Performance Objectives and the AASHTO *Guide Specifications for LRFD Seismic Bridge Design*

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Performance Objectives

- AASHTO *Guide Specifications for LRFD Seismic Bridge Design* (SGS) is primarily a displacement-based design approach
- SGS addresses a single performance objective
- No collapse as a result of the single hazard level (1000 year event)

Performance Objectives

- <u>User expectations, down time, economics</u>

- Need for better seismic bridge performance
  - *Minimal* damage ~ some yielding
  - *Repairable* damage ~ spalling
  - *No collapse* ~ buckling or rupture

- A “functional level” EQ may be needed (100 year event) with minimal or repairable damage

Performance Objectives

- *CALTRANS* MTD 20-1 (July 2010)

Bridge Category	Seismic Hazard Evaluation Level	Post Earthquake Damage Level	Post Earthquake Service Level
Important	Functional	*Minimal*	*Immediate*
	Safety	*Repairable*	*Limited*
Ordinary	Safety	*Significant*	*No Collapse*

- Oregon DOT also has multiple hazard level design approach

Performance Objective

- How to design for performance objectives?
  - Displacement ductility
  - Plastic hinge rotation
  - Material strain limits
- SGS provides strain limits (e.g. Table 8.4.2-1)
- Perhaps add performance objective strain limits

No Collapse Performance

- SGS strain-based deformation limits

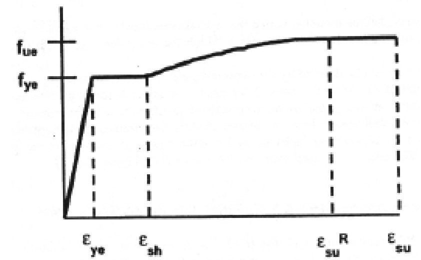


Figure 8.4.2-1 Reinforcing Steel Stress-Strain Model.

Table 8.4.2-1 Stress Properties of Reinforcing Steel Bars.

Property	Notation	Bar Size	ASTM A706	ASTM A615 Grade 60
Specified minimum yield stress (ksi)	f_y	#3 - #18	60	60
Expected yield stress (ksi)	f_{ye}	#3 - #18	68	68
Expected tensile strength (ksi)	f_{ue}	#3 - #18	95	95
Expected yield strain	ε_{ye}	#3 - #18	0.0023	0.0023
Onset of strain hardening	ε_{sh}	#3 - #8	0.0150	0.0150
		#9	0.0125	0.0125
		#10 - #11	0.0115	0.0115
		#14	0.0075	0.0075
		#18	0.0050	0.0050
Reduced ultimate tensile strain	ε_{su}^R	#4 - #10	0.090	0.060
		#11 - #18	0.060	0.040
Ultimate tensile strain	ε_{su}	#4 - #10	0.120	0.090
		#11 - #18	0.090	0.060

Table 8.4.2-1

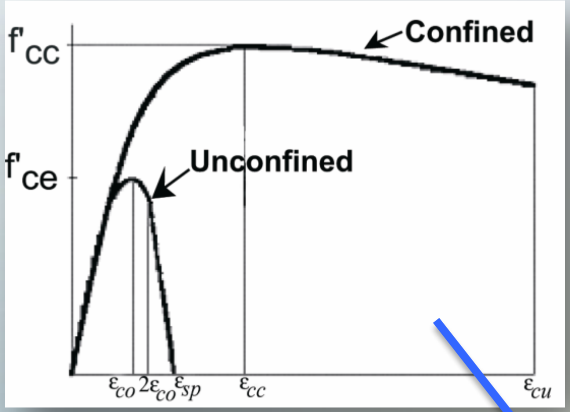


Figure 8.4.4-1

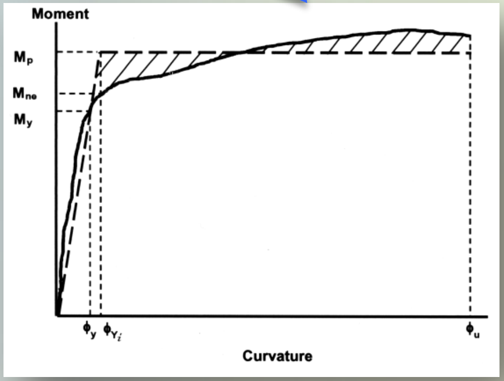


Figure 8.5-1

Performance Objective

- Some performance strain limits of interest
  - Concrete tensile cracking
  - Concrete compressive spalling
  - Confined concrete core crushing
  - Longitudinal bar tensile yielding
  - Longitudinal bar buckling
  - Longitudinal bar tensile rupture
  - Transverse bar yielding
  - Transverse bar rupture

Performance Objective

- Sample strain limits

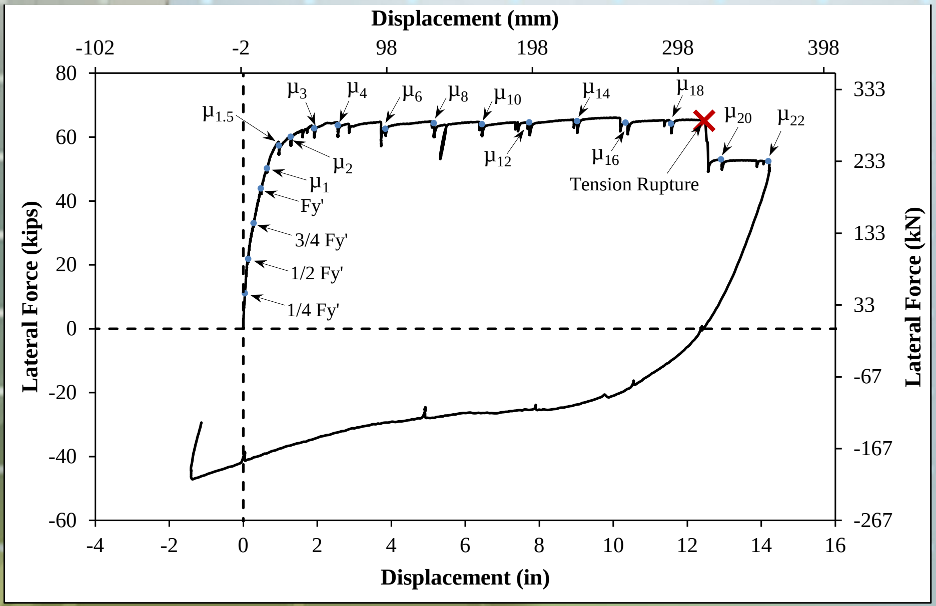
Performance Objective	Concrete Strain Limit (Compression)	Steel Strain Limit (Tension)
Minimal (proposed)	~ 0.005 in/in	~ 0.003 in/in
Repairable (proposed)	Spalling of cover concrete, onset of bar buckling, etc.	ε_{sh} onset of strain hardening, residual concrete crack width less than about 1mm, etc.
No Collapse (from SGS)	$\varepsilon_{cu} = 0.004+1.4*\rho_s*f_y*\varepsilon_{su}/f'_{cc}$	ε^R_{su} = 0.09 in/in for $d_b \leq$ #10 ε^R_{su} = 0.06 in/in for $d_b \geq$ #11

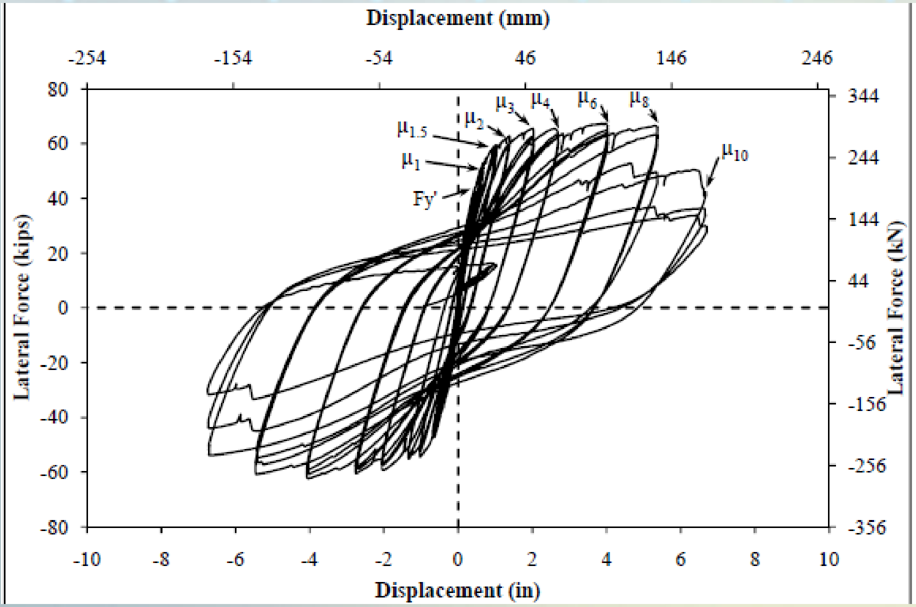
Performance Objective

- But it’s more than just strain limits
  - Permanent drift and settlement limits
  - Multiple EQ hazard levels
  - Statistical calibration / fragility curves
  - Indirect seismic hazards
  - User expectations after EQ event

EQ Load History Effects

- Comparison between quasi-static and the standard three-cycle loading protocol





(Kowalsky et al. 2010 - NCSU)

EQ Load History Effects

- SGS reduced ultimate tensile strain, ε^{R}_{su}, based upon 3-cycle laboratory loading protocol
- SGS appears conservative but “one-size-fits-all” may be inadequate
- Strain limits based upon anticipated EQ deformations may be warranted

EQ Load History Effects

- FHWA *Seismic Retrofitting Manual*

$$\varepsilon_{ap} = 0.08 * (2 * N_f)^{-1/2}$$

where:

ε_{ap} = low-cycle fatigue strain amplitude

N_f = equivalent equal amplitude cycles

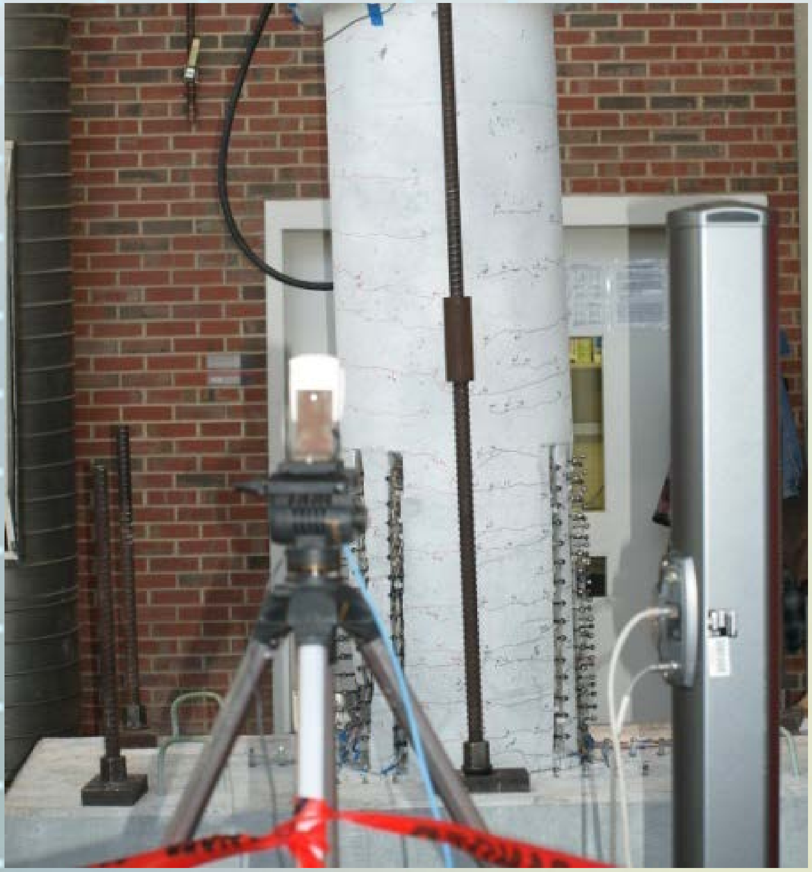
$N_f = 3.5*(T_n)^{-1/3}$ $\quad 2 < N_f < 10$

T_n = natural period of bridge

$\phi_p = 2 * \varepsilon_{ap} / (D')$

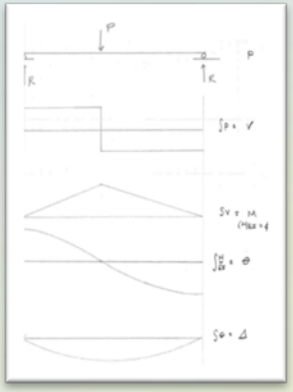
EQ Load History Effects

- Ongoing research includes directional considerations



Strain to Deformation

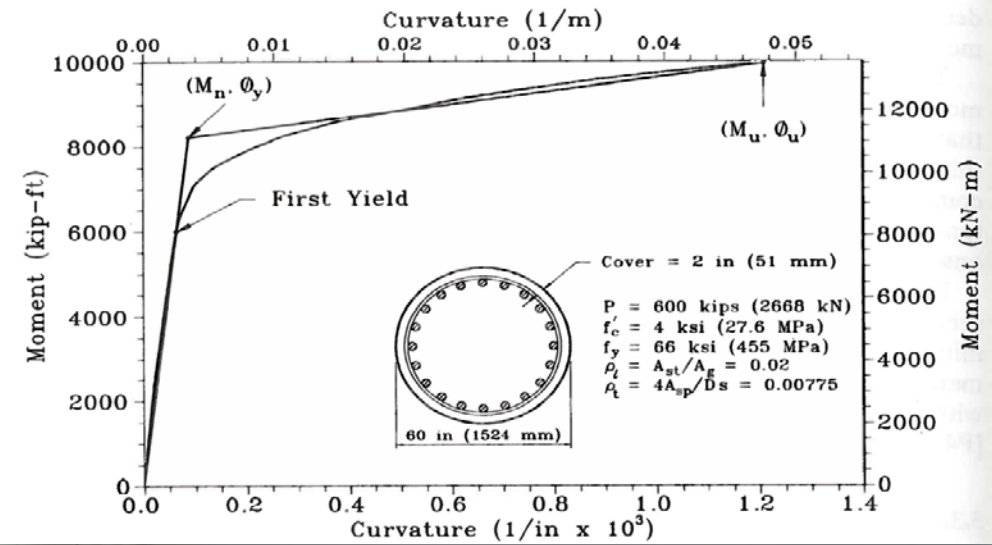
- Integration : load → shear → moment (curvature *M*-ϕ) → slope → deflection



- Numerous approaches to "integrate"

- Analytical plastic hinge length is a simplification used to transform curvature to rotation (slope) and is used in the SGS

Plastic Hinge Length, L_p

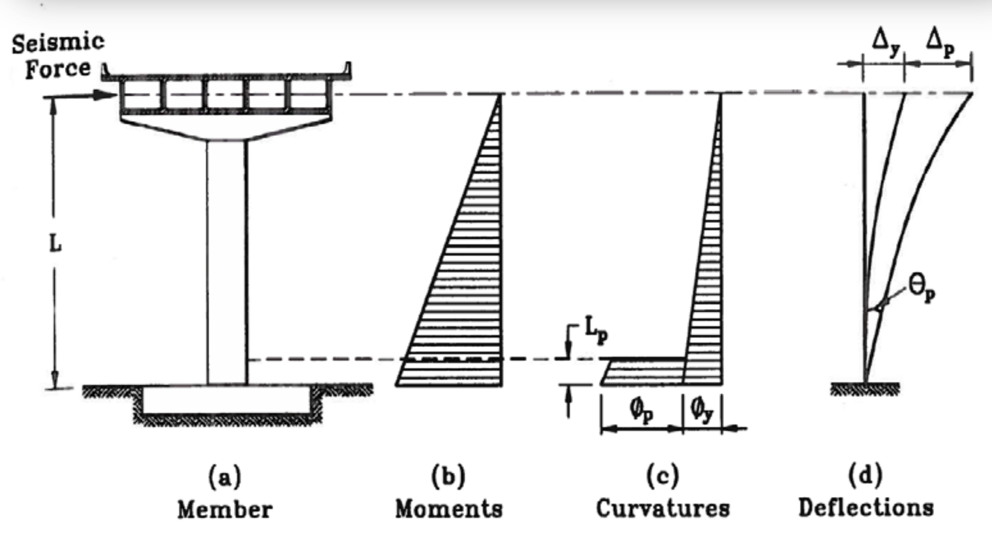


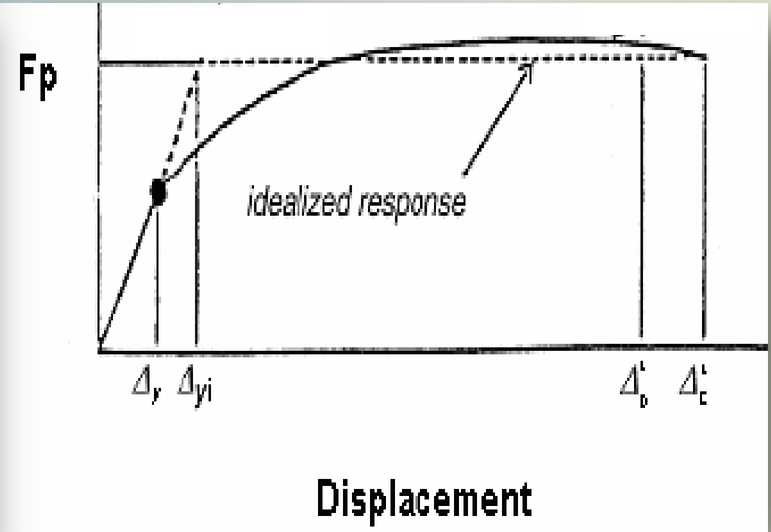
$$\Delta_y \sim \phi_y * L^2 / 3$$

$$\Delta_u \sim \Delta_y + \Delta_p$$

$$\Delta_p \sim \theta_p * L$$

$$\theta_p \sim (\phi_u - \phi_y) * L_p$$





Plastic Hinge Length, L_p

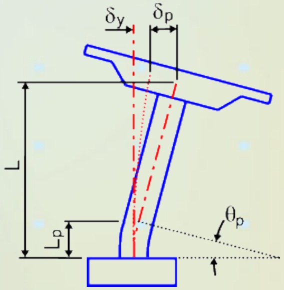
$$L_p = 0.08 * L + 0.15 * f_{ye} * d_{bl}$$

where:

L = distance from hinge to zero moment

f_{ye} = expected bar yield stress

d_{bl} = longitudinal column bar diameter



- Moment gradient part (column) and a strain penetration part (footing / cap / shaft)

Plastic Hinge Length, L_p

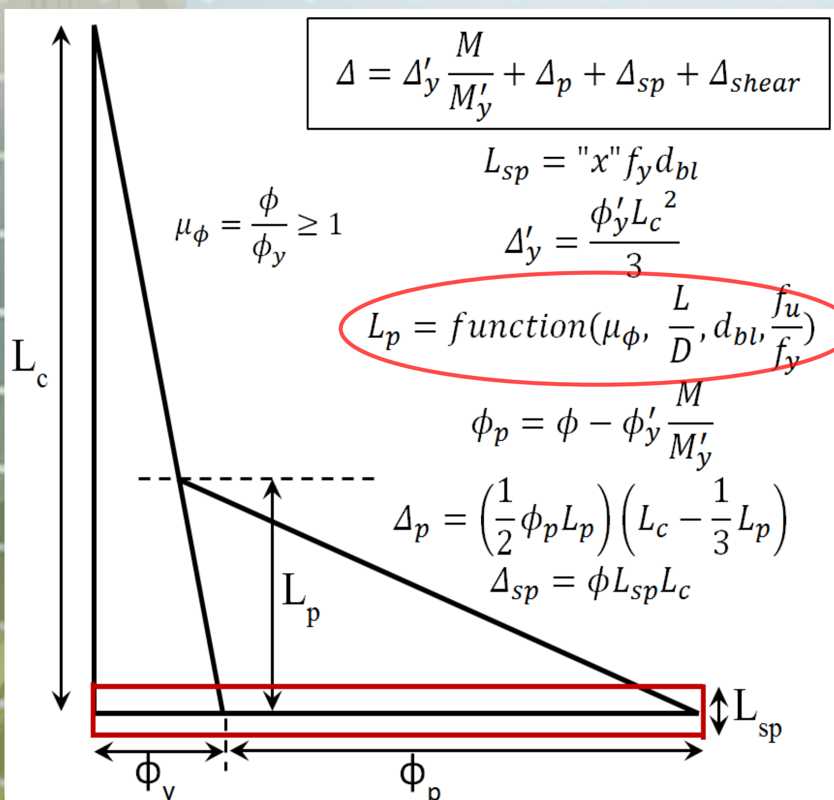
- Reducing either the moment gradient part or the strain penetration part will reduce Δ_u

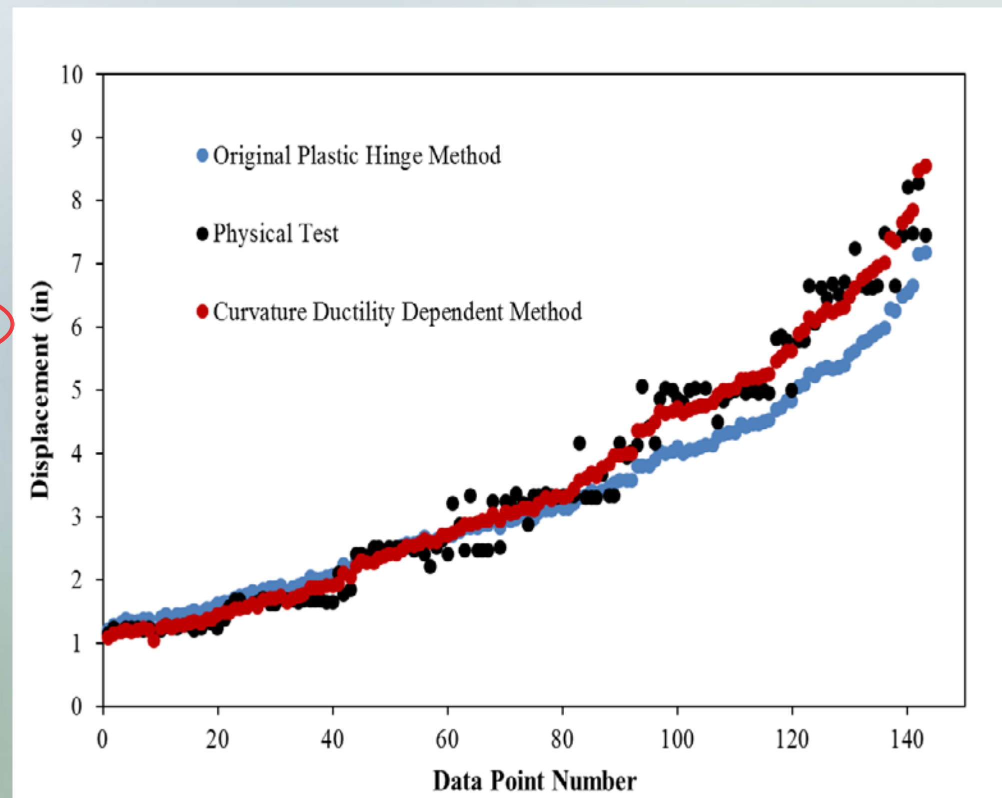
- Calibrated to the ultimate strain limit and corresponding deformation

- Modifications may be required to better correlate deformations at lower strain values

Plastic Hinge Length, L_p

- Curvature dependent plastic hinge length

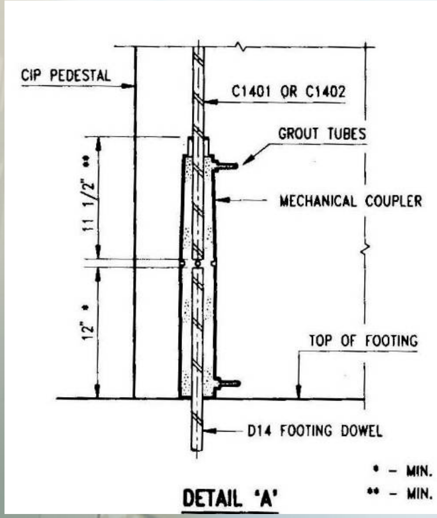


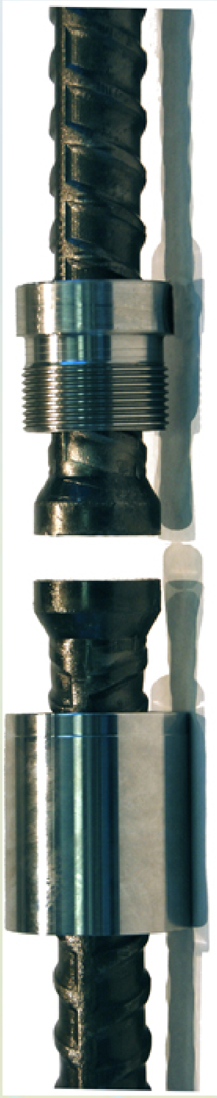


Sidetrack - ABC Connections

- Method of connecting and anchoring reinforcement to prefabricated elements
  - Grouted Bar Couplers
  - Mechanical Bar Couplers
  - Grouted Ducts
  - ~~Welded Bar Splices~~

Sidetrack - ABC Connections





Sidetrack - ABC Connections

- Can develop full tensile strength of bar
- Stiffer stress-strain than un-spliced bar
- These devices may reduce the analytical plastic hinge length
- Smaller L_p suggest higher strains at smaller displacement (performance objectives?)

Longitudinal Bar Buckling

- SGS defines bar failure on tensile rupture
- Under cyclic loading, tensile bar rupture is often proceeded by bar buckling which is proceeded by a large tensile strain and yielding of the transverse reinforcement
- Will likely need strain limits for bar buckling

Longitudinal Bar Buckling

- Bar buckling performance limit

Longitudinal Bar Buckling

- FHWA Seismic Retrofitting Manual

$$\varepsilon_b = 2 * f_y / E_s$$

where:

ε_b = bar buckling strain = ½ * ε_y

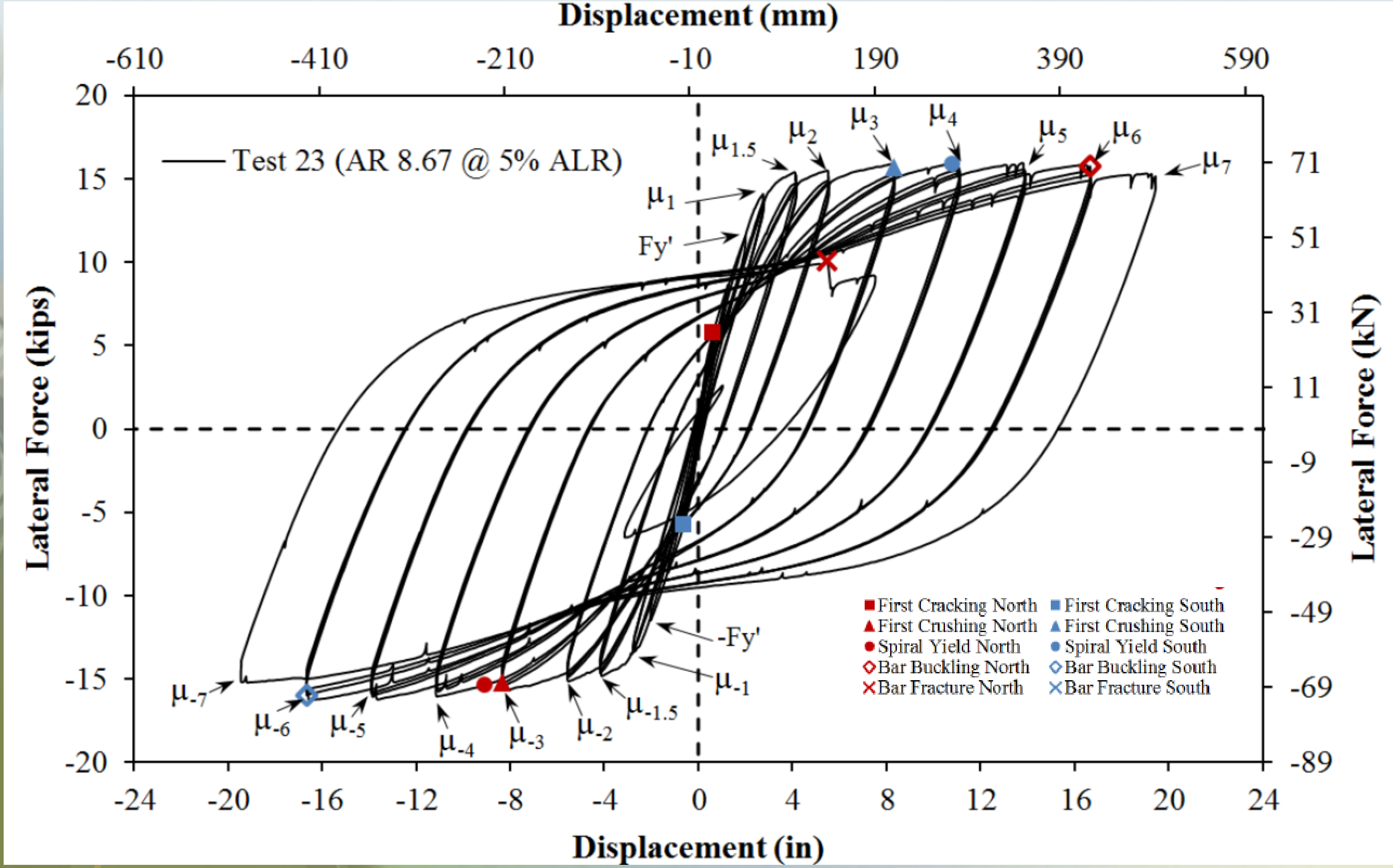
f_y = yield stress

E_s = modulus of elasticity

$\phi_p = \varepsilon_b / (c – d') - \phi_y$

Longitudinal Bar Buckling

- Compressive stress during tensile strain



Longitudinal Bar Buckling

- UW (Berry and Eberhard) bar buckling drift limits based upon the column test database

$$\Delta_{bb}/L = 3.25*(1+k_{e\_bb}*\rho_{eff}*d_b/D)*(1-P/A_g*f'_c)*(1+L/10*D)$$

where:

k_{e_bb} = 40 for rectangular, 150 for circular and 0 if $s/d_b > 6$

$\rho_{eff} = \rho_s*f_{ys}/f'_c$

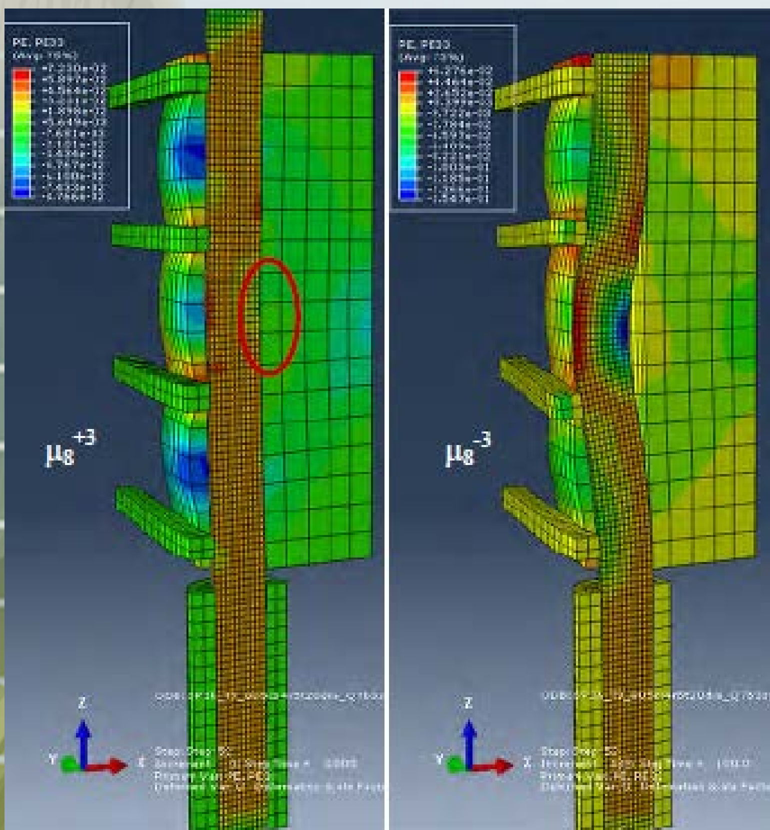
d_b = diameter of longitudinal column bars

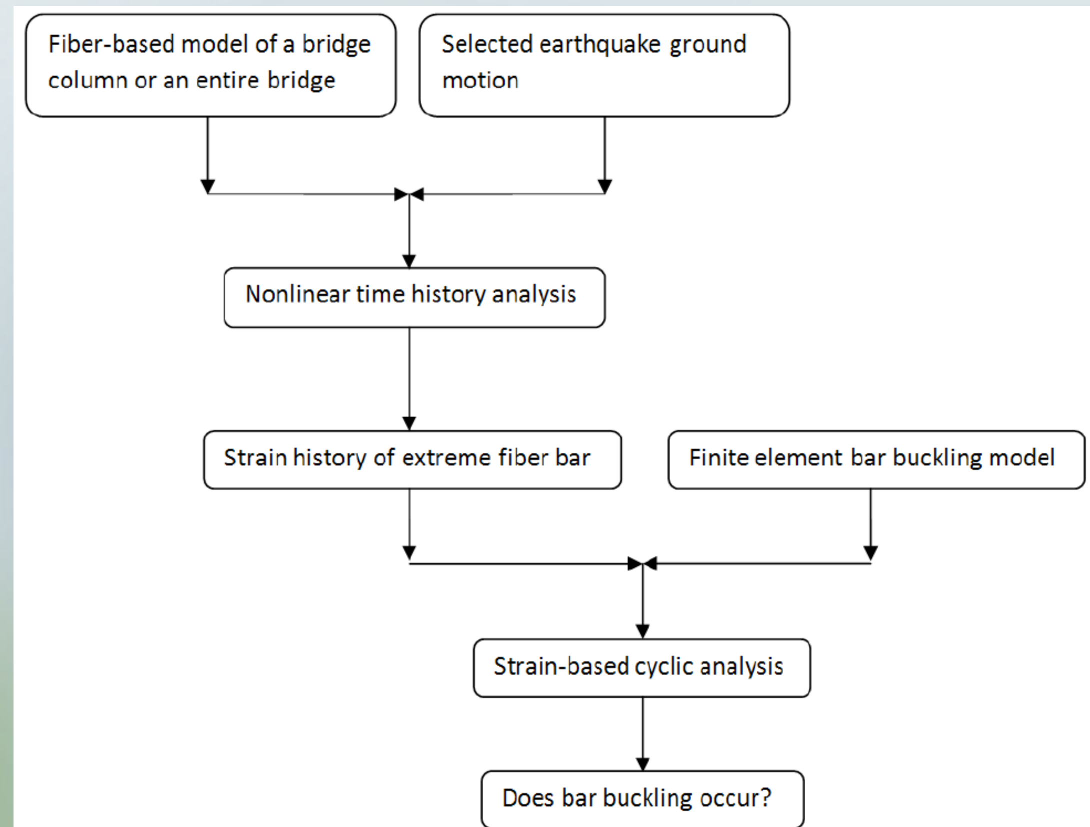
L = distance between plastic hinge and contraflexure point

D = column diameter or depth in direction of loading

Longitudinal Bar Buckling

- NCSU research approach





Longitudinal Bar Buckling

- NCSU recommendations

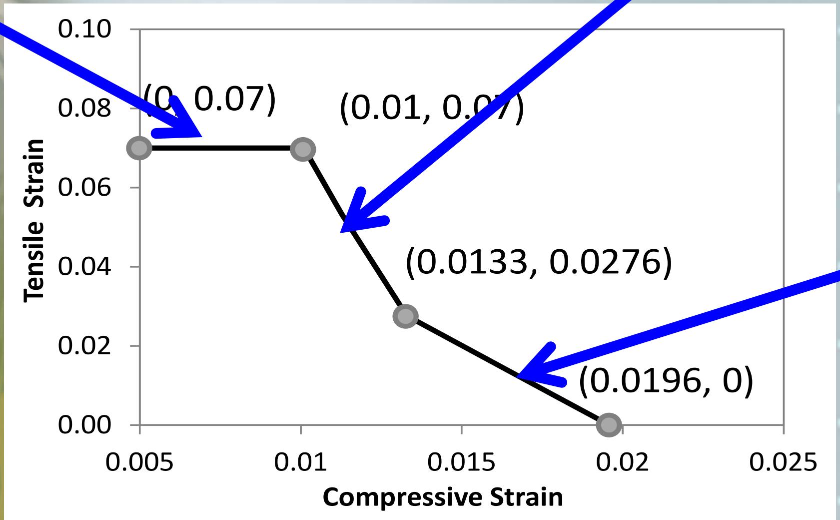
$$\varepsilon_t \le 0.09\text{, if } \frac{s}{d_{bl}} < 3$$

$$\varepsilon_t \le 0.06\text{, if } \frac{s}{d_{bl}} > 4$$

$$\varepsilon_t \le 0.09 - 0.03\left(\frac{s}{d_{bl}} - 3\right)\text{, if } 3 < \frac{s}{d_{bl}} < 4$$

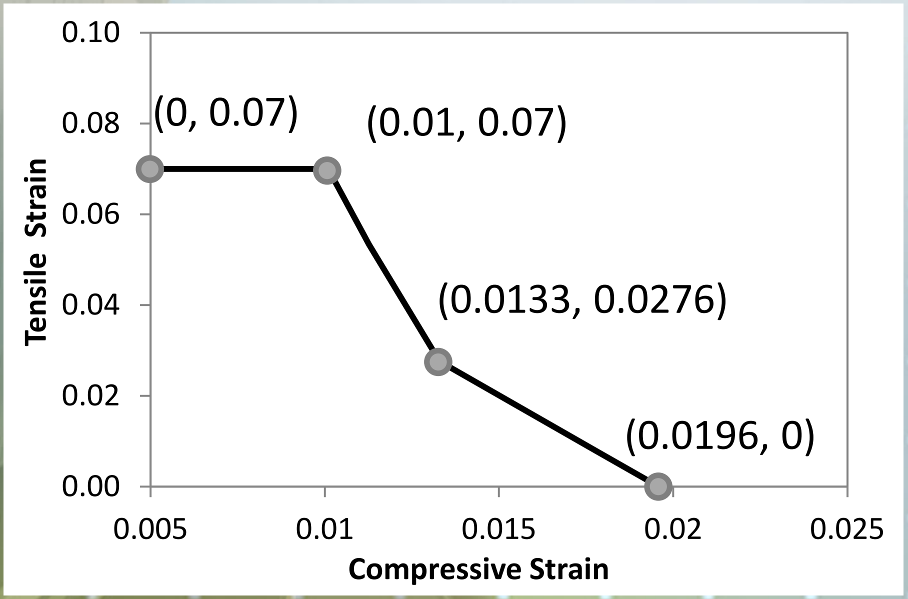
$$\varepsilon_t = \frac{-15\left(\varepsilon_c - \dfrac{0.0205}{\sqrt[3]{\dfrac{s}{d_{bl}} - 1}}\right)}{\left(\dfrac{d_{bl}}{d_h} - 1\right)^2}$$

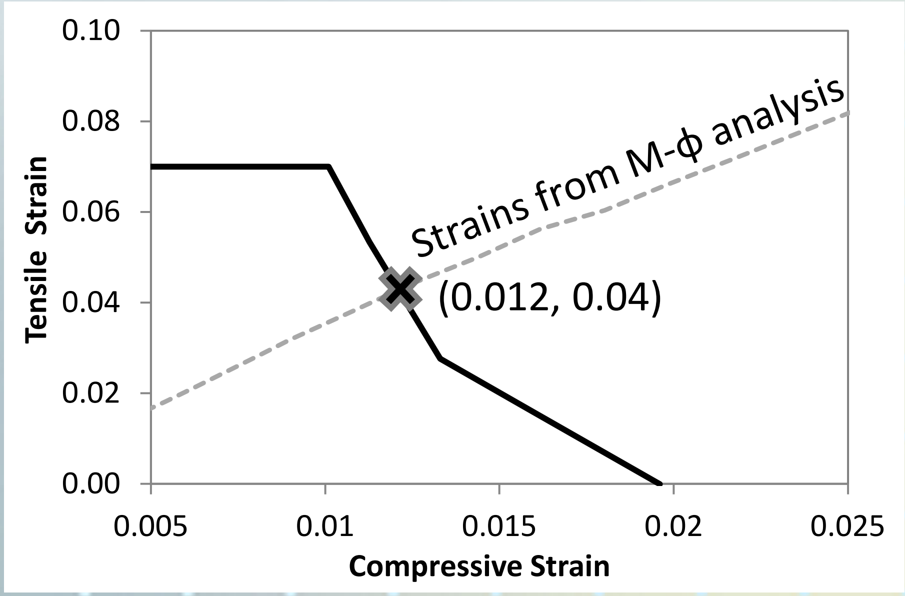
$$\varepsilon_t \ge -1.7\frac{s}{d_{bl}}\sqrt{\frac{d_h}{d_{bl}}}\varepsilon_c + 0.045\sqrt{\frac{s}{d_{bl}}}$$



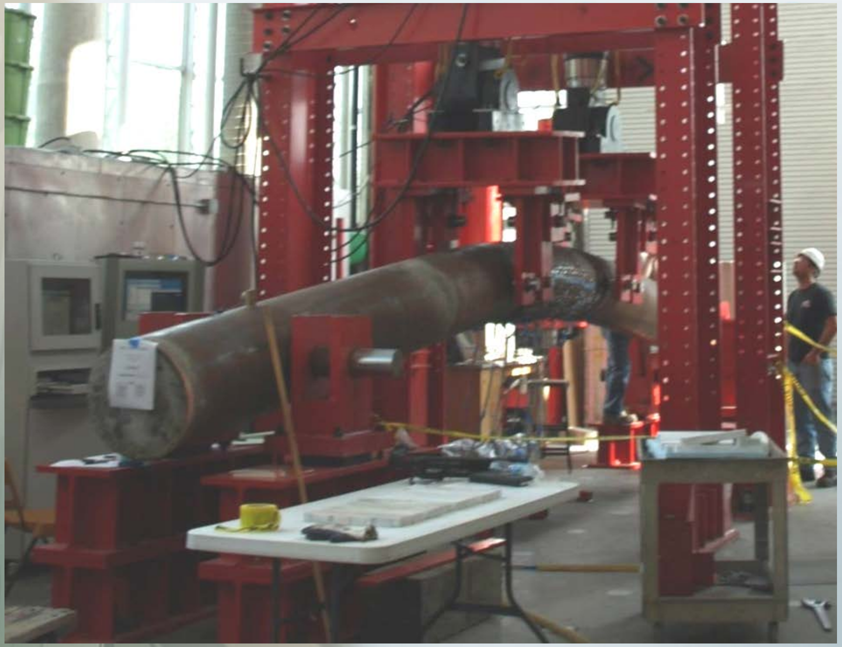
Longitudinal Bar Buckling

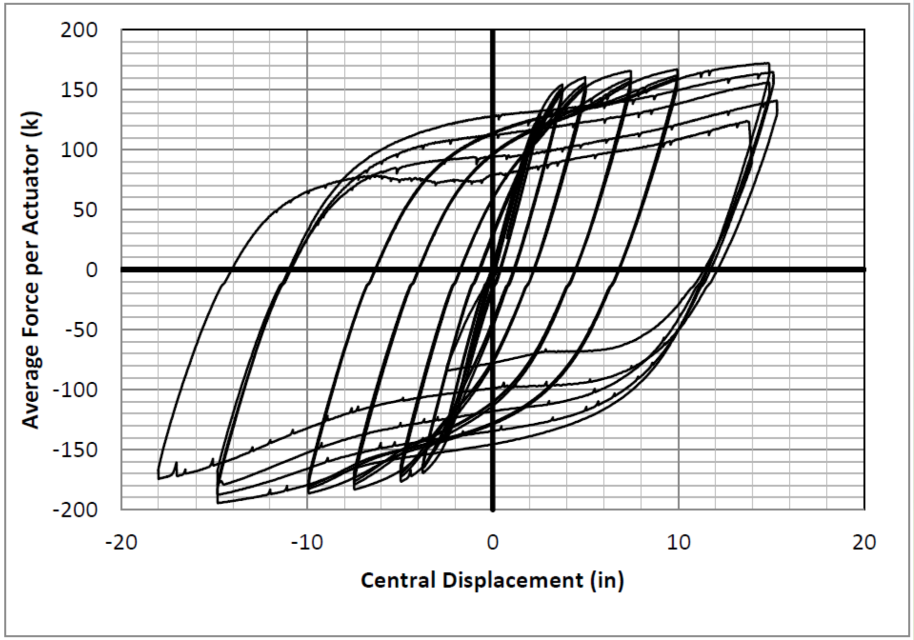
- NCSU recommendations





Concrete Filled Steel Pipes



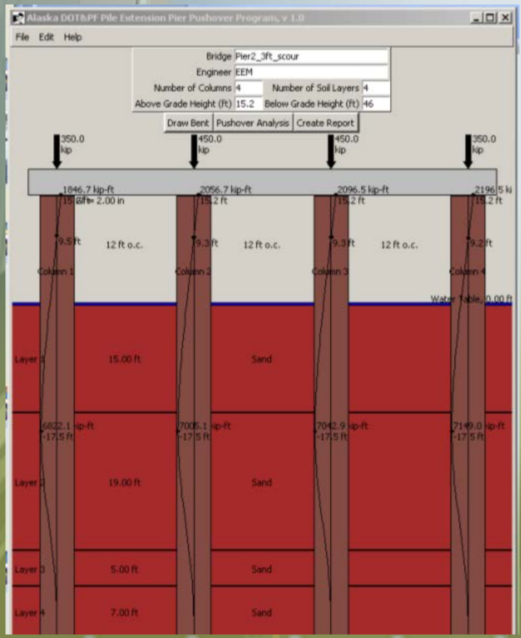


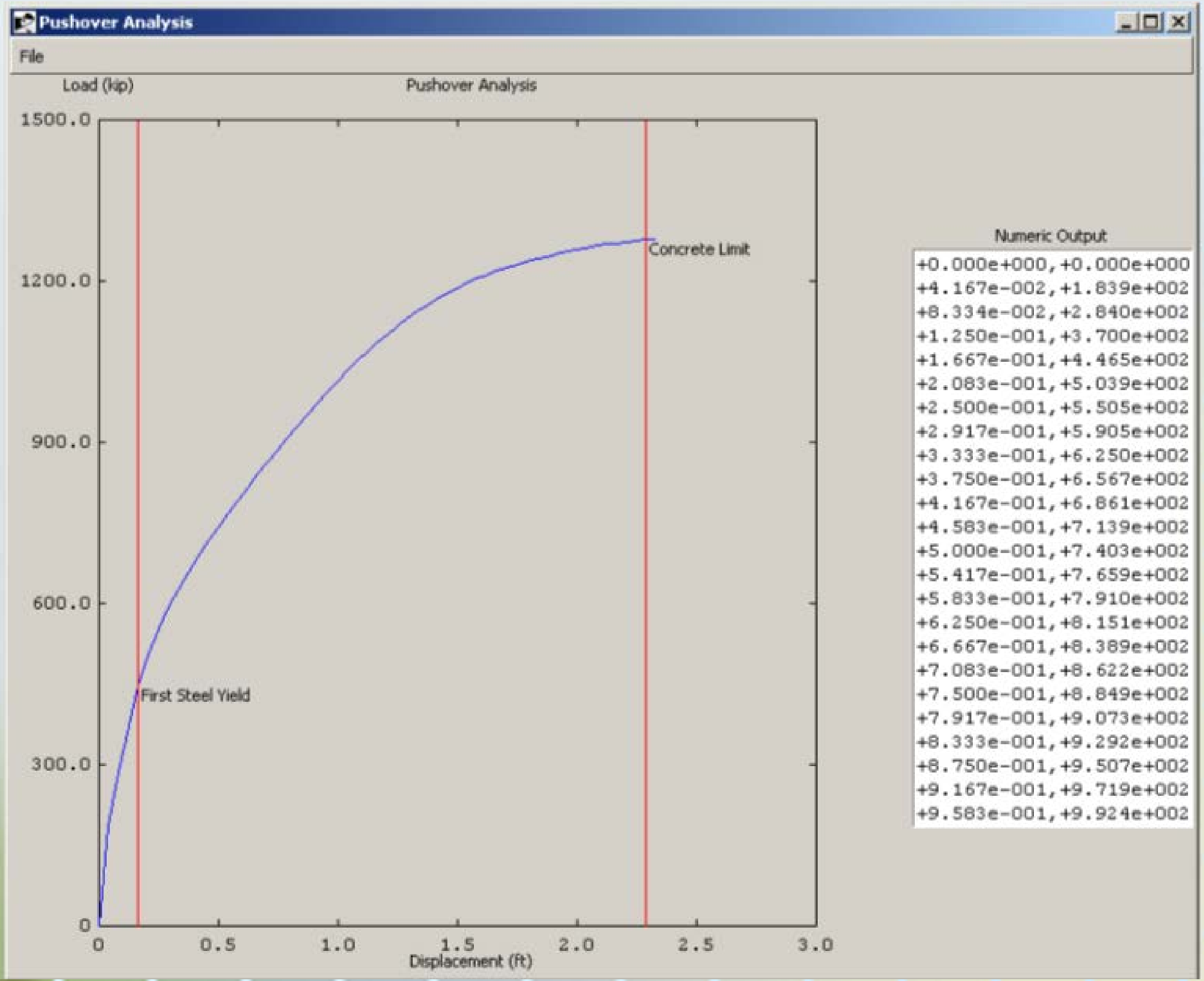
Concrete Filled Steel Pipes

+ Minimize in-water work, no cofferdam
+ High strength, stiffness, seismic resistance
+ Open ended piles for obstruction removal
+ Scour and liquefaction resistant

- Pile availability (API 5L vs. ~~ASTM A 252~~)
- Field welding, QC and QA
- How to connect to “weaker” cap beam?
- Below ground hinging

Concrete Filled Steel Pipes



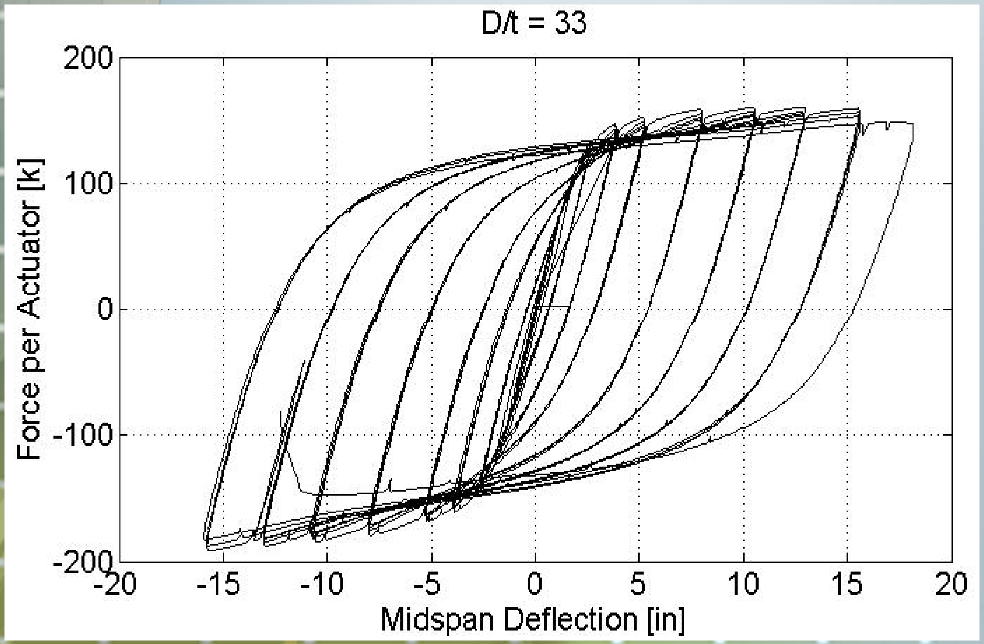


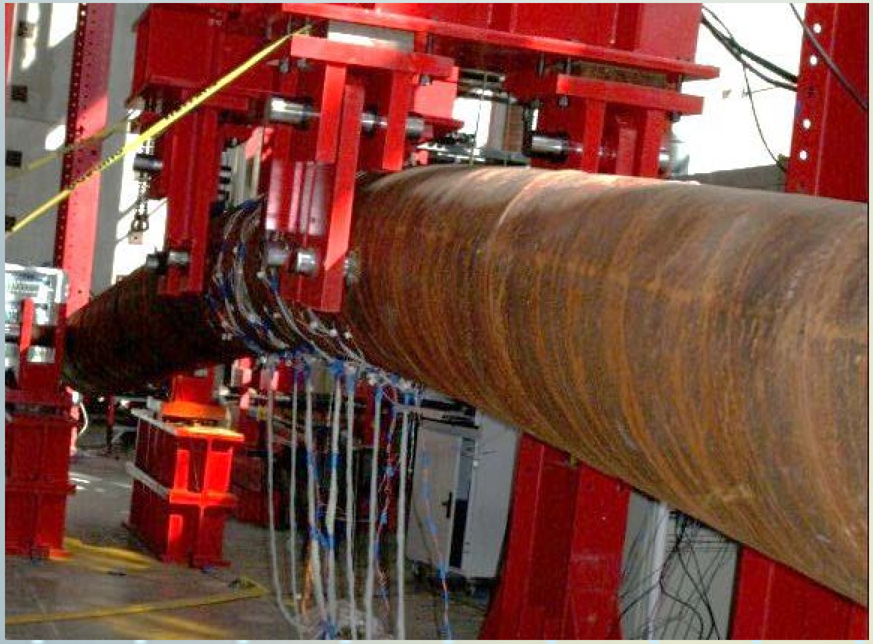
Strain Limits for CFSP

- AKDOT sponsored research at NCSU
  - First principles (equilibrium compatibility)
  - 33 < D/t < 192 (piles and drilled shafts)
  - With and without reinforcing steel
  - Straight seam and spiral welded
  - Buckling and rupture strain limits
  - Analytical plastic hinge length (ongoing)

Strain Limits for CFSP

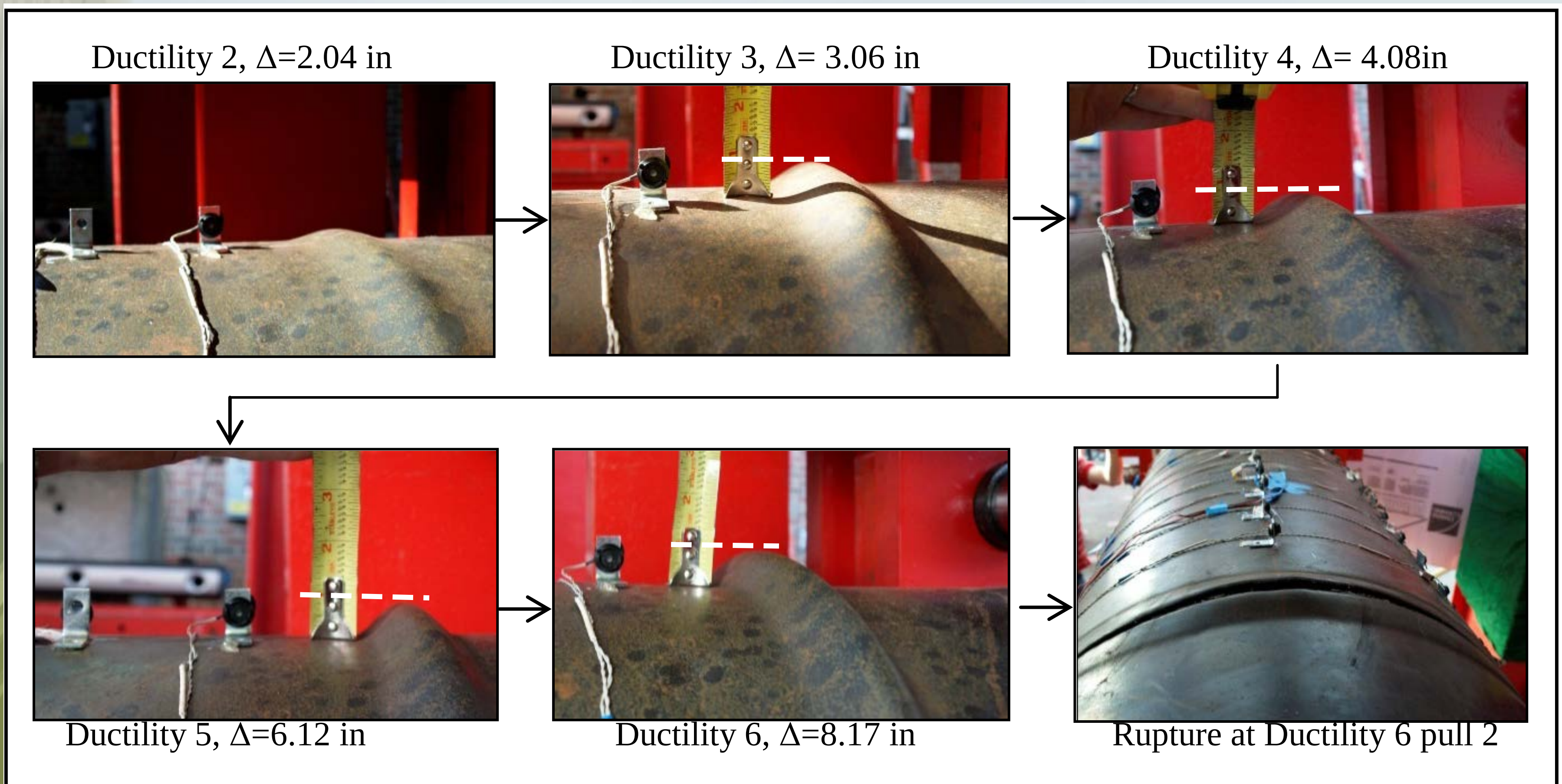
- Large lateral deformation capacity
- Good force-deformation / hysteretic response





Strain Limits for CFSP

- Onset of buckling and rupture



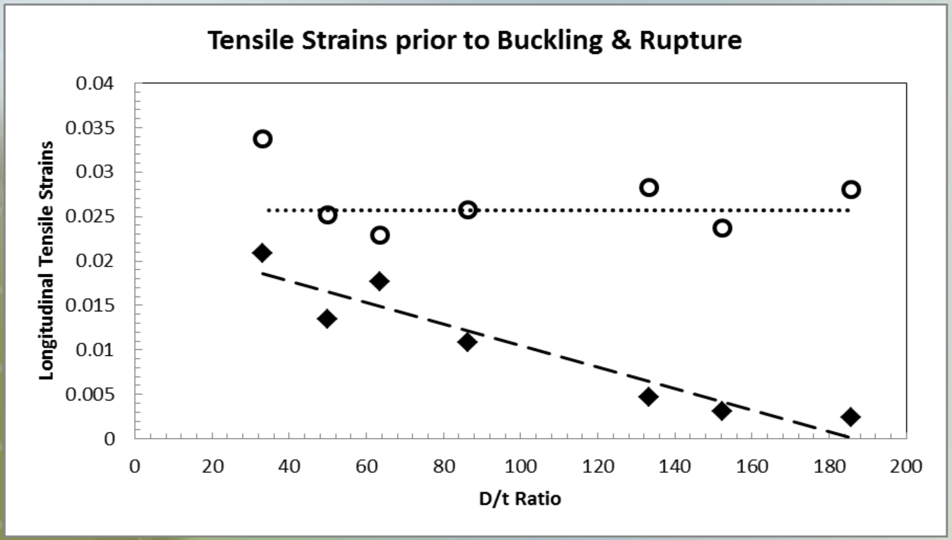
Strain Limits for CFSP

- Onset of pipe wall buckling (tensile strain)

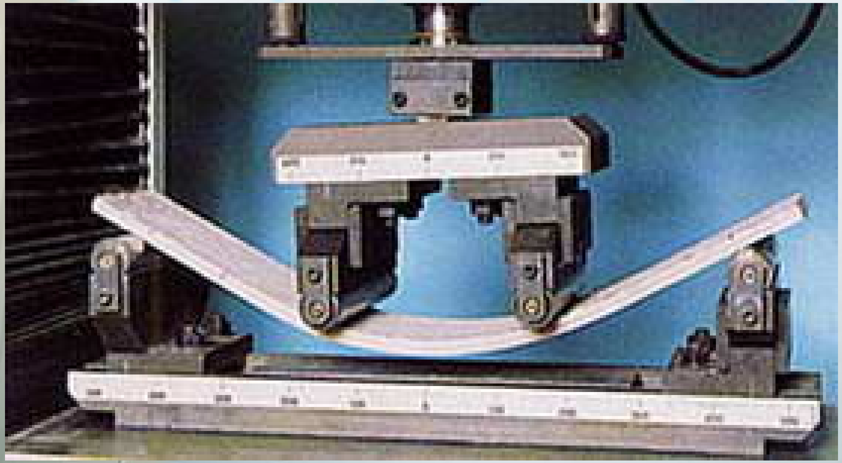
$$\varepsilon_b \sim 0.022 - (D/t)\ /\ 9{,}000$$

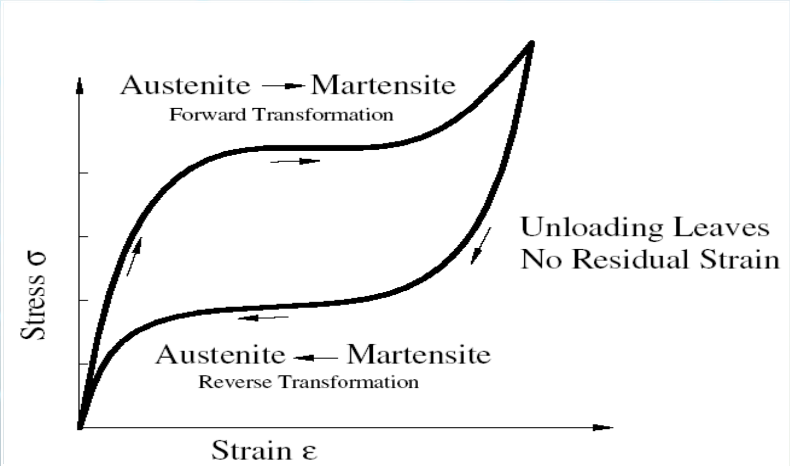
- Reduced ultimate tensile strain

$$\varepsilon^R_{su} \sim 0.026 \text{ in./in.}$$



Nontraditional Systems





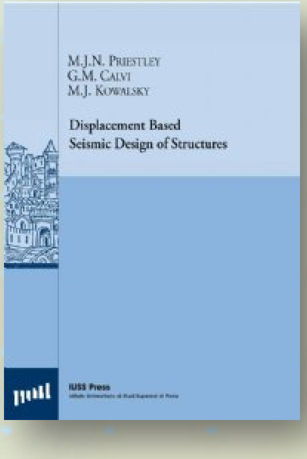
Direct Displacement Design

- Start with performance objective (strain, deflection or ductility limits)
- Size the member (column diameter)
- Reinforce to specified resistance (ρ_l)
- Check non-seismic load combinations

Direct Displacement Design

- Advantages
  - + insensitive to initial stiffness
  - + relatively easy to use
  - + different methodology for QC/QA

- Disadvantages
  - - equivalent viscous damping
  - - complex geometry limitations
  - - limited utilization to date



Questions - Thank you

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