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

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March 26th, 2017
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?
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

- Design Standards do not allow HSRB
- Engineers do not specify HSRB
- Mills do not produce HSRB
- Research cannot be performed on HSRB

- Industry needs guidance from engineers and researcher about which properties to achieve in HSRB
Targeted Material and Structural Testing

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

Clear-Spans
- 4db
- 5db
- 6db

Loading Protocols:
- 2 per bar size
- ±2% and +4%, -1%
- ±2% and +4%, 0%

Manufacturing Techniques
- Microalloying with Vanadium
- Quenching and Tempering
Typical Test

#8 - 6dₜₐₜ - ±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%
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 1: 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  
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.
Test Stopped +9.5%

Gr 80
Test Stopped -8.4%
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
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

<table>
<thead>
<tr>
<th>Grade 100</th>
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<th>Grade 100</th>
<th>Grade 60</th>
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<tbody>
<tr>
<td>T/Y = 1.27</td>
<td>T/Y = 1.16</td>
<td>T/Y = 1.27</td>
<td>T/Y = 1.45</td>
</tr>
<tr>
<td>(H)</td>
<td>(L)</td>
<td>(MMFX)</td>
<td>(H)</td>
</tr>
<tr>
<td>CH100</td>
<td>CL100</td>
<td>CM100</td>
<td>CH60</td>
</tr>
</tbody>
</table>
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**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Yield Strength (ksi)</th>
<th>Ultimate Strength (ksi)</th>
<th>T/Y Ratio</th>
<th>Uniform Elongation (%)</th>
<th>Ultimate Elongation (%)</th>
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</thead>
<tbody>
<tr>
<td>CH100</td>
<td>100.0</td>
<td>127.2</td>
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<tr>
<td>CH60</td>
<td>64.4</td>
<td>93.3</td>
<td>1.45</td>
<td>11.8</td>
<td>17.6</td>
</tr>
</tbody>
</table>
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

- CM100
- CL100
- CH100
- CM100
- CH60
- CH60
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
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

Advisory Committee
Dominic Kelley, Ron Klemencic, Andy Taylor, Loring Wyllie

Sponsors and Contributors
Test Setup
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

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

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:

Acceptable Safety?

Improve Rebar
OR
Adjust Design Criteria

Kuanshi Zhong & Greg Deierlein; Stanford University
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
Performance of HSRB Bends

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

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

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<thead>
<tr>
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<th>$\beta_{ACI}$</th>
<th>$\beta_{Recom}$</th>
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* 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

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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)
Monotonic Beam Tests

John Nicholas Hardisty
Jack Moehle
Two test series

Series 1

Series 2
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

![Graph showing load vs. deflection for different series.]

- 1GBH60 (1.66)
- 1GBL100 (1.18)
- 1GBH100 (1.26)
Series 2 – Explore behavior near lower limits of $\varepsilon_t$

Grade 60

Grade 100

$\varepsilon_y + 0.002 \rightarrow ? \leftarrow 2\varepsilon_y$
Series 2 – High $\rho f_y$
Failure
GRAVITY BEAMS

REINFORCEMENT LIMITS FOR STRUCTURAL CONCRETE ELEMENTS WITH HIGH-STRENGTH STEEL

AISHWARYA Y. PURANAM
SANTIAGO PUJOL
Maximum Reinforcement in Beams

What $\varepsilon_t$ is needed in beams with high-strength steel?

Tests of Continuous Beams with conventional and high-strength longitudinal reinforcement
$f'c = 4500$ psi
$fy = 60$ 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 $\sim 0.005$
at concrete strain of $0.003$
Tests completed so far

Series 1: BEAM 60
11 #8 Gr. 60 Bars
30 in.
18 in.
8 #8 Gr. 60 Bars

Series 1: BEAM 120
5 #8 Gr. 120 Bars
3 #8 Gr. 120 Bars
Test results so far
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
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
Grade 100 Steel Bars (No. 6 Bars)

<table>
<thead>
<tr>
<th>Id.</th>
<th>$f_y$ (ksi)</th>
<th>$T / Y$</th>
<th>$f'_{c}$ (ksi)</th>
<th>$\varepsilon_{su}$ (%)</th>
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<tbody>
<tr>
<td>T1</td>
<td>70</td>
<td>1.34</td>
<td>7.2</td>
<td>12.1</td>
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<tr>
<td>T2</td>
<td>108</td>
<td>1.14</td>
<td>7.9</td>
<td>9.0</td>
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<tr>
<td>T3</td>
<td>99</td>
<td>1.23</td>
<td>7.3</td>
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<tr>
<td>T4</td>
<td>95</td>
<td>1.38</td>
<td>8.6</td>
<td>8.5</td>
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Wall Specimens

Tests Completed

T1 and T3
(October 2015)

T2 and T4
(June 2016)
Wall Cross Section

T1

(12) #6, VERTS
8'-4"
#4 @ 15°, HORIZ
1'-3"
10"

(14) #4, VERTS
#4 @ 15°, HORIZ
5'-0"
2'-6"
10"

(27) #6, VERTS

T2, T3, T4

(6) #6, VERTS
8'-4"
#4 @ 15°, HORIZ
1'-3"
10"

(14) #4, VERTS
#4 @ 15°, HORIZ
5'-0"
2'-6"
10"

(16) #6, VERTS
Shear vs. Drift Ratio

**T1 – 60 ksi**

<table>
<thead>
<tr>
<th>Id.</th>
<th>$f_y$ (ksi)</th>
<th>$T / Y$</th>
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</table>

**T3 – 100 ksi**
Shear vs. Drift Ratio

T1 – 60 ksi

T2 – 100 ksi

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<tr>
<th>Id.</th>
<th>$f_y$ (ksi)</th>
<th>$T / Y$</th>
<th>$f'_c$ (ksi)</th>
<th>$\varepsilon_{su}$ (%)</th>
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Bar fracture

#4

#6
Shear vs. Drift Ratio

### T1 – 60 ksi

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<tr>
<th>Id.</th>
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### T4 – 100 ksi

Bar fracture
Test Results

T1 – 60 ksi

T2 – 100 ksi

2% Drift Ratio
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 $\varepsilon_{su}$. Measured $\varepsilon_{su}$ 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