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Fatigue behavior and modeling of polyether ether ketone (PEEK) under various loading conditions

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SAE/ Fatigue Damage and Evaluation Fall Meeting

October 11th
2018

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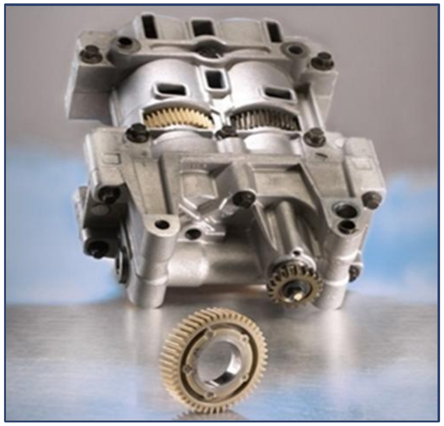
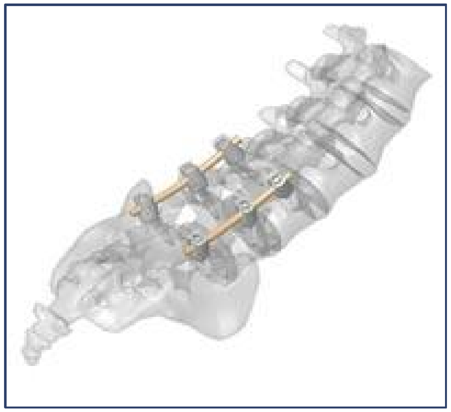
Motivations

- The growing use of plastics in components and structures subjected to cyclic loading
  - Engineering thermoplastic with better strength to weight ratio to improve fuel efficiency and reduce carbon footprint
  - Plastics in matrix of composite materials
  - Plastics in the manufacture of structural component in bio-medical applications



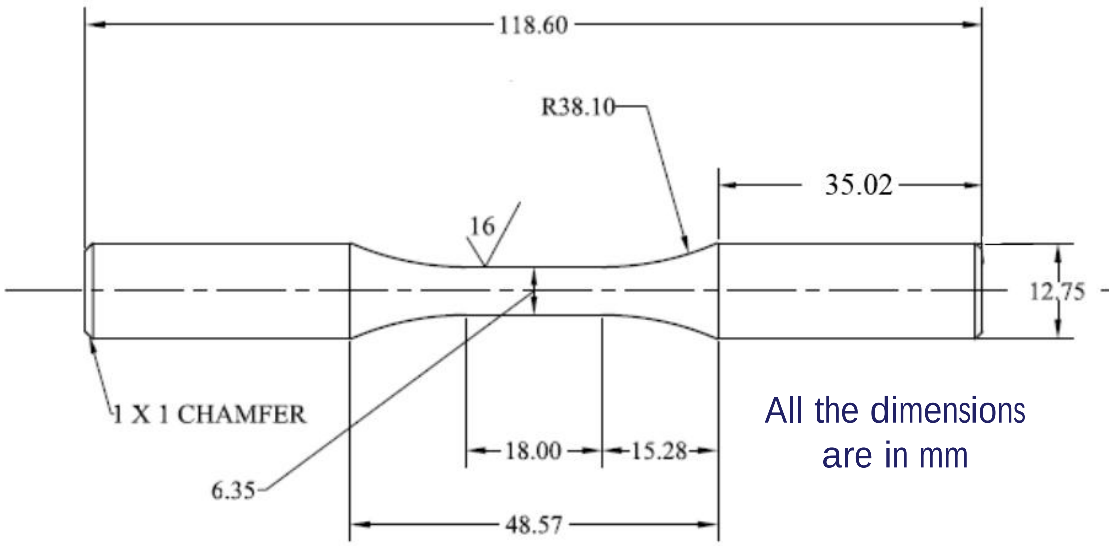


- The need of improving existing and/or developing new predictive fatigue modeling tools specific to plastics
  - Most existing models used for plastics have been designed for metals

Objectives

- Study the fatigue behavior and cyclic deformation of PEEK under various loading
  - To investigate the fatigue behavior of PEEK with and without the mean strains under
    - Uniaxial
      - Constant amplitude loading
      - Block loading
  - More realistic loading conditions such as
    - Multiaxial
      - Proportional In-phase (IP)
      - Non-Proportional 90° Out-of-Phase (OP) loadings
  - To obtain suitable fatigue models to accurately predict the fatigue life of PEEK thermoplastic under different loading conditions based on deformation behavior

Experimental Setup: Specimen

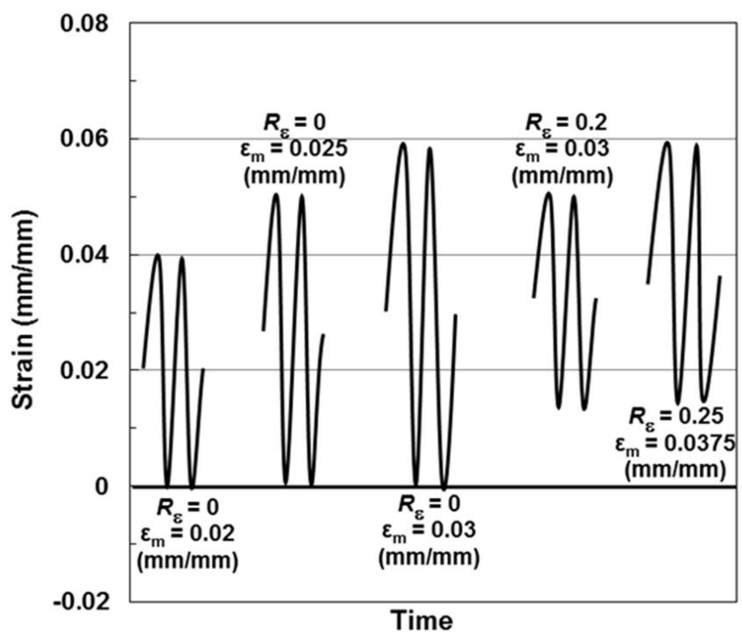


All the dimensions are in mm

- Unfilled PEEK material (TECAPEEK®) 12.7 mm extruded rods
- Machined (turning) to create specimen with uniform gage section following ASTM E606-04 standard

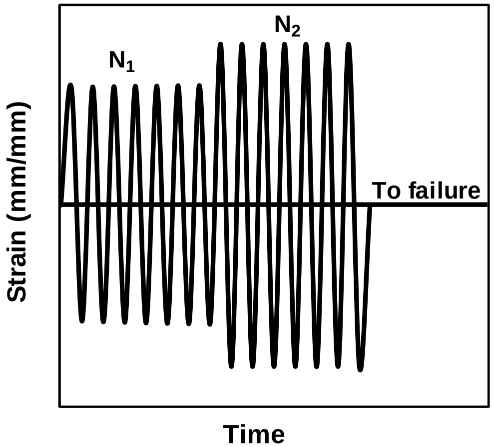
Experimental Setup: Test Program

- Fully-reversed (R_ε = -1) strain-controlled cyclic loading (Various frequency)
  - q ε_a = 0.02 – 0.04 mm/mm at 0.5 - 3 Hz frequency to maintain nominal temperature rise
- Strain-controlled tensile mean strain loading (R_ε = 0, 0.2, 0.25)
  - q ε_m = 0.02 – 0.0375 mm/mm at 0.5 – 1.5 Hz frequency to maintain nominal temperature rise

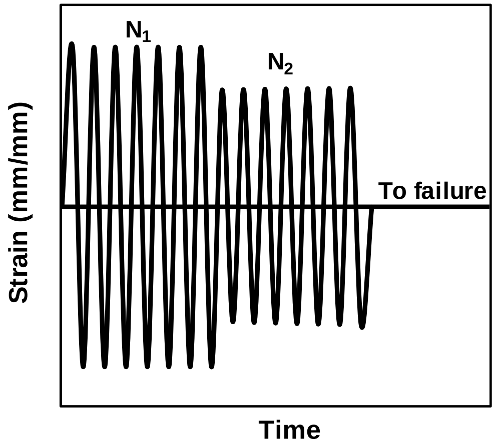


Experimental Setup: Test Program

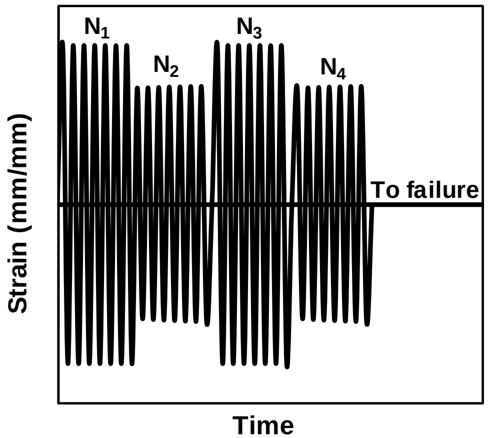
- Block loading with zero and non-zero mean strain and various frequency



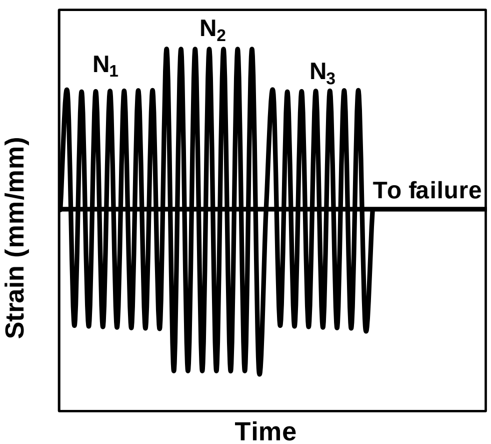
L-H



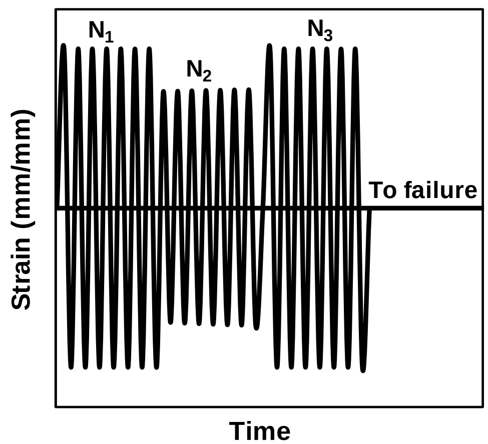
H-L



H-L-H-L



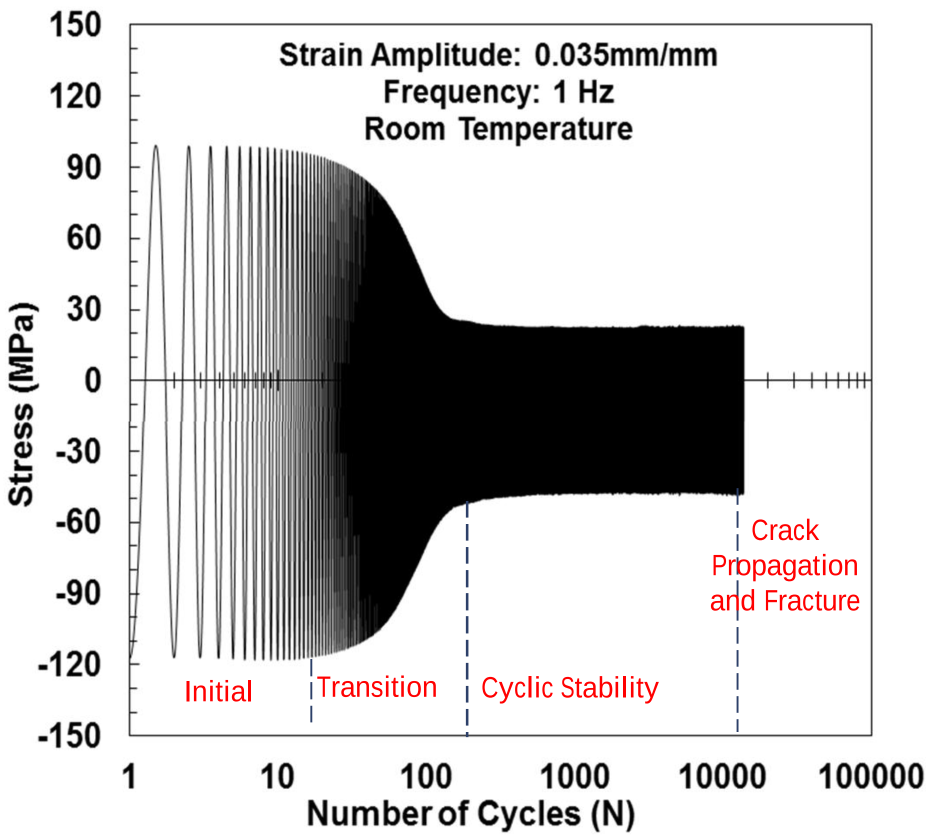
L-H-L

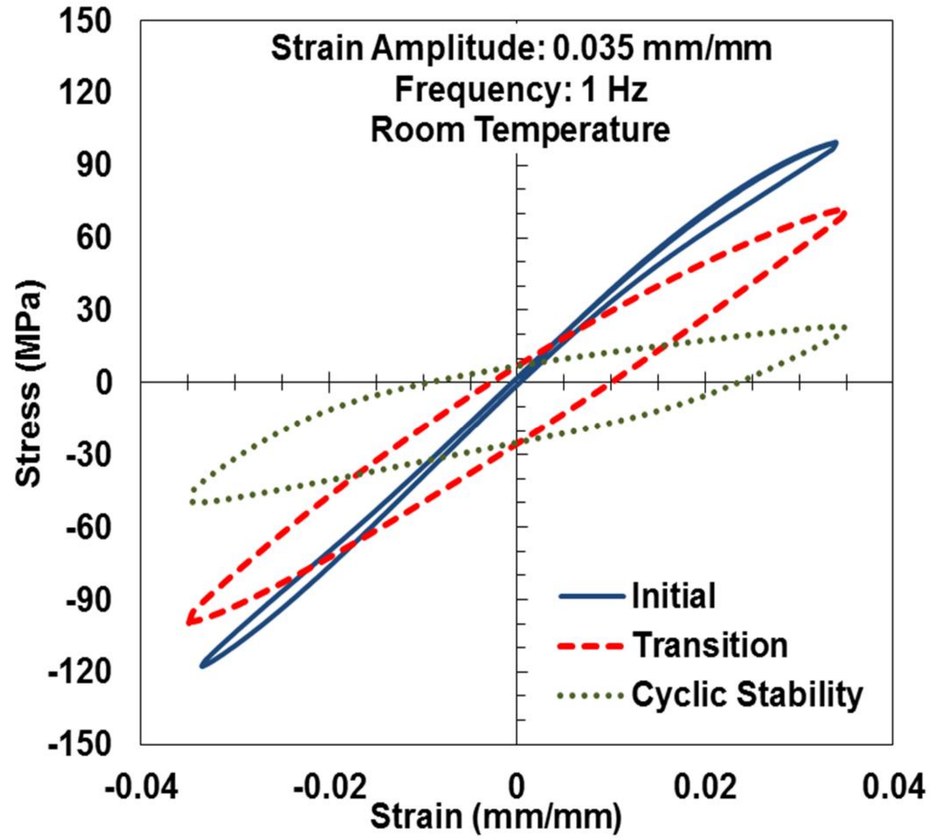


H-L-H

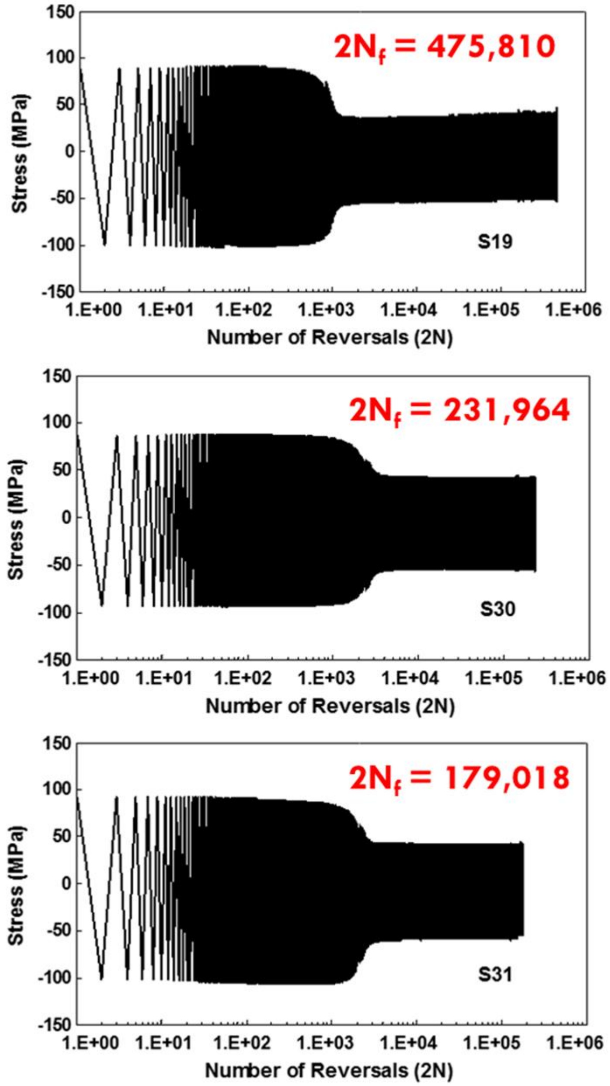
Experimental Results: Deformation Behavior, Fully-Reversed Loading

- *Cyclic softening in fully-reversed $R_{\varepsilon} = -1$ tests*





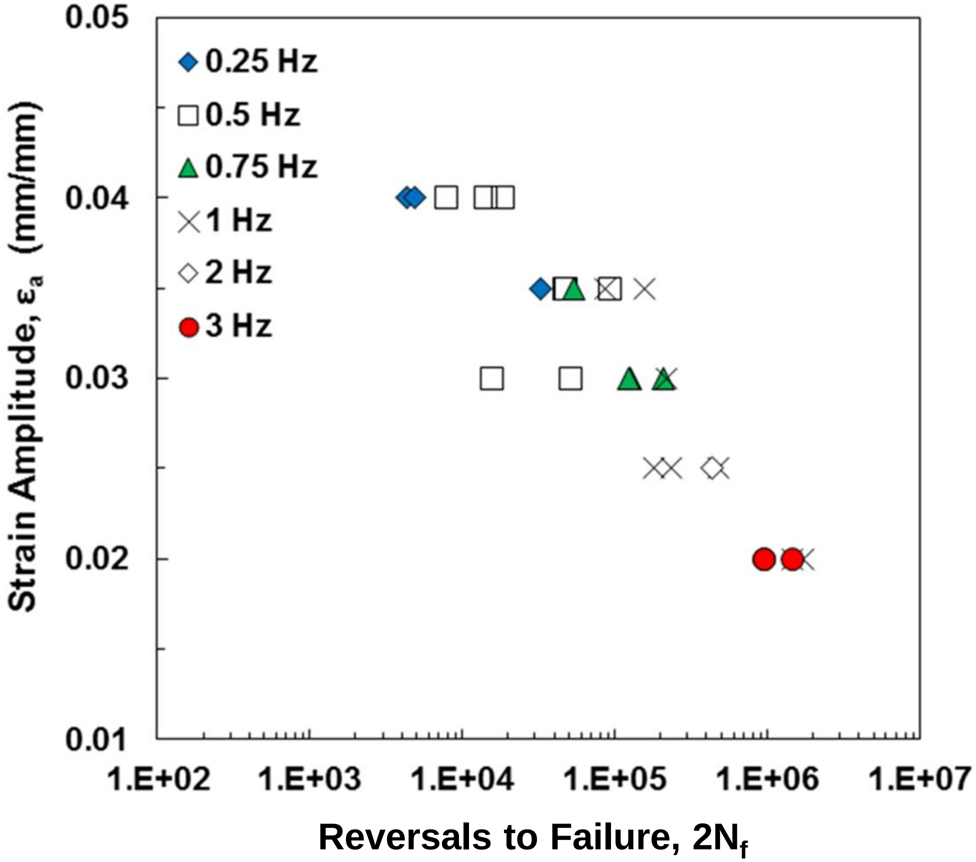
Experimental Results: Deformation Behavior, Fully-Reversed Loading



- 0.025 mm/mm strain amplitude and 1 Hz frequency
- Number of cycles in initial region significantly affects fatigue life of PEEK
- A similar trends was observed in all tests

Experimental Results: Frequency Effect, Fully-Reversed Loading

- Effect of frequency on fatigue life of PEEK



Increase of frequency

↓

Higher strain rate

↓

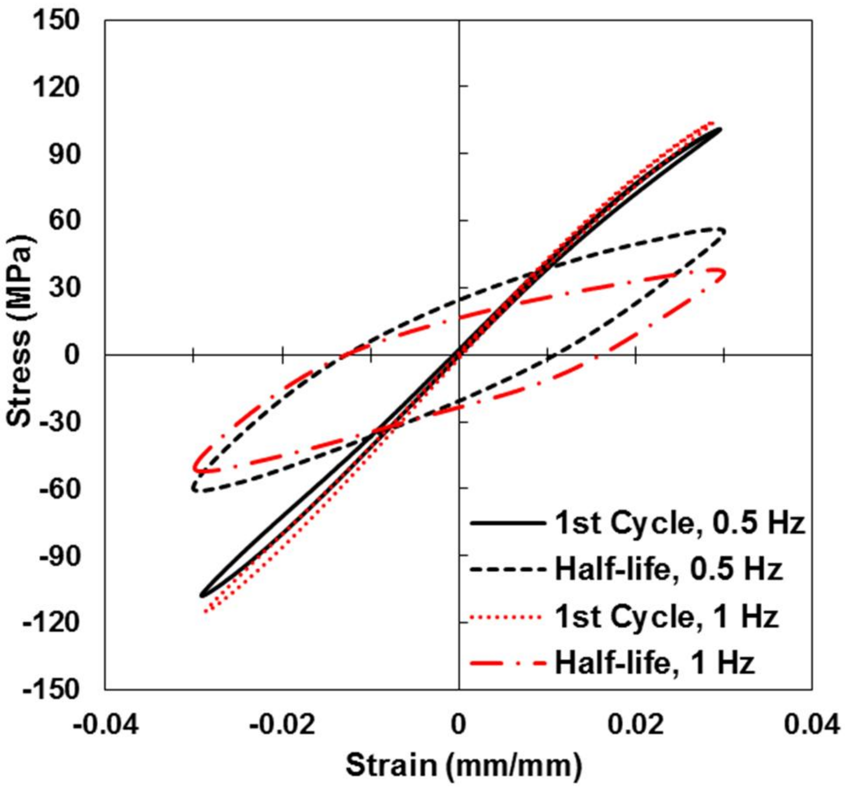
Increase in modulus and yield strength

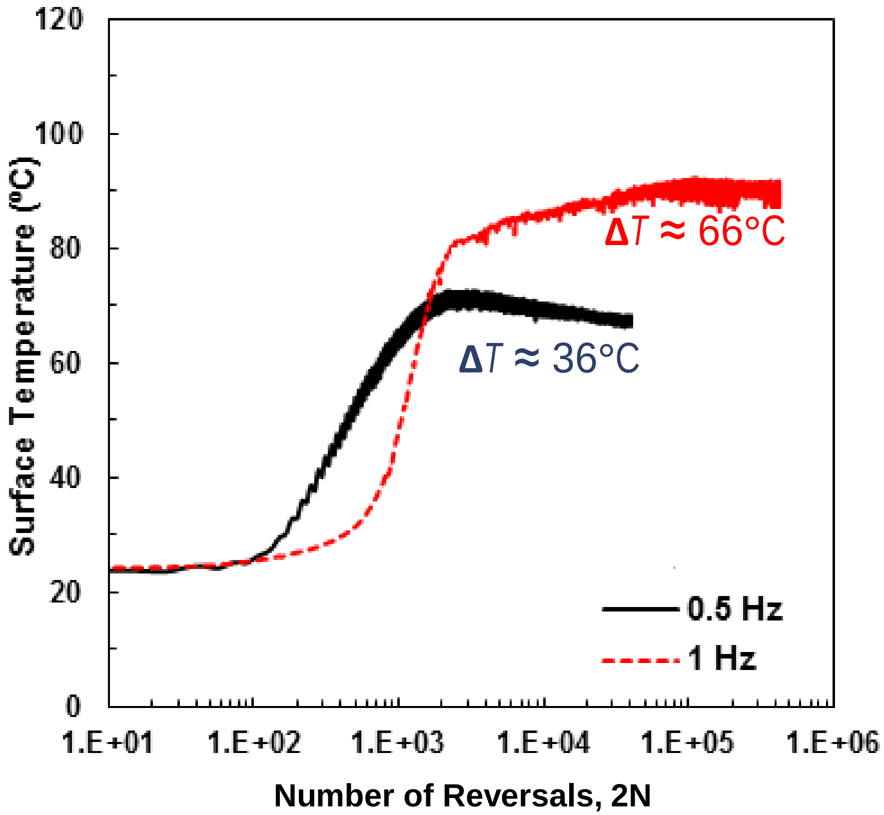
↓

Increase in fatigue lifetime

Experimental Results: Frequency Effect, Fully-Reversed Loading

- Frequency effect : 0.03 mm/mm





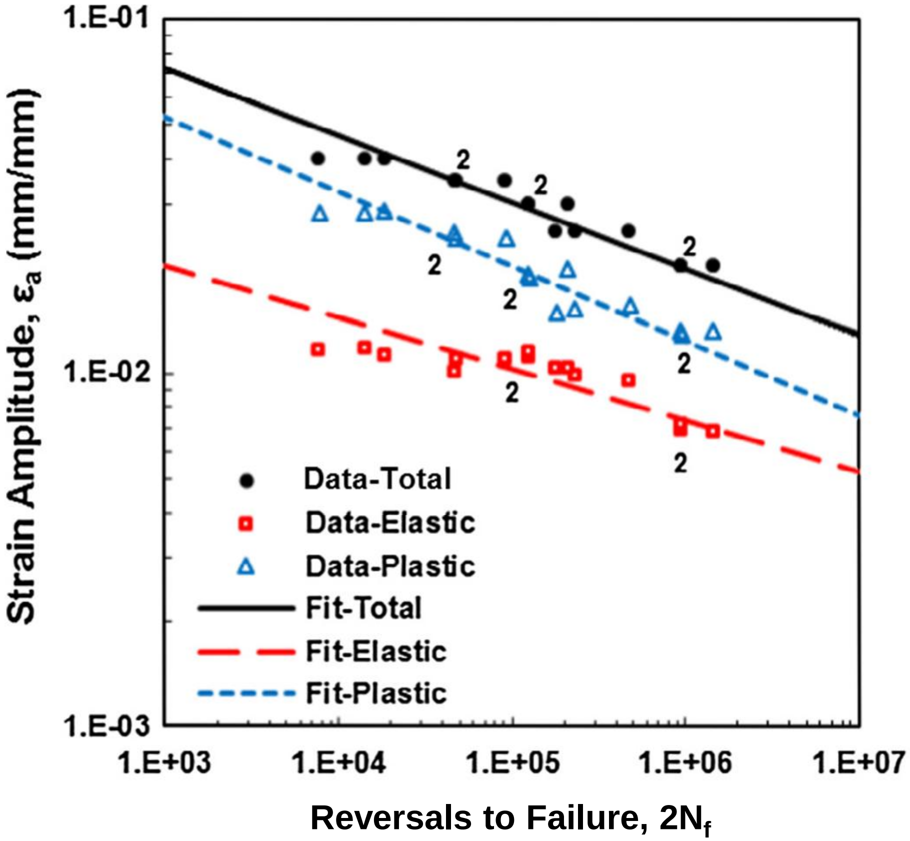
Frequency (Hz)	Reversals to failure, $2N_f$
0.5	51,500
1	217,000

Experimental Results: Fatigue Model, Fully-Reversed Loading

- Strain based Coffin-Manson expression

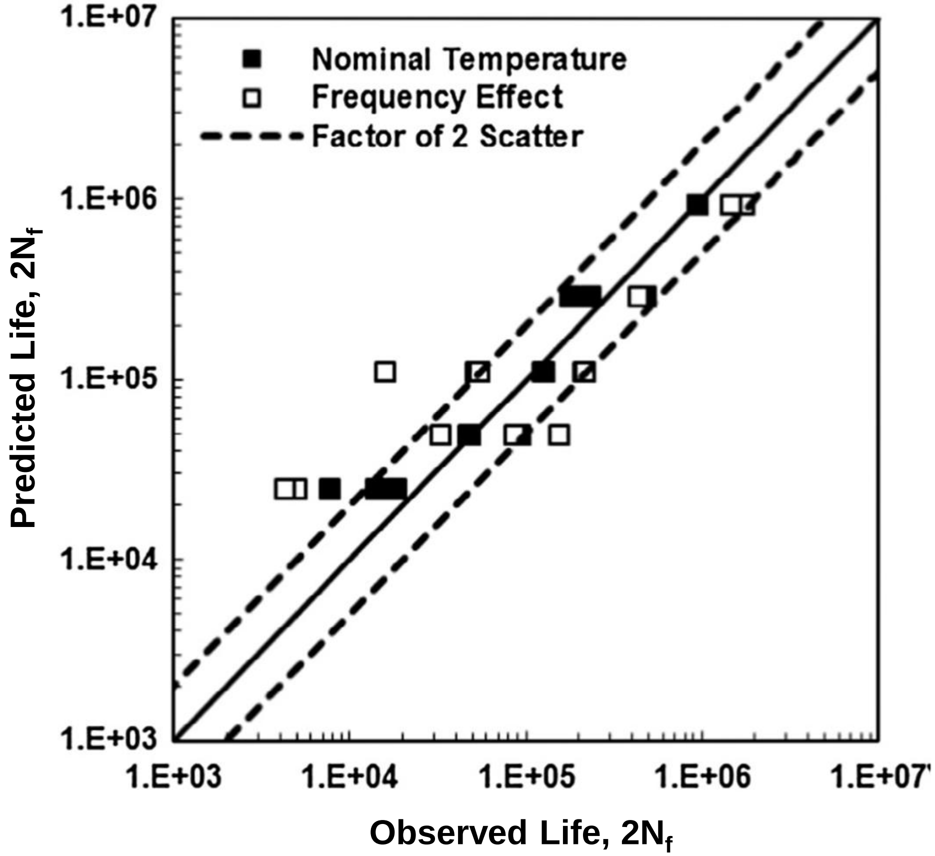
$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \underbrace{\frac{\sigma_f'}{E}(2N_f)^b}_{\text{elastic strain}} + \underbrace{\varepsilon_f'(2N_f)^c}_{\text{plastic strain}}$$

Strain-life Fatigue Properties for PEEK	Value
E' (GPa)	2.98
$S_y{}'$ (MPa)	19.1
K' (MPa)	213.8
n'	0.39
σ_f' (MPa)	373.1
ε_f'	0.37
b	-0.18
c	-0.25



Experimental Results : Fatigue Model, Fully-Reversed Loading

- Predicted fatigue lives using Coffin-Manson equation versus experimentally observed fatigue lives for fully-reversed test

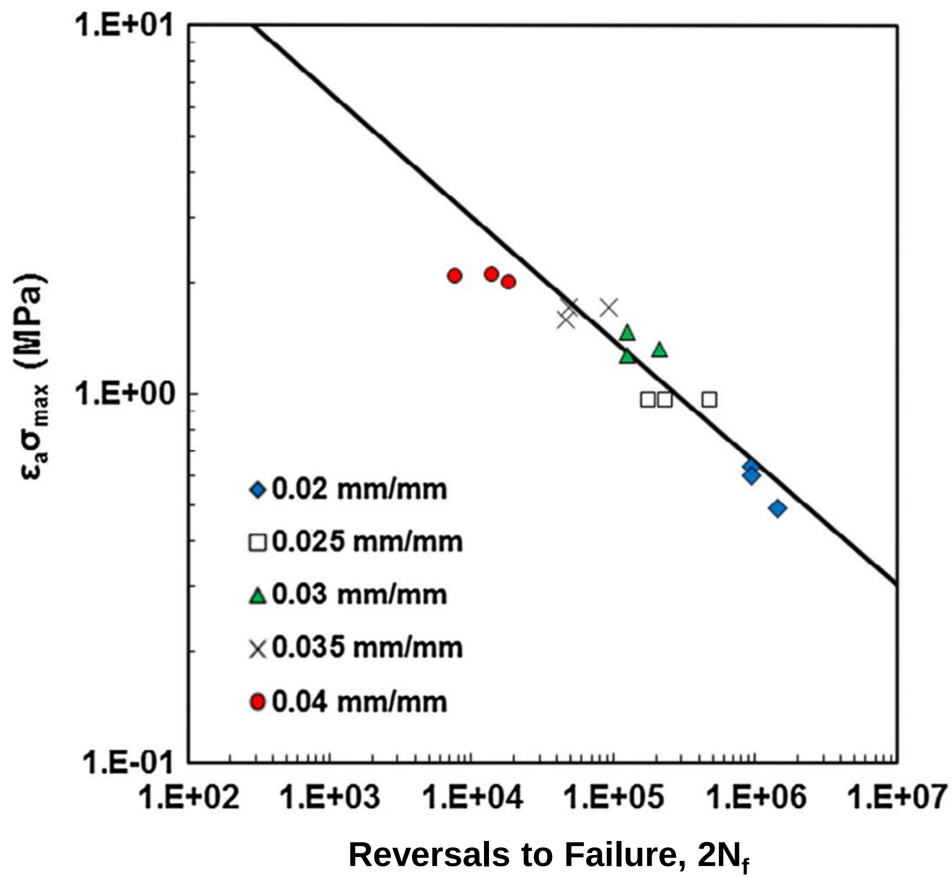


Experimental Results: Fatigue Model, Fully-Reversed Loading

- Strain-Stress based Smith-Watson-Topper (SWT)

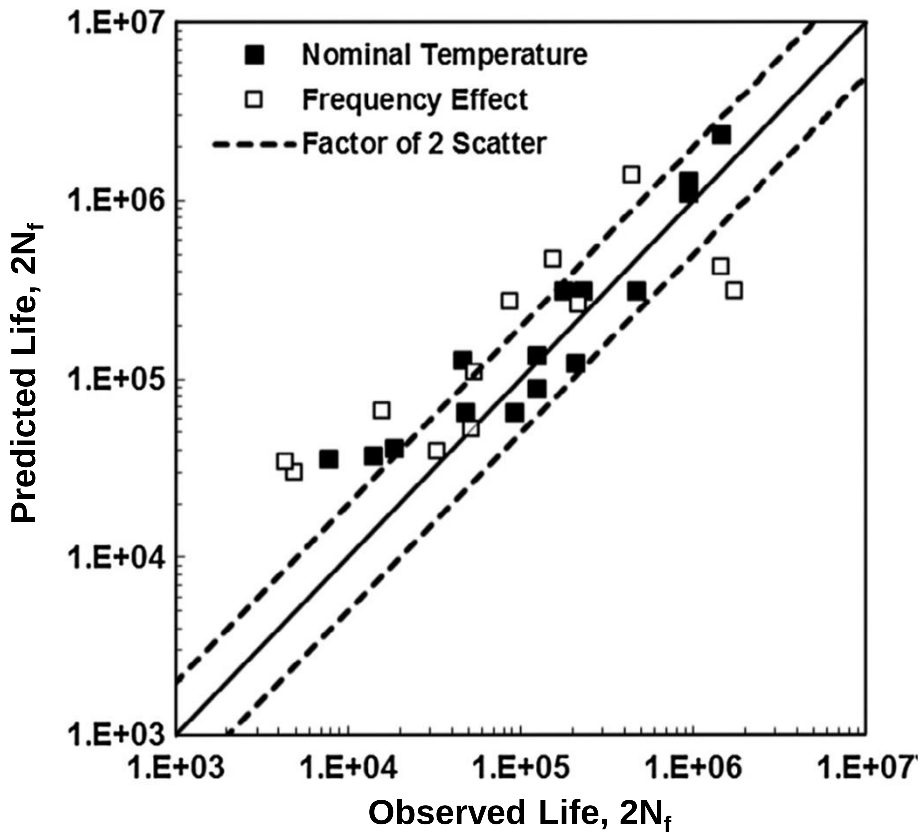
$$\varepsilon_a \sigma_{max} = \frac{1}{E}(\sigma_f')^2 (2N_f)^b + \sigma_f' \varepsilon_f' (2N_f)^{b+c}$$

where $\sigma_{max} = \sigma_m + \sigma_a$



Experimental Results: Fatigue Model, Fully-Reversed Loading

- Predicted fatigue lives using the SWT approach versus experimentally observed fatigue lives for fully-reversed test



Experimental Results: Fatigue Model, Fully-Reversed Loading

- Energy-Based Model with total strain energy density at half-life

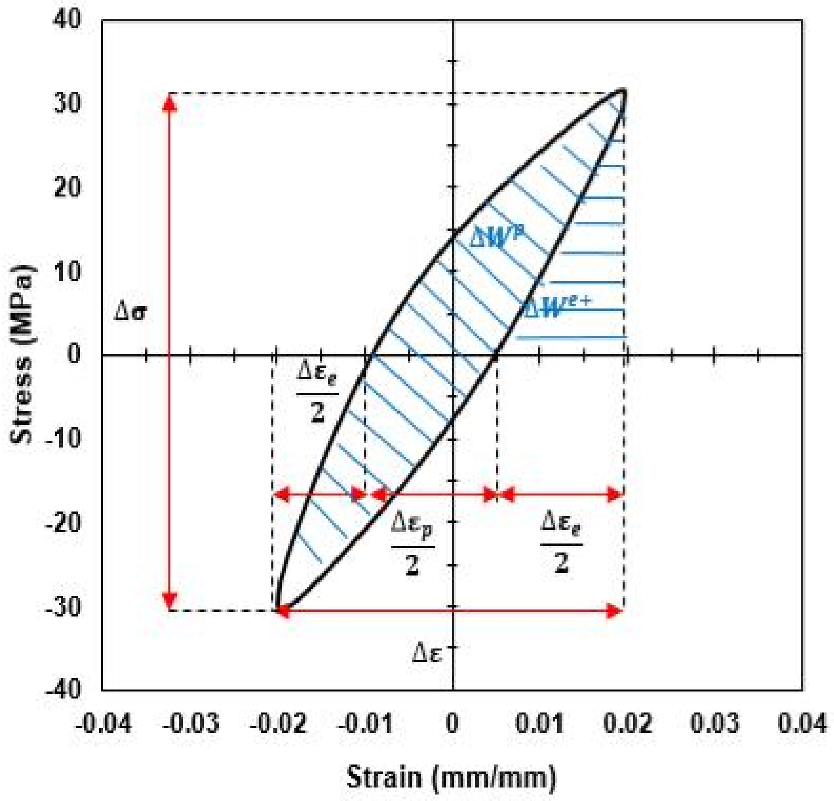
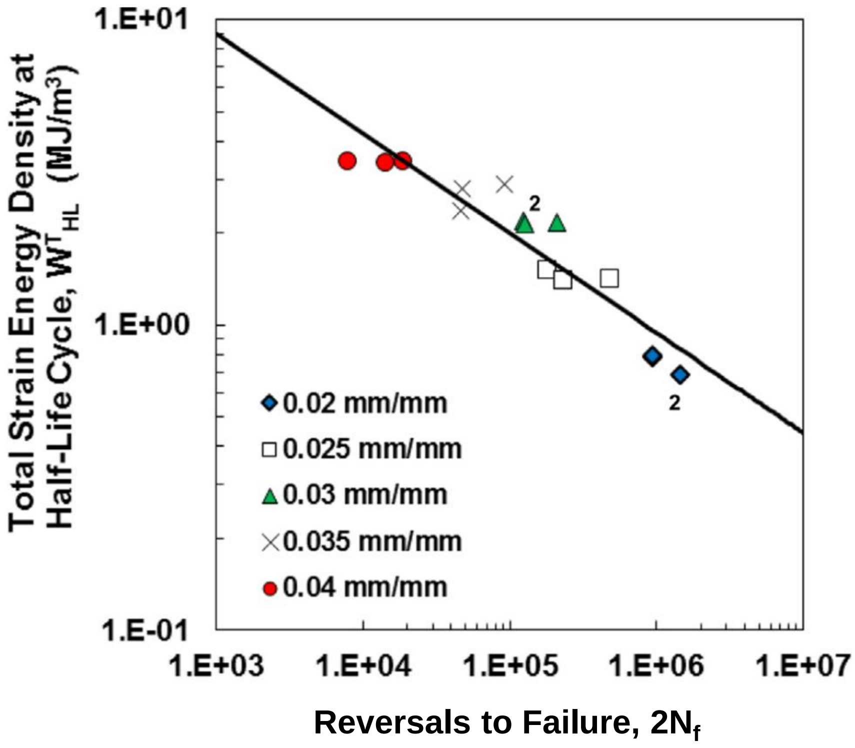
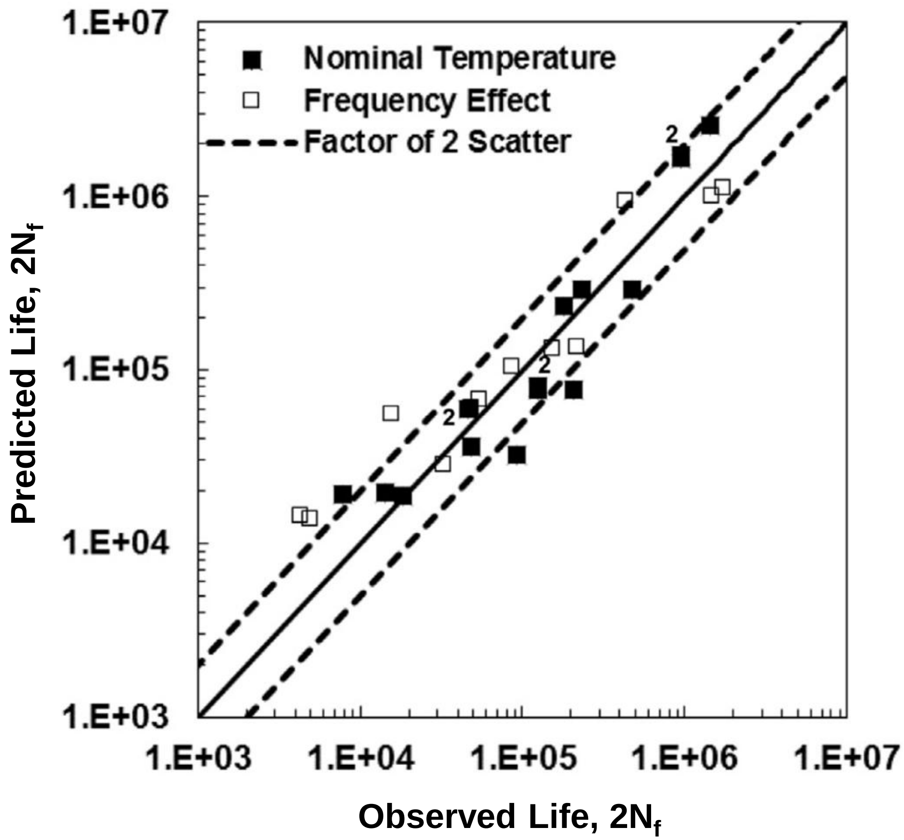


Illustration of the strain energy density components of the fatigue test



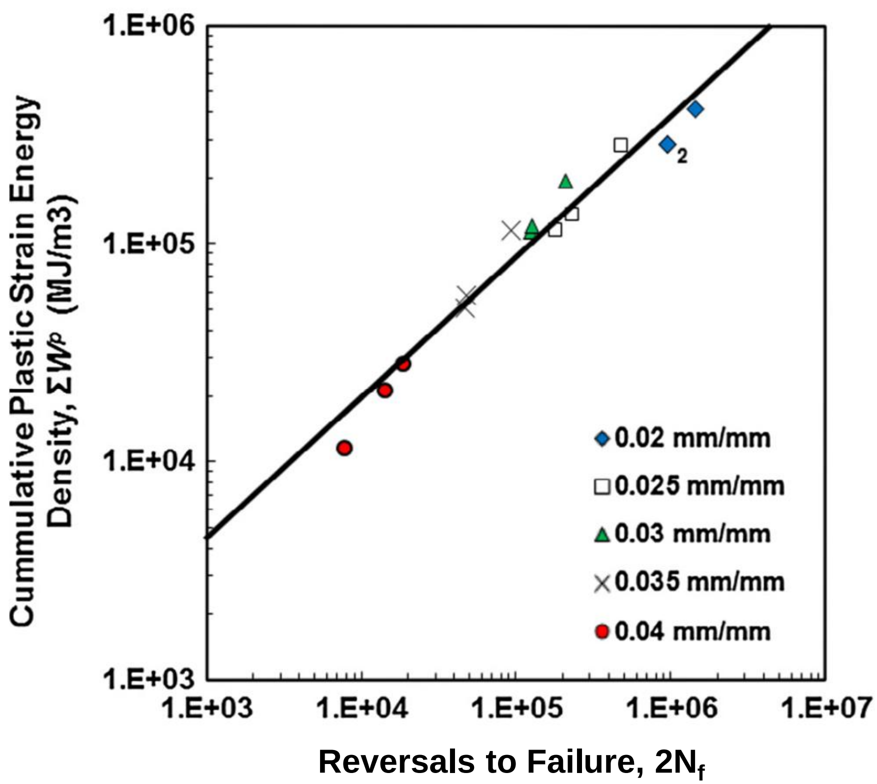
Experimental Results: Fatigue Model, Fully-Reversed Loading

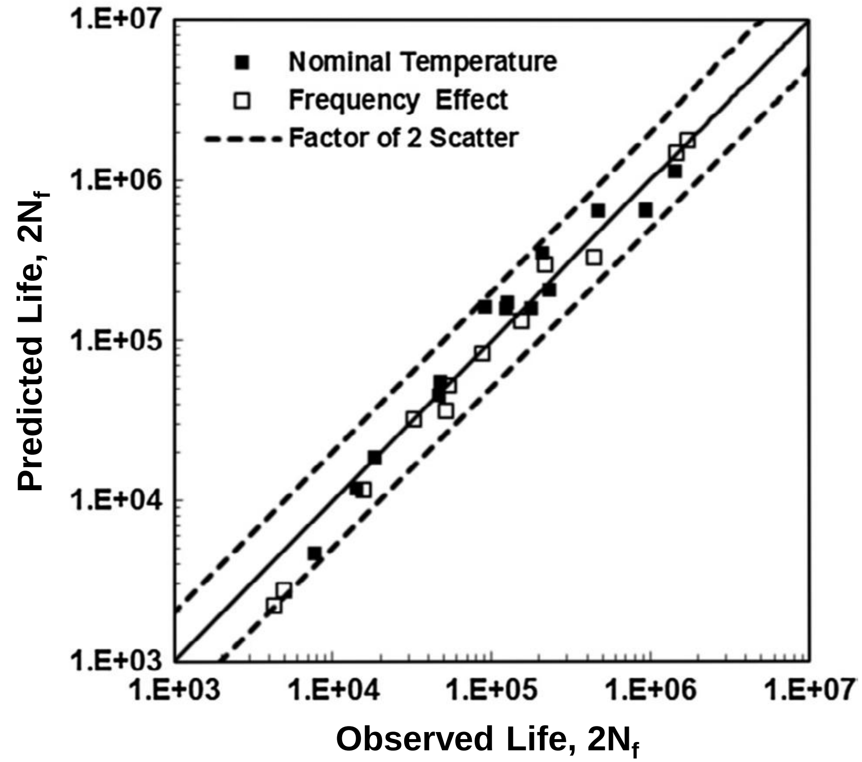
- Predicted fatigue lives using the energy based approach versus experimentally observed fatigue lives for all R_ε values



Experimental Results: Fatigue Model, Fully-Reversed Loading

- Energy-Based Model with cumulative plastic strain energy density

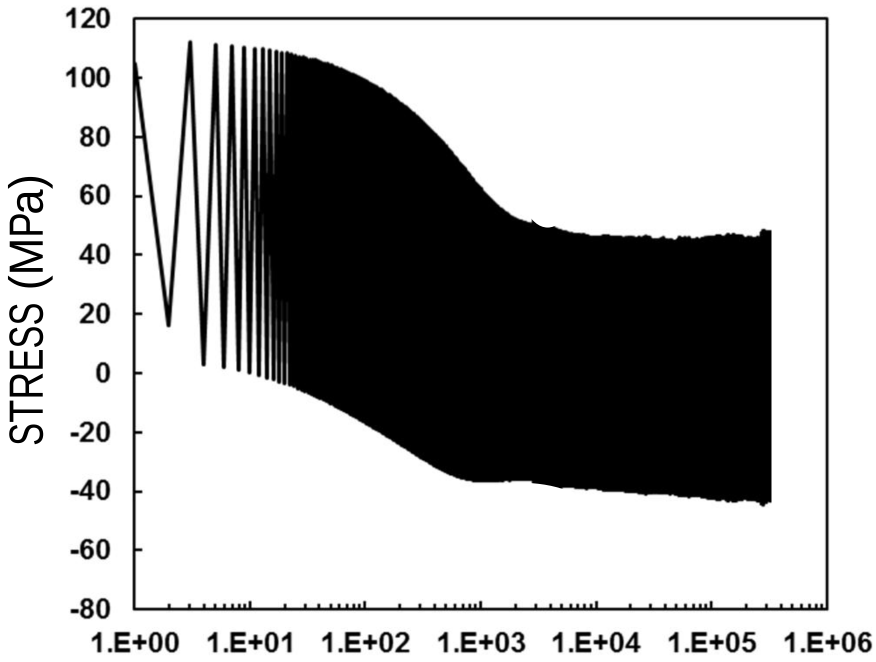


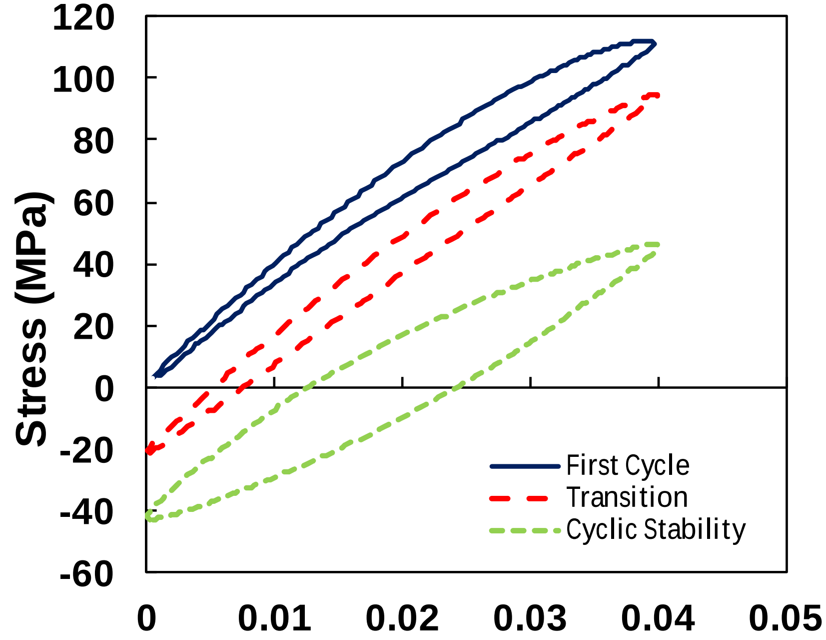


Experimental Results: Fatigue Behavior, Tensile Mean Strain Loading

- Stress Relaxation in tensile mean strain $R_{\varepsilon} = 0$ test

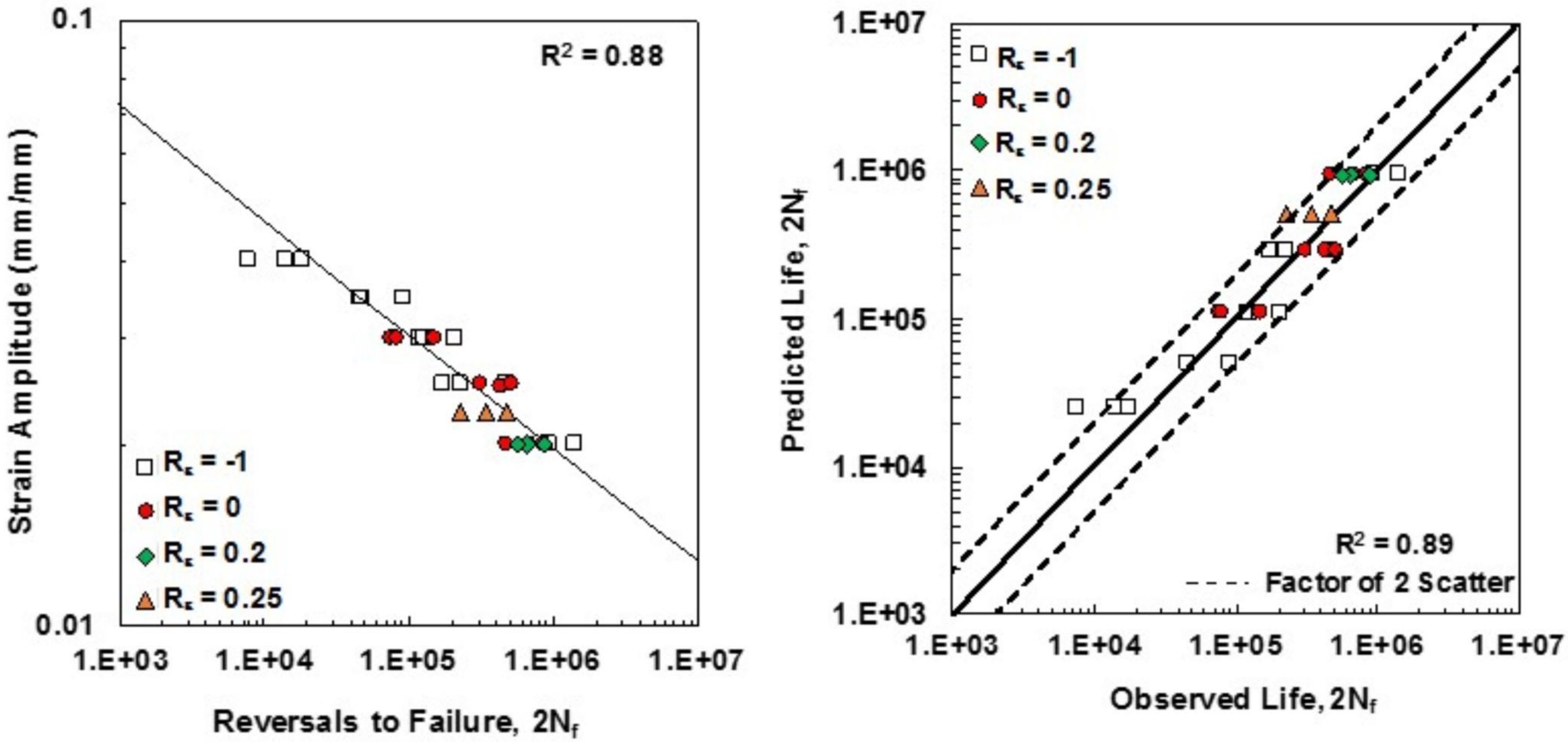
Strain Amplitude: 0.02mm/mm at 1.5Hz





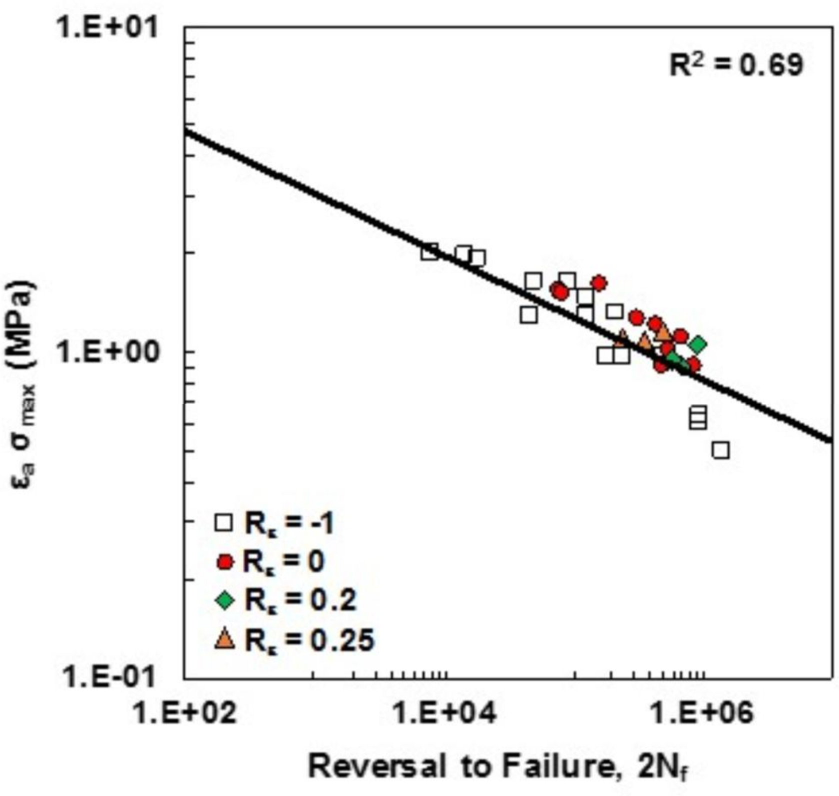
Experimental Results: Fatigue Model, Tensile Mean Strain Loading

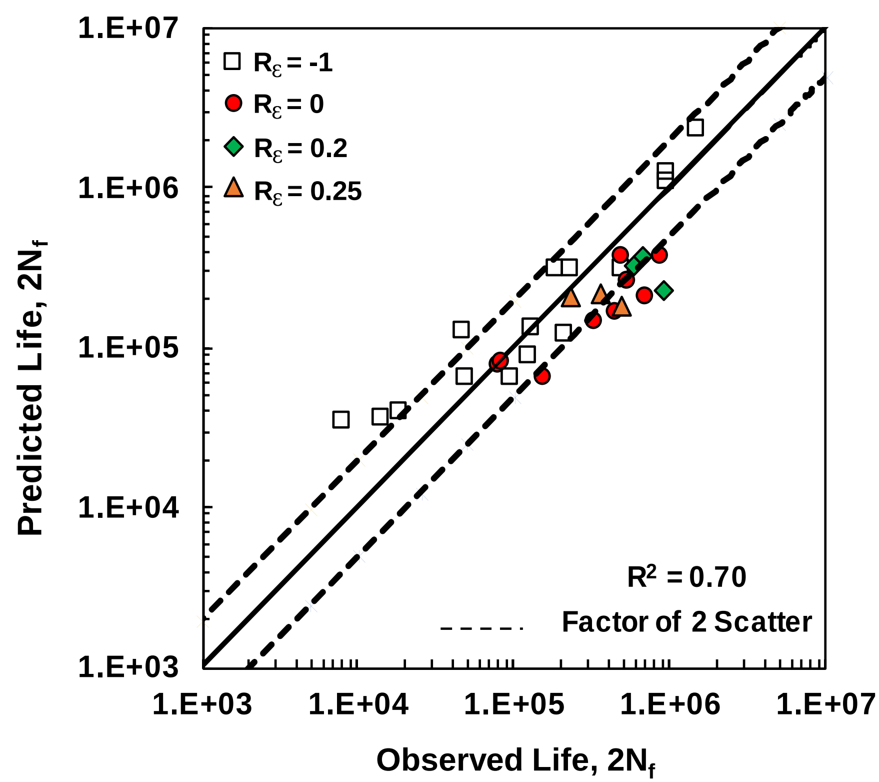
- Strain-based-Coffin-Manson approach



Experimental Results: Fatigue Model, Tensile Mean Strain Loading

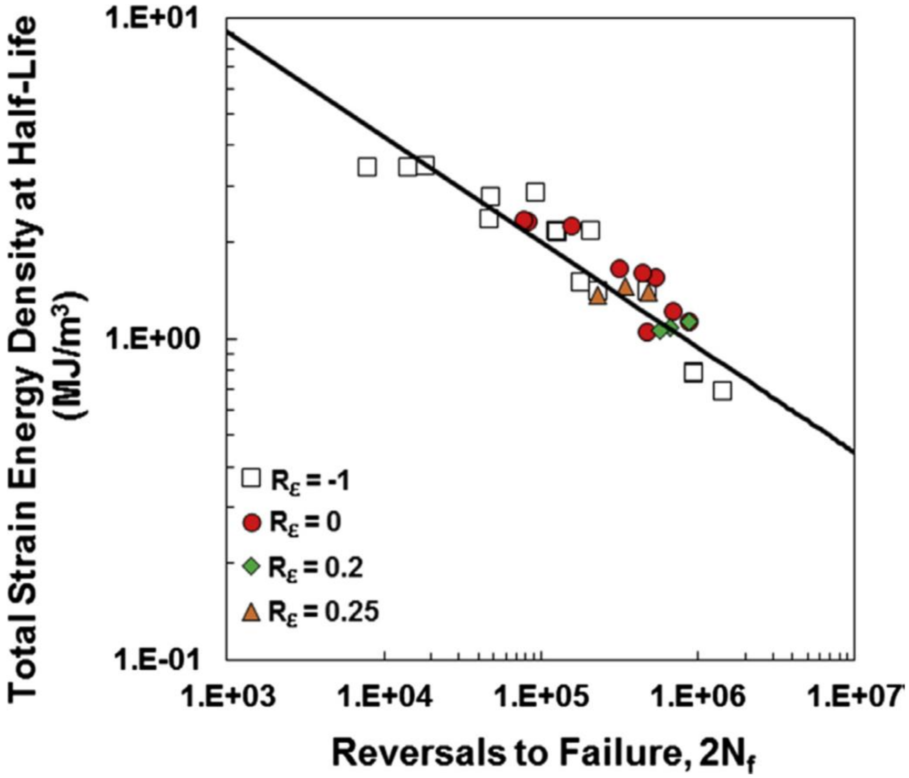
- Strain-Stress-based-Smith-Watson-Topper (SWT) approach

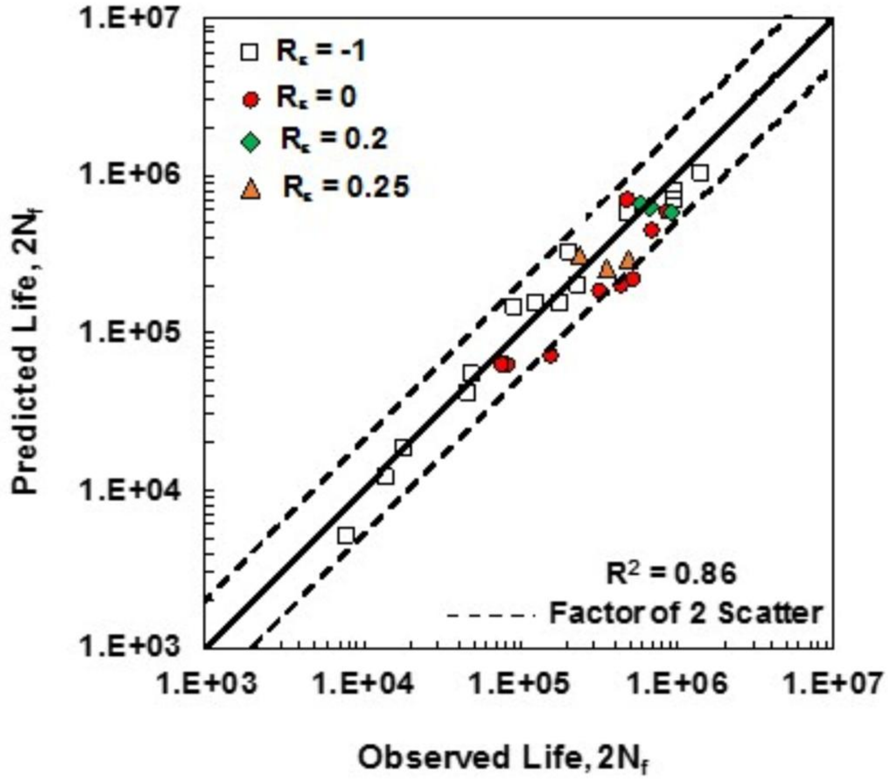




Experimental Results: Fatigue Model, Tensile Mean Strain Loading

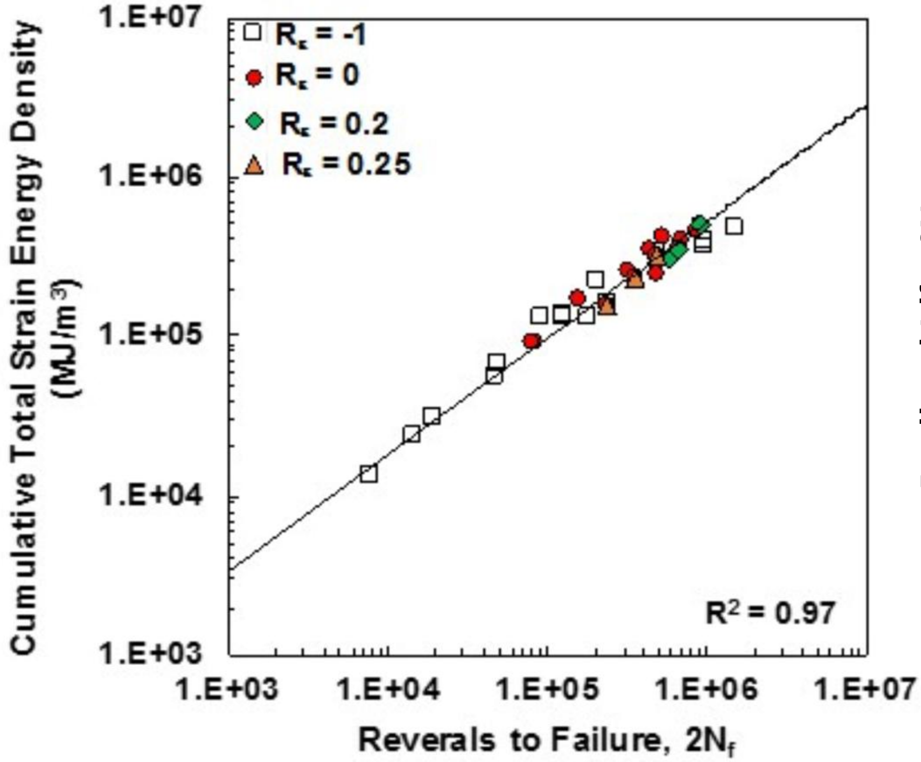
- Energy-Based Model with total strain energy density at half-life

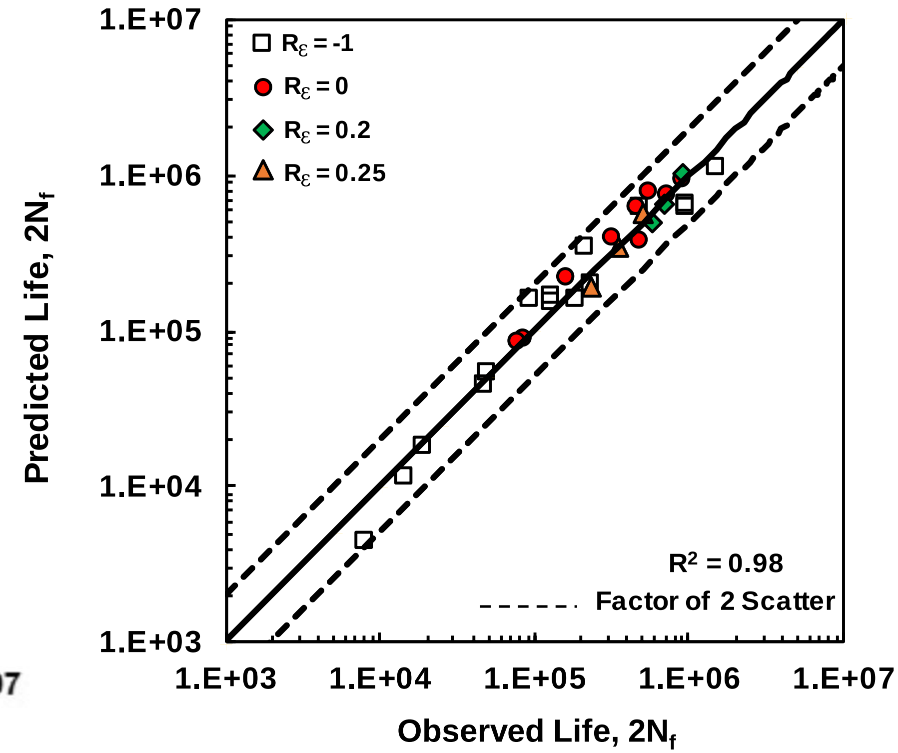




Experimental Results: Fatigue Model, Tensile Mean Strain Loading

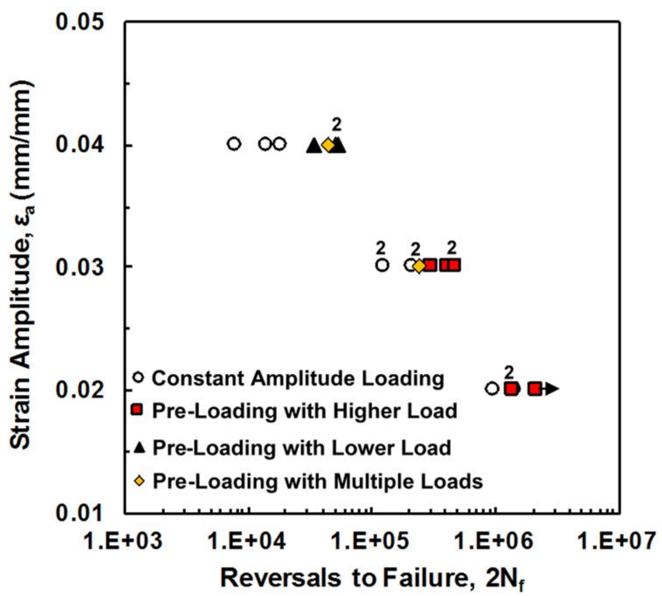
- Energy-Based Model with cumulative total energy density



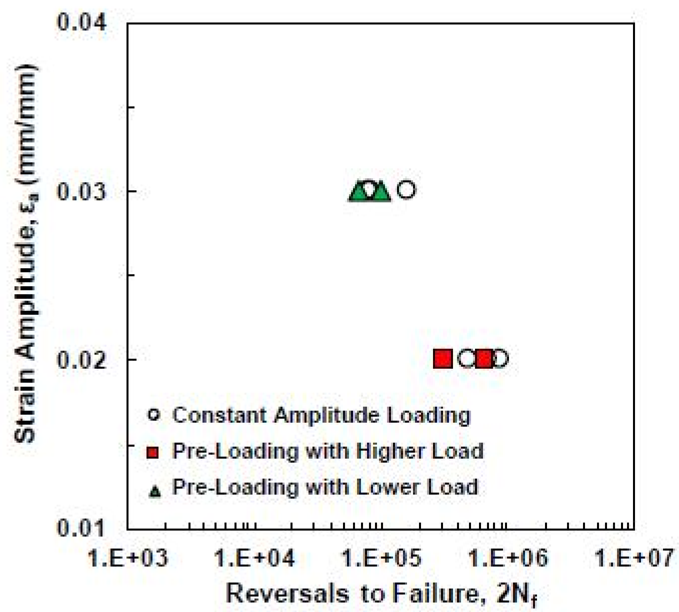


Experimental Results: Block Loading

- Effects of pre-loading on fatigue life of PEEK with and without mean strains
  - Increase in fatigue life observed for test without mean strain ($R_\varepsilon = -1$)
  - Minimal effect of pre-loading observed for tests with mean strain ($R_\varepsilon = 0$)



Nominal Temperature



Pulsating Mean Strain

Experimental Results: Fatigue Modelling, Cumulative Damage Rule

- Palmgren Miner's Linear Damage Rule (LDR)
  - Strain-based
  - Total strain energy density at half-life

$$D_i = \frac{N_i}{N_{fi}}$$

where,

i = number of loading blocks
N_i = number for a specific block of loading
N_{fi} = number of cycles to failure at particular strain or stress level as applied in the loading block *i*
D_i = cycle ratio or a fraction of life that is removed from the material

Failure is predicted to happen when

$$\mathrm{D} = \sum D_i = 1$$

Experimental Results: Fatigue Modelling, Cumulative Damage Rule

- Palmgren Miner's Linear Damage Rule (LDR)
  - Strain-based

Nominal Temperature
Condition I

Frequency Effect
Condition II

Tensile Mean Strain
Condition III

Experimental Results: Fatigue Modelling, Cumulative Damage Rule

- Palmgren Miner's Linear Damage Rule (LDR)
  - Total strain energy density at half-life

Nominal Temperature
Condition I

Frequency Effect
Condition II

Tensile Mean Strain
Condition III

Experimental Results: Fatigue Modelling, Cumulative Damage Rule

- Direct Cumulative Damage (DCD) method
  - Cumulative total strain energy density

Failure is predicted to happen when

$$D = \frac{\boldsymbol{N_{f,e}}}{\boldsymbol{N_{f,p}}} = \mathbf{1}$$

where,

$N_{f,e}$ = overall fatigue life of a specimen
(summation of number of cycles from all loading block)

$N_{f,p}$, = number of cycle, which corresponds to the total summation of $\sum W^T$

$\sum W^T = \sum W_1^T + \sum W_2^T$

$\sum W_1^T$ = Cumulative total strain energy density from first loading block

$\sum W_2^T$ = Cumulative total strain energy density from second loading block

Experimental Results: Fatigue Modelling, Cumulative Damage Rule

- Direct Cumulative Damage (DCD) method

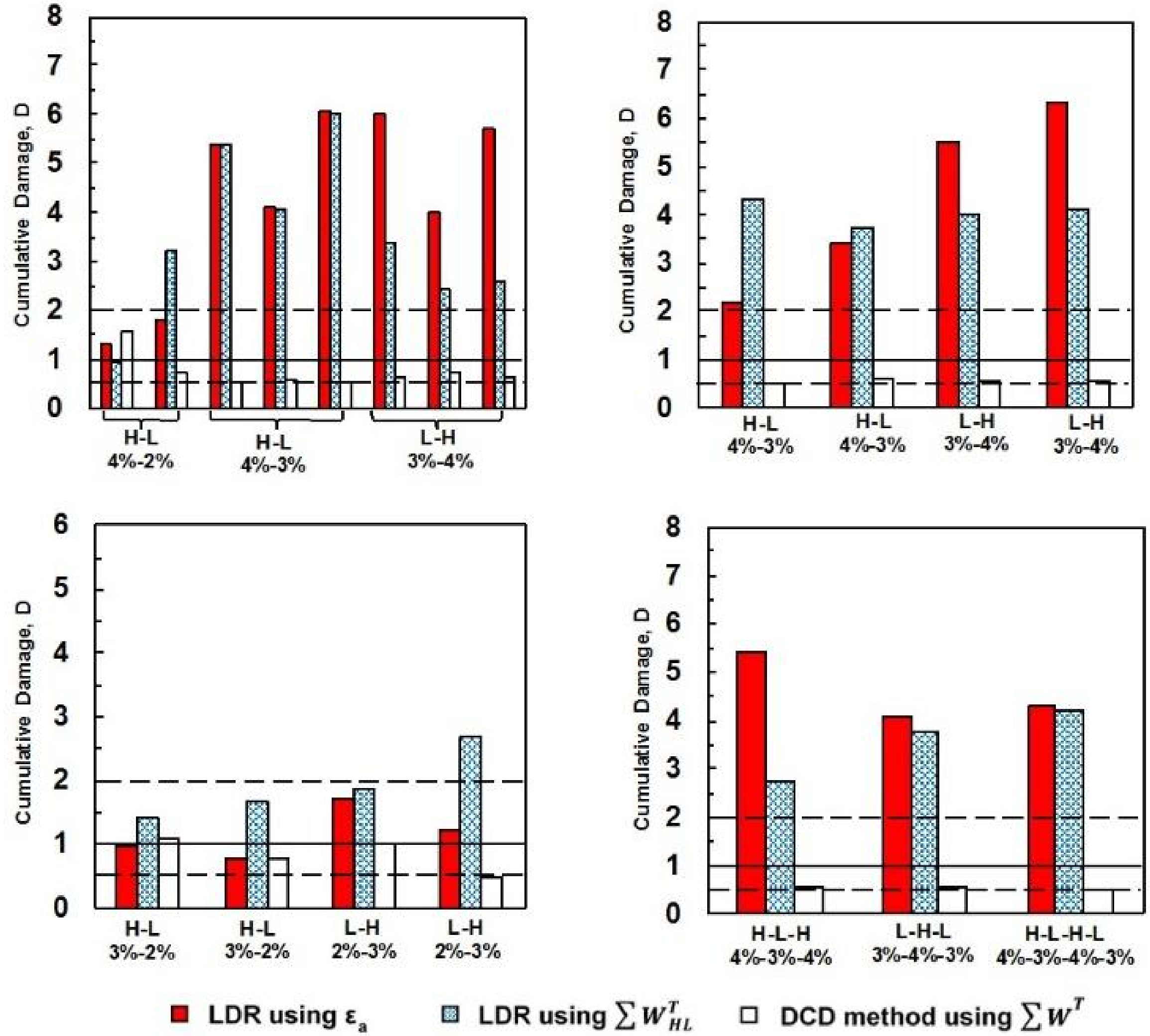
Test Condition IV	
H-L-H	□
L-H-L	■
H-L-H-L	X

Nominal Temperature
Condition I

Frequency Effect
Condition II

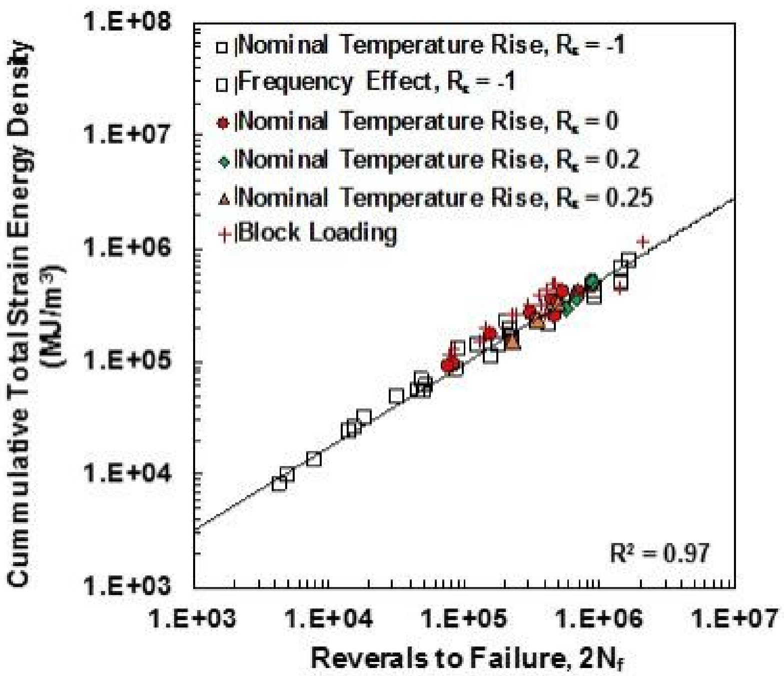
Tensile Mean Strain
Condition III

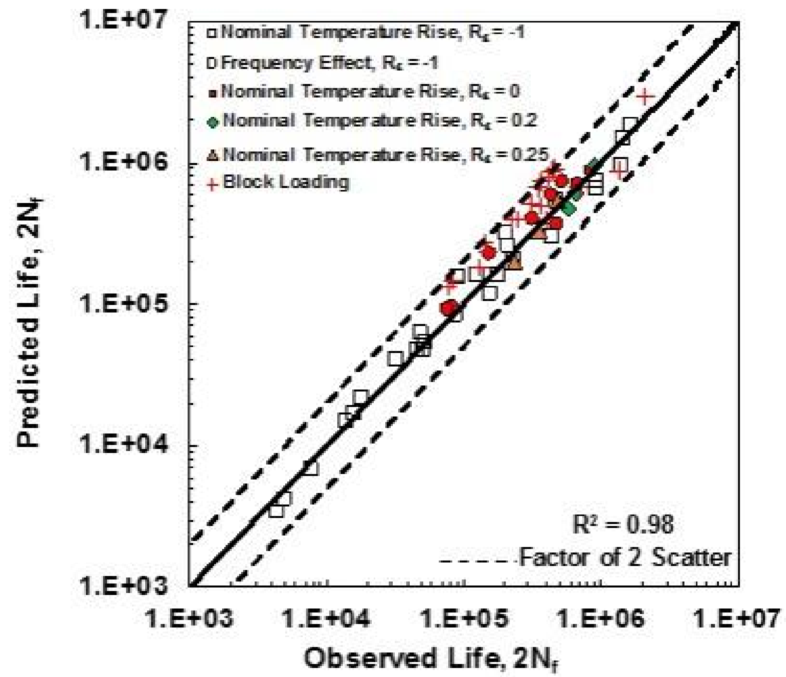
Experimental Results: Cumulative Damage Sum



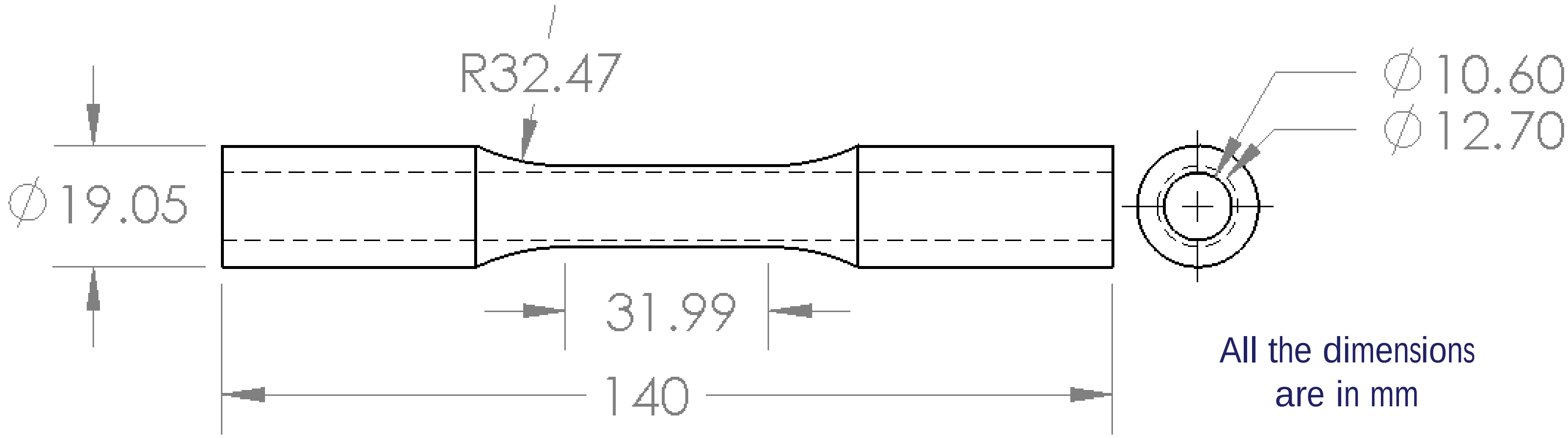
Experimental Results: Fatigue Modelling, Energy-Based Model

- Correlation of fatigue life data using cumulative total strain energy density as damage parameter for all strain-controlled fatigue tests under
  - Constant amplitude (R_ε = -1, 0, 0.2, and 0.25)
  - Block loading (two, three, and four steps block loading, R_ε = -1 and 0)





Experimental Setup: Specimen

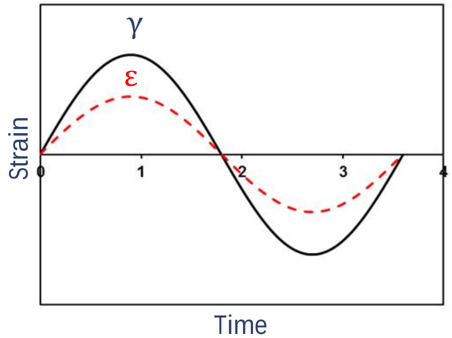


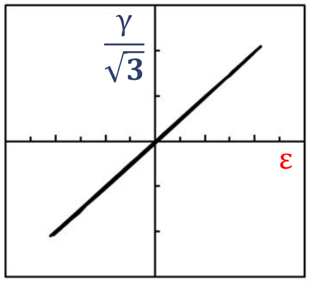
All the dimensions are in mm

- Unfilled PEEK material (TECAPEEK®) 25.4 mm extruded rods
- Machined (turning) to create thin-walled tubular specimen following ASTM E2207-15 standard

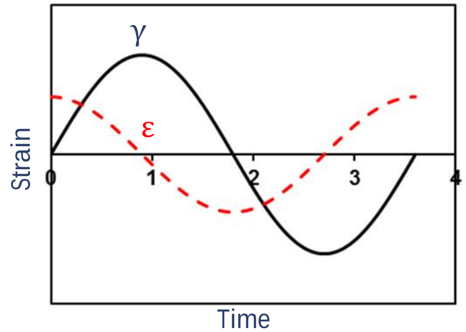
Experimental Setup: Test Program

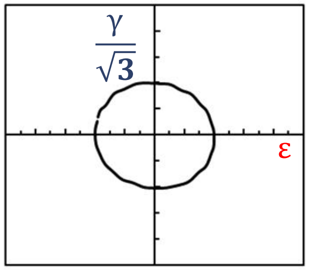
- Fully-reversed (R_ε = -1) strain-controlled axial/torsion cyclic loading
  - Proportional IP
    - εa = 0.02 – 0.04 mm/mm at 0.5 - 3 Hz frequency





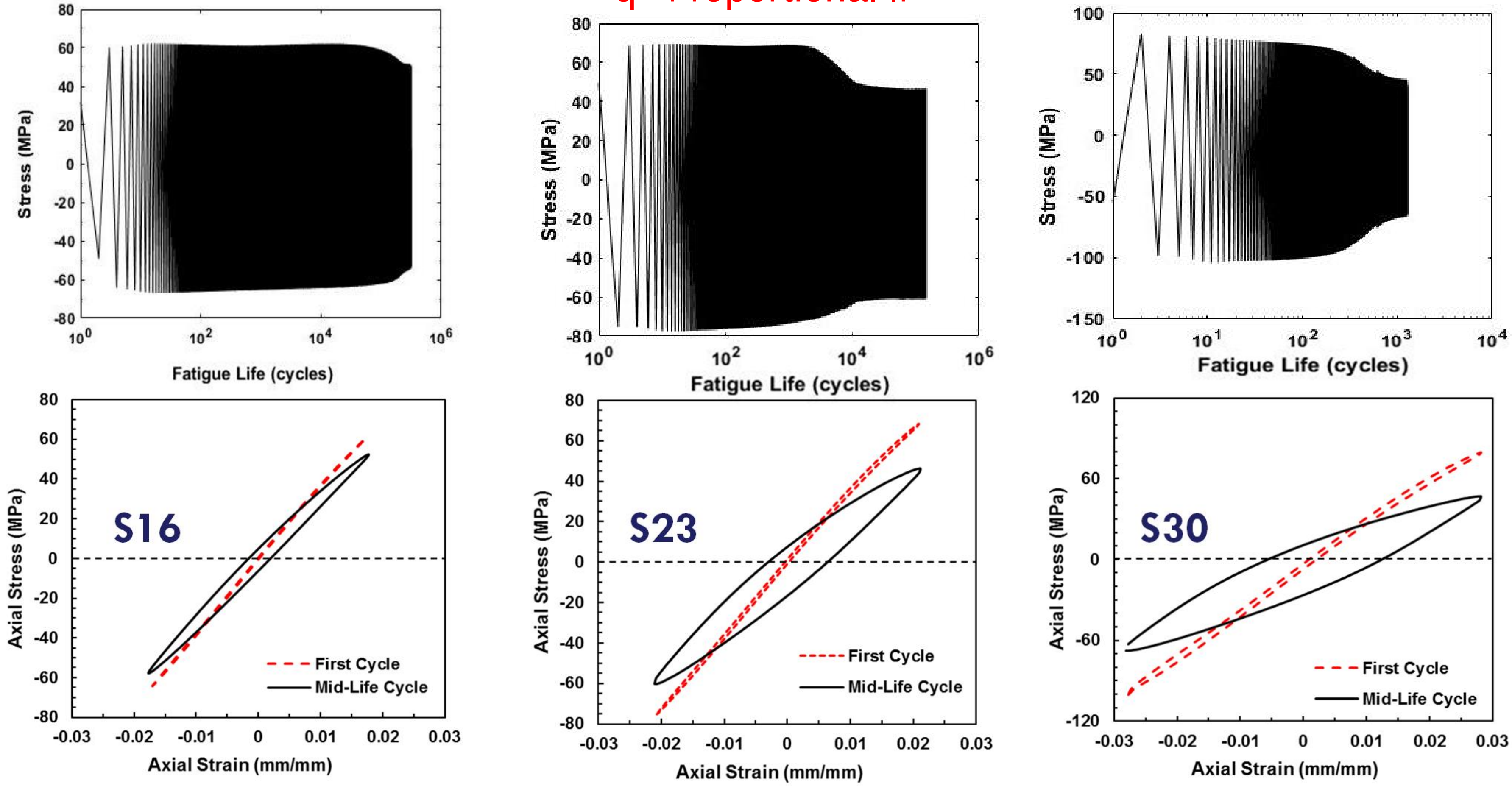
  - Non-proportional 90° OP
    - εa = 0.015 – 0.025 mm/mm at 1 - 4 Hz frequency





Experimental Results: Fatigue Behavior

- Proportional IP



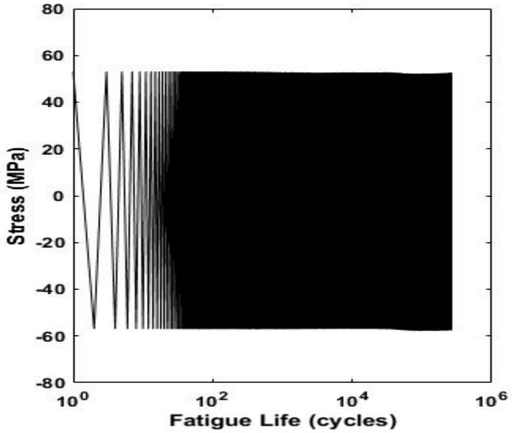
ε_a = 0.0177 mm/mm
ΔT = 26°C
$2N_f$ = 321,684

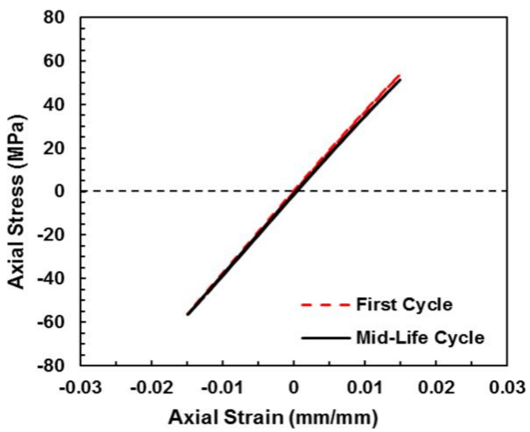
ε_a = 0.0212 mm/mm
ΔT = 24°C
$2N_f$ = 147,758

ε_a = 0.0282 mm/mm
ΔT = 30**°C**
$2N_f$ = 147,758

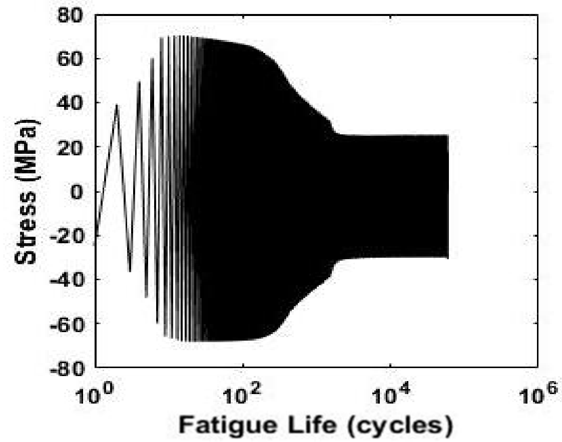
Experimental Results: Fatigue Behavior

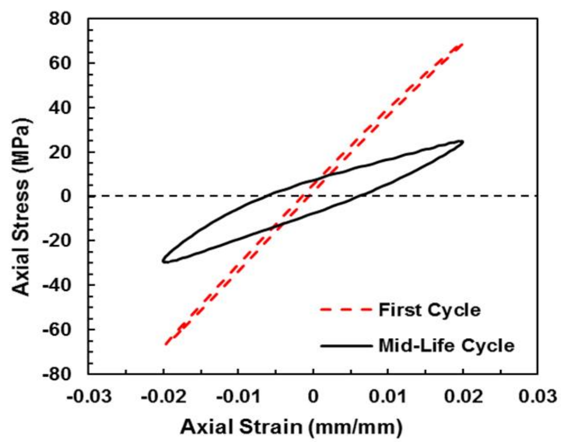
- Non Proportional 90° OP



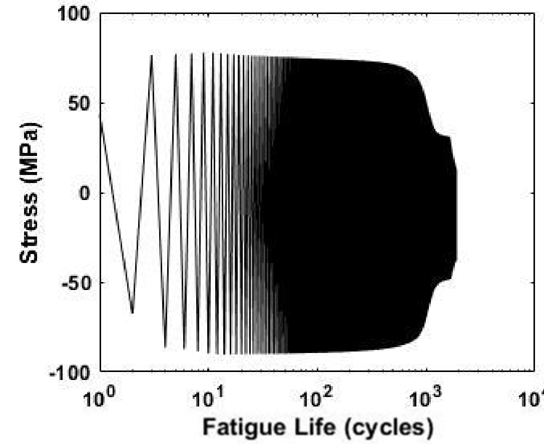


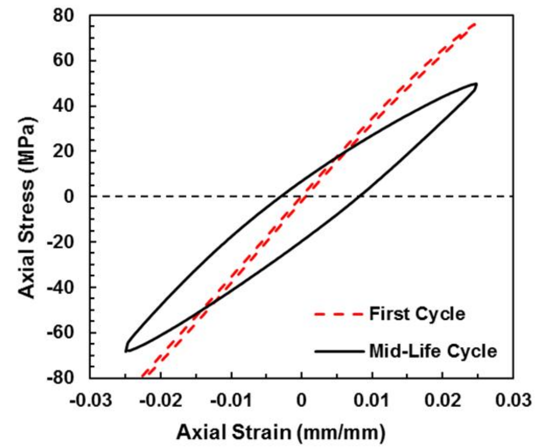
ε_a = 0.015 mm/mm
ΔT = 4°C
$2N_f$ = 266,170 Reversals





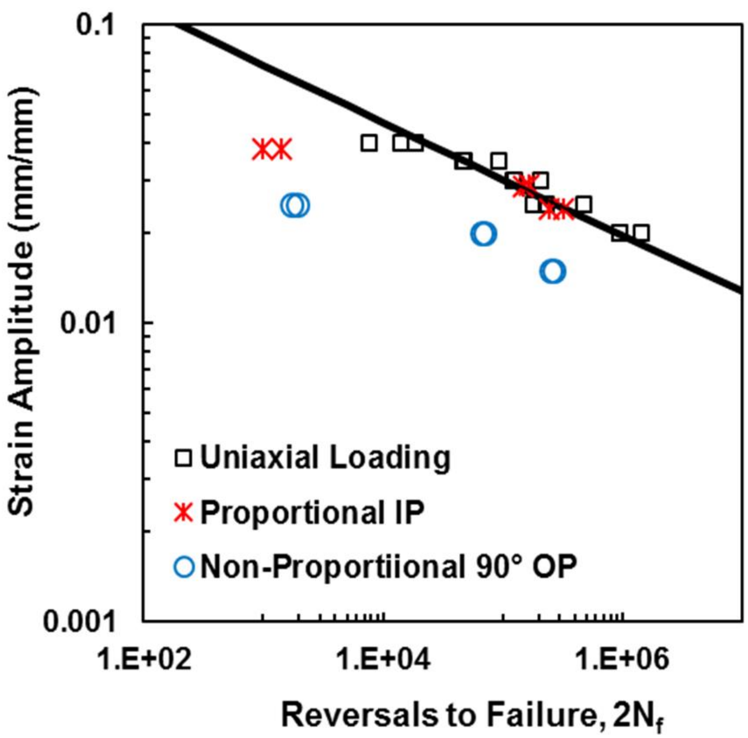
ε_a = 0.02 mm/mm
ΔT = 51°C
$2N_f$ = 66,194 Reversals

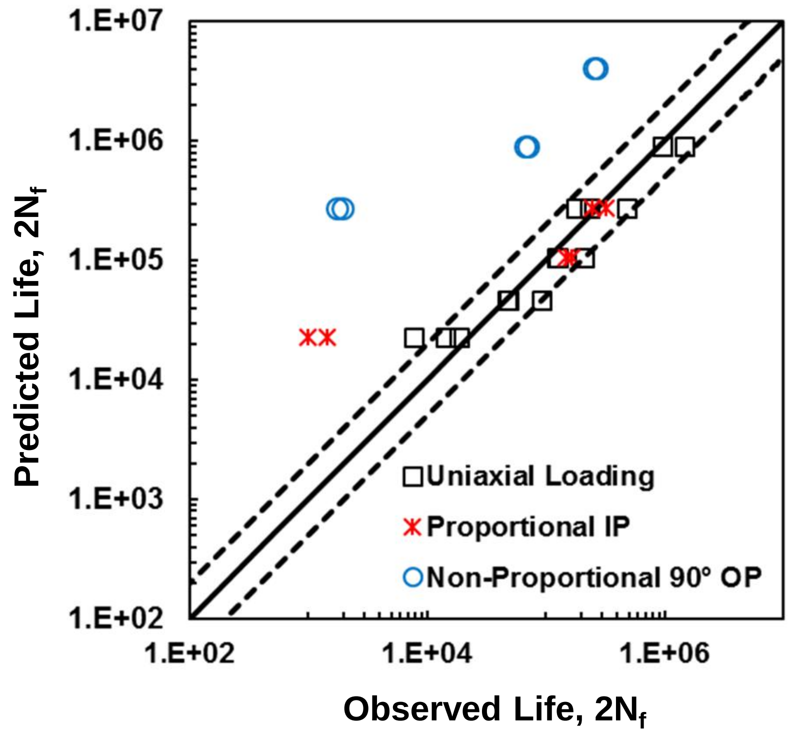




ε_a = 0.025 mm/mm
ΔT = 41°C
$2N_f$ = 1944 Reversals

Experimental Results: Fatigue Modelling, Strain-Based





Summary

- At higher strain amplitudes, longer fatigue lives were obtained by an increase in test frequency.
- Tensile mean strain was observed to have minimal effects on the fatigue life of PEEK.
- The energy-based fatigue model based on the cumulative total strain energy density correlated fatigue data of PEEK under various loading condition fairly well due to its ability to capture the change in shape and size of the hysteresis loop throughout the fatigue lifetime.
- Irrespective to the loading sequence under fully-reversed loading, significant beneficial effect of pre-loading was observed on the fatigue life of PEEK.
- Regardless of the loading condition (zero or non-zero mean strain) and sequence (high-low or low-high), the proposed direct cumulative damage (DCD) approach provided excellent predictive capability for PEEK under variable amplitude loading at various frequencies.

Summary

- PEEK exhibited significantly different fatigue deformation behavior under multiaxial loading compared to one observed under uniaxial loading condition.
- Shorter fatigue life was observed for the test subjected to OP loading when compared to the IP loading under identical equivalent strain amplitudes and frequency.
- Fatigue life modelling based on von Mises equivalent strain amplitude was not able to correlate fatigue life data under OP loading condition.

Ongoing Work

- Based on the fatigue deformation behavior, the other fatigue life models such as Critical Plane approach or Energy-Based model will be investigated to correlate the fatigue life data of PEEK under various types of multiaxial loading paths

Publications

Journal papers

- Simsiriwong J., Shrestha R., Shamsaei N., Lugo M., Moser RD., "Effects of microstructural inclusions on fatigue life of polyether ether ketone (PEEK)", Journal of the Mechanical Behavior of Biomedical Materials 2015;51:388–97
- Shrestha R., Simsiriwong J., Shamsaei N., Moser RD., "Cyclic deformation and fatigue behavior of polyether ether ketone (PEEK)", International Journal of Fatigue 2016;82:411–27.
- Shrestha R., Simsiriwong J., Shamsaei N., "Fatigue data for polyether ether ketone (PEEK) under fully-reversed cyclic loading", Data in Brief, 2016;6:881-84.
- Shrestha R., Simsiriwong J., Shamsaei N., "Mean strain effects on cyclic deformation and fatigue behavior of polyether ether ketone (PEEK)", Polymer Testing, 2016;55:69-77
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- Shrestha R., Simsiriwong J., Shamsaei N., "Fatigue modeling of a thermoplastic polymer under mean strain and variable amplitude block loadings", International Journal of Fatigue, 2017:100: 429-43.

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- Shrestha R., Simsiriwong J., Lugo M., Shamsaei N., "Fatigue behavior and modeling for thermoplastics", In the Proceeding of 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. Orlando, FL, 2015.
- Shrestha R., Simsiriwong J., Shamsaei N., "Fatigue modeling of polyether ether ketone(PEEK) with mean strain effects", ASME 2015 International Mechanical Engineering Congress and Exposition. Houston, TX, 2015.
- Shrestha R., Simsiriwong J., Shamsaei N., Thompson S.M., Bian L., "Effect of build orientation on the fatigue behavior of stainless steel 316L manufactured via a laser-powder bed fusion process", 2016, Proceedings of the 26th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference, Austin, TX.
- Torries B., Shrestha R., Imandoust A., Shamsaei N., "Fatigue life prediction of additively manufactured metallic materials using a fracture mechanics approach", 2018, Solid Freeform Symposium, Austin, TX.

Publications

Conference proceedings

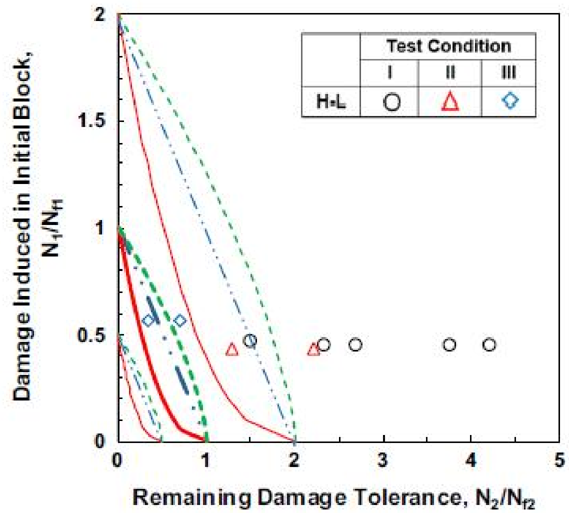
- Shrestha R., Sterling A., Lessel B., Phan N., Sereshk R.V.M., Shamsaei N., “Mechanical Behavior of Additively Manufactured 17-4 PH Stainless Steel Schoen Gyroid Lattice Structures”, 2018, Solid Freeform Symposium, Austin, TX.
- Shrestha R., Dastranjy Nezhadfar P., Massomi M., Simsiriwong J., Phan N., Shamsaei N., “Effects of Design Parameters on Thermal History and Mechanical Behavior of Additively Manufactured 17-4 PH Stainless Steel”, 2018, Solid Freeform Symposium, Austin, TX.

Acknowledgements

- Dr. Nima Shamsaei, Auburn University
- Dr. Jutima Simsiriwong, University of Northern Florida

Questions and Suggestions

Backup Slides



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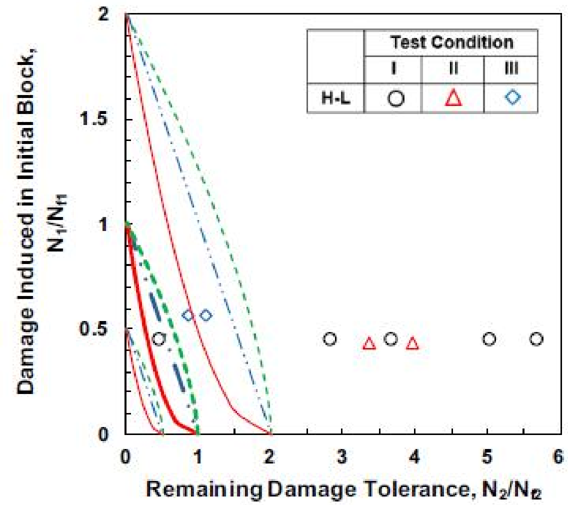

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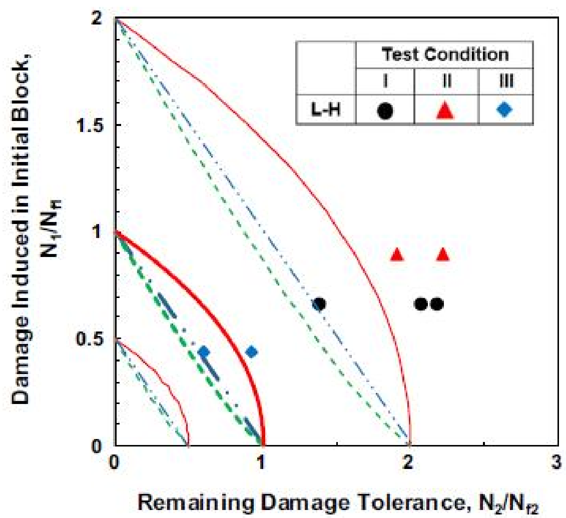

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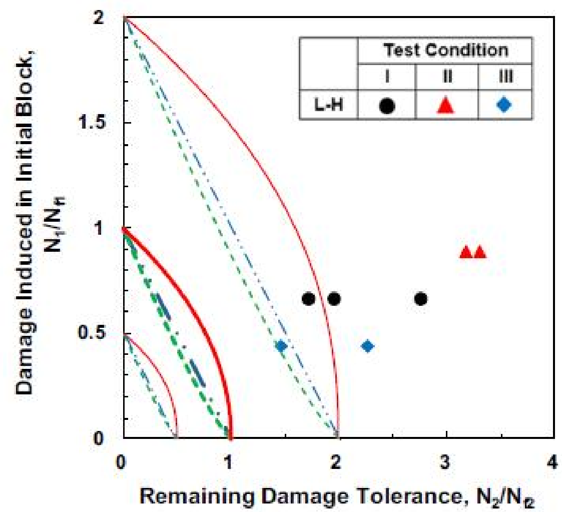


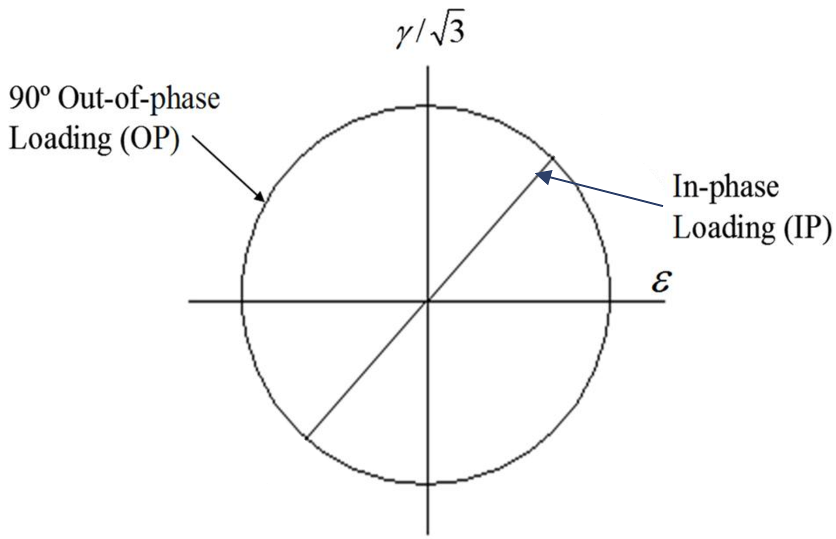
(b)

LDR DCA H-R Model

LDR DCA H-R Model

Experimental Results: Fatigue Modelling, Strain-Based

$$\bar{\varepsilon}_a = \frac{\Delta\bar{\varepsilon}}{2} = \frac{1}{\sqrt{2}(1+\bar{\nu})}\sqrt{2\left(\frac{\Delta\varepsilon}{2}\right)^2(1+\bar{\nu})^2 + \frac{3}{2}\left(\frac{\Delta\gamma}{2}\right)^2}$$



$\bar{\varepsilon}_a = \frac{\Delta\bar{\varepsilon}}{2}$ = Equivalent Strain Amplitude

$\frac{\Delta\varepsilon}{2}$ = Axial Strain Amplitude

$\frac{\Delta\gamma}{2}$ = Shear Strain Amplitude

$\bar{\nu}$ = Effective Poison's Ratio

$$\bar{\nu} = \frac{\nu_e \varepsilon_e + \nu_p \varepsilon_p}{\varepsilon}$$

ν_e = Elastic Poison's Ratio

ε_e = Elastic strain

ν_p = Plastic Poison's Ratio

ε_p = Plastic strain

$$\bar{\sigma}_a = \frac{\Delta\bar{\sigma}}{2} = \sqrt{\left(\frac{\Delta\sigma}{2}\right)^2 + 3\left(\frac{\Delta\tau}{2}\right)^2}$$

$\bar{\sigma}_a = \frac{\Delta\bar{\sigma}}{2}$ = Equivalent Stress Amplitude

$\frac{\Delta\sigma}{2}$ = Axial Stress Amplitude

$\frac{\Delta\tau}{2}$ = Shear Stress Amplitude

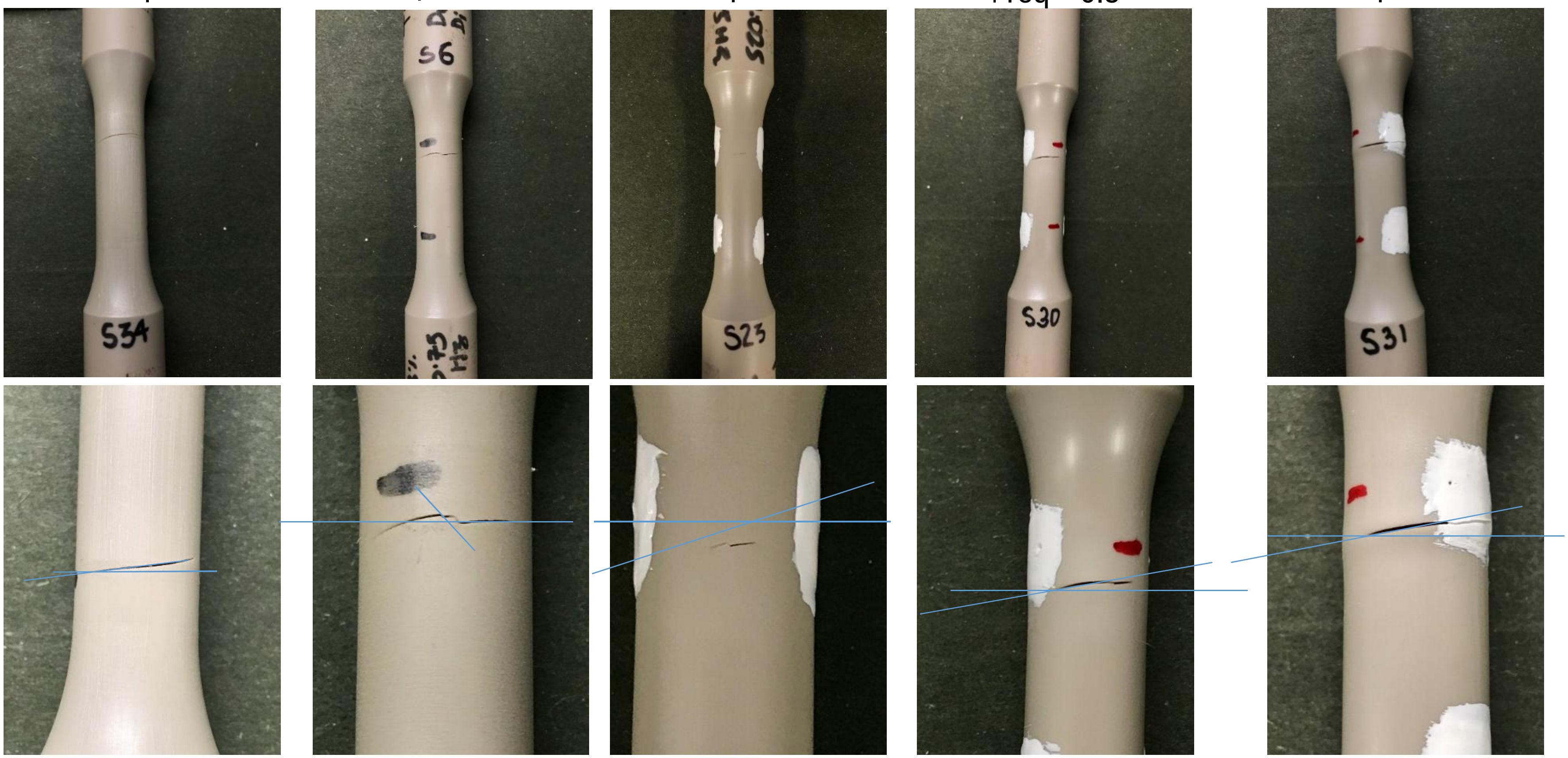
S34
Eq. Strain = 2.5%
2Nf = 243,268
Temp Rise = 30
Freq = 1

S06
Eq. Strain = 3%
2Nf = 165718
Temp Rise = 19
Freq = 0.75

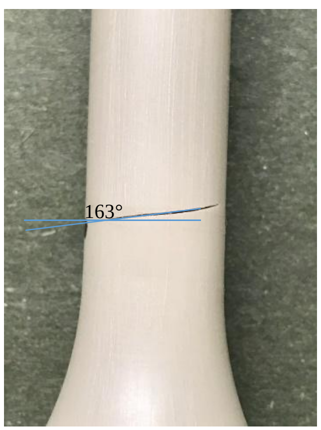
S23
Eq. Strain = 3%
2Nf = 147758
Temp Rise = 24
Freq = 0.75

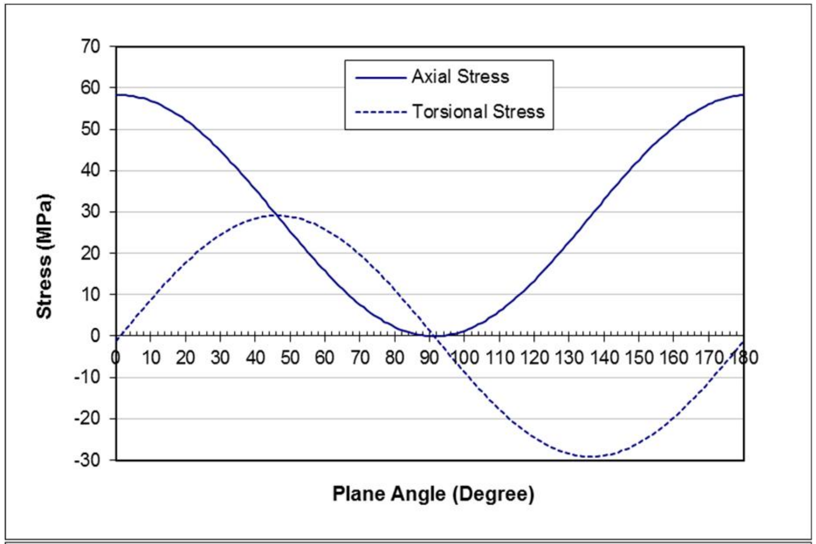
S30
Eq. Strain = 4%
2Nf = 1428
Temp Rise = 30
Freq = 0.5

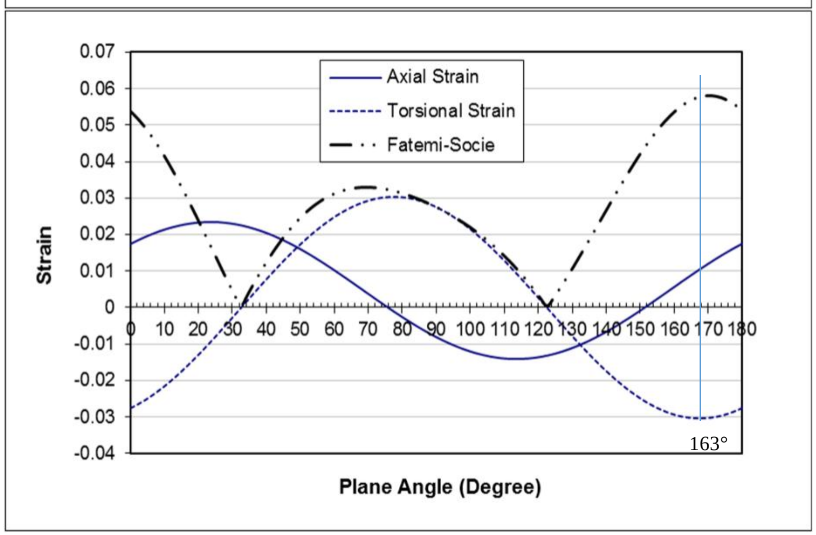
S31
Eq. Strain = 4%
2Nf = 994
Temp Rise = 29
Freq = 0.5

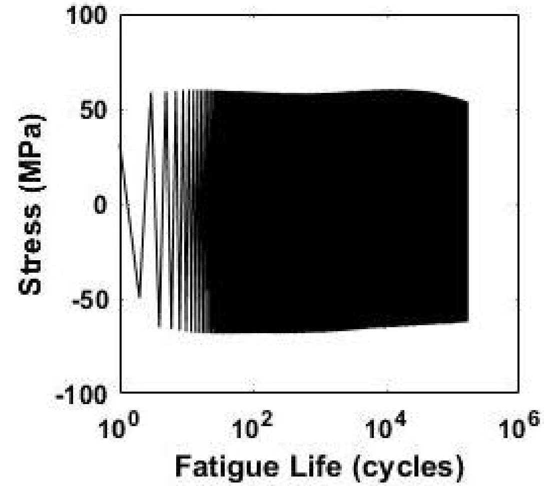


S34
Eq. Strain = 2.5%
2Nf = 243,268
Temp Rise = 30
Freq = 1



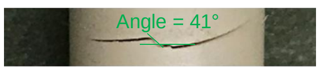


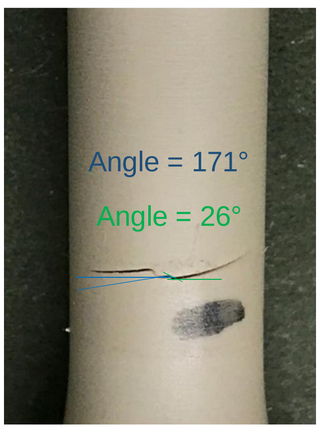


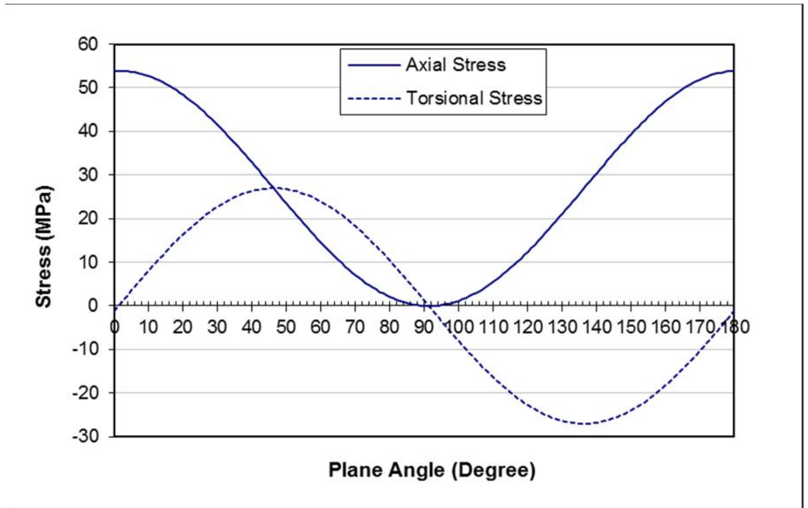


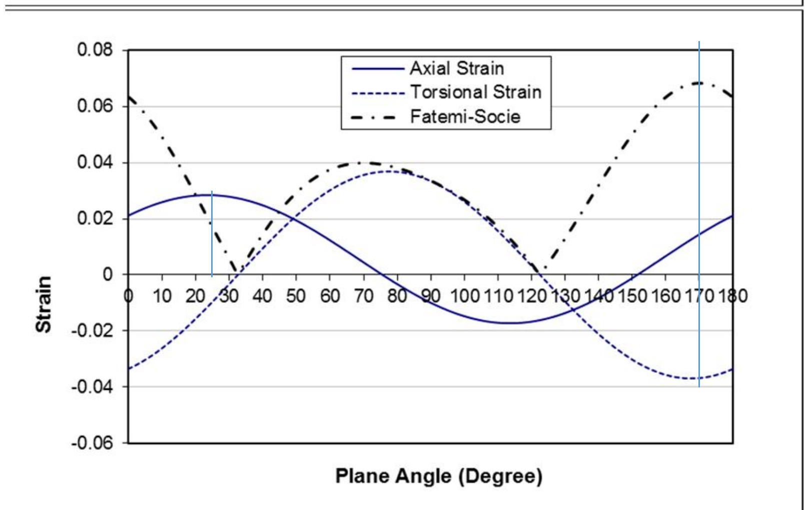
Principal strain	Principal strain	Orientation
0.0236	-0.014	24°
0.023560227	-0.014032527	
Maximum Shear Strain		
0.030373433	-0.030369592	168°
0.030369595		
Principal stress	Principal stress	Principal stress
58.26335774		-0.0281
58.26217589		-0.02691615
Maximum Shear Stress		Orientation
29.14572887		46°
29.14454602	-29.14454795	

S06
Eq. Strain = 3%
2Nf = 165718
Temp Rise = 19
Freq = 0.75



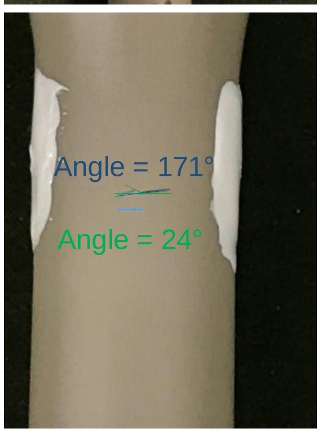


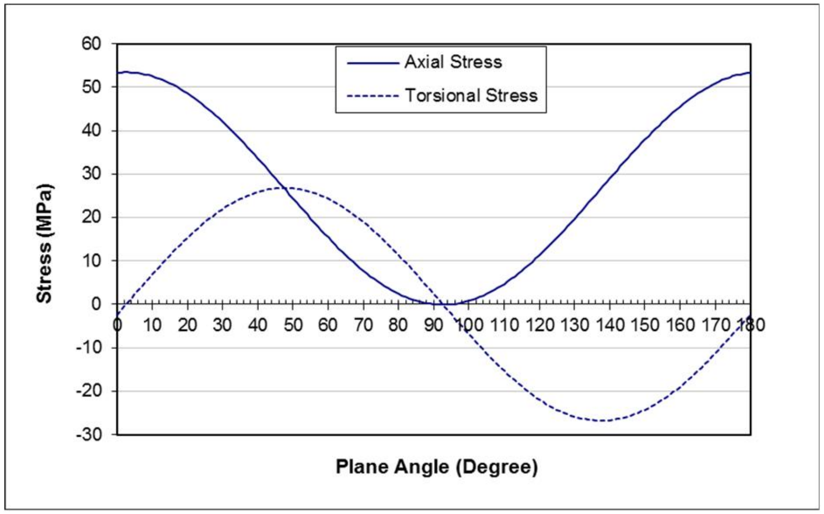


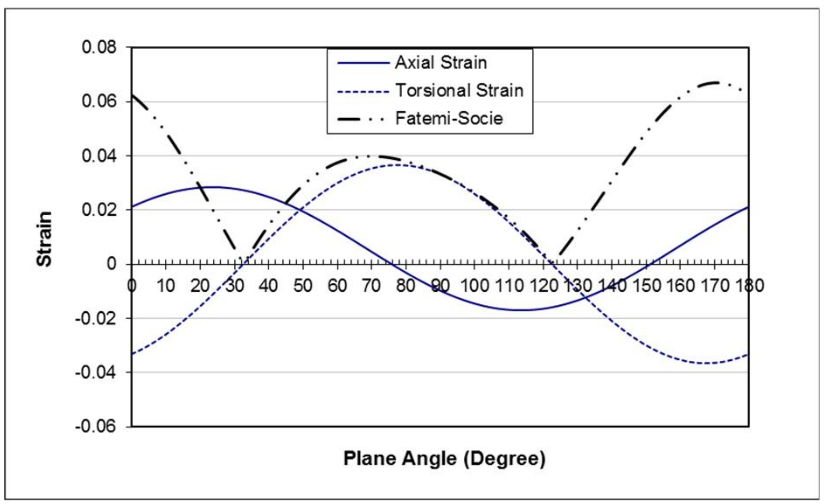


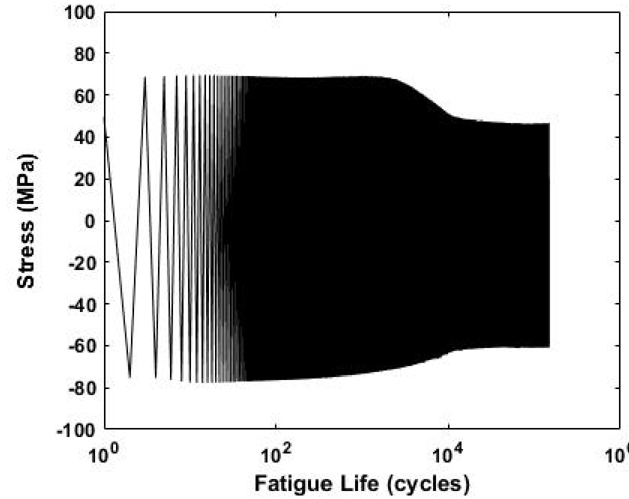
Principal strain	Principal strain	Orientation
0.0285	-0.0172	24°
0.028518285	-0.01715128	
Maximum Shear Strain		Orientation
0.036935701		168°
0.036931797	-0.03693179	
Principal stress	Principal stress	Principal stress
53.9342684		-0.0267
53.93303805		
Maximum Shear Stress		Orientation
26.9804842		46°
26.97923365	-26.9792355	

S23
Eq. Strain = 3%
2Nf = 147758
Temp Rise = 24
Freq = 0.75



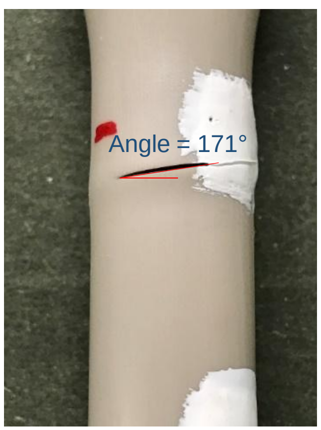


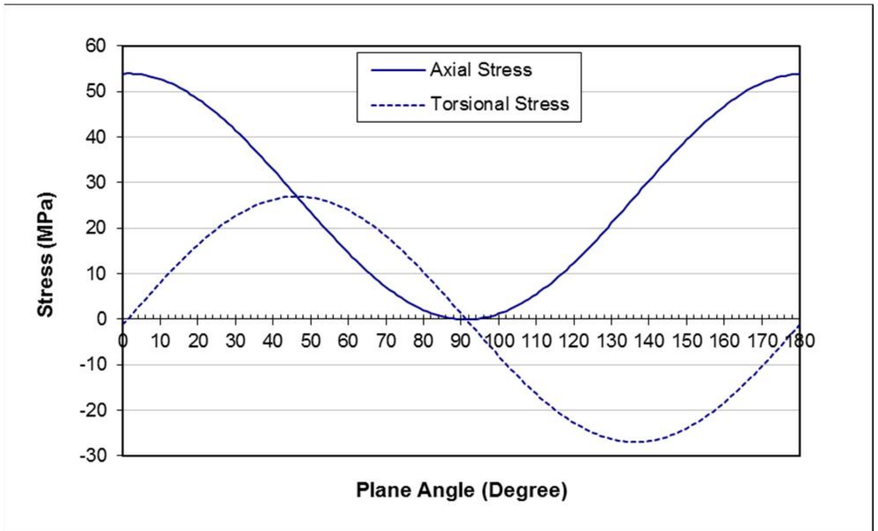


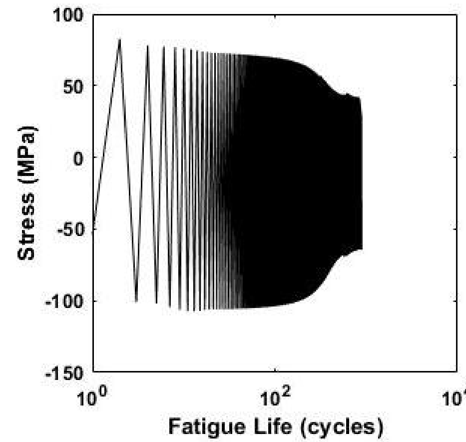


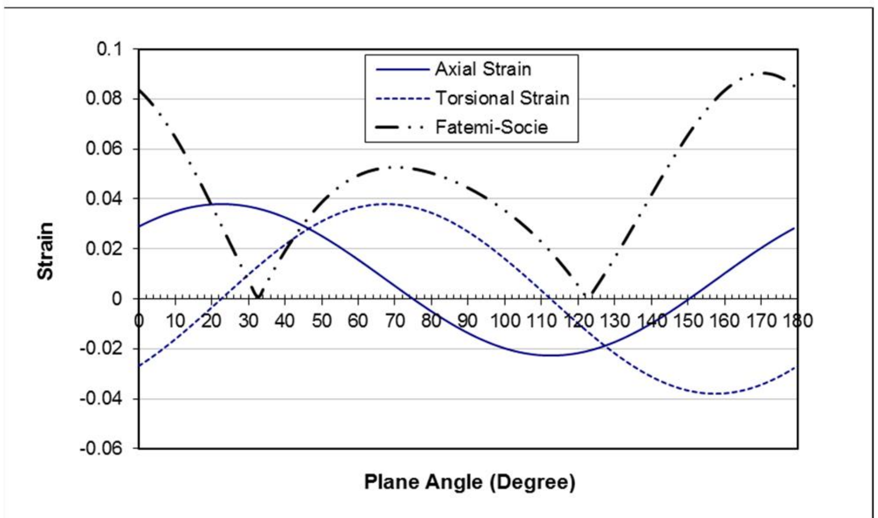
Principal strain	Principal strain	Orientation
0.0283	-0.017	24°
0.028290248	-0.01699995	
Maximum Shear Strain		Orientation
0.036599556	-0.03659508	168°
0.036595081		
Principal stress	Principal stress	Principal stress
53.42355512		-0.104
53.41989342		-0.10031666
Maximum Shear Stress		Orientation
26.76377756		48°
26.76010504	-26.7601018	

S31
Eq. Strain = 4%
2Nf = 994
Temp Rise = 29
Freq = 0.5





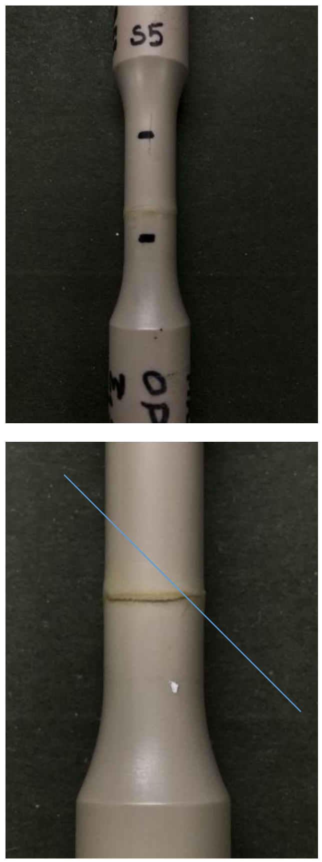




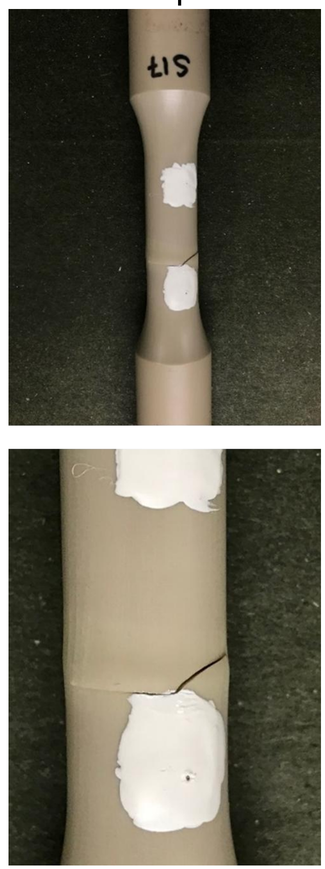
Principal strain	Principal strain	Orientation
0.0283	-0.017	24°
0.028290248	-0.01699995	
Maximum Shear Strain		Orientation
0.036599556	-0.03659508	168°
0.036595081		
Principal stress	Principal stress	Principal stress
53.42355512		-0.104
53.41989342		-0.10031666
Maximum Shear Stress		Orientation
26.76377756		48°
26.76010504	-26.7601018	

S10
Eq. Strain = 1.5%
2Nf = 255298
Temp Rise = 6
Freq = 4

S05
Eq. Strain = 2%
2Nf = 69910
Temp Rise = 54
Freq = 3

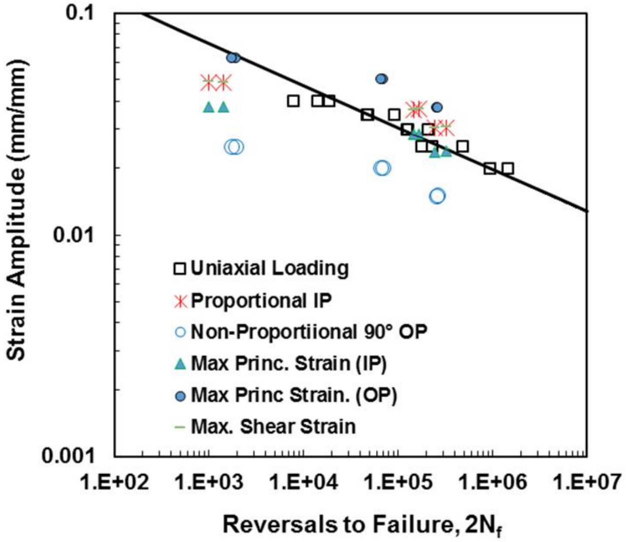


S17
Eq. Strain = 2%
2Nf = 66194
Temp Rise = 51
Freq = 3

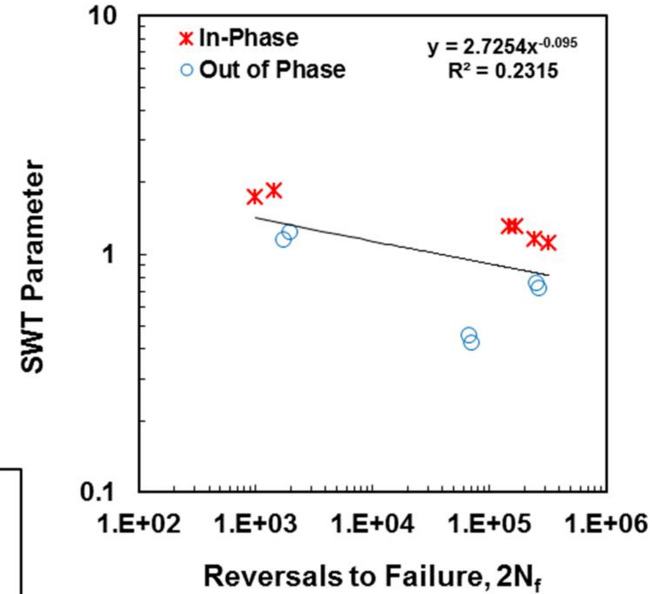


S26
Eq. Strain = 2.5%
2Nf = 1944
Temp Rise = 40
Freq = 1

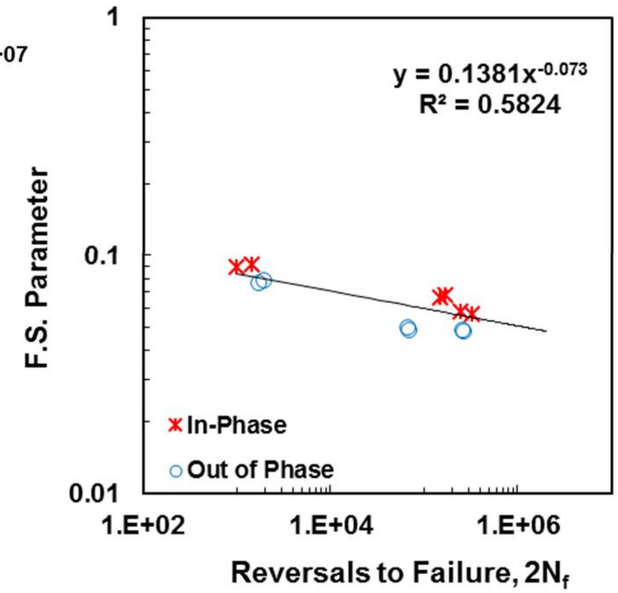
S25
Eq. Strain = 2.5%
2Nf = 1730
Temp Rise = 41
Freq = 1



0.1
0.01
0.001
Strain Amplitude (mm/mm)
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
Reversals to Failure, 2Nf
Uniaxial Loading
Proportional IP
Non-Proportiional 90° OP
Max Princ. Strain (IP)
Max Princ Strain. (OP)
Max. Shear Strain

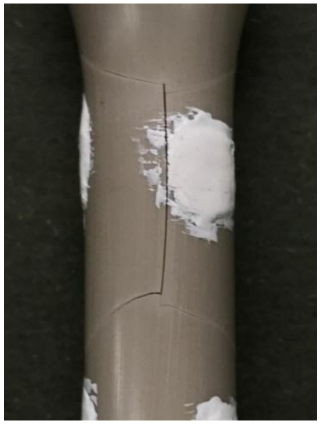


10
1
0.1
SWT Parameter
In-Phase
Out of Phase
y = 2.7254x-0.095
R² = 0.2315
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
Reversals to Failure, 2Nf



1
0.1
0.01
F.S. Parameter
y = 0.1381x-0.073
R² = 0.5824
In-Phase
Out of Phase
1.E+02
1.E+04
1.E+06
Reversals to Failure, 2Nf

S33
Eq. Strain = 4%
2Nf = 739900
Temp Rise = 1
Freq = 2.75



Outline

- *Motivation*
- *Objective*
- *Experimental Setup*
  - *Specimen fabrication*
  - *Test methods/Thermal Simulations*
- *Experimental Results*
  - *Monotonic tensile behavior*
  - *Uniaxial fatigue behavior*
  - *Thermal simulation results*
  - *X-ray CT results*
  - *Fractography analysis*
- *Conclusions*
- *Ongoing Work*