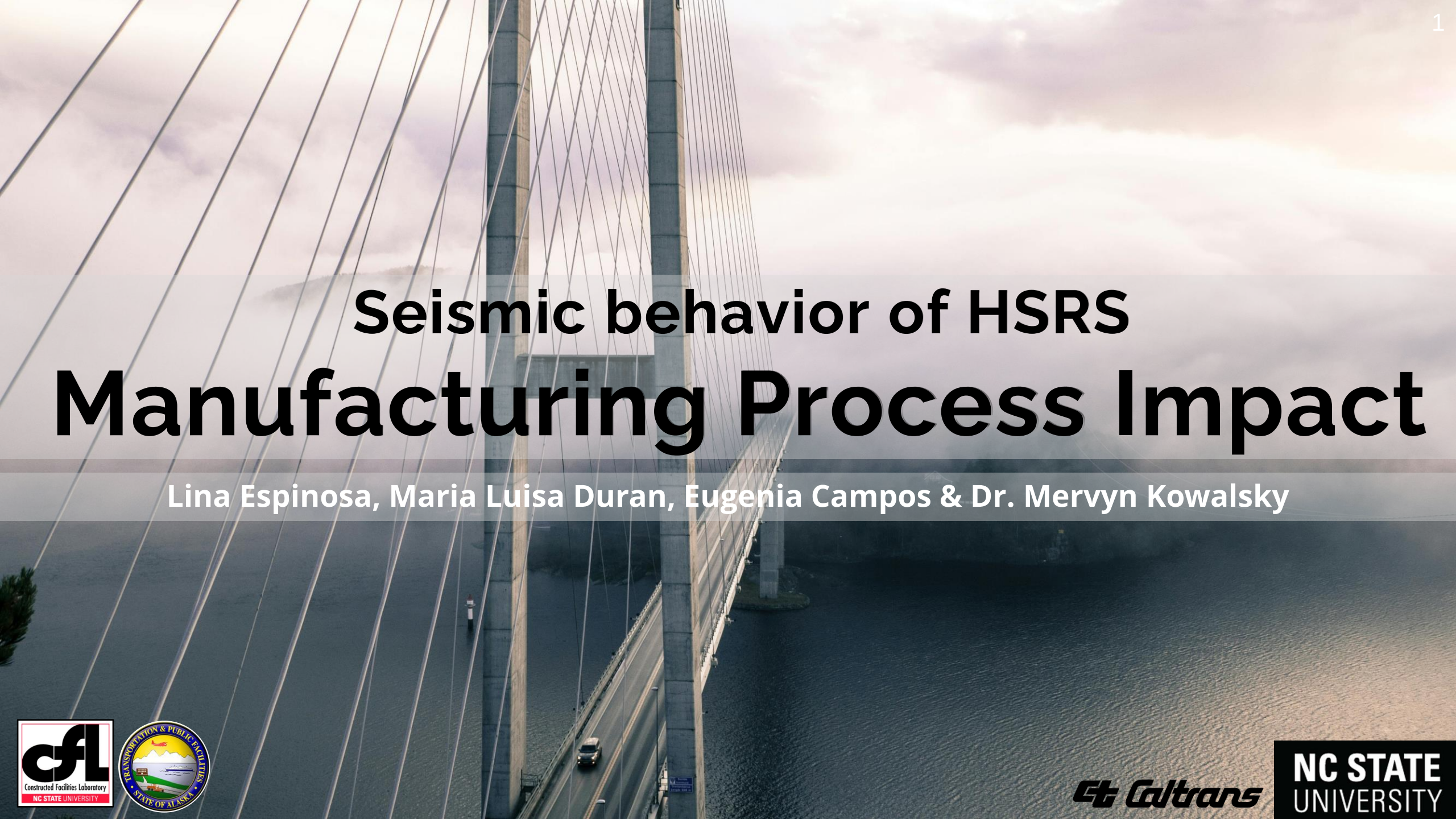


Seismic behavior of HSRS

Manufacturing Process Impact

Lina Espinosa, Maria Luisa Duran, Eugenia Campos & Dr. Mervyn Kowalsky

Constructed Facilities Laboratory
NC STATE UNIVERSITY

TRANSPORTATION & PUBLIC FACILITIES
STATE OF ALASKA

Caltrans

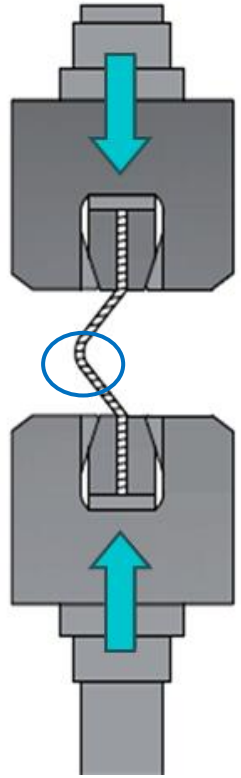
NC STATE UNIVERSITY

Presentation outline

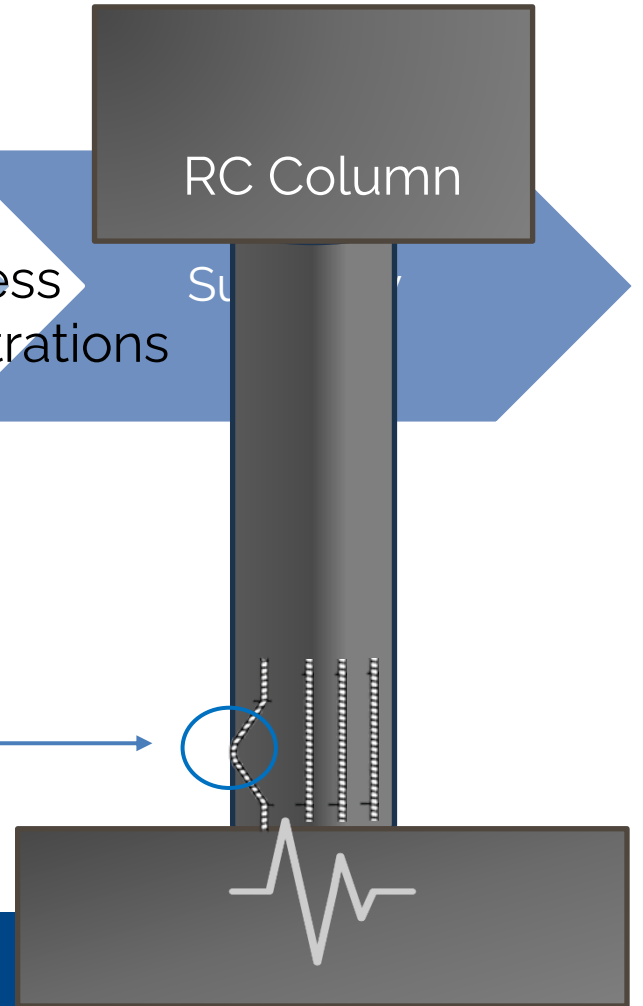
Effect of the manufacturing process on the seismic behavior of HSRS

Introduction

Seismic behavior impact: Stress concentrations



Stress concentrations




Have you considered the manufacturing process of the RS in your design process?

High Strength Reinforcing Steel

Fy ≥ 80 ksi (550 MPa)

Manufacturing processes

Micro alloy (MA)

Quenched self-tempered (QST)

High Strength Reinforcing Steel

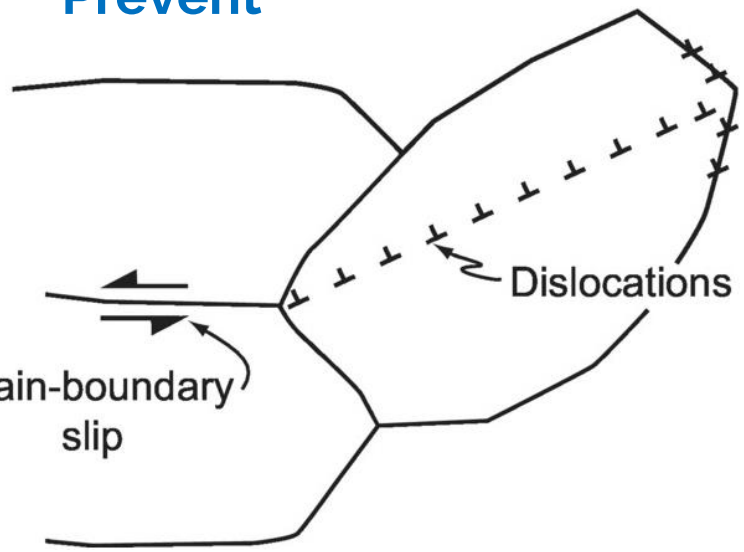
Fy ≥ 80 ksi (550 MPa)

Manufacturing processes

- Micro alloy (MA)
- Quenched self-tempered (QST)

Alloy additions:
Titanium (Ti)
Niobium (N)
Vanadium (V)
0.02 to 0.15% wt.

Prevent



cambridge.org

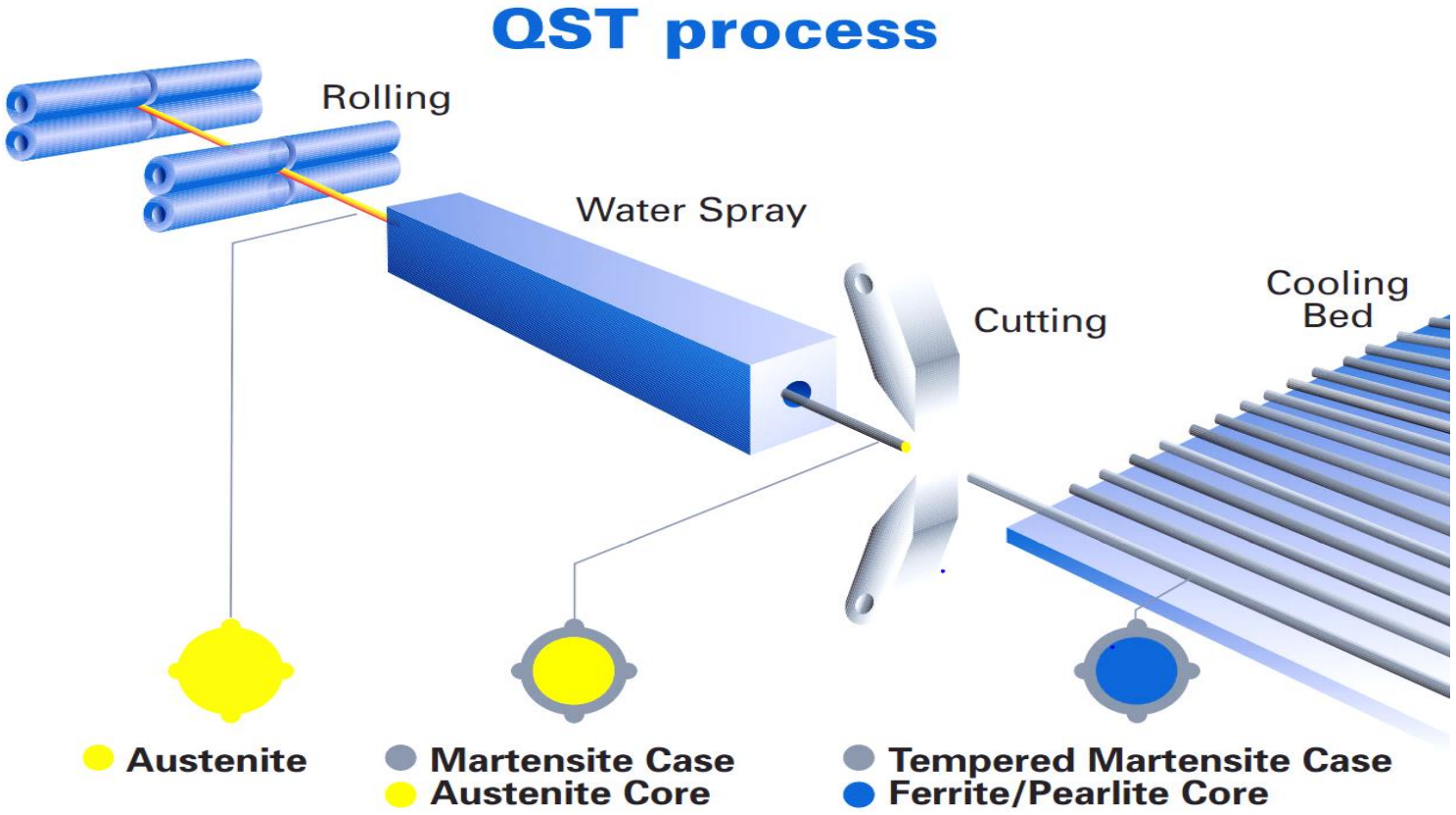
High Strength Reinforcing Steel

Fy ≥ 80 ksi (550 MPa)

Manufacturing processes

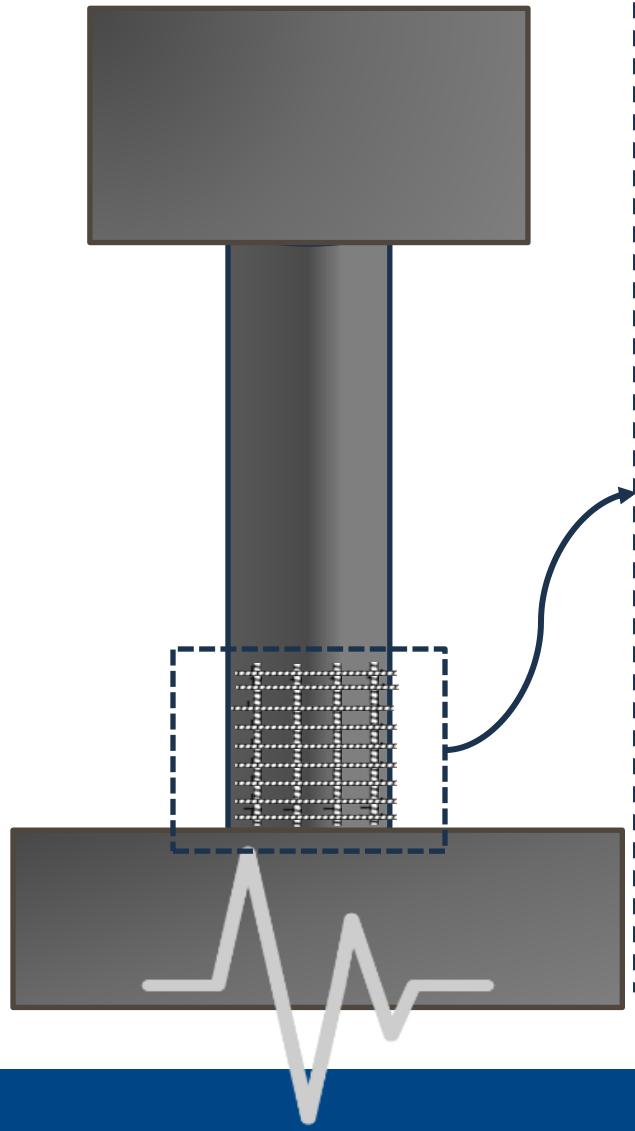
Micro alloy (MA)

Quenched self-tempered (QST)

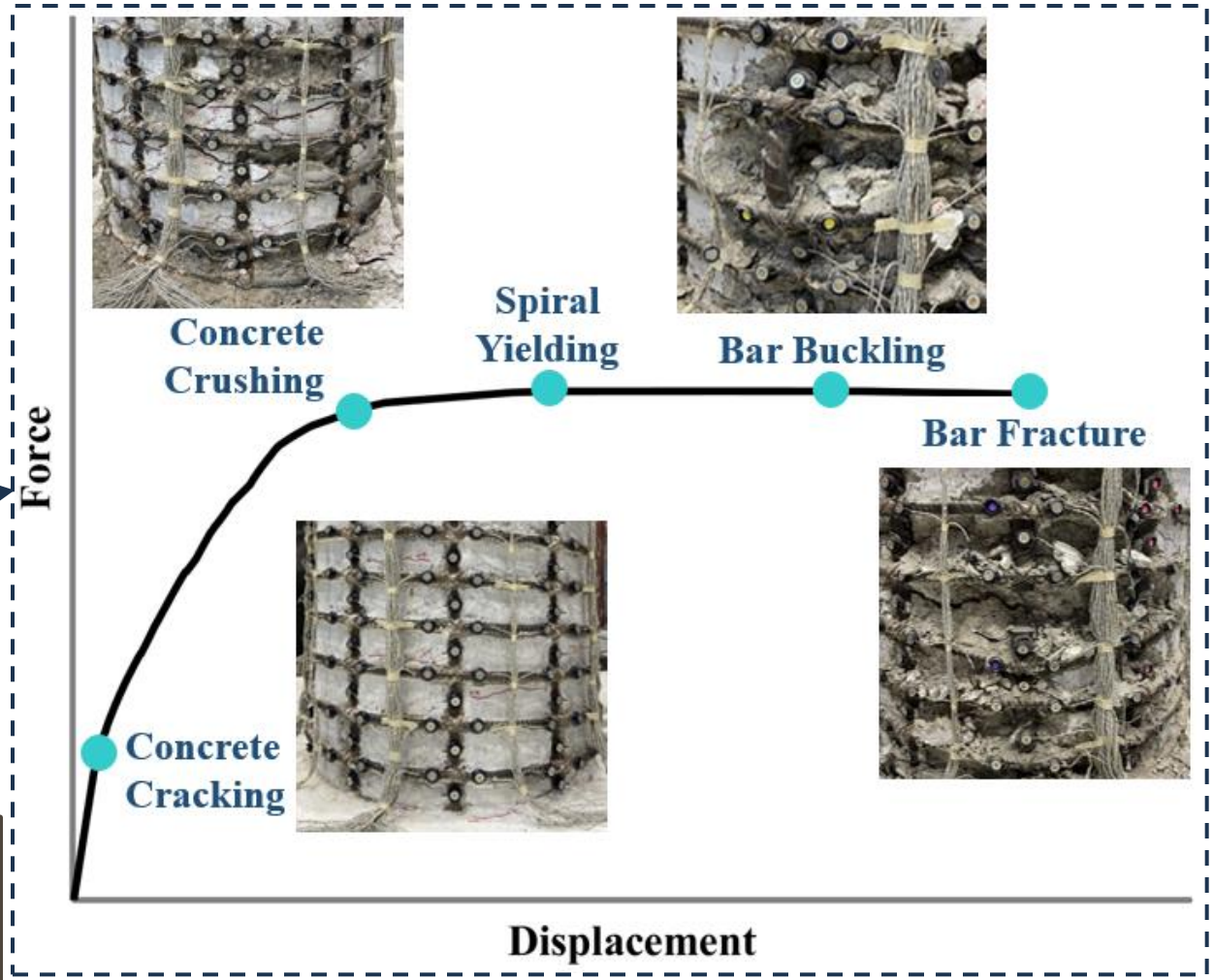


UK CARES, 2011

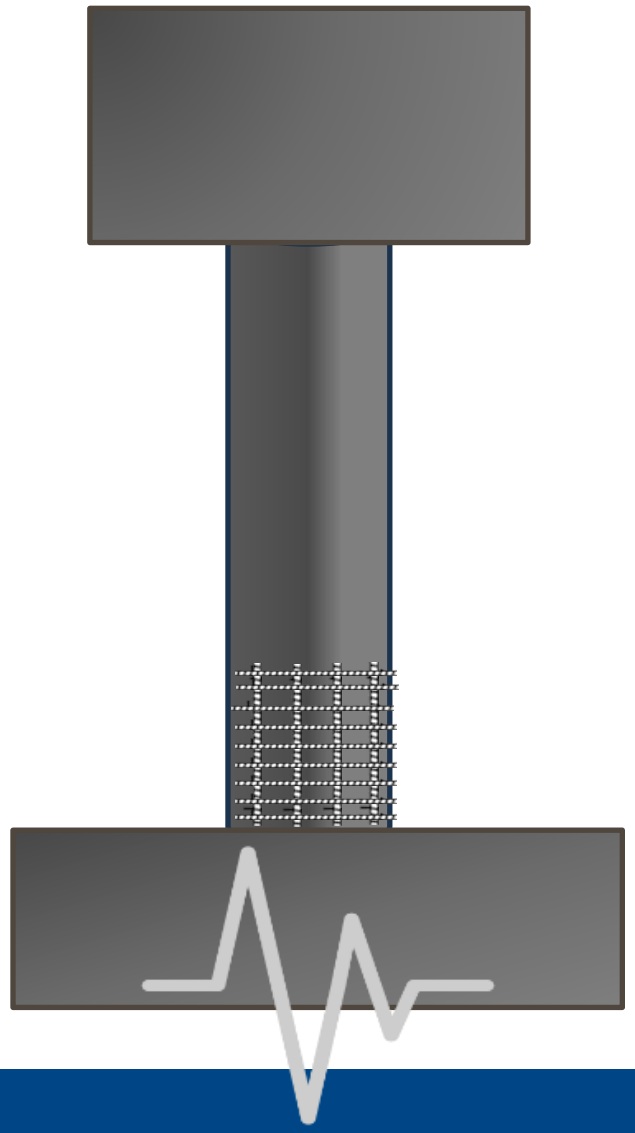
RC Column



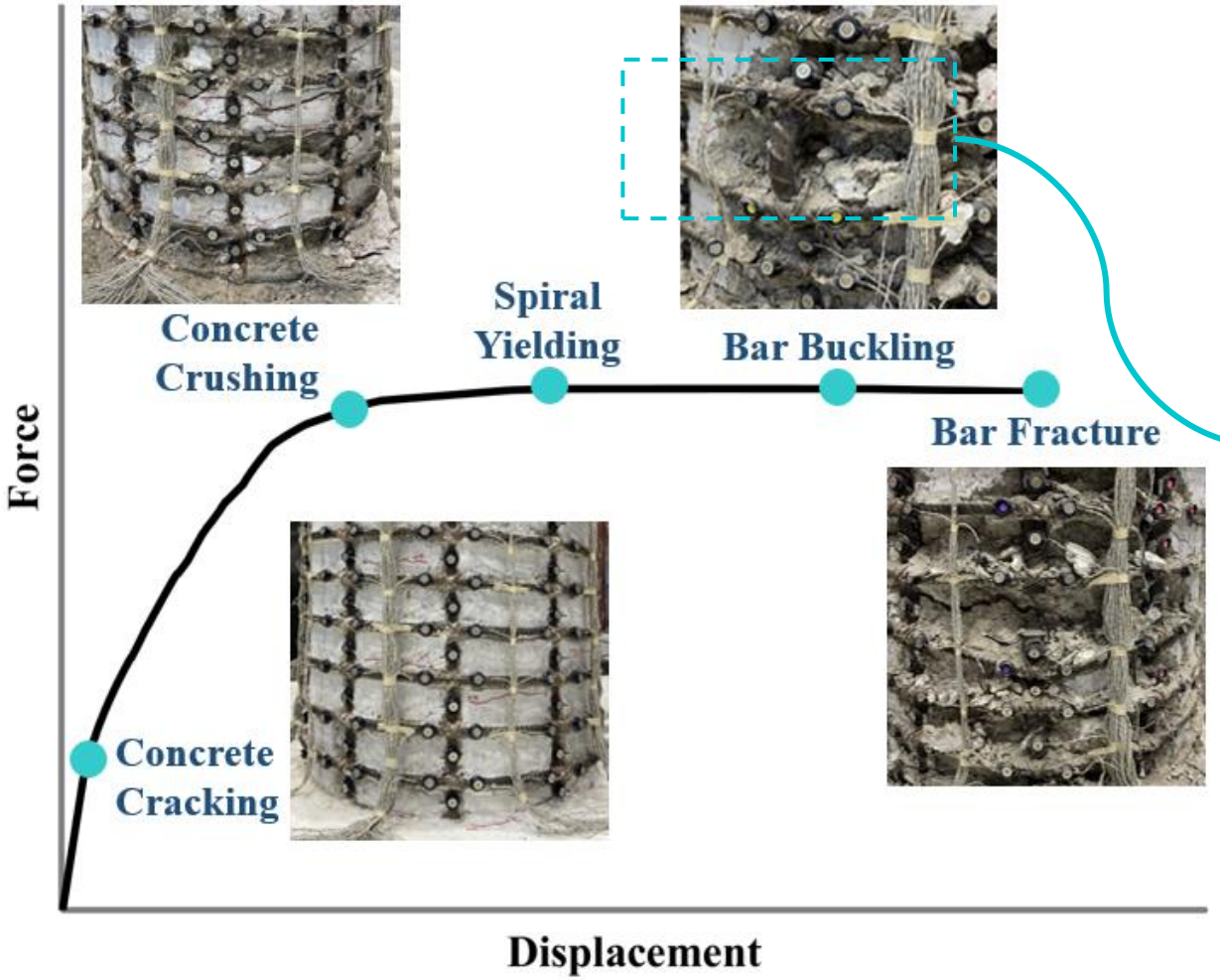
Column performance limit states



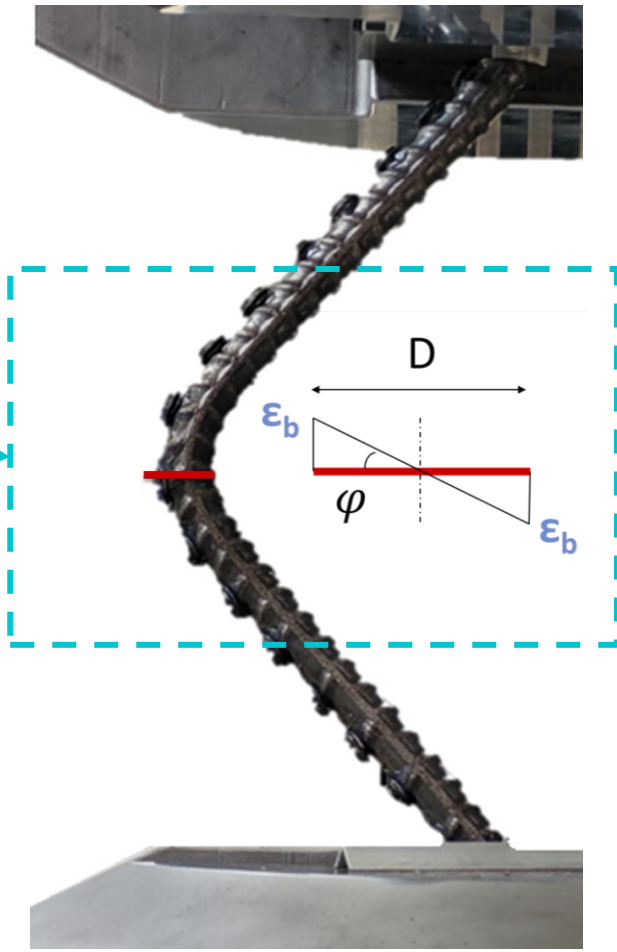
RC Column



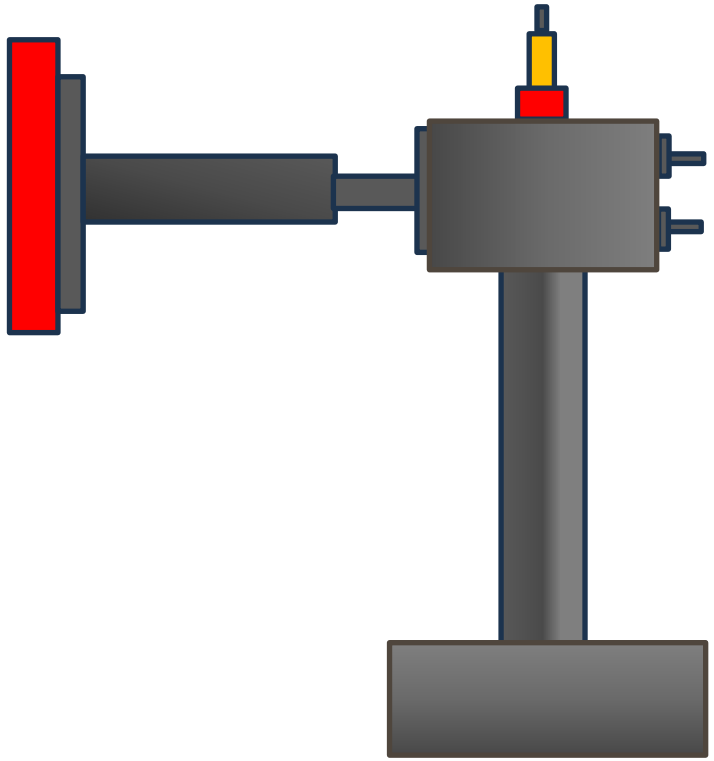
Column performance limit states

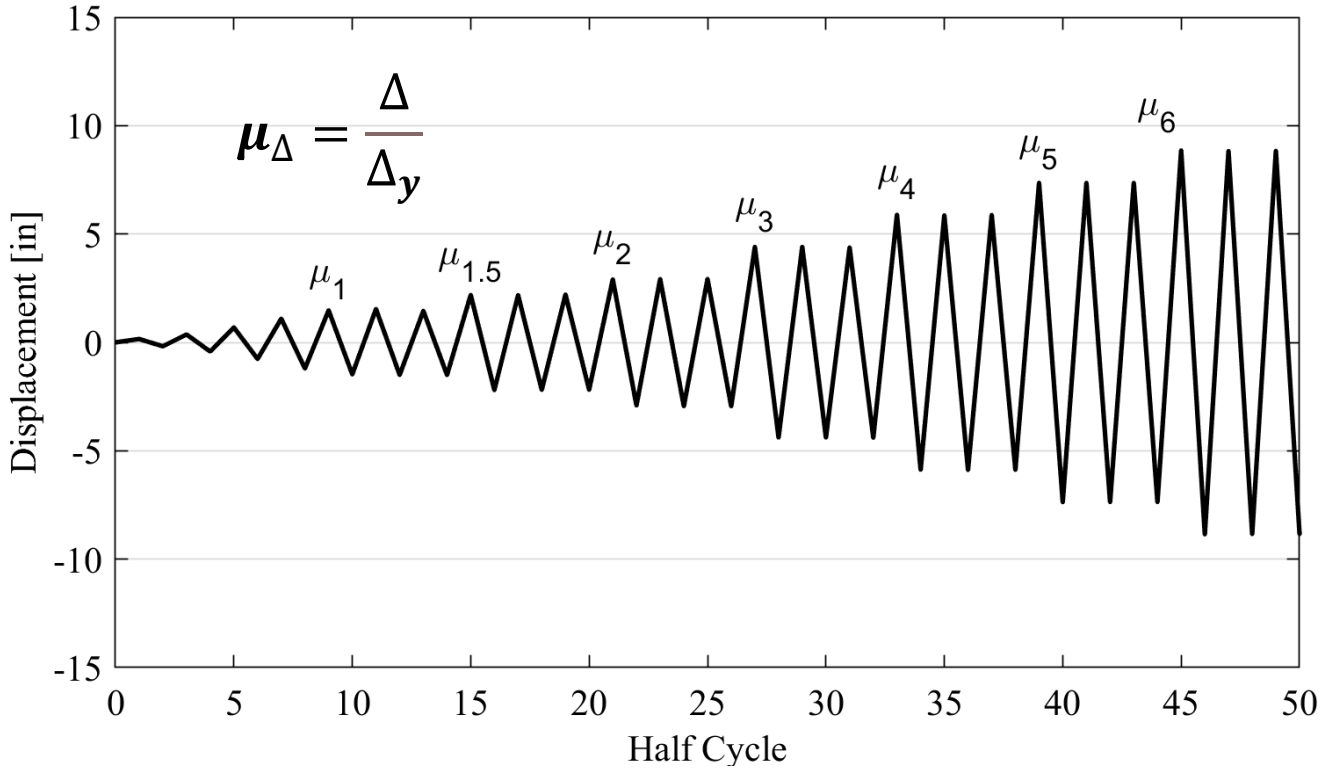


Bending strain capacity



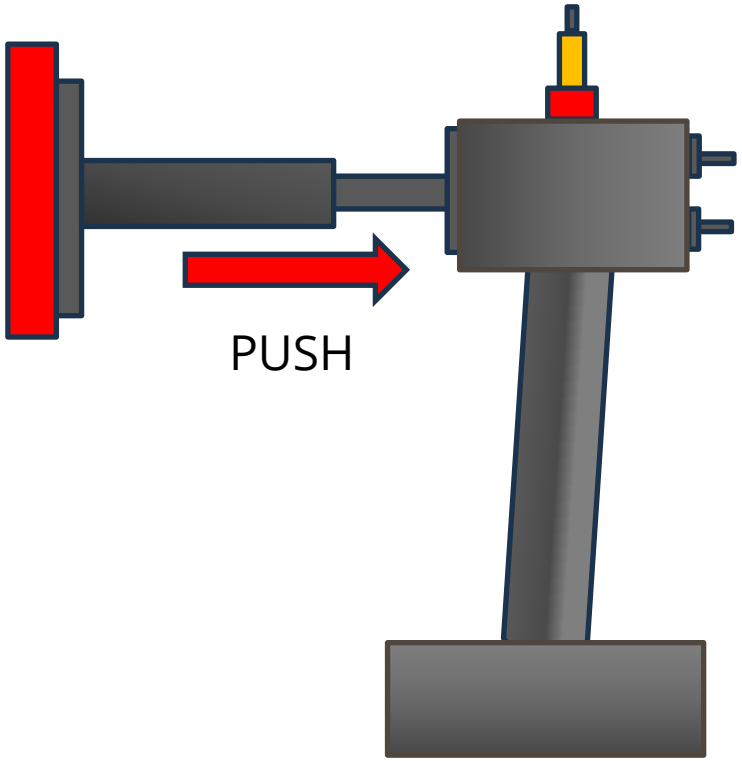
Columns subjected to quasistatic cyclic later loading

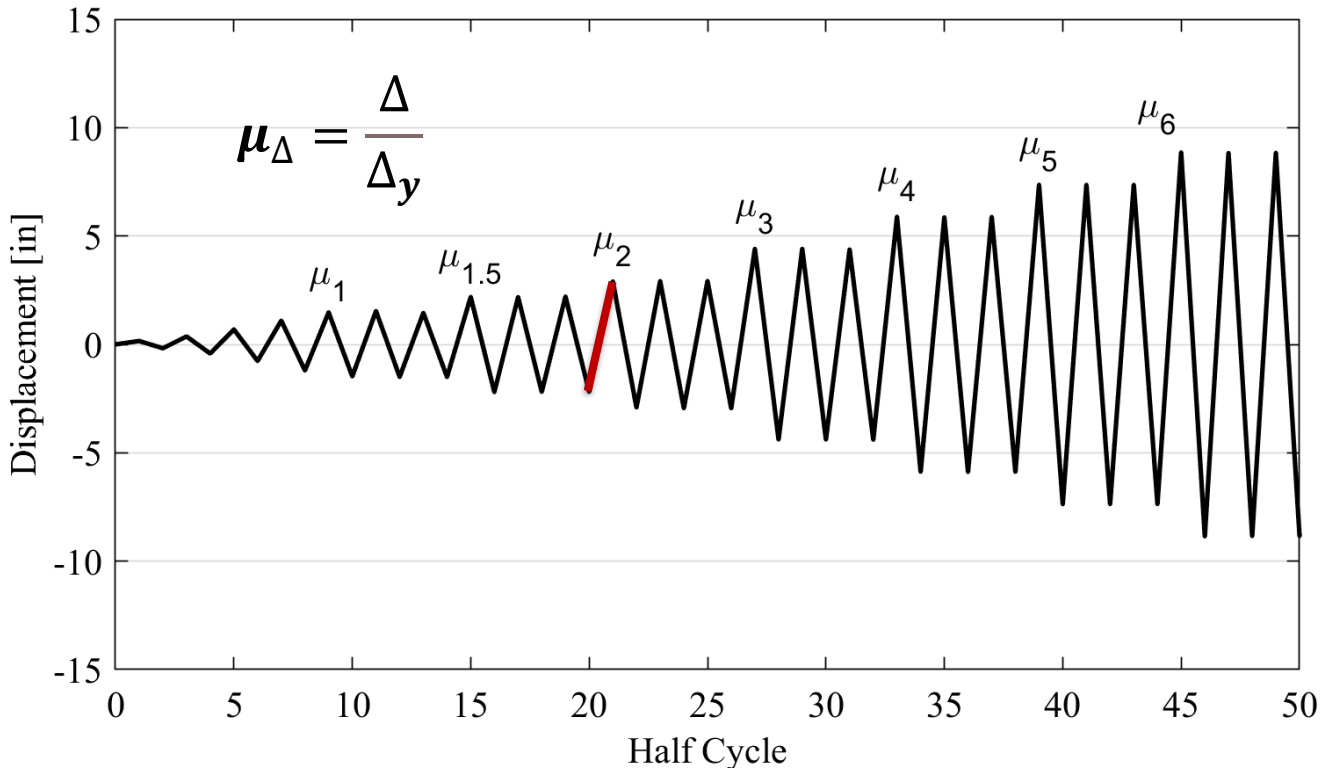




Lu Carranza, PhD student

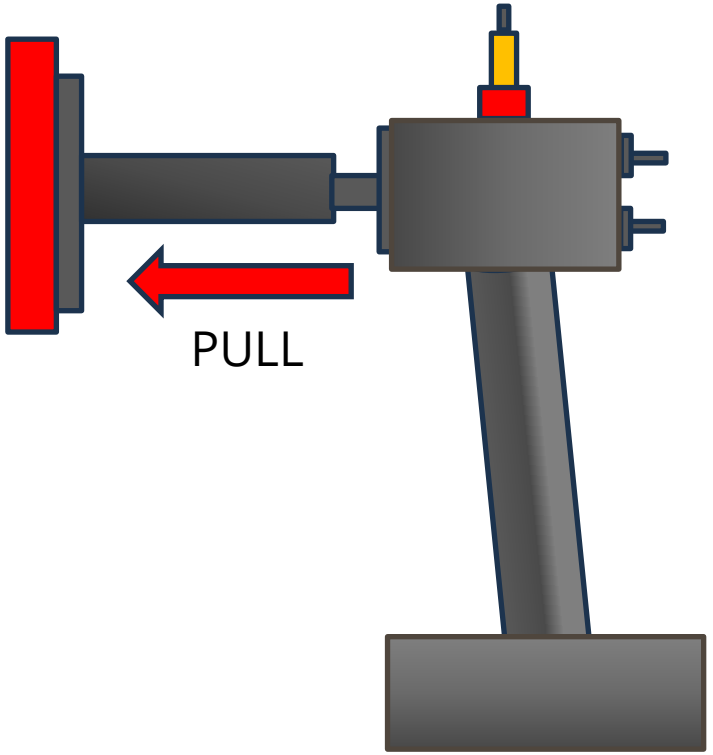
Columns subjected to quasistatic cyclic later loading

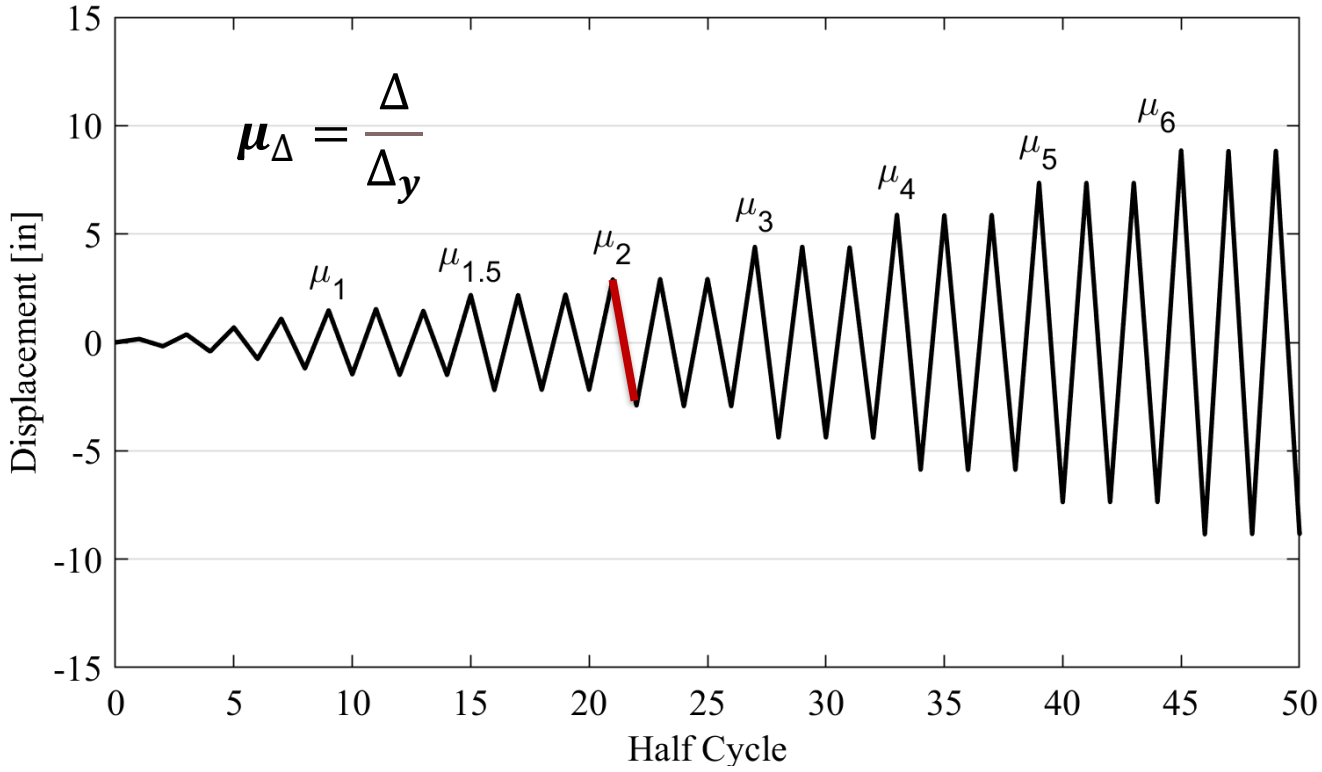




Lu Carranza, PhD student

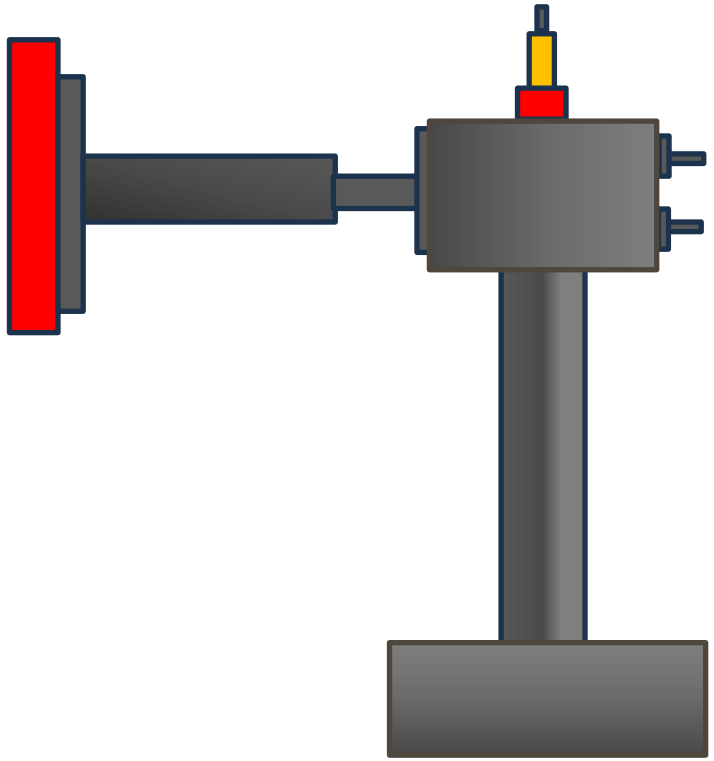
Columns subjected to quasistatic cyclic later loading

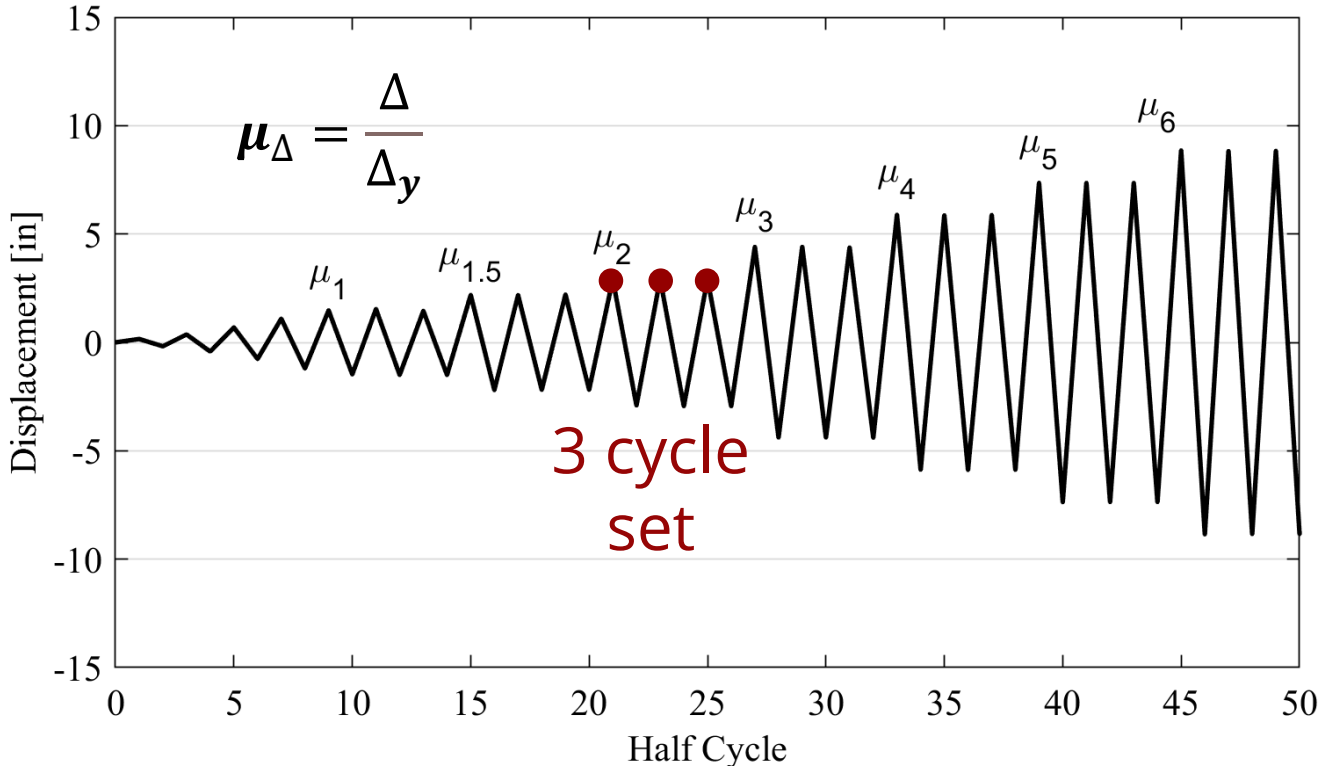




Lu Carranza, PhD student

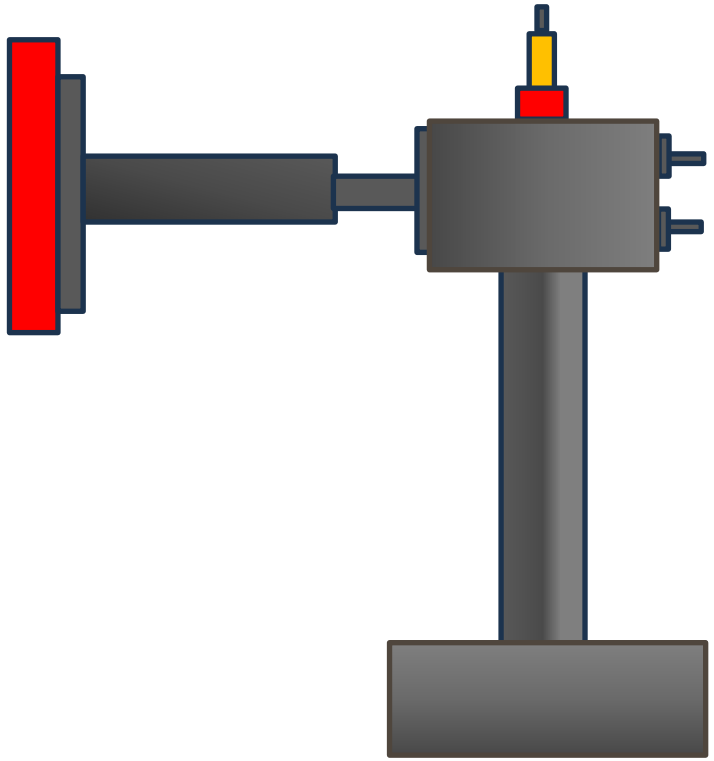
Columns subjected to quasistatic cyclic later loading

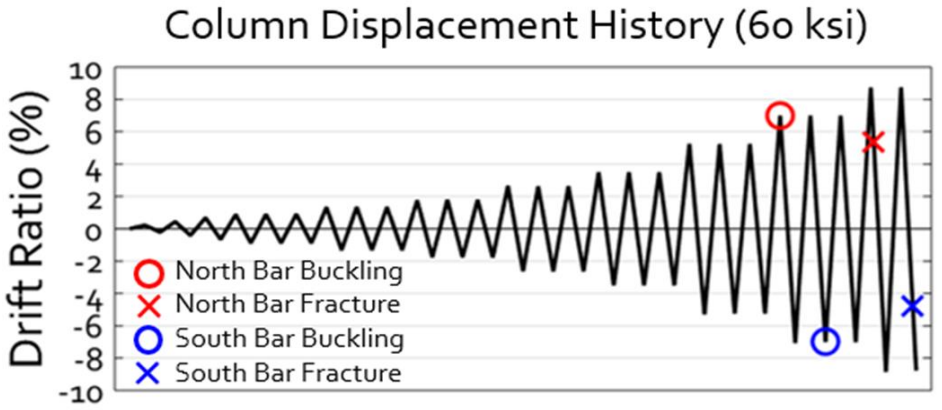


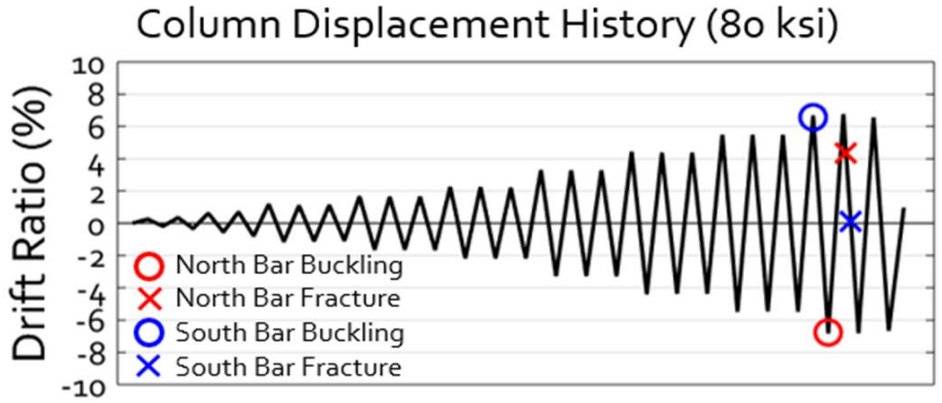


Lu Carranza, PhD student

Columns subjected to quasistatic cyclic later loading







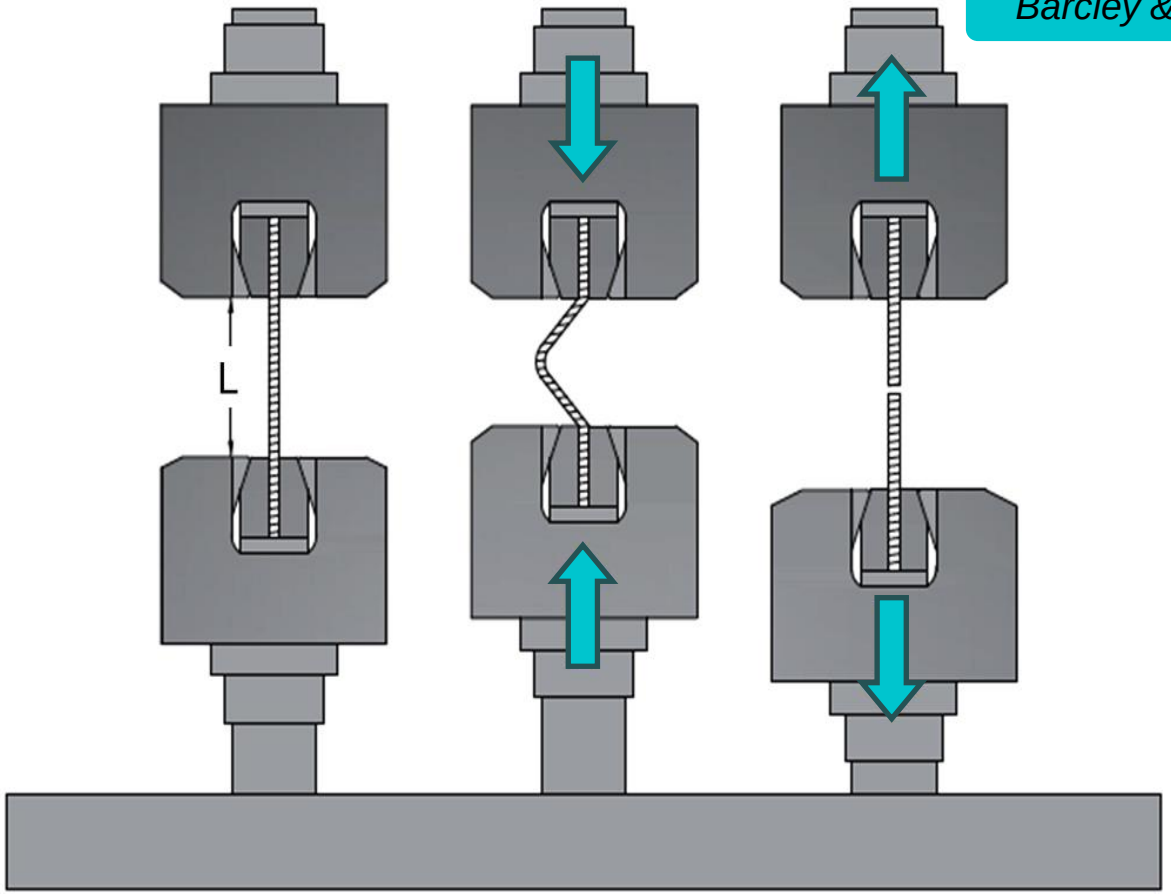
Post Buckling Behavior

Barcley and Kowalsky (2018)

Lu Carranza, PhD student

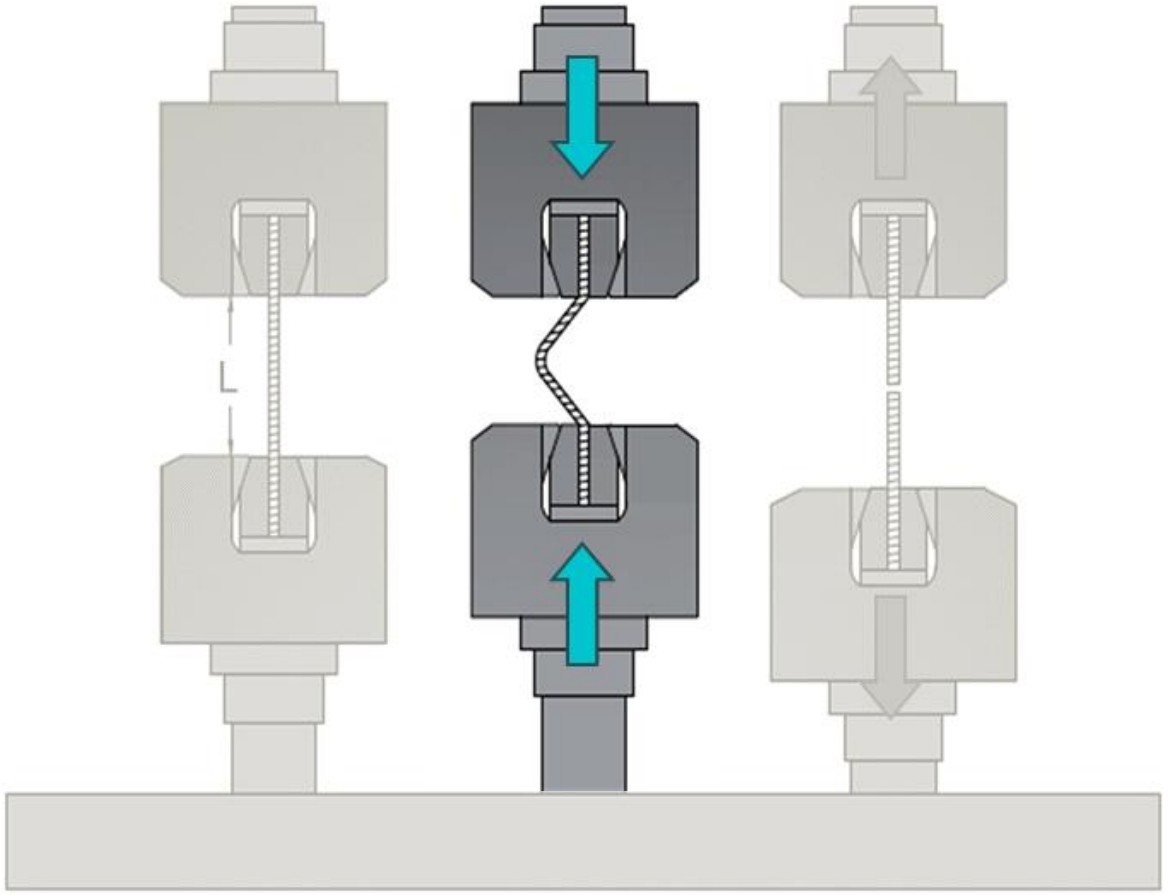
The Buckled Bar Tension Test (BBT test)

Barcley & Kowalsky, 2018



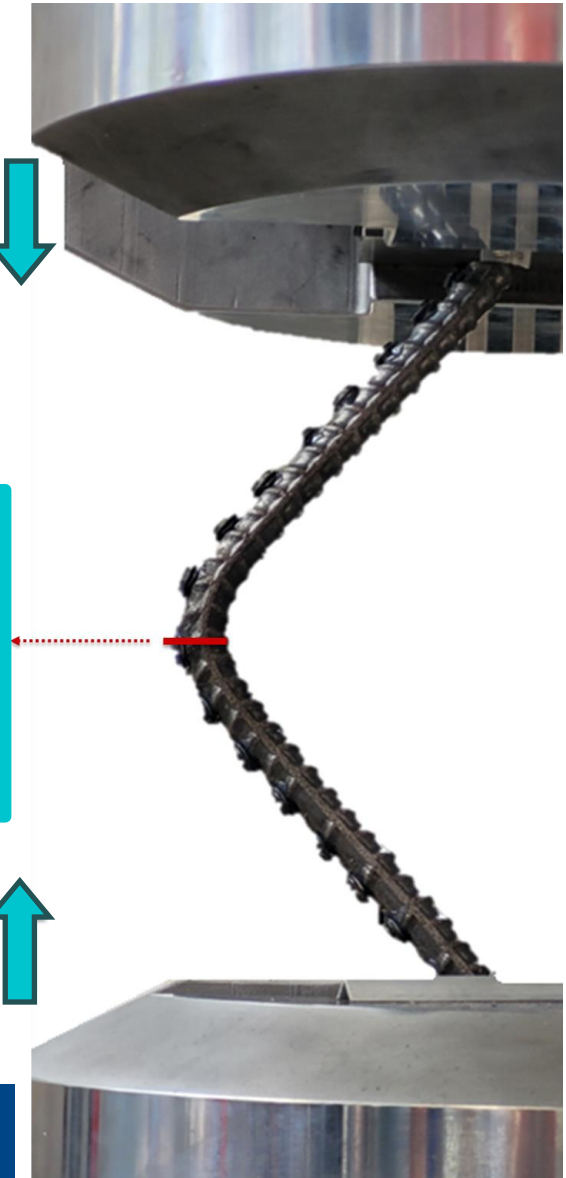
Test sequence

The Buckled Bar Tension Test (BBT test)

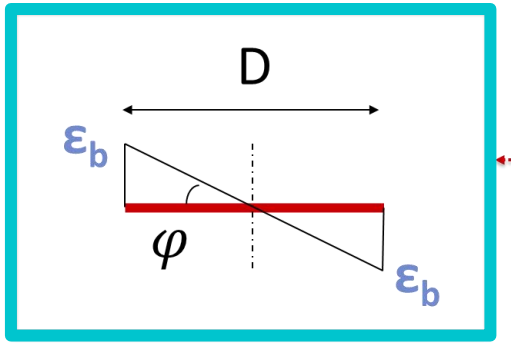


Test sequence

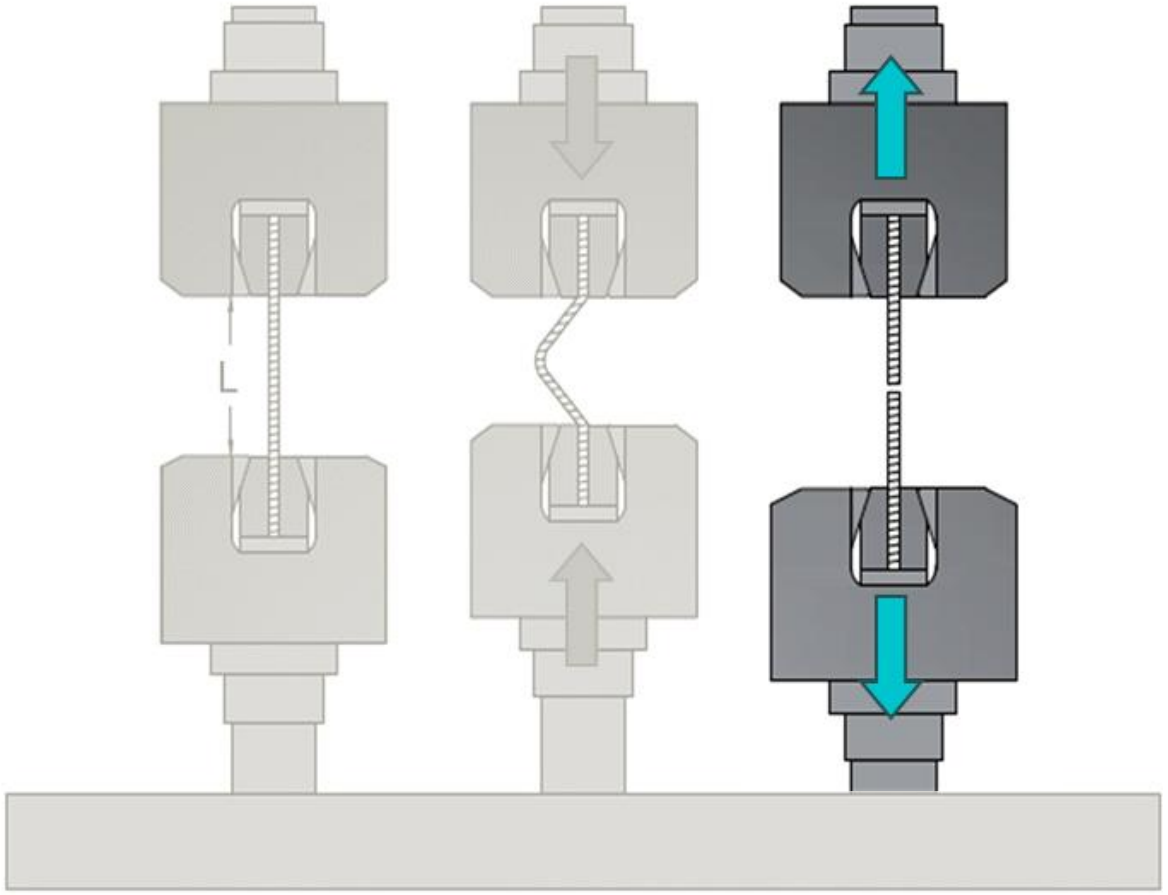
Δ_{axial}



Bending strain



The Buckled Bar Tension Test (BBT test)



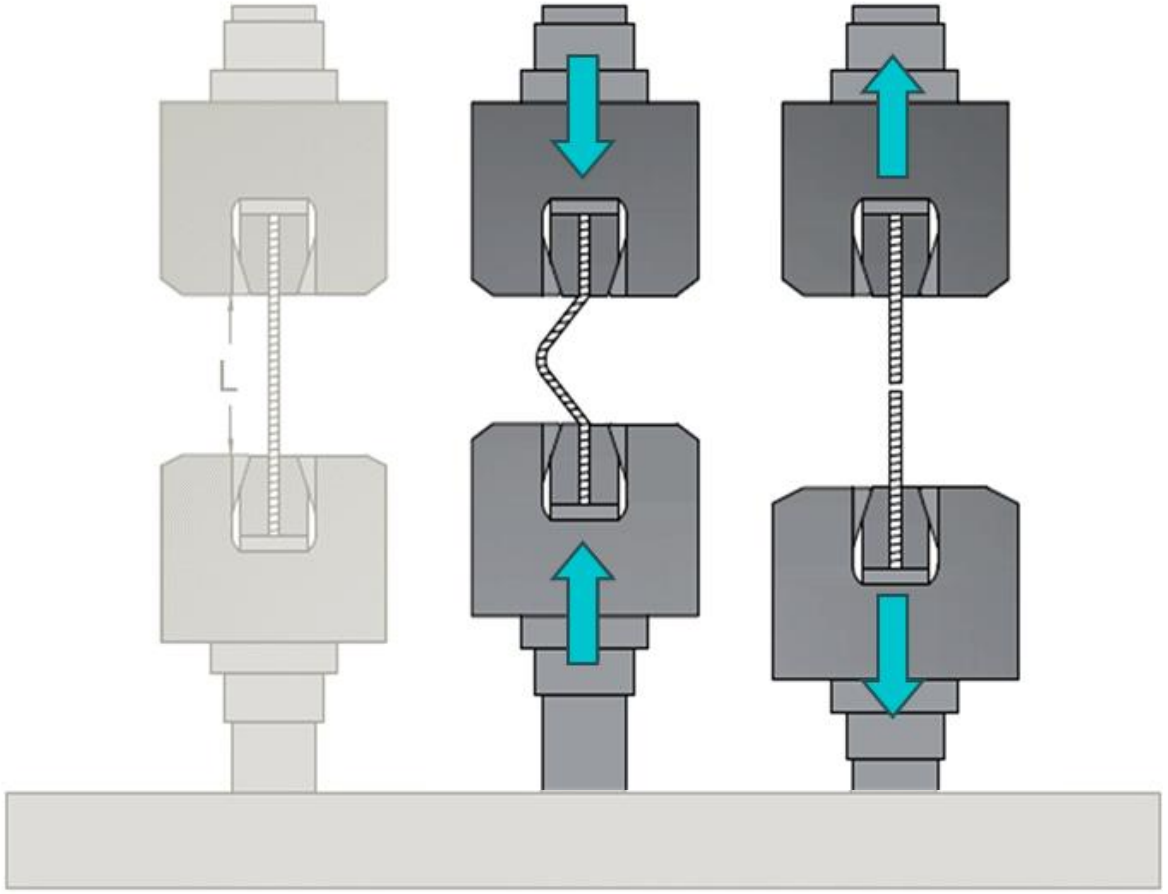
Test sequence

Failure mode – uniform elongation

Ductile Brittle

Transition

The Buckled Bar Tension Test (BBT test)



Test sequence

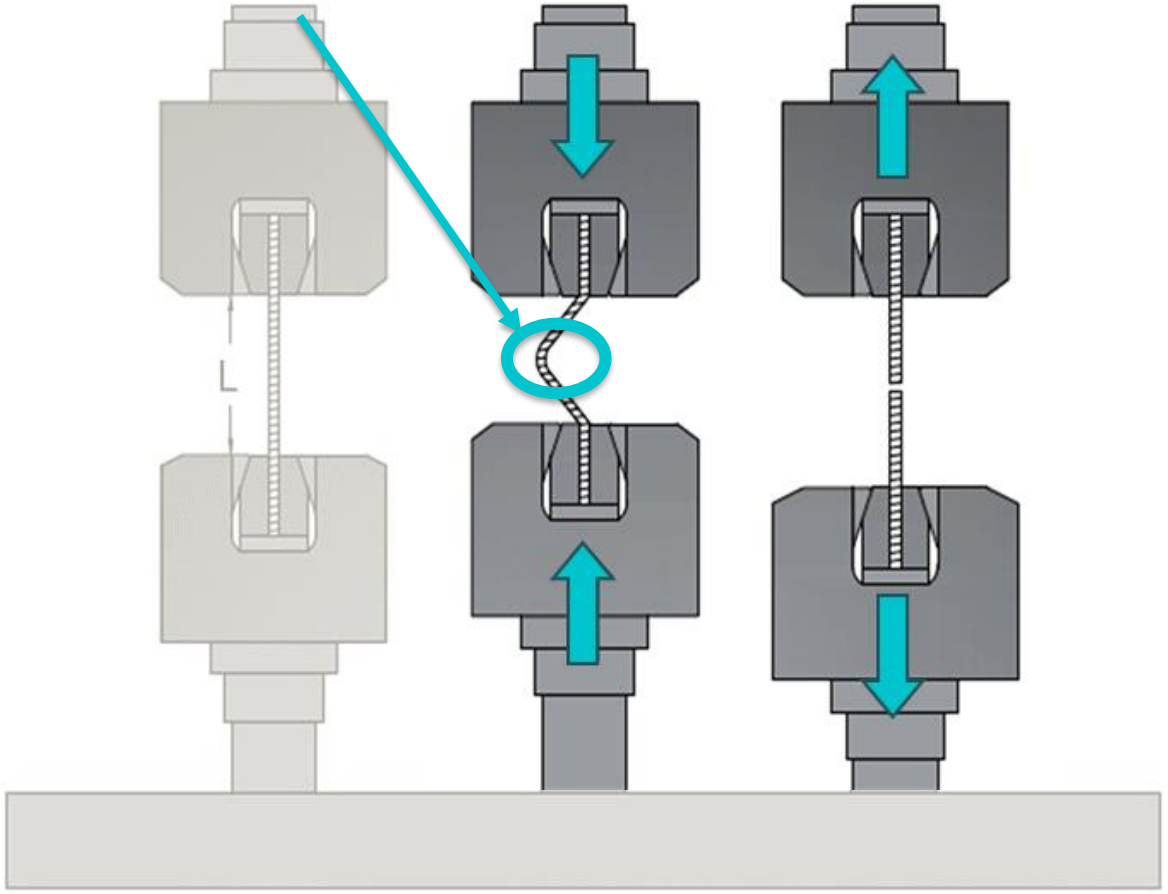
Critical bending strain (ε_{cr})

Ductile — Brittle

Transition

The Buckled Bar Tension Test (BBT test)

Stress concentrations



Test sequence

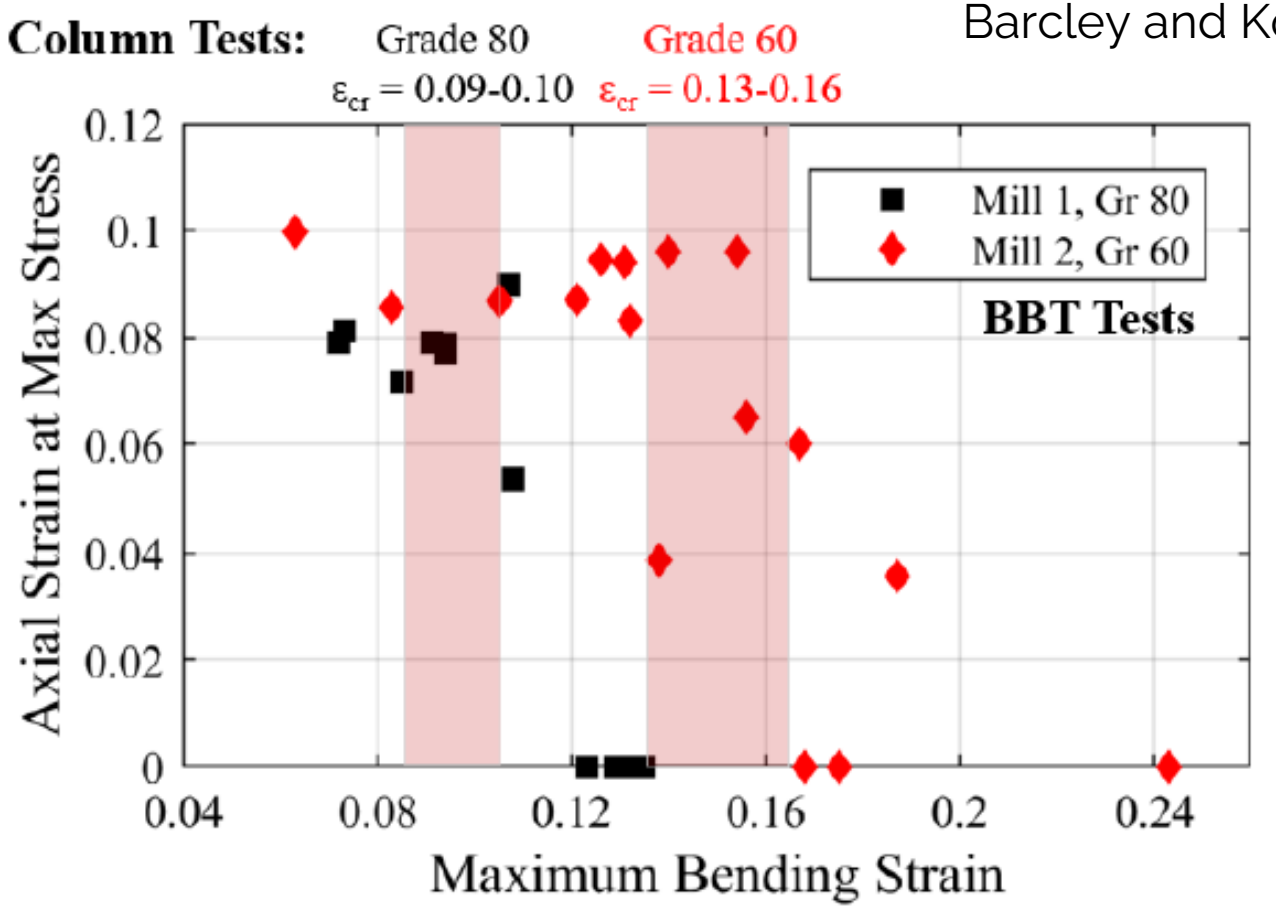
Critical bending strain (ε_{cr})

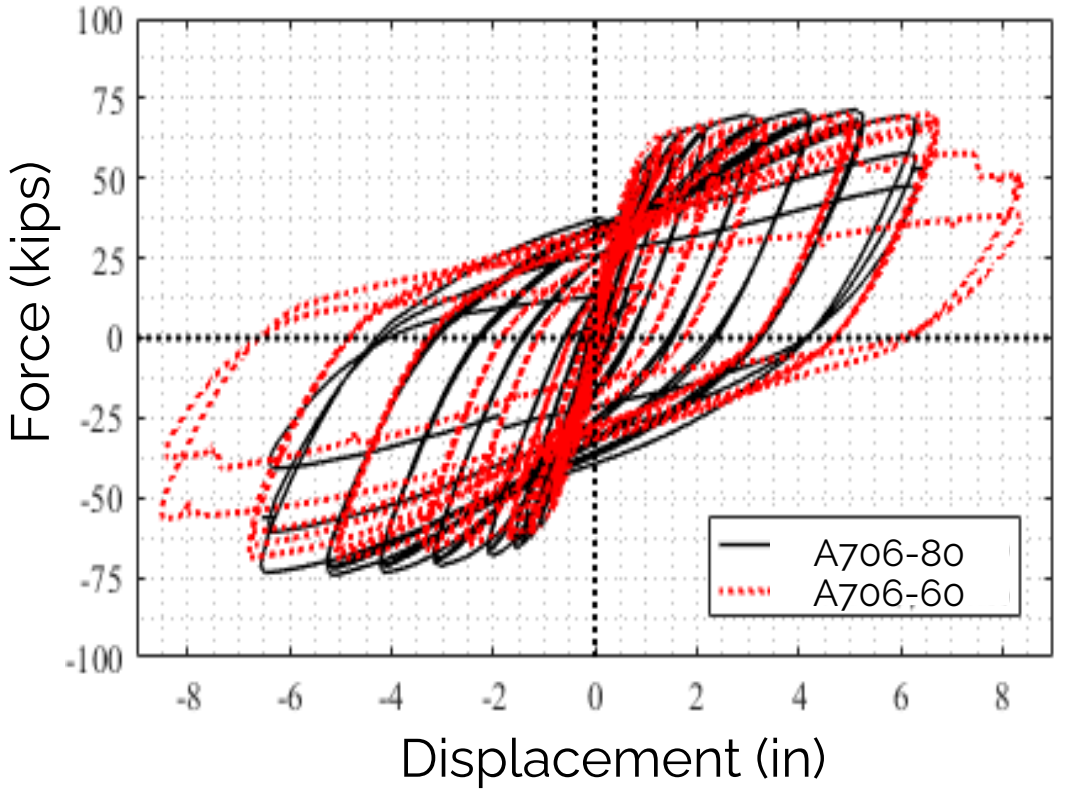
Ductile — Brittle

Transition

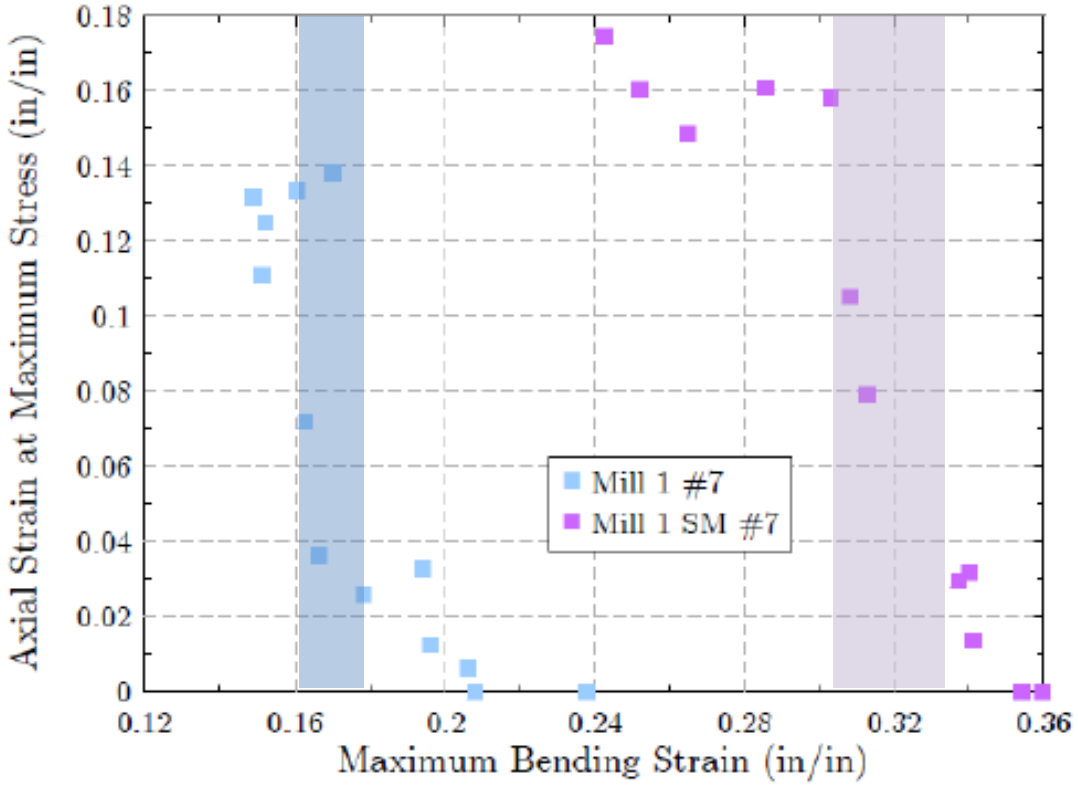
Differences with Grade 60 steel include lower displacement capacity and few post-buckling cycles until fracture – Lower bending strain capacity

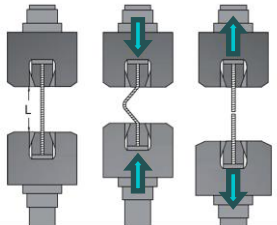
Barcley and Kowalsky (2018)





The Buckled Bar Tension Test (BBT test)



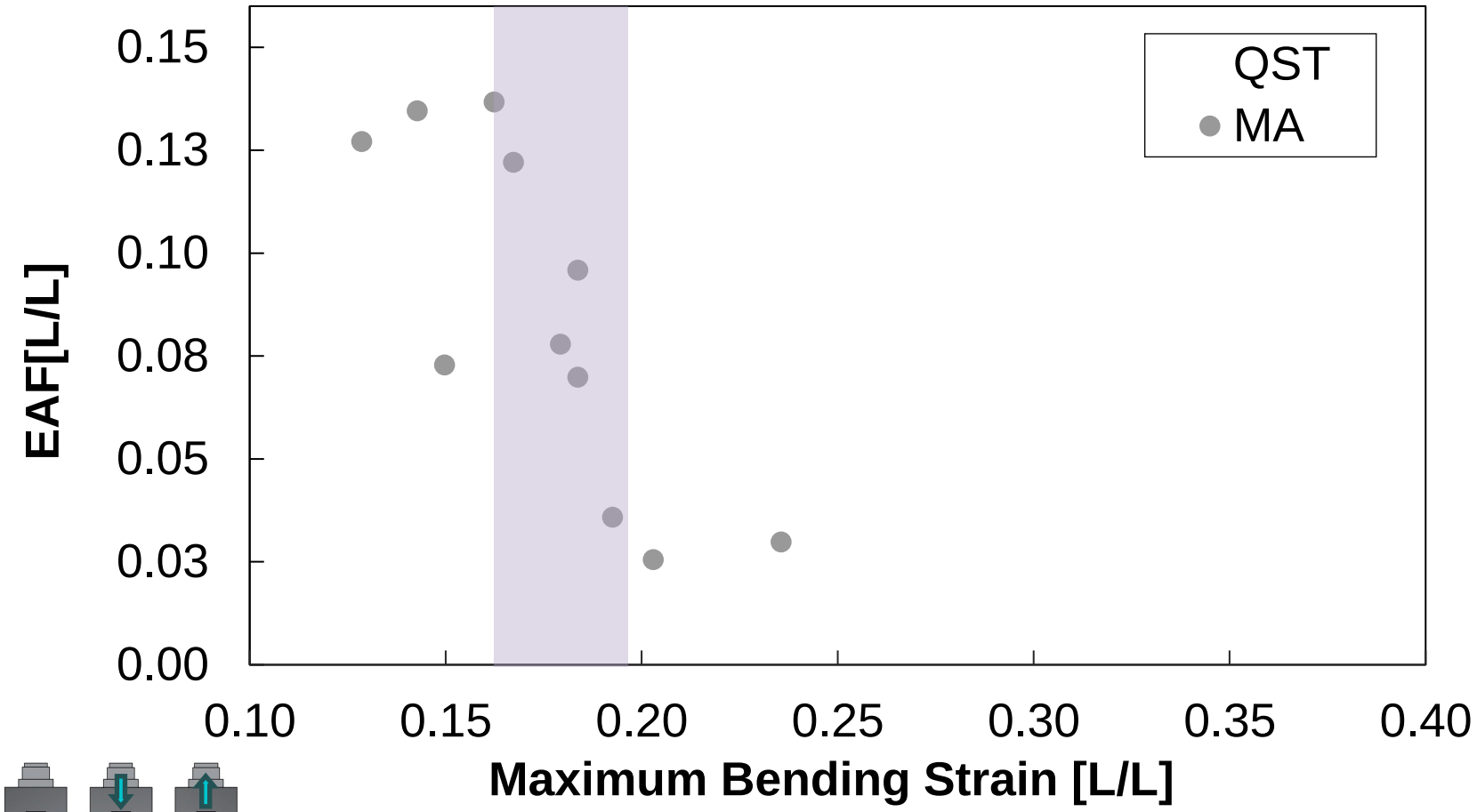


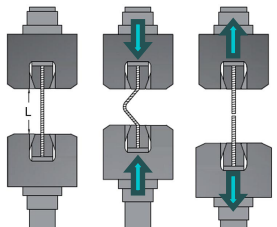
BBT Test Results of Smooth and Ribbed Longitudinal Steel
Thangjitham (2023)

Rib radii

Barcley and Kowalsky (2018)

The Buckled Bar Tension Test (BBT test)



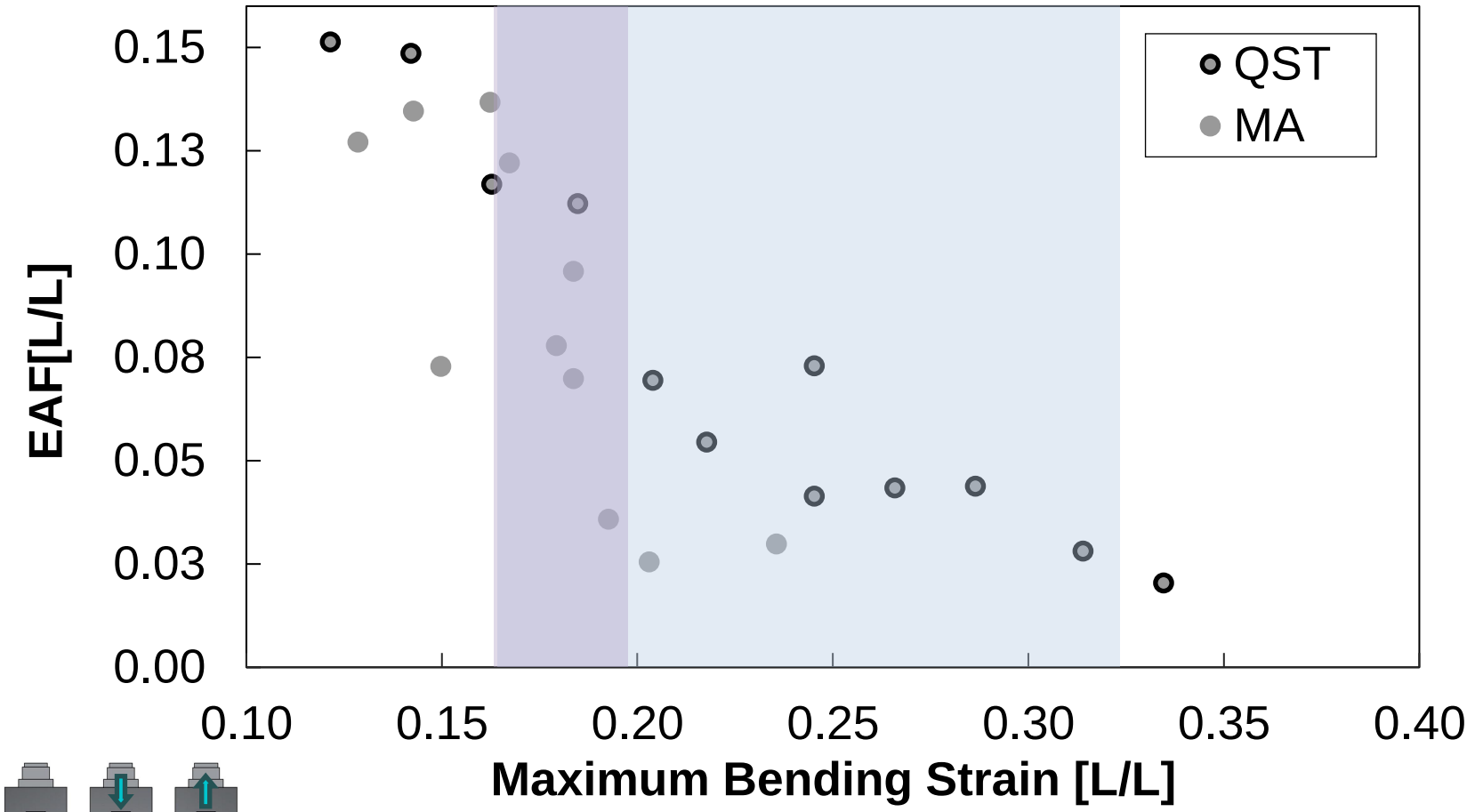


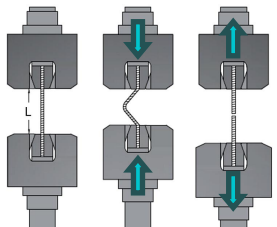
Manufacturing process

Quenched Self Temperated (QST)

Micro Aloyed (MA)

The Buckled Bar Tension Test (BBT test)



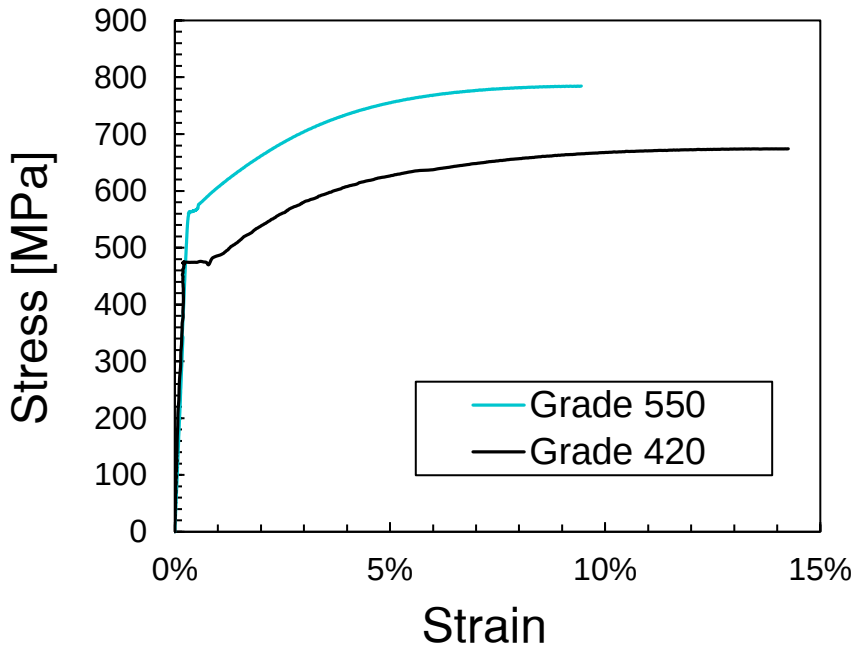


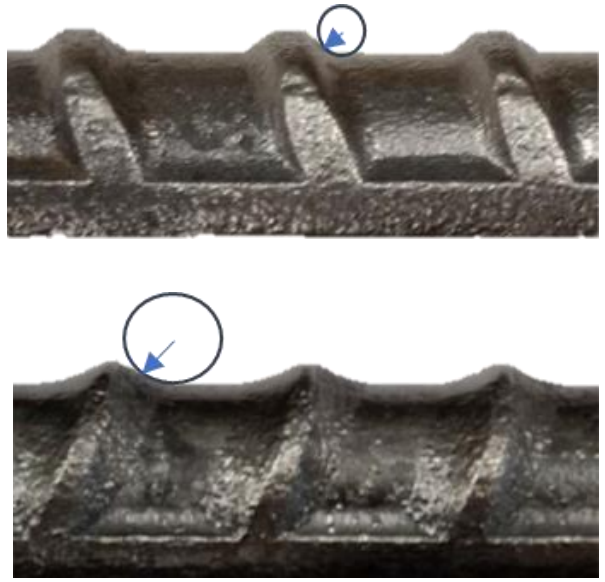
Manufacturing process

Quenched Self Temperated (QST)

Micro Aloyed (MA)

Bending strain capacity
STRESS CONCENTRATIONS





Barcley and Kowalsky (2018)

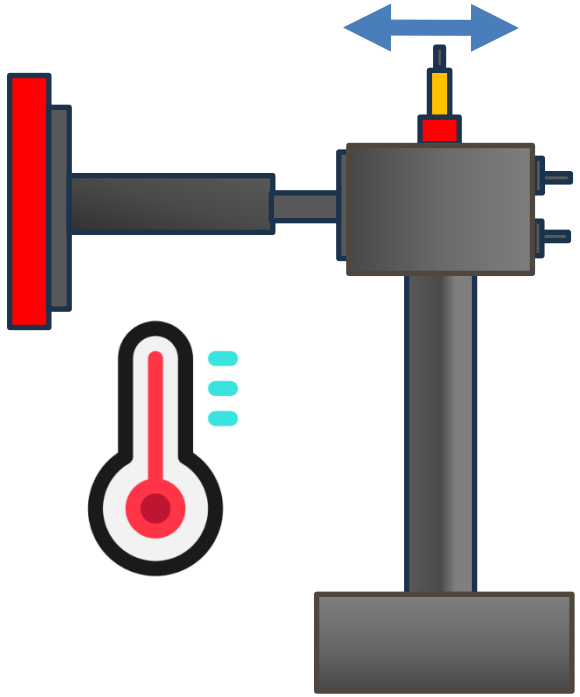
Quenched Self Temperated (QST)

Micro Aloyed (MA)

Bending strain capacity STRESS CONCENTRATIONS

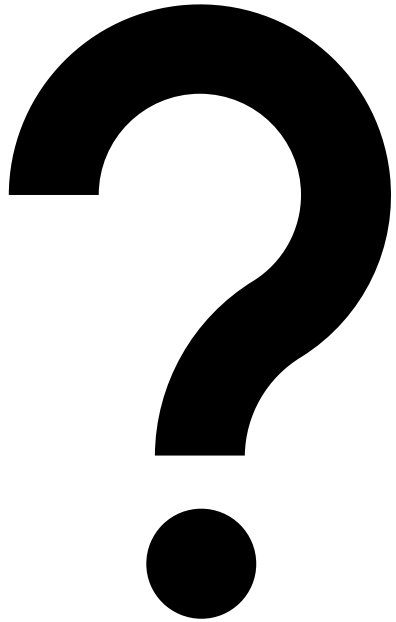
Quenched Self Temperated (QST)

Micro Aloyed (MA)



Quasistatic lateral loading

Room temperatures

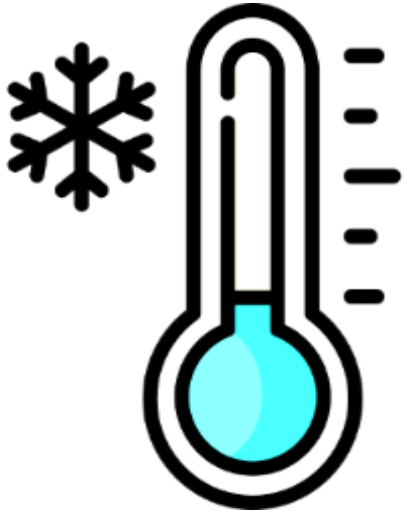


Bending strain capacity STRESS CONCENTRATIONS

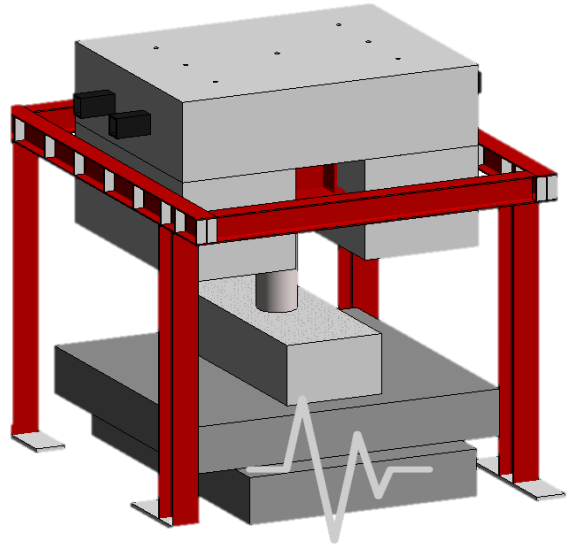
Quenched Self Temperated (QST)

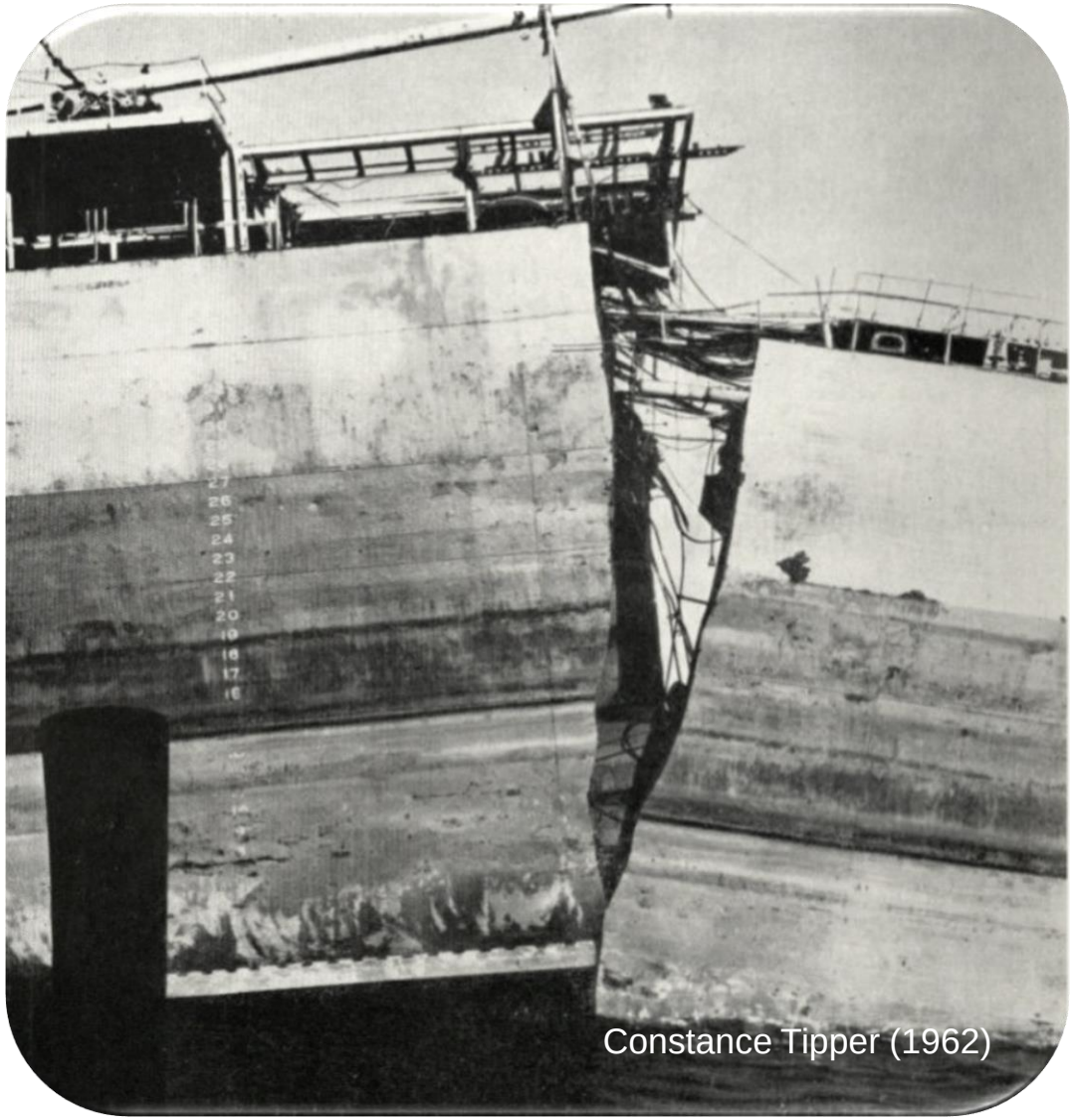
Micro Aloyed (MA)

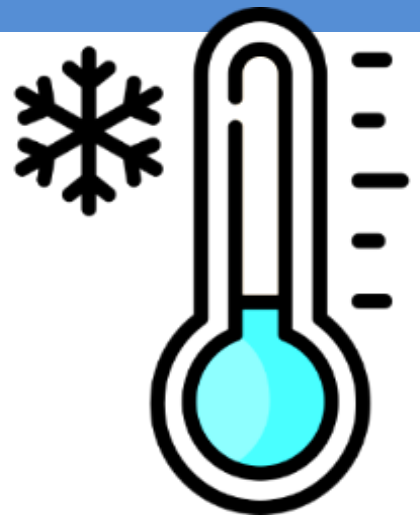
Low Temperature



High strain rates




Constance Tipper (1962)



+ Low temperatures
STRESS
CONCENTRATIONS

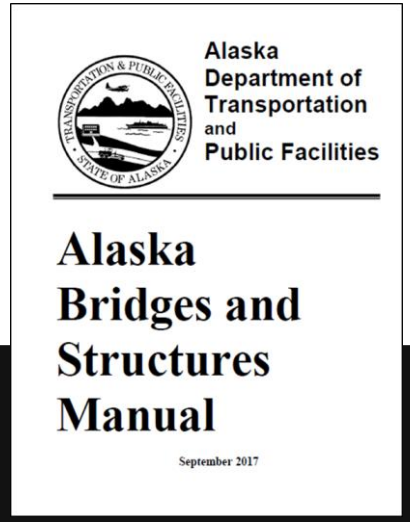
Liberty tanker *Schenectady*

SEISMICITY

Of all seismicity in the United States

TEMPERATURE

Lowest temperature average state in the United States

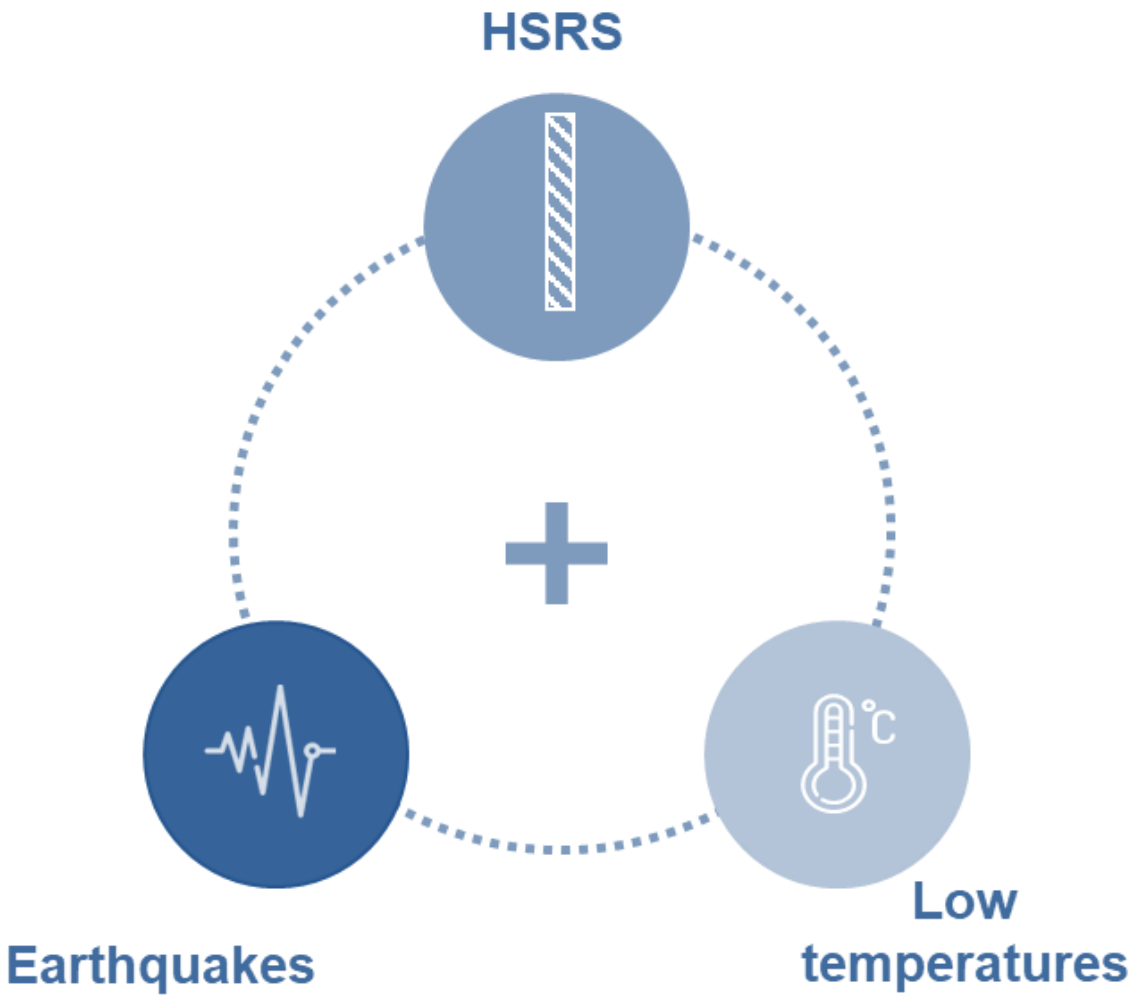


HSRS

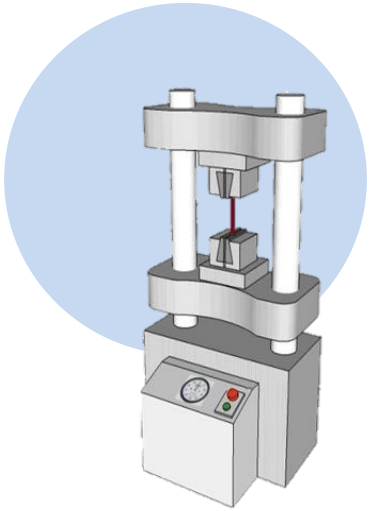
Not allowed in members expected to form plastic hinges

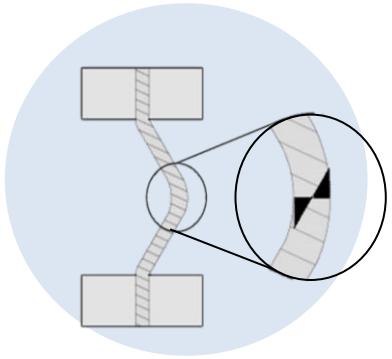
Temperature-dependent requirements

- Expected material properties
- Over strength factors
- Plastic hinge length reduction factor

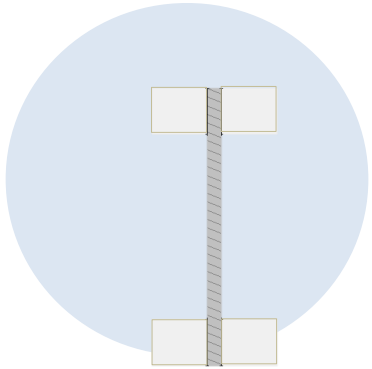

HSRS
Earthquakes
Low temperatures

MATERIAL LEVEL EVALUATION





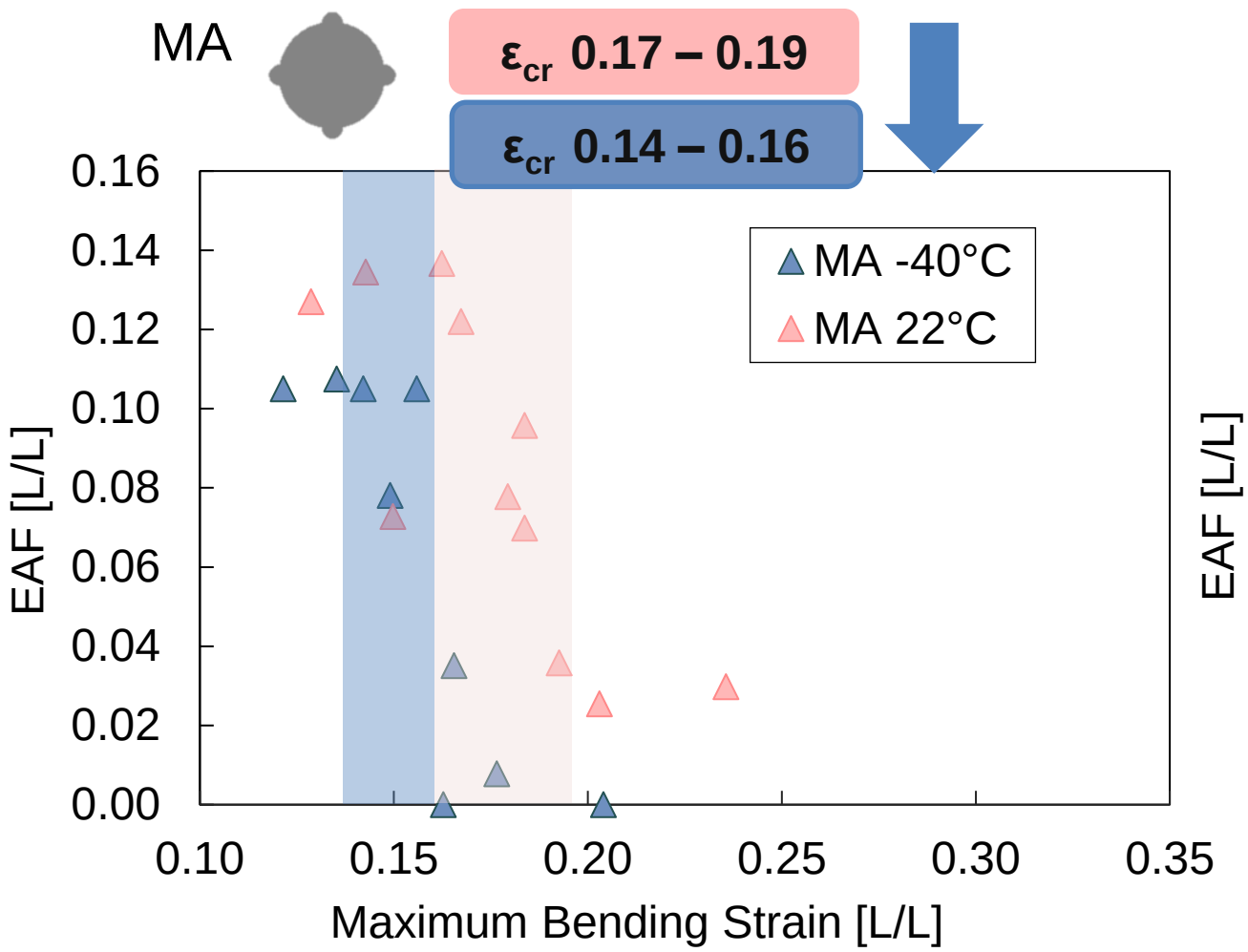
Buckled Bar Tension Test (BBT)

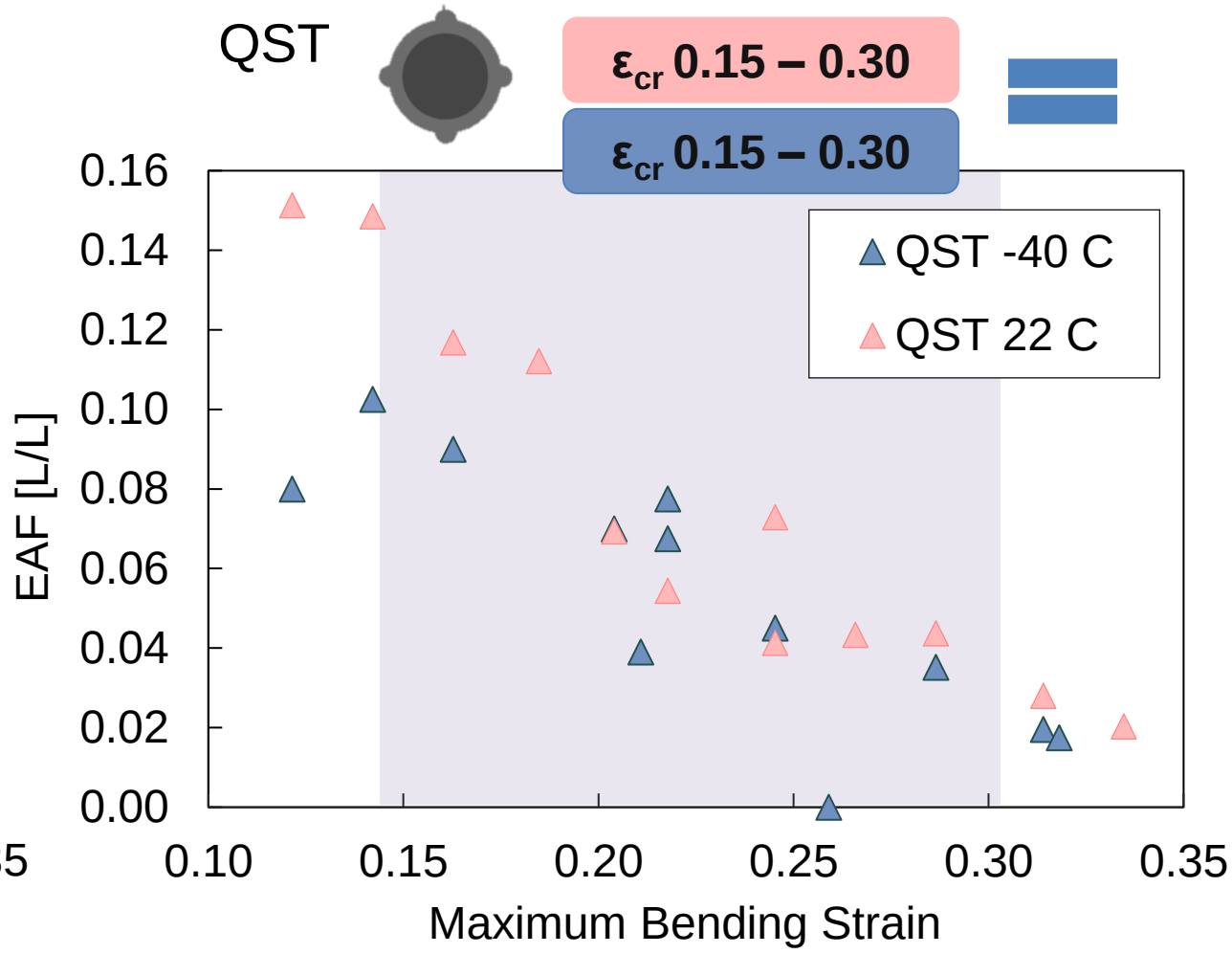


Monotonic Tension Test

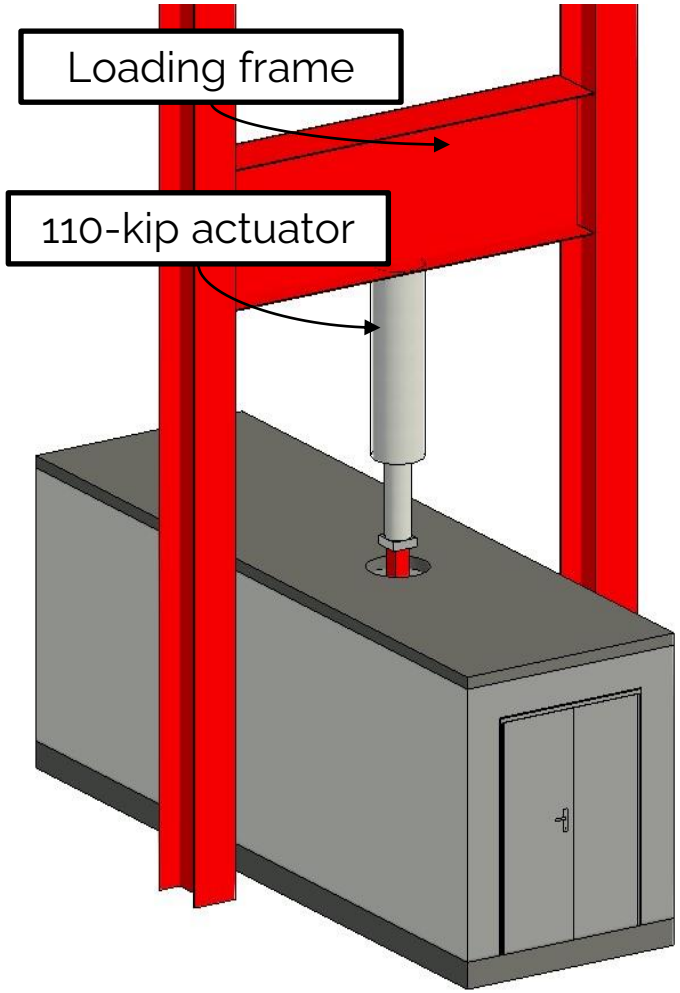
- Manufacturing process
  -  MA
  -  QST
- Steel grade
  - ASTM 706 Gr.80 (550 MPa)
  - ASTM 706 Gr.100 (690 MPa)
- Temperature
  - **72°F (22°C)**
  - **-40°F (-40°C)**

Buckled Bar Tension Test

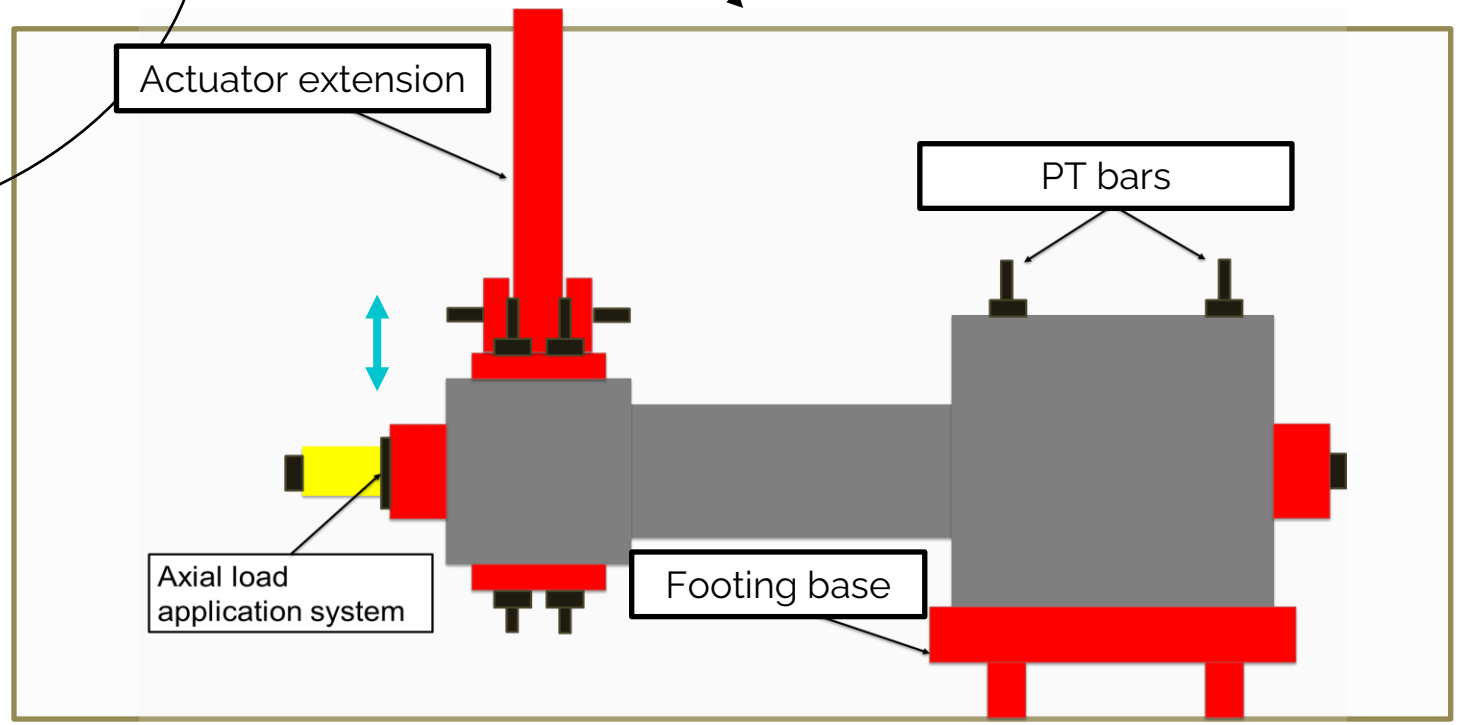




Quasi-static cyclic lateral loading on RC columns



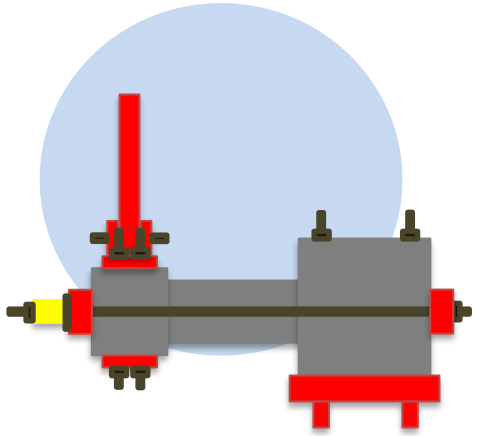
Environmental chamber



Manufacturing process

MA	72°F (22°C)
QST	-40°F (-40°C)

Large scale testing



MA

QST

72°F (22°C)

-40°F (-40°C)

Develop design recommendations to incorporate HSRS in cold seismic regions

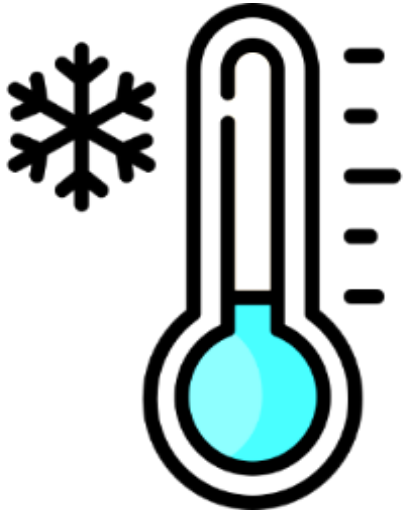
AK DOT&PF

Bending strain capacity STRESS CONCENTRATIONS

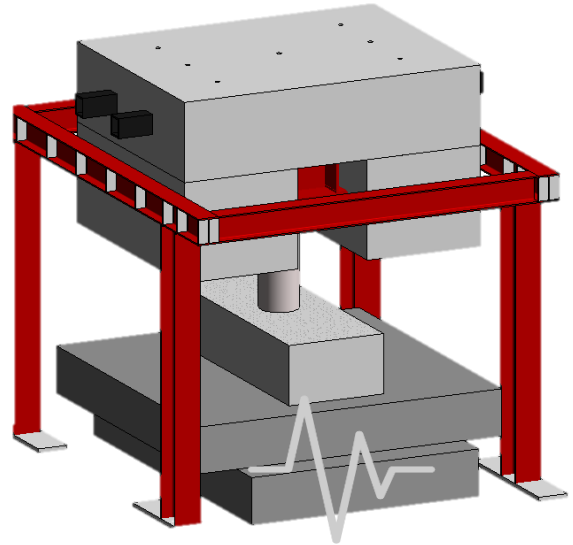
Quenched Self Temperated (QST)

Micro Aloyed (MA)

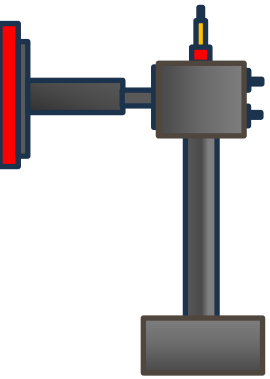
Low Temperature

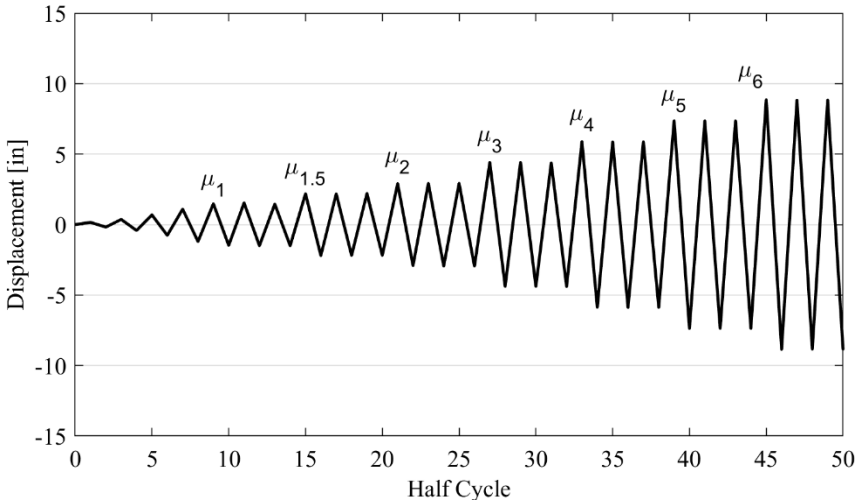


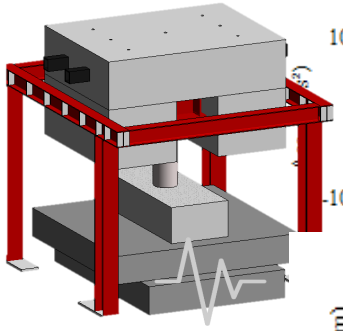
High strain rates

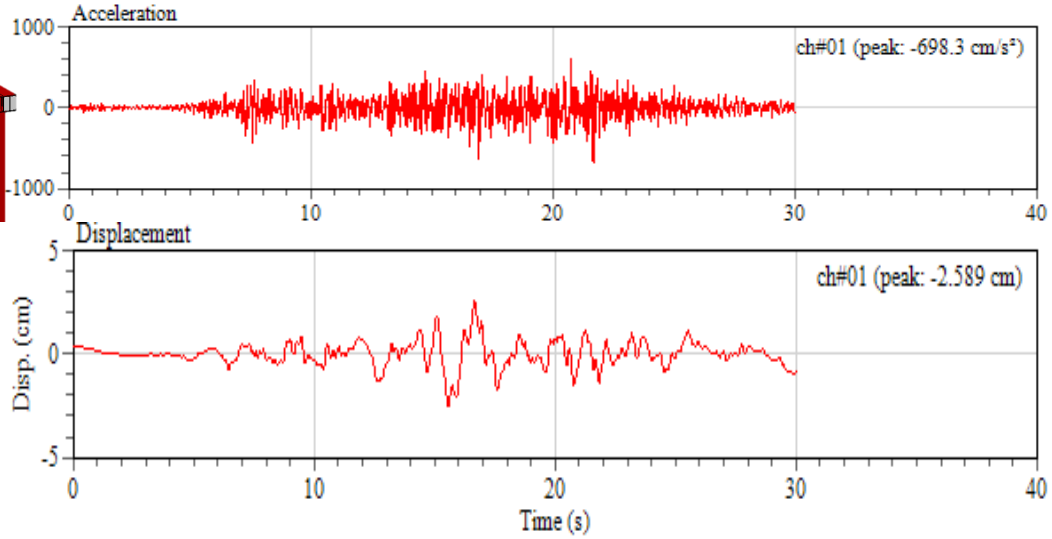


Quasistatic vs Dynamic loading



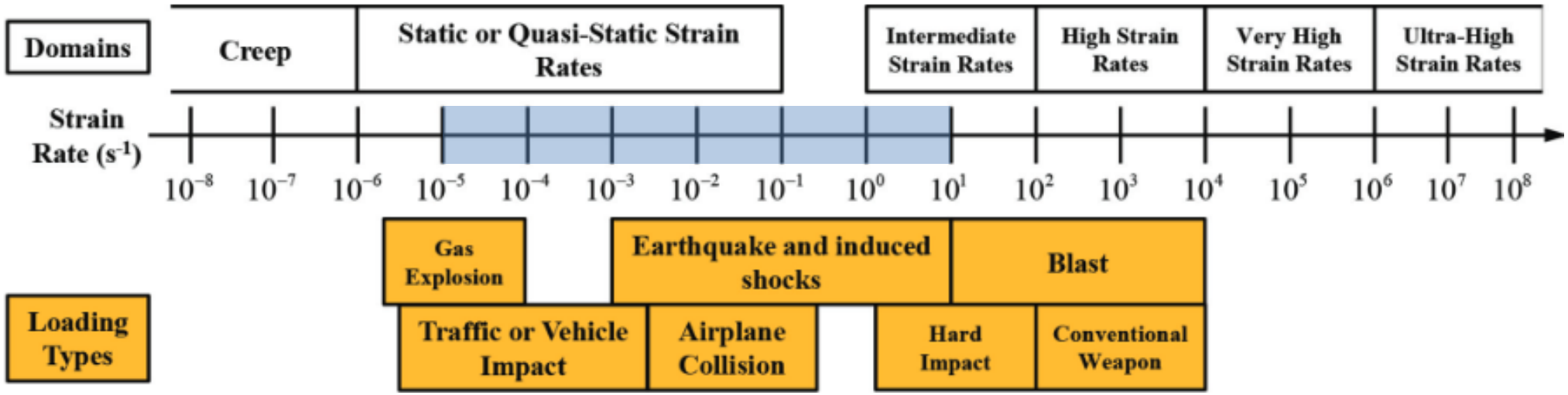




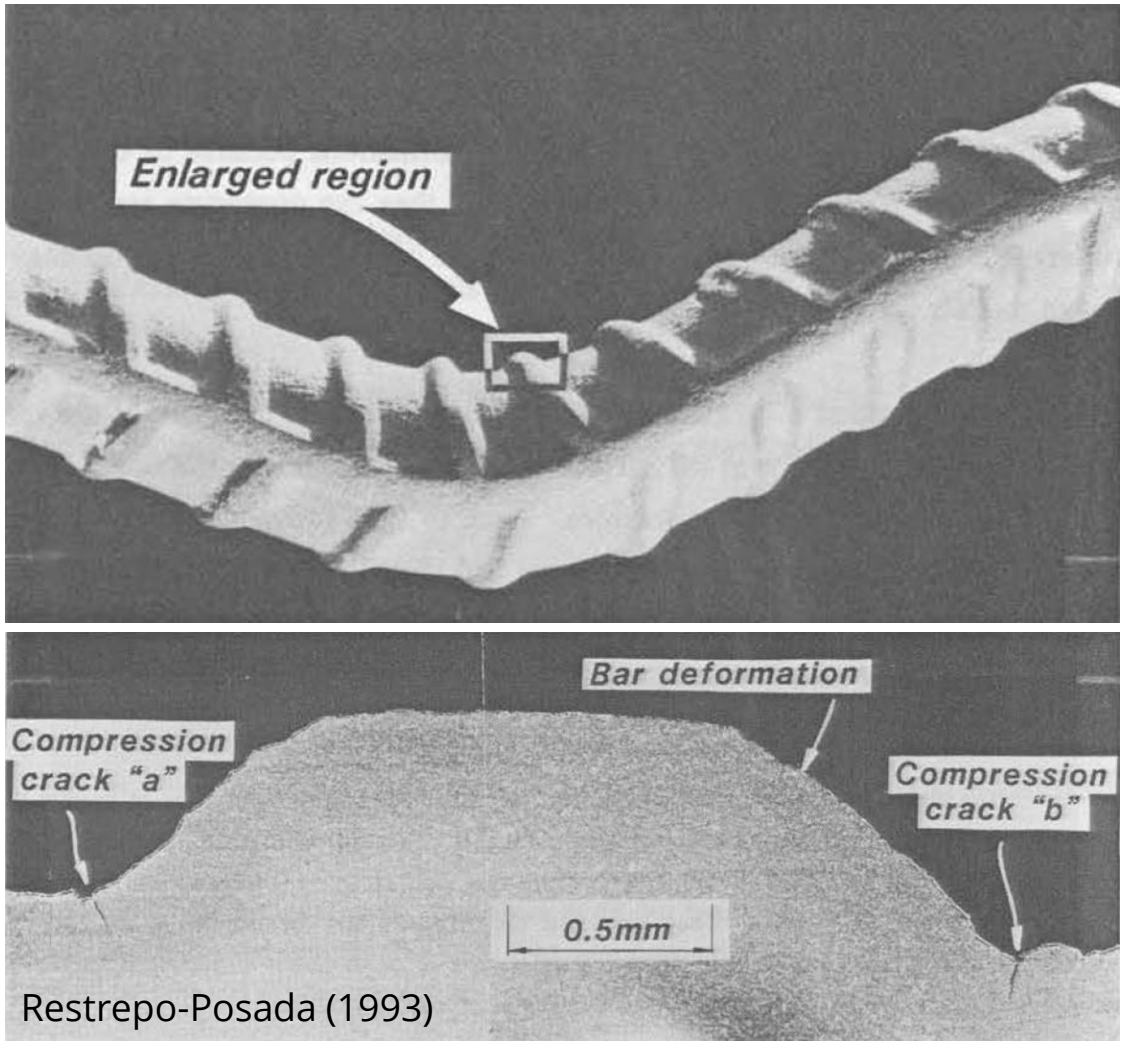


Quasistatic vs Dynamic loading

STRAIN RATE



Seongwon Hong and Thomas H.-K. Kang, 2016



Restrepo-Posada (1993)

Strain rate effect

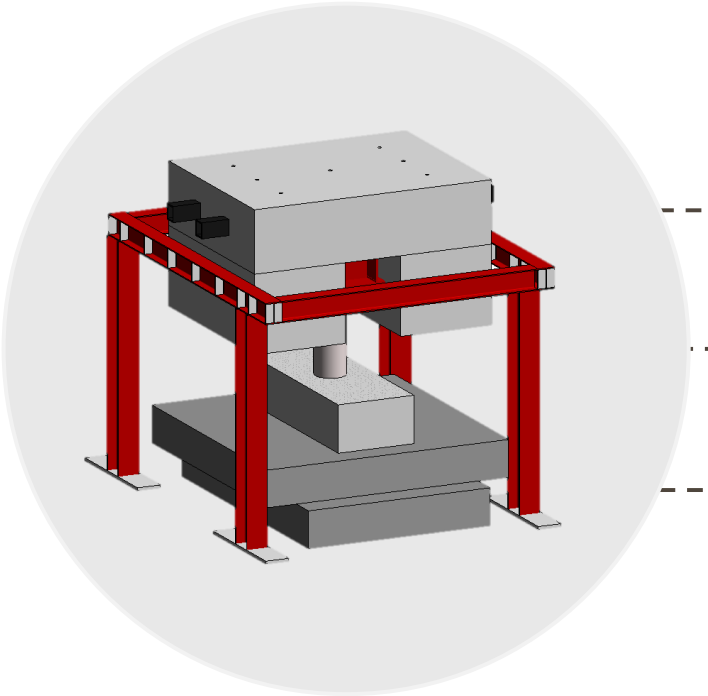
What we know:

- Strength increases with higher strain rates

What we don't know:

- Strain rate impact on stress concentrations
- Manufacturing process impact

Shake table test

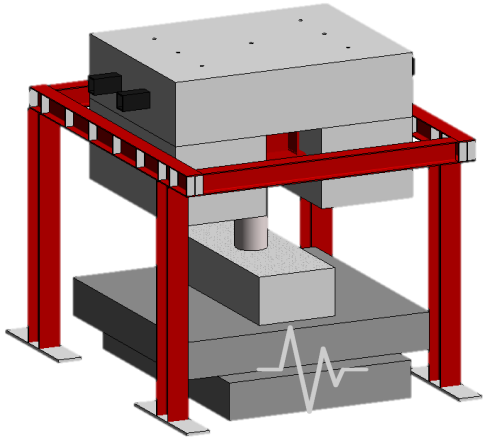


1. Evaluate **demands** under dynamic loading
2. Evaluate **capacity** under dynamic loading
3. **Validate** and **calibrate** previous recommendations on **strain limit states**

Lu Carranza, PhD student

SHAKE TABLE TEST

≈ 16 COLUMNS
With different rebar grade, size, **manufacturing process**, and detailing.



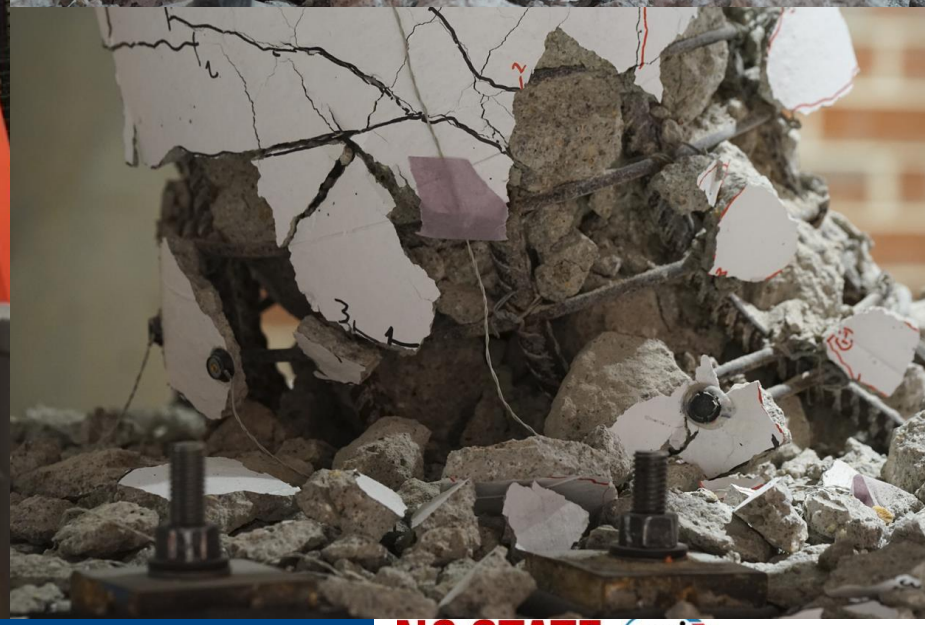
1/4 SCALE

3D OPTICAL MEASUREMENT SYSTEM OPTOTRAK ®

The captured marker positions are processed to calculate **displacement and strains.**

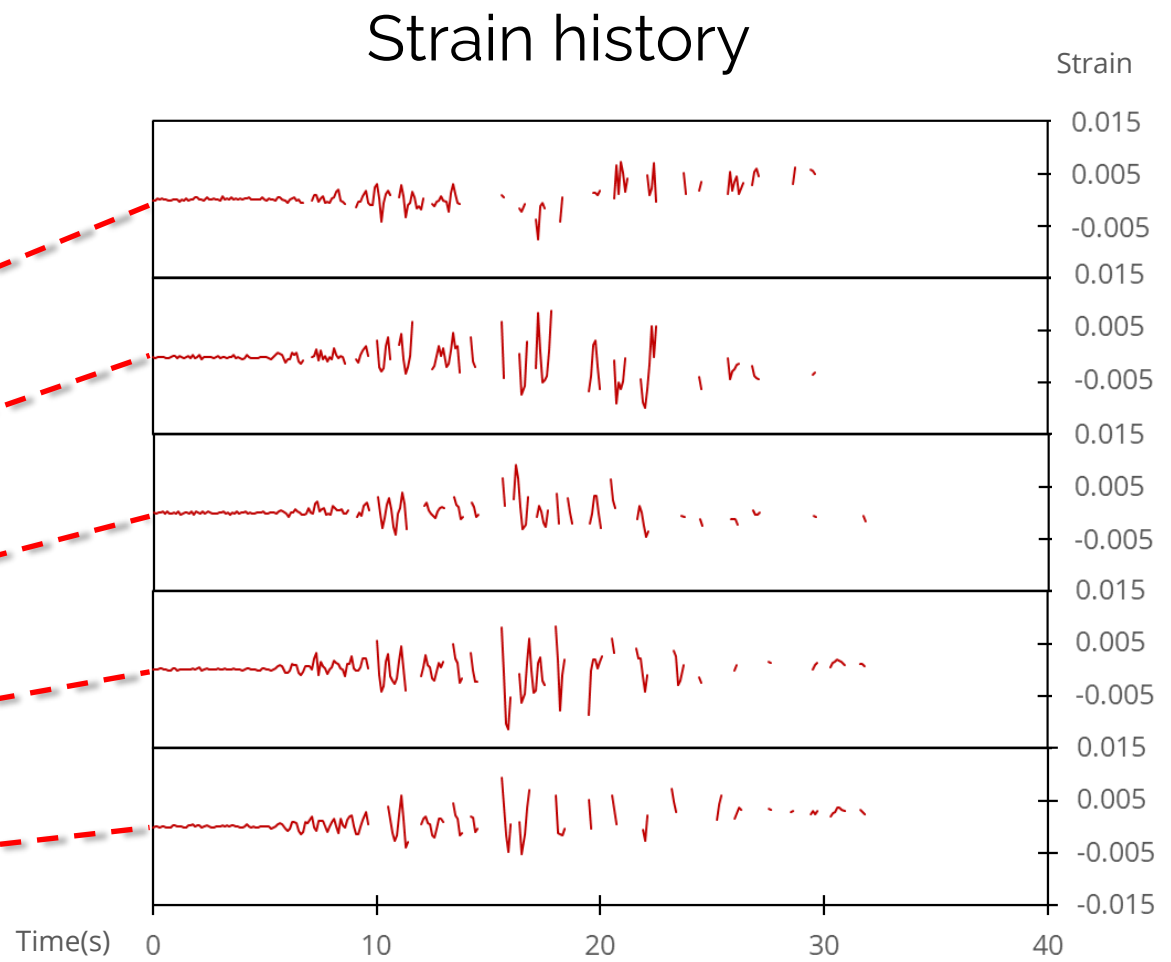
Lu Carranza, PhD student

TEST 1

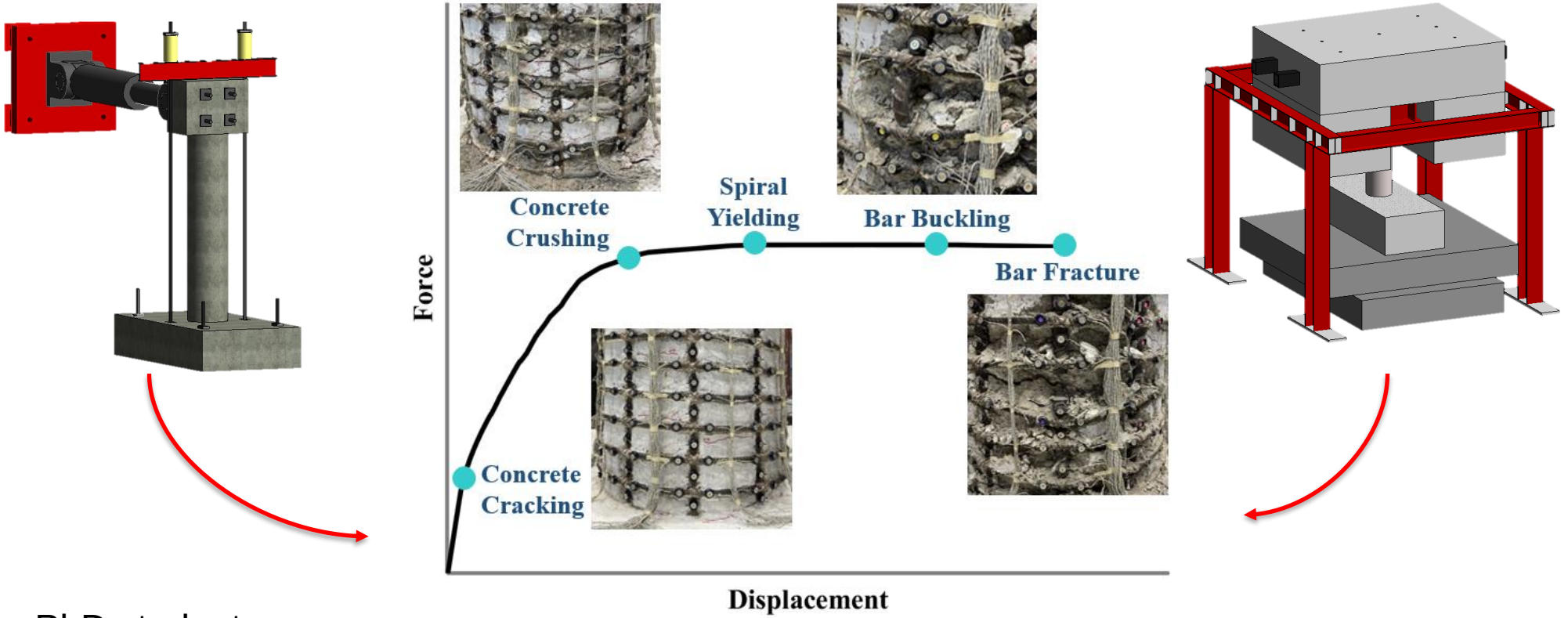


Lu Carranza, PhD student


TEST 2
Lu Carranza, PhD student

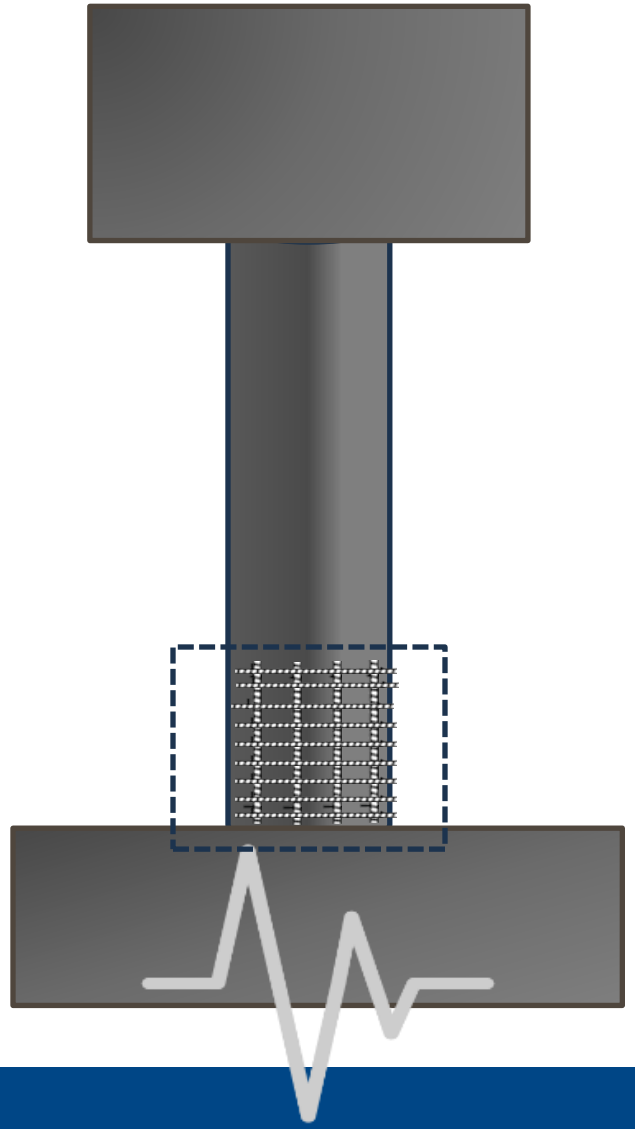

Strain history
Strain
0.015
0.005
-0.005
0.015
0.005
-0.005
0.015
0.005
-0.005
0.015
0.005
-0.005
0.015
0.005
-0.005
Time(s)
0
10
20
30
40

Shake table test: Verification of strain limit states



Lu Carranza, PhD student

RC Column



(QST)

(MA)

Manufacturing process plays an important role in the **seismic performance** on RC Columns

Effect of the manufacturing process on the seismic behavior of HSRS

Motivation

Performance-Based Seismic Design requires Defined Limit States

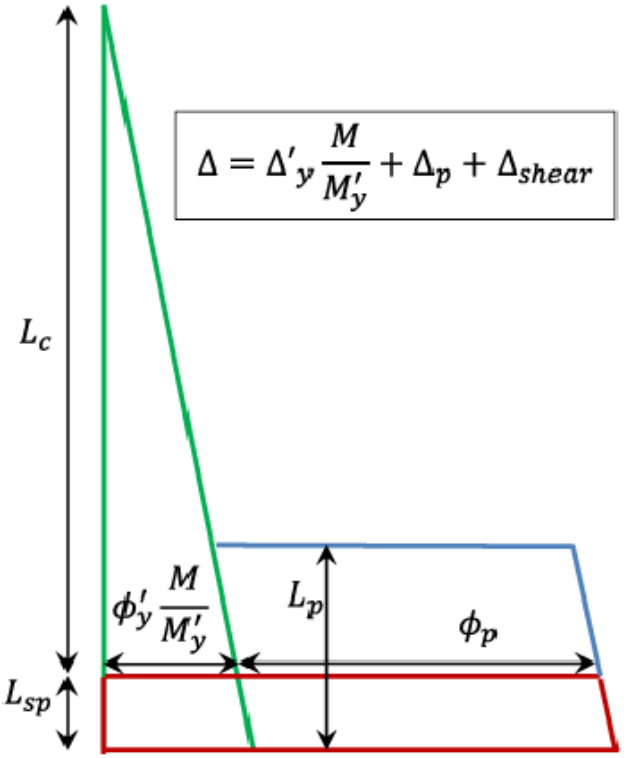
↓

Predict Structural Behavior

↓

Design Provisions depend on material characteristics, usually taken by **Yield Strength** and **Ultimate Tensile Strength**

Example: Plastic Hinge Method



$$\Delta = \Delta'_y \frac{M}{M'_y} + \Delta_p + \Delta_{shear}$$

$$L_{sp} = 0.022 f_y d_{bl} \quad \text{(MPa)}$$

$$L_{eff} = L_c + L_{sp}$$

$$\Delta'_y = \frac{\phi'_y L_{eff}^{\,2}}{3}$$

$$L_p = kL_c + L_{sp} \geq 2L_{sp}$$

$$k = 0.2\left(\frac{f_u}{f_y} - 1\right) \leq 0.08$$

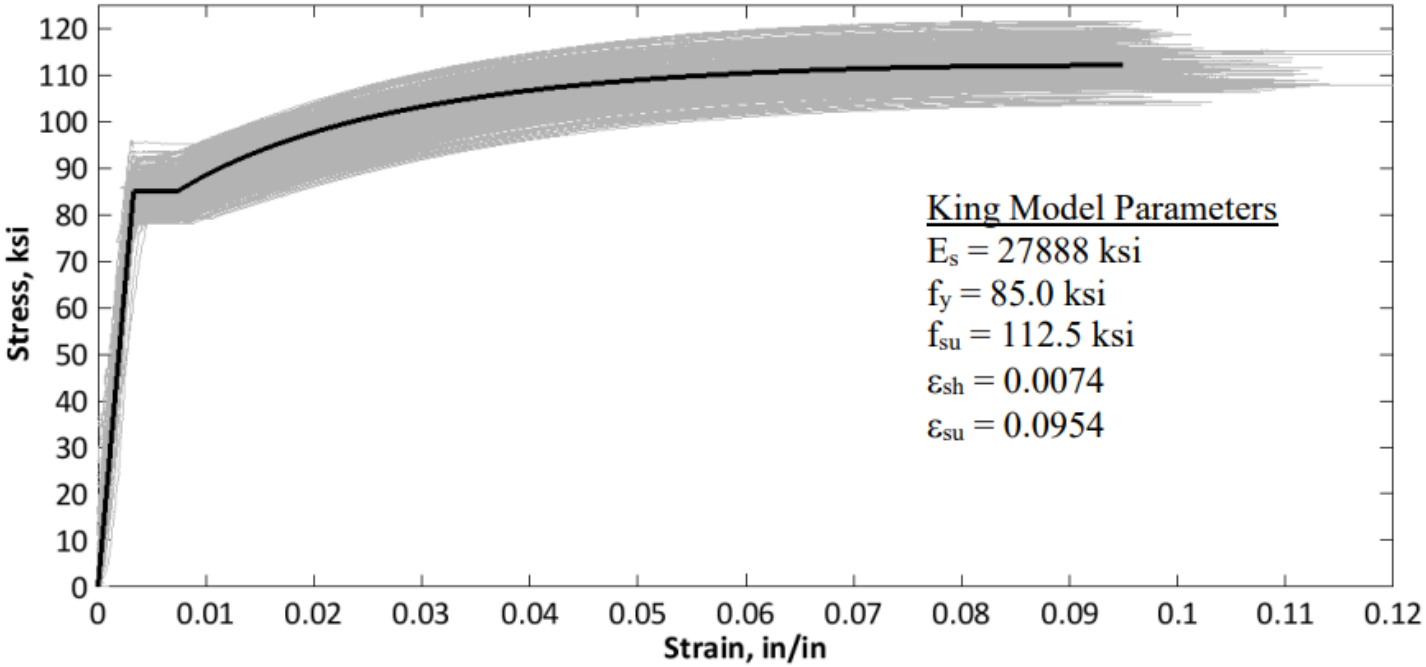
$$\phi_p = \phi - \phi'_y \frac{M}{M'_y}$$

$$\Delta_p = \phi_p L_p (L_c + L_{sp} - 0.5L_p)$$

(Priestley, Calvi and Kowalsky, 2007) .

Expected Material Results

Overby et al. (2016) tested hundreds of specimens and defined expected mechanical properties of ASTM A706 Grade 80 (both MA and QST)

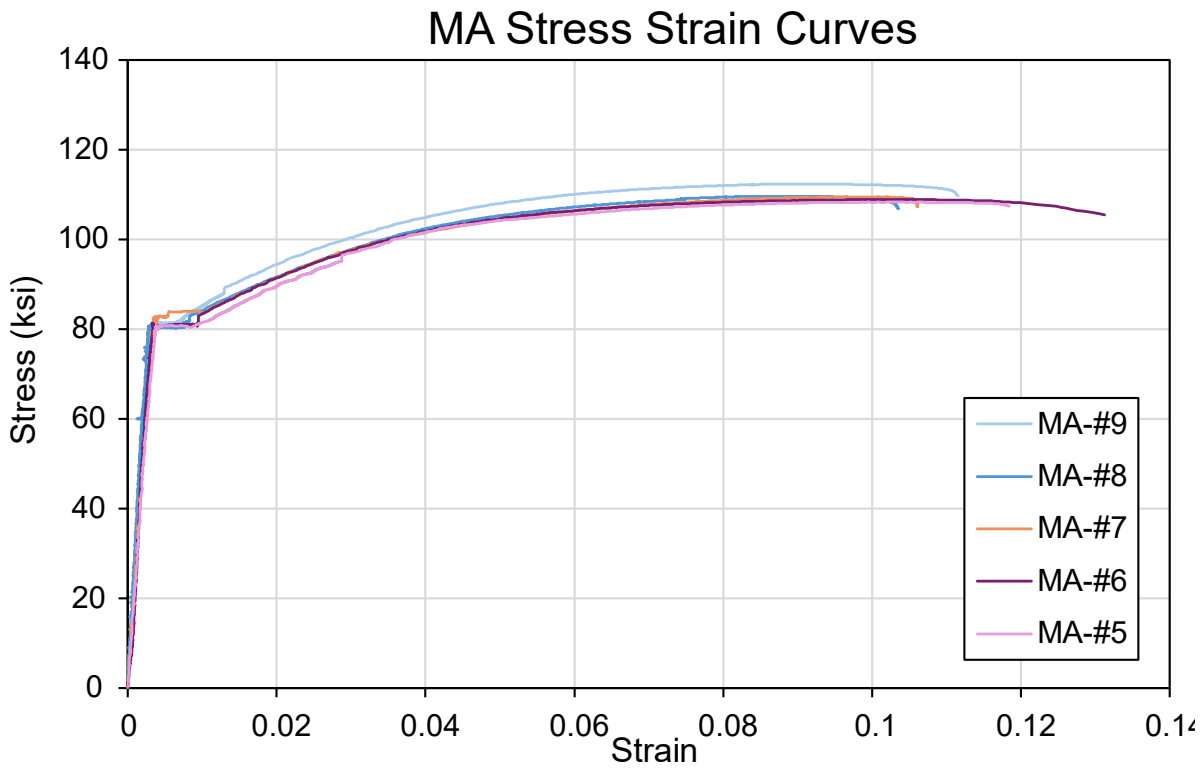


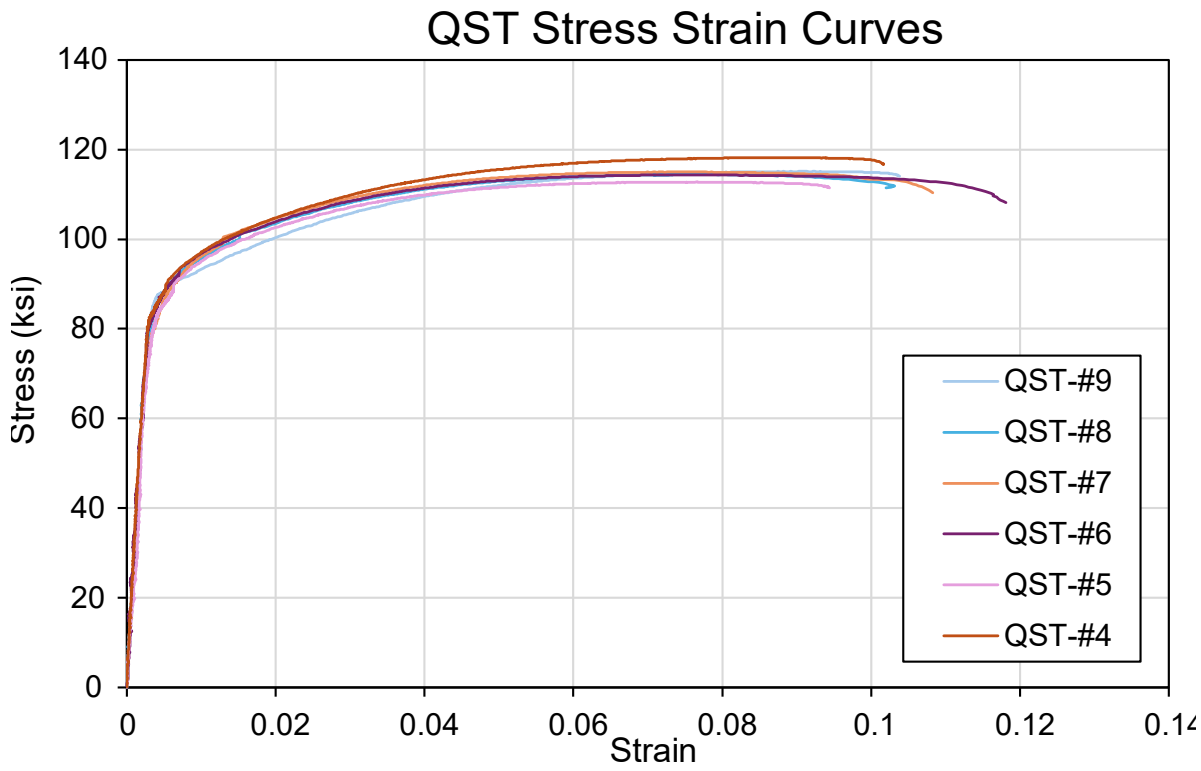
The experimental curves matched well with the king model, and **model parameters** were recommended.

Overby (2016)

What would happen if the curve didn't fit well into the model?

Material Characterization Results



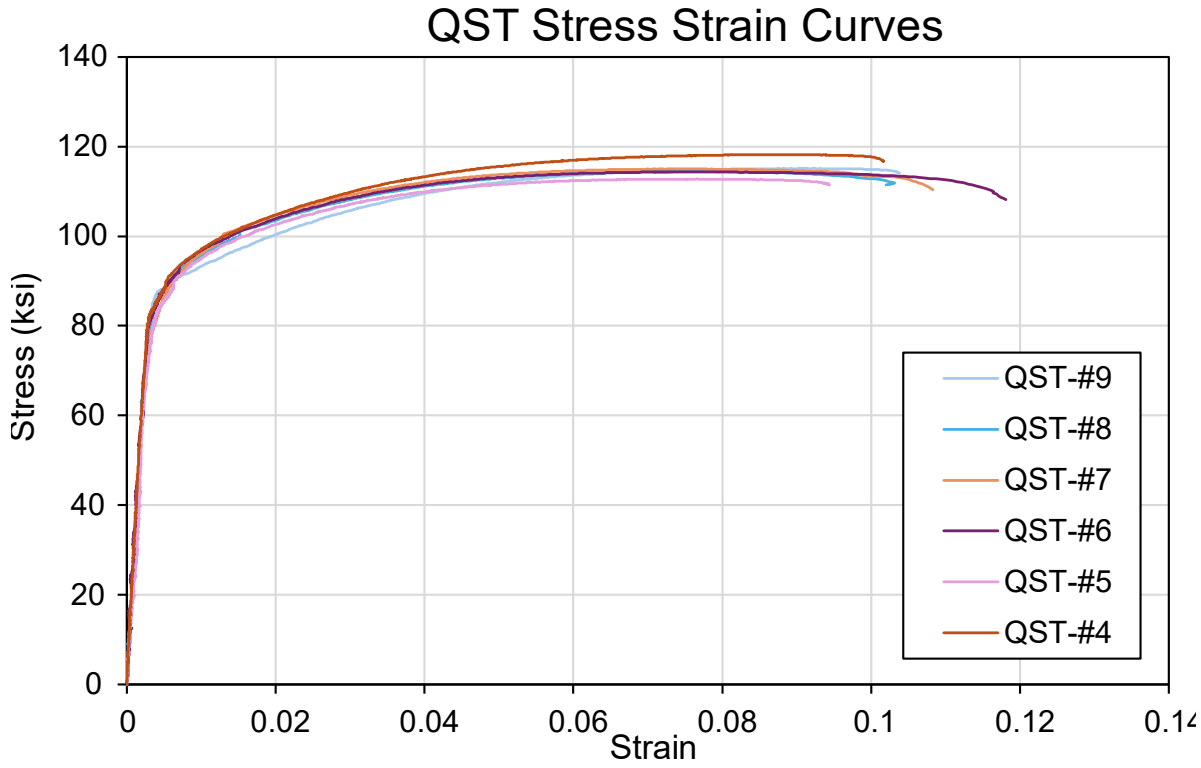


- QST steel presented curve with RoundHouse characteristic
- No defined yield plateau

Material Characterization Results

In this case, the shape of the stress strain curve was modified to achieve certain steel specifications

Could the **shape of the stress-strain curve** have an impact on seismic behavior?



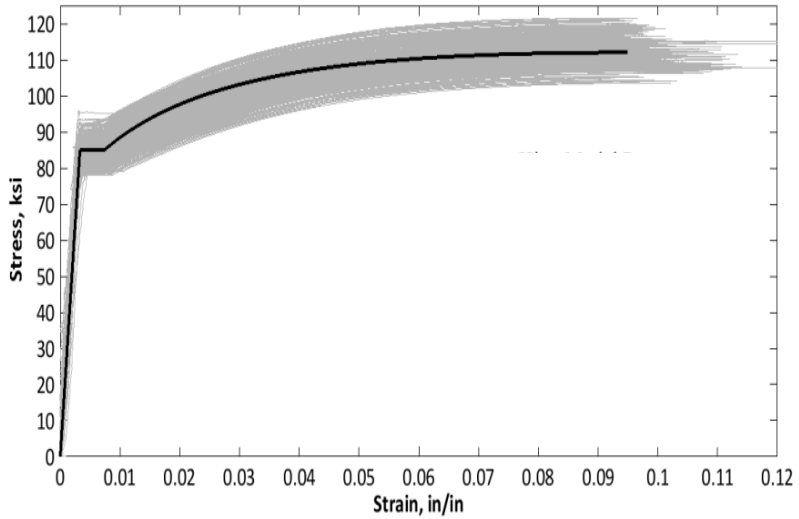
Parametric Study – Moment Curvature Analysis

Axial Load Ratio → 5% and 10%

Longitudinal Steel Ratio → 0.5%, 1%, 1.5%, 2%, 2.5%, 3%, 3.5% and 4%

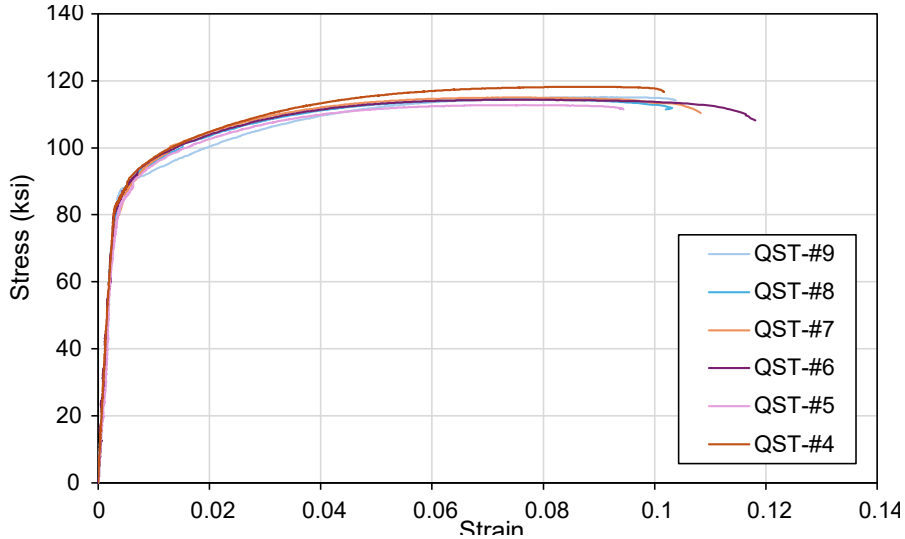
32 Moment-Curvature Analysis

King Model for Steel

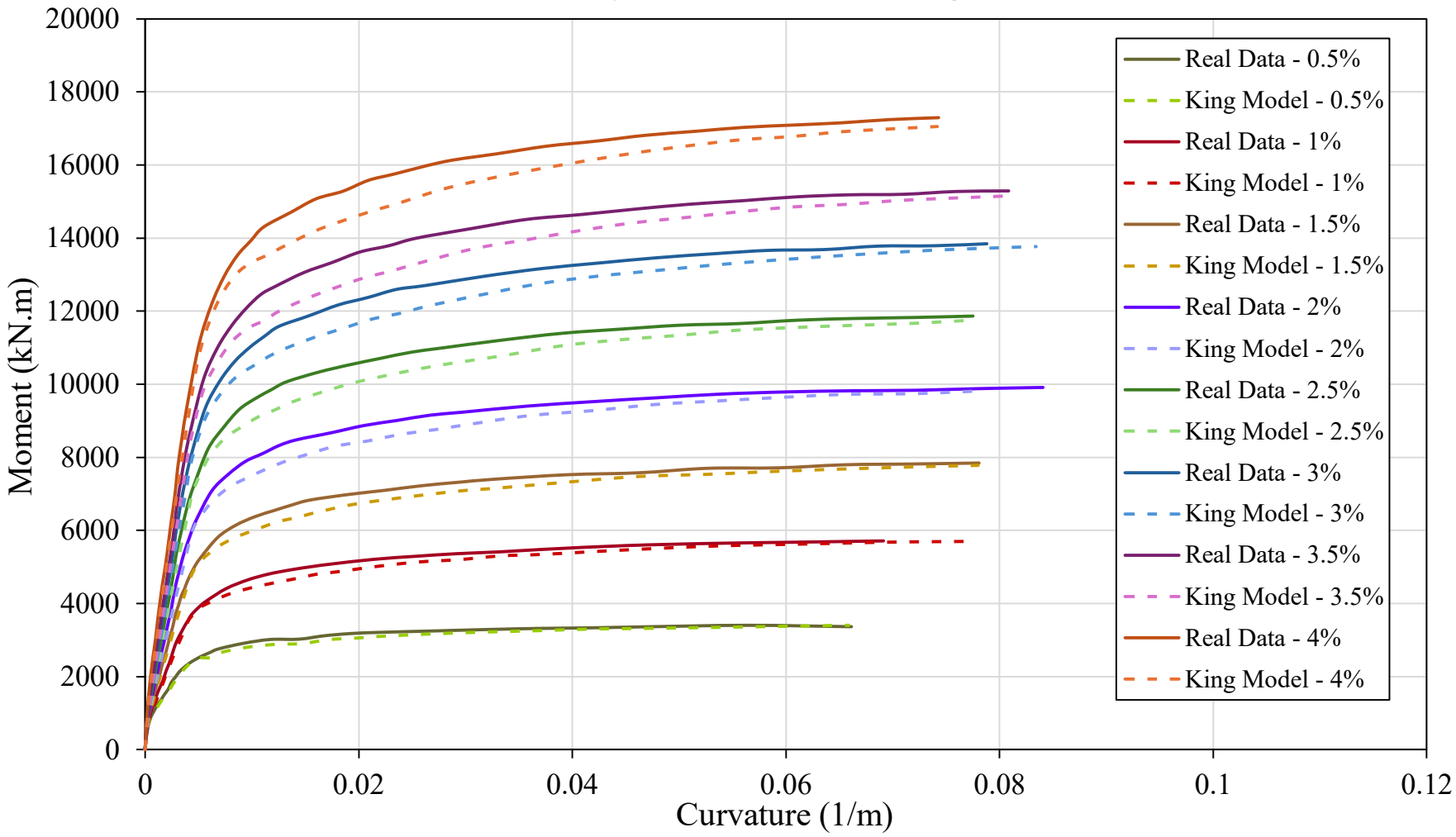


- Using **Yield Strength** calculated using the **0.2% Offset Method** for the real data (ASTM)
- Using real **Ultimate Tensile Strength**

Real Stress-Strain Data



Moment Curvature Analysis – King Model vs. RoundHouse Shape

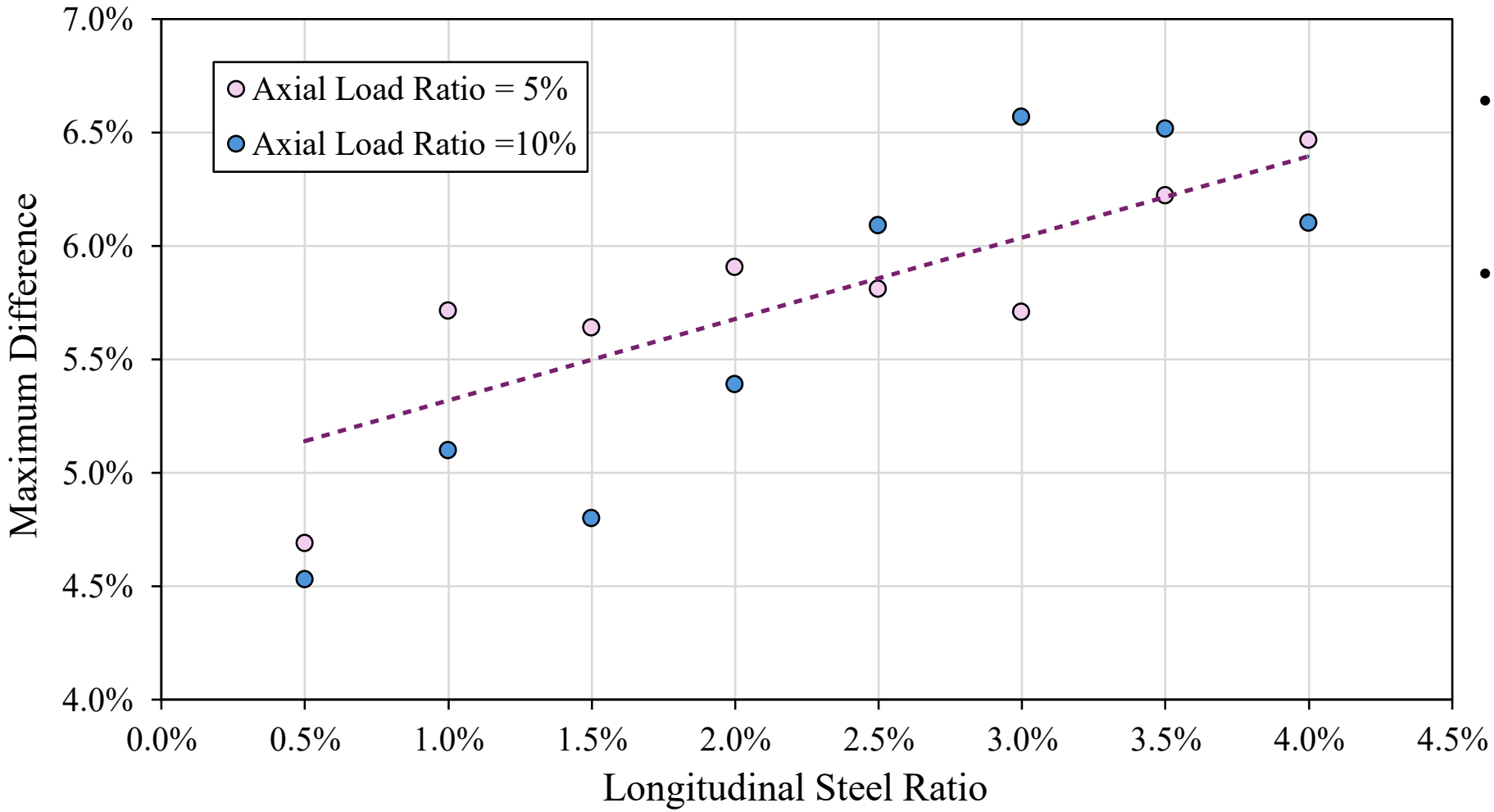


Columns analyzed with **RoundHouse** stress-strain curve had **higher moments** at service level

↓

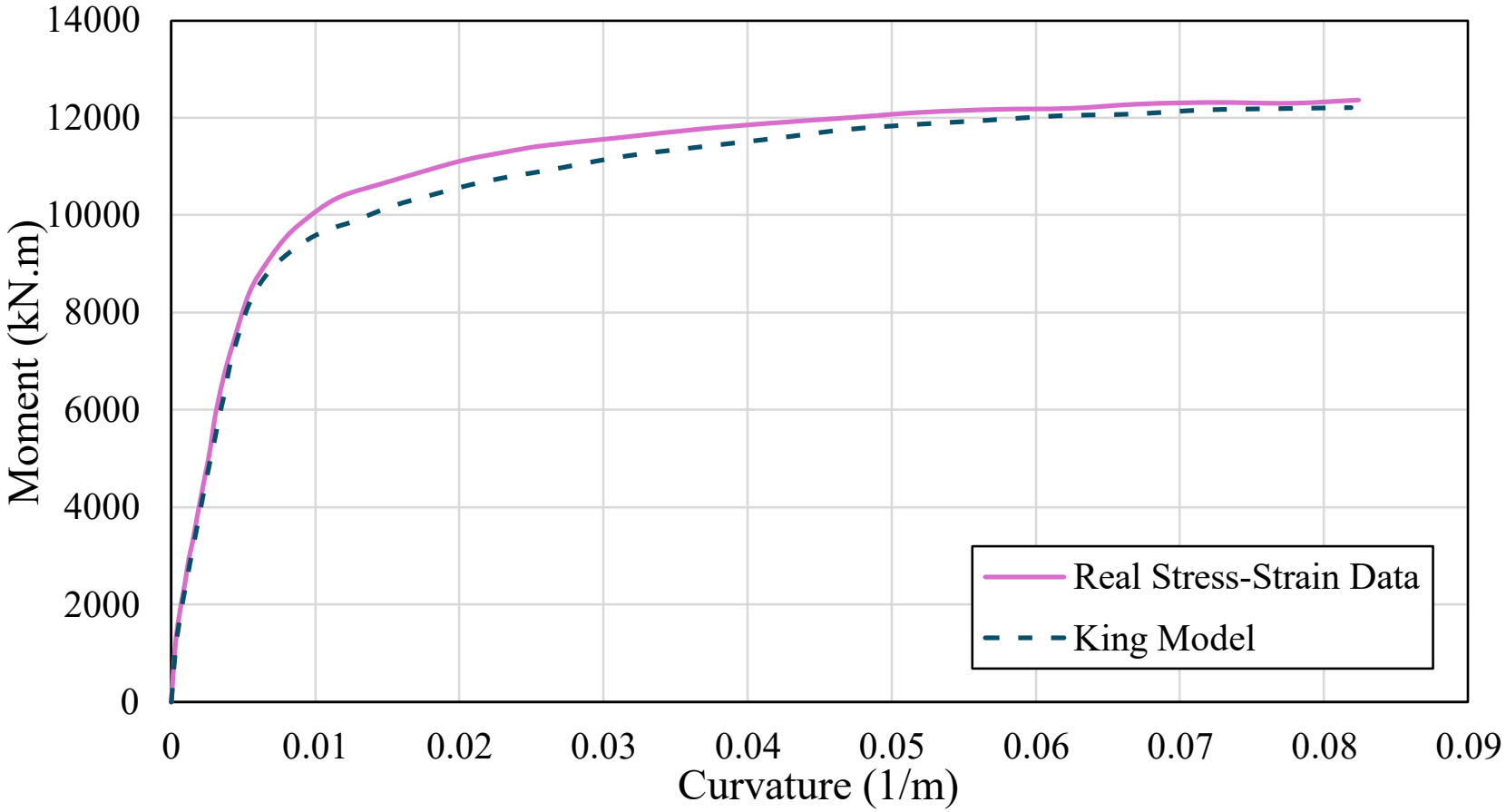
Bigger gaps proportional to longitudinal steel ratio increase

Moment Curvature Analysis – King Model vs. RoundHouse Shape



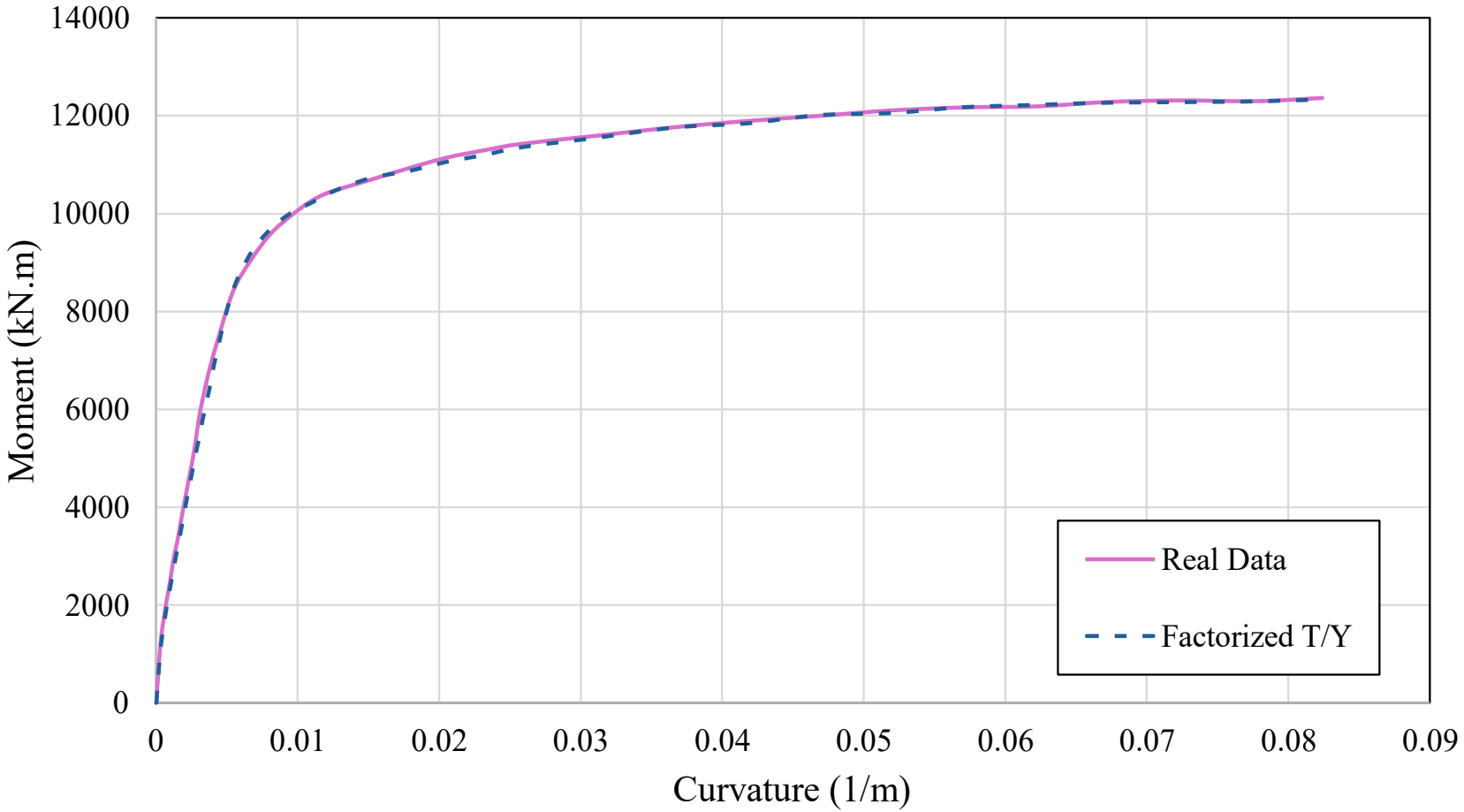
- Maximum Moment distances of about 6.5%
- Axial Load Ratio didn't have an impact on this behavior

Moment Curvature Analysis – King Model vs. RoundHouse Shape



Yield Strength modified to **get a T/Y that matches the behavior** of the real stress-strain data

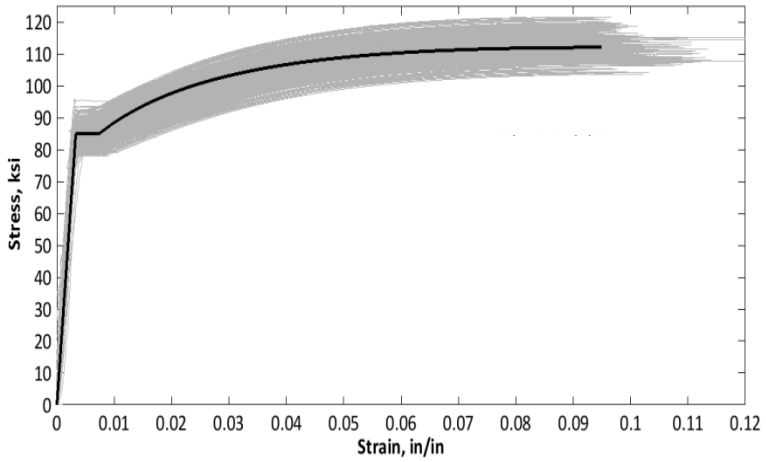
Moment Curvature Analysis – King Model vs. RoundHouse Shape



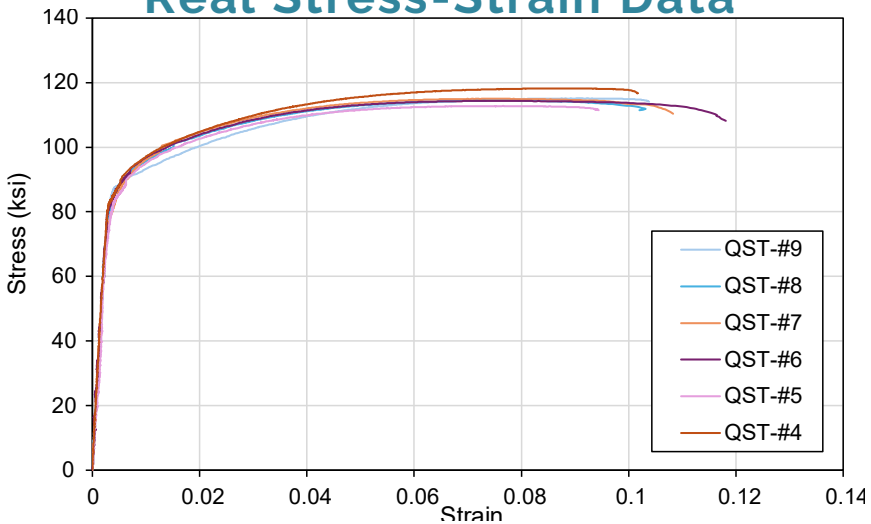
Yield Strength modified to **get a T/Y that matches the behavior** of the real stress-strain data

On average, a factor of **0.92** , when multiplied by T/Y, gets the expected behavior of a RoundHouse curve steel

King Model w/ Real T/Y



Real Stress-Strain Data



- **0.2% offset method may not fully represent** the yield characteristic for reinforcing steel without a defined yield plateau
- For design provisions that rely on Yield and Tensile Strength, a factorized T/Y may **accurately predict structural behavior**
- The parametric study conducted suggests a value of **0.92** as a **reducing factor of T/Y for ASTM Grade 80** reinforcing steel with RoundHouse characteristic curve
  - More research should be conducted to validate this hypothesis.

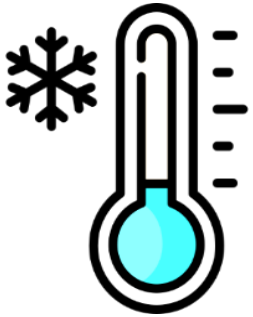
Effect of the manufacturing process on the seismic behavior of HSRS

Conclusions

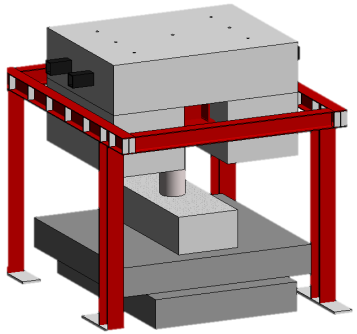
- Manufacturing process plays an important role in the **seismic performance** on RC Columns

  - Stress concentrations

Low Temperature

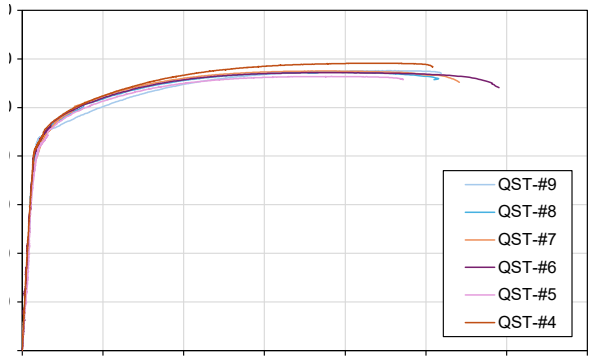


High Strain Rates



  - Stress-Strain curve shape

T/Y dependent Design provisions



Should we consider the manufacturing process of the RS in our design process?

Thank you!

Lina Espinosa, PhD student. lmespino@ncsu.edu
Maria Luisa Duran, MSc student. mcurvel@ncsu.edu
Eugenia Campos, PhD student. egcampos@ncsu.edu
Dr. Mervyn Kowalsky, kowaslky@ncsu.edu

Constructed Facilities Laboratory
NC STATE UNIVERSITY

Caltrans

TRANSPORTATION & PUBLIC FACILITIES
STATE OF ALASKA