Structure and Properties of Large Diameter Hot Rolled NiTi Bars for Seismic Applications

Weimin Yin, Frank Sczerzenie, Matt Long, Clarence Belden, R.M. Manjeri, Rich Lafond

SAES Smart Materials,
New Hartford, New York, USA

saes group

making innovation happen, together

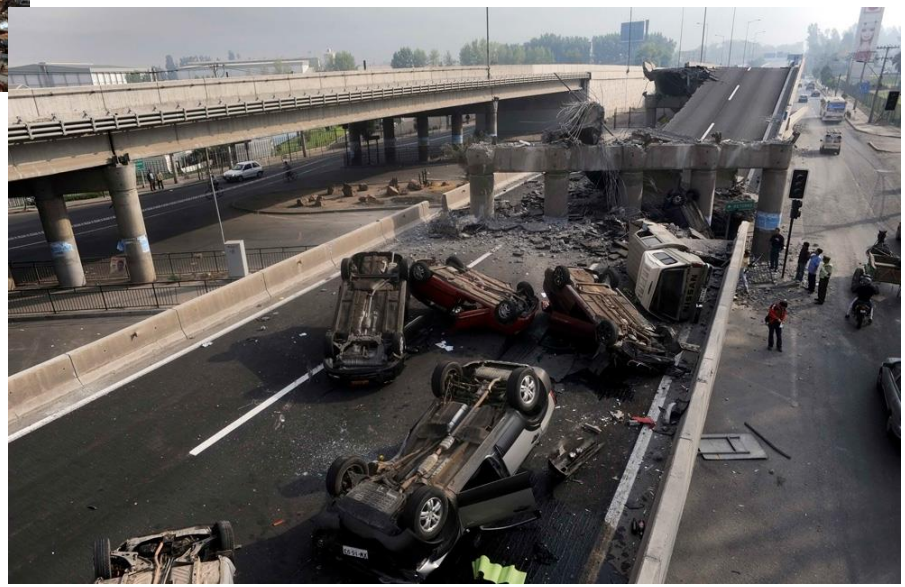
Outline

- Nitinol and Applications in Civil Structures
- Materials, Testing and Properties Evaluation
- Investigation of Binary NiTi Bars
  - Superelastic Behavior at Room Temperature
  - Cyclic Tests
  - Temperature Range for Superelasticity
- Development of NiTiCo
- Summary

Background

Tōhoku Japan earthquake (2011), M9.0

Chile earthquake (2010), M8.8



Loma Prieta earthquake (1989) M6.9

~ US$6 billion in property damage

Nitinol and Applications in Civil Structures

- Unique Properties of Nitinol
  - Shape memory effect
  - Superelasticity
- Advantages in Civil Structures
  - Hysteretic damping
  - Large strain recovery
  - Excellent corrosion resistance
- Civil Applications (Song, Engineering Structure, 2006)
  - Passive Structural Control
  - Active Frequency Tuning (Semi-active)
  - Active Damage Control

Material	Nitinol	Prestressing Steel Bar
Grade/Type	Ti-50.8 at.%Ni (nominal)	Type 2*
Recoverable Elongation, %	6	0.4
Modulus, GPa	40 (M)/ 75(A)	207
UTS, MPa	1100-1390	1035
YS, MPa	--	828
UPS, MPa	400-550	--

*Bridge Engineering Handbook, ASTM A722; AASHTO M275

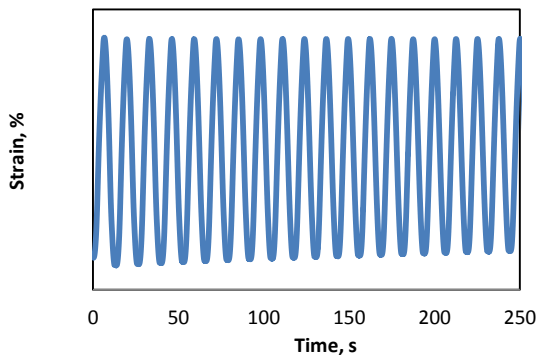
Processing and Materials

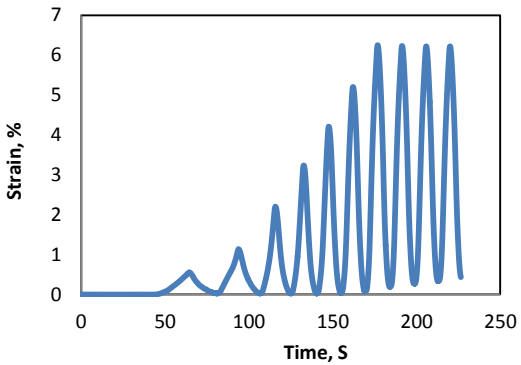
- Fabrication of Binary NiTi Bars
  - Vacuum induction melting followed by vacuum arc remelting
  - Forging
  - Bar rolling and straightening
  - Heat treatment
  - Large diameter bars

- Development of Ternary NiTiCo Alloy
  - Vacuum induction melting followed by vacuum arc remelting
  - Forging
  - Flat rolling
  - Heat treatment
  - Thick plates

Mechanical Testing

- Testing methods
  - Dog-bone tensile specimens
  - Tensile tests
  - Cyclic tensile tests
    - Constant maximum strain
    - Variable maximum strain





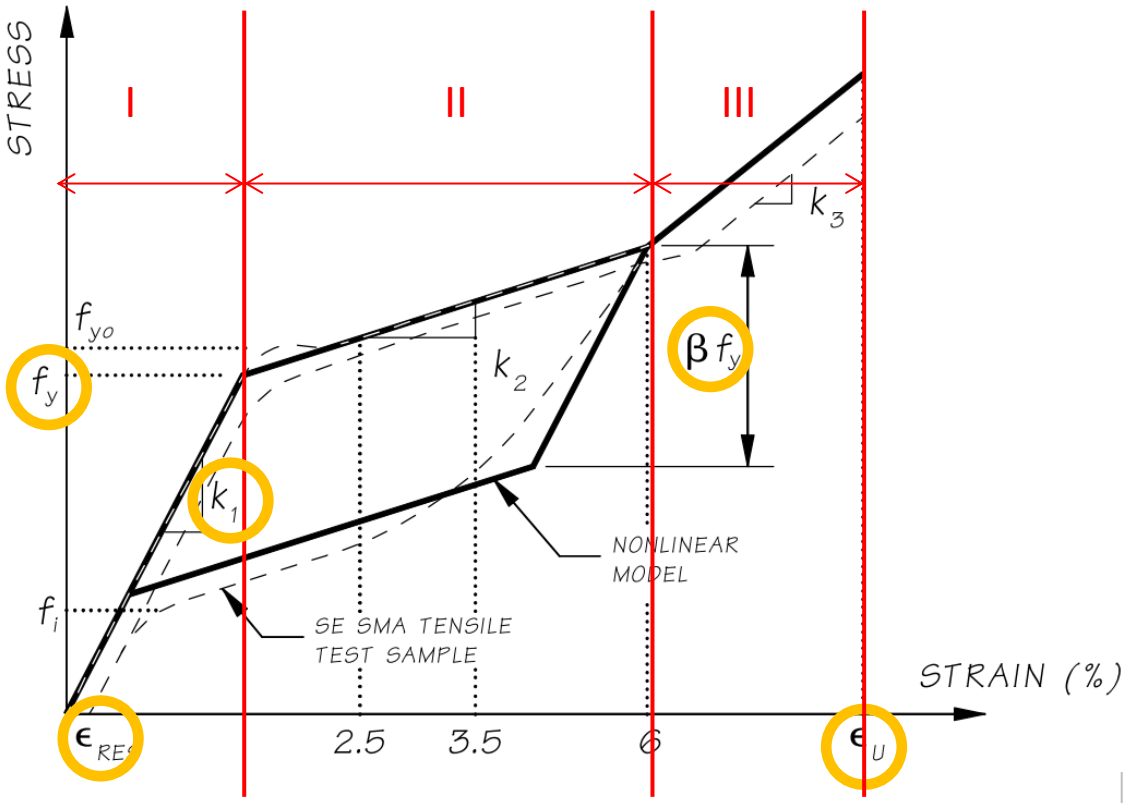
DesRoches, McCormick and Delemont, 2004

- Temperature range
  - Room temperature and extreme environmental conditions.

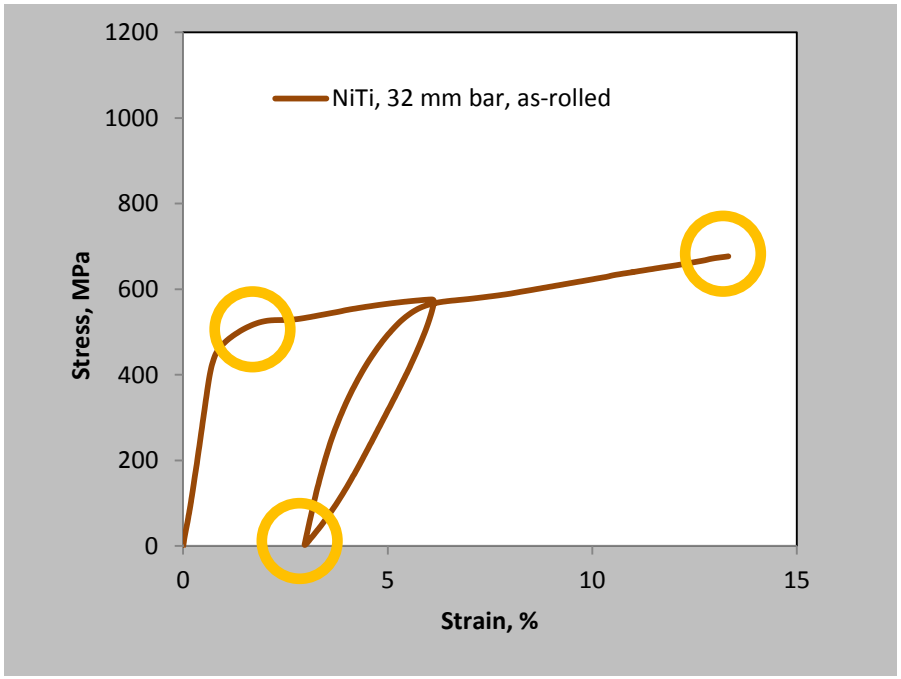
Data Processing for Civil Engineering Design

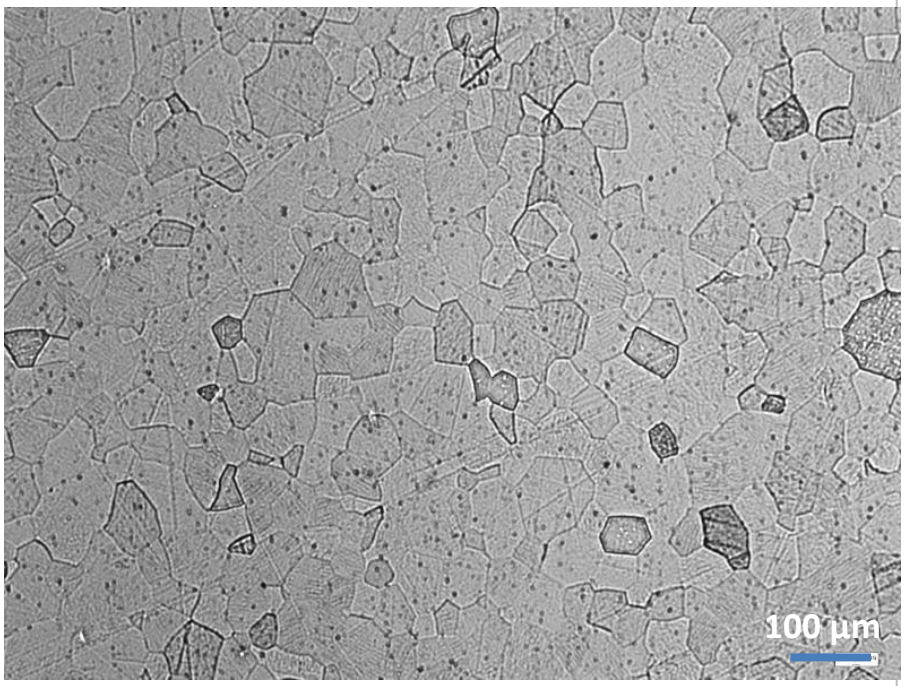
- Three Constitutive Stress - Strain Variation Rule (Tazarv & Saiidi, J. Struct. Eng. 2014)
  - Stage I
  - Stage II
  - Stage III
  - Key parameters
    - Yield strength f_y
    - Modulus, k_1
    - Residual strain ε_{RES}
    - Ultimate strain ε_U
    - LPS factor β

$$\beta = 1 - f_i / f_y$$

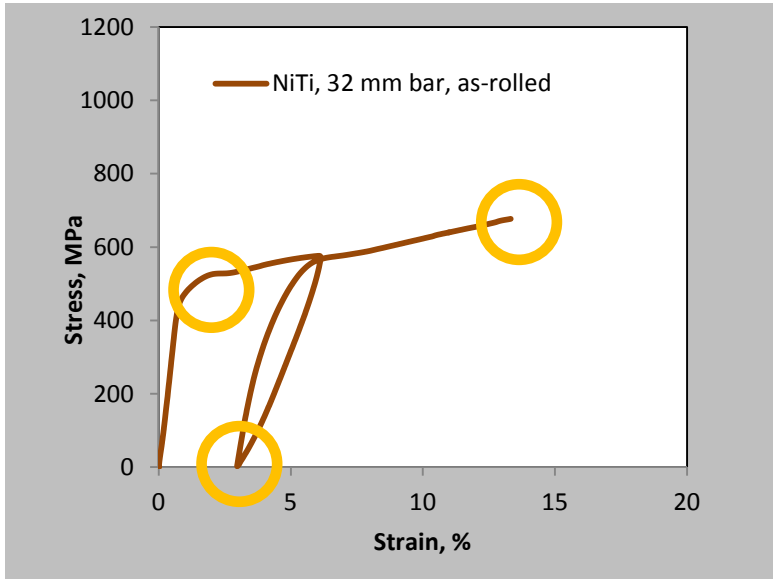


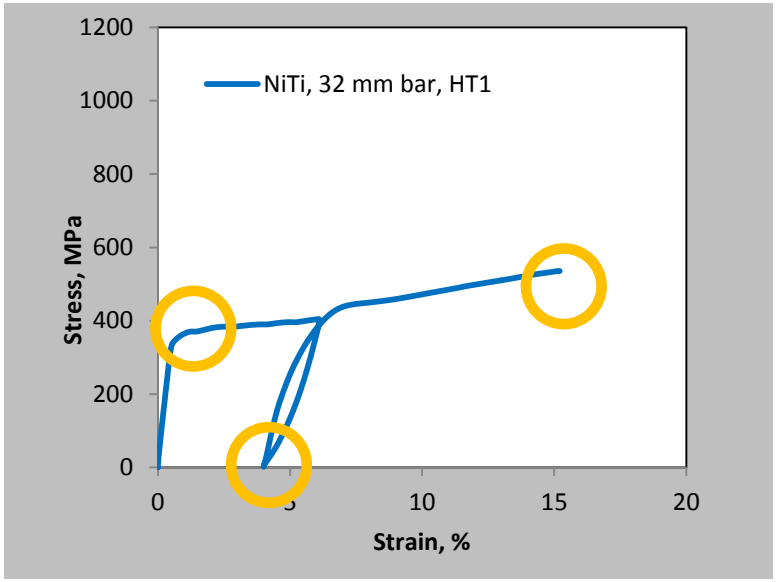
Binary NiTi - Hot Rolled Bars

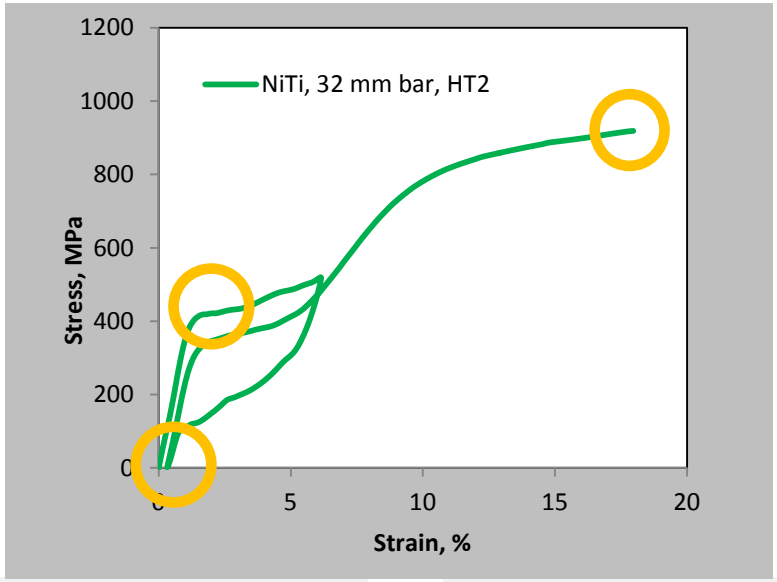


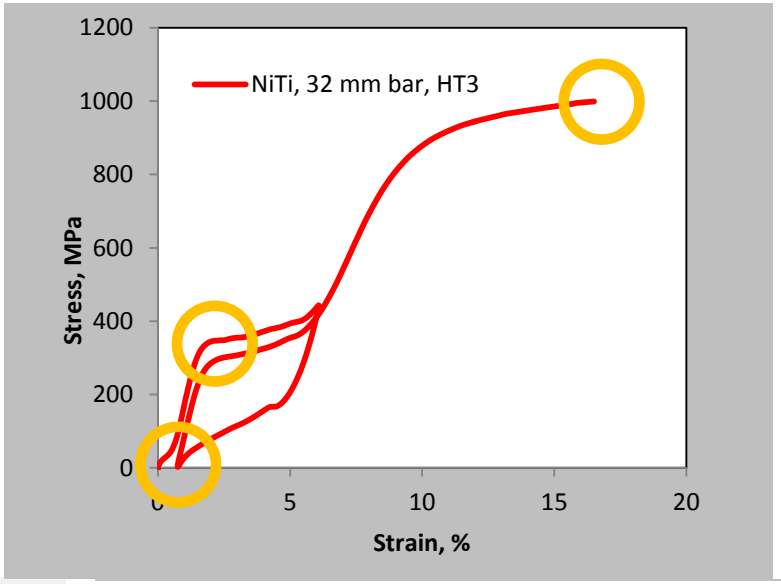


Binary NiTi – Tensile Behavior at Room Temperature

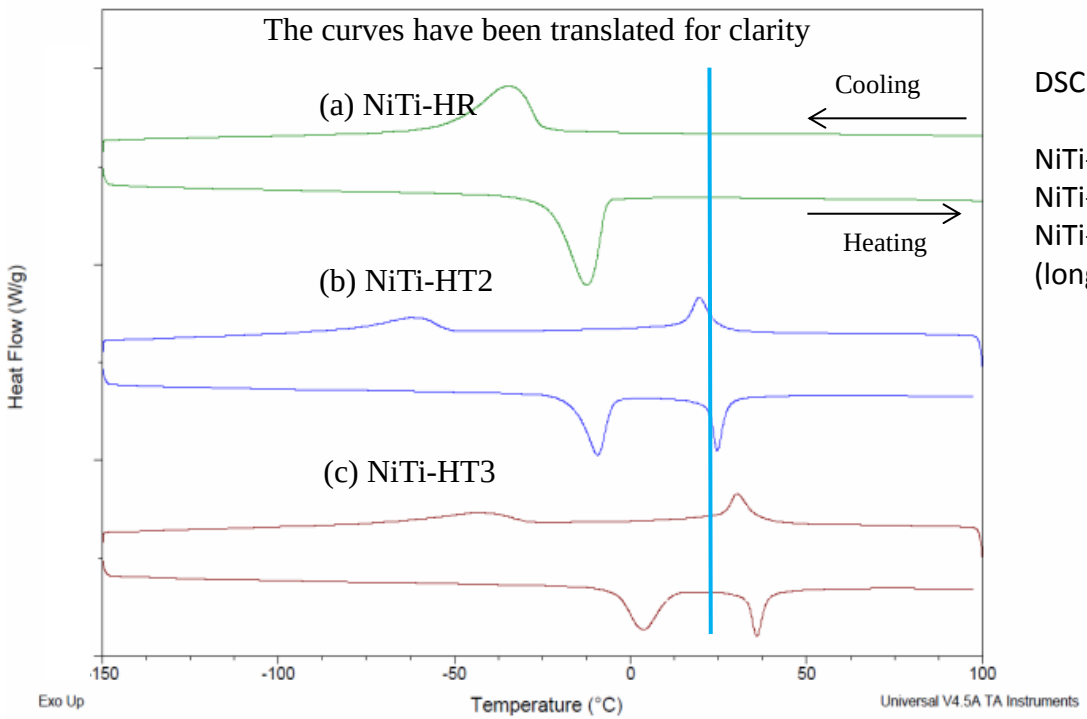








Phase Transformation – Binary NiTi



DSC measurement per ASTM F2004-05

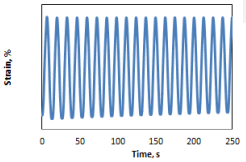
NiTi-HR: as hot-rolled
NiTi-HT2: hot-rolled + aging heat treated
NiTi-HT3: hot-rolled + aging heat treated (longer time)

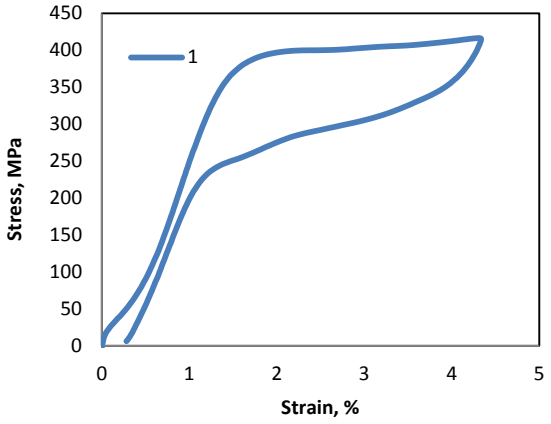
Cooling, Unit: deg C						
	Mf	Mp	Ms	Rf	Rp	Rs
NiTi-HR	-51.5	-34.9	-24.8	X	X	X
NiTi-HT2	-81.7	-64.9	-46.6	14.4	18.8	24.6
NiTi-HT3	-64.5	-44.1	-28.8	26.1	30.3	36.5

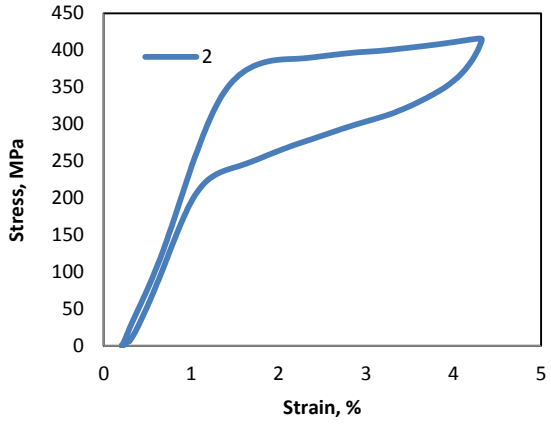
Heating, Unit: deg C						
	R's	R'p	R'f	As	Ap	Af
NiTi-HR	X	X	X	-23.0	-12.5	-6.7
NiTi-HT2	-21.3	-12.3	-5.4	20.6	23.6	27.5
NiTi-HT3	-4.1	3.7	12.3	32.8	35.9	39.2

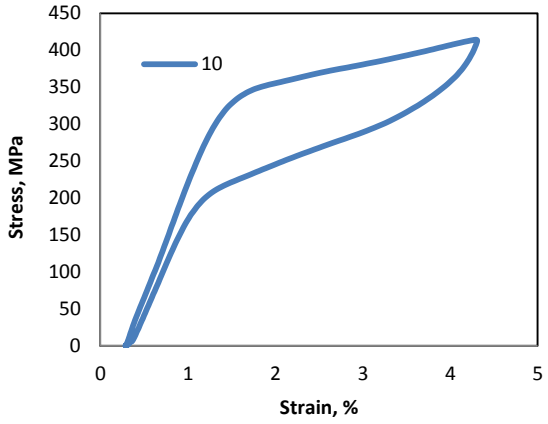
NiTi - Cyclic Test at Room Temperature

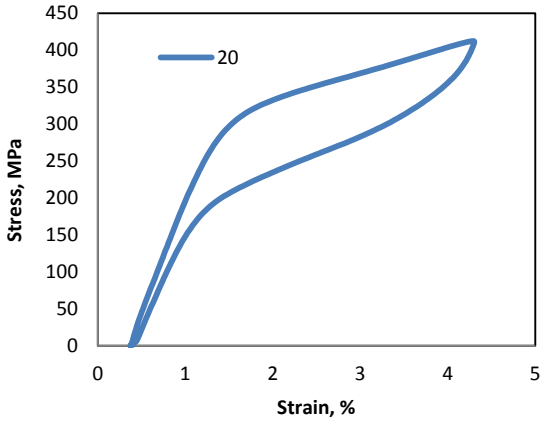
Maximum Strain = 4%

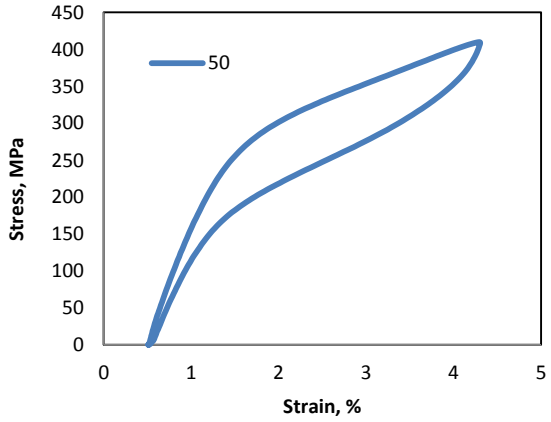


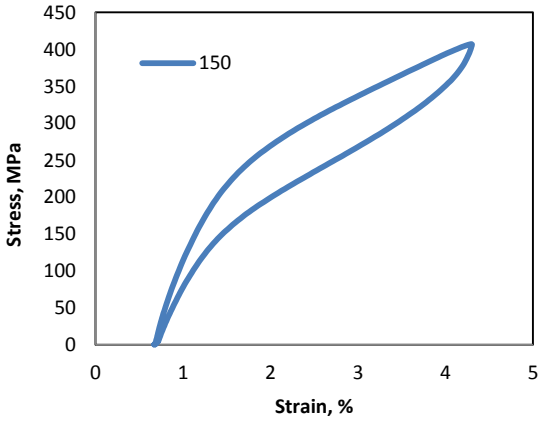






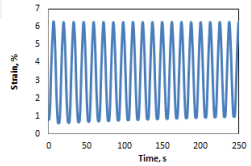


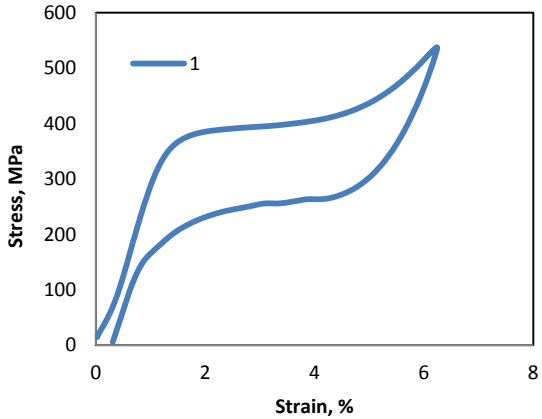


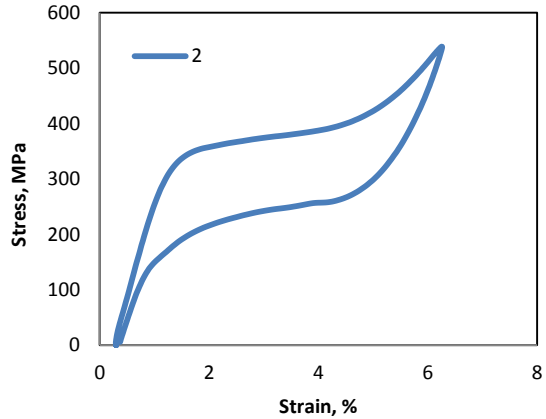


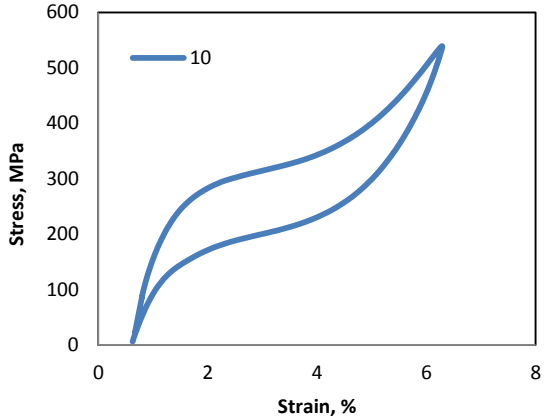
NiTi - Cyclic Test at Room Temperature

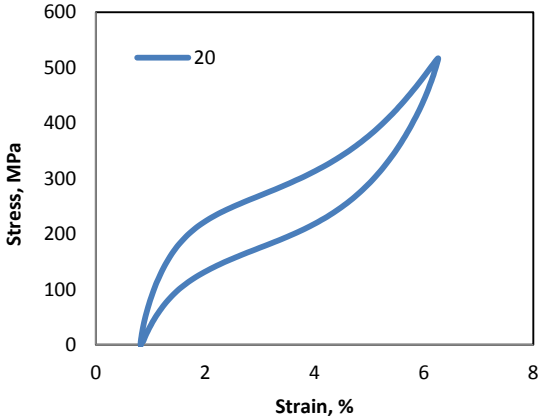
Maximum Strain = 6%

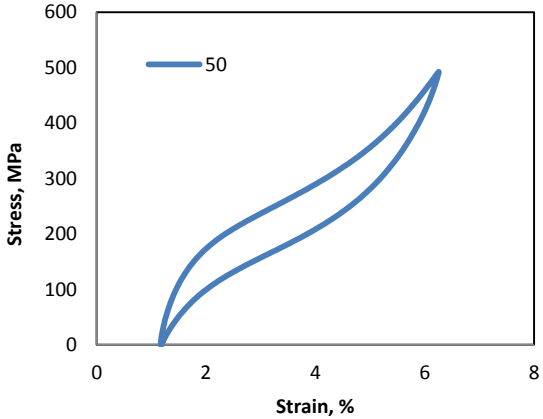


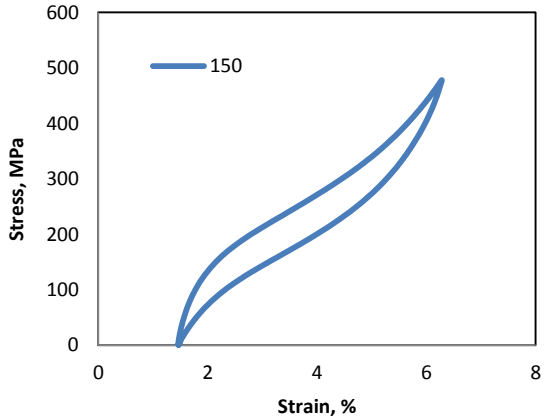






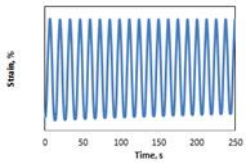


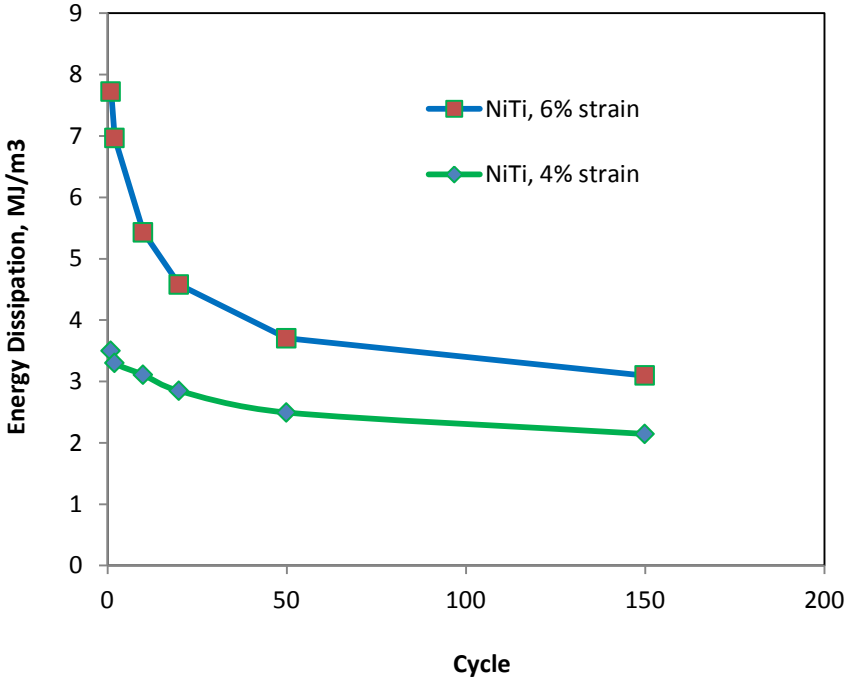


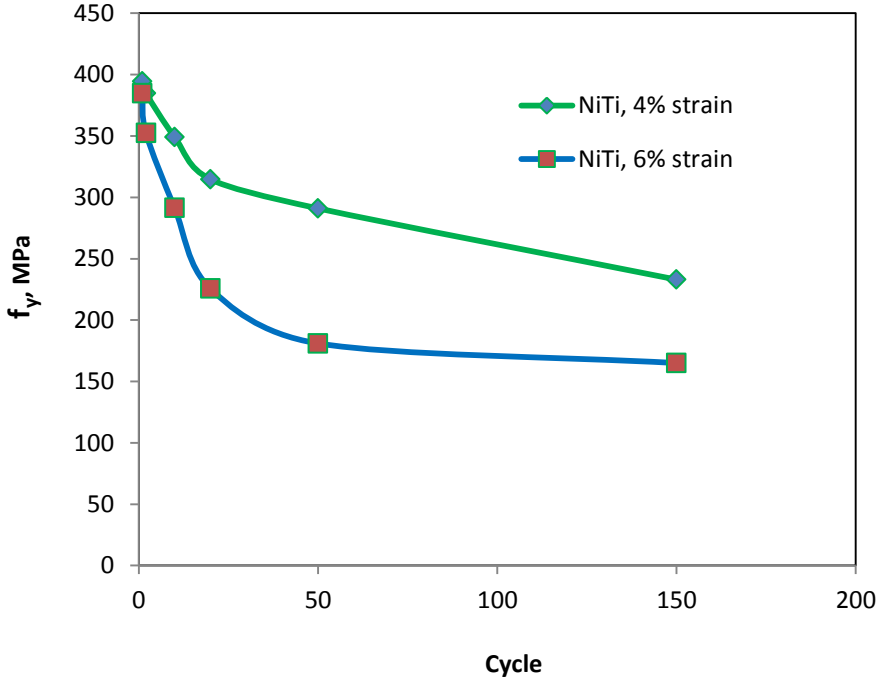


Mechanical Properties Evolution

Constant Maximum Strain





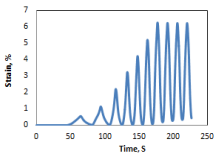


At 6% strain, energy dissipation decreases from ~8 MJ/m^3 to ~ 5 MJ/m^3 at 20 cycles; reaches a plateau ~3.5 MJ/m^3 after 50 cycles.

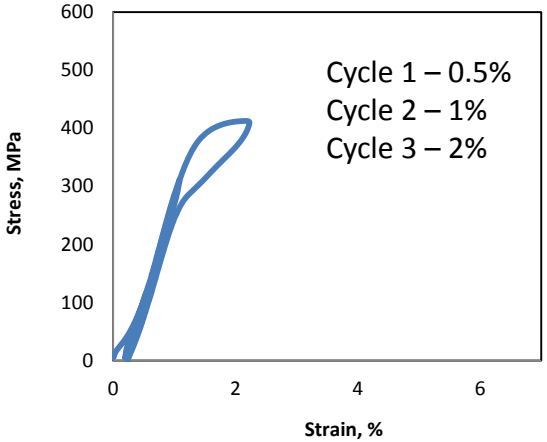
At 6% strain, f_y decreases from 400 MPa to ~ 200 MPa at 20 cycles; reaches a plateau 160 MPa after 50 cycles.

NiTi - Cyclic Test at Room Temperature

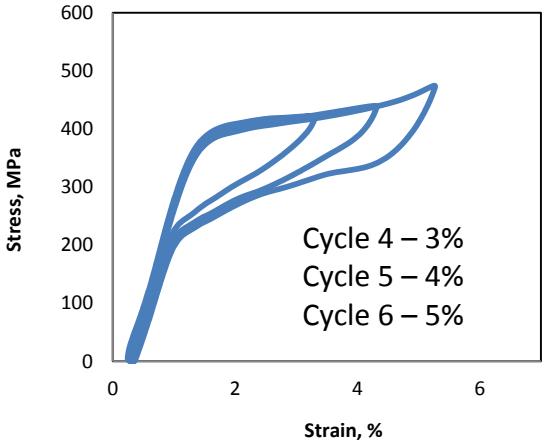
10-Cycle Variable Maximum Strain



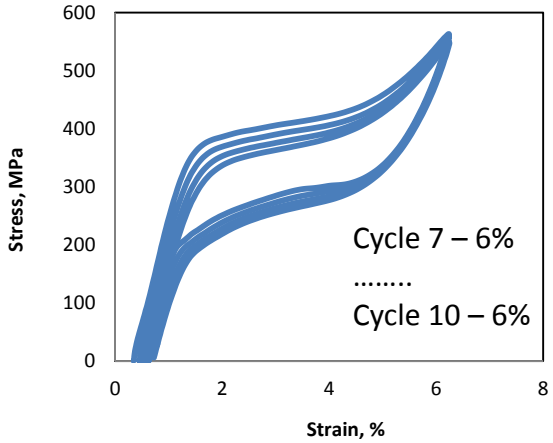
DesRoches, McCormick and Delemont, 2004



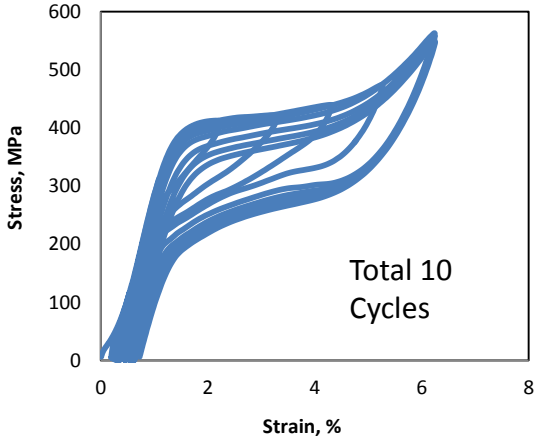
+



+

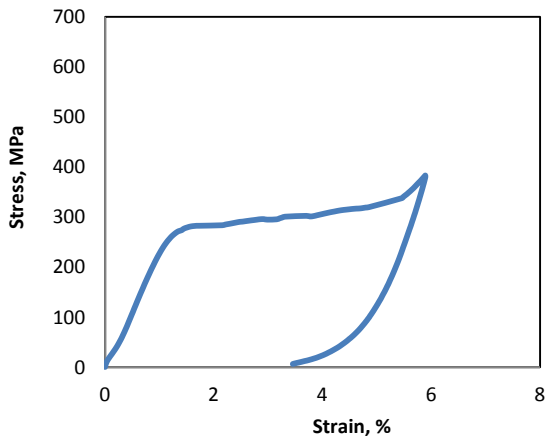


=

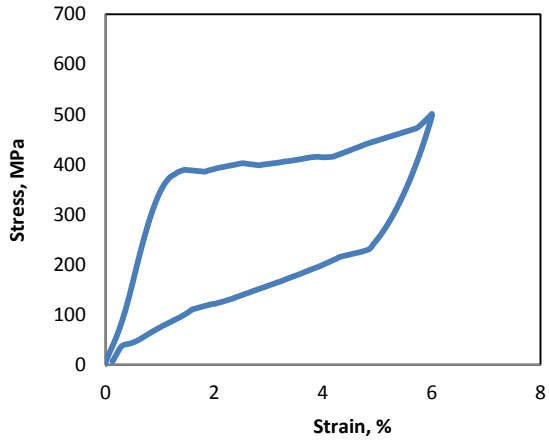


NiTi – Effect of Testing Temperatures

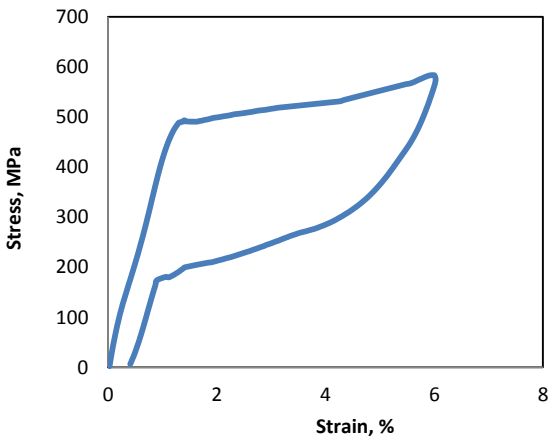
0°C



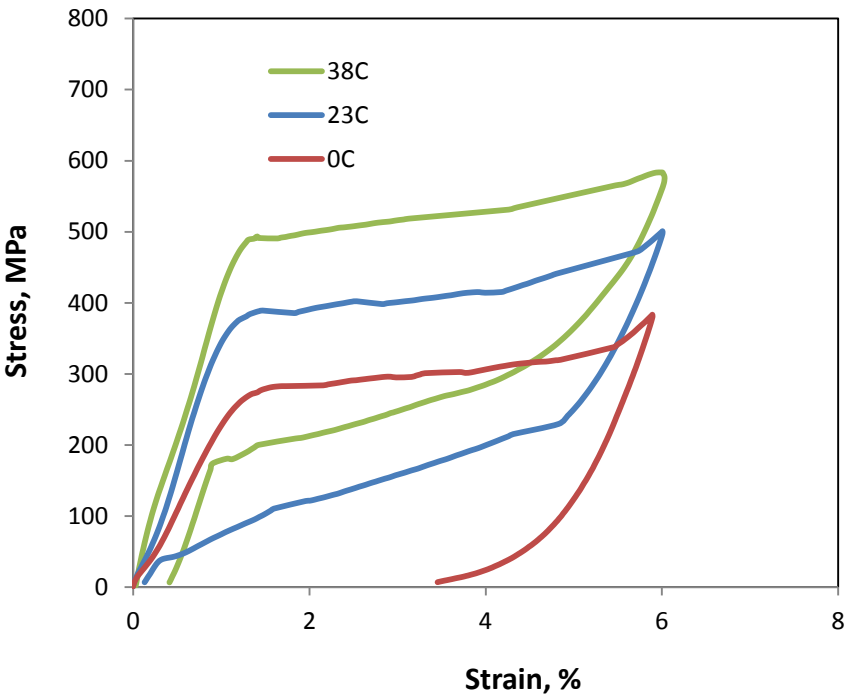
23°C

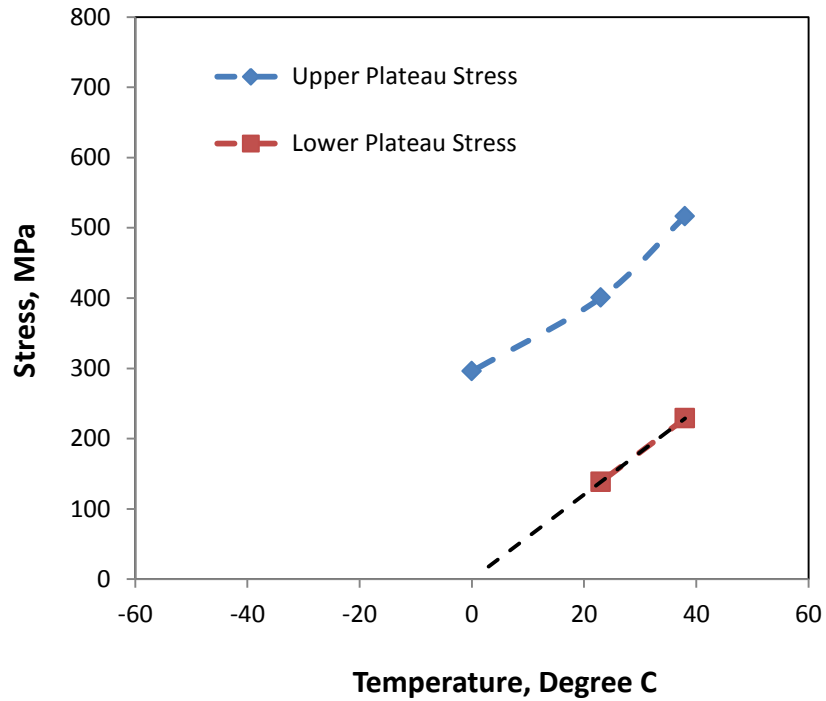


38°C



NiTi – Effect of Testing Temperatures





Upper plateau stress @ 3% strain

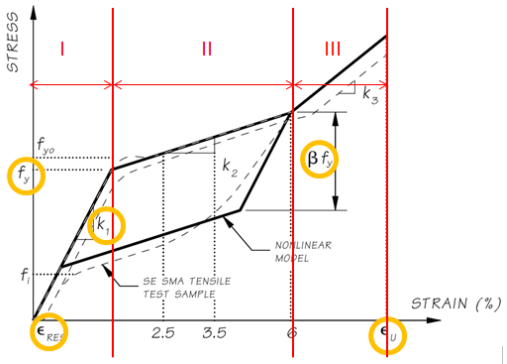
Lower plateau stress @ 2.5% strain

Beyond Binary NiTi

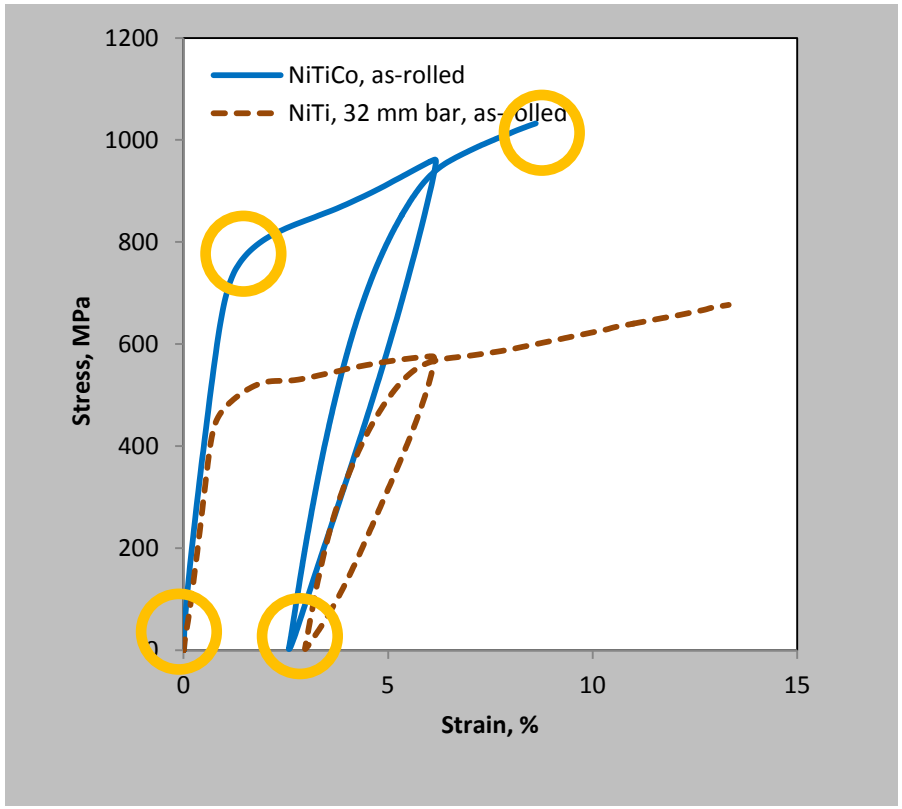
- Summary of Key Properties

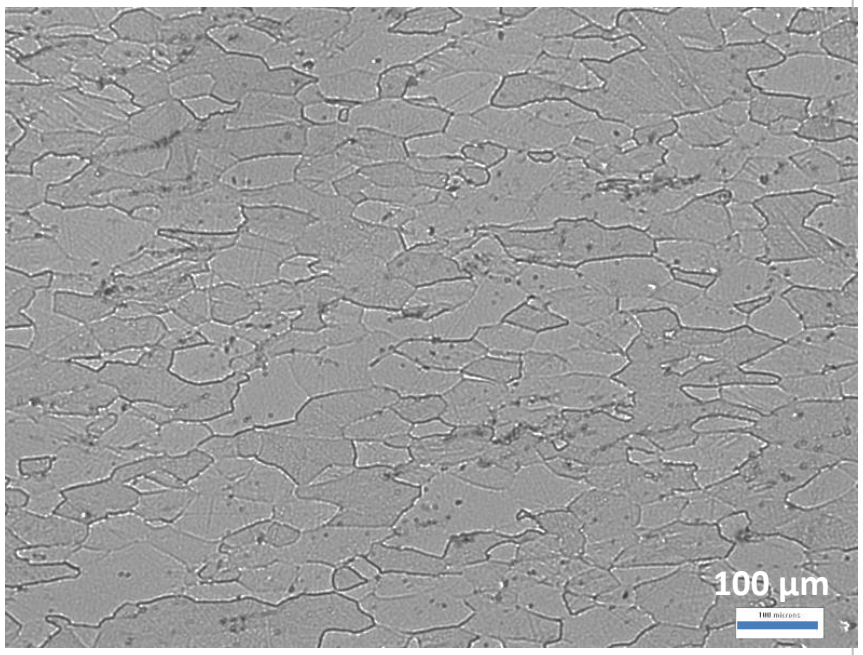
	NiTi Bars
Elastic Modulus, k_1	33 GPa - 44 GPa
Yield Strength, f_y	382 MPa - 412 MPa
Residual Strain, ε_{RES}	0.33 % - 0.41 %
Elongation, ε_U	14 % - 18 %
LPS factor β	0.63 – 0.74

- Further Development
  - Higher strength
  - Wider temperature range for superelasticity
  - NiTi ratio
  - Alloying elements

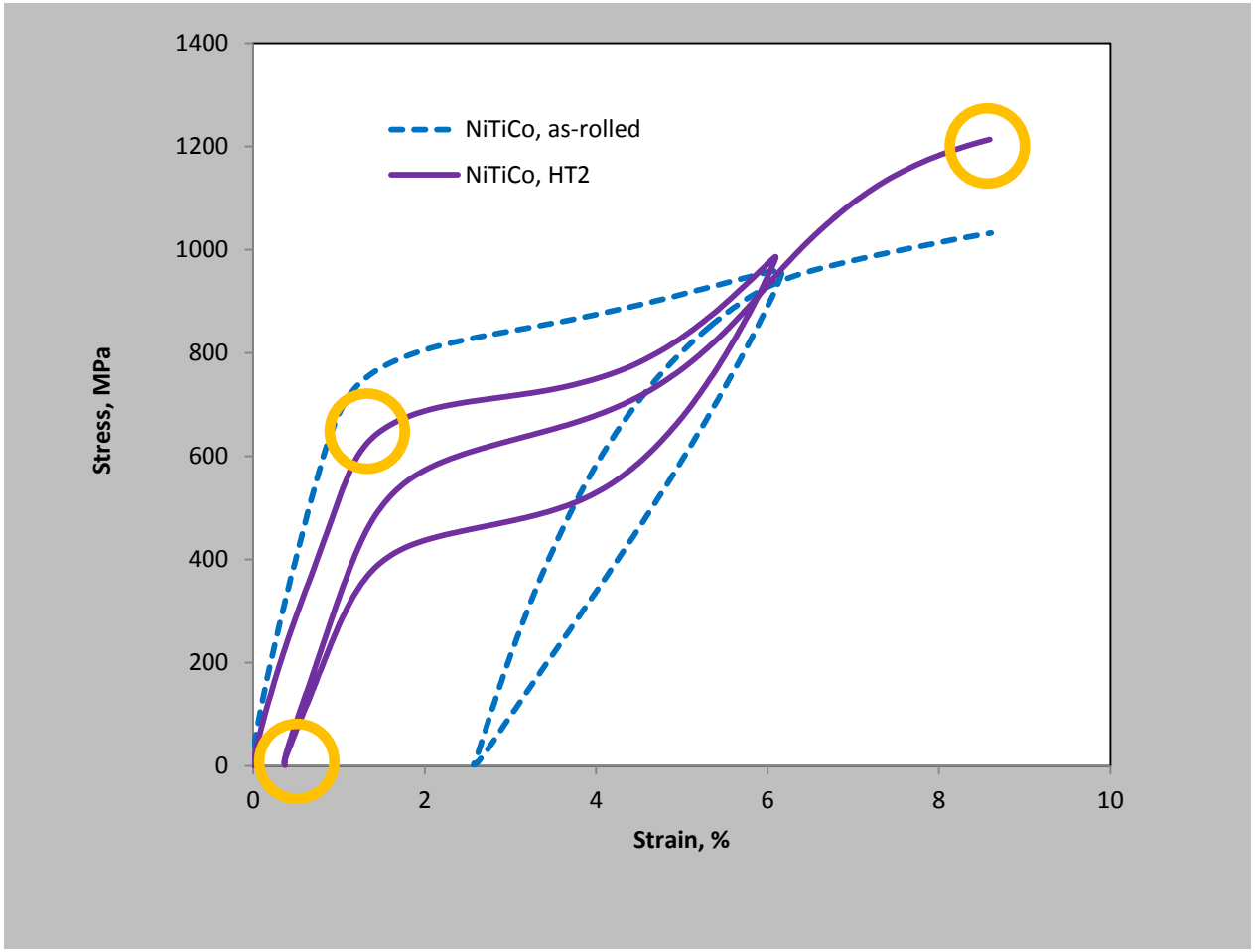


Ternary NiTiCo - Hot Rolled Plate

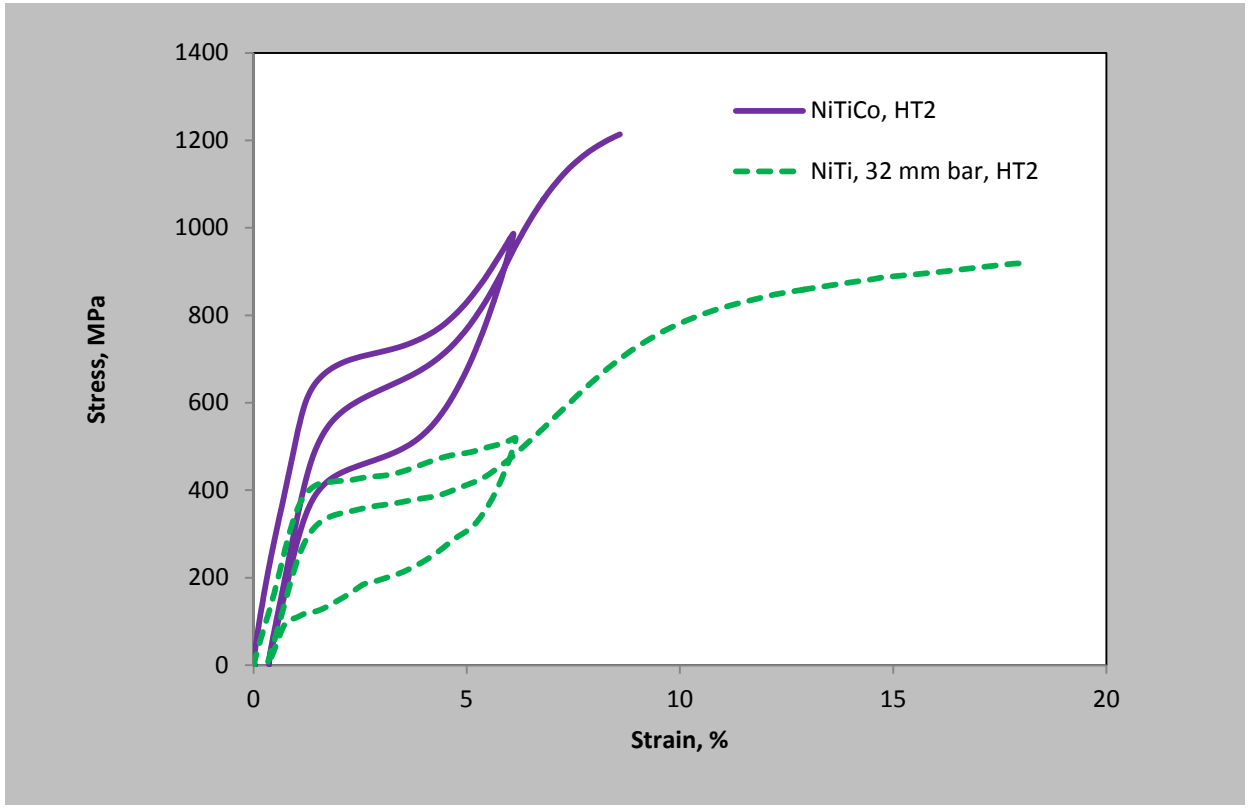




Ternary NiTiCo – Heat Treated

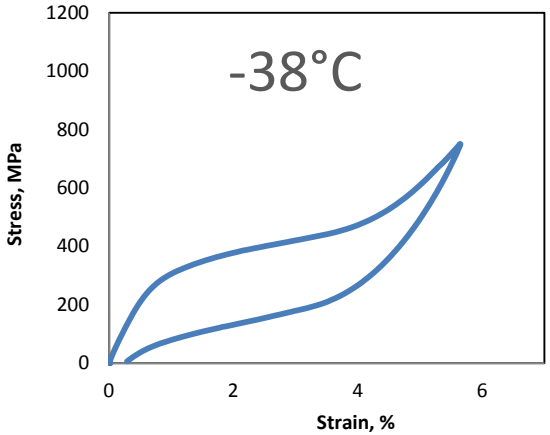


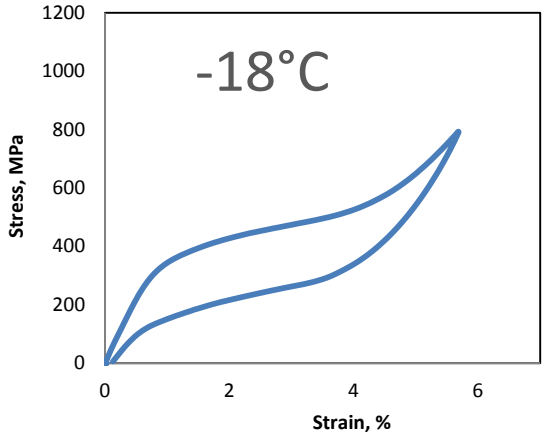
Ternary NiTiCo - Hot Rolled Plate

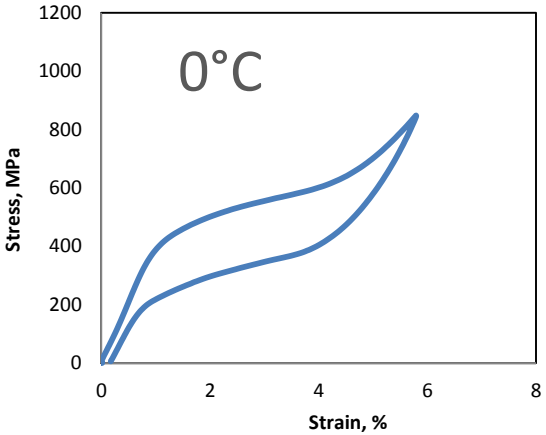


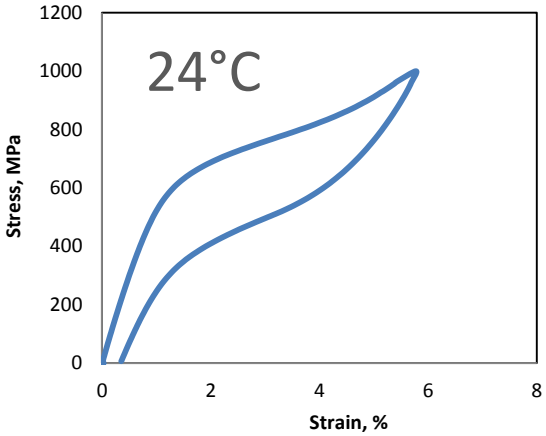
	NiTi	NiTiCo	Change, %
Modulus, GPa	37	47	28%
Yield Stress, MPa	400	680	70%
Residual Strain, %	0.36	0.36	0%
UTS, MPa	884	1214	37%
Elongation, %	15.9	8.6	-46%

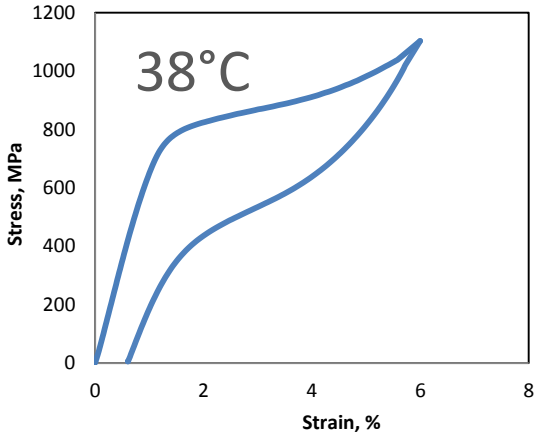
NiTiCo – Effect of Testing Temperatures



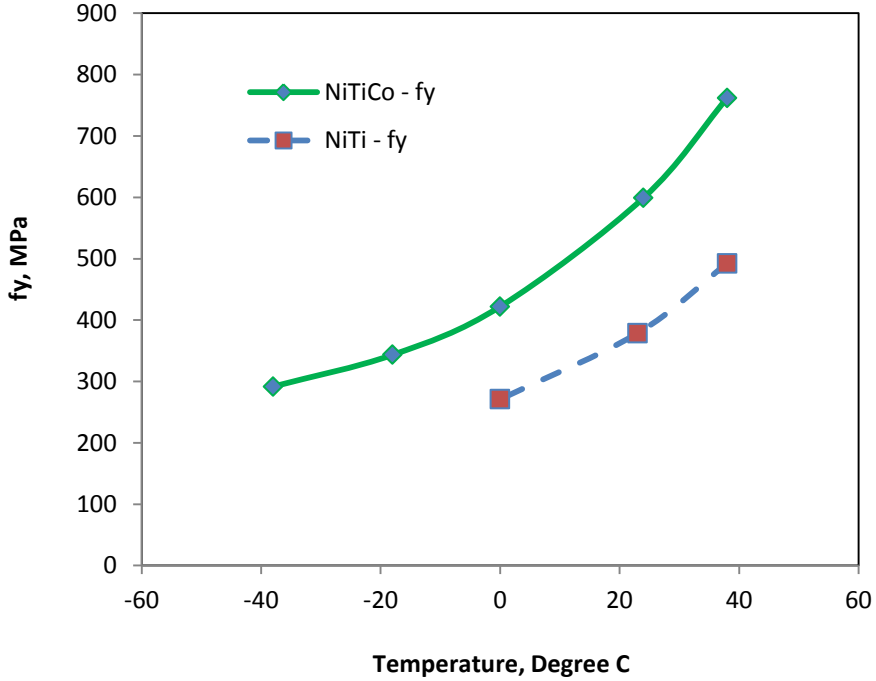


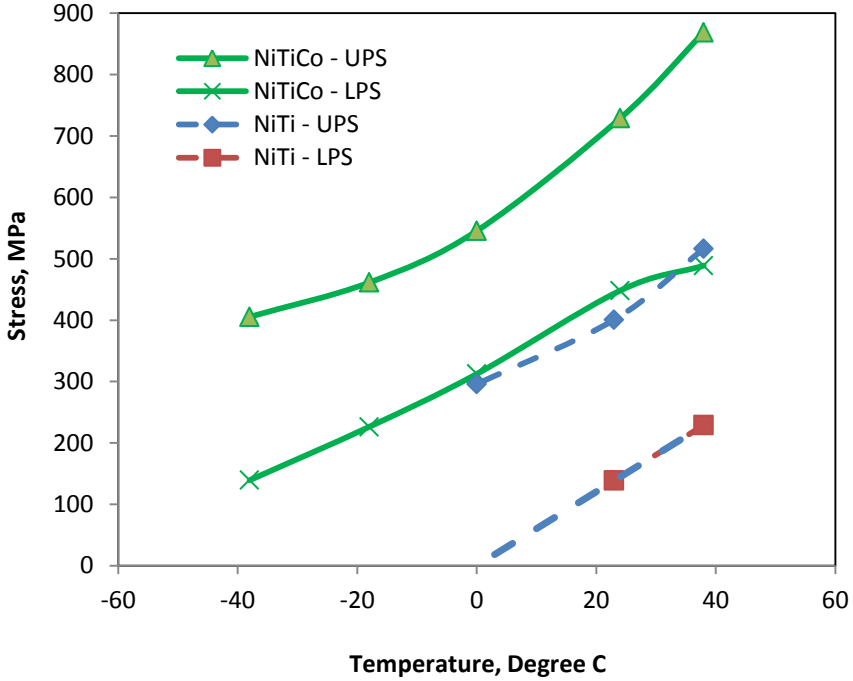






Effect of Formulation and Testing Temperature

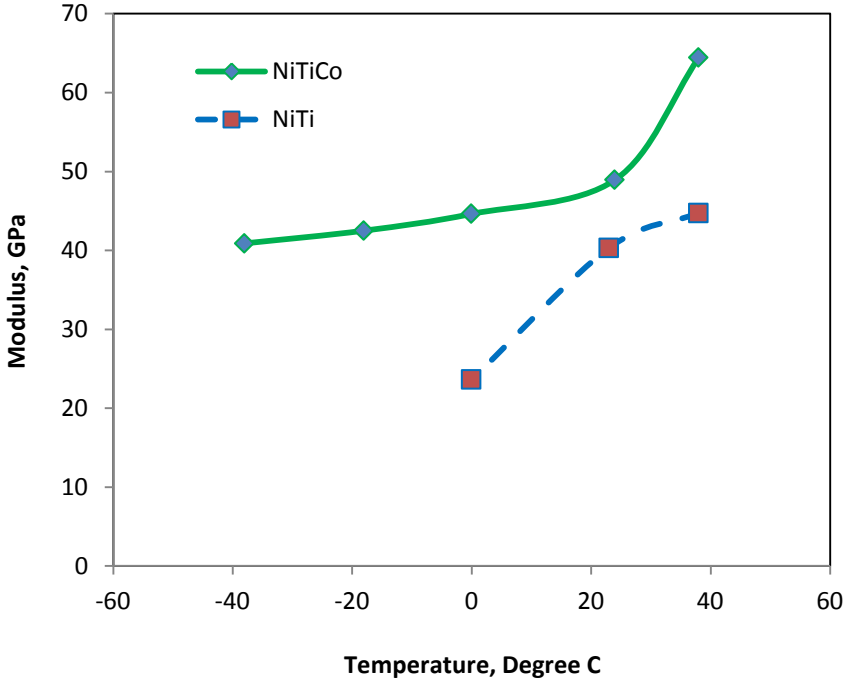


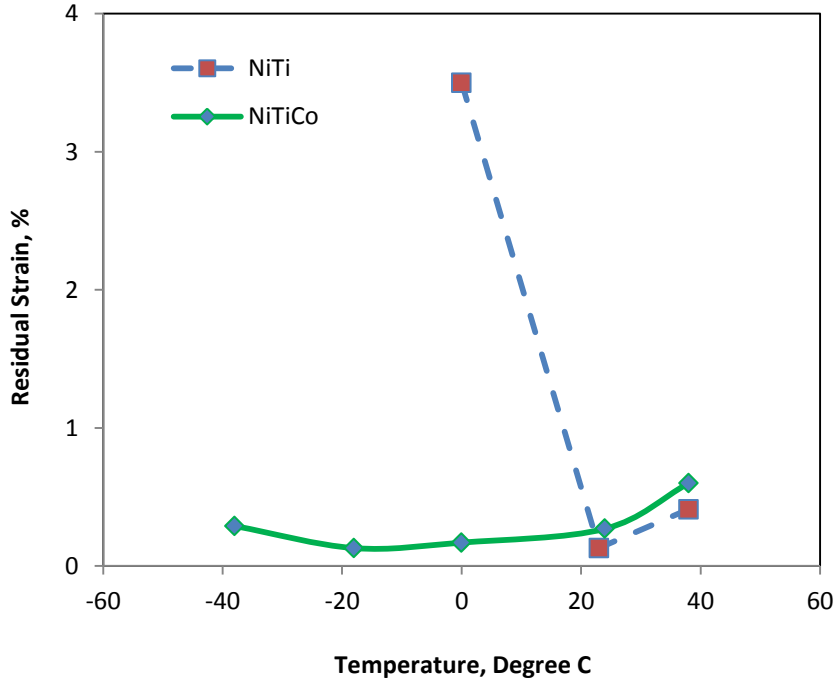


Upper plateau stress - the stress at 3% strain during loading.

Lower plateau stress – the stress at 2.5% strain during unloading.

Effect of Formulation and Testing Temperature

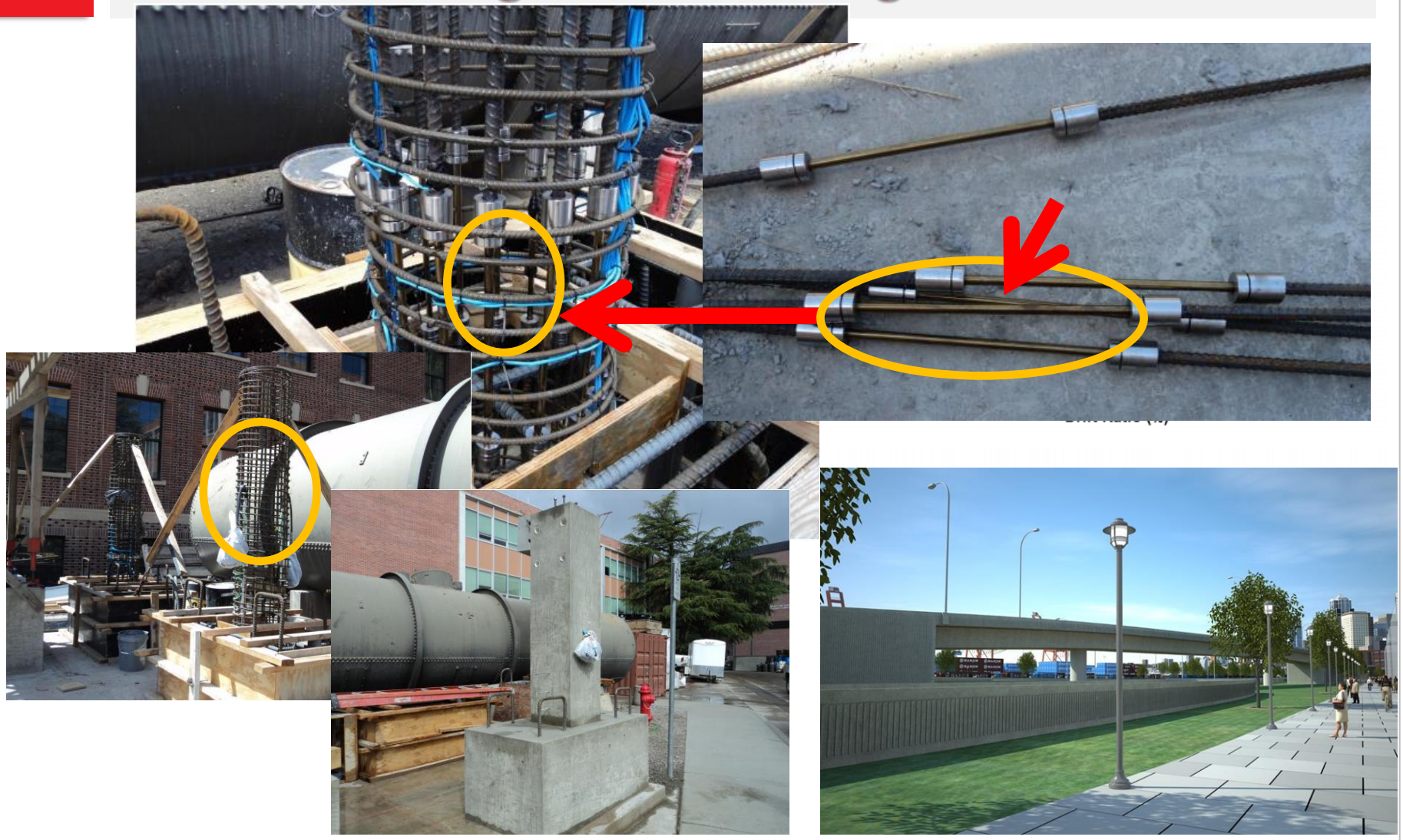




Summary

- Large diameter NiTi bars have been manufactured on a commercial scale.
- With proper heat treatment, the NiTi hot rolled bars exhibit good superelastic behavior at room temperature.
- Strength and energy dissipation decrease gradually with increase of stress cycles and reaches a plateau after 50 cycles.
- The preliminary study on ternary NiTiCo alloy indicates that this material displays superior strength and excellent temperature range of superelasticity.

Washington SR 99 Bridge Structure



This project was funded by the WashDOT and FHWA-IBRD programs and directed by Prof. M. Saiidi at the University of Nevada, Reno.

Acknowledgements:

Prof. M. S. Saiidi

Dr. M. Tazarv

University of Nevada, Reno

Dr. Darel Hodgson

Nitinol Technology

Thank you for your attention

saes group

www.saesgroup.com