High Performance Steel Reinforcing Bars

Sami Rizkalla, Raafat El-Hacha
Constructed Facilities Laboratory (CFL)
North Carolina State University (NCSU)

and

Salem Faza
Concrete Reinforcement Technologies

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MMFX Steel

Highly corrosion resistant, as a result of its patented chemical composition and microstructure during production.

High yield strength allows for design reduction of rebar quantities.
## Product Evaluation

<table>
<thead>
<tr>
<th>Rebar Product Classification</th>
<th>Approximate ratio of installed cost of rebar to A615 rebar</th>
<th>Estimated years of service life</th>
</tr>
</thead>
<tbody>
<tr>
<td>A615</td>
<td>1</td>
<td>15 – 30 years</td>
</tr>
<tr>
<td>Epoxy Coated (A615)</td>
<td>1.4 – 1.6</td>
<td>20 – 40 years</td>
</tr>
<tr>
<td>304 SS / 316 SS</td>
<td>4.3 – 4.9</td>
<td>75 + years</td>
</tr>
<tr>
<td><strong>MMFX</strong></td>
<td><strong>1.5 – 1.7</strong></td>
<td><strong>75 + years</strong></td>
</tr>
</tbody>
</table>
Testing Program

Evaluate the fundamental mechanical characteristics

Validate the performance and the acceptability of the MMFX bars as reinforcement for concrete structures
Preliminary Characteristics

- Mechanical properties:
  - Tension
  - Compression
  - Shear strength
  - Fatigue strength
  - Tensile strength of bent bars
  - Bond strength and development length
  - Behaviour as compression steel in reinforced concrete columns
Mechanical Properties in Tension

- Test method follow: ASTM A370, E8, and E111

- Determine the stress-strain characteristics of three MMFX bar sizes (#4, #6, and #8)

- Provide the following fundamental characteristics:
  - Modulus of elasticity: $E$
  - Yield strength: $f_y$
  - Ultimate stress: $f_u$ and corresponding strain
  - Ultimate strain: $\varepsilon_{su}$
Results of Tension Tests
Results of Tension Tests

#4MMFX Reinforcing Steel Rebar

- **Elastic Young's Modulus**: 29000 ksi
- **Yield Strength (0.2% offset)**: 116 ksi, STDEV 7 ksi
- **Yield Strength (0.5% strain)**: 107 ksi, STDEV 6 ksi
- **Ultimate Strength**: 165 ksi, STDEV 4 ksi
- **Strain at Ultimate stress**: 4.4 %, STDEV 0.6 %
- **Ultimate Strain**: 7.7 %, STDEV 1.5 %

*Extensometer removed*
#6MMFX Reinforcing Rebar

E = 29000 ksi

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic Young's Modulus</td>
<td>29000 ksi</td>
<td>2 ksi</td>
</tr>
<tr>
<td>Yield Strength (0.2% offset)</td>
<td>120 ksi</td>
<td>2 ksi</td>
</tr>
<tr>
<td>Yield Strength (0.5% strain)</td>
<td>108 ksi</td>
<td>2 ksi</td>
</tr>
<tr>
<td>Ultimate Strength</td>
<td>176 ksi</td>
<td>1 ksi</td>
</tr>
<tr>
<td>Strain at Ultimate</td>
<td>5.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Ultimate Strain</td>
<td>12%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

x Extensometer removed
Results of Tension Tests

#8MMFX Reinforcing Steel Rebar

- Elastic Young’s Modulus: 29000 ksi
- Yield Strength (0.2% offset): 119 ksi, STDEV 7 ksi
- Yield Strength (0.5% strain): 111 ksi, STDEV 6 ksi
- Ultimate Strength: 176 ksi, STDEV 1 ksi
- Strain at Ultimate: 5.5%, STDEV 0.3%
- Ultimate Strain: 9.7%, STDEV 1.6%

E = 29000 ksi
× Extensometer removed
Stress-Strain Curves (2" Gage Length)

- MMFX Steel
- ASTM A615 Grade 60

E = 29,000 ksi

Results of Tension Tests

Stress (ksi) vs. Strain (in/in) graph with data points:
- 120 ksi
- 177 ksi

Failure point indicated at 177 ksi.
Mechanical Properties in Compression

- Test method follow: ASTM E9, and E111
- Determine the stress-strain characteristics of three MMFX bar sizes (#4, #6, and #8)
- Length of the specimens = 2d_{BAR}
- Provide the following fundamental characteristics:
  - Modulus of elasticity: $E$
  - Yield strength: $f_y'$
Test Set-Up

Top Loading Plate

Universal Testing Machine

Bottom Loading Plate
Stress-Strain Curves

Compressive Stress (ksi)

Transversal Strain (in/in) Longitudinal

#6&8 MMFX

A615 #8 Grade 60

E=29,000ksi

145ksi

A615 #8 Grade 60

Compressive Stress (ksi)
Failure Mode

#4MFFX  #6MFFX  #8MFFX
Shear Strength

- Determine the Shear Strength of three bar sizes (#4, #6, #8) using five specimens for each size.
- The test specimen is subjected to double shear action.

Shear strength is determined based on the failure load.
# Results of Shear Strength

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Shear Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>#4MMFX</strong></td>
<td>Shear Strength</td>
</tr>
<tr>
<td>specimen</td>
<td>ksi</td>
</tr>
<tr>
<td>1</td>
<td>110.6</td>
</tr>
<tr>
<td>2</td>
<td>108.6</td>
</tr>
<tr>
<td>3</td>
<td>108.9</td>
</tr>
<tr>
<td>4</td>
<td>109.9</td>
</tr>
<tr>
<td>5</td>
<td>111.8</td>
</tr>
<tr>
<td>Average</td>
<td><strong>110.0</strong></td>
</tr>
<tr>
<td>st.dv.</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>#6MMFX</strong></td>
<td>Shear Strength</td>
</tr>
<tr>
<td>specimen</td>
<td>ksi</td>
</tr>
<tr>
<td>1</td>
<td>111.2</td>
</tr>
<tr>
<td>2</td>
<td>111.8</td>
</tr>
<tr>
<td>3</td>
<td>111.8</td>
</tr>
<tr>
<td>4</td>
<td>110.2</td>
</tr>
<tr>
<td>5</td>
<td>111.2</td>
</tr>
<tr>
<td>Average</td>
<td><strong>111.2</strong></td>
</tr>
<tr>
<td>st.dv.</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>#8MMFX</strong></td>
<td>Shear Strength</td>
</tr>
<tr>
<td>specimen</td>
<td>ksi</td>
</tr>
<tr>
<td>1</td>
<td>107.2</td>
</tr>
<tr>
<td>2</td>
<td>111.8</td>
</tr>
<tr>
<td>3</td>
<td>110.6</td>
</tr>
<tr>
<td>4</td>
<td>112.9</td>
</tr>
<tr>
<td>Average</td>
<td><strong>110.6</strong></td>
</tr>
<tr>
<td>st.dv.</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Shear Strength MMFX = **110.7 ksi**
st.dv. = **1.5 ksi**
Fatigue Strength

Test method follow: ASTM E466

Determine the endurance limit for bar sizes #4 & #6

Determine the stress-number of cycles curve (S-N curve) for each bar size

The maximum tensile stress level varied: 90%, 80%, 75%, 70%, and 65% of the yield strength

The minimum tensile stress level was set at 20% of the yield strength
Tensile Strength of Bent Bars

Examine the bend effect on the strength of the MMFX reinforcing steel bent bars

Two different bar sizes (#4, and #6) were used

The radius of the bent is 90° (ACI 318-99)
Bend Effect on Tensile Strength

Plastic tube for debonding
Bend Effect on Tensile Strength

Test Set-up
#4MMFX
Tensile Strength of Bent Bars

#4MMFX Reinforcing Steel Bars

Stress (ksi) vs. Strain (in/in)

- Stress peaks at 165 ksi.
Tensile Strength of Bent Bars

#6MMFX Reinforcing Steel Bars

Tensile Strength of Bent Bars

Stress (ksi) vs. Strain (in/in)

- The graph shows the stress-strain relationship for #6MMFX reinforcing steel bars.
- The maximum tensile strength is indicated at 177 ksi.

0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08

Stress (ksi)

Strain (in/in)

0 20 40 60 80 100 120 140 160 180

0.08
Bond Strength and Development Length

Evaluate the bond strength and the development length of bar sizes #4, #6, and #8.

Different embedment length of $8d_b$, $18d_b$, $38d_b$, $58d_b$, $78d_b$ and $98d_b$ were examined for each selected size (\(d_b\) is the diameter of the bar).
Bond Test Specimen

Development length

LVDT

Load Cell

Jack

Elevation

Plan

12in
Bond Specimens

Concrete T-section heavily reinforced with Grade 60 steel

Plastic tubes

Specially designed RC T-section
Test Set-Up

self-reacting steel frame against the flange of the T-section

Jack

Load Cell
#4MMFX Embedment Length = 4in (8d)

Axial stress = 70.6 ksi
Maximum Load = 13830 lb

Bond Stress (ksi) vs. Slip at the Free End (in)
Results of Bond Tests

#6MMFX Embedment Length = 7in (9d)

Axial stress = 83.8ksi
Maximum Load = 36875lb

Bond Stress (ksi) vs. Slip at Free End (in)

(2.24ksi, 0.04975in)
# Results of Bond Tests

## #4MMFX

<table>
<thead>
<tr>
<th>Embedment Length</th>
<th>4in</th>
<th>9in</th>
<th>19in</th>
<th>29.25in</th>
<th>39in</th>
<th>49in</th>
</tr>
</thead>
<tbody>
<tr>
<td>8d</td>
<td>13830</td>
<td>31940</td>
<td>34820</td>
<td>32725</td>
<td>33526</td>
<td>33418</td>
</tr>
<tr>
<td>Bond Stress (ksi)</td>
<td>2.2</td>
<td>2.26</td>
<td>1.16</td>
<td>0.71</td>
<td>0.55</td>
<td>0.43</td>
</tr>
<tr>
<td>Axial Stress (ksi)</td>
<td>70.6</td>
<td>163</td>
<td>178</td>
<td>167</td>
<td>171</td>
<td>170.5</td>
</tr>
<tr>
<td>Slip at Free End (in)</td>
<td>0.019804</td>
<td>0.038281</td>
<td>0.003812</td>
<td>0.000342</td>
<td>0.000150</td>
<td>0.000014</td>
</tr>
<tr>
<td>Failure Mode</td>
<td>Slip</td>
<td>Slip</td>
<td>Rupture</td>
<td>Rupture</td>
<td>Rupture</td>
<td>Rupture</td>
</tr>
</tbody>
</table>

## #6MMFX

<table>
<thead>
<tr>
<th>Embedment Length</th>
<th>7in</th>
<th>14in</th>
<th>29in</th>
<th>44in</th>
<th>59in</th>
<th>74in</th>
</tr>
</thead>
<tbody>
<tr>
<td>9d</td>
<td>36875</td>
<td>71626</td>
<td>74084</td>
<td>75572</td>
<td>65951</td>
<td>---</td>
</tr>
<tr>
<td>Bond Stress (ksi)</td>
<td>2.24</td>
<td>2.10</td>
<td>1.08</td>
<td>0.73</td>
<td>0.47</td>
<td>---</td>
</tr>
<tr>
<td>Axial Stress (ksi)</td>
<td>84</td>
<td>163</td>
<td>168</td>
<td>172</td>
<td>150</td>
<td>---</td>
</tr>
<tr>
<td>Slip at Free End (in)</td>
<td>0.04975</td>
<td>0.04891</td>
<td>0.02927</td>
<td>0.01247</td>
<td>0.00156</td>
<td>---</td>
</tr>
<tr>
<td>Failure Mode</td>
<td>Slip</td>
<td>Slip</td>
<td>Rupture</td>
<td>Rupture</td>
<td>Didn't Fail</td>
<td>not tested</td>
</tr>
</tbody>
</table>

## #8MMFX

<table>
<thead>
<tr>
<th>Embedment Length</th>
<th>8in</th>
<th>18in</th>
<th>38in</th>
<th>57in</th>
<th>78in</th>
<th>98in</th>
</tr>
</thead>
<tbody>
<tr>
<td>8d</td>
<td>8d</td>
<td>18d</td>
<td>38d</td>
<td>57d</td>
<td>78d</td>
<td>98d</td>
</tr>
</tbody>
</table>

(test in progress)
Development Length

\[ l_d = d_b \frac{f_y \alpha \beta \lambda}{25 \sqrt{f'_c}} \]  

(ACI 318 –99)

\[ f'_c : \text{ compressive strength of concrete} = 7000 \text{ psi} \]

**Grade 60 steel:**  
\[ f_y = 60,000 \text{ psi} \quad \rightarrow \quad l_d = 29d_b \]

**MMFX steel:**  
\[ f_y = 120,000 \text{ psi} \quad \rightarrow \quad l_d = 57d_b \]

<table>
<thead>
<tr>
<th>MMFX Rebar</th>
<th>#4</th>
<th>#6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embedment Length</td>
<td>9in</td>
<td>19in</td>
</tr>
<tr>
<td></td>
<td>18d</td>
<td>38d</td>
</tr>
<tr>
<td>Failure Mode</td>
<td>Slip</td>
<td>Rupture</td>
</tr>
<tr>
<td></td>
<td>Slip</td>
<td>Rupture</td>
</tr>
</tbody>
</table>
Compression Steel in Short RC Column

Two RC concrete columns were constructed:

- **C1:** 6#6MMFX longitudinal reinforcing bars
- **C2:** 6#6 Grade 60 longitudinal reinforcing bars

Columns are laterally reinforced with **#3 Grade 60**

Columns are 3ft. long and 12in. diameter

Columns were tested under axial compression up to failure

The concrete strength = 5000psi
Details of Short Columns

- #6 MMFX
- #3 Grade 60
- 8in
- 3ft
- 12in

#6 MMFX  6# Grade 60
Test Set-Up

PI gage
Results of RC Columns

12in. Reinforced Concrete Columns

Applied Axial Load (lb) vs. Strain (in/in) for MMFX Grade 60.
Failure Mode

#6 MMFX

6# Grade 60
Flexural Testing
(UNF & WVU)
Effect of Reinforcement Ratio

Beam B2-1
- $A_s = 2.012 \text{ in}^2$

Beam B3-1
- $A_s = 1.246 \text{ in}^2$

Beam B1-1
- $A_s = 0.623 \text{ in}^2$
Conclusion

Research in Progress
Typical MMFX Applications

- Oklahoma DOT Bridge Girders
- Pennsylvania DOT Bridge Deck
- Florida Residential Construction
- Kentucky DOT Bridge Deck
Thank You