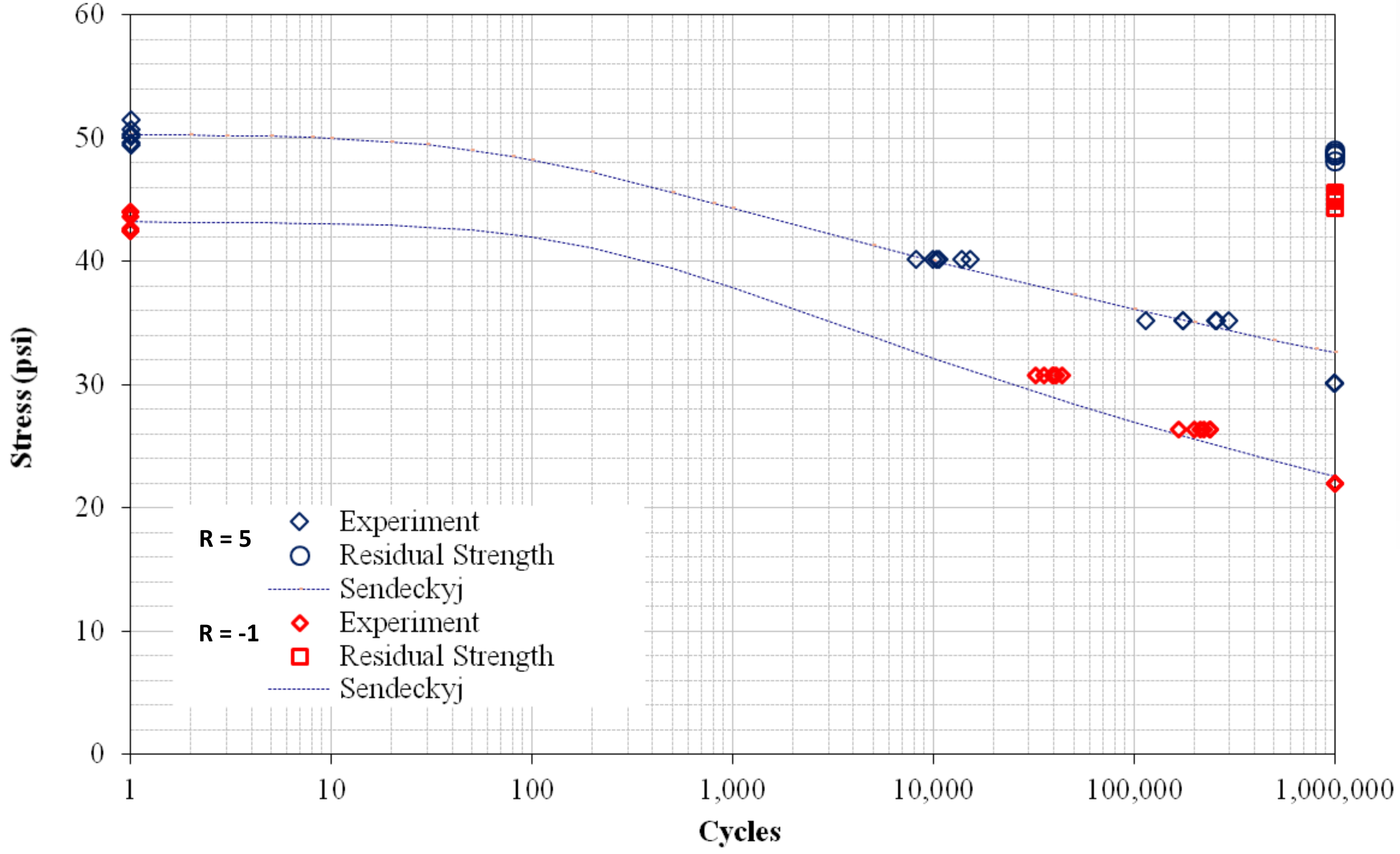


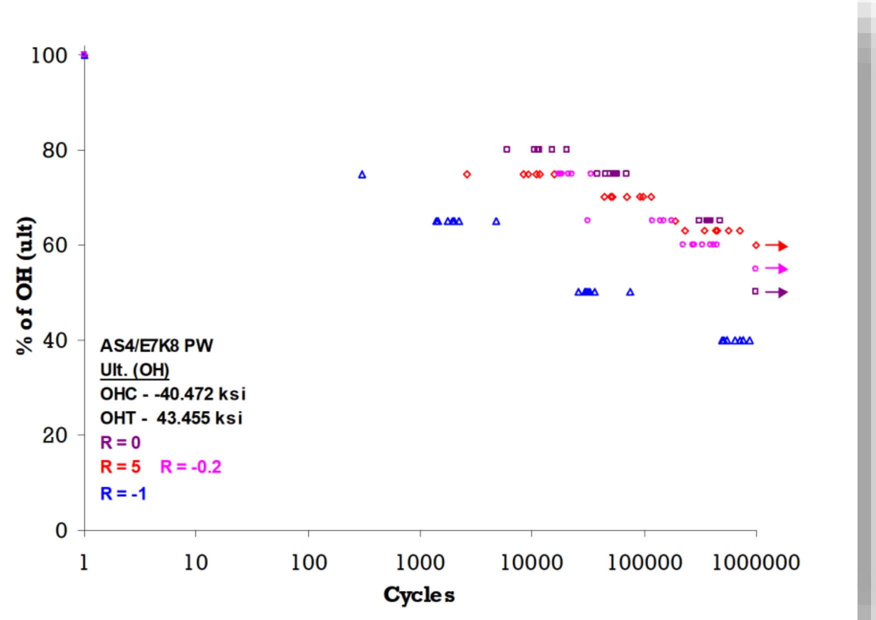


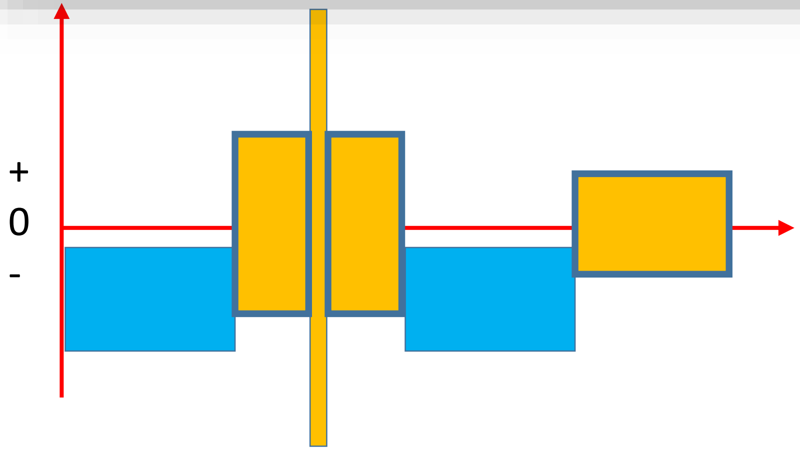


Ref: DOT/FAA/AR-10/6

ST Method - Spectra with Multiple Stress Ratios







REF: Seneviratne, W. P., Tomblin, J. S., and Palliyaguru, U. **“Fatigue and Residual Strength Analysis of Out-of-Autoclave T650/5320 Plain Weave Fabric Composite Material,”** *CAMX 2014*.

Validation of ST Method – 25/50/25 PW Preliminary Results

Fatigue Analysis

	25/50/25											
Block	Σ n	σ_e	S	C	R	σ_a	σ_{max}	σ_{min}	n_i	n_{eqv}	n_{tot}	$\sigma_r(n,R,\sigma)$
1	0	50.254	0.045	0.015	5	30	-6.000	-30.000	300000	0	300000	50.143
2	300000	50.254	0.045	0.015	5	35	-7.000	-35.000	50000	9760	59760	49.470
3	350000	50.254	0.045	0.015	5	40	-8.000	-40.000	5000	3075	8075	46.992
4	355000	50.254	0.045	0.015	5	35	-7.000	-35.000	45517	156963	202480	35.007
									400517			
Block	Σ n	σ_e	S	C	R	σ_a	σ_{max}	σ_{min}	n_i	n_{eqv}	n_{tot}	$\sigma_r(n,R,\sigma)$
1	0	44.923	0.077	0.005	-1	25	25.000	-25.000	200000	0	200000	42.930
2	200000	44.923	0.077	0.005	-1	30	30.000	-30.000	10000	18623	28623	41.101
3	210000	44.923	0.077	0.005	-1	35	35.000	-35.000	1000	3847	4847	38.537
4	211000	44.923	0.077	0.005	-1	30	30.000	-30.000	4609	36065	40674	33.878
									215609			
Block	Σ n	σ_e	S	C	R	σ_a	σ_{max}	σ_{min}	n_i	n_{eqv}	n_{tot}	$\sigma_r(n,R,\sigma)$
1	0	50.254	0.045	0.015	5	30	-6.000	-30.000	200000	0	200000	50.180
2	200000	44.923	0.077	0.005	-1	25	25.000	-25.000	200000	-1445345	-1245345	49.752
3	400000	50.254	0.045	0.015	5	35	-7.000	-35.000	20000	40512	60512	49.458
4	420000	44.923	0.077	0.005	-1	30	30.000	-30.000	12373	-104239	-91866	49.123
									432373			

Fatigue Test Results

R = 5

705000	
475210	475210
352423	352423
351936	351936
705000	
362621	362621
492032	**385548**

R = -1

1	210043
1	210558
1	210125
2	174580
2	200190
2	201477
2	205083
2	205070
2	205533
	202518

R = 5 & -1

420000
405122
421213
415445

Validation of ST Method – 40/20/40 PW Preliminary Results

Fatigue Analysis

	40/20/40	[0/90/0/90/45/-45/90/0/90/0]s										
Block	Σ n	σ_e	S	C	R	σ_a	σ_{max}	σ_{min}	n_i	n_{eqv}	n_{tot}	$\sigma_r(n,R,\sigma)$
1	0	50.847	0.035	0.209	5	30	-6.000	-30.000	500000	0	500000	50.798
2	500000	50.847	0.035	0.209	5	35	-7.000	-35.000	50000	5961	55961	50.327
3	550000	50.847	0.035	0.209	5	40	-8.000	-40.000	3000	1207	4207	47.066
4	553000	50.847	0.035	0.209	5	35	-7.000	-35.000	23766	195134	218900	35.217
									576766			
Block	Σ n	σ_e	S	C	R	σ_a	σ_{max}	σ_{min}	n_i	n_{eqv}	n_{tot}	$\sigma_r(n,R,\sigma)$
1	0	51.298	0.080	0.006	-1	25	25.000	-25.000	500000	0	500000	49.503
2	500000	51.298	0.080	0.006	-1	30	30.000	-30.000	50000	50465	100465	46.374
3	550000	51.298	0.080	0.006	-1	35	35.000	-35.000	3000	14452	17452	43.663
4	553000	51.298	0.080	0.006	-1	30	30.000	-30.000	18240	121320	139560	30.013
									571240			
Block	Σ n	σ_e	S	C	R	σ_a	σ_{max}	σ_{min}	n_i	n_{eqv}	n_{tot}	$\sigma_r(n,R,\sigma)$
1	0	50.847	0.035	0.209	5	30	-6.000	-30.000	500000	0	500000	50.798
2	500000	51.298	0.080	0.006	-1	25	25.000	-25.000	500000	160578	660578	48.721
3	1000000	50.847	0.035	0.209	5	35	-7.000	-35.000	50000	154754	204754	46.224
4	1050000	47.509	0.070	0.038	-1	30	30.000	-30.000	12334	5893	18227	30.071
									1062334			

Fatigue Test Results

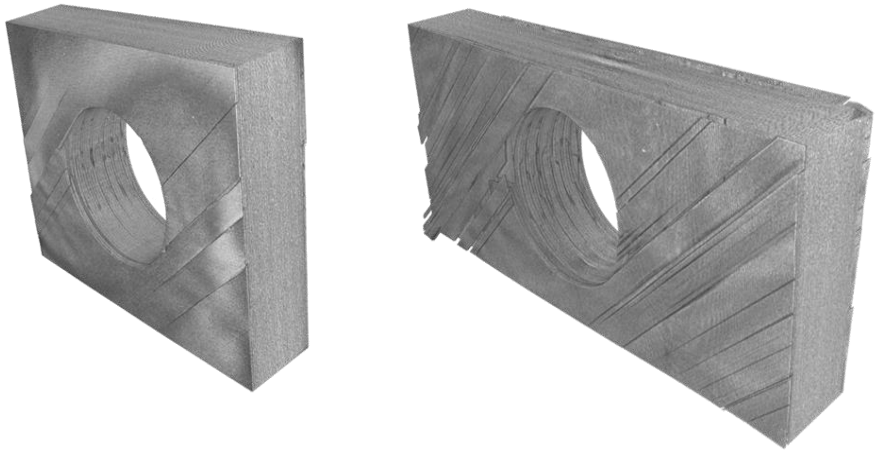
3 Specimens of R = 5 survived 1,103,000 cycles

R = -1
550,165
539,141
523,164
521,419
533,781
522,465
531,689

R = 5 & -1	R = -1 & 5
1,015,810	1,000,190
1,046,541	1,006,941
1,050,001	1,035,966
1,037,451	1,014,366

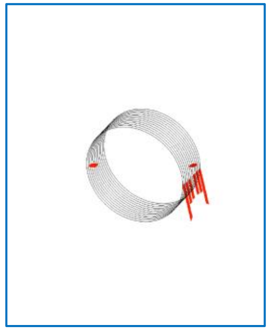
High-Fidelity Inspections for Damage Characterization

X-Ray Computed Tomography (XCT)



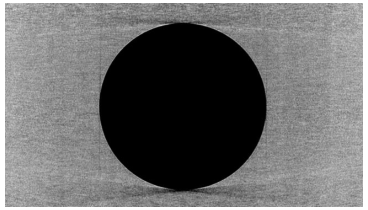
X-Ray Computed Tomography

4D XCT - Fatigue Damage Progression (Ply-by-Ply)



after 25,000 cycles

0˚ Ply #6



Industry Partners

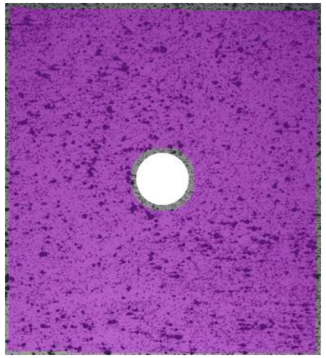
GLOBAL ENGINEERING & MATERIALS, INC.

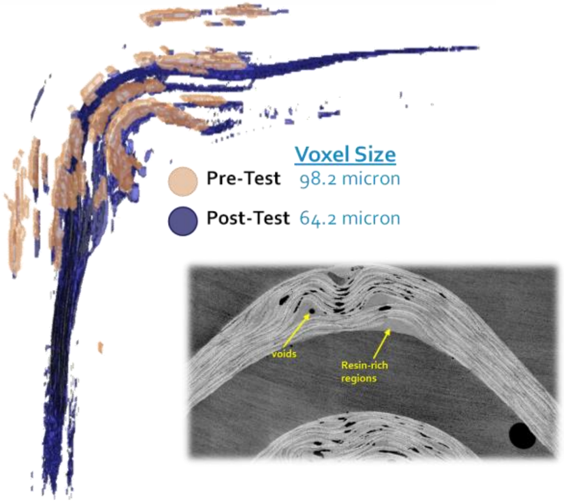
Engineering and Innovative Solutions

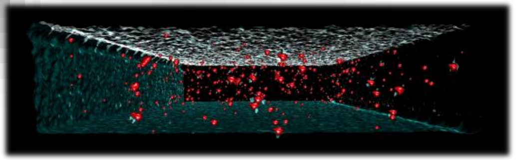
U.S. NAVAL RESEARCH LABORATORY

NAVAIR

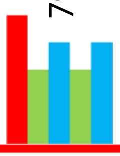
XCT++





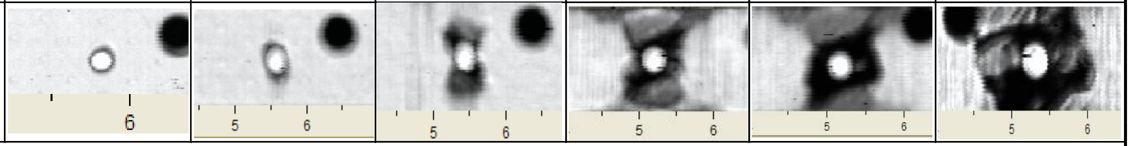
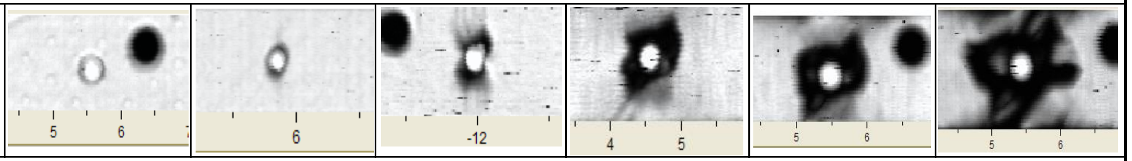
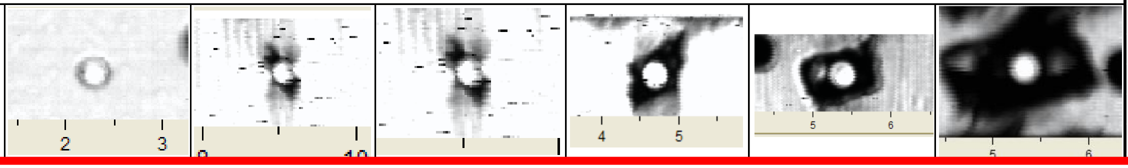


Load Sequencing Effects – Open Hole (UNI)

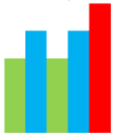


70-40-55-40-55 (High-Low)

Fatigue Profile 5

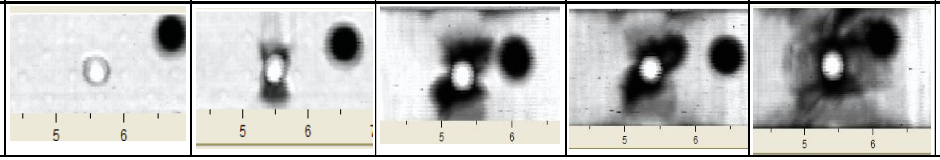
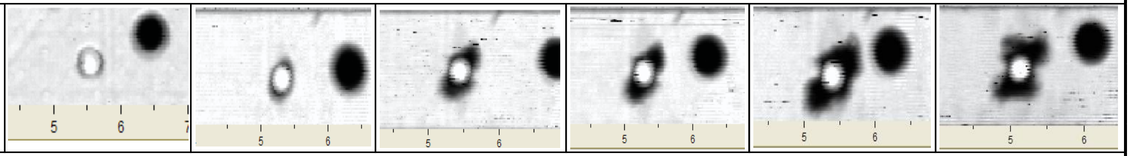
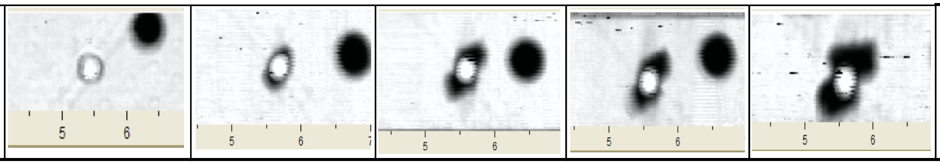
NAME	n=0 Reference	70% - n=3,000 Load Block 1	40% - n=403,010 Load Block 2	55% - n=519,340 Load Block 3	40% - n=919,350 Load Block 4	55% - n=1,035,680 Load Block 5
UNI-EX-11						
UNI-EX-13						
UNI-EX-14						

6 spec. survived profile 5



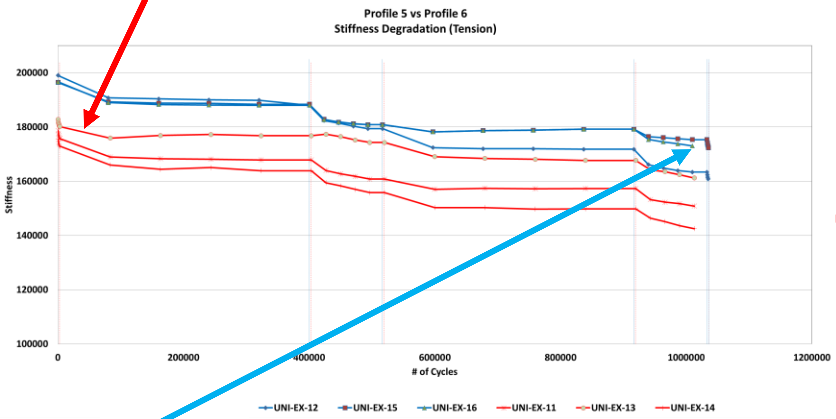
40-55-40-55-70 (Low-High)

Fatigue Profile 6

NAME	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-EX-12						Failed at 1,035,455 cycles
UNI-EX-15						
UNI-EX-16						Failed at 1,033,152 cycles

4 spec. failed and 2 spec. survived profile 6

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

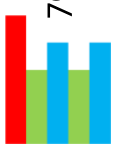


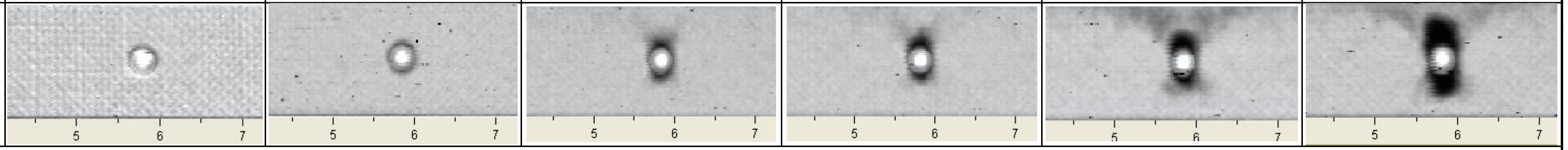
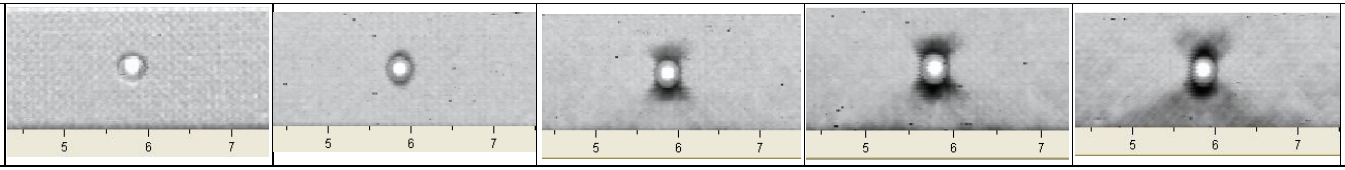
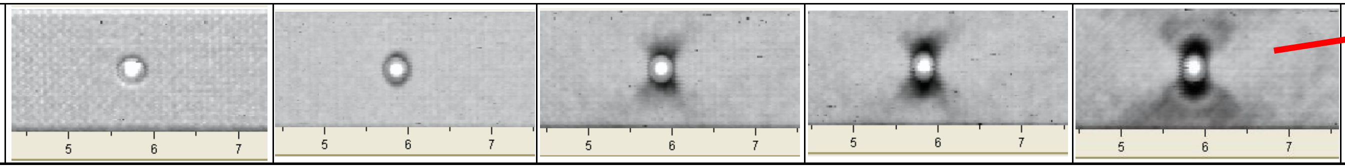
Fatigue Profile 6	
Stress Level	**# of Cycle**
40	400010
55	116330
40	400010
55	116330
70	3000

T650/5320 UNI
R = -1
F = 5 Hz

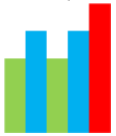
Validation of ST Method – 25/50/25 PW Load Sequencing

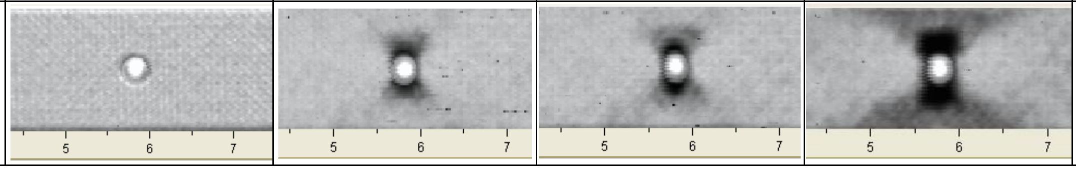
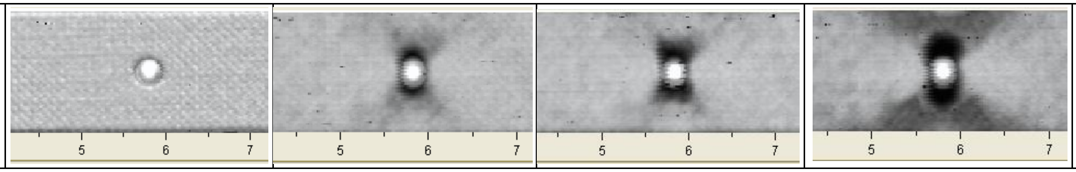
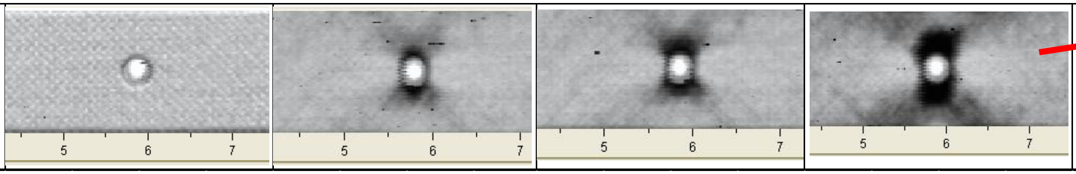
70-40-55-40-55 (High-Low)

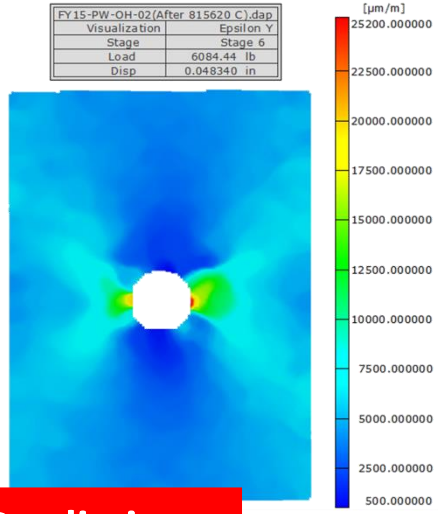


Fatigue Profile 5	NAME	n=0 Reference	70% - n=1,040 Load Block 1	40% - n=401,050 Load Block 2	55% - n=415,610 Load Block 3	40% - n=815,620 Load Block 4	55% - n=830,180 Load Block 5
	PW-OH-27						
	PW-OH-1						Failed at 823,523 cycles
	PW-OH-2						Failed at 827,830 cycles

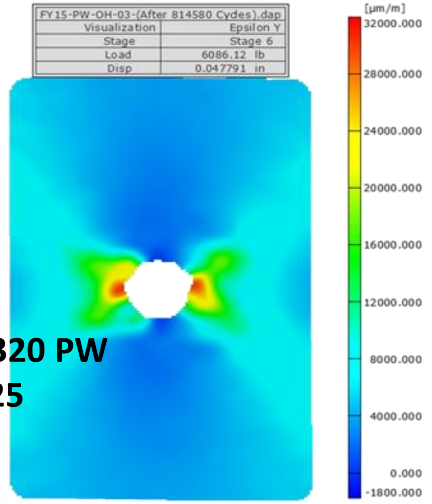
40-55-40-55-70 (Low-High)



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	



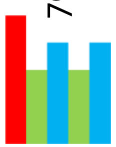
ST Predictions
n = 830,180



T650/5320 PW
25/50/25
R = -1
F = 5 Hz

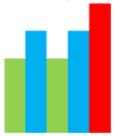
Progressive Damage Growth (X-Ray CT)

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

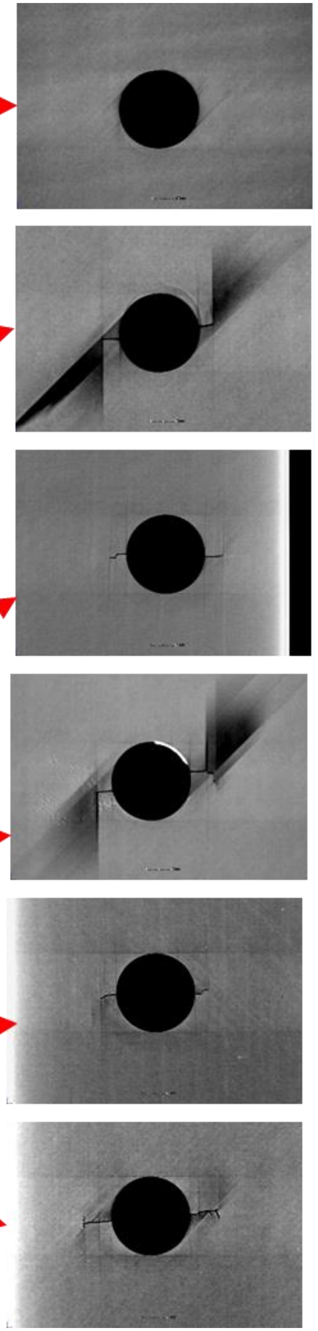


Fatigue Profile - 5		n=0 Reference	70% - n=3,000 Load Block 1	40% - n=403,010 Load Block 2	55% - n=519,340 Load Block 3	40% - n=919,350 Load Block 4	55% - n=1,035,680 Load Block 5
	UNI-OH - 3						
	UNI-OH - 4						
	UNI-OH - 9						

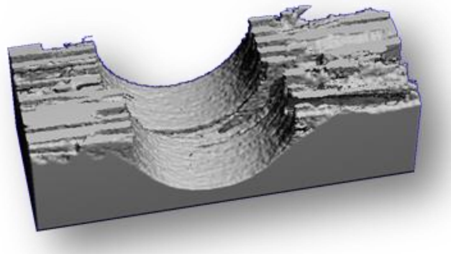
40-55-40-55-70 (Low-High)

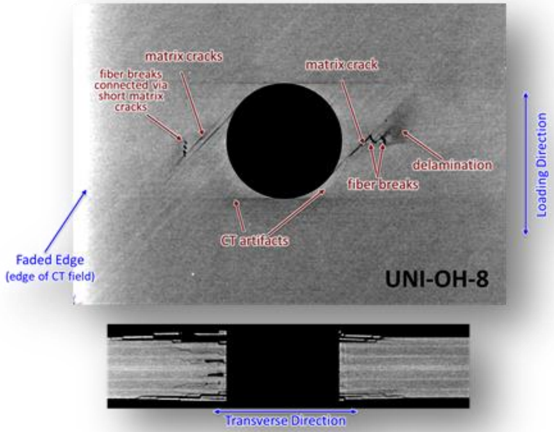


Fatigue Profile - 6		n=0 Reference	40% - n=400,010 Load Block 1	55% - n=516,340 Load Block 2	40% - n=916,350 Load Block 3	55% - n=1,032,680 Load Block 4	70% - n=1,035,680 Load Block 5
	UNI-OH - 6						
	UNI-OH - 7						
	UNI-OH - 8						



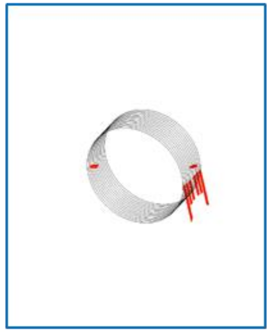
Collaboration with Dr. David Mollenhauer (AFRL)

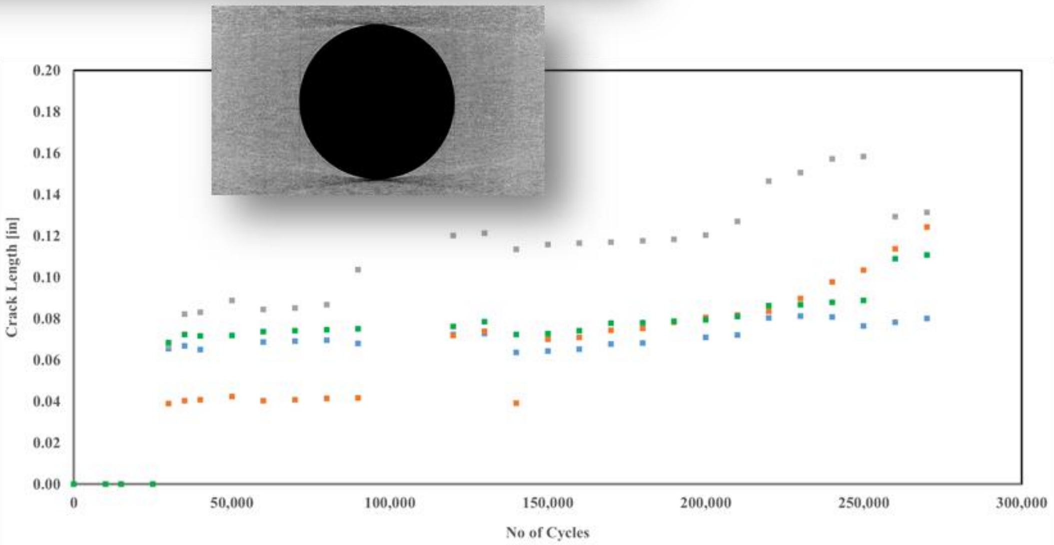


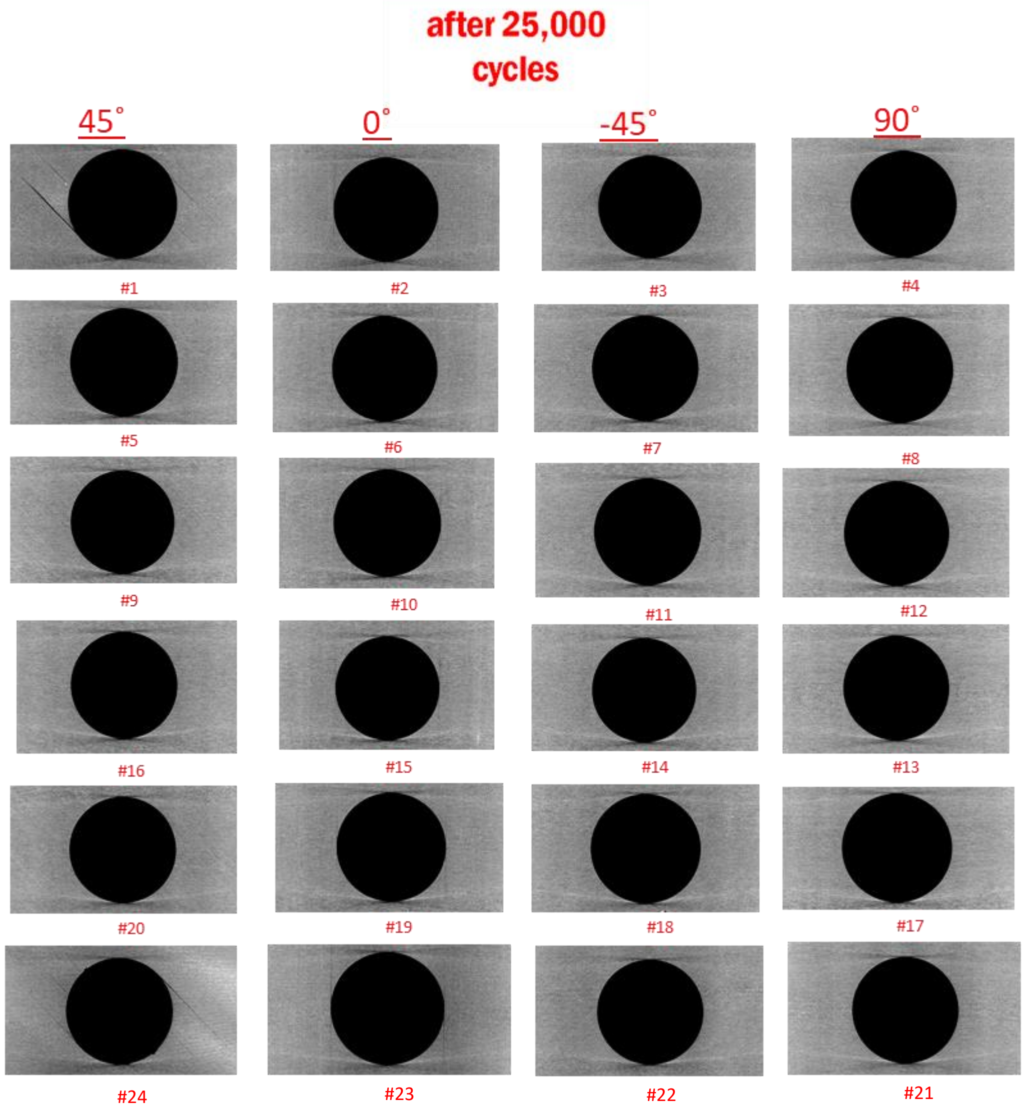


High-Fidelity Inspections

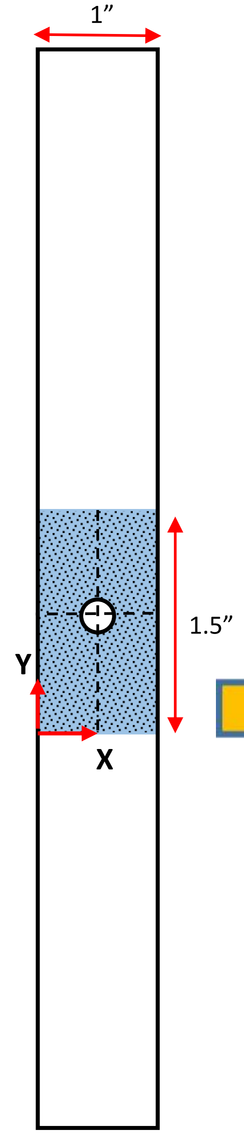
4D XCT - Fatigue Damage Progression (Ply-by-Ply)

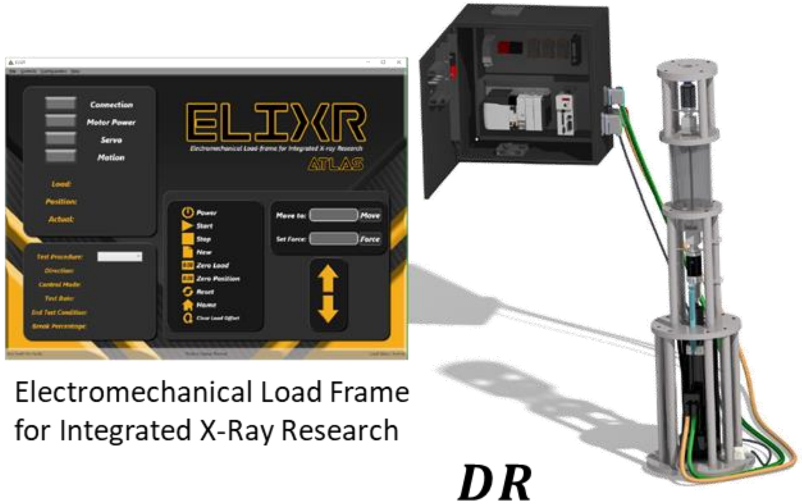






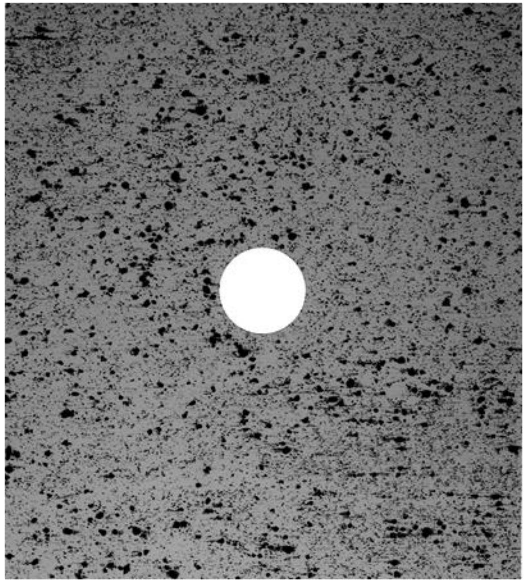
Internal Full-Field Strain Measurements (XCT+DIC)

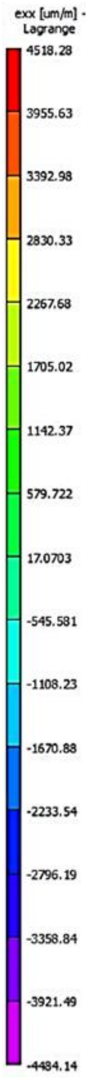




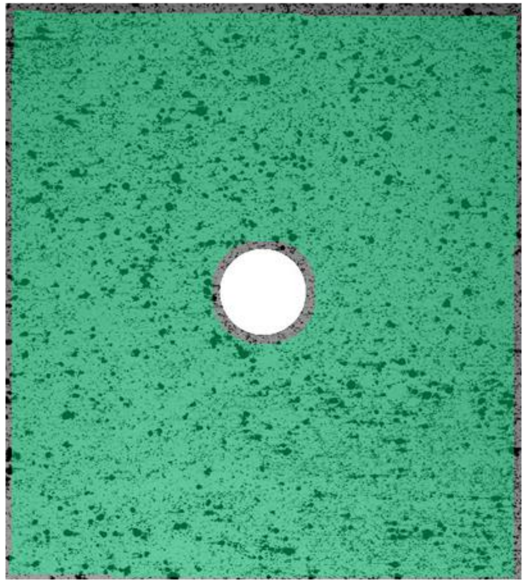
Electromechanical Load Frame for Integrated X-Ray Research

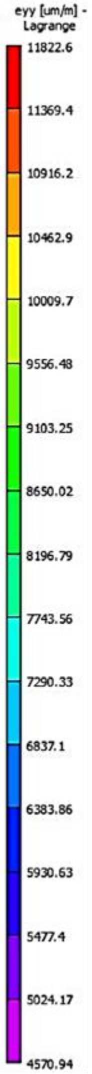
DR



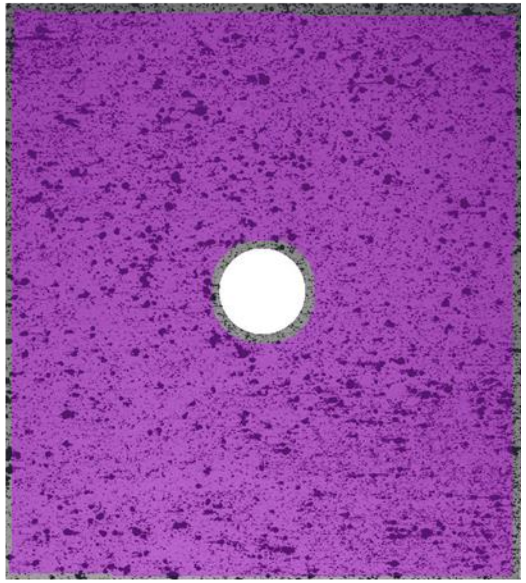


ε_x



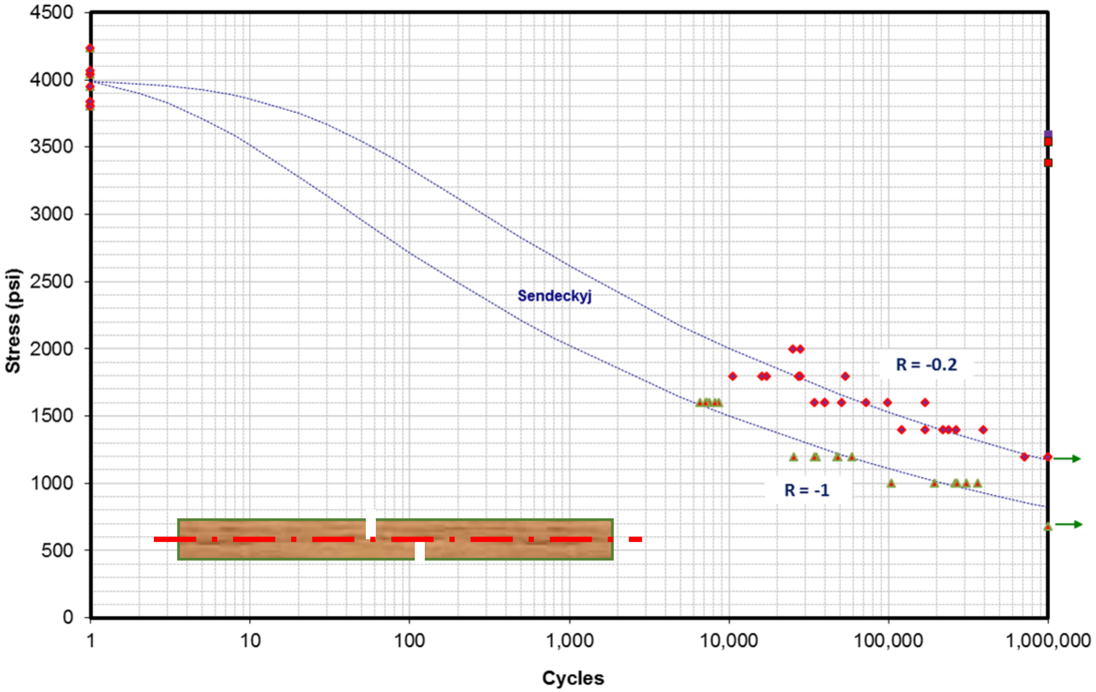


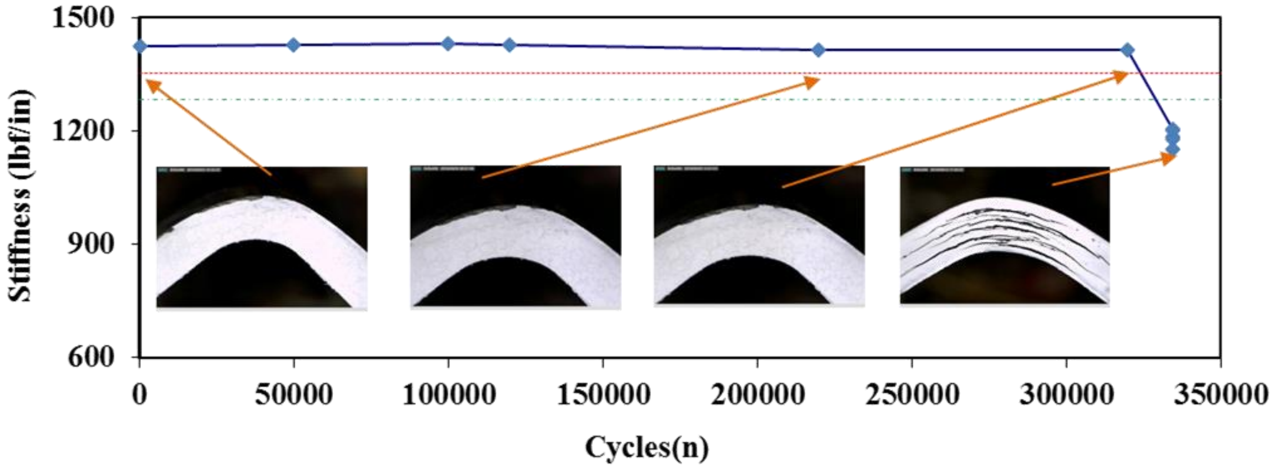
ε_y



Matrix Dominant Failure Modes

- Significant residual strength degradation
  - Steep SN curves
  - Significant fatigue cracks and stiffness degradation prior to “obvious” fatigue failure
- Multiple crack paths
- High data scatter



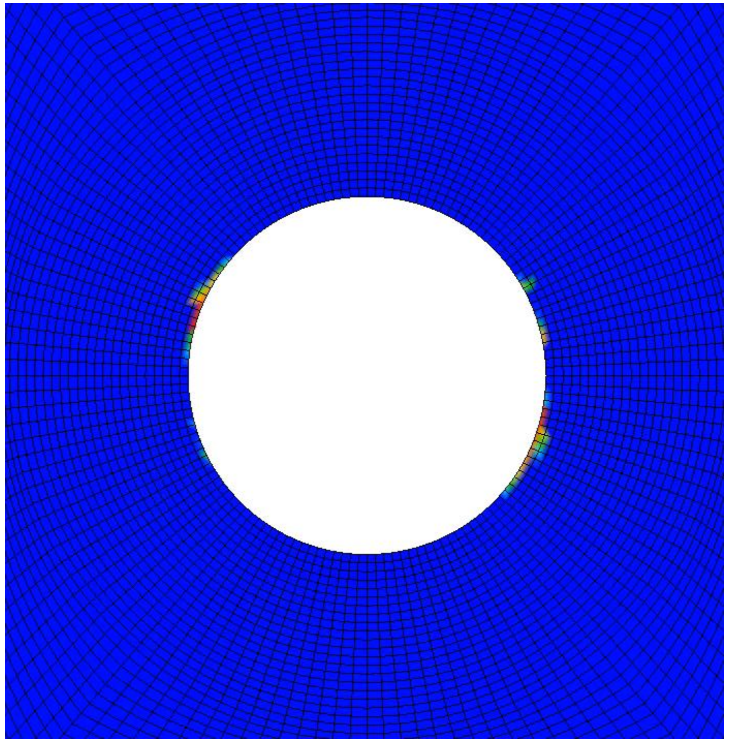


Verification and Validation of Discrete Damage Modeling

Regularized Extended Finite Element Analysis (RX-FEM)

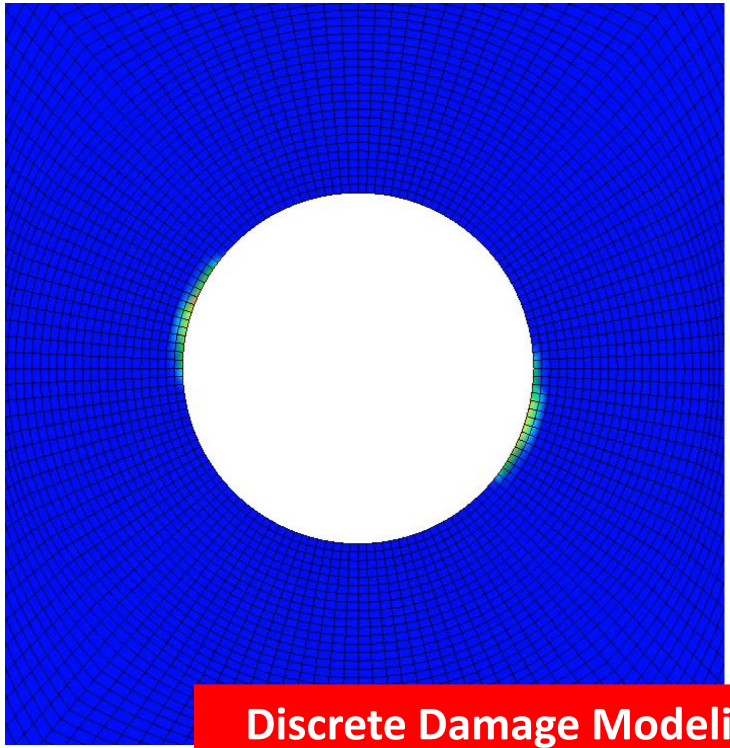
Delamination Propagation - OHT

0 degree ply



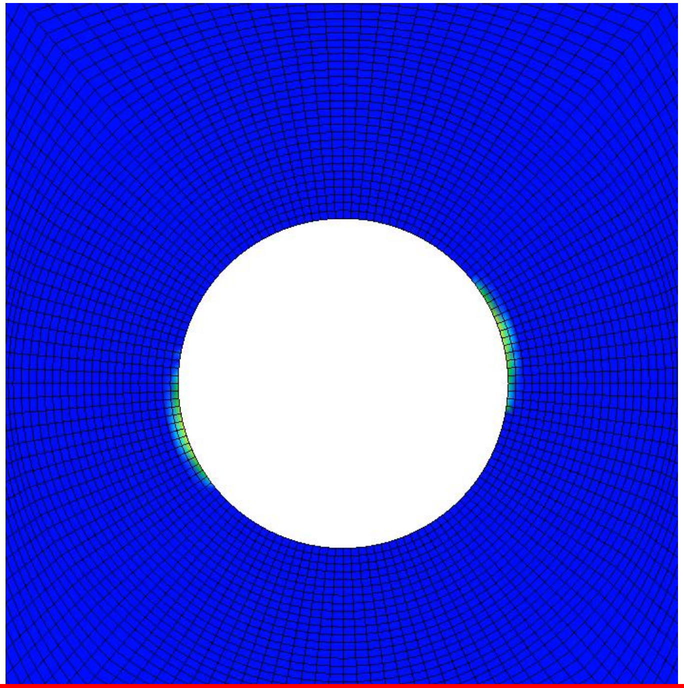
Delamination in 0/-45 interface

-45 degree ply



Delamination in -45/90 interface

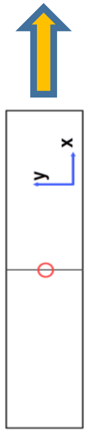
90 degree ply



Delamination in 90/45 interface

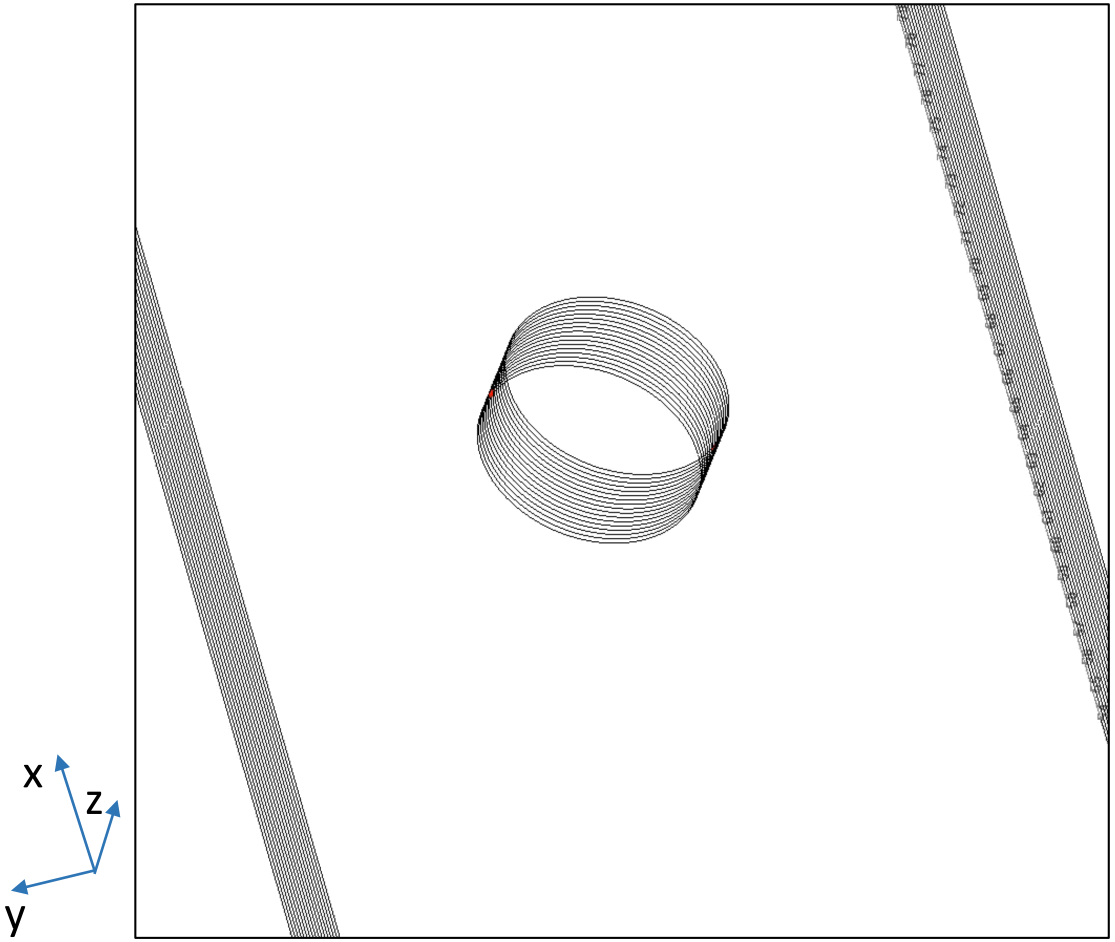
Discrete Damage Modeling (DDM) using Mesh-independent regularized extended finite element modeling (Rx-FEM)

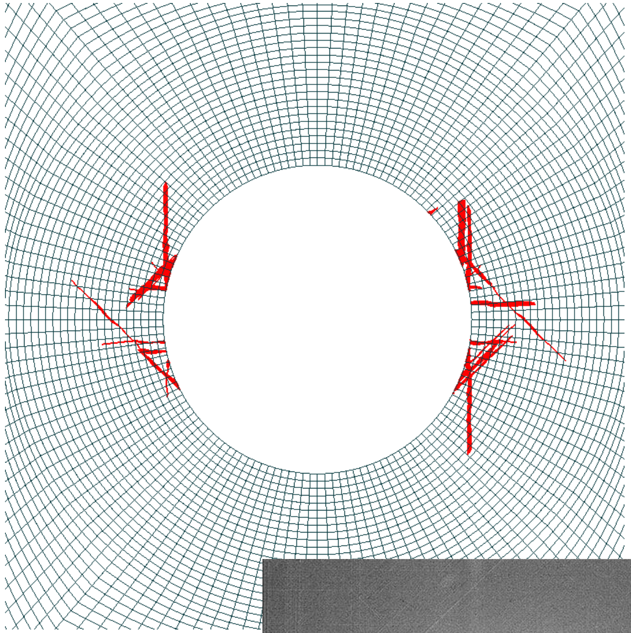
[45/90/-45/0/45/90/-45/0/0/-45/90/45/0/-45/90/45]

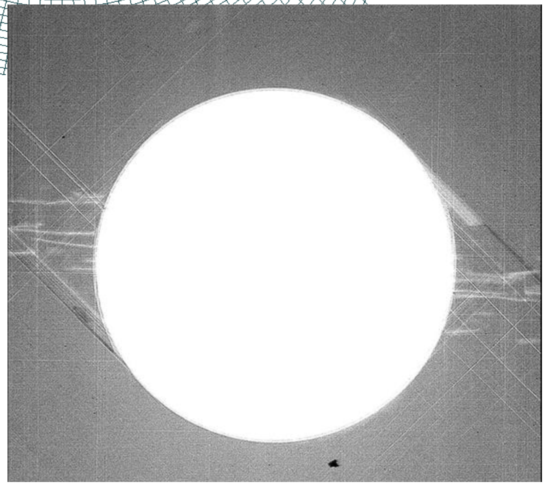


Fixed

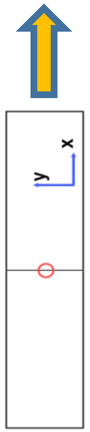
Matrix Crack Growth - OHT



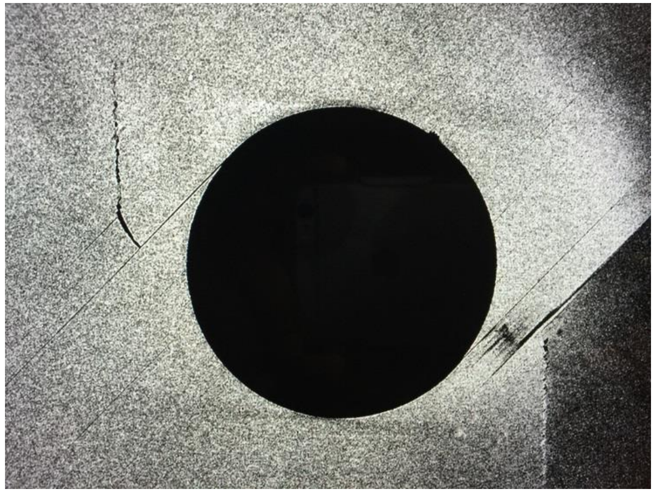


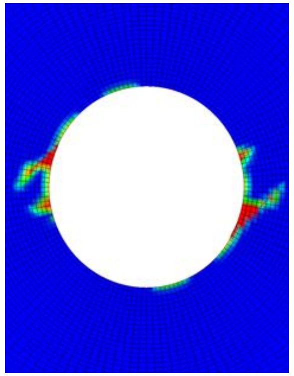


$[45/90/-45/0]_{2S}$



3D XCT UNI OH

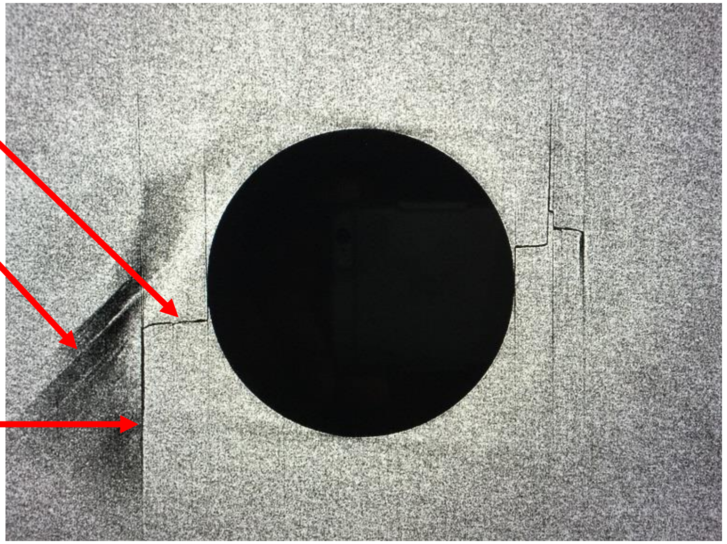


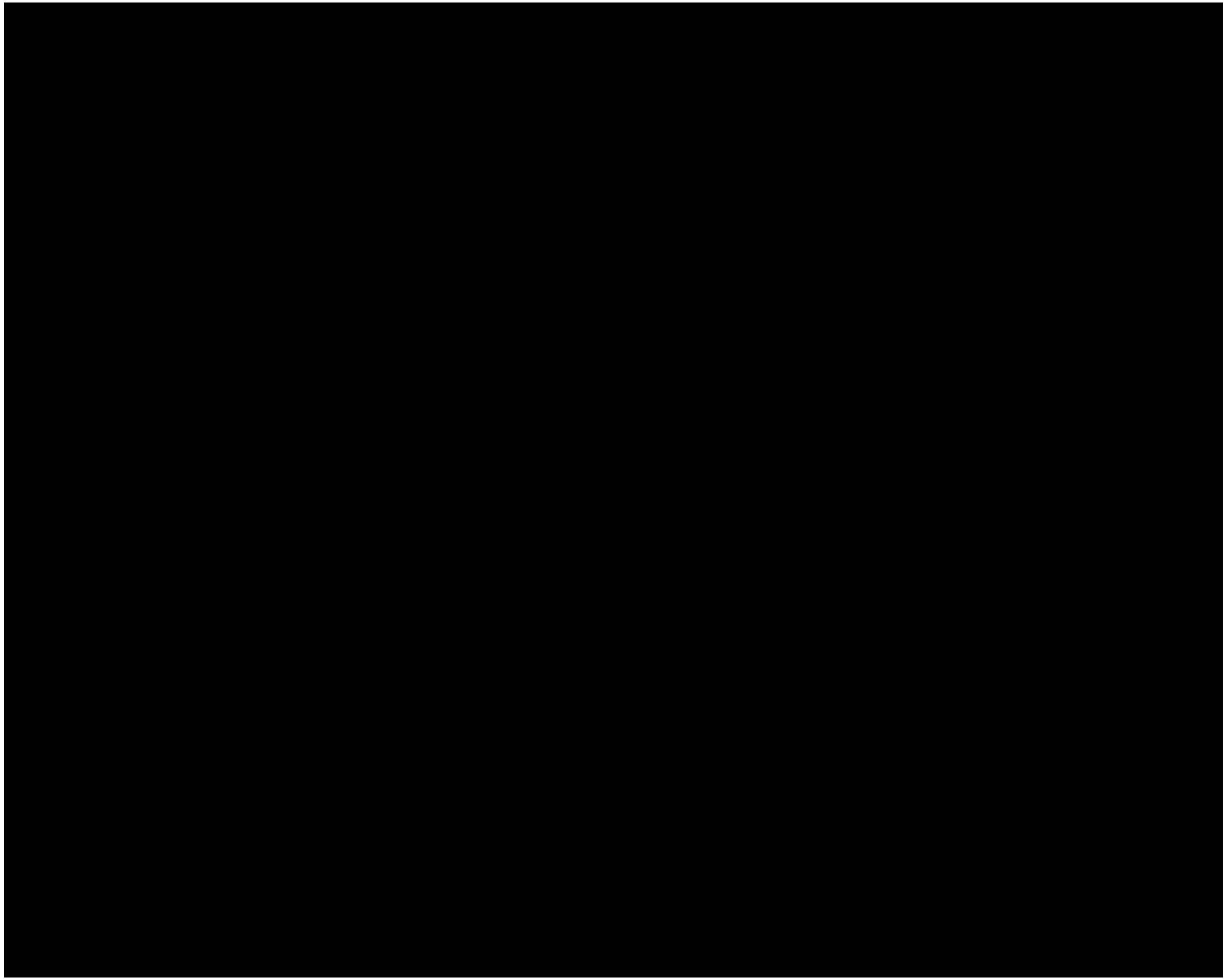


Fiber Break
(Fiber Failure)

Delamination
(Interface Failure)

Fiber Splitting
(Matrix Cracks)

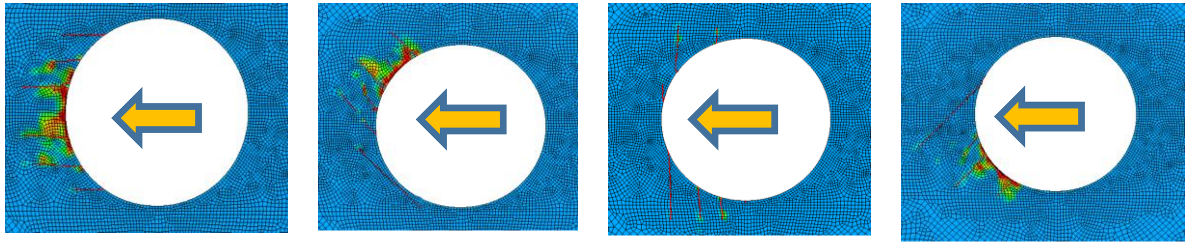




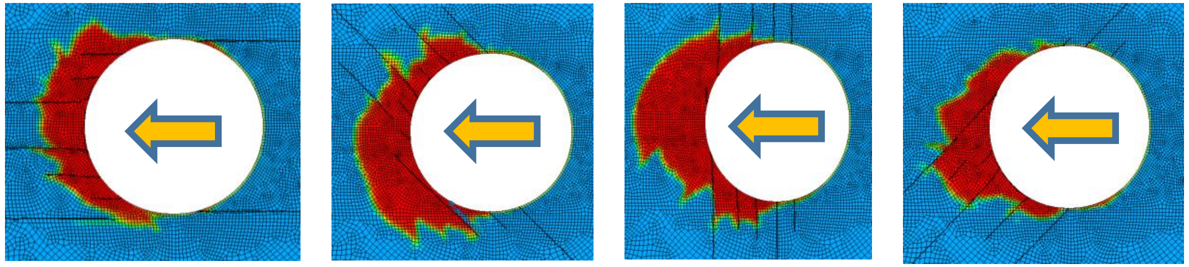
T650/5320-1 UNI (UNI-OHC-15)
Quasi-Isotropic; R = -1; 55% Stress level; n = 200,000

Double Shear Bearing – AFP Defects & Features

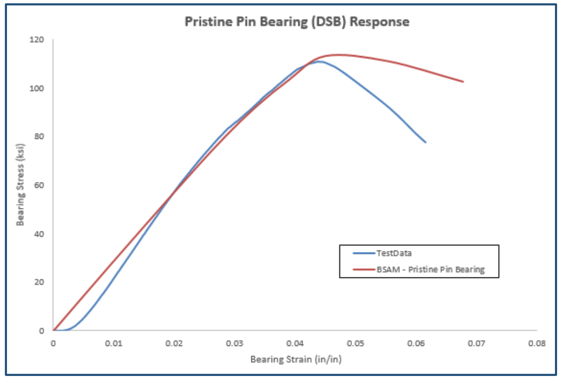
0° 45° 90° -45°



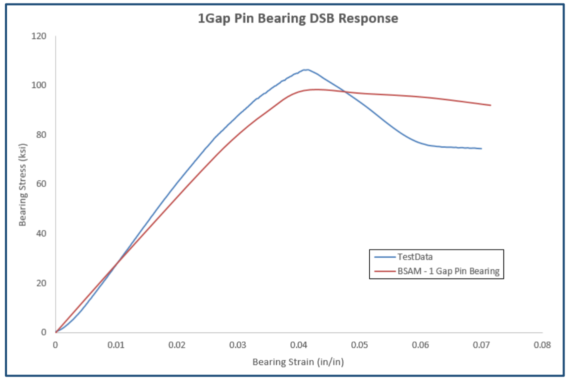
Matrix Crack and Fiber Crushing



Delamination and Matrix Crack Paths

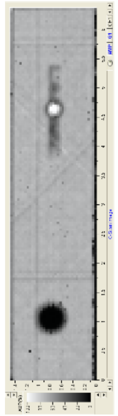


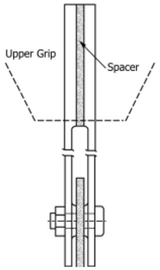
FEA vs. Test
Pristine Configuration

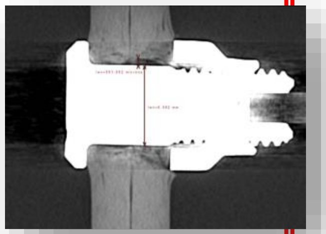


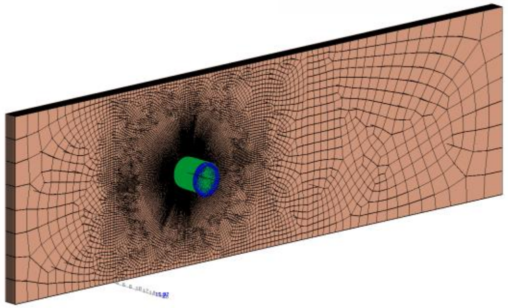
FEA vs. Test
1 AFP-Gap Configuration

embedded
AFP-Gap

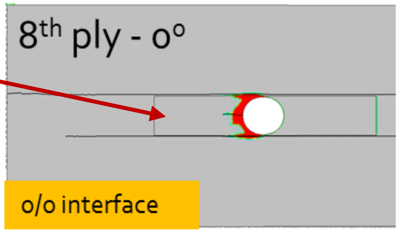




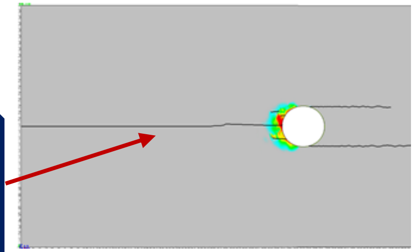




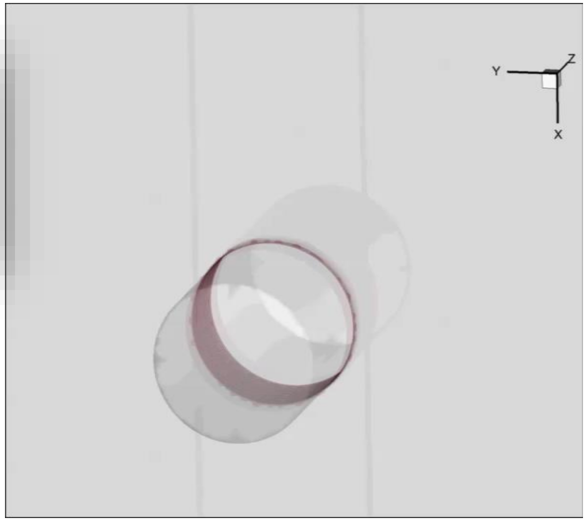
AFP-Gap Modeled as a resin pocket



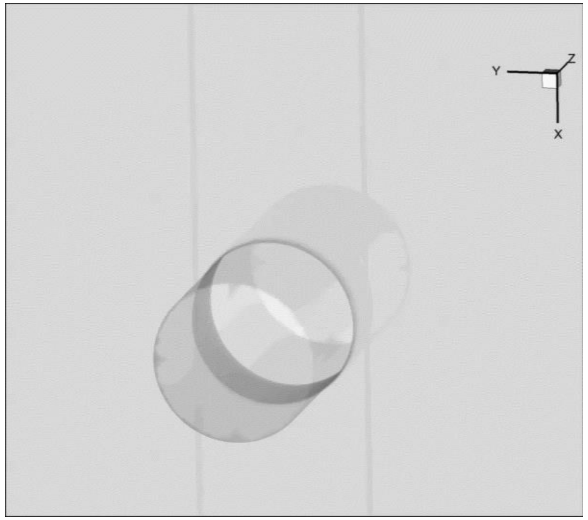
Crack-paths inserted on pristine 0° ply



Delamination around defect

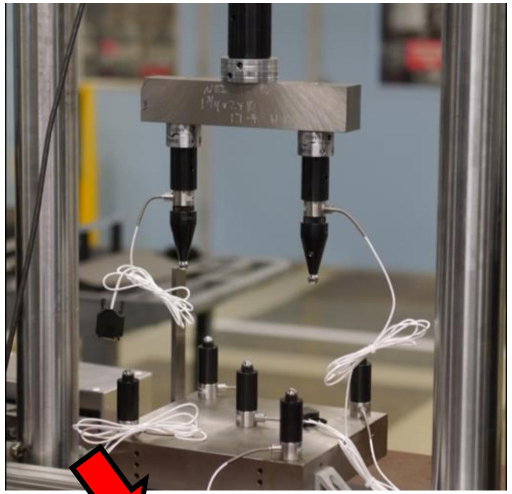


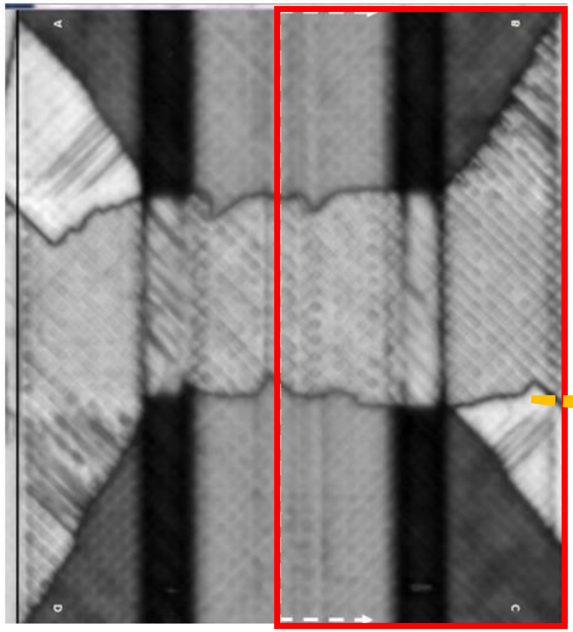
Fiber crushing under pin



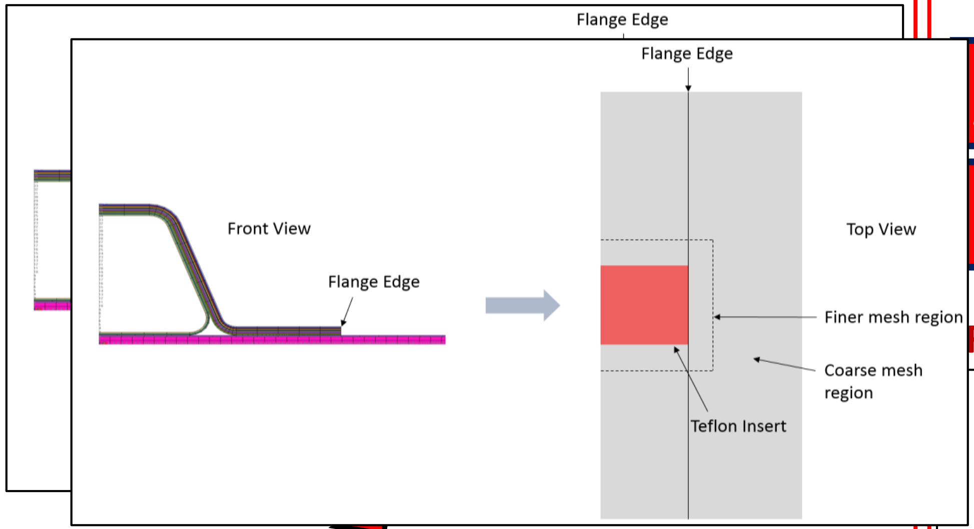
HIGH-FIDELITY DAMAGE MODELING

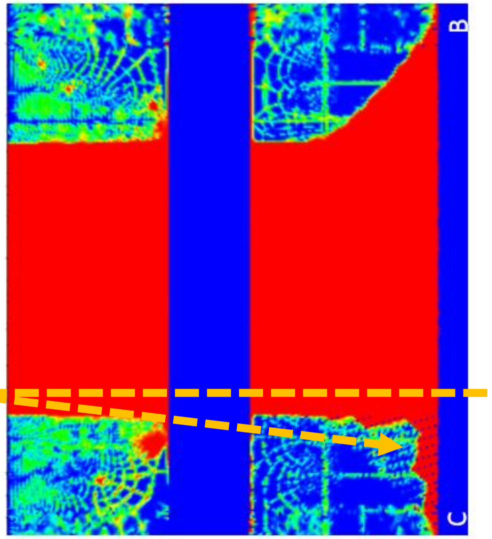
Experiment

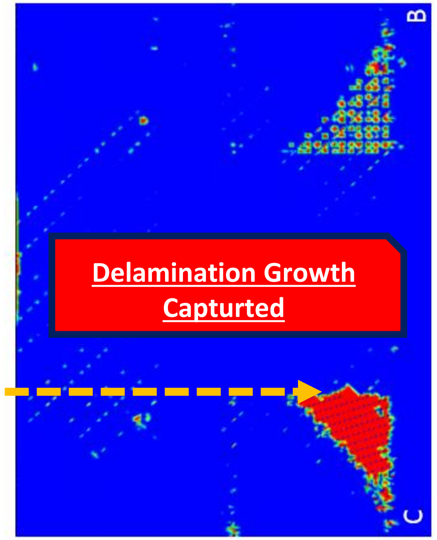




FE Model [Half-Model]







Delamination Growth Capturted

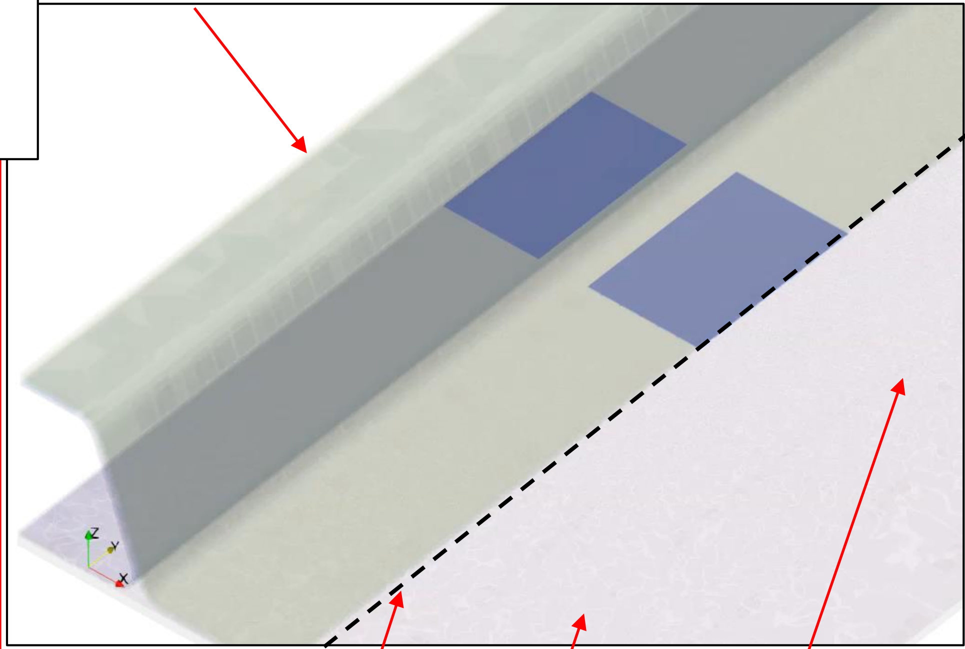
Isometric View of Delamination Growth

Interface 0 = Between the Skin and the Flange/Hat Stringer

Interface 1 = Between the first two ply of the skin

Light Blue = At Interface 0
Red = At Interface 1

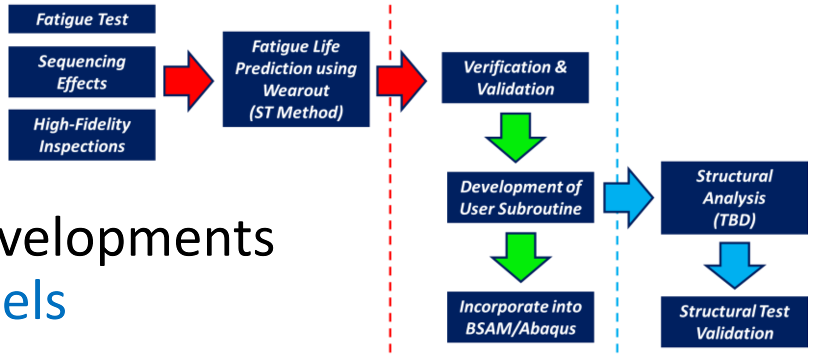
Flange/Hat Stringer

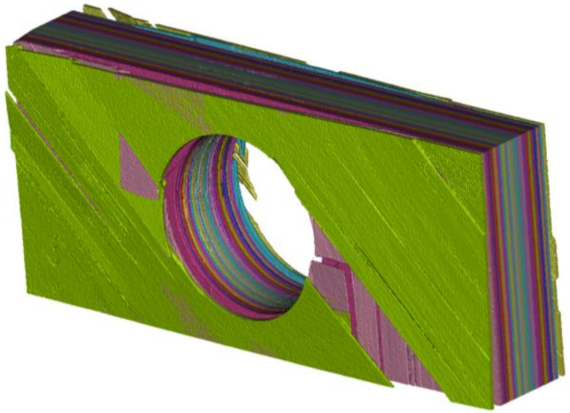


Flange Edge Skin Loading Point

Summary - Strength Tracking (ST) Method

- Fatigue damage growth of composites under constant or variable amplitude (block/random) fatigue loading can be assessed
  - Multiple R ratios
  - Sequencing effects will be incorporated
- Any validated residual strength degradation (wearout) model can be used
  - Sendeckyj wearout model is used for examples due to its robustness (ex., fitting curve for SN data provides an assessment of fitting parameters)
    - Incorporate reliability (analysis of fatigue data scatter)
    - Residual strength degradation for arbitrary stress levels
    - Simple Excel worksheet can be setup for life assessment
  - Provide opportunity to improve the technique for future developments of wearout models, both semi-empirical and analytical models





Thanks!


NIAR
Wichita State University
National Institute for Aviation Research