Test Verification of the Effect of Stress Gradient on Webs of Cee and Zee Sections

submitted to the AISI and MBMA

by Ben Schafer, Ph.D.

1 Introduction

This report provides a brief synopsis of current progress on the project “Test Verification of the Effect of Stress Gradient on Webs of Cee and Zee Sections”. Progress to date includes:

9-2000 Project commenced
10-2000 Detailed examination of existing test data
10-2000 Analytical work on web/flange interaction issues in current AISI Specification
10-2000 Finite strip and further hand analysis to determine dimensions of specimens for testing
10-2000 Detailed testing plan and approval of AISI task group
11-2000 Physical overhaul of JHU structures lab facility in preparation of project
11-2000 C and Z specimens delivered to JHU
12-2000 Two undergraduate assistants: Sam Phillips and Liakos Ariston joined project part-time
12-2000 Specimens organized and labeled, damaged specimens re-ordered as needed
12-2000 Additional structural steel for reaction frame and loading mechanisms acquired
1-2001 One graduate student: Cheng Yu joined project full-time
1-2001 Detailed dimensional measurements of 8.5" Z's and 8" C's completed
1-2001 Controller, DAQ system acquired
1-2001 Finalization of testing apparatus for tests on 8.5" Z's
2-2001 (anticipated) Completion of first full specimen and testing

Progress is kept updated at www.ce.jhu.edu/bschafer. This report focuses primarily on the analytical work leading up to the experimental investigation. The marriage of this work with the test results in the lab will be provided in the next progress report (summer 2001).

2 Design Methods

2.1 Existing methods for C's and Z's in flexure

2.1.1 Expressions for the web (AISI, S136 (Cohen), Schafer)


2.1.2 Expressions for the flange

Expressions for the flange considered here: AISI (1996) and the change proposed by Dinovitzer (1992) and adopted by AISI in 2000. The methods for effective width of flanges proposed by Schafer and Peköz (1999) and Hancock (1997) are not explicitly considered at this time, as the focus of this study is on local buckling, not distortional buckling. However, since distortional buckling involves the web, ultimately this issue must be revisited.

2.1.3 Direct Strength Design

Current Direct Strength methods, as summarized in AISI task group on the Direct Strength method, (AISI February 2001 meeting) will be considered in this project. At this time, comparisons have not been completed.
2.2 Analytical evaluation of existing methods

2.2.1 web expressions

2.2.1.1 The AISI web equation is effectively using 1.5ρ

Peculiarities, discontinuities and inconsistencies of the existing AISI (1996) expressions for the effective width of a web have been previously investigated (most recently: Schafer and Peköz 1999). The following example shows the primary difference between the AISI (1996) method and proposed methods (as demonstrated using the method of S136).

Consider defining
\[ \rho^* = \frac{b_1 + b_2}{b_{\text{comp}}} \]

thus \( \rho^* \) is the ratio of effective portion of the element in compression. For the case of \( \zeta=2 \) (\( \psi=-1 \)), i.e. pure bending then the S136 method calculates

\[ b_1 = \frac{b_e}{4}, \quad b_2 = \frac{b_e}{2} - b_1 = \frac{b_e}{4}, \quad \text{where} \quad b_e = \rho w. \]

Therefore for the S136 method:

\[ \rho^* = \frac{b_1 + b_2}{b_{\text{comp}}} = \frac{\frac{b_e}{4} + \frac{b_e}{4}}{\frac{b_e}{2}} = \frac{\rho w}{\frac{w}{2}} = \rho. \]

For the same example AISI (1996) gives

\[ b_1 = \frac{b_e}{4}, \quad b_2 = \frac{b_e}{2}, \quad \text{and therefore,} \]

\[ \rho^* = \frac{b_1 + b_2}{b_{\text{comp}}} = \frac{\frac{b_e}{4} + \frac{b_e}{2}}{\frac{b_e}{2}} = \frac{3\rho w}{\frac{w}{2}} = 3 \rho. \]

Thus, the effective width expressions for the web using current AISI expressions result in a 50% greater capacity for the web alone. In essence, the effective width expression for an element in pure bending by AISI is

\[ \rho_{\text{AISI}}^* = \frac{3}{2} \left(1 - \frac{0.22}{\lambda}\right) \frac{1}{\lambda}, \]

which for \( \rho^*=1.0 \) implies a limiting \( \lambda=1.25 \).

2.2.1.2 Compactness / slenderness (h/t) AISI vs. S136

AISI predicts fully effective webs for much deeper (more slender) members than alternative methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>slenderness fully effective h/t limit limit for yield stress of</th>
<th>30 ksi</th>
<th>50 ksi</th>
<th>55 ksi</th>
<th>60 ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexure</td>
<td>AISI (k=24)</td>
<td>1.25</td>
<td>183</td>
<td>141</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td>S136 (k=24)</td>
<td>0.673</td>
<td>98</td>
<td>76</td>
<td>73</td>
</tr>
<tr>
<td>Compression</td>
<td>AISI (k=4)</td>
<td>0.673</td>
<td>40</td>
<td>31</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>AISI (k=0.43)</td>
<td>0.673</td>
<td>13</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>
2.2.2 flange expressions

2.2.2.1 $k_a$ and $k_u$ in AISI B4.2
The $k_a$ term in AISI B4.2 expressions attempt to account for flange/lip local buckling interaction. The expression is a linear fit to the experimentally observed elastic buckling in Desmond et al.’s (1981) experiments. This choice is unusual because experimental buckling predications based on strain reversal methods are sensitive to imperfections and the details of the specific test, which are generally accounted for in the strength expressions for $\rho$, as opposed to $k$. All other portions of the AISI Specification use theoretical $k$ values, not experimental $k$ values.

The $k_u$ term in AISI B4.2 accounts for local buckling of the lip alone, but ignores the beneficial effect of a stress gradient on the lip. The current expressions for $k_a$ and $k_u$ are overly conservative, and unfairly penalize the performance of members with longer lip lengths. Schafer (1997) and Schafer and Peköz (1999) provide more accurate, and less conservative, expressions for flange/lip local buckling interaction that could be used to replace $k_a$ and lip local buckling under a stress gradient that could be used to replace $k_u$.

2.2.3 flange/web interaction
The existing AISI specification does not explicitly account for flange/web interaction in local buckling. The existing AISI web expressions empirically rely on a high degree of beneficial flange/web interaction. This is discussed in greater detail in the following section.

2.3 Local flange/web interaction

2.3.1 Expressions for flange/web local buckling
Expressions for prediction of flange/web interaction in local buckling are provided in Schafer and Peköz (1999). Those expressions have been extensively refined and are presented in the following graphs, of which the key expressions from the graph are:

$k_{wss}$: web plate buckling coefficient when simply supported (as a function of stress gradient),

$k_m$: max web plate buckling coefficient, effectively $k_u$ with fixed edges (as a function of stress gradient) and

$k_1$: web plate buckling coefficient at $h/b = 1$.

Note, $(k_{wss}/k_1)^{0.5} = h/b$ value at which the web reaches the simply supported value (e.g. $k_{wss} = 24$ in pure bending) - for $h/b$ in excess of this value (e.g., $h/b > 2.27$ in pure bending) the actual $k_w$ is greater than the simply supported value. A cautionary note, as the final graph shows, as $h/b$ is increased the web plate buckling coefficient continues to increase; however, eventually the flange plate buckling coefficient will decrease, as it must.

2.3.2 Impact of local flange/web interaction
Using the finite strip results as a guide, and comparing to current practice in the AISI (1996) Specification we may make some interesting observations:

- $k$ for the web may be overly conservative for many common members; however this is apparently offset by effective width equations which increase $\rho$ to $1.5\rho$,
- $k$ for the flange may be unconservative for common members, however, in some cases the AISI Spec. still arrives at approximately the correct value, by implementing a reduction on $k$ as a function of $I/I_a$ when actually the reduction is a flange/web interaction issue that can better be expressed through the $h/b$ ratio.

Since current methods do not separate between local and distortional buckling of members, it is difficult to distinguish all the ramifications of ignoring local flange/web interaction. Comparison against existing experimental data presented in subsequent sections addresses this further.
Figure 1 Web plate buckling coefficient as a function of flange width to web height ratio for local buckling including web/flange interaction, approximate hand expressions also given

Figure 2 Web plate buckling coefficient as a function of web height to flange width for a variety of different stress gradients ($\xi$) on the web.
2.3.3 Fixed bc is optimistic for web equation

Finite strip analysis, and the previous discussion, suggest that use of a higher $k$ value for the web is justified (but not with current expressions for $b_1$ and $b_2$) in many cases.

How high would $k$ have to increase if the S136 expressions were used for effective width, but the resulting strength was to be the same as AISI’s current values? A lot, $k$ would have to be approximately 2.4 times its current value. Assuming fixed boundary conditions ($k_m$ in the previously given expressions) the maximum increase in $k_m$ is approximately 1.6 times its current value.

As the previous graphs show, typical members $3.1 < h/b < 3.7$ may expect increases smaller than 1.6 times $k$. This discussion has ignored, the detrimental effect on the flange of members with higher $h/b$ ratios. Use of the maximum $k$ value for the web, combined with the S136 web expressions, will go a long ways towards providing comparable strength predictions to the existing AISI method – but the choice of $k$ is optimistic. Nonetheless, it is more justifiable and rational than the arbitrary $b_1, b_2$ equations in current practice.

3 Evaluation via Existing Experiment

3.1 Member geometry

The geometric range of C and Z flexural members used in practice, and those studied experimentally are provided in the following table; where $h =$ web height, $b =$ flange width, $d =$ lip length, and $t =$ thickness.

Table 2 Range of geometry for industry members and available experimental data

<table>
<thead>
<tr>
<th></th>
<th>$h/t$</th>
<th>$b/t$</th>
<th>$d/t$</th>
<th>$h/b$</th>
<th>$d/b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min</td>
<td>max</td>
<td>min</td>
<td>max</td>
<td>min</td>
</tr>
<tr>
<td>MBMA Z’s</td>
<td>53</td>
<td>170</td>
<td>17</td>
<td>47</td>
<td>5</td>
</tr>
<tr>
<td>SSMA members</td>
<td>25</td>
<td>318</td>
<td>11</td>
<td>132</td>
<td>1</td>
</tr>
<tr>
<td>Rack members</td>
<td>23</td>
<td>136</td>
<td>16</td>
<td>45</td>
<td>6</td>
</tr>
<tr>
<td>Elhouar and Murray (1985)</td>
<td>68</td>
<td>165</td>
<td>24</td>
<td>52</td>
<td>3</td>
</tr>
<tr>
<td>Schafer and Peköz (1999)</td>
<td>43</td>
<td>270</td>
<td>15</td>
<td>75</td>
<td>3</td>
</tr>
</tbody>
</table>
3.1.1 MBMA Z members
For this study, CECO, VP, and Butler each provided detailed cross-section information on their Z members for depths between 6.5 and 11.5 inches deep. The most striking geometric feature of the MBMA Z members is the apparent optimization of the web height to flange width ratio - h/b is in a remarkably tight range.

However, data provided by LGSI for an earlier study indicates that in some cases Z members with h/b as high as 5.9 are used in current practice. Further, other common Z members (e.g. 10x2.5) have h/b in excess of the collected MBMA Z members. While these sections do not appear to be in common use for the pre-engineered metal building industry, it is conceivable that Z’s with high h/b ratios are used within the cold-formed industry.

3.1.2 Elhouar and Murray study
A compilation of industry tests on purlins was reported by Elhouar and Murray (1985). This database of tests covers member geometries consistent with those used as purlins for pre-engineered metal buildings. However, this database does not cover Z members reported by LGSI, nor does it cover the wider class of members reported in other industries.

3.1.3 Compilation of C’s with known experimental results
A large compilation of experimental data on C’s in flexure was examined in Schafer and Peköz (1999). From this compilation the tests of: Cohen (1987), LaBoube and Yu (1978), Moreyra (1993), Rogers (1995), Schardt and Schrade (1982), Schuster (1992), Shan et al. (1994), and Willis and Wallace (1990) are included in discussions presented here. This database of members covers a broad range of geometric ratios, but does not include members with h/b near 1.0.

3.1.4 Geometric range of SSMA members
The geometric summaries attributed to the SSMA were compiled based on the geometry of C members submitted by Dietrich and Clark collected in an earlier study. Examination of the current SSMA profiles indicates a wide range of available products. Note in particular the wide range of h/b ratios employed.

3.1.5 Geometric range of Rack Manufacturer members
The geometric summaries attributed to the Rack members were provided by Unarco for and earlier study. The rack members include C shapes with nearly square aspect ratio (h/b=1.0) up to those that have aspect ratios common with the MBMA Z members, h/b ~ 3.

3.1.6 A note on yield stress
The geometric parameters discussed in the previous sections uniquely determine the elastic buckling of the member. However, strength and failure mode is a function of the yield stress, as well as the geometry. Therefore, the adequacy of the available experimental data to address the strength of members is not completely assessed because yield stress is not examined. In general, current members have higher, and in some cases markedly higher, yield stress than the members experimentally tested and summarized in Elhouar and Murray (1985) and Schafer and Peköz (1999).

3.2 AISI Performance
The following analyses are based on the experimental testing of C’s compiled by Schafer and Peköz (1999) and summarized in the previous section.

3.2.1 For geometry used by MBMA
Of 180 specimens, 21 have 3.1 < h/b < 3.7 and 0.28 < d/b < 0.45 (geometry consistent with MBMA member company Z profiles) for these 21 specimens the mean test to predicted ratio for the AISI (1996) Specification is 1.00 with a standard deviation of 0.09.

3.2.2 For geometry used by Elhouar and Murray
Of 180 specimens, 64 have 2.6 < h/b < 3.8 and 0.1 < d/b < 0.5 (geometry consistent with industry tests on Z’s compiled by Elhouar and Murray (1985)) for these 64 specimens the mean test to predicted ratio for the AISI (1996) Specification is 1.03 with a standard deviation of 0.10.
3.2.3 As a function of web height to flange width ratio

Although the AISI (1996) Specification provides a reliable prediction for limited ranges of h/b and d/b (such as those often used by MBMA member companies) it can be quite unsafe out of these ranges. Consider the mean test to predicted ratio for specimens with a 0.1 < d/b < 0.5 as a function of h/b.

The figure shows the test to predicted ratio for all members with h/b greater than a given “x” value. For example, if h/b is > 3 the mean test to predicted ratio is 0.97 (this does not imply that the test to predicted ratio at h/b = 3 is 0.97). The majority of change in the accuracy occurs in the 2 < h/b < 4 range.

![Figure 4 Test to predicted ratio for members in excess of a given h/b ratio](image)

3.3 Alternative web expressions performance

3.3.1 As a function of web height to flange width ratio

Replacing only the AISI (1996) Specification web expressions does not fully relieve the systematic error on h/b shown in the previous graph. Use of S136’s web equations or those proposed in Schafer and Peköz (1999) is shown below. The alternative expressions are more conservative, and closer to a test to predicted ratio of 1.0 for a much wider range of members. The expressions from Schafer and Peköz (1999) have the smallest amount of systematic error. None of the existing expressions alone rectify the systematic error, which is a function of flange/web local buckling interaction.

3.4 Ramifications of adopting alternative methods on MBMA Z members

3.4.1 Adoption of new web expressions with no other change (S136)

If the current AISI expressions for the web are replaced by the S136 expressions, the average strength prediction for MBMA Z members will decrease by 5%. Individual members may see as much as a 9% change. (Findings are similar for the web expressions proposed by Schafer and Peköz 1999)

3.4.2 Comparisons with modified flange expressions only (ka, S136 web)

If the current AISI expressions for the web are replaced by the S136 expressions, and the current kₘ expression for the flange is improved to more accurately account for flange/lip local buckling, the average strength prediction for MBMA Z members will decrease by 4%. Individual members may see as much as a 8% change. (Findings are similar for the web expressions proposed by Schafer and Peköz 1999)
3.4.3 Comparisons with fully effective flanges (>>kf, S136 web)

If the current AISI expressions for the web are replaced by the S136 expressions, AND the flange is assumed to be fully effective, then the average strength prediction for MBMA Z members equals or exceeds current AISI predictions. Individual members may still see as much as a 5% reduction in predicted capacity.

Thus, if the S136 web expressions are adopted, corrections and improvements to the flange expressions alone, will not alleviate the concerns of MBMA members regarding changes to the web expressions. Conclusions: the strength of many typical MBMA Z members are strongly influenced by changes in the web expressions alone, many of the MBMA Z members have fully effective, or nearly fully effective flanges. (Findings are similar for the web expressions proposed by Schafer and Peköz 1999).

3.4.4 Comparisons with modified flange and web expressions (ka, 1.6kw, S136 web)

If the current AISI expressions for the web are replaced by the S136 expressions, the $k_a$ expression for the flange is improved to properly account for flange/lip local buckling, AND the web expressions for local buckling are replaced by the maximum $k_w$, ~1.6 times the current $k$ for the web (i.e, assume fixed boundaries instead of simple supports) then the average strength prediction for MBMA Z members is the same as currently predicted by the AISI Specification. Individual members may see as much as a 4% reduction, or a 2% increase in strength.

The above changes represent a solution that maintains the status quo in strength prediction while correcting the sharp inconsistency of the current AISI method. However, as previously noted, assuming the $k$ for the web is fixed is an optimistic (upperbound) assumption. Further, this solution will not alleviate systematic error for members with high $h/b$ values. HOWEVER, it is a significant step in the right direction and re-focuses attention on the problems with the plate buckling coefficient ($k$ and $k(h/b)$) instead of the strength expression ($\rho$).

3.5 A few words about distortional buckling

Lack of an explicit treatment for distortional buckling has been cited as a problem in the AISI Specification (Hancock 1997, Schafer and Peköz 1999) However, work on C and Z members in compression (Schafer 2000) demonstrate that the Specification’s lack of a treatment for local web/flange interaction is as important as problems related to distortional buckling.

Demonstration of the systematic error in the current AISI Specification as a function of $h/b$ does not purely place the blame on web/flange interaction in local buckling. Examination of the predicted failure strength for local and distortional buckling using the Direct Strength method will be employed to provide further insight on this matter.

For nearly constant geometry ($h, b, d$ constant) distortional buckling is more likely to be a problem for thicker members than for thinner members.
Distortional buckling is more likely to be a problem for members with higher yield stress than lower yield stress. Local web/flange interaction and distortional buckling are two separate issues. While distortional buckling is roughly accounted for through the use of \( I_s/I_a \) in the current AISI Specification, local web/flange interaction is entirely ignored.

Attachment of a deck to a flange may stabilize distortional buckling to some extent; however it is unlikely to have much of an effect, if any, on local buckling and local web/flange interaction issues discussed herein.

3.6 Overall ideas/comments on the AISI Specification

The following comments are based on the analytical work conducted for this project and existing research to date. The experimental research currently being conducted will allow for a more direct examination of local web/flange interaction issues and, no doubt, some of the points listed below will continue to evolve.

Within the confines of the current unified effective width approach the following points are worthy of mention.

**web buckling**
- For a wide class of members the current “k” used by AISI for the web is overly conservative.
- Local web/flange interaction is ignored in AISI’s “k” expressions for the web.
- Distortional buckling is ignored in AISI’s “k” expressions for the web.
- Expressions for local web/flange interaction in C’s and Z’s have been determined and could be included.

**web effective width**
- AISI’s effective width equations are unintuitive, discontinuous, and inconsistent.
- For sections in common use by MBMA members the equations provide reasonable strength prediction.
- For a wider class of members current AISI strength prediction can be unconservative.
- Alternative effective width equations (S136, Schafer and Peköz 1999) result in average reductions in strength prediction of 5%, if adopted with no other changes.
- Current expressions for effective width of the web indirectly account for an assumed beneficial web/flange interaction. This interaction should be directly accounted for through appropriate selection of k.
- If current strength predictions are justified, then either change \( \rho \) for flexural members to reflect increased post-buckling capacity for these elements, or change k to reflect increased web buckling stress for these elements.

**flange buckling**
- AISI’s “k” for the flange ignores local web/flange interaction.
- AISI’s \( k_s \) value for flange/lip interaction is overly conservative.
- AISI’s \( k_u \) value for lip local buckling is overly conservative.
- AISI’s “k” for the flange only partially accounts for distortional buckling.
- Expressions for local web/flange interaction and distortional buckling impact “k” for the flange.

**flange effective width**
- AISI’s current effective width equations for the flange are complicated but adequate; however, the primary input to these equations “k” requires significant modification as discussed above.

**General comments**

The integration of local web/flange interaction and distortional buckling into the current AISI Specification methodology is a difficult task, because the behavior inherently involves more than one element, and the current approaches are based on treating each element of the cross-section separately. In current methods, only h/t influences local buckling of the web and it does not matter whether that web is attached to the a slender flange or a compact flange. Looking to the future, allowing numerical prediction of the local buckling stress, and implementing Direct Strength design which accounts for the interaction of the elements may alleviate these problems and systematic error.
4 Flexural Tests on C’s and Z’s

4.1 Motivation for new studies
Existing tests on C- and Z-Sections do not provide definitive evaluations of the design expressions for the web due to: incomplete restriction of the distortional mode, arrangement of the specimens (back-to-back vs. toe- to-toe), and lack of information on bracing details. A series of new flexural tests focused on the role of web slenderness in local buckling failures of C- and Z-Sections is proposed. Through careful bracing and an understanding of the inherent interaction between the flange and the web the results may be used for evaluation of existing and proposed methods for strength prediction of webs.

4.2 Specimen selection
The AISI (1996) Specification calculates the effective width of webs as a function of the web slenderness (h/t) alone. The proposed tests are designed to provide systematic variation in h/t while at the same time varying the other non-dimensional parameters (h/b, h/t, d/t, d/b) enough to determine the adequacy of existing and proposed design rules. Because the focus of the testing is on the webs, significant variation in d/b is not investigated.

The primary consideration in investigating the web slenderness (h/t) is whether to achieve this variation by varying t, while holding h, b, d approximately constant – or varying h while holding b, d and t approximately constant. Practical considerations (available industry specimens) dictate that studies on the Z purlins vary t, while holding h, b, and d approximately constant. However, the wide variety of C specimens commonly produced allow both methods of variation to be examined.

Figure 6 Local and distortional buckling stress of a typical purlin as t or h is varied as a function of web slenderness.

The need to examine both variations is demonstrated through a simple study of a typical purlin in which the same h/t values are investigated, but in one set h is varied with t constant, in the other set t is varied with h constant, see the finite strip results of Figure 6. In the example, the two members are identical at an h/t of 144 – however as h/t is reduced by either varying h or t – the two diverge. (With regard to the distortional buckling stress, a longer lip, or attachment to decking may preclude this mode see section 3.5 for further comments on this issue).

Traditionally local buckling of the web = f(h/t, E, ν, ξ)  (note, ξ = stress gradient)
Accounting for web/flange interaction local buckling of the web = f(h/t, h/b, E, ν, ξ)
Traditionally the effective width of the web = f(fy, h/t, E, ν, ξ)
Accounting for web/flange interaction local buckling of the web = f(fy, h/t, h/b, E, ν, ξ)
Therefore, varying \( t \), while holding \( h, b, d \) constant examines the effective width (post-buckling behavior) for only one unique \( h/b \) value. Varying \( h \), samples across many different \( h/b \) values but does so for a constant \( b/t \). By using industry standard specimens a wide variation is still investigated, but the focus remains on practical members.

### 4.3 Selected Specimen dimensions

Based on discussions with the Task Group Members and Chairmen in September the original work plan from the proposal for this project was amended (same number of total tests was kept). The overall test plan in to conduct: 3 tests to work out the bracing details, 10 standard tests on C’s, 12 standard tests on Z’s, and an additional 4 tests to be conducted on “outlier” test results for a total of 29 tests. The summary of the geometry follows:

<table>
<thead>
<tr>
<th>Table 3 Summary of Geometry to be Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tests to be performed</td>
</tr>
<tr>
<td>Determination of bracing config.</td>
</tr>
<tr>
<td>Z Study 1: h,b,d fixed, ( t ) varied</td>
</tr>
<tr>
<td>Z Study 2: h,b,d fixed, ( t ) varied</td>
</tr>
<tr>
<td>C Study 1: ( b,d ) fixed, ( h ) varied</td>
</tr>
<tr>
<td>C Study 2: ( b,d ) fixed, ( h ) varied</td>
</tr>
<tr>
<td>Additional tests on outliers</td>
</tr>
<tr>
<td>TOTAL</td>
</tr>
</tbody>
</table>

With regard to the original proposal: A greater number of tests on Z’s will be conducted, more tests on Z’s require elimination of the proposed testing of C’s with the neutral axis lowered, one set of the tests on C’s have been changed from varying \( h \) while \( b, d, t \) are constant to varying \( t \), while \( h, b, d \) are constant – this provides comparisons to the tests on Z’s where use of industry standard sections only allow variations in \( t \), with \( h, b, \) and \( d \) held constant.

The details of the geometry of the specimens anticipated for testing are given below.

<table>
<thead>
<tr>
<th>Table 4 Details of Geometry to be Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identifier/Label</td>
</tr>
<tr>
<td>h (in.)</td>
</tr>
<tr>
<td>Z Study 1: h,b,d fixed, ( t ) varied</td>
</tr>
<tr>
<td>Varco-Pruden 8.5x2.5x0.7057x0.059</td>
</tr>
<tr>
<td>Varco-Pruden 8.5x2.5x0.78x0.065</td>
</tr>
<tr>
<td>Varco-Pruden 8.5x2.5x0.9260x0.073</td>
</tr>
<tr>
<td>Varco-Pruden 8.5x2.5x0.9382x0.082</td>
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<tr>
<td>Varco-Pruden 8.5x2.5x0.9577x0.092</td>
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<tr>
<td>Varco-Pruden 8.5x2.5x0.9832x0.105</td>
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\( \text{indicates that for } f_y = 60 \text{ ksi, h/t is in a range where AISI 1996 predicts fully effective web, but proposed methods predict partially eff. web} \)

### 4.4 Testing Details

Details of the testing plan are provided in the following figures. The plan itself is discussed in subsequent sections.
Figure 7 Elevation view of overall test arrangement for four point bending test

Figure 8 End-on elevation view of specimen at end support

Figure 9 Range of specimens to be tested
Figure 10 Paired specimen and tube detail

Figure 11 Support and loading apparatus
4.5 Testing Plan

The proposed plan consists of a series of 4 point bending tests. The basic specimen length is 16 ft., with the loading applied at the 1/3 points. Two members oriented in an opposing fashion are selected. The member are attached to one another by: standard steel decking (t = 0.019 in., 1.25 in. high ribs) screwed down at the center of the compression flange, small angles at the center of the tension flange (also screwed), and tubes at the loading point and at the supports (bolted), as detailed in the previous section.

Overall Setup

- 4 pt. bending test (loading at 1/3 points.)
- Total span length 16 ft. (actual member length 18 ft.)
- 2 members (C or Z), 10 in. apart, orientation: opposed

Orientation

- The members are selected to be in an opposed fashion; such that in-plane rotation of the C’s and Z’s would lead to tension in the panel, and thus provide additional restriction against distortional buckling of the compression flange.

Length

- Length is selected considering: shear demands, actuator capacity, actuator stroke, and future testing.
- Shear demands, actuator capacity, and actuator stroke are discussed further below. The future testing consideration is that the constant moment length in the center should be long enough that distortional buckling would form in an unbraced member (~2×distortional buckling half wavelength is used as a minimum). In these tests the center span will be braced, but in future tests this restriction may be lifted and distortional buckling investigated further.

Bracing

- Screw down panel attached to compression flange
  (typical industry panel t ~ 0.019 in. max rib height 1.25 in.)
- 1 ¼ x 1 ¼ x 0.057 in. Angles attached (every 12 in.) to tension flange
- ¼ in. thick steel tube 10 in. wide 7.5 in high and 6 in. long will be placed between the 2 specimens at the loading pt. and the supports (see details).
- Screw down spacing of panel will be studied in initial tests, 12 in. spacing may be sufficient to engage enough of the panel’s stiffness, but tighter spacing may be required, particularly on the thicker specimens due to propensity for distortional buckling.

Attachment

- It is assumed that the panels and angles will be attached by screws through the center of the flanges. Though better performance may be achieved by attachment away from the center, this effect is intentionally ignored in this work.
- the tubes connecting the two members will be bolted to the specimens, 4 bolts are sufficient of the maximum shear transfer required.

Limit States

Local buckling

- Local buckling is the target failure mode for all tests, the bracing schemes, panel etc. are selected with the goal of achieving this failure mode.

Shear

- Based on a moment capacity equal to the AISI (1996) prediction and a moment arm of 5’-4” shear capacity is adequate for all members.

Web Crippling

- Web crippling is adequate due to the tube at the loading point, and angles at the end supports.
- At the loading point the tube which is bolted to the two specimens will stiffen the web, further the tube will be flush with the top of the flange, so loading will be through bearing on the tube and transferred as shear to the flanges.
- At the end support a 4 x 4 x ¼ in. angle is bolted to the specimens to insure the bottom of the specimen does not cripple at the support.
Lateral buckling
- Preliminary calculations of the deepest C section (most prone to lateral buckling) show lateral buckling will not be a problem at these span lengths if the two members act together.
- The members are bolted to one another at the loading point and supports.
- Additional calculations will be performed before initiating work on the 11.5 in. deep Z’s and deep C’s, but work will continue on the 8.5 in. Z’s and 8 in. C’s in the interim.

Distortional buckling
- Calculations indicate that a fully engaged panel provides sufficient torsional resistance to limit distortional buckling.
- Calculations (finite strip) were performed to determine the stiffness required of a torsional spring connected to the center of the compression flange, this stiffness is less than the rotational (bending) stiffness of the panel over the short length between specimens (i.e., success of a typical panel spaced 5 ft. on centers is not assessed, rather the panel in this test, spaced 10 in. on center, can provide necessary resistance.)

Shear + bending
- Not explicitly checked – though shear demand to capacity is relatively low. It is intended to avoid problems with shear + bending through the use of the large tube bracing between the two members at the loading point (when shear + bending are both at a maximum)

Instruments

Actuator Capacity
- The 20 kip actuator will be at capacity on the thicker 11.5 in. deep Z’s. It is important that these members have an fy at or near 50 ksi. The constant moment length in the center can be decreased (thus increasing the moment arm for the member) as additional capacity is needed.
- For typical members approx. 50% of actuator capacity will be used.

Actuator stroke
- The stroke of the actuator (6 in.) will be near its limits for the smallest C sections tested.
- For typical members approx. 40% of actuator stroke will be used.

Monitoring
- LVDT’s for deflection, and strain gages on a limited number of specimens

4.6 Measured dimensions of specimens
Dimensions of the 8 in. C’s and 8.5 in. deep Z’s have been completed. Measurements were taken at the center of the specimen and mid-distance between the center and loading points (A total of 3 measurement locations for each specimen). Measurements for the Z’s follow.

![Figure 12 Definition of specimen dimensions for a Z](image)
### Table 5 Measured specimen dimensions for 8.5 in. deep Z’s

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*blank rows indicate the specimen was damaged on delivery. Yellow indicates the wider of the two flanges – wider flanges will be paired and used for the compression flange.*
4.7 Current status and timeline

Experimental status as of February 6, 2001

We are in the process of preparing the first 8.5 in. deep Z specimens. The specimens have been measured and marked, and currently holes are being drilled in order to bolt the two specimens to the tubes. All other materials: decking, angles, tubes etc. are in the lab and will be attached to the specimens as soon they are bolted together. The reaction frame, and end supports have been designed and fabricated and await the first specimen. The actuator and controller have recently been repaired and the actuator is ready to be mounted to the reaction frame. The computer and DAQ system has recently been purchased – we will be using LabView for the control and we are in the process of setting this up. Testing on the first specimens is expected in the month of February.

Experimental Timeline

Definitive comments regarding the timeline are difficult, with the first tests commencing in February, barring any major changes in the loading apparatus, etc. then March and April will focus on testing the 8.5 in. deep Z’s. Testing in May will be on the 8 in. deep C’s. Preliminary results of this testing at the summer 2001 AISI meeting is anticipated. Completion of all testing by the end of summer 2001 is the goal of the testing program.

Analytical work

While the experimental work progresses the analytical work discussed in the proposal also continues. Evaluations of the experiments using current and proposed methods for the effective width of the web will be completed. Further, use of the Direct Strength method on these tests will also be given.

5 Acknowledgment

The sponsorship of AISI and MBMA and the donation of materials by Varco-Pruden, and Clark Steel is gratefully acknowledged. The assistance of the AISI task group in developing the testing plan is appreciated. Don Johnson, Maury Golovin, Joe Nunnery, Joe Wellnhoff, and Steve Thomas have all been helpful with their ideas and generous with their time. Johns Hopkins undergraduates: Liakos Ariston and Sam Phillips have provided additional support in the lab and deserve recognition as well. The assistance of Jack Spangler in re-invigorating the JHU structural testing facility has been invaluable. The donation of miscellaneous steel parts by Prosser Steel has also been invaluable.

6 References


Dinovitzer (1992) complete cite unavailable at this time.


