Advances in High-Strength Reinforcing Bar Research in the U.S.

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Roadblocks for Implementing HSRB

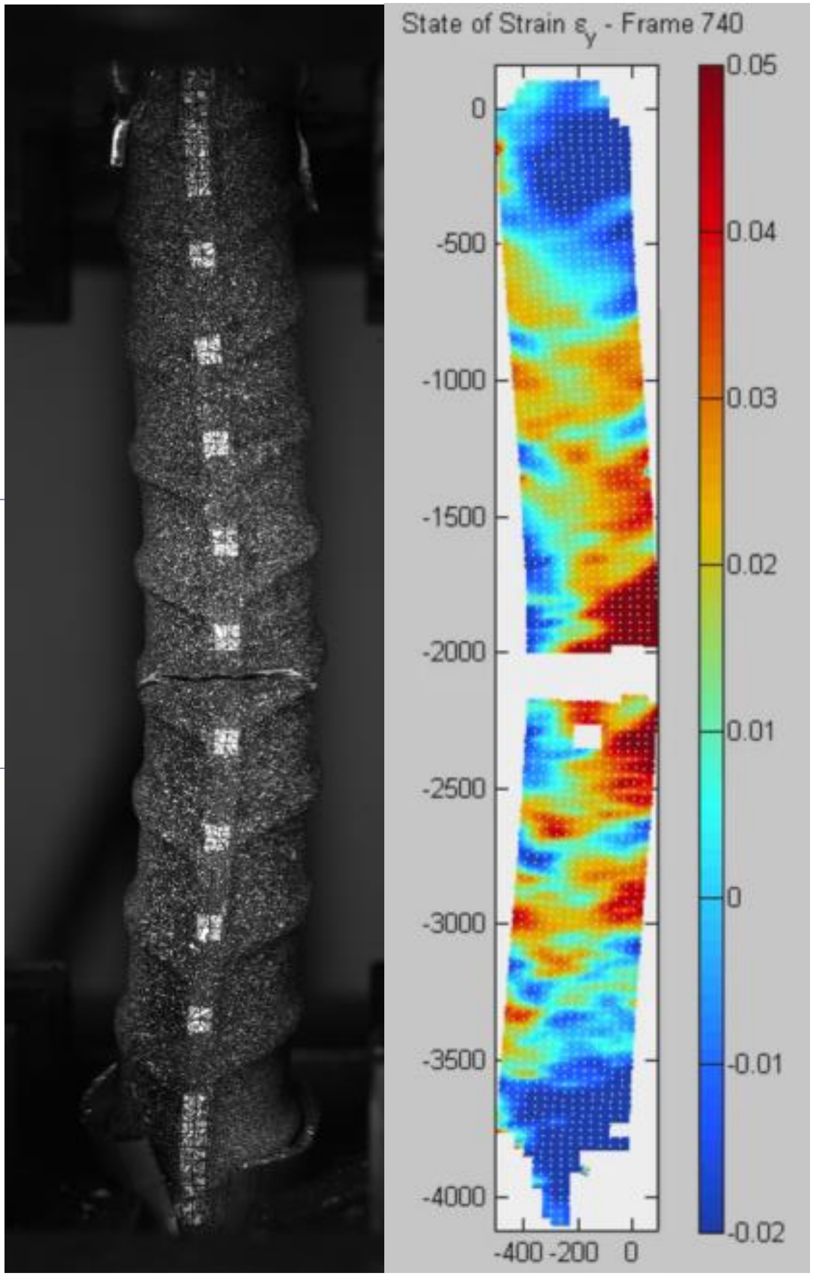
1- Material Issues

- Stress-strain behavior
- Fatigue behavior
- Production Repeatability

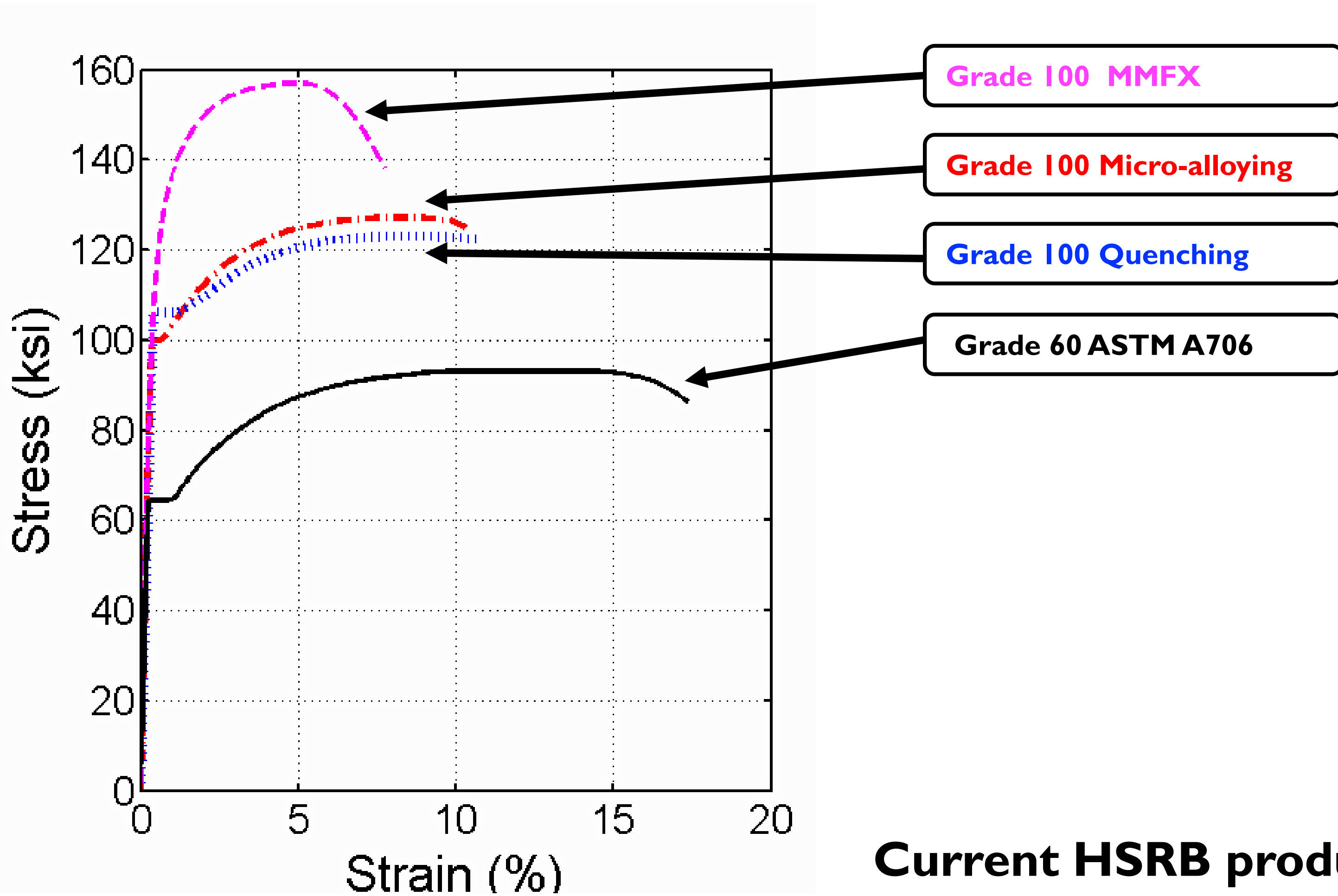
2- Structural Issues

- Stiffness
- Strain compatibility
- Bar demands
- Detailing

Material Issues

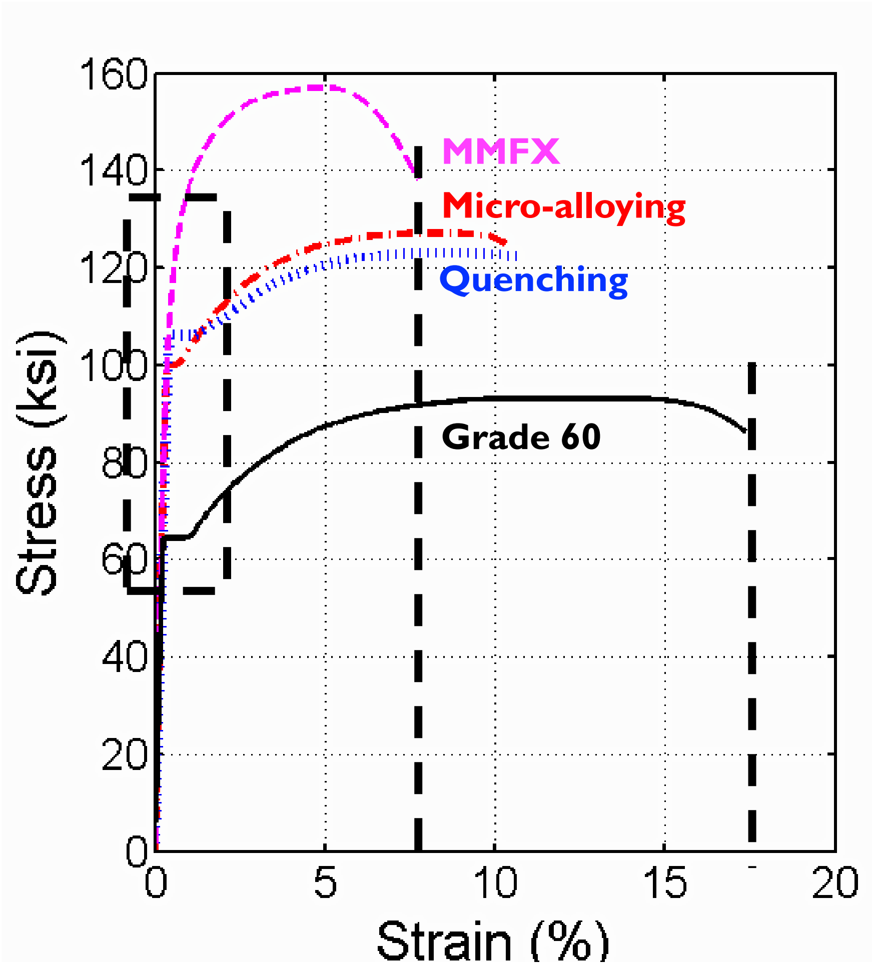


Stress Strain Behavior



Current HSRB produced have very different stress-strain relations

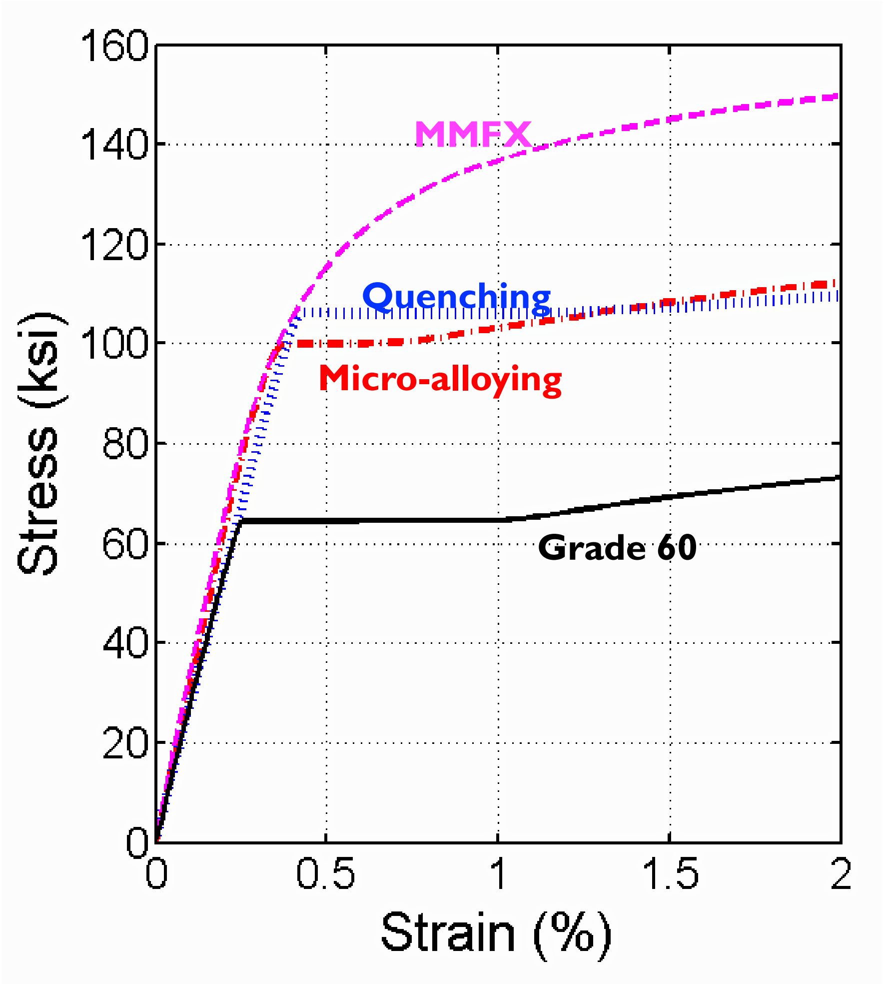
Stress Strain Behavior



Fracture elongation?

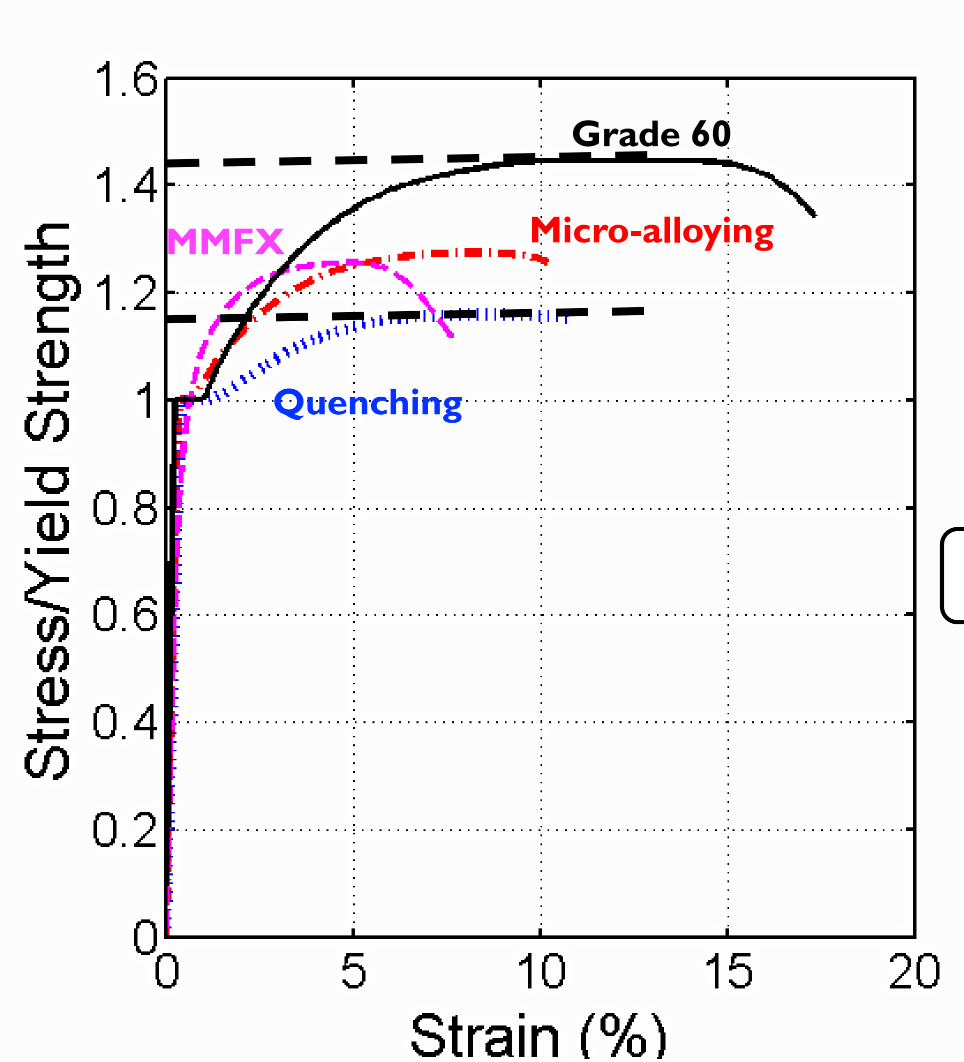
Yield plateau?

Stress Strain Behavior



Yield plateau?

Stress Strain Behavior

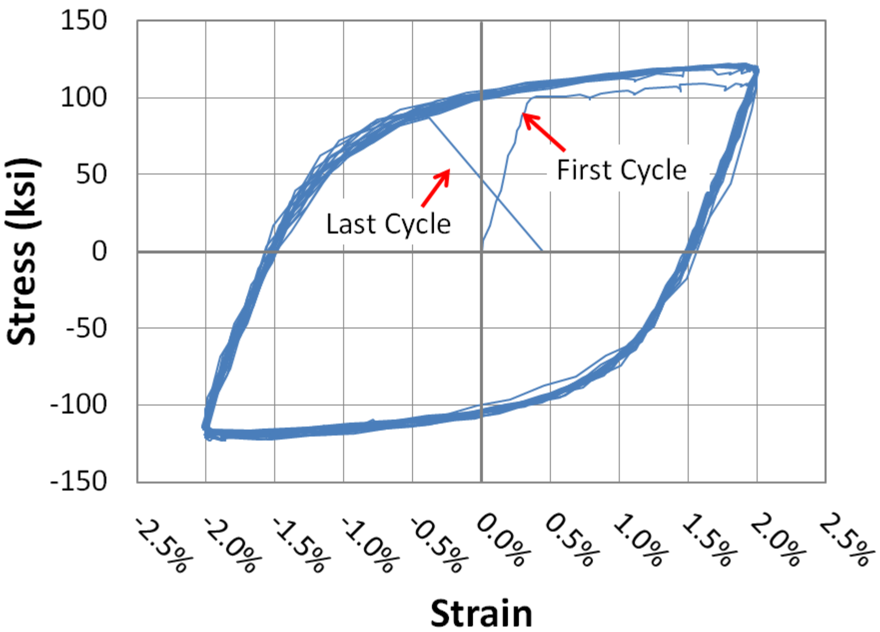


Tensile-to-Yield Strength Ratio?

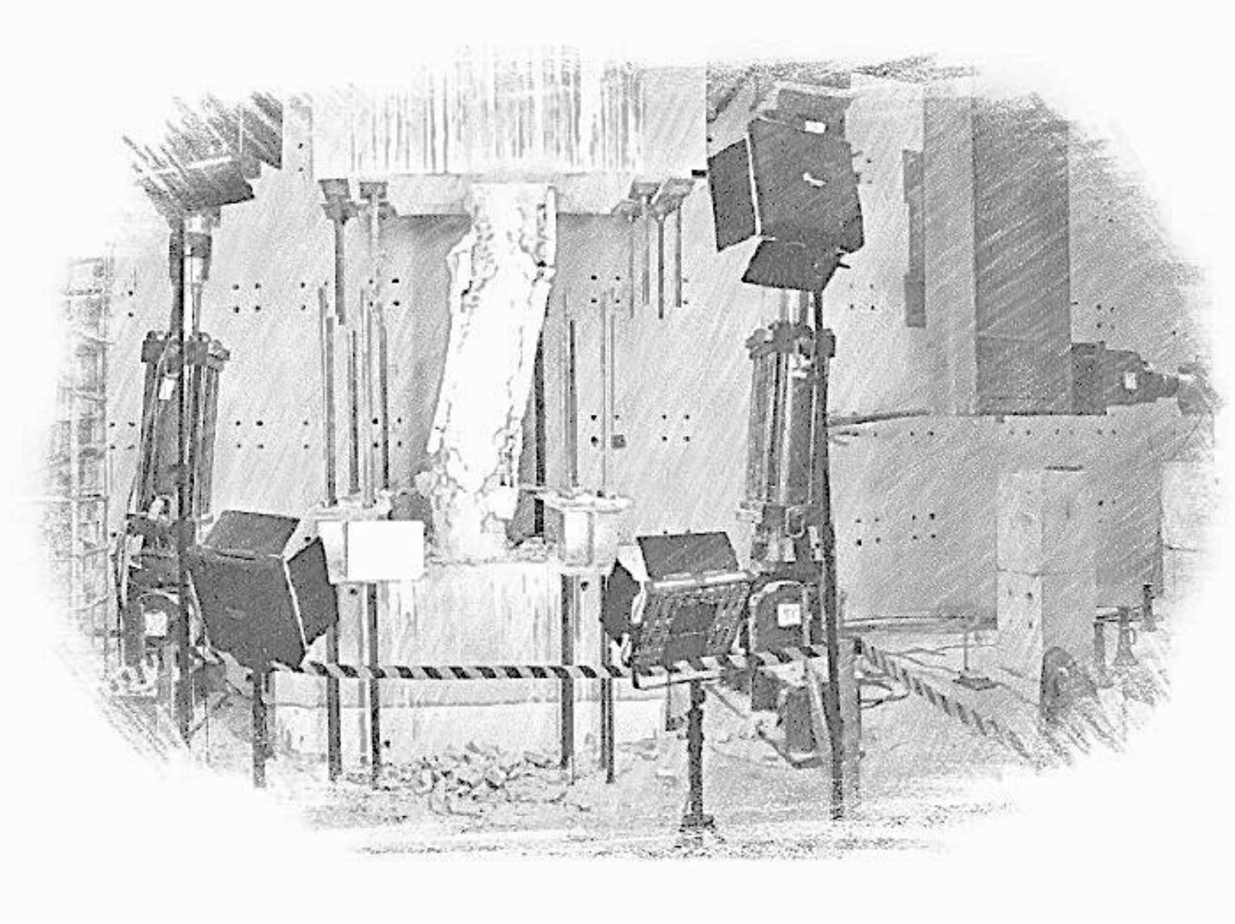
Other Issues

What about cyclic fatigue?

What properties should the mills target?



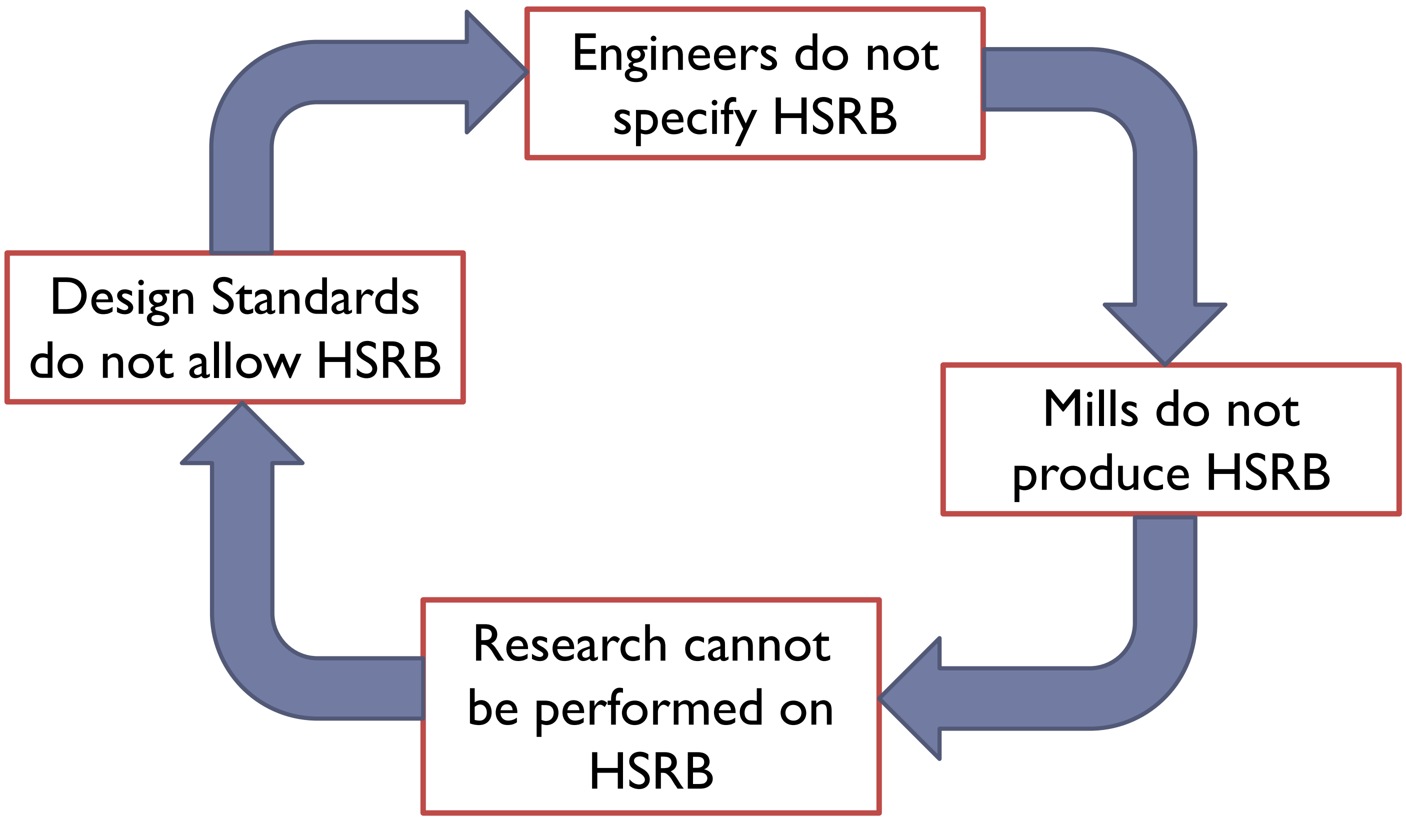
Structural Issues



Overview of Structural Concerns

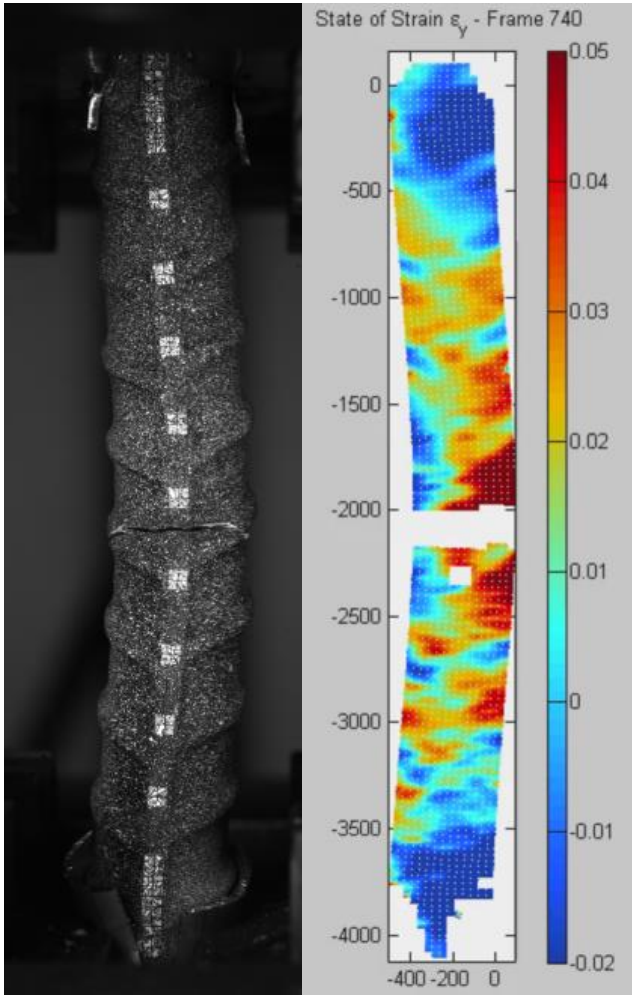
- Higher strain at yield
  - larger cracks
  - larger deflections
  - strain compatibility
  - effectiveness as shear reinforcement
- Higher strength
  - larger tensile forces
    - increase in bond demands
    - increased forces in hooks and heads
  - larger compressive forces
    - increased bar buckling susceptibility given the same lateral bracing
- Less ductile bars
  - less ductility for seismic members
- Tensile-to-yield strength (T/Y) ratio
  - plasticity spread
  - strain concentration at cracks
  - higher strains can lead to premature fracture

Cycle of Inaction



- Industry needs guidance from engineers and researcher about which properties to achieve in HSRB

Targeted Material and Structural Testing



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aci Foundation

Material Testing Program

Low-Cycle Fatigue

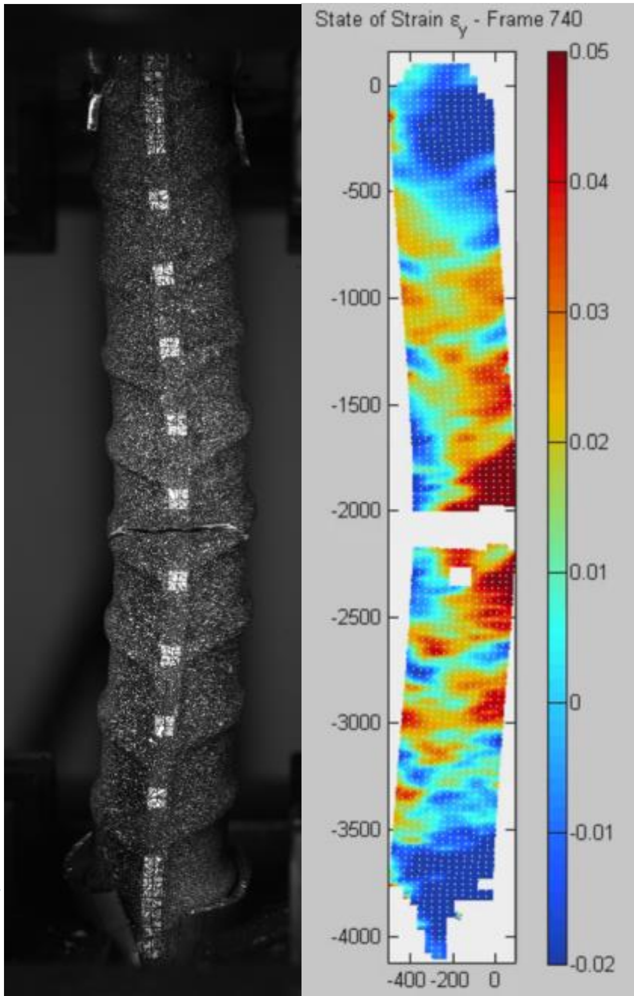
Ghannoum, W.M., Slavin, C.M., "Low-Cycle Fatigue Performance of High-Strength Steel Reinforcing Bars," ACI Materials Journal, V. 113, No. 6, pp. 803-14, 2016.

Slavin, C.M., Ghannoum, W.M., "Defining Structurally Acceptable Properties of High-Strength Steel Bars through Material and Column Testing, PART I: MATERIAL TESTING REPORT," (05-14), Charles Pankow Foundation, pp. 135, August 2015.

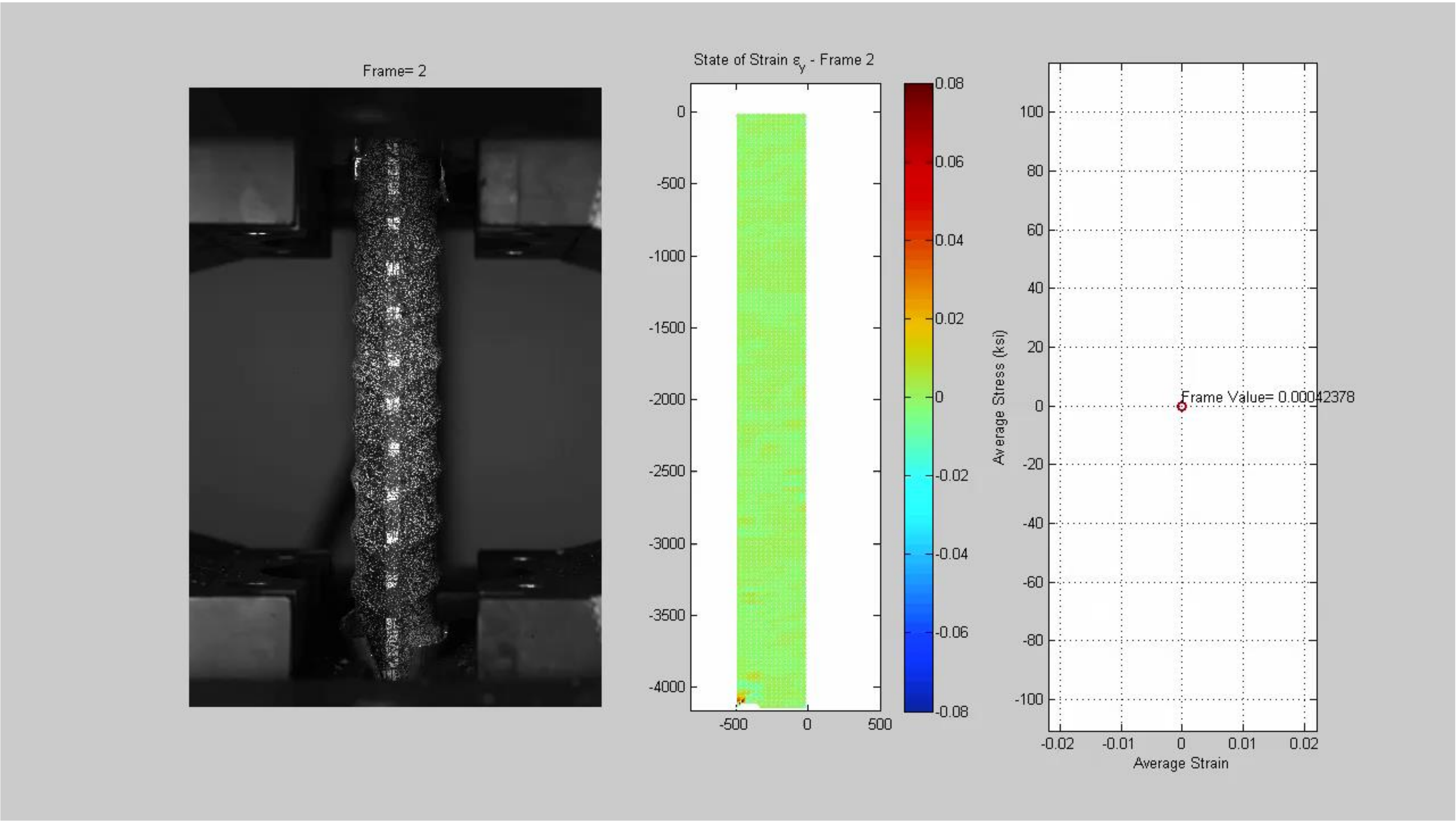
Experimental Program

Compare low-cycle fatigue behavior of HSRB and grade 60 bars

- Grades
  - 60; A-706
  - 80; A-706
  - 100; "Ductile"
- Bar Sizes
  - #5 - Transverse
  - #8 - Longitudinal
  - #11 - Longitudinal
- Manufacturing Techniques
  - Microalloying with Vanadium
  - Quenching and Tempering
- Clear-Spans
  - $4d_b$
  - $5d_b$
  - $6d_b$
- Loading Protocols:
- 2 per bar size
  - ±2% and +4%, -1%
  - ±2% and +4%, 0%



Typical Test



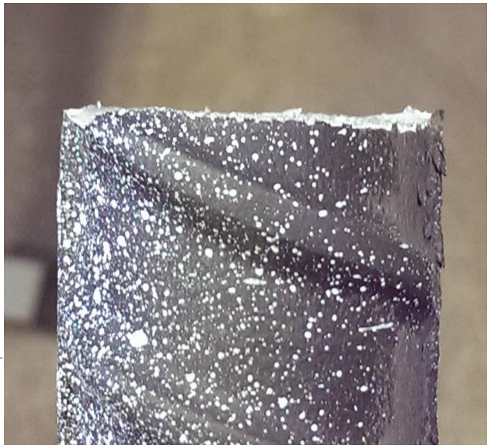
#8 - $6d_b$ - ±2%

Ghannoum Vision System

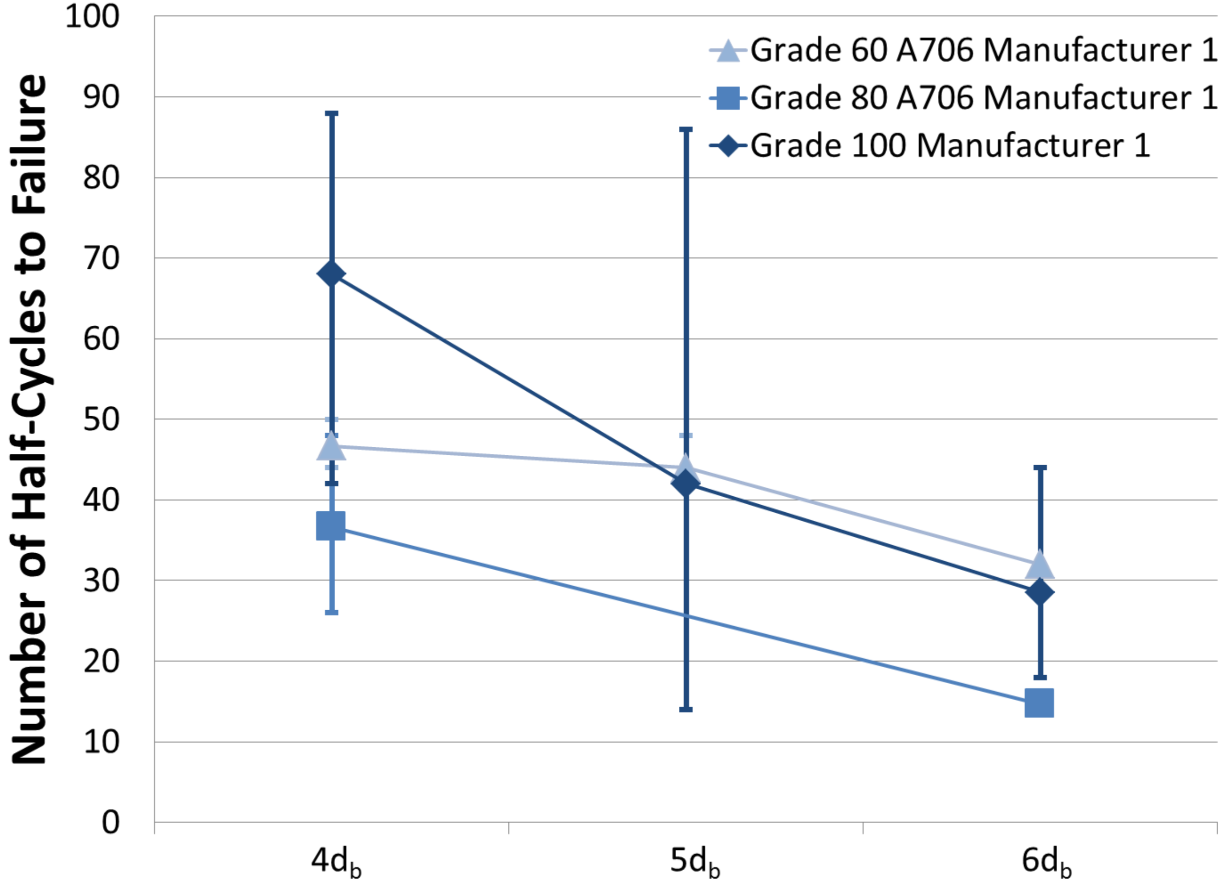
Summary of Findings

Grade 100 HSRB

1. Overall grade 100 bars showed ~90% of cycles to failure than grade 60 bars
2. Large variability in performance of grade 100
    1. Worse performance for larger bars
    2. Variable performance at low clear spans
    3. Significant differences between manufacturing processes



Results of Cyclic Tests – #8 at ±2%



Summary of Findings

Grade 80 HSRB

1. Large variability in performance of grade 80 bars
   1. Some samples performed much better than grade 60
   2. Others much worse (~50% of cycles to failure of grade 60)
   3. Specifically A706 bars performed much worse

2. Few tests on grade 80 bars in this first study

Column Testing Program

Series I: HSRB in Shear and Confinement

Three columns under high shear and axial stresses

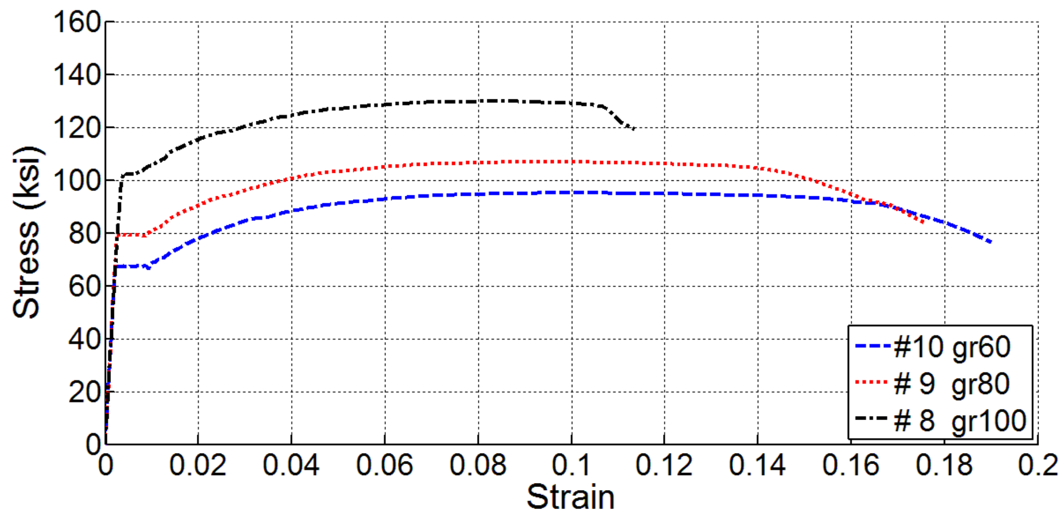
Results published in ACI Structural Journal May-June 2016

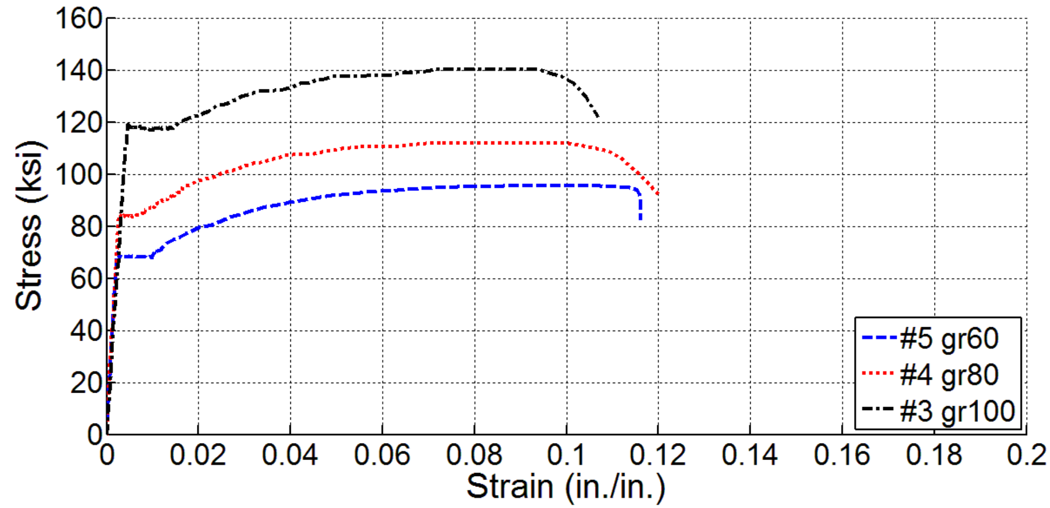
Series 2: Plasticity Spread and Strain Demands

Four columns under low shear axial stresses

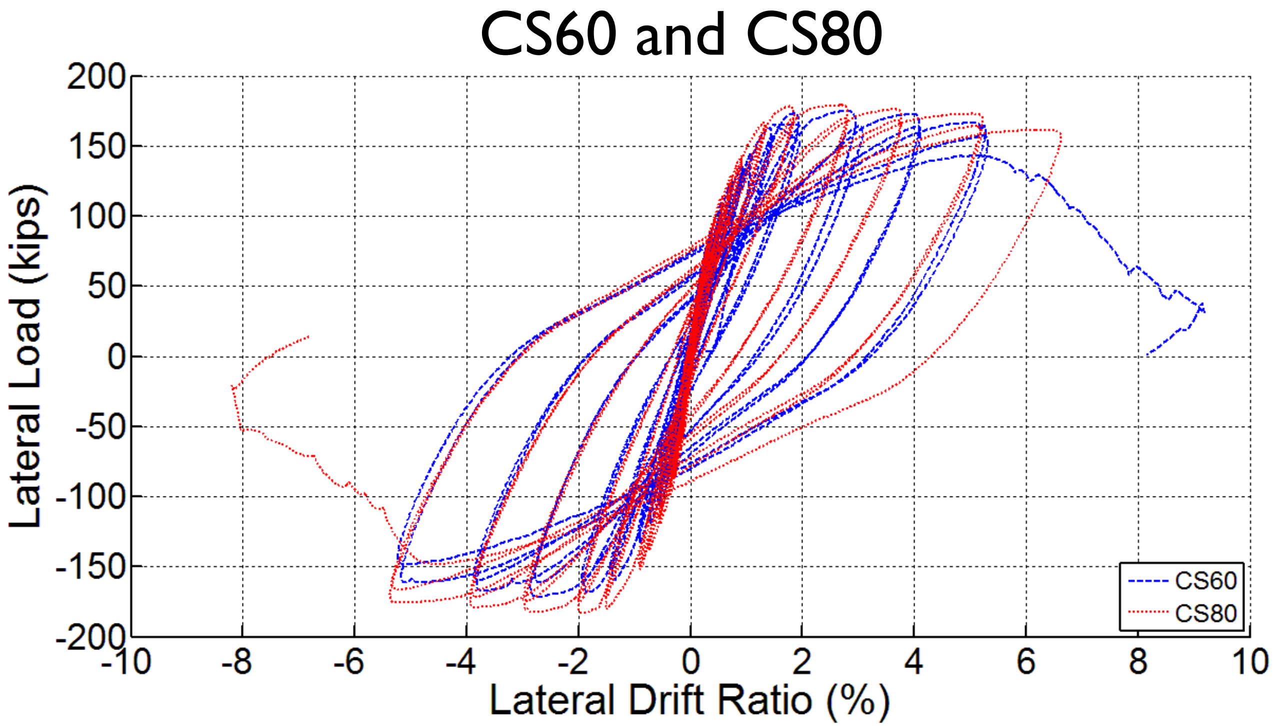
Testing completed – Report published

Series 1 Material Properties





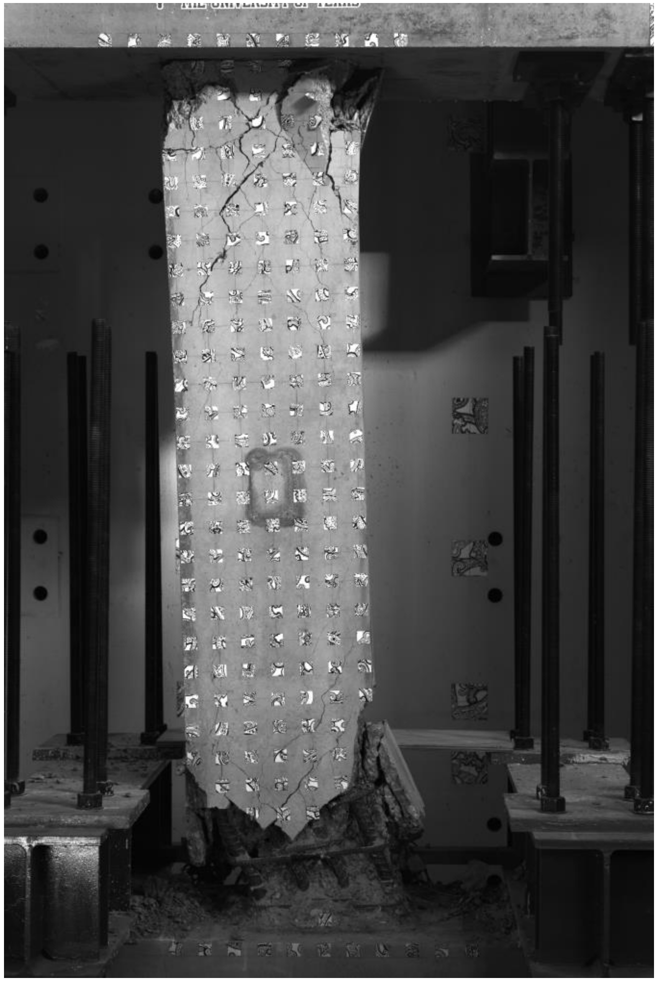
Series 1 Global Results



GOOD PREFORMANCE

- Almost identical behavior for CS60 and CS80
- Both specimens sustained shear and axial failures at large drifts and remained stable up to a drift ratio of 5.5%

Series 1 Global Results

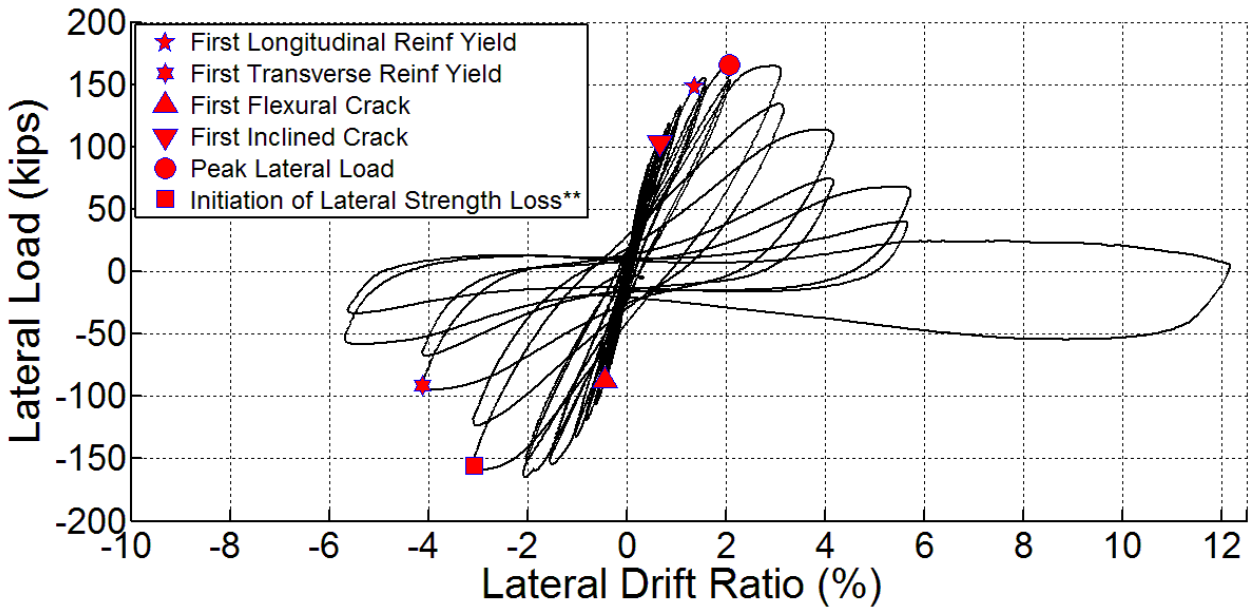


Gr 60 Pushed after lowering axial load. **Gr 80**

Test Stopped +9.5% **Test Stopped -8.4%**

Series 1 Global Results

CS100



CS 100

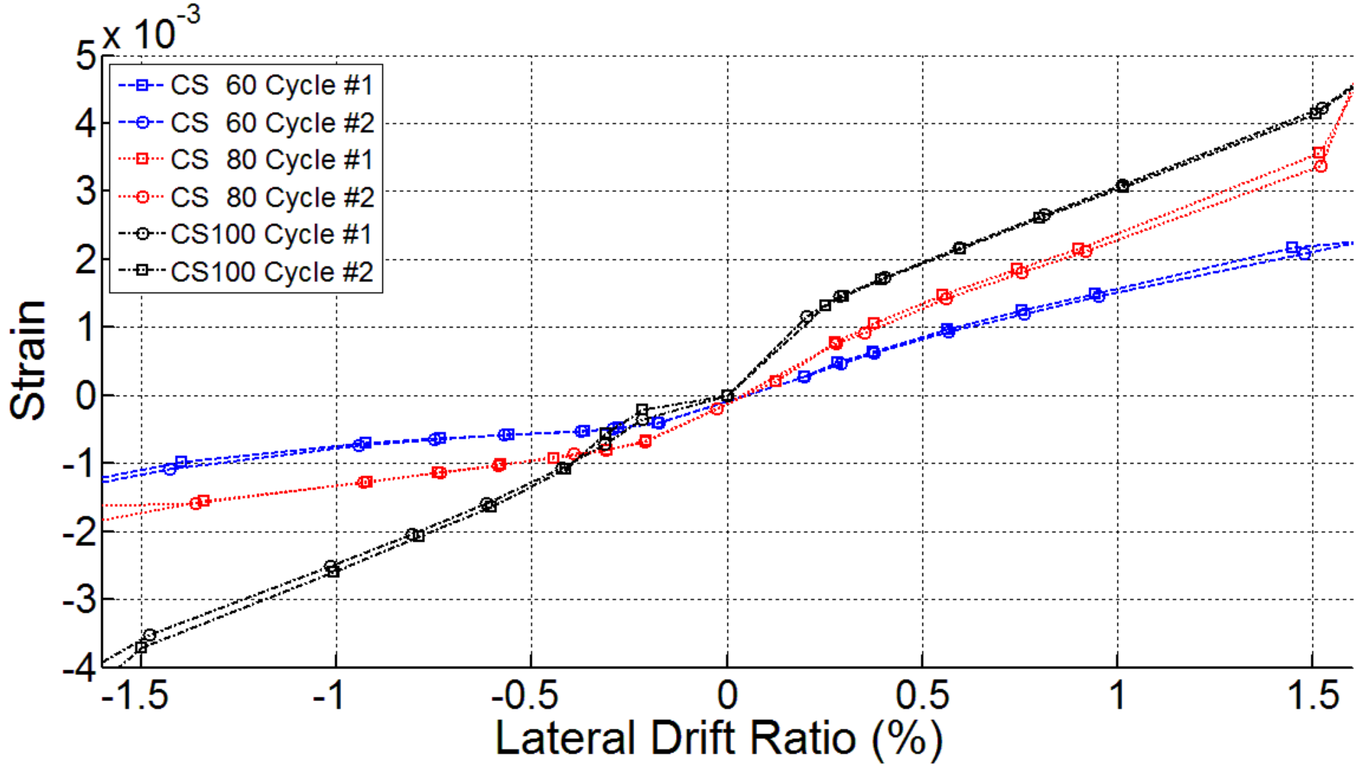
Bond failure at a drift ratio of 3%

Deficiency in ACI 318 anchorage provisions / Ballot in progress

Test Stopped +11.5%

Series 1 Bar Demands

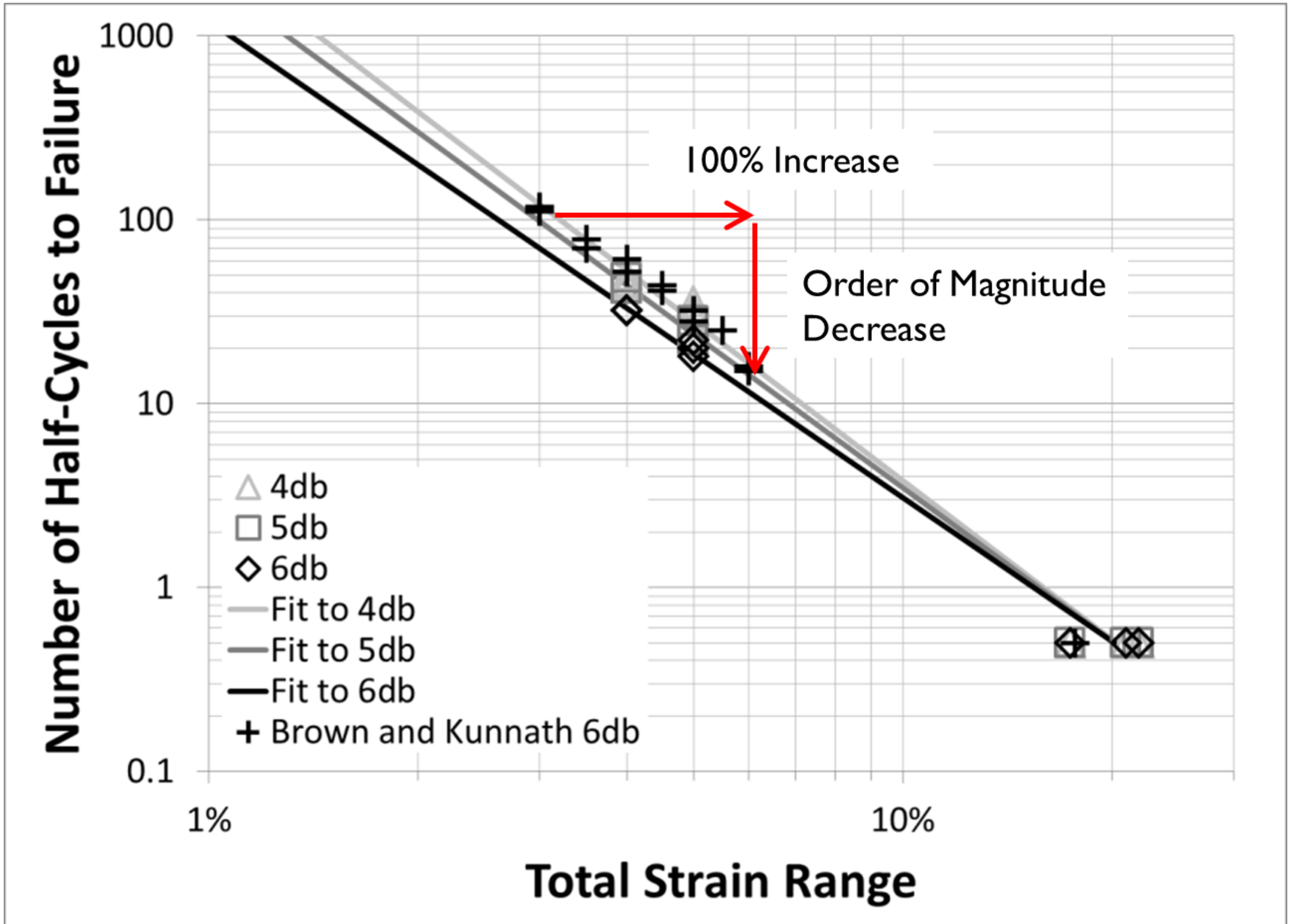
Longitudinal bars



CS80 larger ~65% larger than CS60
CS100 strain ~100% larger than CS60

Same trends in transverse bars

Low-Cycle Fatigue Demand to Capacity

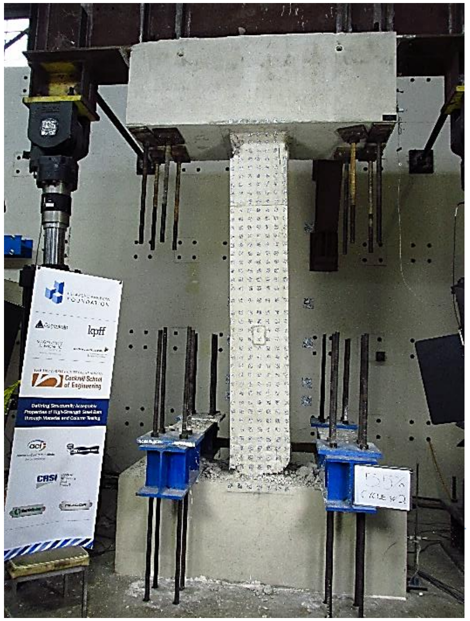


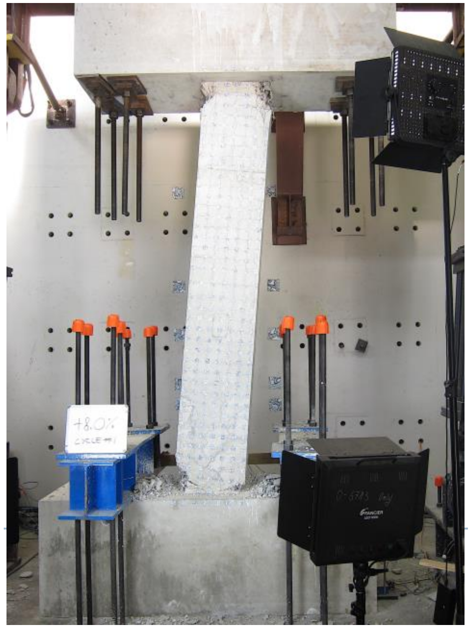
- HSRB may need better low-cycle fatigue performance than grade 60 bars

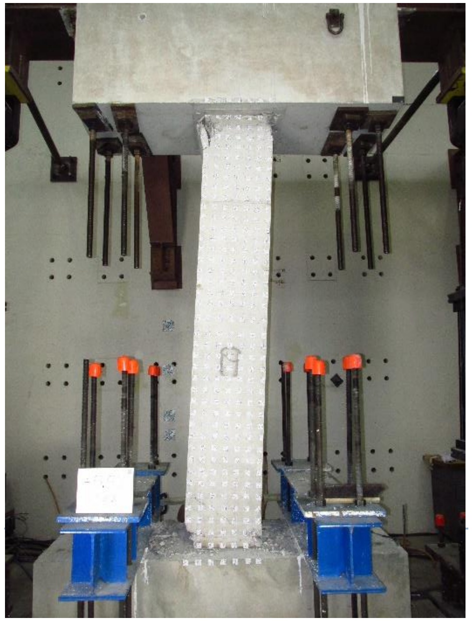
Series 2 — Overview

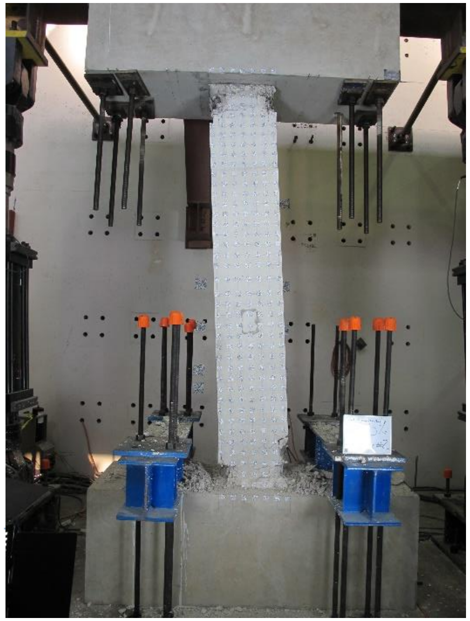
- Maximize strain demands in the bars
- Investigate three main types of HSRB being produced in US

Grade 100 T/Y = 1.27 (H)	**Grade 100 T/Y = 1.16 (L)**	**Grade 100 T/Y = 1.27 (MMFX)**	**Grade 60 T/Y = 1.45 (H)**
CH100	**CL100**	**CM100**	**CH60**



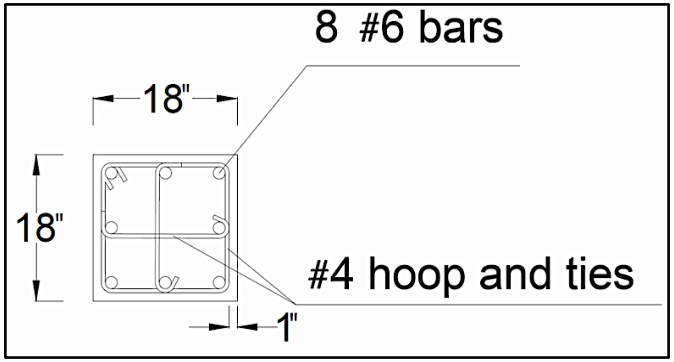


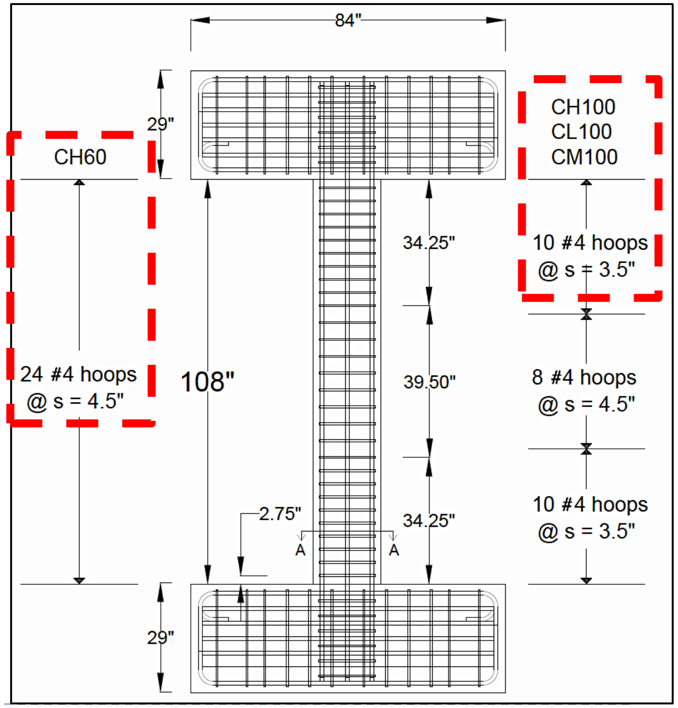




Series 2 Design

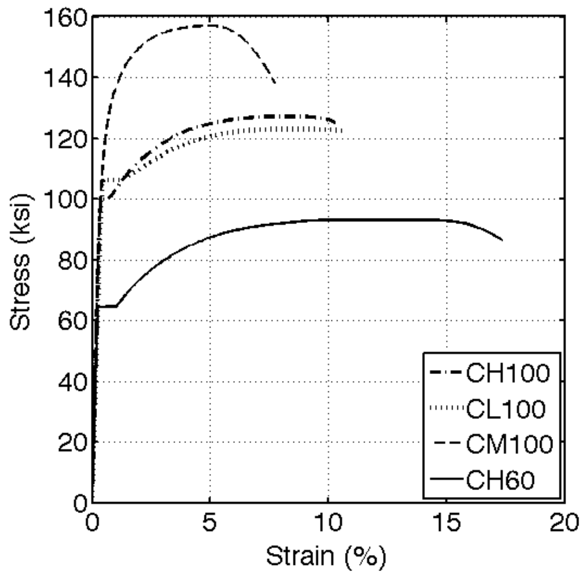
- Moderate axial load:
  - 15% of gross capacity
- Low shear stresses:
  - $< 4.0\sqrt{f_c'}$
- Concrete compressive strength:
  - 5 ksi
- Same longitudinal reinforcement ratio and bar arrangement
- Hoop spacing varied

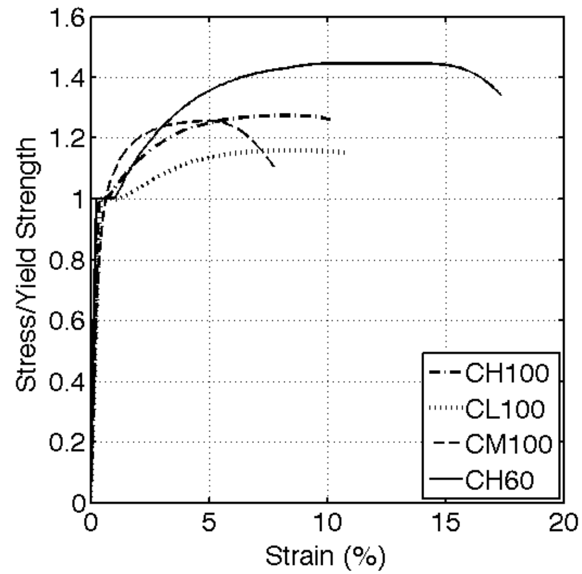




Series 2 Reinforcing Steel Properties

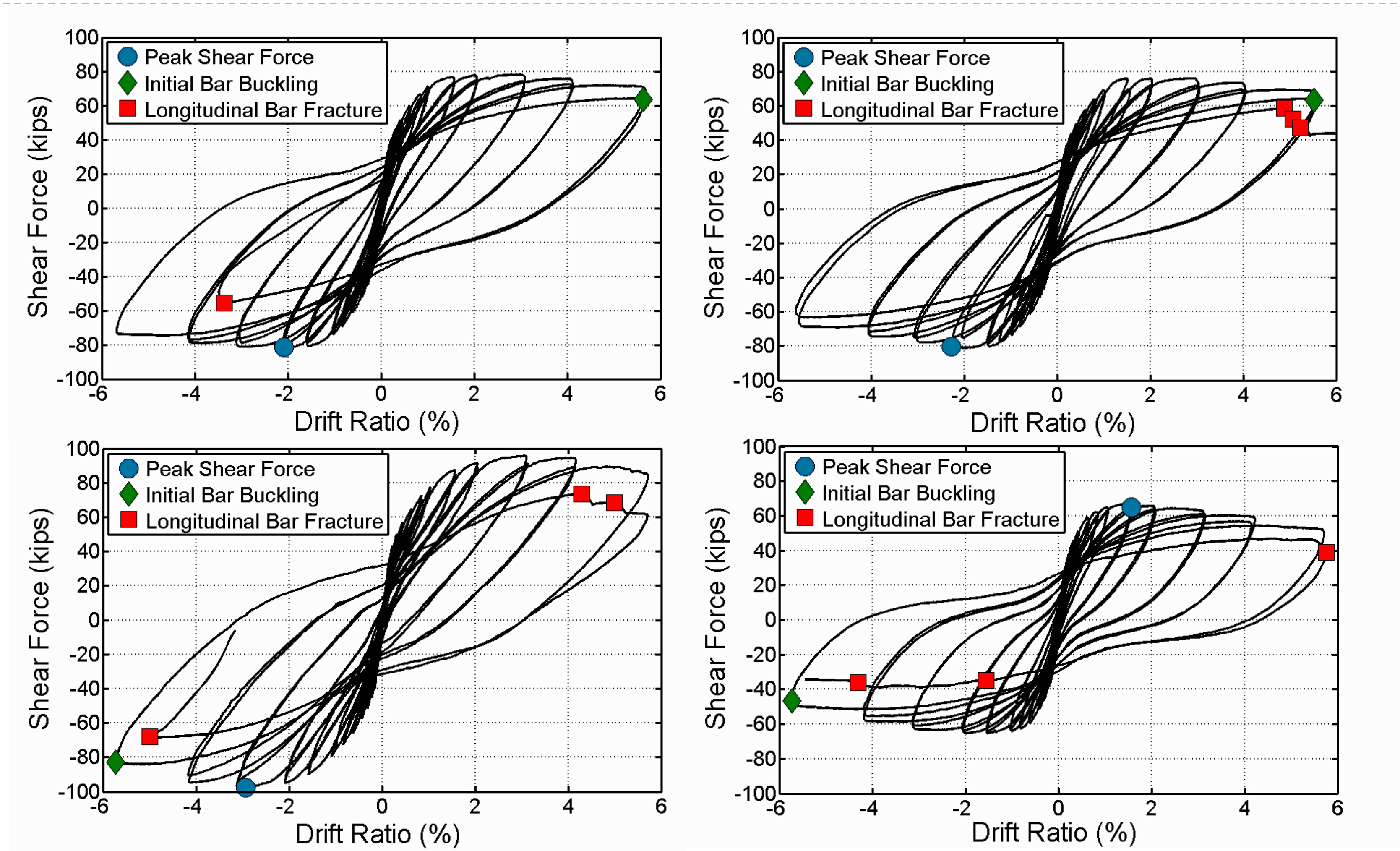
#6 longitudinal bars in all columns





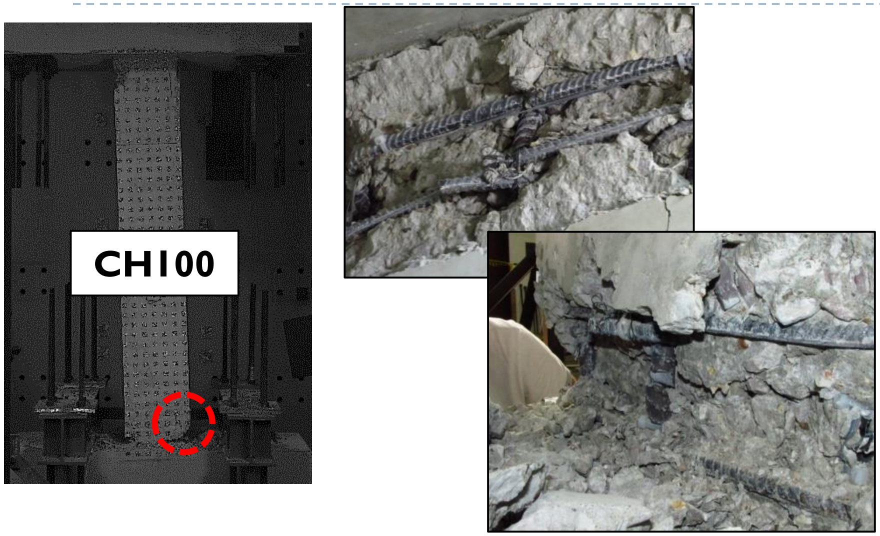
Specimen	Yield Strength (ksi)	Ultimate Strength (ksi)	T/Y Ratio	Uniform Elongation (%)	Ultimate Elongation (%)
CH100	100.0	127.2	1.27	7.6	10.4
CL100	106.4	123.4	1.16	8.6	12.5
CM100	124.2	157.4	1.27	4.9	9.8
CH60	64.4	93.3	1.45	11.8	17.6

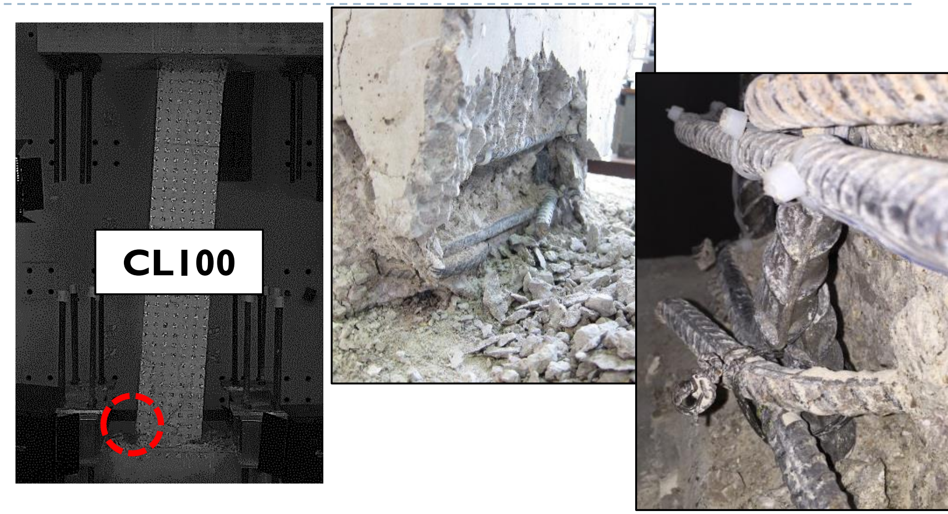
Series 2 Test Results

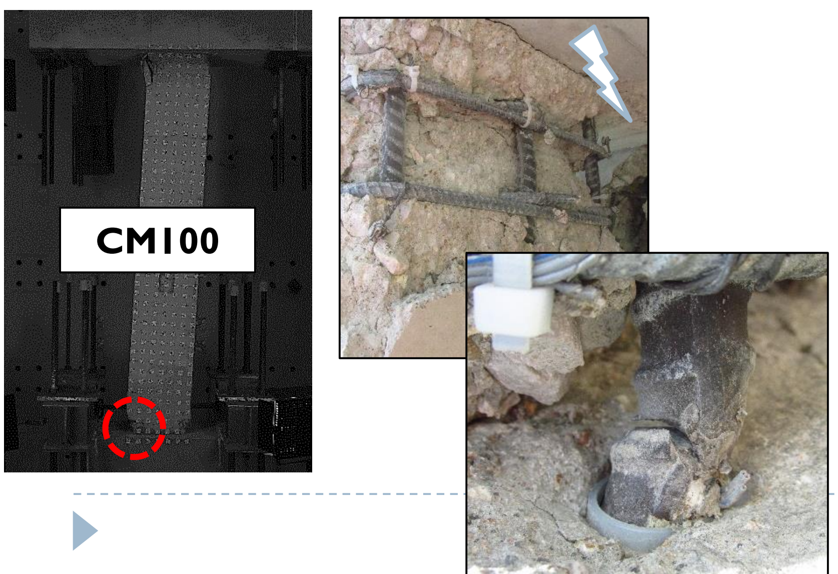


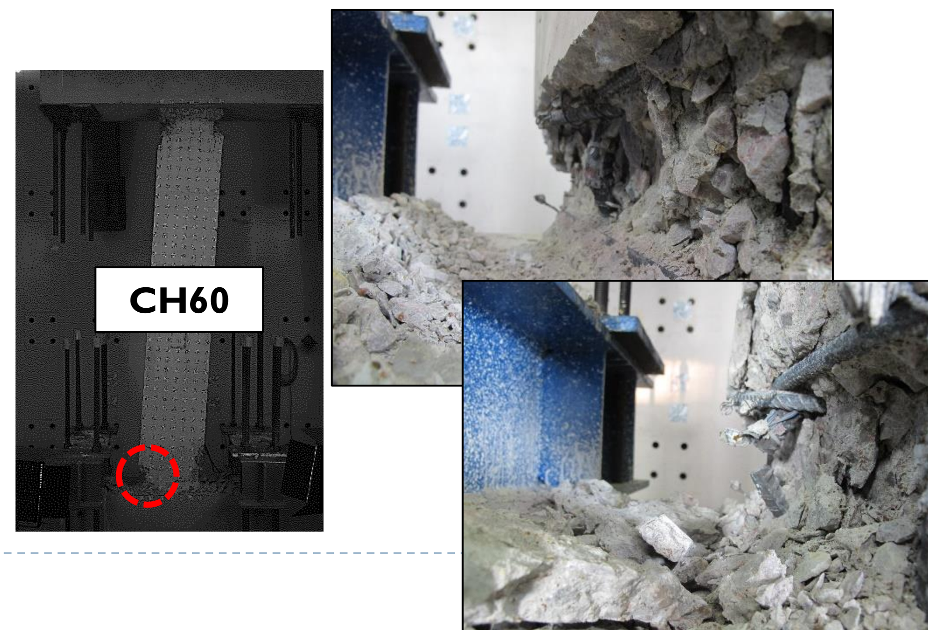
- Similar behavior – bar fracture failure mode
- All specimens completed at least one full cycle to 5.5% drift ratio, before significant bar buckling or bar fracture.

Series 2 Failure Mode



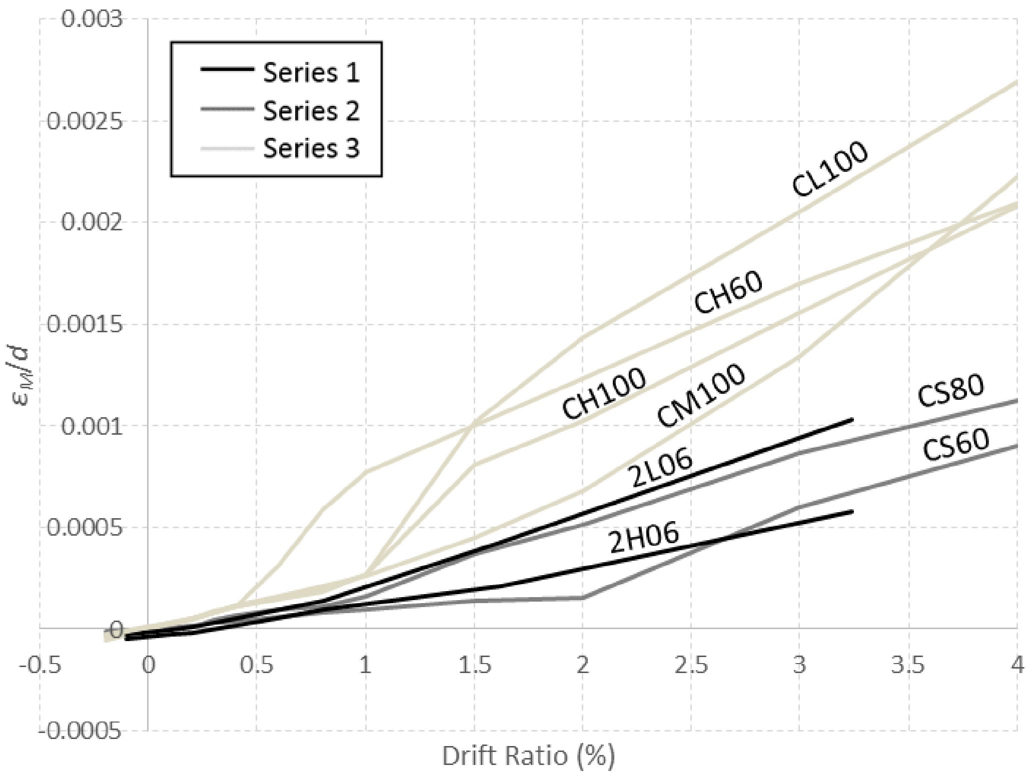






Series 2 Strain Demands

Mean tension strain in longitudinal bars at critical section (normalized by section effective depth d)



- Complex behavior
- Directly comparable tests CL100 and CH100 indicate influence of T/Y ratio
- A1035 bars behave differently

Series 2 Conclusions

- Overall similar and good seismic behavior for all four columns regardless of steel type and grade
- Strain demands in longitudinal bar related to
  - Axial load
  - Bar strength
  - Bar T/Y ratio
  - Shear stress
- But what is an acceptable fatigue performance for HSRB?
  - Follow up project is investigating this further

Performance Characterization of Beams with High-Strength Reinforcement

Project Team

Duy Vu To, Nick Hardisty, Jack Moehle

Berkeley

UNIVERSITY OF CALIFORNIA

Advisory Committee

Dominic Kelley, Ron Klemencic, Andy Taylor, Loring Wyllie

Sponsors and Contributors

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CRSI Concrete Reinforcing Steel Institute

CLARK CONSTRUCTION

NUCOR

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MAGNUSSON KLEMENCIC ASSOCIATES Structural + Civil Engineers

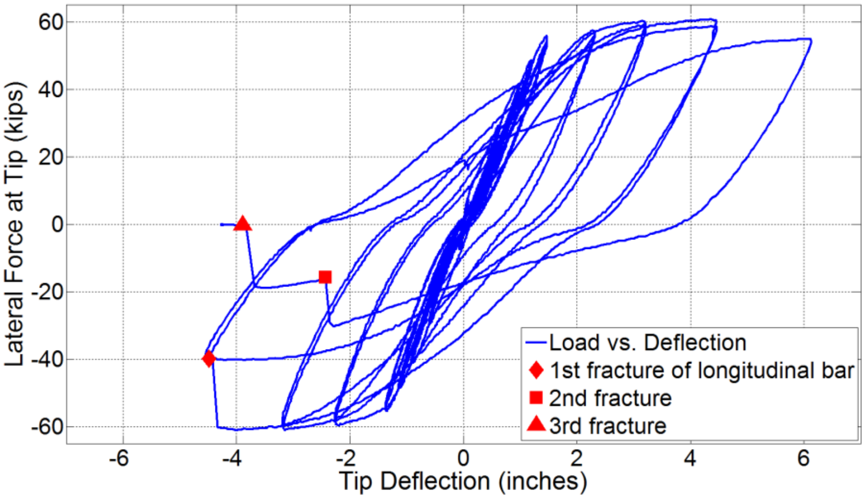
CMC Commercial Metals

aci American Concrete Institute Always advancing

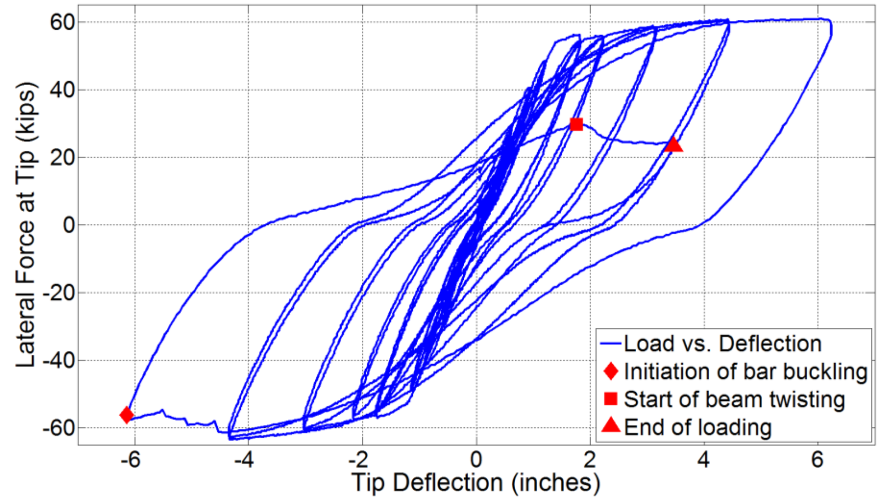
MMFX STEEL

Test Setup

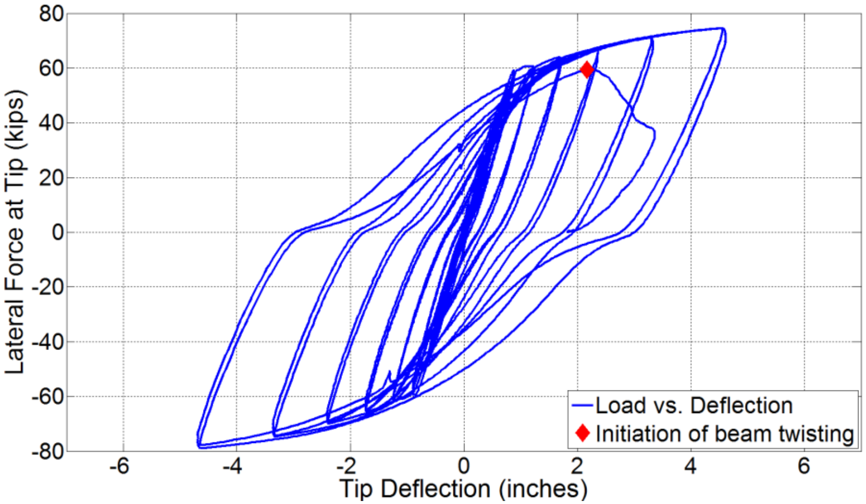
Results



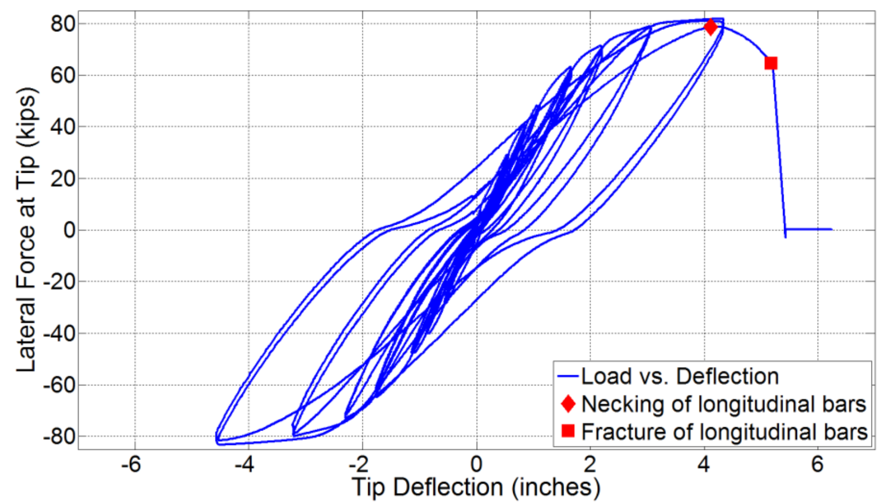
Beam 1 – Grade 100 T/Y = 1.18



Beam 2 – Grade 100 T/Y = 1.30



Beam 3 – Grade 60 A706



Beam 4 – Grade 100 A1035

Acceptable Elongations and Low-Cycle Fatigue Performance for High-Strength Reinforcing Bars

2016 to 2018 timeline

Acceptable Performance for HSRB

Tasks

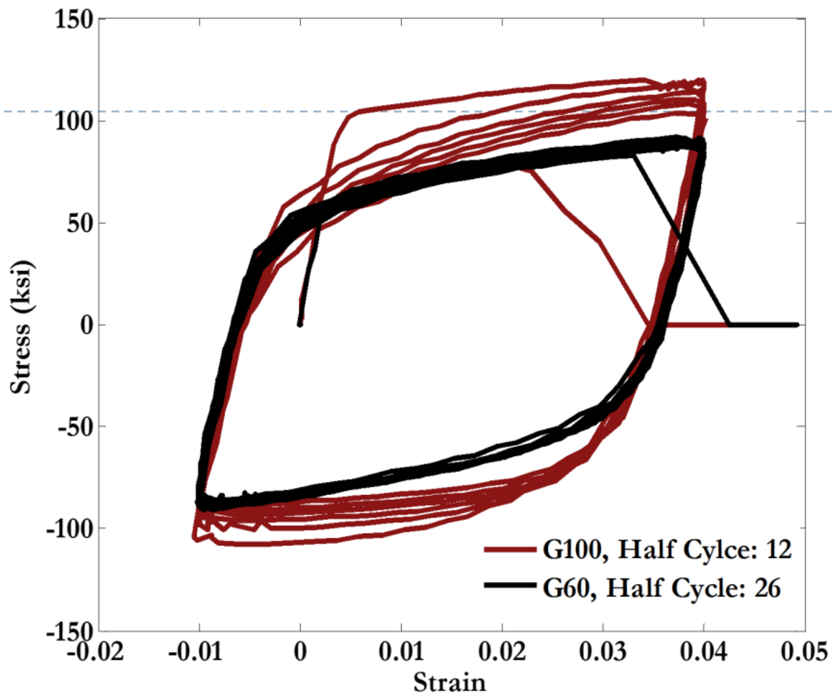
1. Quantify low-cycle fatigue performance of HSRB in production in the U.S.
   - Associated experiments working with some mills to improve their bar performance

2. Develop model for predicting bar fracture in concrete members during seismic motions
   - Columns ,beams, wall, coupling beams

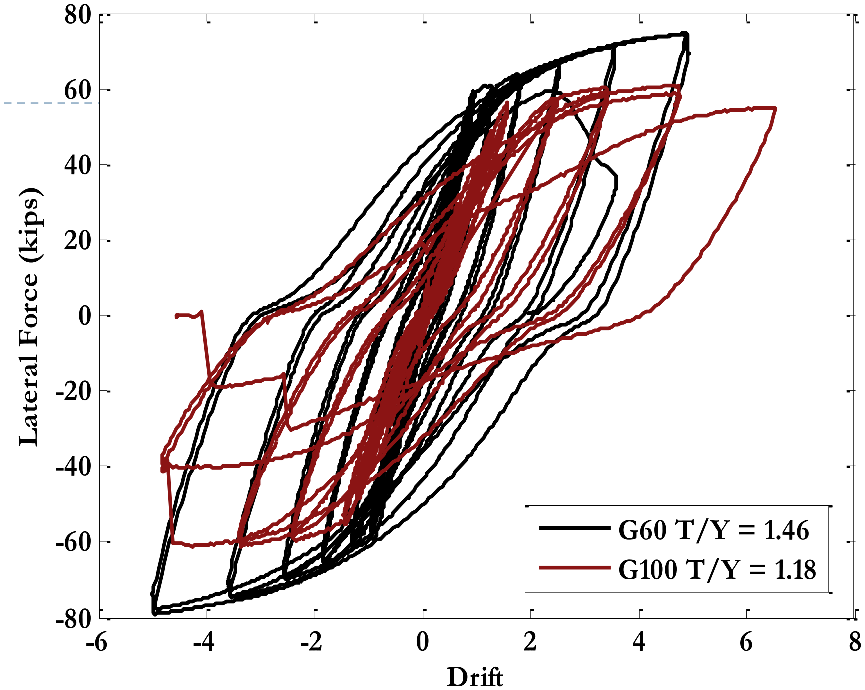
3. Quantify differences in probability of collapse of seismically designed buildings due to reinforcement differences (in collaboration with G. Deierlein at Stanford)

4. Recommend design and ASTM bar specification adjustments to committee consensus probabilities of collapse

Objective and Scope



Reinforcing Bar Test - Low-cyclic capacity of G60 vs. G100 (Slavin et al. 2015)



Concrete Column Test - Component behavior with G60 vs. G100 (To et al. 2016)

Influence from high-strength reinforcing steel:

- Reduced initial stiffness (less steel area, same $f_y A_s$)
- Damage Concentration (lower T/Y ratio)
- Premature fracture (lower fracture resistance)

→

Acceptable Safety?

Improve Rebar
OR
Adjust Design Criteria

Broader Ongoing Research

While steel bar production and ASTM specifications are being finalized

Ongoing and Future Research

Charles Pankow Foundation commissioned study

"Roadmap for the use of high-strength reinforcement in reinforced concrete design," Applied Technology Council Project 115

- Over $26 million of research needed to get Grades 80 and 100 into ACI 318 standard over the next decade

- Bar Bends
- Gravity Beams
- Shear Walls
- Anchorage and Bond
- Coupling Beams

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Performance of HSRB Bends

Objective
Quantify residual capacities of bends and recommend bend diameters for HSRB

Zhao, S.D., Ghannoum, W.M., "Setting Bar-Bending Requirements for High-Strength Steel Bars," (01-15), Charles Pankow Foundation, pp. 92, July 2016.

Test Matrix

Test variables for bend/re-bend tests: Bar Size, Manufacturing Process, Grade, Bend Diameter, and Strain Aging

1. Manufacturer 1 (M1): Micro Alloyed Steel
2. Manufacturer 2 (M2): Patented Microstructure MMFX
3. Manufacturer 3 (M3): Combination of Quench and Tempering and Micro Alloying
4. Manufacturer 4 (M4): Combination of Quench and Tempering and Micro Alloying

Option 1: 95% confidence of achieving YSPO

		Bar Size	β_{ACI}	β_{Recom}
ASTM A615	Grade 60	3 to 5 Transverse	4.0	5.0*
		3 to 5 Longitudinal	6.0	6.0
		6 to 8	6.0	6.0
		11	8.0	8.0
	Grade 80	3 to 5 Transverse	4.0	5.0*
		3 to 5 Longitudinal	6.0	6.0
		6 to 8	6.0	6.0
		11	8.0	8.0
	Grade 100	3 to 5 Transverse	Not Specified	6.0
		3 to 5 Longitudinal	Not Specified	6.0
		6 to 8	Not Specified	8.0
		9 to 11	Not Specified	9.0
ASTM A706	Grade 60	3 to 5 Transverse	4.0	5.0
		3 to 5 Longitudinal	6.0	6.0
		6 to 8	6.0	6.0
		9 to 11	8.0	8.0
	Grade 80	3 to 5 Transverse	4.0	5.0
		3 to 5 Longitudinal	6.0	6.0
		6 to 8	6.0	6.0
		9 to 11	8.0	8.0

- * these bend ratios result in higher than 5% probabilities of failing the yield stress objective, which is deemed acceptable for A615 ties

Option 2: HSRB match Gr60 bend performance

		Bar Size	β_{ACI}	β_{Recom}
ASTM A615	Grade 60	3 to 5 Transverse	4.0	4.0
		3 to 5 Longitudinal	6.0	6.0
		6 to 8	6.0	6.0
		11	8.0	8.0
	Grade 80	3 to 5 Transverse	4.0	5.0
		3 to 5 Longitudinal	6.0	6.0
		6 to 8	6.0	6.0
		11	8.0	8.0
	Grade 100	3 to 5 Transverse	Not Specified	5.0
		3 to 5 Longitudinal	Not Specified	6.0
		6 to 8	Not Specified	8.0
		9 to 11	Not Specified	9.0
ASTM A706	Grade 60	3 to 5 Transverse	4.0	4.0
		3 to 5 Longitudinal	6.0	6.0
		6 to 8	6.0	6.0
		9 to 11	8.0	8.0
	Grade 80	3 to 5 Transverse	4.0	5.0
		3 to 5 Longitudinal	6.0	6.0
		6 to 8	6.0	6.0
		9 to 11	8.0	8.0

Next Steps

- Cold weather bend performance?
- New project investigating bend performance at cold temperatures (Sponsored by CRSI)
- Will revisit bend diameters for HSRB when results are out (~end of 2017)

GRAVITY BEAMS

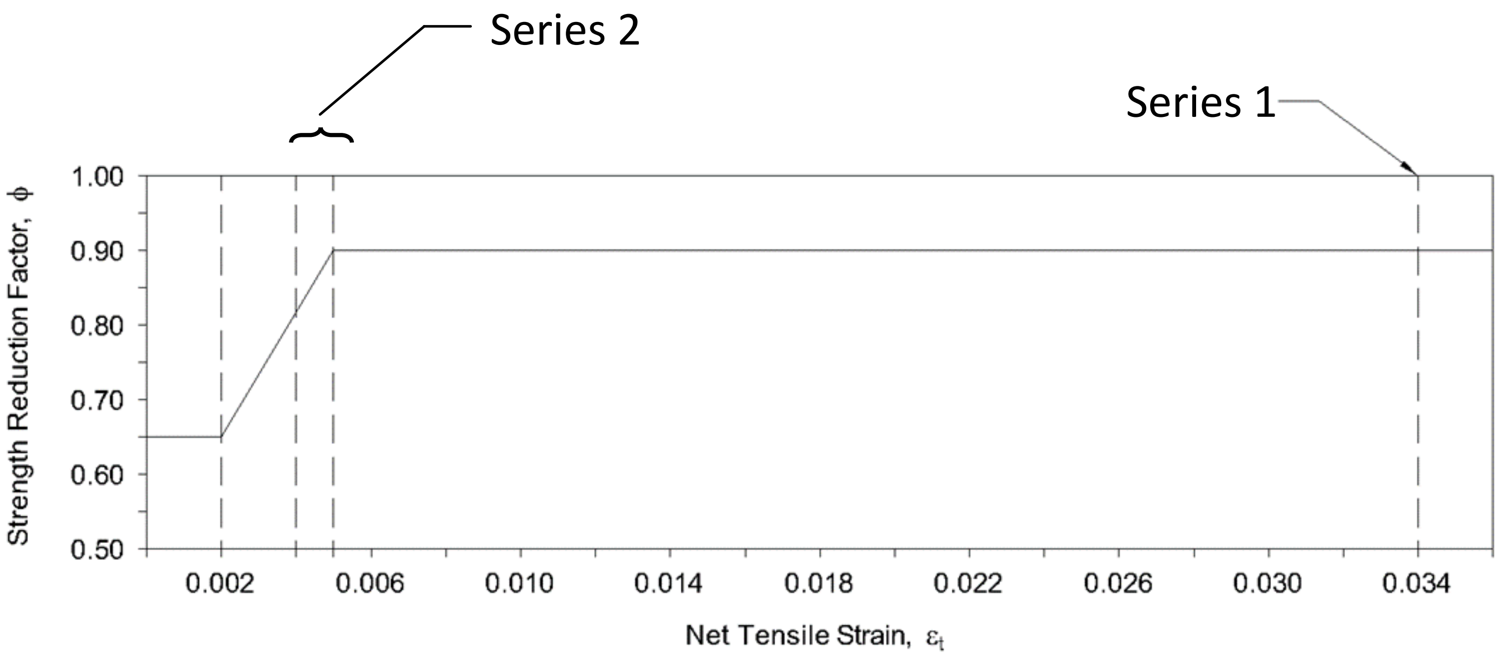
Monotonic Beam Tests

John Nicholas Hardisty

Jack Moehle

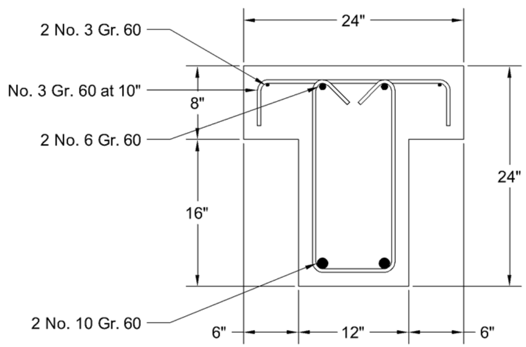
Berkeley
University of California

Two test series

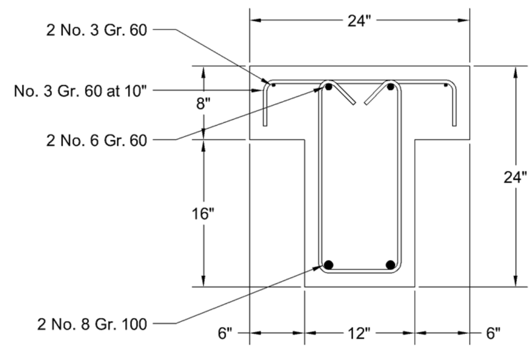


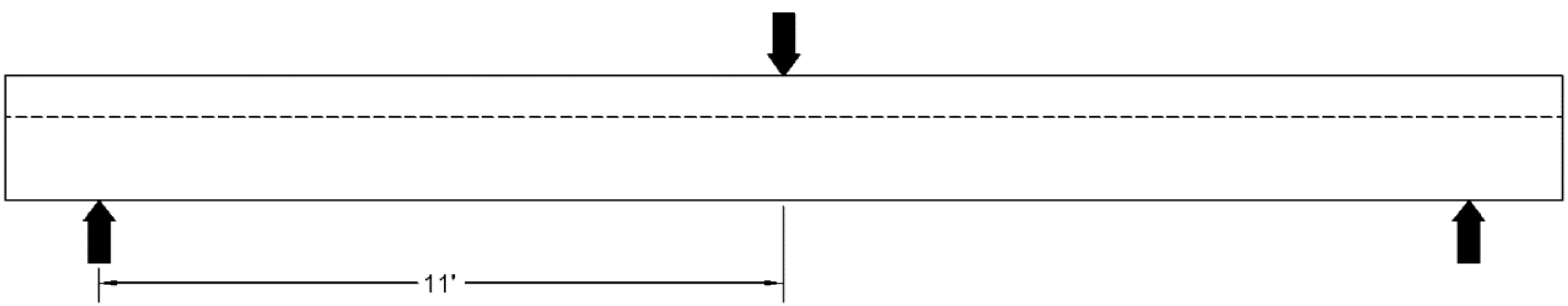
Series 1: $\varepsilon_t = 0.034$

Grade 60 Beams:
1GBL60 (T/Y =1.42) and 1GBH60 (1.66)

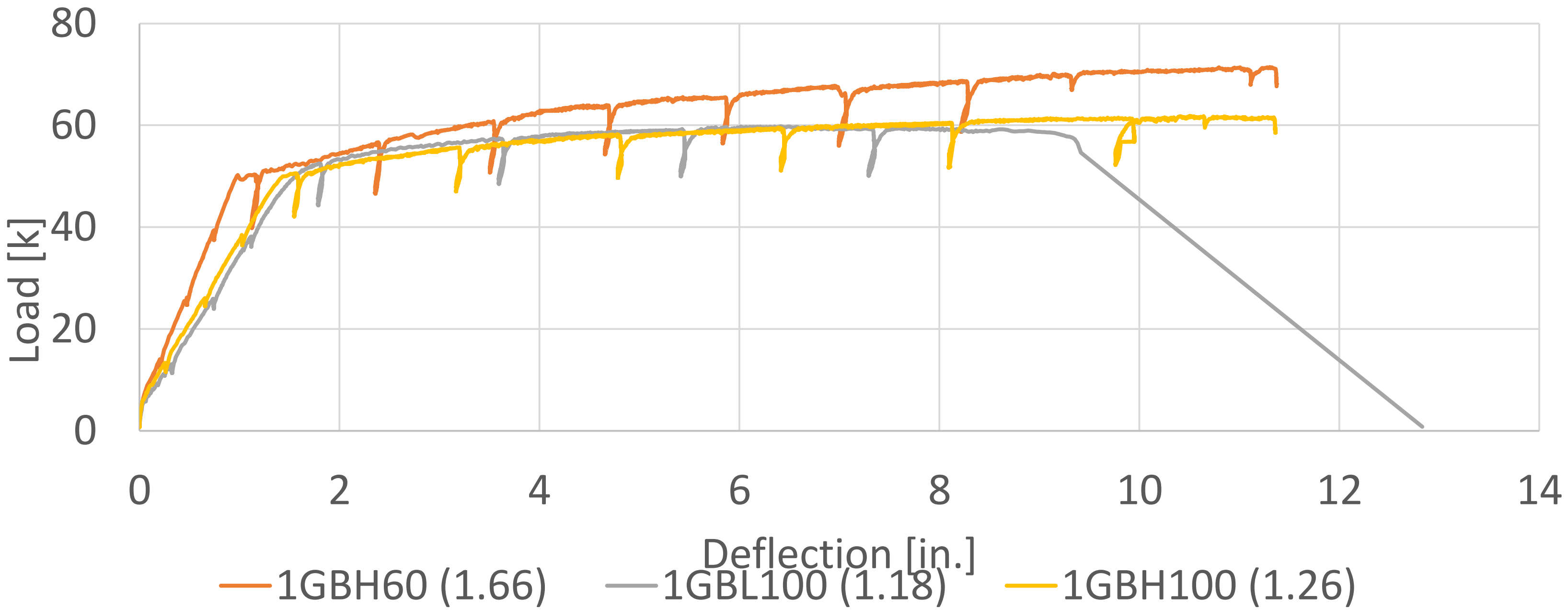


Grade 100 Beams:
1GBL100 (1.18) and 1GBH100 (1.26)



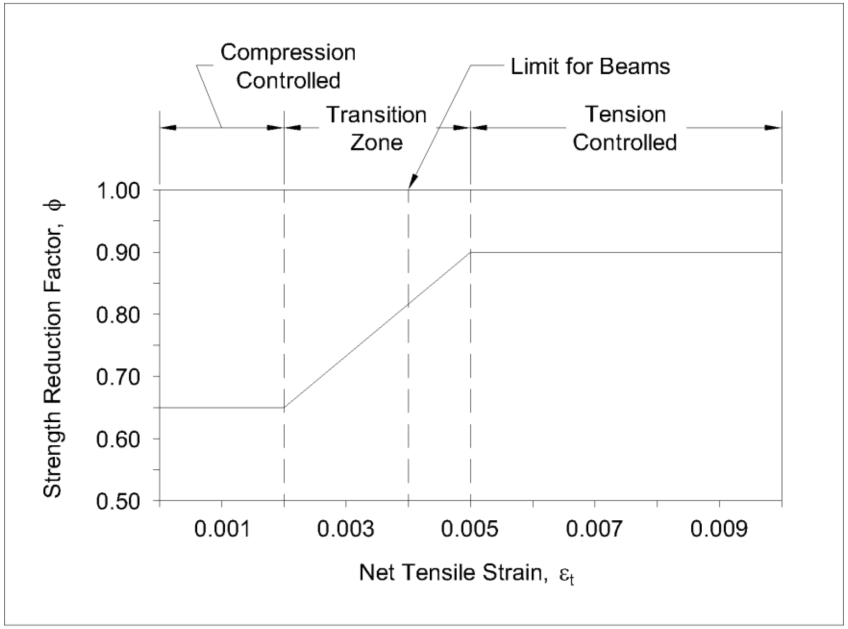


Series 1 – Load-Deflection

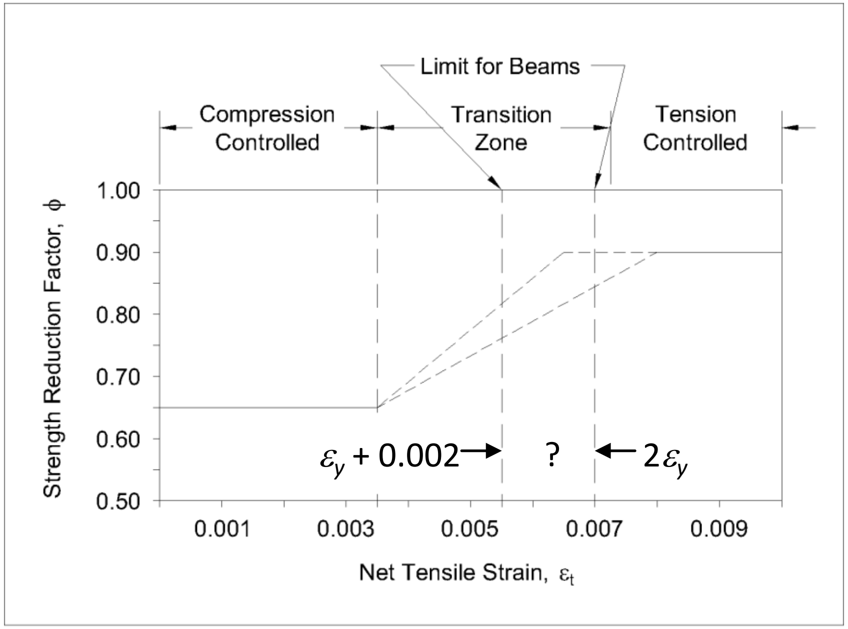


Series 2 – Explore behavior near lower limits of ε_t

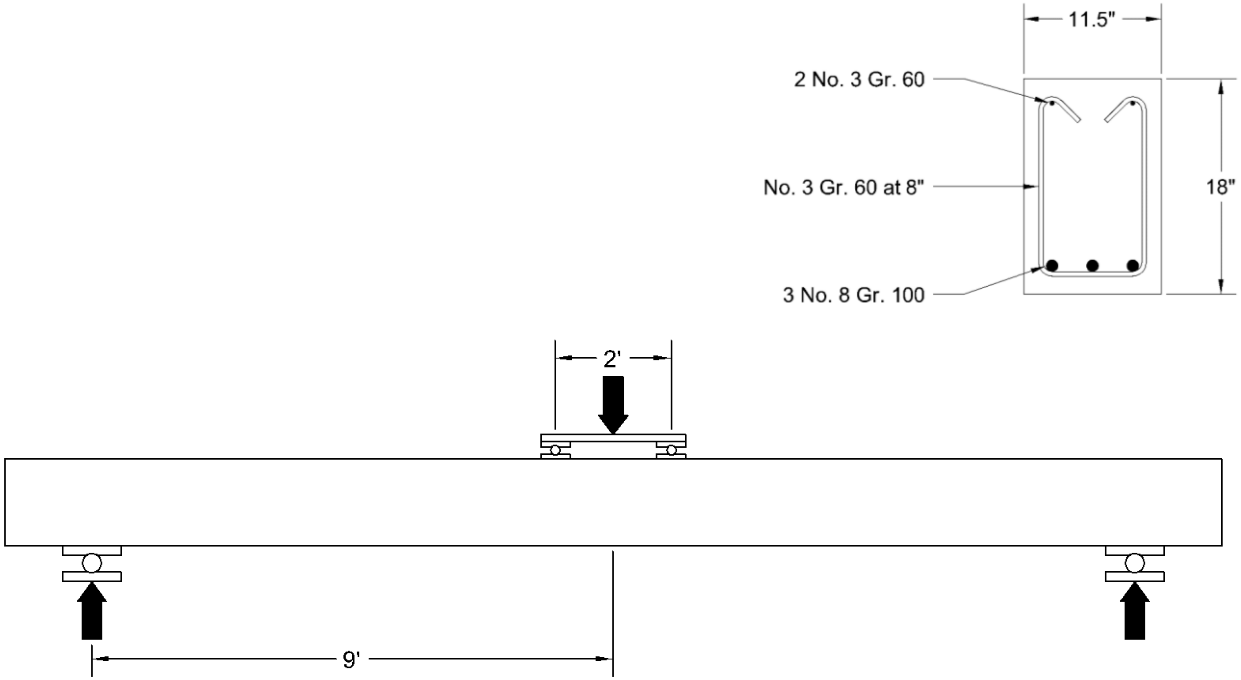
Grade 60



Grade 100



Series 2 – High ρf_y



Failure

GRAVITY BEAMS

Purdue University

REINFORCEMENT LIMITS FOR STRUCTURAL CONCRETE ELEMENTS WITH HIGH-STRENGTH STEEL

CRSI Concrete Reinforcing Steel Institute

HarrisRebar

AISHWARYA Y. PURANAM

SANTIAGO PUJOL

NUCOR

MMFX TECHNOLOGIES CORP

Maximum Reinforcement in Beams

What ε_t is needed in beams with high-strength steel?

Tests of Continuous Beams with conventional and high-strength longitudinal reinforcement

f'_c= 4500 psi

f_y= 60 ksi, 100 ksi, 120 ksi

Series 1 Cross-Section: 18 in. x 30 in.

Series 2 Cross-Section: 14 in. x 20 in.

Designed so that net tensile strain is ~0.005 at concrete strain of 0.003

Tests completed so far

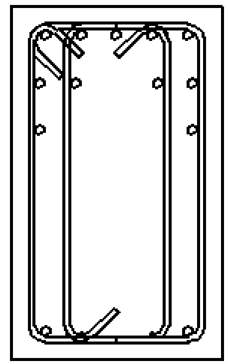
Support

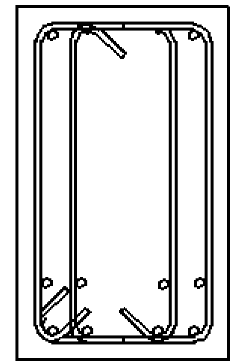
Mid-span

11 #8 Gr. 60 Bars

Series 1:
BEAM 60

30 in.



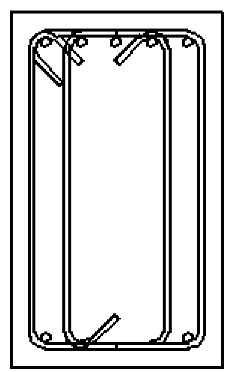


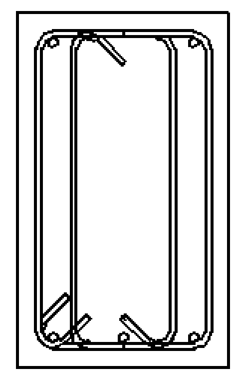
18 in.

8 #8 Gr. 60 Bars

5 #8 Gr. 120 Bars

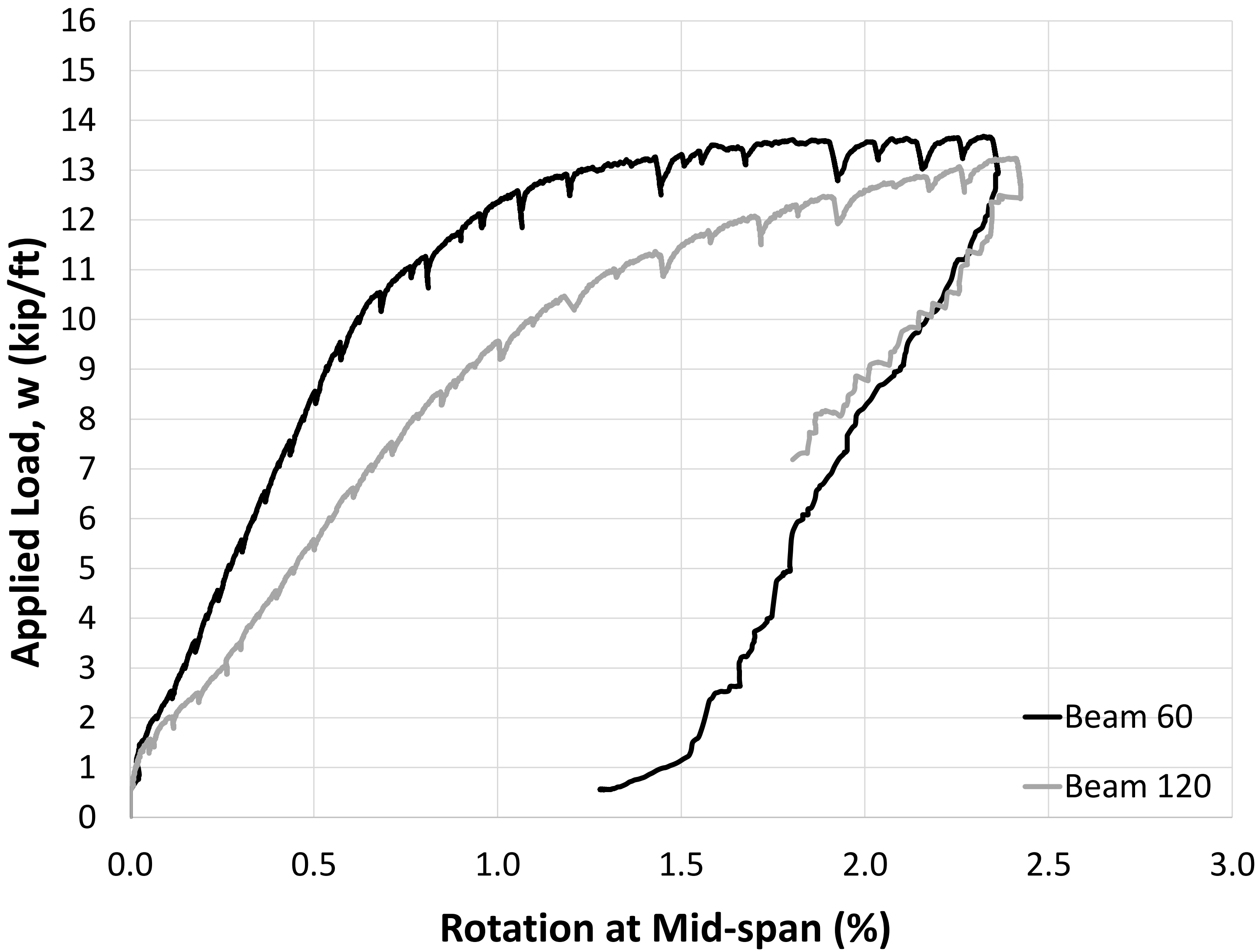
Series 1:
BEAM 120





3 #8 Gr.120 Bars

Test results so far



WALLS

High-Strength Steel Bars in RC Walls:
Influence of Mechanical Properties of Steel on Deformation Capacity

Principal Investigators

Andrés Lepage
Rémy Lequesne

Graduate Students

Mohammad S. Huq
Alex Weber-Kamin
Shahedreen Ameen

CHARLES PANKOW FOUNDATION
Building Innovation through Research

KU

Project Participants

Charles Pankow Foundation (RGA #06-14)

The University of Kansas (Dept. of CEAE)

Concrete Reinforcing Steel Institute (CRSI, M. Mota)

- CMC - Arizona: J. Selzer
- NUCOR - Seattle: E. Nissen
- Harris Rebar - Kansas City: P. Fosnough, M. King, J. Meddings

American Concrete Institute

Advisory Panel

- Dave Fields, MKA, Seattle
- Ramón Gilsanz, GMS, New York
- Dominic Kelly, SGH, Boston
- Conrad Paulson, WJE, Los Angeles

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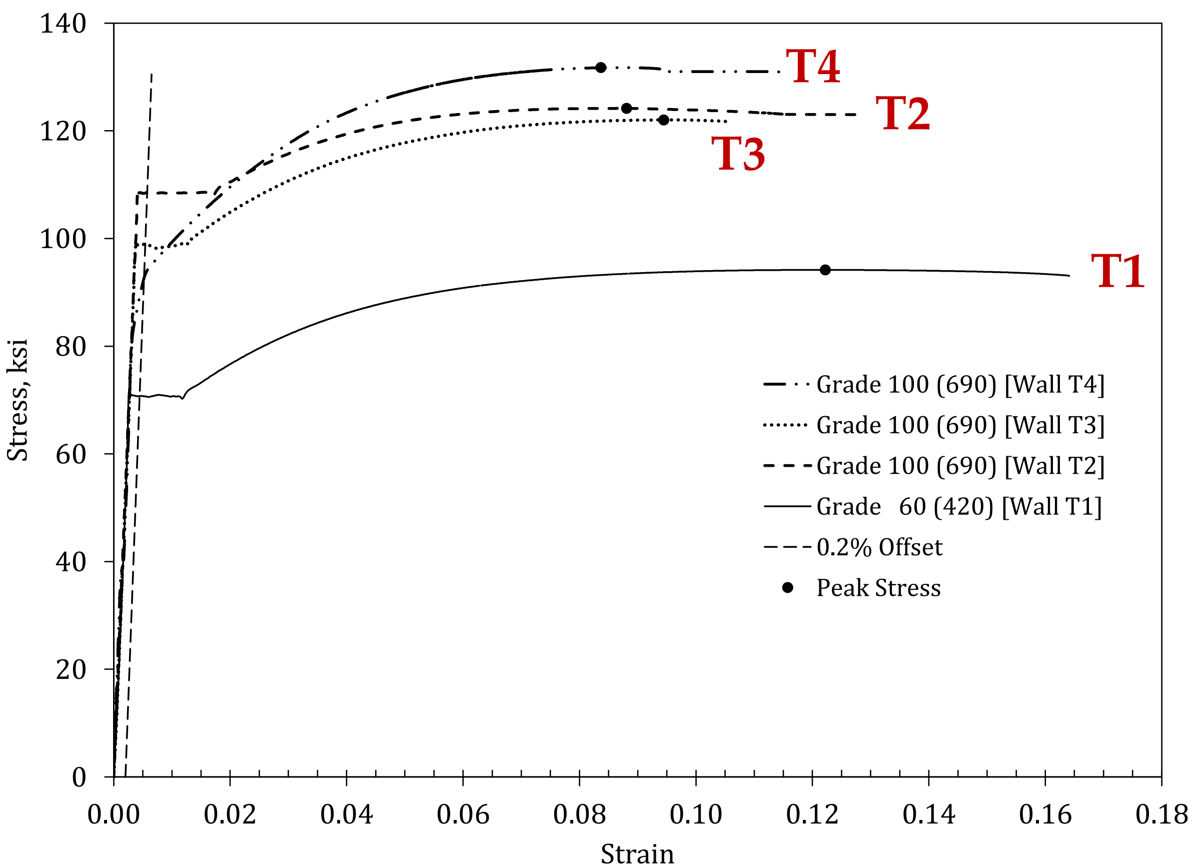
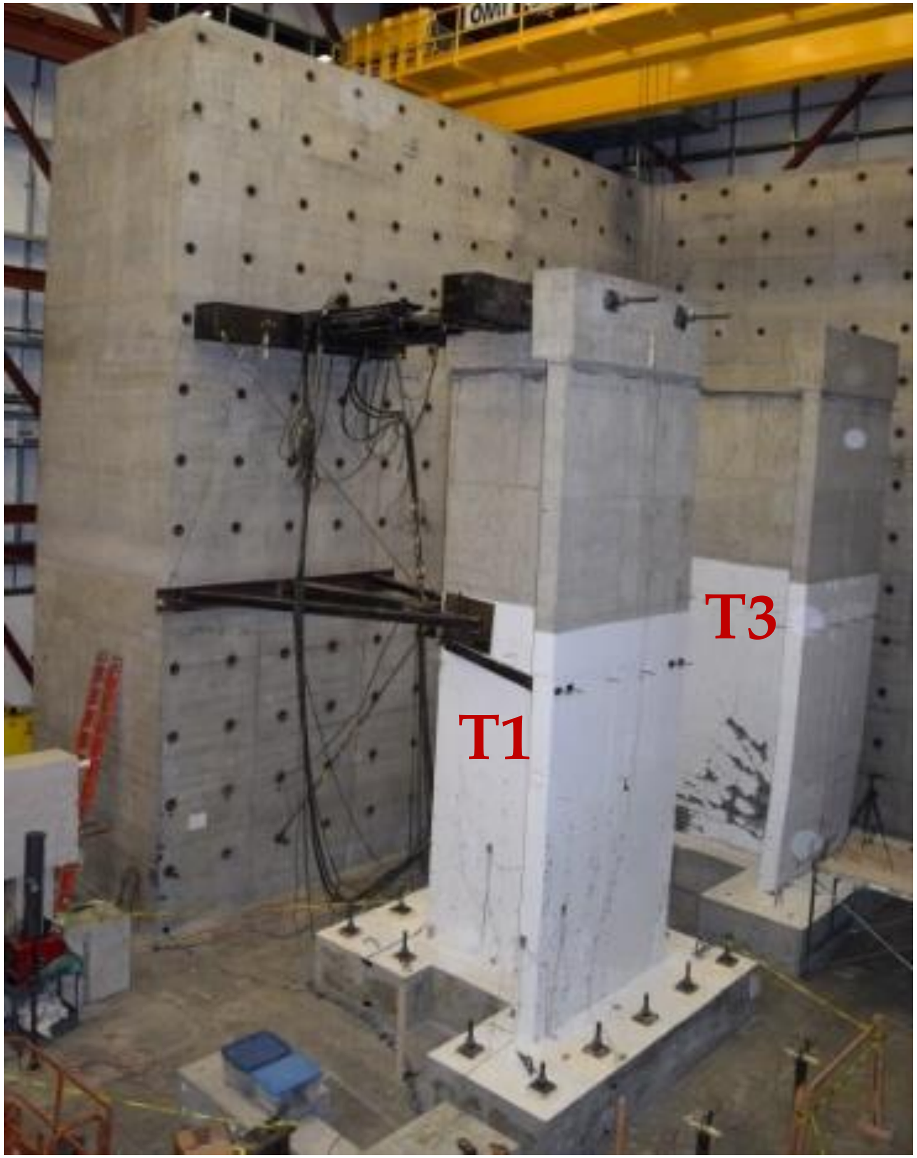
Grade 100 Steel Bars (No. 6 Bars)



Id.	f_y (ksi)	T / Y	f'_c (ksi)	ε_{su} (%)
T1	70	1.34	7.2	12.1
T2	108	1.14	7.9	9.0
T3	99	1.23	7.3	9.2
T4	95	1.38	8.6	8.5

Wall Specimens



Tests Completed

T1 and T3 (October 2015)

T2 and T4 (June 2016)

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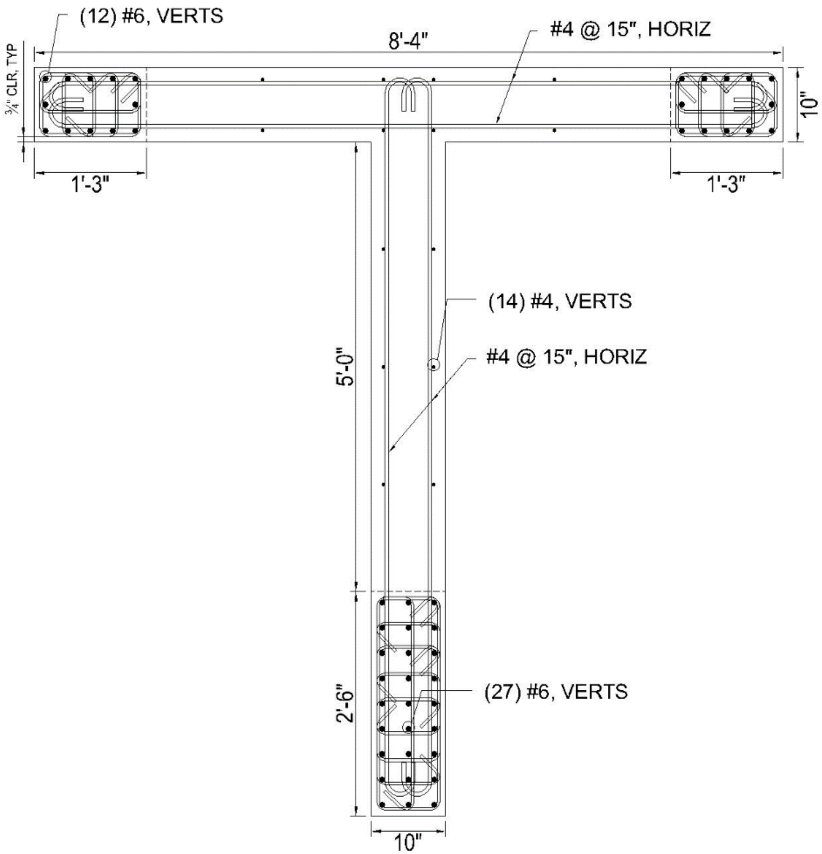
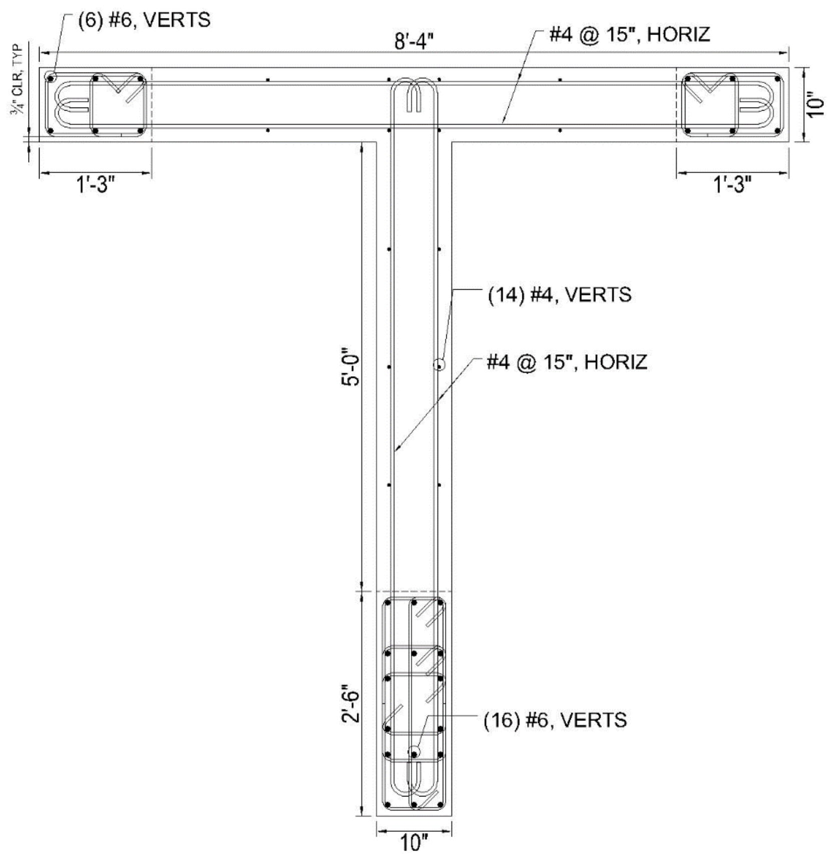
Wall Cross Section



T1



T2, T3, T4

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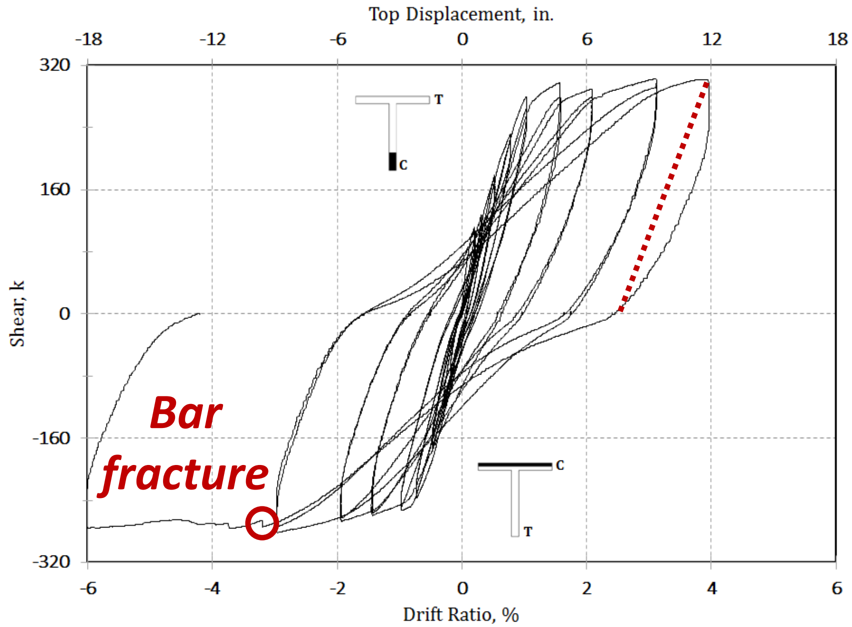
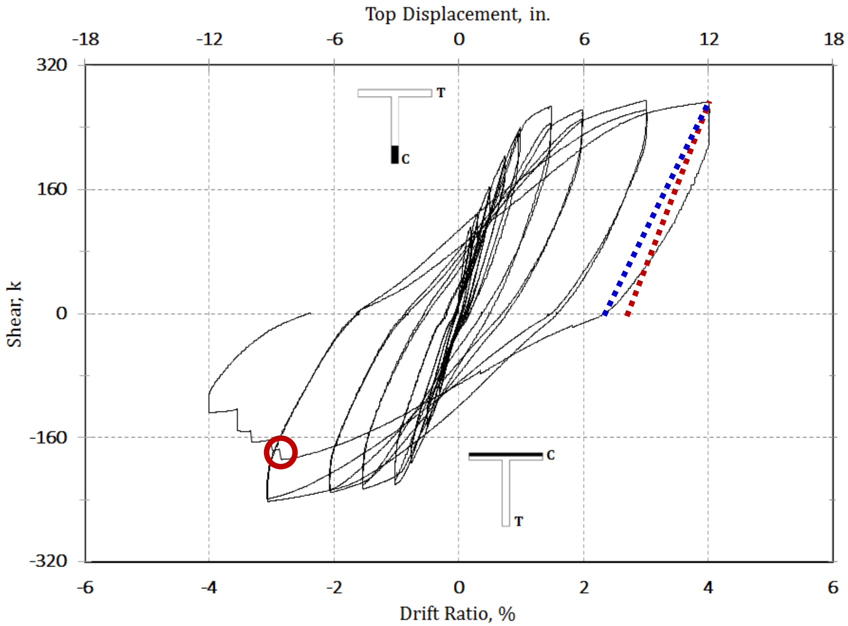
Shear vs. Drift Ratio





T1 – 60 ksi

T3 – 100 ksi

Id.	f_y (ksi)	T / Y	f'_c (ksi)	ε_{su} (%)
T1	**70**	**1.34**	**7.2**	**12.1**
T2	**108**	**1.14**	**7.9**	**9.0**
T3	**99**	**1.23**	**7.3**	**9.2**
T4	**95**	**1.38**	**8.6**	**8.5**

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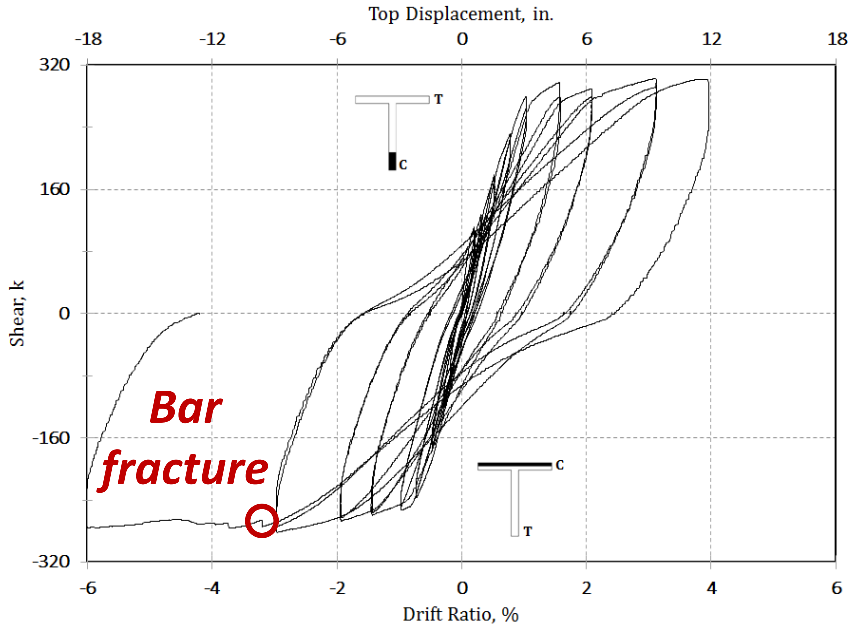
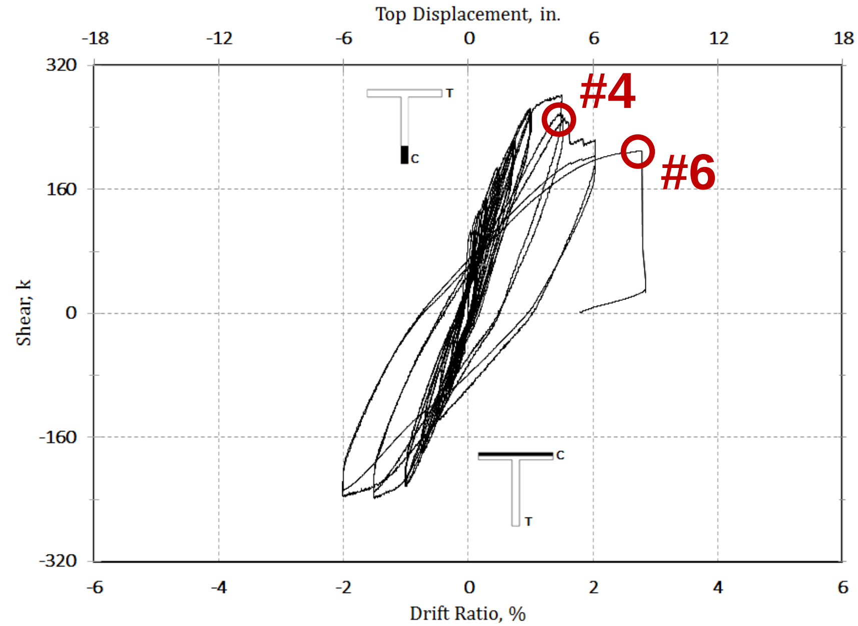
Shear vs. Drift Ratio



T1 – 60 ksi



T2 – 100 ksi

Id.	f_y (ksi)	T / Y	f'_c (ksi)	ε_{su} (%)
T1	70	1.34	7.2	12.1
T2	108	1.14	7.9	9.0
T3	99	1.23	7.3	9.2
T4	95	1.38	8.6	8.5

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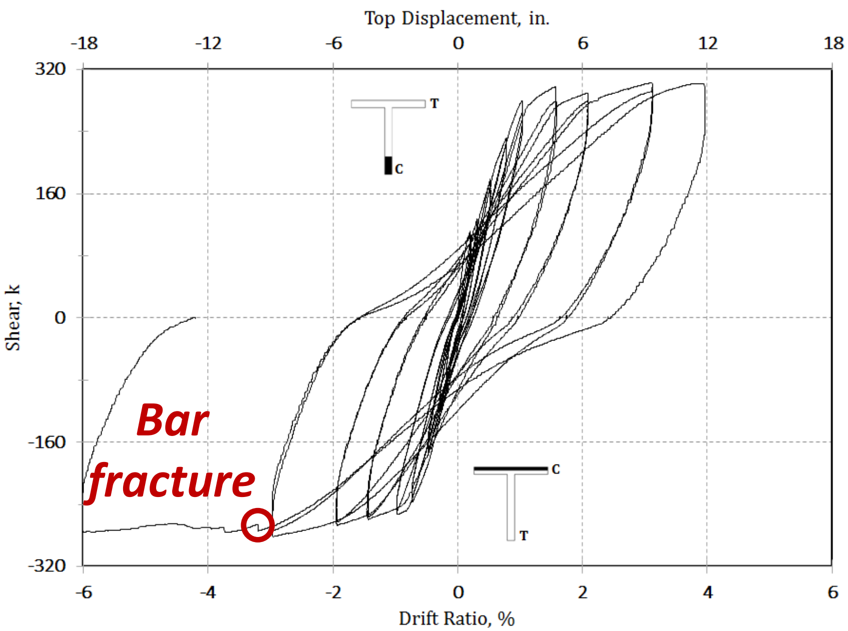
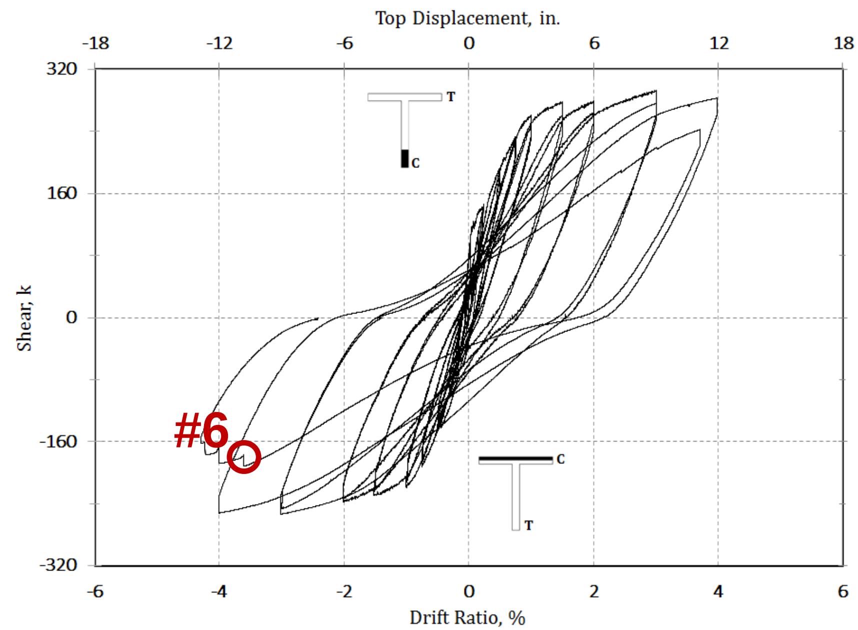
Shear vs. Drift Ratio



T1 – 60 ksi



T4 – 100 ksi

Id.	f_y (ksi)	T / Y	f'_c (ksi)	ε_{su} (%)
T1	70	1.34	7.2	12.1
T2	108	1.14	7.9	9.0
T3	99	1.23	7.3	9.2
T4	95	1.38	8.6	8.5

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Test Results

T1 – 60 ksi

T2 – 100 ksi

2% Drift Ratio

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Special attributes of steel bars in T2

(1) No. 4 bars in T2 had the lowest T/Y ratio of all bars.
Measured T/Y was 1.14

(2) No. 4 bars in T2 had the lowest ε_{su}.
Measured ε_{su} was 5.6%

(3) Sharp edges in deformation pattern of longitudinal bars.
(Reported poor performance in low-cycle fatigue tests)

(4) Strain gauges on No. 4 bars at the wall-base interface.
(Potentially creating a weak plane)

CONCLUSIONS

Conclusions

- Overall good behavior of concrete members with HSRB
- Some concerning tests that highlight
  - Detailing issues
  - Importance of selecting acceptable bar properties
  - Importance of reliable bar production
- Seems like HSRB will be the future
  - Similar concerns were overcome when moving from Gr40 to Gr60

The End