CONFLUENT

Effect of Tensile and Compressive Pre-Strains on Superelastic Diamond Surrogates

Karthikeyan Senthilnathan

Ali Shamimi

Ich Ong

Lot Vien

Craig Bonsignore

Tom Duerig

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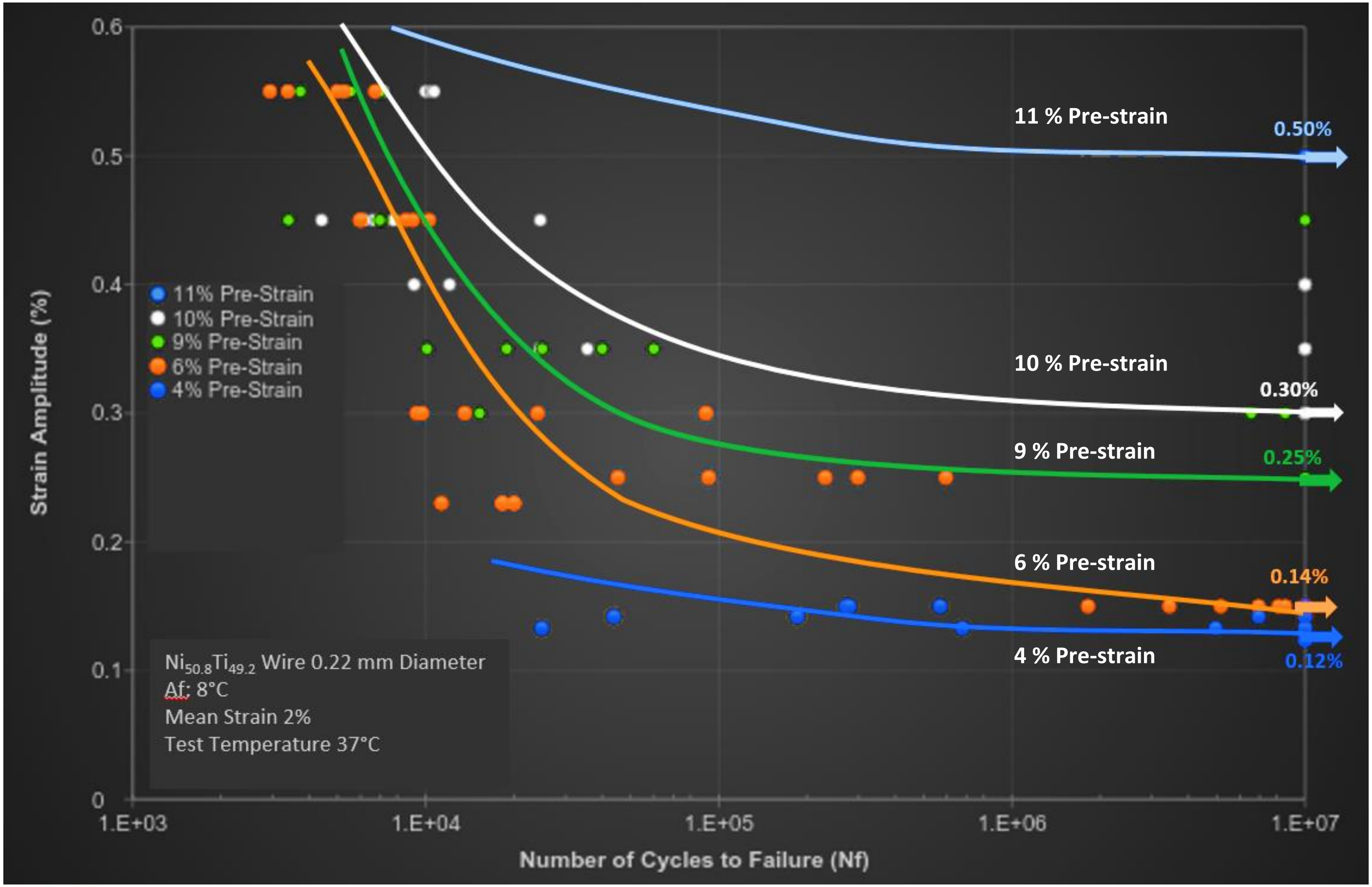
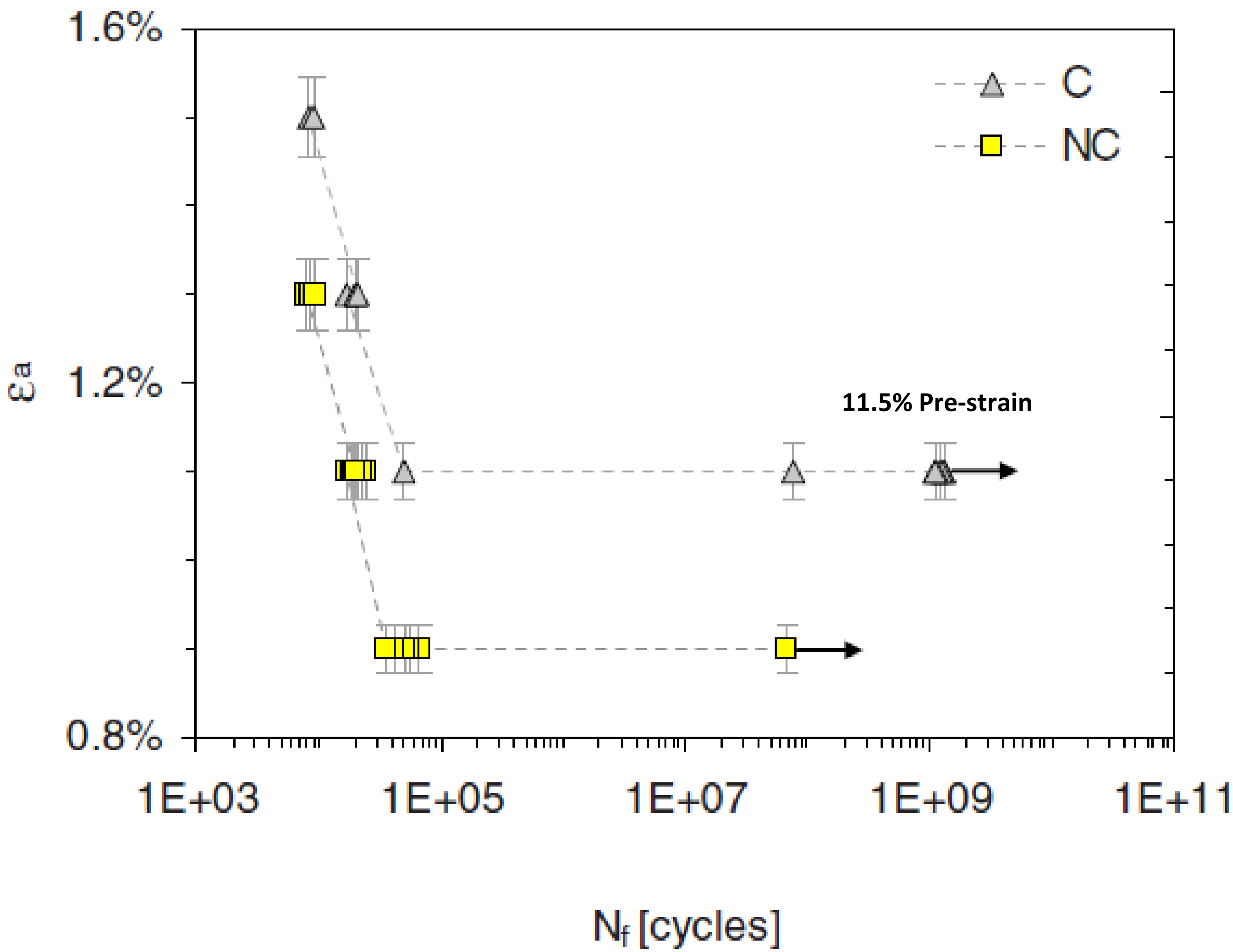
SHAPE MEMORY AND SUPERELASTIC TECHNOLOGIES CONFERENCE AND EXPOSITION

Tension – Tension (0<R<1 ; $\varepsilon_M \neq 0$)



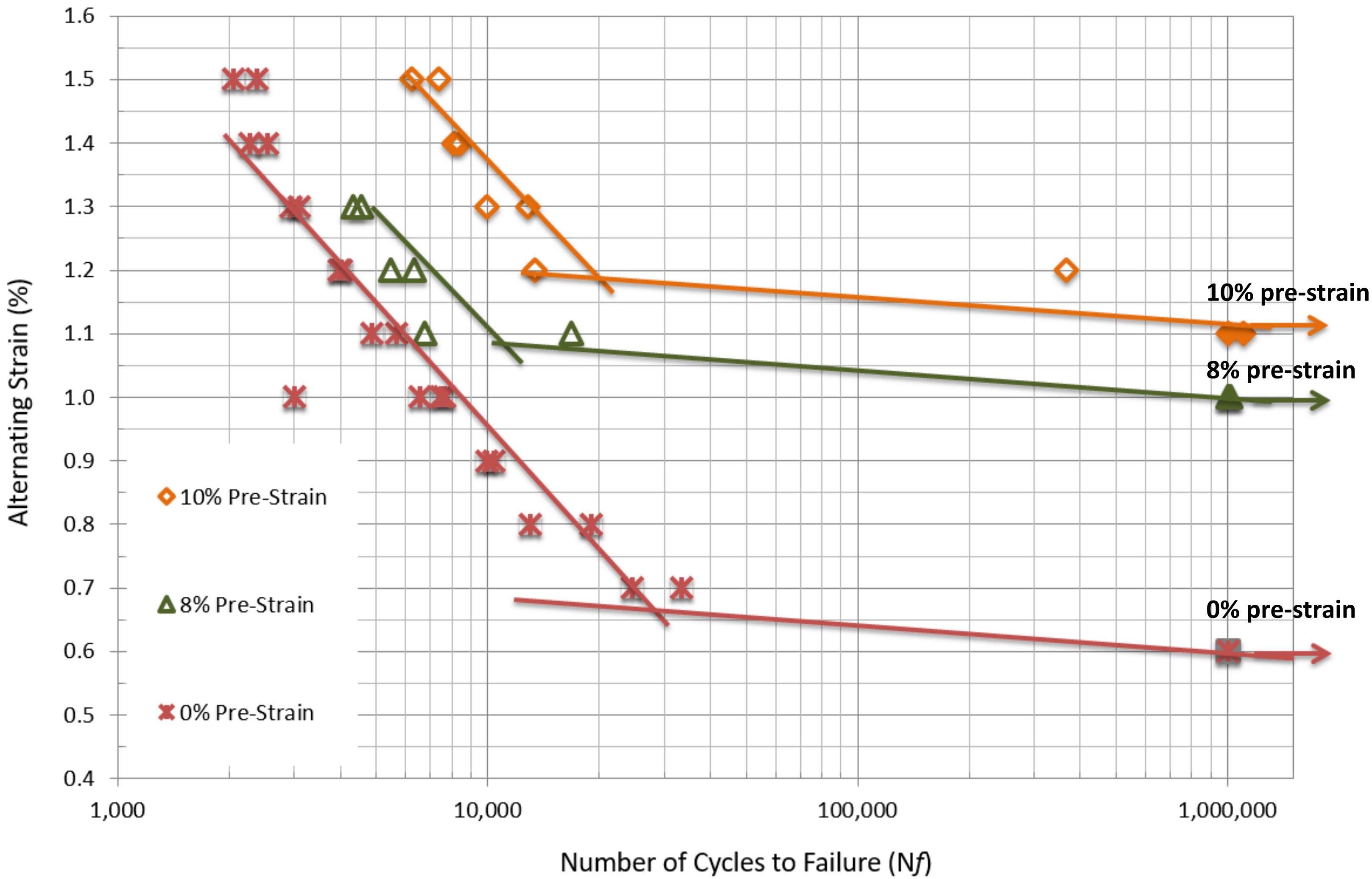
Shamimi et al., SMST 2015

Rotary Bend Fatigue (R= -1 ; $\varepsilon_M = 0$)



Schaffer, J.E., "Mechanical Conditioning of Superelastic Nitinol Wire for Improved Fatigue Resistance", Journal of ASTM International, Vol. 7, No. 5

Rotary Bend Fatigue (R= -1 ; $\varepsilon_M = 0$)



Shamimi et al., Unpublished Data

Objective

Determine whether residual stresses are the primary mechanism for durability improvement in Nitinol

Origins of Residual Stresses

- Localized yielding from a surface notch or from a multi-axial stress state (Bending, Torsion etc.)
- Microstructural inhomgeneities (Presence of inclusions)
- Grain orientation in a poly-crystalline material

Outline

Computational Modeling of Residual Stresses under

- Bending load (diamond specimens)
- Presence of inclusions (tension specimens)

Test Results of Pre-strain Diamond Study

- Test Methodology
- Baseline without pre-strain on diamonds
- Effect of tensile pre-strain on fatigue life
- Effect of compressive pre-strain on fatigue life

Role of superelasticity in residual stresses

Modeling Residual Stresses

Diamond Specimens

Tension Specimens

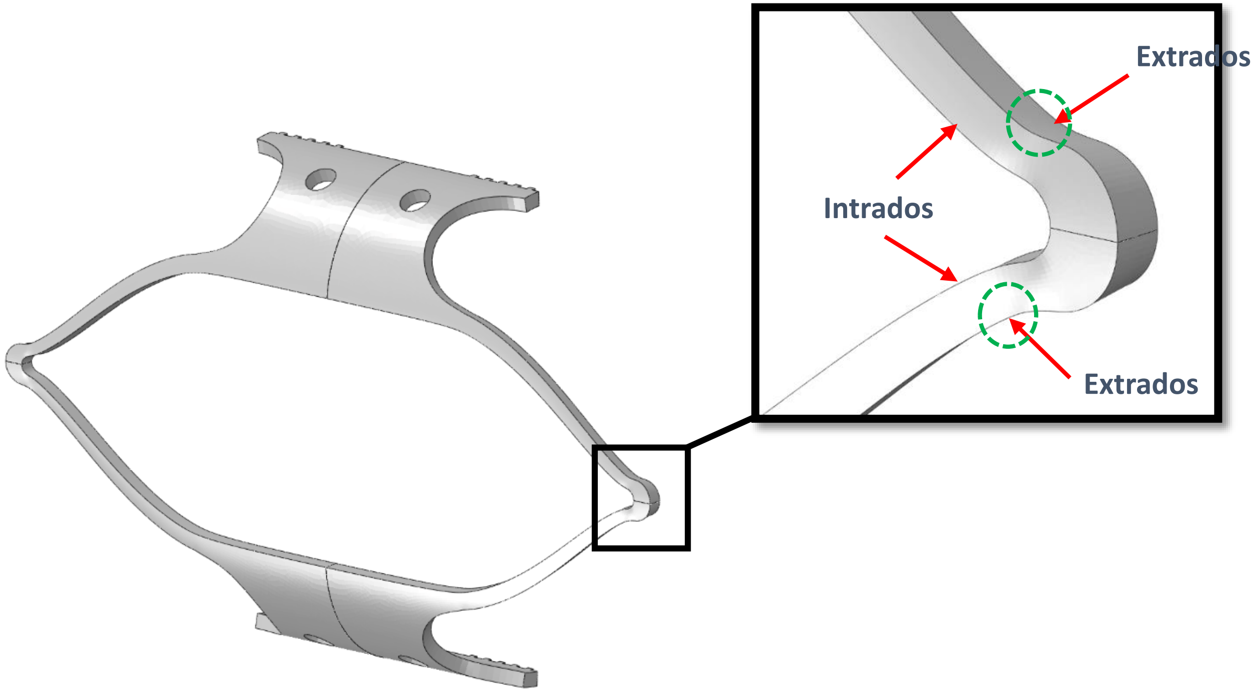
Pre-strain Diamond Test Results

Role of Superelasticity in Residual Stresses

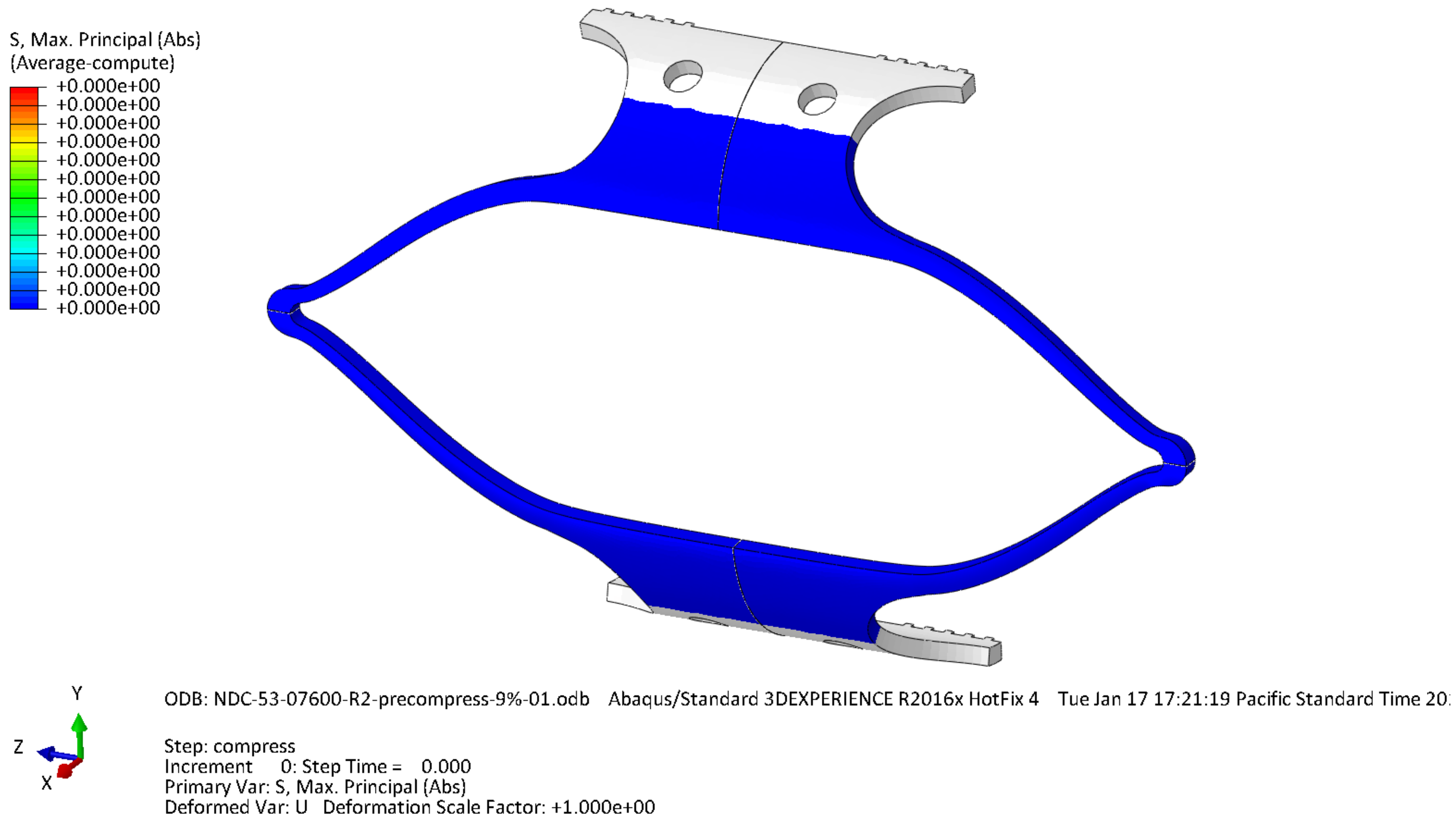
Pre-Strain Diamond Geometry

Diamonds were designed to achieve high pre-strains.

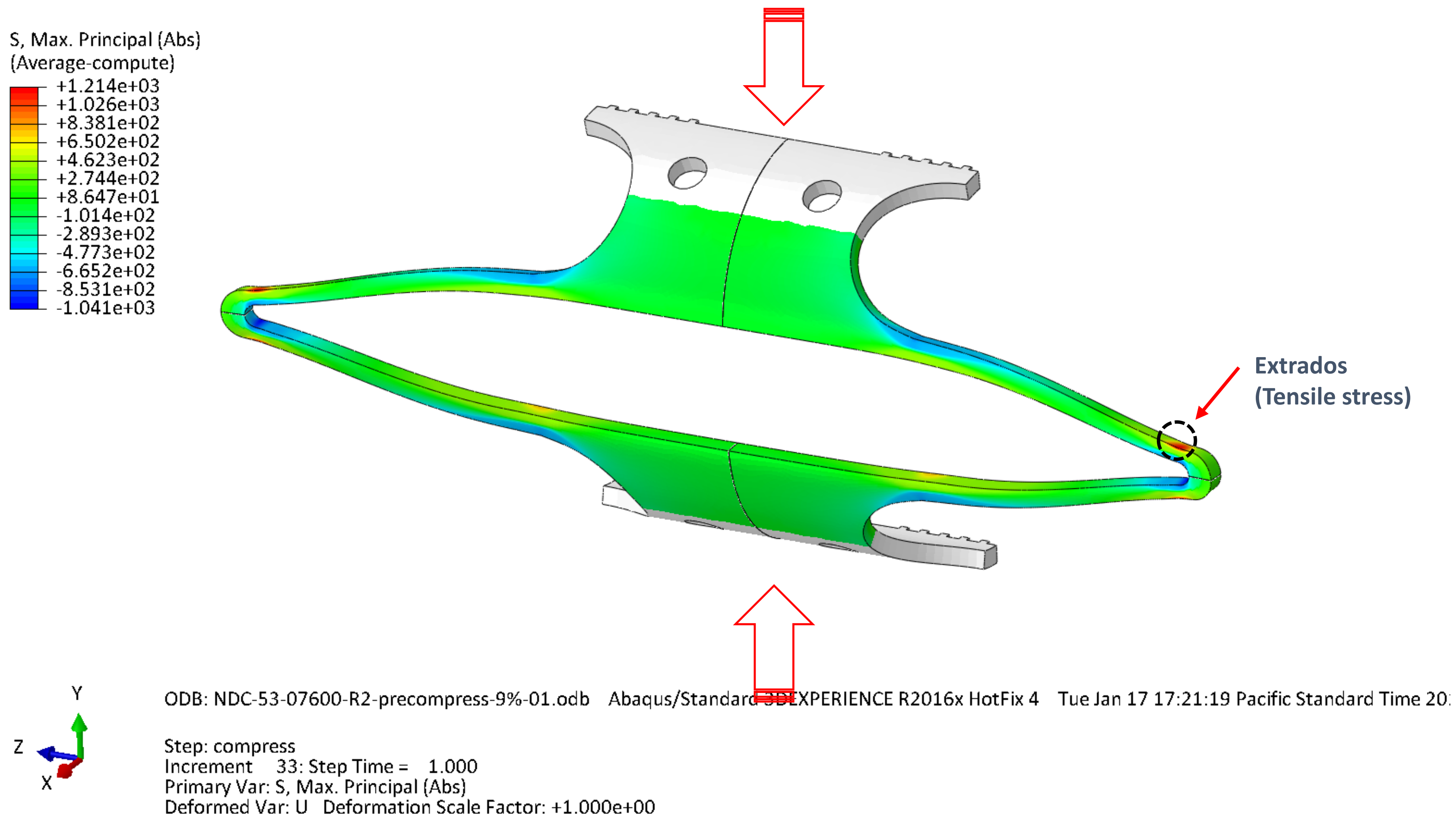
Only the extrados location of the diamond was focused to achieve the desired stress/strain state.



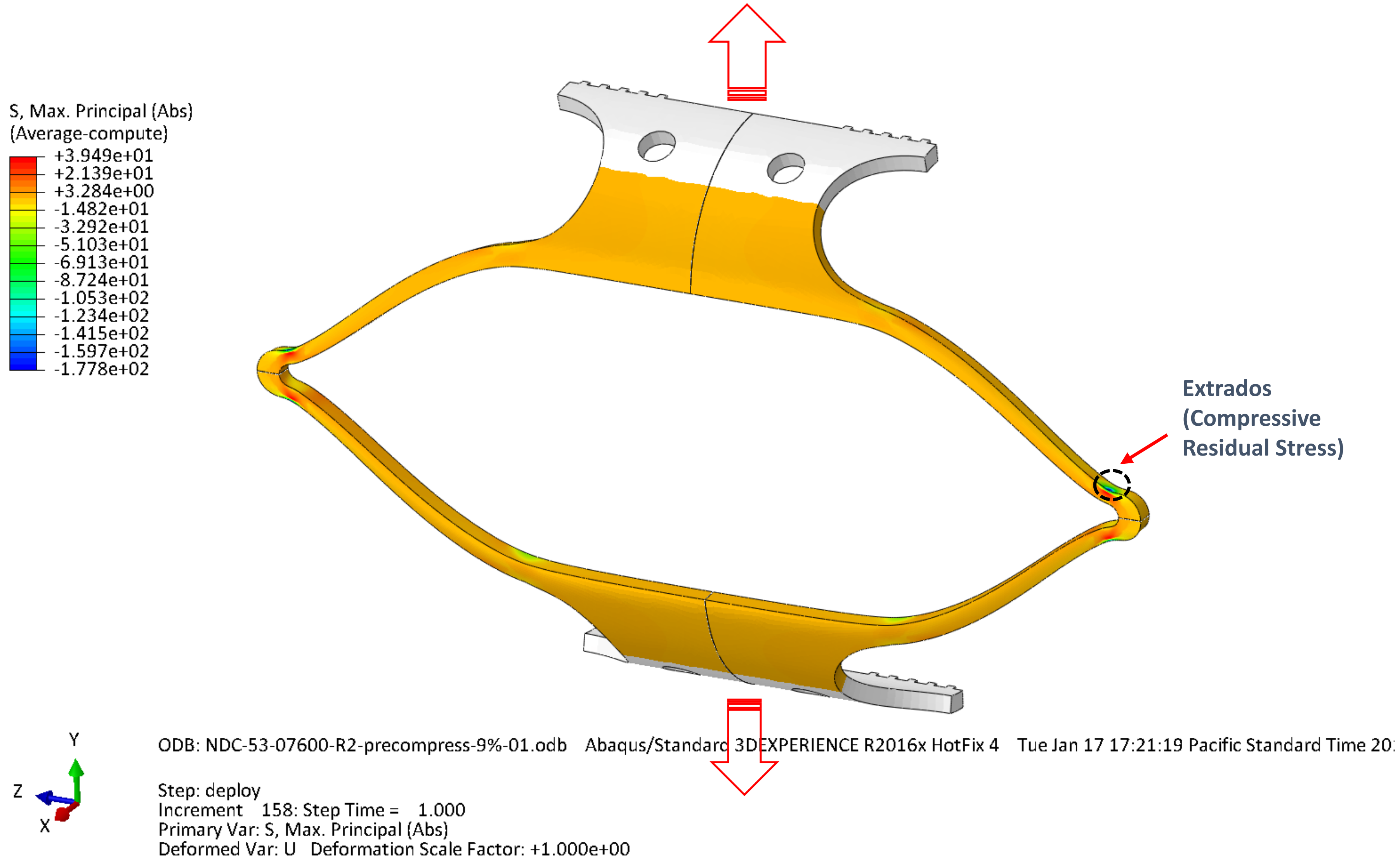
Stress Free Diamond



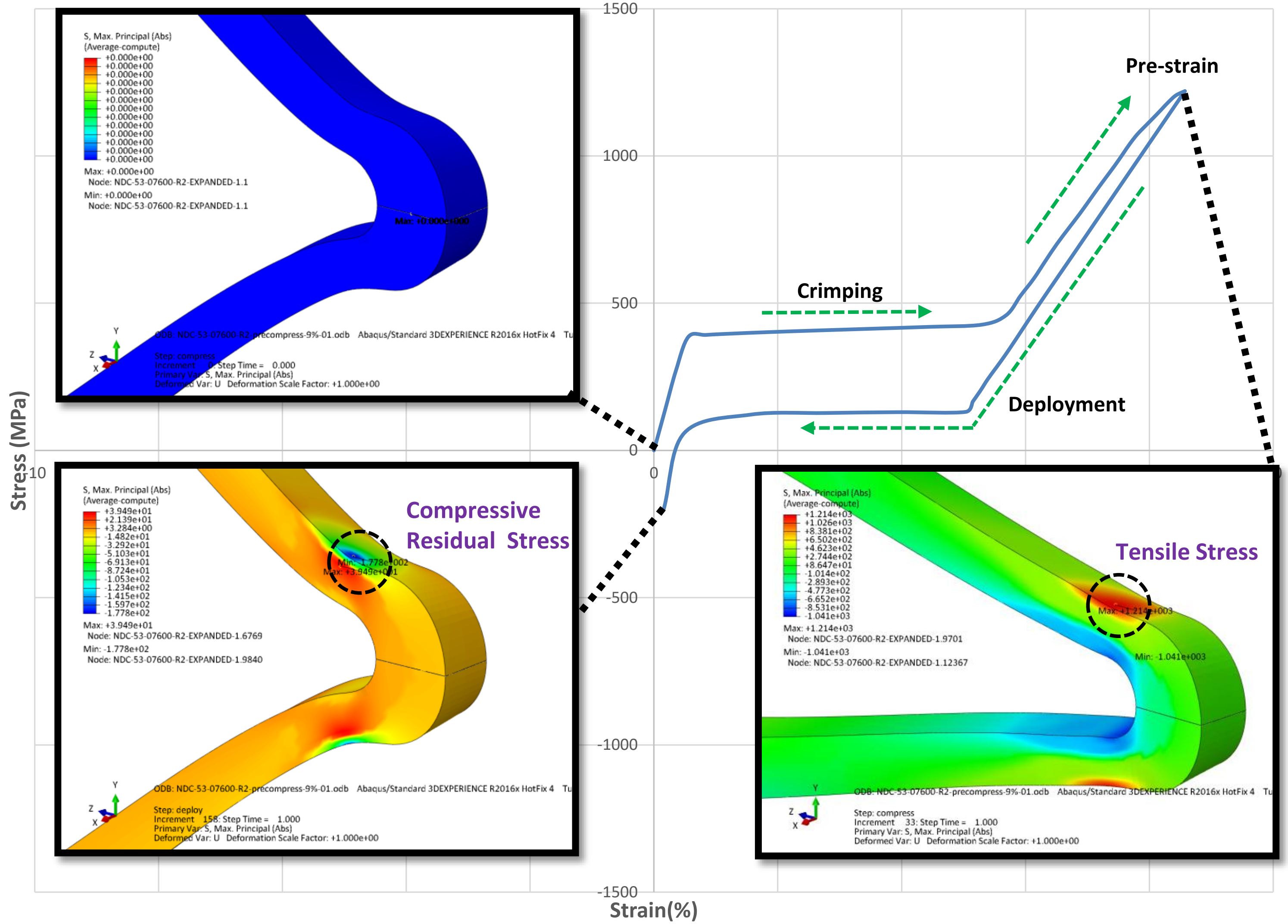
Tensile Pre-Stress State



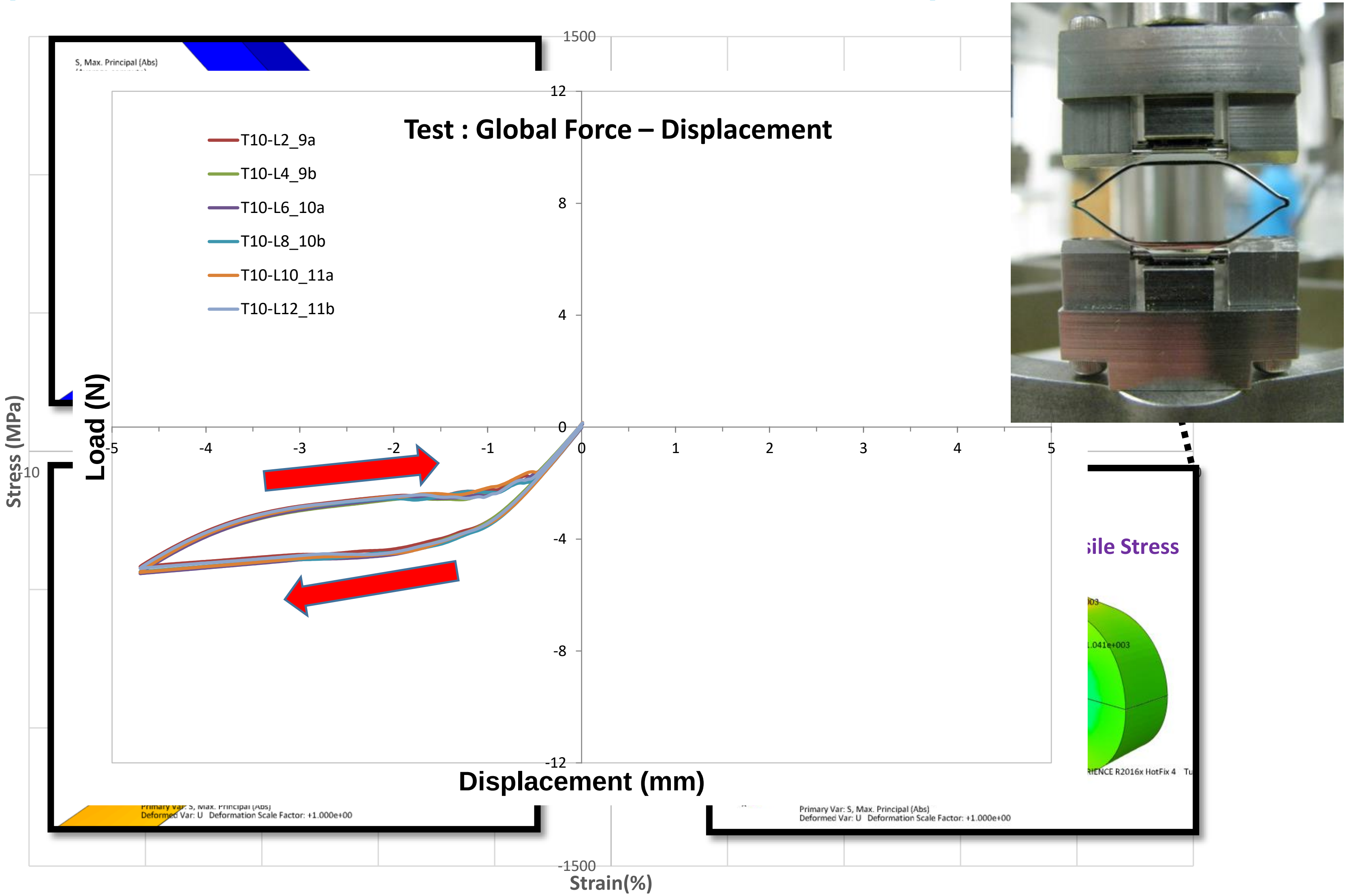
Compressive Residual Stress State



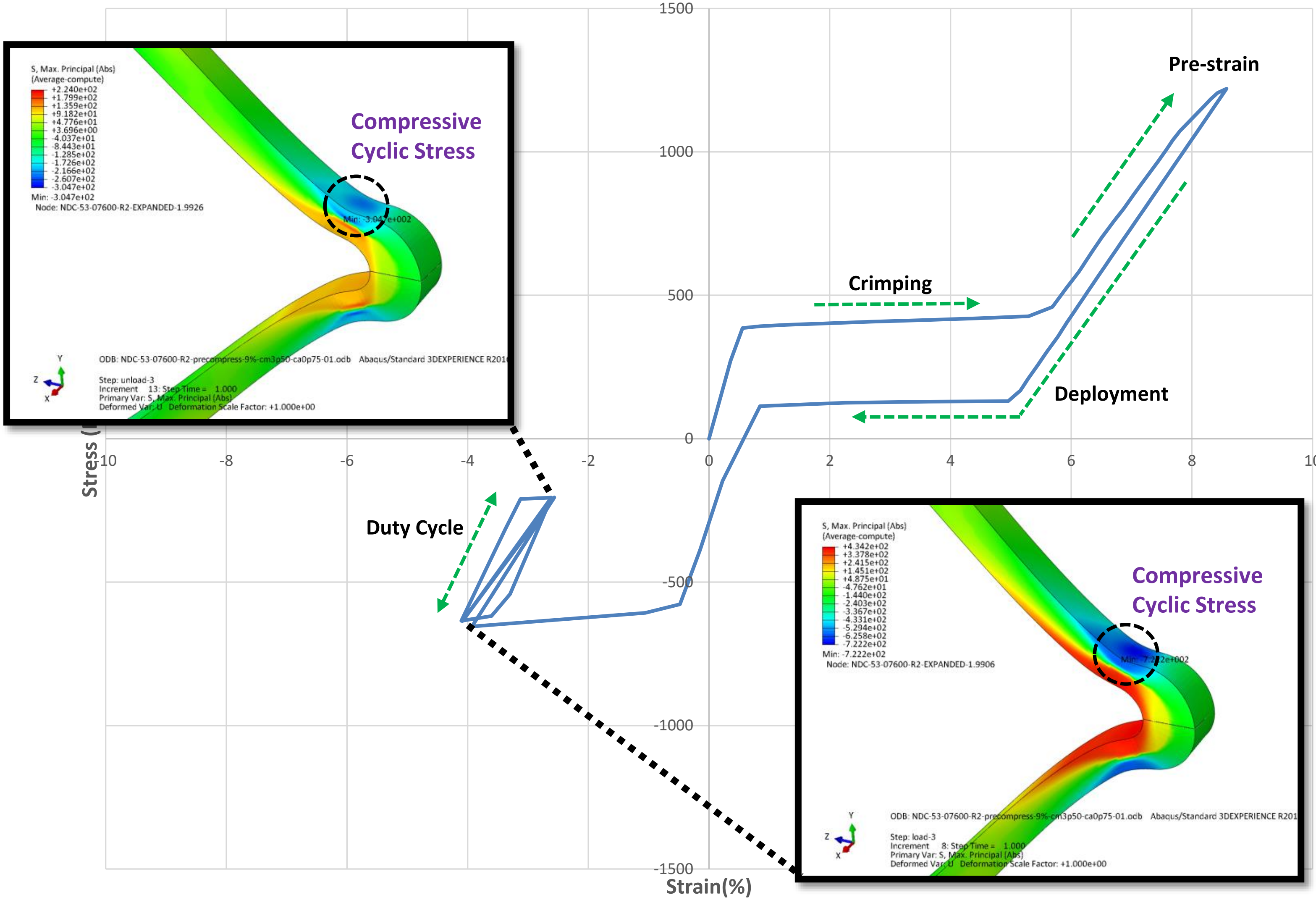
Compressive Residual Stress – FEA Sequence



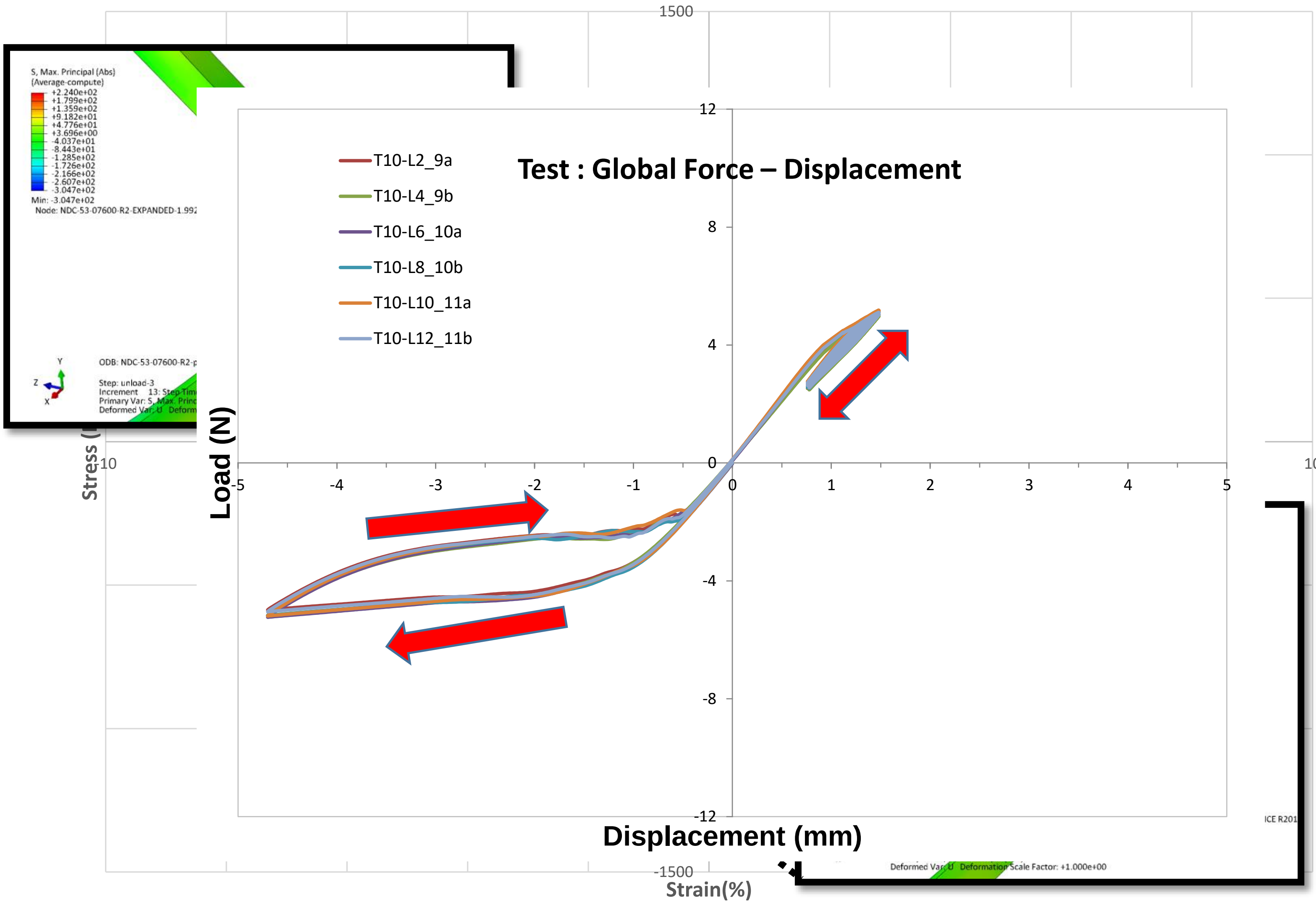
Compressive Residual Stress – Test Sequence



Compressive Cyclic Stress – FEA Sequence



Compressive Cyclic Stress – Test Sequence



Modeling Residual Stresses

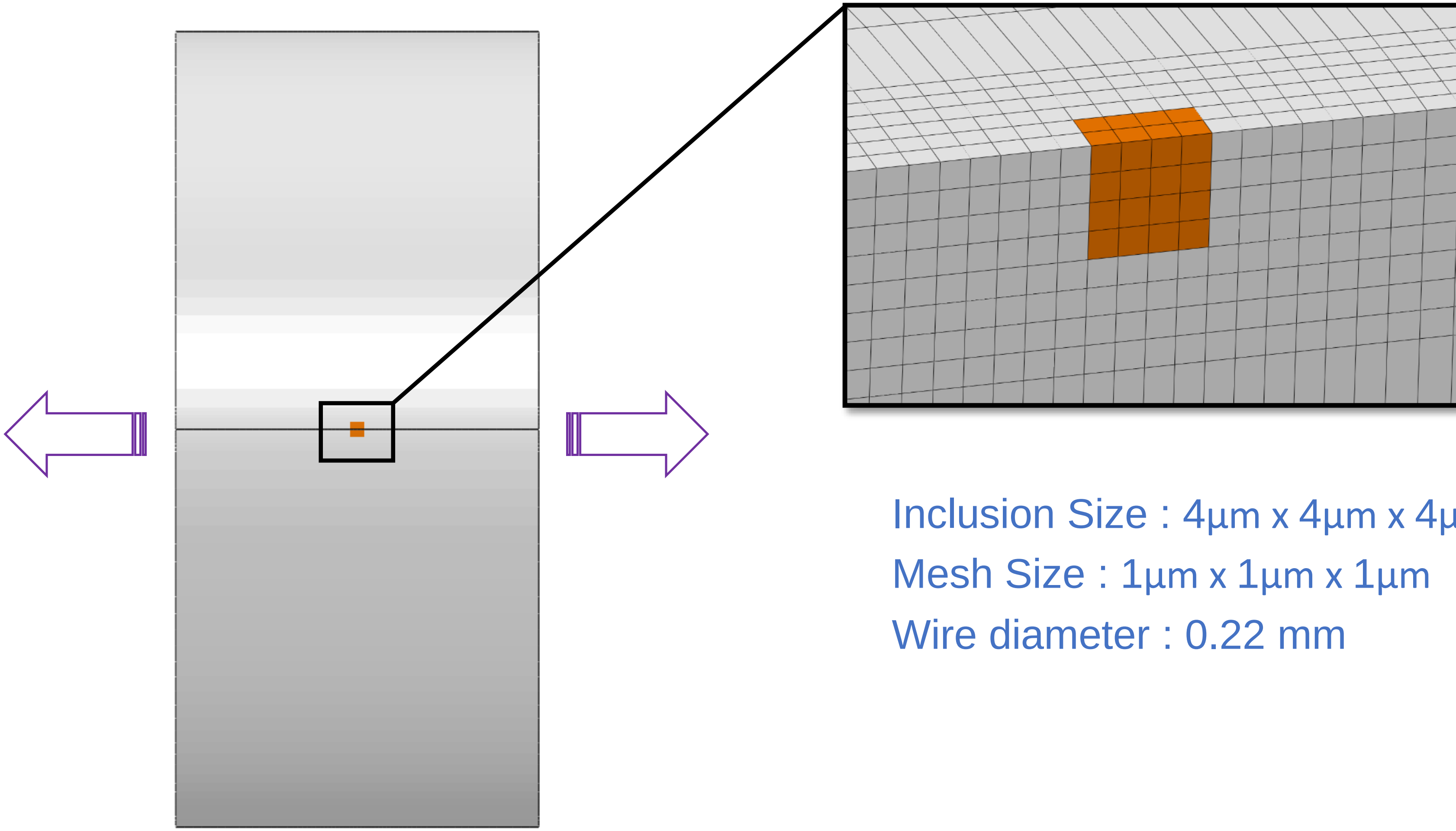
Diamond Specimens

Tension Specimens

Pre-strain Diamond Test Results

Role of Superelasticity in Residual Stresses

Tension Inclusion FEA

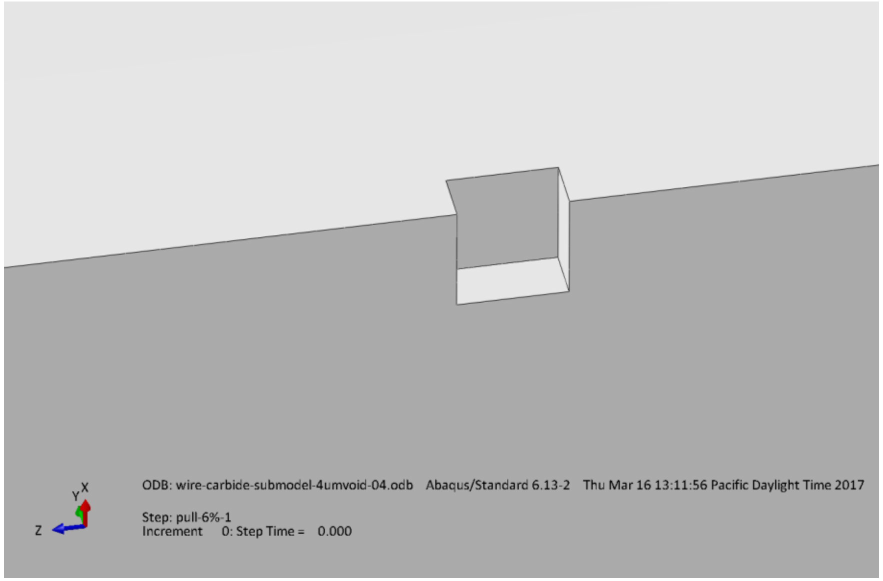


Inclusion Size : 4µm x 4µm x 4µm

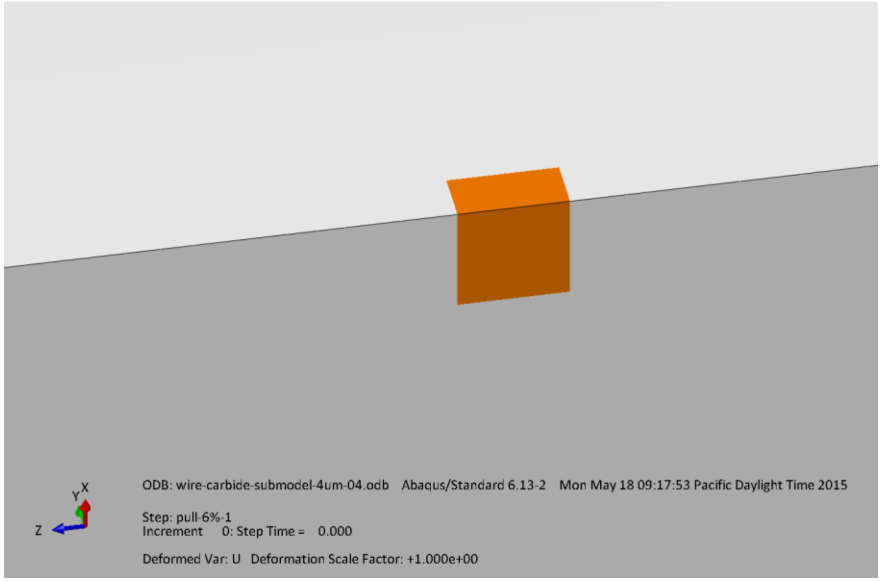
Mesh Size : 1µm x 1µm x 1µm

Wire diameter : 0.22 mm

Starting State

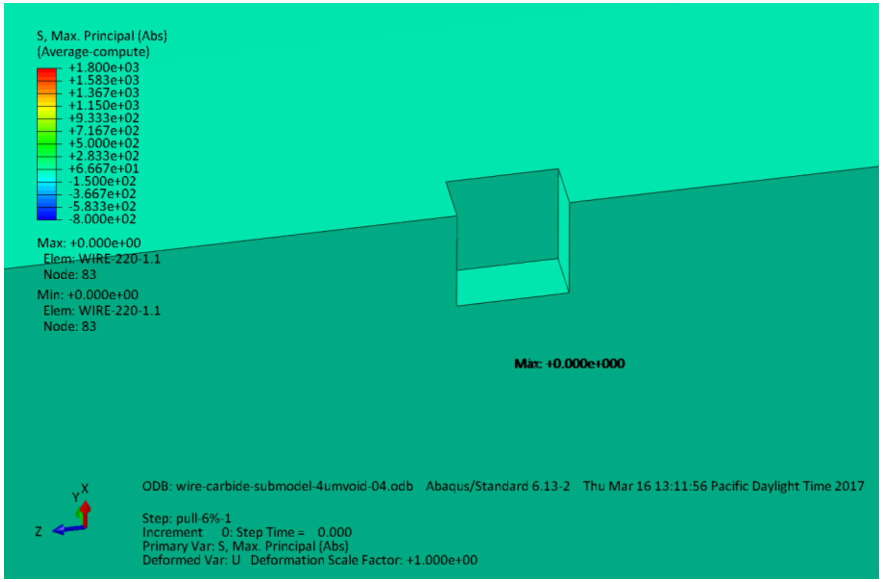


Void

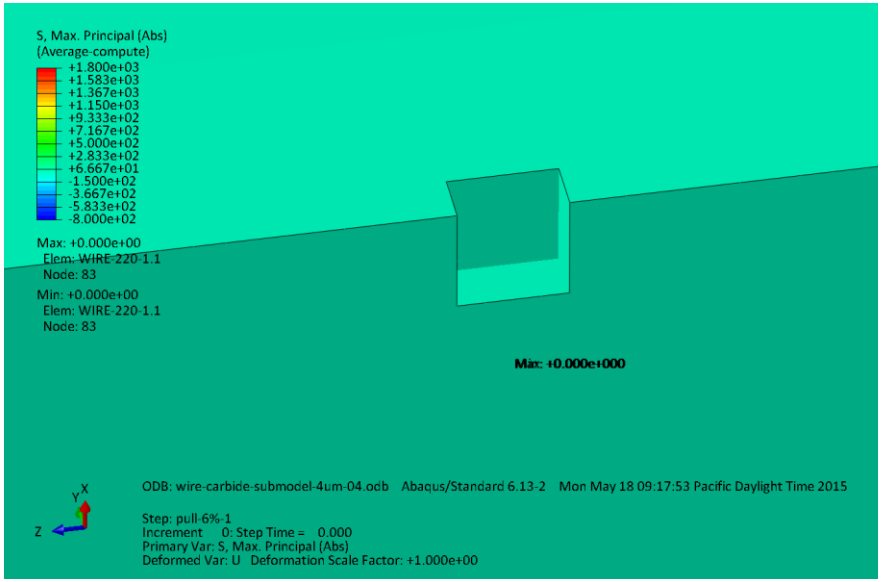


Inclusion Attached

Stress State – Initial

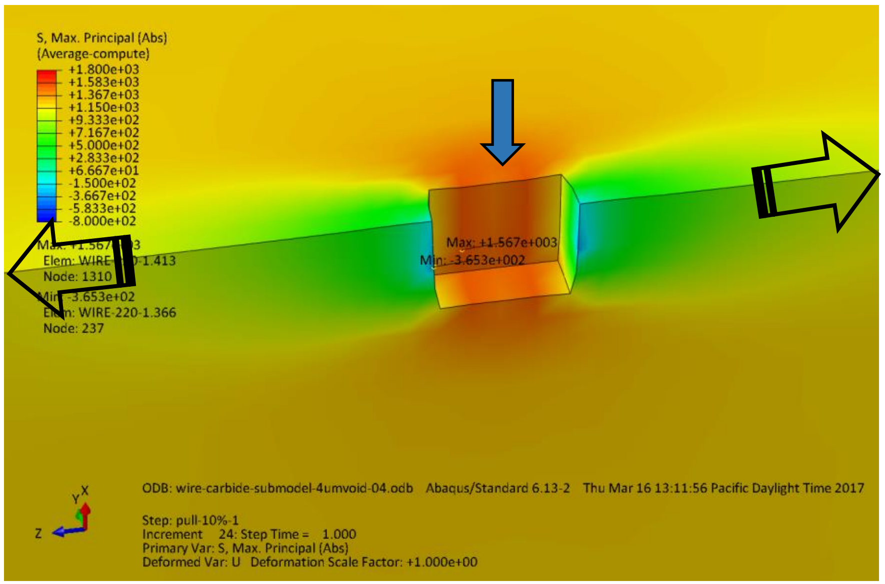


Void
0 MPa



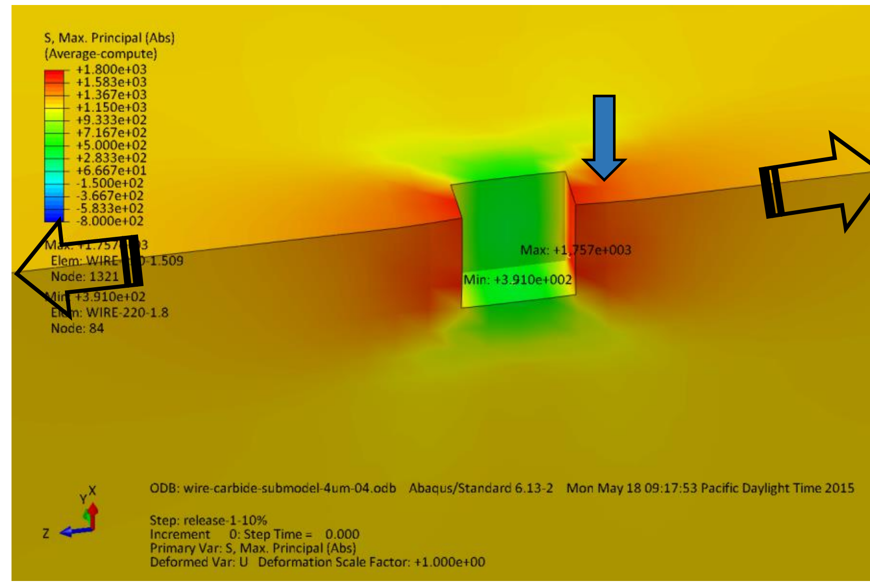
Inclusion Attached
0 MPa

Stress State – Pull 10% Global Strain



Void

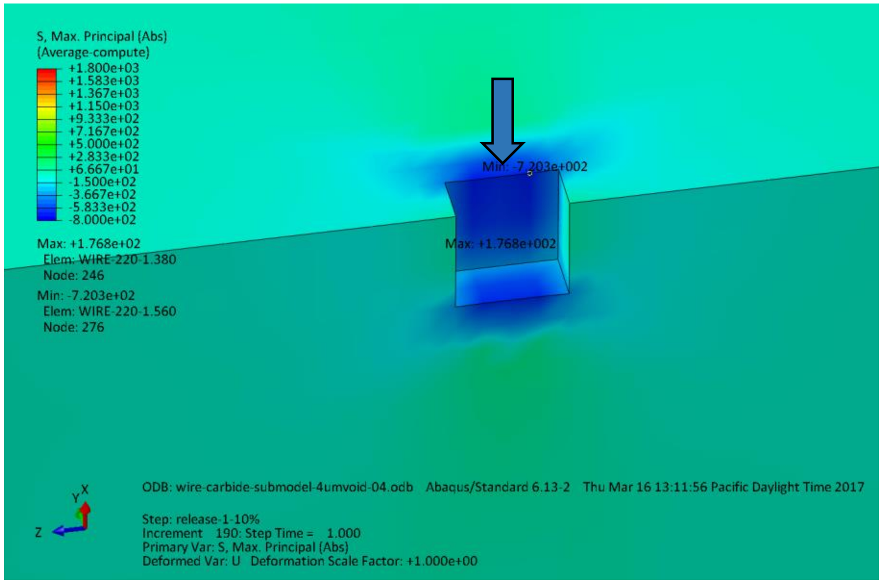
1567 MPa; SIF= 1.27



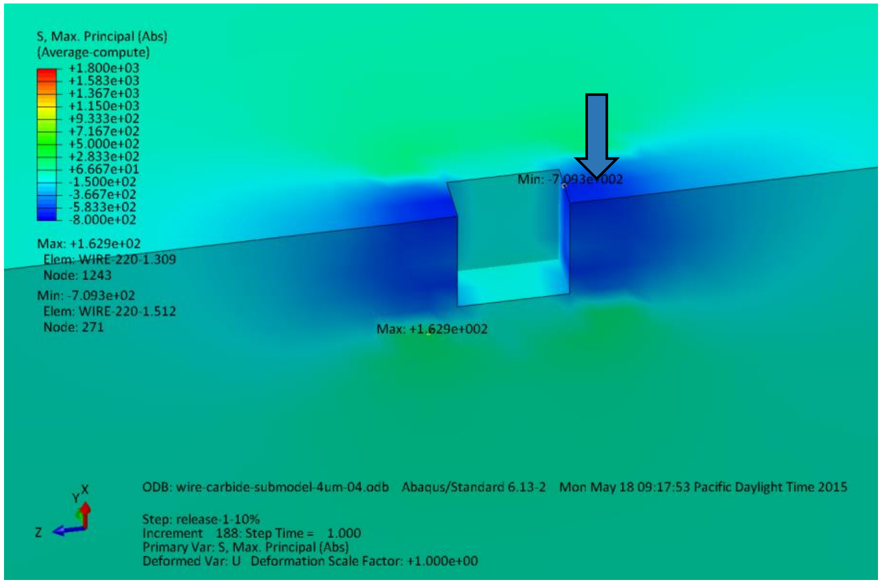
Inclusion Attached

1757 MPa ; SIF= 1.41

Stress State – Released

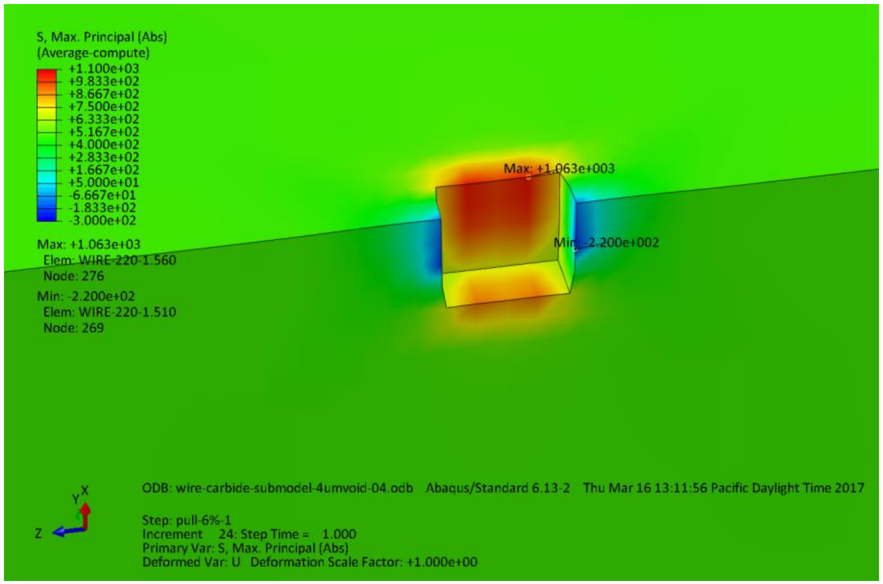


Void
-720 MPa

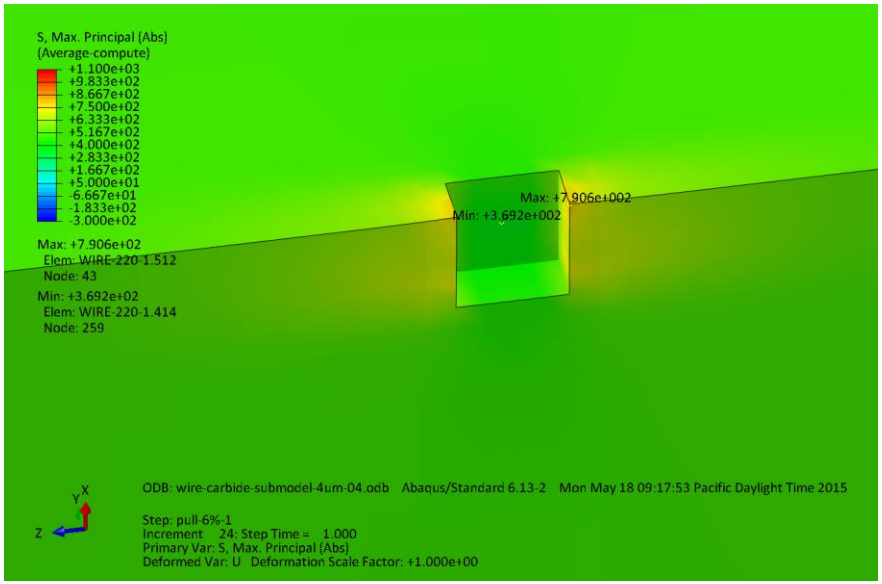


Inclusion Attached
-710 MPa

Effect of Residual Stresses on Upper Plateau Stress – Without Pre-straining (6% global strain)

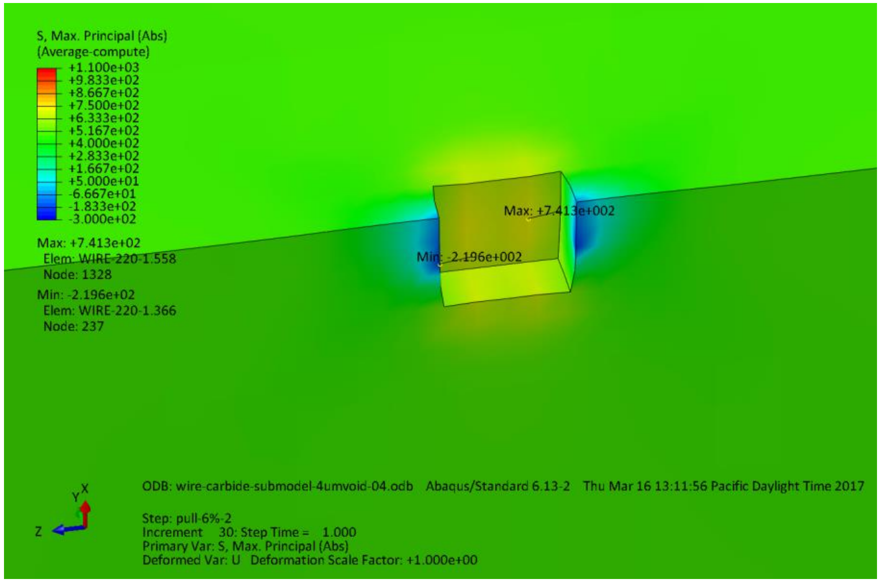


Void
1063 MPa

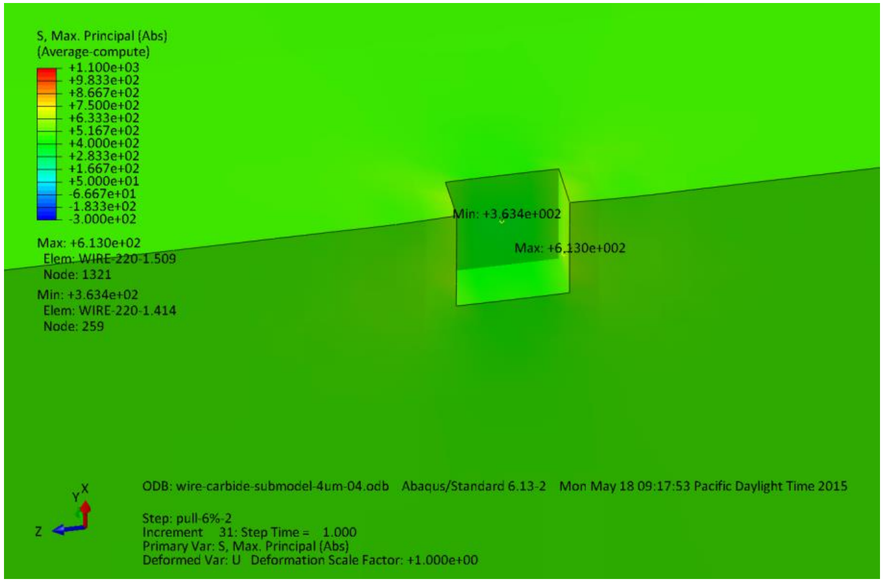


Inclusion Attached
790 MPa

Effect of Residual Stresses on Upper Plateau Stress – With 10% Pre-straining (6% global strain)



Void
741 MPa
30% drop



Inclusion Attached
613 MPa
22% drop

Modeling Residual Stresses

Pre-strain Diamond Test Results

- Test Methodology
- Baseline
- Tensile Pre-strain
- Compressive Pre-strain

Role of Superelasticity in Residual Stresses

Extrados Stress States – Naming Convention

Pre-Stress/Strain – PS

Residual Stress/Strain – RS (Depends on Pre-Stress history)

Cyclic Stress/Strain – CS

Combination	Pre-Stress State (PS)	Residual Stress State (RS)	Cyclic Stress State (CS)
A	(+)	(-)	(-)
B	(-)	(+)	(-)
C	(+)	(-)	(+)
D	(-)	(+)	(+)

(+) Tensile
(-) Compressive

Inverse Sign

Hypotheses

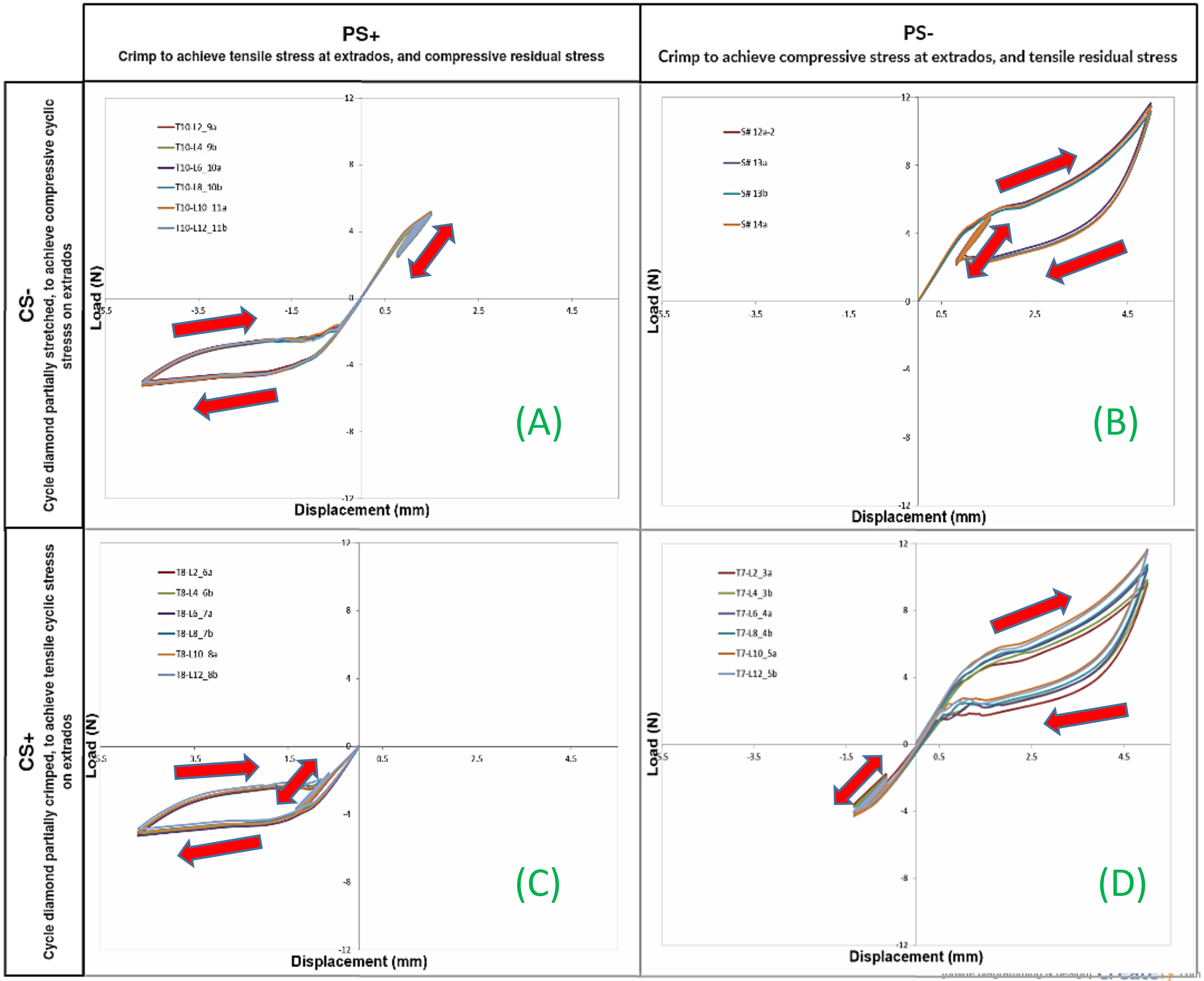
Fatigue life improves when pre-stress and cyclic stress are of same polarity.

Combination	Pre-Stress State (PS)	Residual Stress State (RS)	Cyclic Stress State (CS)
A	(+)	(-)	(-)
B	(-)	(+)	(-)
C	(+)	(-)	(+)
D	(-)	(+)	(+)

Inverse Sign

(+) Tensile
(-) Compressive

Global Force Displacement – Test



Pre-Stress Diamond Test Conditions

Material: SE508-ELI

Sample size: 6 Diamonds (or 12 ‘V’ s at each condition)

Test Temperature: 37°C

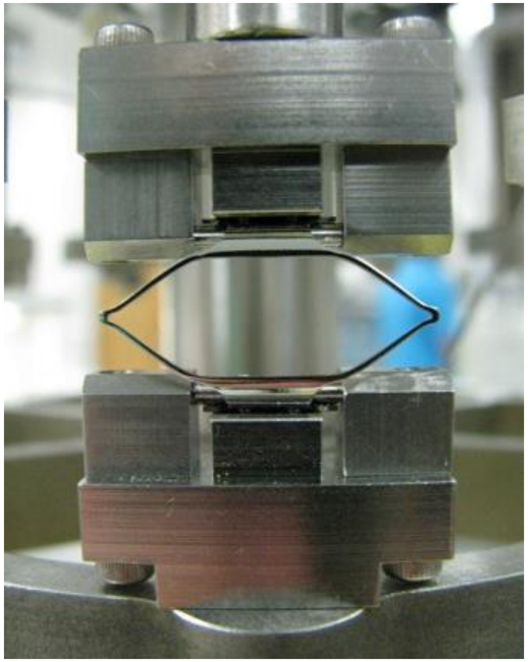
Pre-strain (Tensile or compressive) : 9%

Mean strain: 3.50%

Starting strain amplitude: 0.75%

Run out: 1 million cycles ;

Increase cyclic displacements until specimens fracture



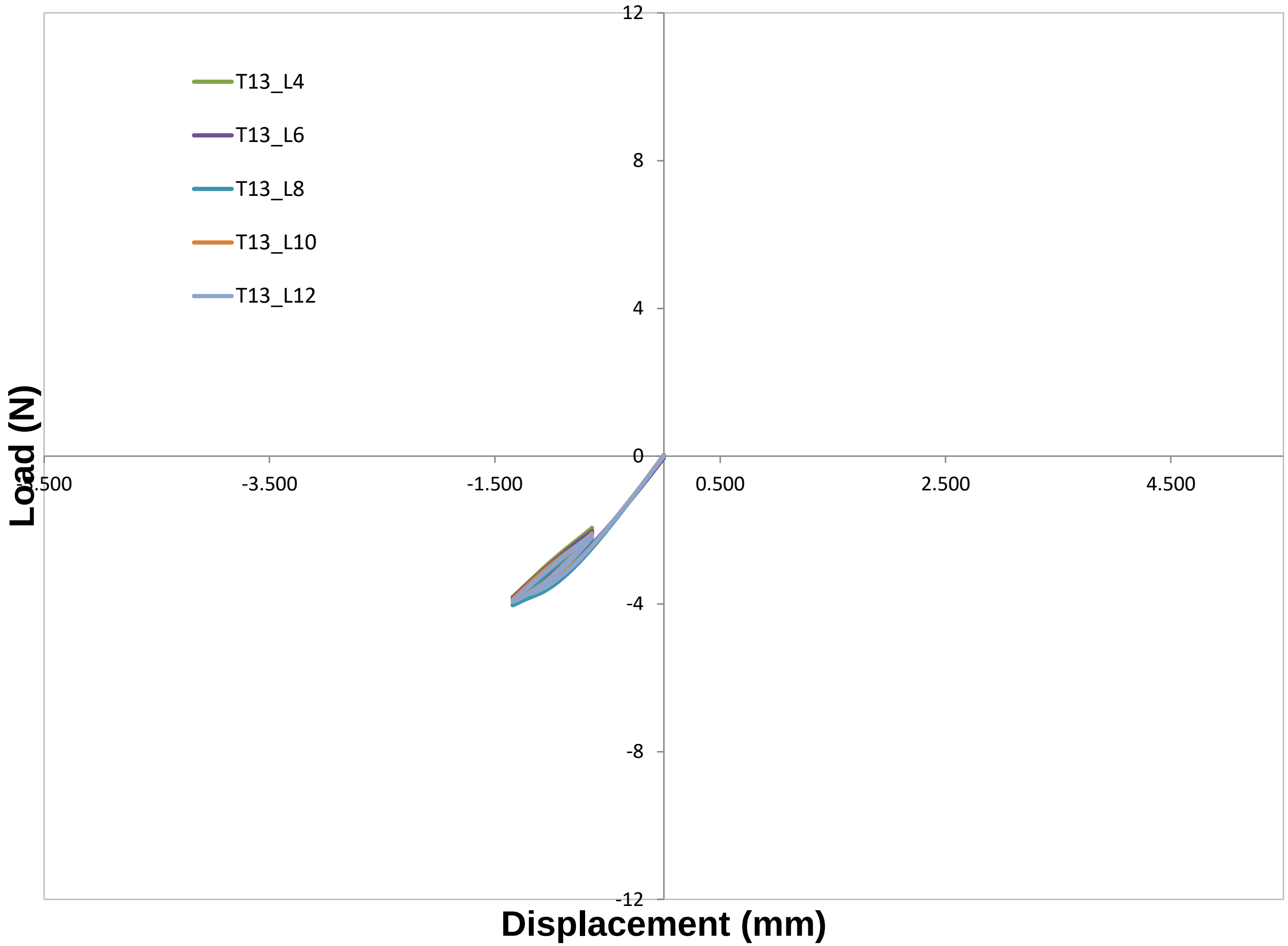
Modeling Residual Stresses

Pre-strain Diamond Test Results

- Test Methodology
- **Baseline**
- Tensile Pre-strain
- Compressive Pre-strain

Role of Superelasticity in Residual Stresses

Baseline Test Force Displacement



Baseline Test Results

Mean strain: 3.50%

Run out: 1 million cycles

Sample size: 12 at each condition

Strain Amplitude (%)	Baseline (PS0, CS+)	Combination A (PS+, RS-, CS-)	Combination B (PS-, RS+, CS-)	Combination C (PS+, RS-, CS+)	Combination D (PS-, RS+, CS+)
0.75	Run Out				
1.30	Run Out				
1.88	Run Out				
2.24	Fracture (2)				
2.76	Fracture (5)				
2.90	Fracture (3)				
3.03					
3.16					
3.50					

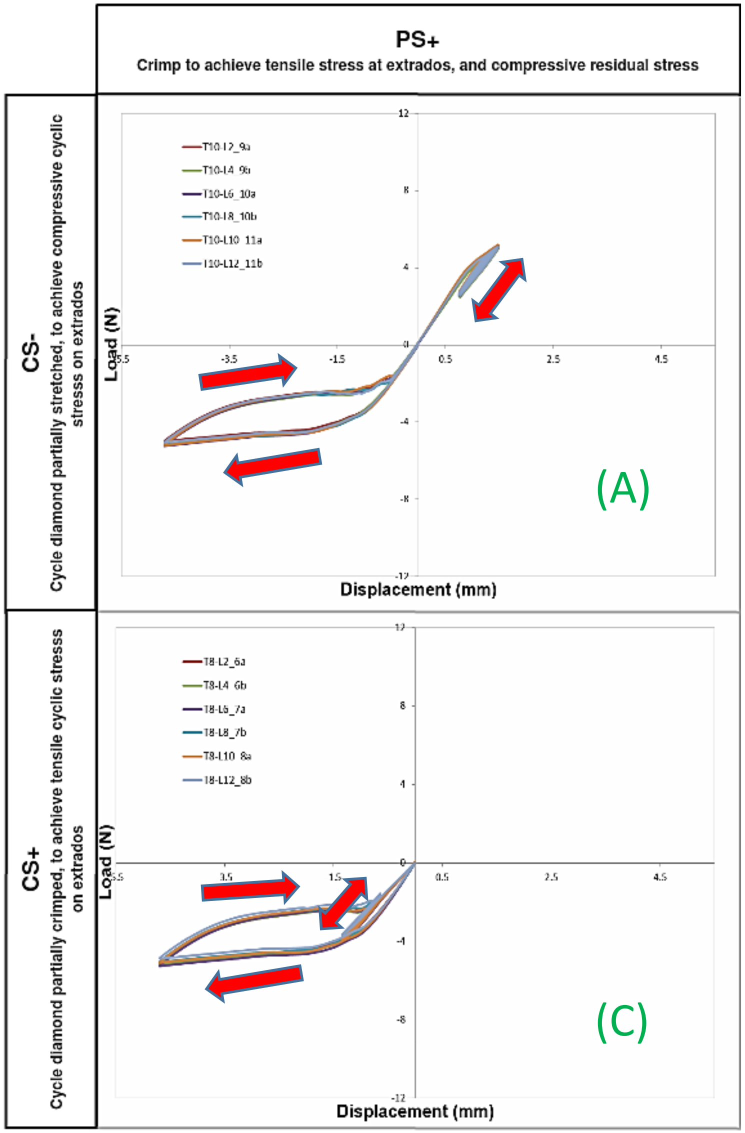
Modeling Residual Stresses

Pre-strain Diamond Test Results

- Test Methodology
- Baseline
- Tensile Pre-strain
- Compressive Pre-strain

Role of Superelasticity in Residual Stresses

Global Force Displacement – Test



Tensile Pre-Strain Results

Pre-strain: (+) 9.00%

Mean strain: 3.50%

Run out: 1 million cycles ; Sample size: 12 at each condition

Strain Amplitude (%)	Baseline (PS0, CS+)	Combination A (PS+, RS-, CS-)	Combination B (PS-, RS+, CS-)	Combination C (PS+, RS-, CS+)	Combination D (PS-, RS+, CS+)
0.75	Run Out	Run Out		Run Out	
1.30	Run Out	Fracture (3)		Run Out	
1.88	Run Out	Fracture (4)		Run Out	
2.24	Fracture (2)	Fracture (1)		Run Out	
2.76	Fracture (5)			Fracture (1)	
2.90	Fracture (3)			Fracture (1)	
3.03				Fracture (1)	
3.16				Fracture (3)	
3.50				Fracture (2)	
		Fracture Initiation: Intrados		**Fracture Initiation: Extrados**	

Modeling Residual Stresses

Pre-strain Diamond Test Results

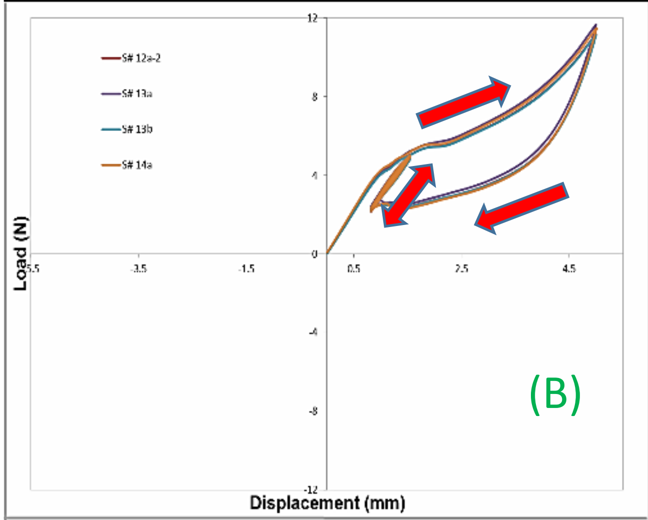
- Test Methodology
- Baseline
- Tensile Pre-strain
- Compressive Pre-strain

Role of Superelasticity in Residual Stresses

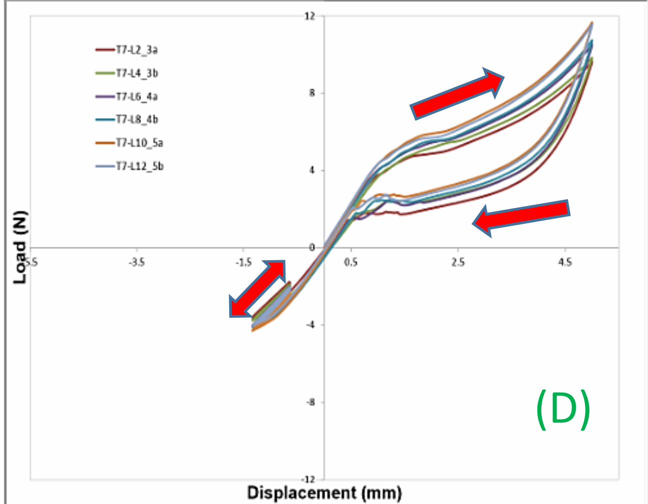
Global Force Displacement – Test

PS-
Crimp to achieve compressive stress at extrados, and tensile residual stress

CS-
Cycle diamond partially stretched, to achieve compressive cyclic stresss on extrados



CS+
Cycle diamond partially crimped, to achieve tensile cyclic stress on extrados



Compressive Pre-Strain Results

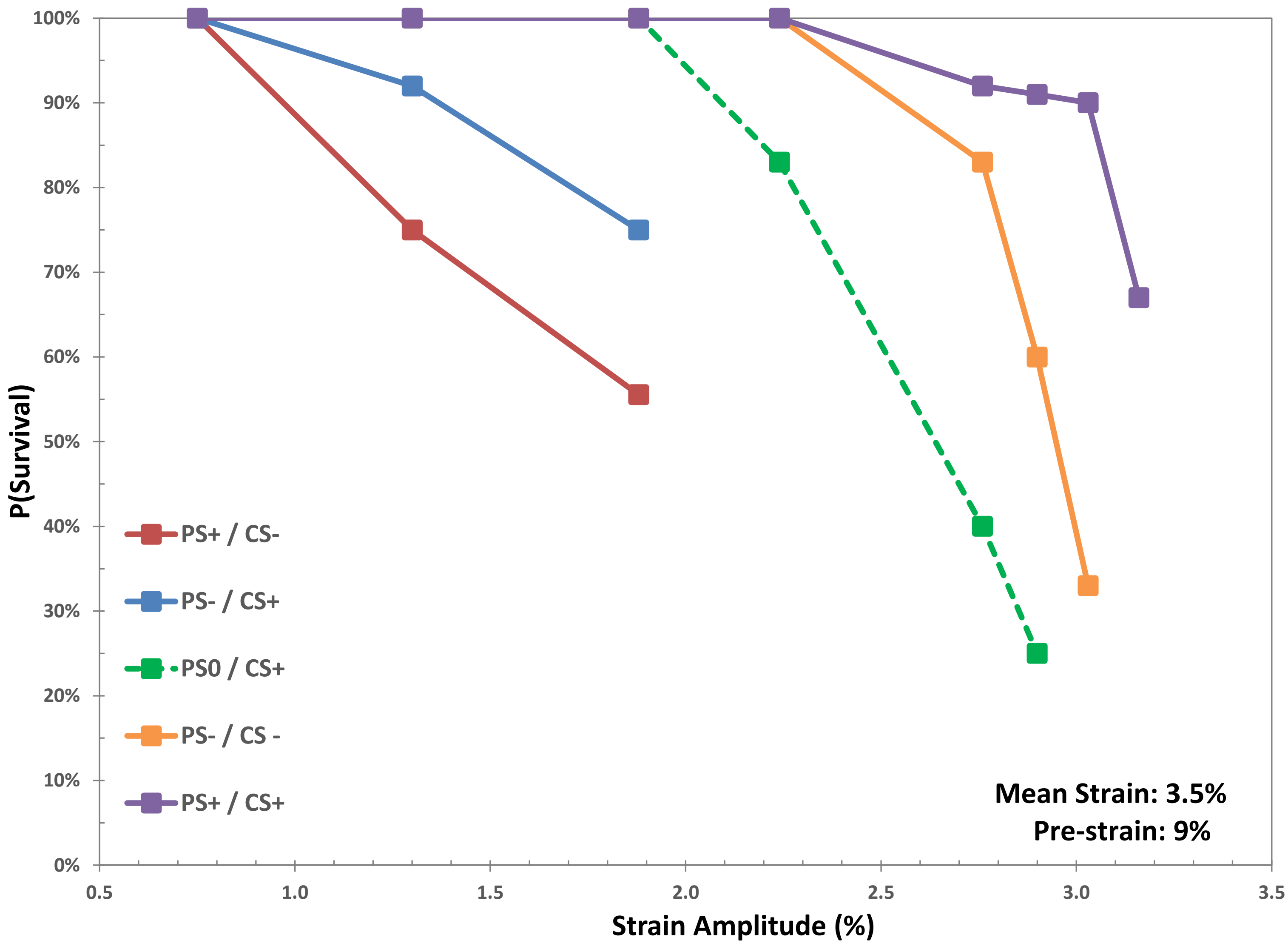
Pre-strain: (-) 9.00%

Mean strain: 3.50%

Run out: 1 million cycles ; Sample size: 12 at each condition

Strain Amplitude (%)	Baseline (PS0, CS+)	Combination A (PS+, RS-, CS-)	Combination B (PS-, RS+, CS-)	Combination C (PS+, RS-, CS+)	Combination D (PS-, RS+, CS+)
0.75	Run Out	Run Out	Run Out	Run Out	Run Out
1.30	Run Out	Fracture (3)	Run Out	Run Out	Fracture (1)
1.88	Run Out	Fracture (4)	Run Out	Run Out	Fracture (3)
2.24	Fracture (2)	Fracture (1)	Run Out	Run Out	Fracture (2)
2.76	Fracture (6)		Fracture (2)	Fracture (1)	
2.90	Fracture (3)		Fracture (4)	Fracture (1)	
3.03			Fracture (4)	Fracture (1)	
3.16				Fracture (3)	
3.50				Fracture (2)	
		Fracture Initiation: Intrados	**Fracture Initiation: Intrados**	Fracture Initiation: Extrados	**Fracture Initiation: Extrados**

Survival Plot – Diamond Surrogates

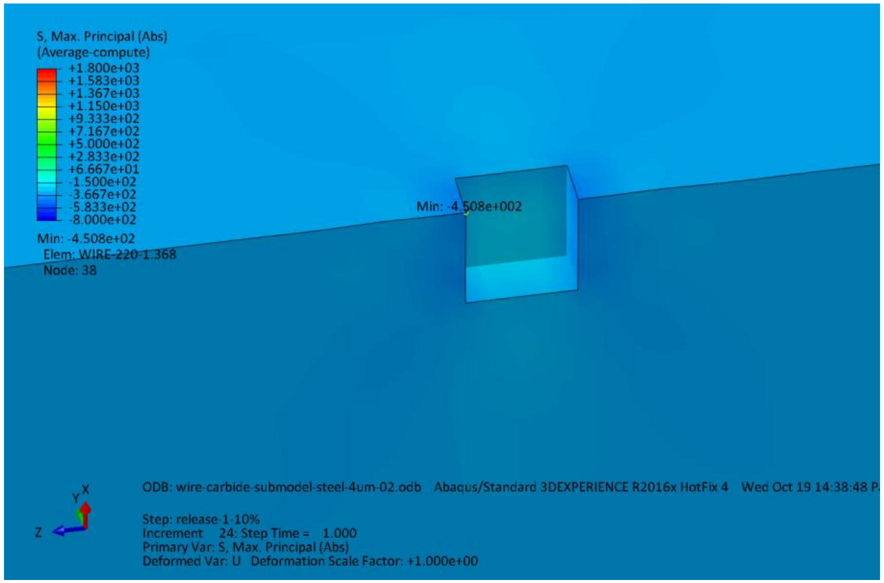


Modeling Residual Stresses

Pre-strain Diamond Test Results

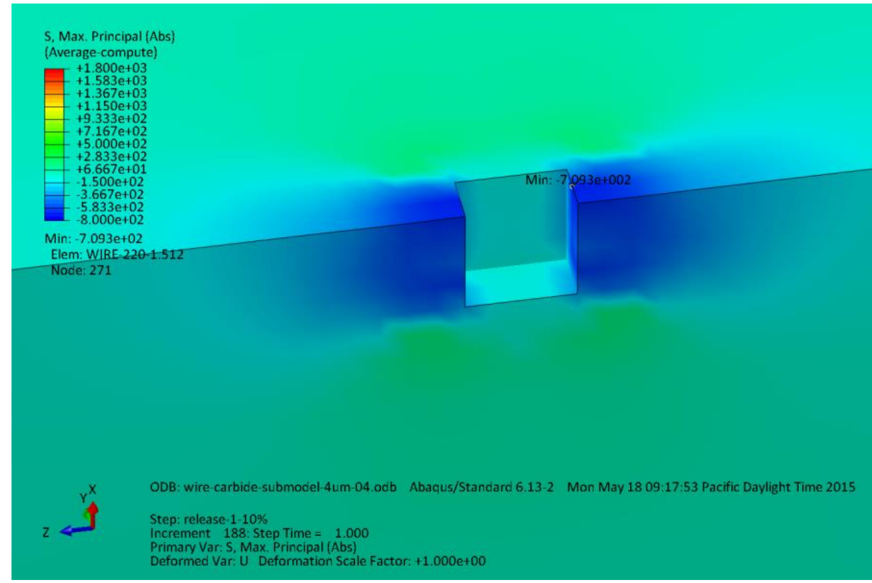
Role of Superelasticity in Residual Stresses

Residual Stress State – Inclusion Attached (Steel vs. Nitinol)



Inclusion Attached

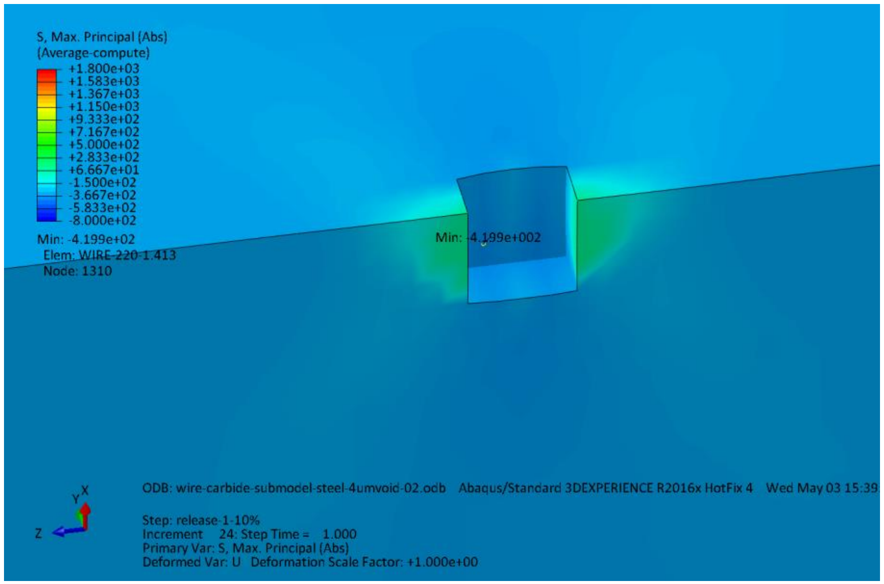
Steel 316L
-450 MPa

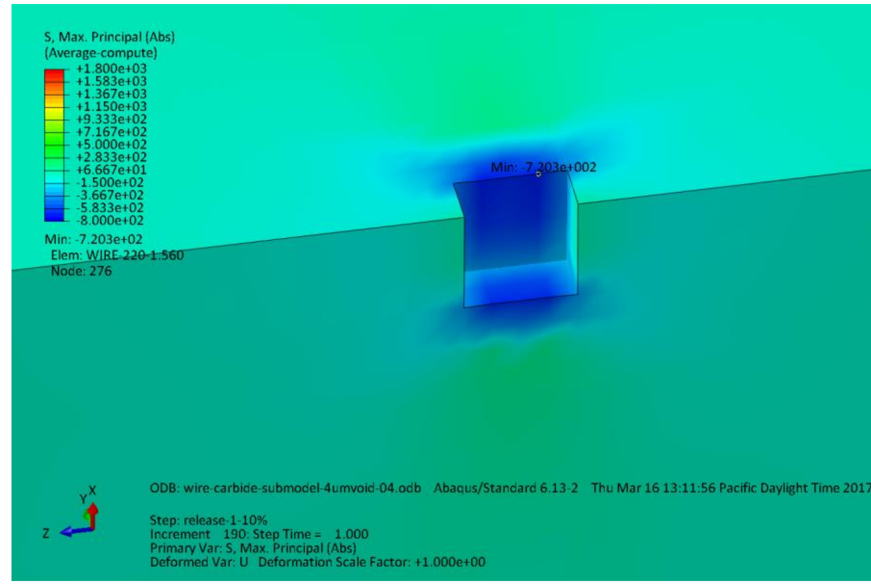


Inclusion Attached

Nitinol
-710 MPa

Residual Stress State – Void (Steel vs. Nitinol)





Void	Void
Steel 316L	Nitinol
-420 MPa	-720 MPa

Summary

Residual stresses through pre-straining can increase or decrease the fatigue life depending on the nature of pre-strain and cyclic stress state.

Fatigue life improves when the pre-stress and cyclic stress are of the same polarity (i.e., tensile or compressive).

The effect of residual stresses is more pronounced in Nitinol compared to a traditional metal.

bit.ly/smst17ndc

Karthikeyan Senthilnathan
Confluent Medical Technologies

Karthikeyan.senthilnathan@confluentmedical.com