Cold-Formed Steel Design by the Direct Strength Method

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• Jack Spangler
• Sam Phillips, Liakos Ariston, Tom Lydigsen, Andrew Meyers, Brent Bass

Introduction and motivation
• Buckling and the finite strip method
• Experiments and design of beams
• Direct Strength Method for Beams and Columns
• Advocacy and extensions (as time allows)

Specification complication

• “Anyone who has ever attempted to design a light-gage member following the Specification provisions probably realized how tedious and complex the process was.”
• “When such [cold-formed] framing is needed one of two things tend to happen to the engineers: they either uncritically rely on the suppliers’ literature, or simply avoid any cold-formed design at all...”

Alexander Newman 1997, in Metal Building Systems
Specification complication explained

- Sections are not doubly-symmetric
- Element elastic buckling calculation (k’s)
- Effective width
  - effective width = \( f(\text{stress, geometry}) \)
  - stress = \( f(\text{effective properties: e.g., } A_{\text{eff}}, I_{\text{eff}}) \)
  - iteration results
- Web crippling calculations
- Inclusion of system effects

Plate vs. cross-section buckling

\[
 f_{\text{cr}} = \frac{\pi^2 E}{(12(1-\nu^2))^{2/3}} (\frac{h}{b})^2
\]

\[ P_{\text{cr}} = A_f f_{\text{cr}} \]

Why cross-section buckling?

(element interaction)

How to find cross-section buckling?

- Tables and charts
  - essentially limited to two elements
  - not widely available
- Finite element solutions
  - requires more advanced modeling (plate elements)
  - generality of method is great, but complicates too
  - not widely available
- Other methods?
  - finite element variant called the finite strip method
Modeling a CFS member

finite element  finite strip

Finite Strip Analysis

“cubic” beam function

CUFSM
(Cornell University Finite Strip Method)

- Free, open source, software that allows you to explore the elastic buckling of any cold-formed steel cross-section using the finite strip method
- Mechanics employed are IDENTICAL to the mechanics used to derive the plate buckling coefficient “k” values in current use

My = 192 kip-in.
Local buckling

Distortional

Lateral-torsional

CUFSM 2.6

Elastic Buckling Analysis of Thin-Walled Members
by Finite Strip Analysis

DEMO
(www.ce.jhu.edu/bschafer)
• Introduction and motivation
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Conclusions from part 1?
Part 2: DSM and an experimental investigation of beams

Direct strength prediction

\[ M_n = \left/ (M_y, M_{cre}, M_{crd}, M_{crl}) \right/ \]

- Input
  - Yield moment, \( M_y \)
  - Euler buckling load, \( M_{ew} \)
  - Distortional buckling load, \( M_{ud} \)
  - Local buckling load, \( M_{crl} \)
- Output
  - Strength, \( M_n \)
Motivation for recent experimental research

Problems:
2. The Direct Strength Method (proposed by Schafer and Peköz 1998) provides specific strength predictions for distortional buckling.
3. Previous tests did not distinguish between local and distortional buckling.
   Existing data is not representative of sections currently used in practice.

Therefore, two series of bending tests were performed to study the local and distortional buckling of CFS beams separately and analysis was also performed to develop complete design methods.

Tests of CFS Beams – Local Buckling (Phase 1)

25 tests…

Tests of CFS Beams
- range of specimens

Tested industry standard CFS Z and C-sections

Tests of CFS Beams
- panel fastener configuration for Phase 1 tests

Panel fastener configuration

continuous spring analysis (FSM)

fe (elastic) model to develop detail
Tests of CFS Beams
- comparison of two series of tests

Test 8.5Z073-5E6W
8.5Z073-4E3W
8.5Z073-5E6W 8.5Z073-4E3W

Tests of CFS Beams
- test summary

- Total 25 local buckling tests and 24 distortional buckling tests have been completed.

Comparison with design methods

<table>
<thead>
<tr>
<th></th>
<th>$M_{test}/M_{NAS}$</th>
<th>$M_{test}/M_{ASD}$</th>
<th>$M_{test}/M_{S136}$</th>
<th>$M_{test}/M_{MA136}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local buckling tests</td>
<td>1.01</td>
<td>1.07</td>
<td>1.02</td>
<td></td>
</tr>
<tr>
<td>Distortional buckling tests</td>
<td>0.08</td>
<td>0.06</td>
<td>0.07</td>
<td></td>
</tr>
</tbody>
</table>
1.2.2 Beam Design

The nominal flexural strength, \( M_n \), is the minimum of \( M_{ne} \), \( M_{nl} \), and \( M_{nd} \) as given below. For beams meeting the geometric and material criteria of Section 1.1.1.2, \( \phi_b \) and \( \omega_b \) are as follows:

<table>
<thead>
<tr>
<th>USA and Mexico</th>
<th>Canada</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi_b ) (ASD)</td>
<td>1.67</td>
</tr>
<tr>
<td>( \omega_b ) (LRFD)</td>
<td>0.85</td>
</tr>
</tbody>
</table>

For all other beams, \( \phi_b \) and \( \omega_b \) of Section A1.1.1 apply.

1.2.2.1 Lateral-Torsional Buckling

The nominal flexural strength, \( M_{ne} \), for lateral-torsional buckling is

- for \( M_{cre} < 0.56M_y \)
  \[ M_{ne} = M_{cre} \]
- for \( 2.78M_y > M_{cre} > 0.56M_y \)
  \[ M_{ne} = \frac{M_{cre}}{\frac{M_{cre}}{M_y} + \frac{1}{10}} \]
- for \( M_{cre} > 2.78M_y \)
  \[ M_{ne} = M_y \]

where \( M_y = S_f F_y \), where \( S_f \) is the gross section modulus referenced to the extreme fiber in first yield.

1.2.2.2 Local Buckling

The nominal flexural strength, \( M_{nl} \), for local buckling is

- for \( \lambda \leq 0.776 \)
  \[ M_{nl} = M_{ne} \]
- for \( \lambda > 0.776 \)
  \[ M_{nl} = M_{ne} \left( 1 - 0.15 \left( \frac{M_{cre}}{M_y} \right)^{0.4} \left( \frac{M_{cre}}{M_y} \right)^{0.4} \right) \]

where \( \lambda \) is defined in Section 1.2.2.1. \( M_{cre} \) is the critical elastic local buckling moment determined in accordance with Section 1.1.2.

1.2.2.3 Distortional Buckling

The nominal flexural strength, \( M_{nd} \), for distortional buckling is

- for \( \lambda_d \leq 0.673 \)
  \[ M_{nd} = M_y \]
- for \( \lambda_d > 0.673 \)
  \[ M_{nd} = \frac{M_y \left( 1 - 0.29 \left( \frac{M_{cre}}{M_y} \right)^{0.5} \right) \left( \frac{M_{cre}}{M_y} \right)^{0.5} \}}{M_y} \]

where \( \lambda_d \) is defined in Section 1.1.2. \( M_{cre} \) is the critical elastic distortional buckling moment determined in accordance with Section 1.1.2.
• Total 25 local buckling tests and 24 distortional buckling tests have been completed.

<table>
<thead>
<tr>
<th></th>
<th>M_{test}/M_{Mean}</th>
<th>M_{test}/M_{DES}</th>
<th>M_{test}/M_{NAS}</th>
<th>M_{test}/M_{136}</th>
<th>M_{test}/M_{AI96}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local buckling tests</td>
<td>1.01</td>
<td>1.07</td>
<td>1.02</td>
<td>1.04</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>0.06</td>
<td>0.07</td>
<td>0.06</td>
<td>0.09</td>
</tr>
<tr>
<td>Distortional buckling tests</td>
<td>0.86</td>
<td>0.92</td>
<td>0.87</td>
<td>1.01</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>0.08</td>
<td>0.09</td>
<td>0.07</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Introduction and motivation
• Buckling and the finite strip method
• Experiments and design of beams
• Direct Strength Method for Beams and Columns
• Advocacy and extensions (as time allows)

Part 3: DSM columns, more beams!, reliability

Direct strength prediction
\[ P_n = f(P_y, P_{cre}, P_{crd}, P_{cr}) \]

• Input
  – Squash load, \( P_y \)
  – Euler buckling load, \( P_{cre} \)
  – Distortional buckling load, \( P_{crd} \)
  – Local buckling load, \( P_{cr} \)

• Output
  – Strength, \( P_n \)
**Direct Strength design**

- Elastic buckling

\[ P_n? \]

**Elastic buckling**

- Direct Strength Curve
  (university of sydney testing)

\[ P_{crd} = \frac{A_f}{f_{crd}} \]

\[ P_{el} = \frac{A_f}{f_{el}} \]

\[ \beta = 2.5, \phi = 0.84 \]

**Columns**

- Lipped channels
- Lipped zeds
- Lipped channels with intermediate web stiffener
- Hat sections
- Rack post sections


**267 columns, \( \beta = 2.5, \phi = 0.84 \)**

\[ \lambda = \sqrt{\frac{F_u}{P_{crd}}}, \quad \lambda = \sqrt{\frac{F_u}{P_{el}}} \]

\[ \lambda = \frac{F_u}{P_{crd}} \]
1.2.1 Flexural, Torsional, or Flexural-Torsional Buckling

The nominal axial strength, $P_{n}$, for flexural, torsional, or flexural-torsional buckling is

\begin{align*}
\text{for } \lambda_\phi < 1.5 & \quad P_n = \frac{P_{ne} \phi^2}{\phi^2} \\
\text{for } \lambda_\phi > 1.5 & \quad P_n = \frac{0.887}{\lambda_\phi^2} P_{nE} 
\end{align*}

(1.2.1-1)

(1.2.1-2)

where $\lambda_\phi = \sqrt{P_{nE}/P_{nL}}$

$P_{nE}$ = Maximum of the critical elastic column buckling load in flexural, torsional, or flexural-torsional buckling

1.2.2 Local Buckling

The nominal axial strength, $P_{nL}$, for local buckling is

\begin{align*}
\text{for } \lambda_\phi < 0.776 & \quad P_{nL} = \frac{P_{nE}}{\phi} \\
\text{for } \lambda_\phi > 0.776 & \quad P_{nL} = \left[0.9 \left(\frac{P_{nE}}{P_{nL}}\right)^{\frac{1}{3}} + \frac{1}{2} \left(\frac{P_{nE}}{P_{nL}}\right)\right] P_{nE}
\end{align*}

(1.2.2-1)

(1.2.2-2)

where $\lambda_\phi = \sqrt{P_{nL}/P_{nE}}$

$P_{nL}$ = Critical elastic local column buckling load

Beams

- Lipped and plain channels
- Lipped zeds
- Hats with and without intermediate stiffener(s) in the flange
- Trapezoidal decks with and without intermediate stiffener(s) in the web and the flange


569 beams, $\beta = 2.5$, $\phi = 0.9$

Reliability

U.S. LRFD format: $\phi R_{1} > \sum Q_{i}$

$\beta_{1} = 2.5$

<table>
<thead>
<tr>
<th></th>
<th>$\phi$ Beams</th>
<th>$\phi$ Columns</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AISI Specification</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specified</td>
<td>0.90 or 0.95</td>
<td>0.85</td>
</tr>
<tr>
<td>Data</td>
<td>0.77</td>
<td>0.82</td>
</tr>
<tr>
<td><strong>Direct Strength</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local</td>
<td>0.89</td>
<td>0.79</td>
</tr>
<tr>
<td>Distortional</td>
<td>0.93</td>
<td>0.90</td>
</tr>
<tr>
<td>Combined</td>
<td>0.92</td>
<td>0.85</td>
</tr>
</tbody>
</table>

1 not all members in the data set can be designed by AISI Spec. these members are omitted from the AISI summary statistics.

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Direct strength advocacy

- No effective width, no elements, no iteration
- Gross properties
- Element interaction
- Distortional buckling
- Wider applicability and scope
- Encourage cross-section optimization

Your computer performs analysis that employs fundamental mechanics instead of just mimicking old hand calculations. DSM integrates known behavior into a straightforward design procedure.

2004 Supplement at AISI
www.steel.org click on publications

provided examples

STRENGTH AND STIFFNESS
1. C-Section with lips: Bending, Compression (AISI’96 Ex. 1-8)
2. C-Section without lips: Bending (AISI’96 Ex. 1-9)
3. Z-Section with lips: Bending, Comp., Deflections (AISI’96 Ex. 1-10)
4. L-Section with lips: Compression (AISI’96 Ex. 1-11)
5. L-Section without lips: (+) & (-) Bending (AISI’96 Ex. 1-12)
6. H-Section: Bending, Compression (AISI’96 Ex. 1-13)
7. Wall Section: (+) & (-) Bending, Deflections (AISI’96 Ex. 1-14)

ELASTIC BUCKLING
1. C-Section With Lips - Axial, Elastic Buckling Load by Hand
2. C-Section With Lips - Bending: Elastic Buckling Moment by Hand

AISI is sponsoring the creation of a design guide (under development)

Plenty of future research needed

- optimization – your product, made better
- beam-columns and eccentric loads, (NSF)
- isolated and patterned perforations, (AISI)
- significant neutral axis shift in the post-buckling regime,
- geometric limitations and definition of applicability,
- fine-tuning and further calibration of strength expressions,
- interaction of distortional buckling with other modes,
- shear and shear interaction issues,
- calibration of new cross-sections.

Potential for DSM in beam-columns

work motivated by Rusch and Lindner (2001)
Eccentric axial load

Minor axis interaction diagram

Major axis interaction diagram

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Concluding thoughts

Direct Strength Method
  – Price:
    Careful calculation of member buckling
  – Reward:
    No effective width, no iteration,
    Simple strength equations for all limit states,
    Optimization potential....

The method is on the street, please think about using it! More tools to ease the use are coming.

Resources

• Research
  www.ce.jhu.edu/bschafer
• Finite strip
  www.ce.jhu.edu/bschafer/cufsm
• Direct Strength
  www.ce.jhu.edu/bschafer/direct_strength
• Appendix 1: Direct Strength Method
  www.steel.org click on publications
  get the 2004 Supplement to the North American Specification for CFS...