Buckling-Induced Shortening of Deep W-Shape Columns in Seismic Steel Moment Frames

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Steel Special Moment Frames

Deep Wide-Flange Columns:
• Higher Moment of Inertia to Control Story Drift
• Lighter/Economical
### Issue of Deep-Column Section

<table>
<thead>
<tr>
<th>Section</th>
<th>$I_x$ (in$^4$)</th>
<th>$\lambda_f$ ($= b_f/2t_f$)</th>
<th>$\lambda_w$ ($= h/t_w$)</th>
<th>$\lambda_L$ ($= L/r_y$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow Column</td>
<td>10,800</td>
<td>2.1</td>
<td>4.4</td>
<td>47.5</td>
</tr>
<tr>
<td>(W14×605)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Deep Column</td>
<td>10,800</td>
<td>4.0</td>
<td>24.4</td>
<td>64.3</td>
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<tr>
<td>(W27×258)</td>
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</tr>
</tbody>
</table>

$L = 18$ ft assumed
Test Setup for ATC/NIST Project

Seismic Response Modification Device (SRMD) Laboratory
Type 1: Symmetric Flange Buckling (SFB)

- Shallow Columns
- Limited Axial Shortening
- Large Ductility Capacity
Type 2: Antisymmetric Local Buckling (ALB)

- Deep Column with In-Plane Hinging
- Significant Axial Shortening & Strength Degradation
Type 3: Coupled Buckling (CB)

(Specimen 1L)
Factors Affecting Column Axial Shortening

• Axial Force
  - Level of Axial Force
  - Constant vs. Varying Axial Force

• Loading Protocol
  - Monotonic vs. Cyclic Loading
  - Far-field vs. Near-field Loading

• Boundary Condition
  - Fixed-Fixed
  - Fixed-Rotating
Performance-Based Seismic Evaluation

• Limitation of Computer Software
  - Concentrated Hinge Component Model
  - Fiber-type Model

• Local Buckling & Resulting Axial Shortening not Simulated
Postulation

- Dissipated Energy at Column End Remains the Same Whether Local Buckling Is Simulated or Not
Normalized Axial Shortening vs. Cumulative Ductility

\[
\frac{\Delta_{axial}}{L} = 9.3 \times 10^{-4} e^{48.8\mu}
\]

\[
\eta = \frac{E_h}{M_p} = \left( \frac{\int M_{end} d\theta}{M_p} \right)
\]

(Specimen 3L)
Normalized Axial Shortening vs. Cumulative Ductility

Model:

\[ \frac{\Delta_{\text{axial}}}{L} = \left( \frac{P}{EA} \right) e^{\beta \eta} \]

Elastic Axial Shortening
• Regression Model

\[ \beta = a_1 \lambda_{f}^{a_2} \lambda_{w}^{a_3} \lambda_{L}^{a_4} \left( 1 - \frac{P_u}{P_y} \right)^{a_5} \]

• Result from 19 Test Data and 96 FEA Models:

\[ \beta = C \left( h \frac{1.56}{t_w} \left( 1 - \frac{P_u}{P_y} \right)^{-2.1} \right) \]

where \( C = 0.028 \) for Antisymmetric Local Buckling

\( = 0.022 \) for Coupled Buckling
Future Work

• Long-term Solution
  o Incorporate Local Buckling & Resulting Axial Shortening in “Practical” Computer Software

• Short-term Solution
  o Validate the Postulation
  o Improve and Calibrate Proposed Model for Other Parameters (e.g., Varying Axial Load, Loading Sequence Effect, etc.)
Acknowledgements

• Applied Technology Council (ATC)
• National Institute of Standards and Technology (NIST)
• American Institute of Steel Construction (AISC)
• The Herrick Corporation

\[
\zeta = \frac{2}{C_S} \left( \frac{\lambda_W}{\lambda_f} \right) \left( \frac{t_f}{t_w} \right)^2
\]

where

\[
C_S = \frac{2\pi c \sinh^2 \pi c}{(\sinh \pi c \cosh \pi c - \pi c)}
\]
## Test Matrix

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Shape</th>
<th>Specimen Designation</th>
<th>$\frac{h}{t_w}$</th>
<th>$\frac{b_f}{2t_f}$</th>
<th>$\lambda_f$</th>
<th>$\lambda_w$</th>
<th>$\lambda_L$</th>
<th>$C_a$</th>
<th>$P$ (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>W24×176</td>
<td>1L</td>
<td>0.67</td>
<td>0.57</td>
<td>1.42</td>
<td>0.2</td>
<td>465</td>
<td>0.2</td>
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<td></td>
<td></td>
<td>1M</td>
<td></td>
<td></td>
<td></td>
<td>0.4</td>
<td>931</td>
<td>0.4</td>
<td>931</td>
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<tr>
<td></td>
<td></td>
<td>1H</td>
<td></td>
<td></td>
<td></td>
<td>0.6</td>
<td>1396</td>
<td>0.6</td>
<td>1396</td>
</tr>
<tr>
<td>2</td>
<td>W24×131</td>
<td>2Z</td>
<td>0.93</td>
<td>0.66</td>
<td>1.46</td>
<td>0.0</td>
<td>0</td>
<td>0.2</td>
<td>347</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2L</td>
<td></td>
<td>0.70</td>
<td></td>
<td>0.2</td>
<td>347</td>
<td>0.2</td>
<td>347</td>
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<td></td>
<td></td>
<td>2L-P</td>
<td></td>
<td>0.70</td>
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<td>347</td>
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<tr>
<td></td>
<td></td>
<td>2M</td>
<td></td>
<td>0.76</td>
<td></td>
<td>0.4</td>
<td>693</td>
<td>0.4</td>
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<td></td>
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<td>2H</td>
<td></td>
<td>0.82</td>
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<td>0.6</td>
<td>1040</td>
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<td>3</td>
<td>W24×104</td>
<td>3L</td>
<td>1.18</td>
<td>0.85</td>
<td>1.49</td>
<td>0.2</td>
<td>276</td>
<td>0.2</td>
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<tr>
<td></td>
<td></td>
<td>3M</td>
<td></td>
<td>0.91</td>
<td></td>
<td>0.4</td>
<td>551</td>
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<tr>
<td></td>
<td></td>
<td>3H</td>
<td></td>
<td>1.00</td>
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<td>0.6</td>
<td>826</td>
<td>0.6</td>
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<tr>
<td>8</td>
<td>W24×131</td>
<td>8M</td>
<td>0.93</td>
<td>0.76</td>
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<td>693</td>
<td>0.4</td>
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<tr>
<td>11</td>
<td>W24×176</td>
<td>11H-VA</td>
<td>4.81</td>
<td>28.7</td>
<td>71.0</td>
<td>0.6</td>
<td>Varies</td>
<td>1396</td>
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<tr>
<td></td>
<td></td>
<td>11H-BC</td>
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<td></td>
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<td>13M</td>
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<td>40.8</td>
<td>63.1</td>
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<td>13M-BC</td>
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<td>W18×192</td>
<td>15L</td>
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<td>16.7</td>
<td>77.4</td>
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<td>506</td>
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<td>W18×130</td>
<td>16M</td>
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<td>23.9</td>
<td>80.0</td>
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<td>690</td>
<td>0.4</td>
<td>690</td>
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</tbody>
</table>

Note: $\lambda_f$, $\lambda_w$, and $\lambda_L$ represent the normalized slenderness values. $C_a$ is the column slenderness factor, and $P$ is the column axial load in kips. The figures in the table represent the slenderness ratios and load capacities for various specimen designs. The graph shows the relationship between the normalized slenderness and the slenderness factor for different column designs.