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DISTORTIONAL BUCKLING OF C AND Z MEMBERS IN BENDING

Project Plan for PHASE 2 of TEST VERIFICATION OF THE EFFECT OF
STRESS GRADIENT ON WEBS OF CEE AND ZEE SECTIONS

Submitted to:
The American Iron and Steel Institute (AISI)

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Abstract

Distortional buckling of cold-formed steel C and Z members in bending remains an unaddressed problem in the current North American Specification (AISI 2002). When the compression flange is not stabilized by fastening to panels or sheathing, such as in negative bending of continuous members (joists, purlins, etc.) and wind suction on walls and panels (without interior sheathing) members are prone to distortional failures. Adequate experimental data on unrestricted distortional buckling in bending is unavailable. It is proposed to extend a recently completed experimental project on local buckling of C and Z members in bending, to a second phase on distortional buckling. Further, it is proposed to begin work on understanding the role of restraint in distortional buckling both experimentally and numerically. The experimental work may be completed by using geometry similar to that of the Phase 1 testing, but removing the through-fastened panel attached to the compression flange. Subsequently, exploratory work on fastener details and panel stiffness may be pursued. The experimental data will help develop and validate an efficient and reliable design procedure for C and Z members in bending with and without panels attached to the compression flange failing in local or distortional buckling and form the basis for more advanced design methods that account for situations of partial restraint.

1. Background

Existing experimental and analytical work indicates current provisions, North American Specification (AISI 2002), are inadequate for predicting bending capacity of C and Z members when distortional buckling occurs (e.g., Hancock et al. 1996, Rogers and Schuster 1995, Schafer and Peköz 1999, Yu and Schafer 2002). While recent work on the effective width of webs to combine the best of the AISI (1999) and S136 (1994) methods has been completed and adopted (AISI 2002) a great deal of work remains on local buckling interaction (Figure 1a) between the flange and the web, and distortional buckling (Figure 1b).

(a) local buckling
½ wavelength ~ 5 in. (127 mm)

(b) distortional buckling
½ wavelength 27 in. (686 mm)

Figure 1 Local and distortional buckling of a typical 8.5 in. (216 mm) deep Z in bending

A joint MBMA-AISI project recently completed at Johns Hopkins University: Test Verification of Effect of Stress Gradient on Webs of Cee and Zee Sections, provided necessary experimental support to address local buckling and shed light on local web/flange interaction. However, the testing was focused exclusively on local failure modes, and distortional buckling was restricted by the use of a panel through-fastened to the compression flange at a close fastener spacing. This "Phase 1" testing provides the upper-bound capacity for a bending member failing in the local mode. This proposal details "Phase 2" work on distortional buckling of the same C and Z members examined in Phase 1.

There is a significant need for the Phase 2 work. Although most C and Z members in bending have attachments (panel or otherwise) which stabilize the compression flange and restrict distortional buckling many do not. Negative bending of continuous members (joists, purlins, etc.) and wind suction on walls and panels (without interior sheathing) are common examples where no such beneficial attachments exist – these members are prone to distortional failures. Even when attachment to the compression flange exists it may not fully restrict distortional buckling – as may be the case for thin panels with large center to center fastener spacing and thick insulation between the purlin and panel. Further, flexural members are in general more prone to distortional failures than compression members, due to the dominance of local web buckling in typical compression members. Geometry, unique to flexural members, such as the sloping lip stiffeners used in Zs are inefficient in retarding distortional buckling. For example, a typical 8 in. (216 mm) deep Z with $t = 0.120$ in. (3 mm) has a distortional buckling stress that is ½ the local buckling stress. The advent of higher strength steels also increases the potential for distortional failures (Schafer 1999, 2002a). The AISI Committee on Specifications has listed distortional buckling in its strategic plan; in many flexural members, left unrestricted, distortional buckling is the expected failure mode.

2. Statement of Work

2.1 *Sections*

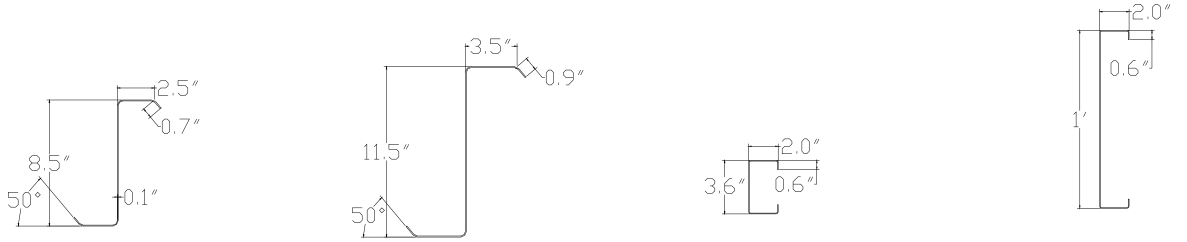
It is proposed to use the same specimen geometry as employed in the Phase 1 studies. For Phase 1 the Zs were provided by an MBMA member company and consisted of standard 8.5 in. (216 mm) and 11.5 in. (292 mm) deep members at several different thicknesses. The Cs were provided by an SSMA member company and consisted of 8 in. (203 mm) deep Cs with 2 in. (51 mm) flanges at several different thicknesses, as well as a set of 3.6 in. (91 mm) to 12 in. (305 mm) deep Cs with 2 in. (51 mm) flanges and constant thickness. A selection of the cross-sections to be tested is summarized in Figure 2 and Table 1.

The members are selected to provide a compromise between testing at the extremes (i.e., variations in h/t, h/b, etc.) while still testing those products that see significant use in current practice. With the panels removed from the compression flange, both local buckling and distortional buckling are free to form. Examination of the ratio of the elastic distortional buckling moment (M_{crD}) to the elastic local buckling moment (M_{crL}) indicates that a large number of members, particularly the Zs, are anticipated to fail in a mechanism dominated by distortional buckling (i.e., $M_{crD}/M_{crL} < 1$). Note even when $M_{crD}/M_{crL} > 1$ distortional buckling may govern because of reduced post-buckling strength in distortional failures (Schafer 1999).

Table 1 Summary of Proposed Specimens for Testing

		h/t		h/b		b/t		d/t		d/b		McrD/McrL	
Tests to be performed	num	min	max	min	max	min	max	min	max	min	max	min	max
Z Study 1: h,b,~d fixed, t varied	7	70.8	144.1	3.4	same	20.8	42.4	8.4	12.6	0.28	0.41	0.52	0.83
Z Study 2: h,b,~d fixed, t varied	5	95.8	157.5	3.3	same	29.2	47.9	8.4	12.6	0.26	0.29	0.61	0.88
C Study 1: h,b,d fixed, t varied	5	82.5	242.4	4.0	same	20.6	60.6	6.4	18.9	0.31	same	0.69	1.79
C Study 2: b,d,t fixed, h varied	5	67.0	222.2	1.8	6.0	37.0	same	11.6	same	0.31	same	0.72	1.27
Additional tests on outliers	6	dimensions to be determined based on test results											
TOTAL	28	67.0	242.4	1.8	6.0	20.6	60.6	6.4	18.9	0.26	0.41	0.52	1.79

h = out-to-out web depth
b = out-to-out flange width
d = out-to-out lip length
r = inside corner radius
t = thickness



(a) 8.5 in. Z (b) 11.5 in. Z (c) Min depth C (d) Max depth C

Figure 2 Typical geometry of C and Z members to be tested

2.2 *Testing*

The four point bending test setup developed in Phase 1 will be used for the Phase 2 testing proposed herein. The only anticipated modification is the removal of the through fastened panel in the constant moment region of the test (Figure 3). The length of the constant moment region was specifically selected to insure that at least 2 distortional buckling half waves could occur in the constant moment region (half-wavelength was predicted by finite strip analysis of the nominal specimens). The Phase 1 testing arrangement is shown in Figure 4 along with a typical failure with the panel in place (Figure 5). Full details of the testing arrangement, development of the testing details, progress reports, pictures, and all other details related to the Phase 1 work can be found at www.ce.jhu.edu/bschafer.

It is proposed, that if a reduced number of tests in each group may be used to establish the distortional buckling lower bound, then the remaining tests will be used to experimentally study the influence of panel stiffness on the behavior. Further, additional fastener details may be investigated as well. These experiments will be used to provide an initial exploration of the influence of partial restraint, and provide data for use in numerical studies.

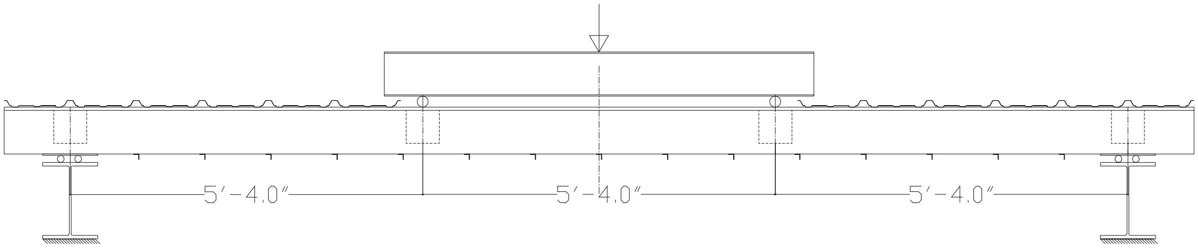


Figure 3 Proposed Test Arrangement

Figure 4 Phase 1 testing setup
(top panel in the constant moment region will be removed and dist. buckling allowed to occur in Phase 2)

Figure 5 Phase 1 failure mode

(top panel in the constant moment region will be removed and dist. buckling allowed to occur in Phase 2)

2.3 Evaluation

The experimental results will be used to directly evaluate the effectiveness of existing and proposed procedures for the bending capacity of laterally braced C and Z members without compression flange support (panel, sheathing, etc.). The following methods will be evaluated:

- North American Specification (AISI 2002)
- Australian/New Zealand Specification (AS/NZS 4600)
- Proposed methods from related Phase 1 work (Schafer and Peköz 1999)
- Direct Strength method (Schafer 2002b)

When appropriate, existing tests may be used to supplement the results of the proposed study in the evaluation phase.

2.4 Analysis

The proposed experimental data is large enough in scope to provide insight on a variety of common members, but like any experiment it is necessarily limited. To augment the experimental data and develop further insight on the role of restraint in bending of C and Z beams with and without attached panels, it is proposed to perform:

- finite strip analysis of all members tested,
- eigenvalue finite element analysis of the complete setup, member + attachments, and
- general nonlinear finite element analysis of the complete setup.

The nonlinear analysis is anticipated to be particularly useful in examining flanges which are partially restrained. The role of discrete fastener spacing and panel stiffness may be readily modified once initial modeling verification is completed. The proposed analysis will only serve to augment the experimental work and large parametric studies are not envisioned as part of this proposal.

2.5 Work Product

Brief progress reports will be provided electronically (email and web page) through the duration of the project. In addition, a written report will be provided every 6 months. A report will be provided upon completion of the project. Upon review and incorporation of comments a final report will be provided. All test data and reports will be made available in electronic format (Excel, Word, PDF files – as appropriate).

The work will include a ballot and an example problem for the suggested method to predict the flexural strength of laterally braced C and Z members with and without through-fastened panels in the compression flange.

3. Impact on Industry

C and Z members are arguably the most common cold-formed steel members in use today. Reliable innovation in cold-formed steel products and applications requires that the ultimate strength of these members be predicted accurately. Current North American Specification procedures only partially account for distortional buckling and ignore local web/flange interaction. Adoption of new methods that account for these effects will obviously provide different strength prediction than current methods. In some cases the new methods will indicate increased capacity – previous work on columns indicates that members with relatively long lips (compared to current practice) and certain h/b ratios will likely be rewarded. In other cases, for example, members without any attachment to the compression flange, a reduction compared to current strength predictions is likely. The author of this proposal submits that a more accurate and robust Specification will in the long-term lead the industry towards better members, even if in the short-term predicted strength in some situations decreases.

4. Schedule

The proposed schedule for this project is for completion twelve months after the required material for the test specimens are obtained. It is anticipated that a task force of interested parties from the AISI Committee on Specification and all funding participants will be assigned to this project. The active participation of this task force will significantly benefit the final outcome.

5. Facilities

Research facilities are located in the Structural Engineering Laboratory at the Department of Civil Engineering, Johns Hopkins University. Hydraulic actuators, hydraulic and screw driven universal testing machines, load cells, extensometers, LVDTs and traditional dial gauges are all available for use. Multi-channel data acquisition systems are available to simultaneously gather strain, load and displacement data during the tests. A machine shop with milling equipment, lathe etc. is available for machining pieces, supports, braces etc. needed in the test setup.

6. Personnel

A graduate student (Cheng Yu, recipient of a 2002 MBMA Fellowship) will be assigned to the project to work under Assistant Professor Ben Schafer. In addition, Jack Spangler, the Civil Engineering Department Technician will be available to help in the experimental setup and measurement systems for the duration of the project. A one page resume of the principal investigator is attached.

7. References

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EDUCATION

Ph.D / M.S.	*Cornell University* (1995–1997) Civil/Structural Eng., Minor: Theoretical and Applied Mech. Thesis: Cold-Formed Steel Behavior and Design: Analytical and Numerical Modeling of Elements and Members with Longitudinal Stiffeners. Advisor: Teoman Peköz
B.S.E.	*University of Iowa* (1989–1993) Civil Engineering

PROFESSIONAL

Senior Engineer	*Simpson Gumpertz & Heger, Inc., Arlington, MA* (1998 – 2000) Eng. Mech. & Infrastructure Division. Failure Investigations, Buried Structures, Seismic Consulting

RESEARCH

Assistant Professor	*The Johns Hopkins University* (2000 – Present) Current Projects: Decision-Theoretic Methodology for Performance-Based Structural Engineering, Completed Projects: Test Verification of the Effect of Stress Gradient on Webs of Cee and Zee Sections, Distortional Buckling of Cold-Formed Steel Columns
Postdoctoral Associate	*Cornell University* (1997–1998) Cold-formed steel members: distortional buckling behavior, torsional behavior, design procedures. Elastic post-buckling frame stability via bar/spring modeling.

TEACHING

Asst. Prof.	*The Johns Hopkins University* (2000-2001) What is Engineering? , Steel Structures, Structural Stability
Instructor	*Cornell University* (1997-1998) Structural Behavior, Modern Structures
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SERVICE & ACTIVITIES

Member	*American Society of Civil Engineers (ASCE)* (1991–Present) *United States Association for Computational Mechanics (USACM)* (1998-Present) *Structural Stability Research Council (SSRC)* (2001–Present)
Committee Work	*American Iron and Steel Institute Committee on Specifications* (AISI-COS) (1995–Present) Member of main committee and subcommittees: 10, 22, 24, 26, 30, 31. *ASCE-SEI Committee on Cold-Formed Steel*, member (1997-2000) Chairmen (2001–Present) *ASCE-SEI Committee on Compression and Flexural Members*, member (2001–Present) *ASCE-EMD Committee on Stability* (2001–Present) *SSRC TG 13, Thin-Walled Metal Construction*, member (2001–Present)

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