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T.R. Higgins Lecture

Gusset Plates: The Evolution of Simplified Design Models

May 6, 2021

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Course Description

Gusset Plates: The Evolution of Simplified Design Models
May 6, 2021

In the design of steel structures, each member is isolated and evaluated using the appropriate AISC *Specification* requirements. Similarly, gusset plate connections can be complex structural systems that are separated into several elements for design purposes. The behavior of these gusset plate elements can be captured with simple design models, where portions of the plate are treated as structural members with well-documented and predictable behavior. This webinar will provide a brief history of gusset plate design methods and their evolution over the last century. It will cover current design provisions where column and beam models are used to predict the strength of gusset plates in various configurations, including wrap-around gusset plates.
The session will wrap up with a preview of a new method to predict the compression strength of gusset plates using notional loads.

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Learning Objectives

- Gain an historical perspective on gusset plate design.
- List current design methods for gusset plates in various configurations.
- Identify recent research developments and new design methods for gusset plates.
- Explain the behavior of gusset plates as it relates to stability, and how stability is ensured through the design methods.

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BO DOWSWELL
PE, PhD

ARC International, LLC

Gusset Plates:
The Evolution of Simplified Design Models

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T.R. HIGGINS LECTURESHIP AWARD

Introduction

INTRODUCTION

Vertical Bracing

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INTRODUCTION

Trusses

11

INTRODUCTION

Horizontal Bracing

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INTRODUCTION

Design Zones

For design, gusset plates are separated into zones that are treated independently.

- Whitmore zone
- Edge interfaces

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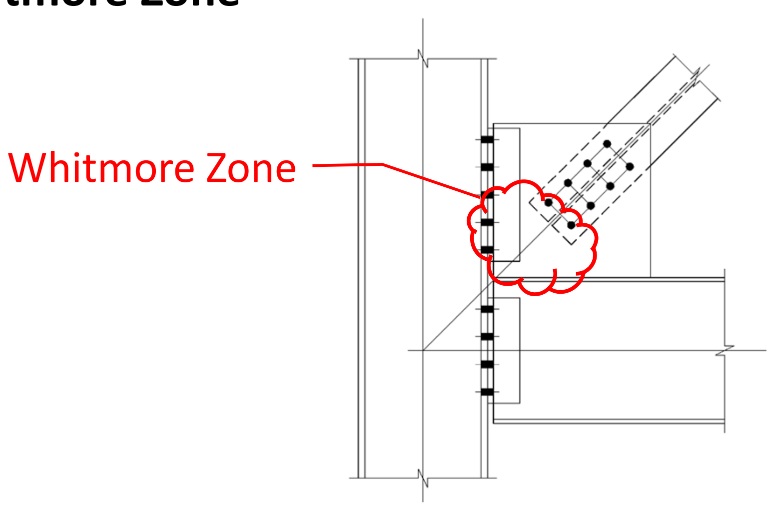
INTRODUCTION

Whitmore Zone



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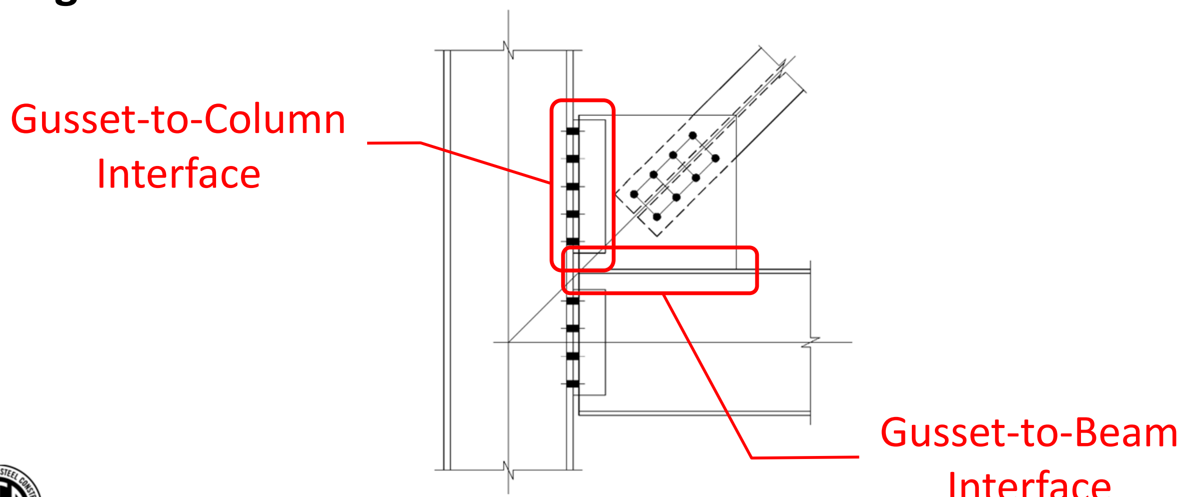
INTRODUCTION

Edge Interfaces



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INTRODUCTION

Presentation Topics

- Design models
- Whitmore zone
- Wrap-around gusset plates

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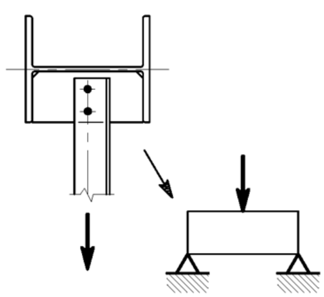
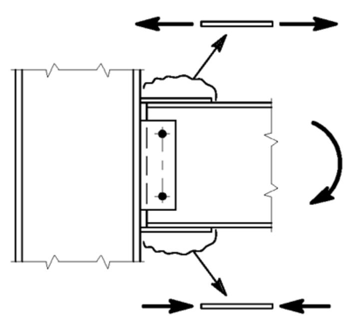
Design Models

DESIGN MODELS

For design, connections are separated into independent elements. Each element is modeled as a member with predictable behavior.



Flexural Elements



Axial Elements

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DESIGN MODELS

The equations in AISC *Specification* Chapters D, E, F, G and H were developed for members.

Can these equations be used for connection elements?

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Design Models

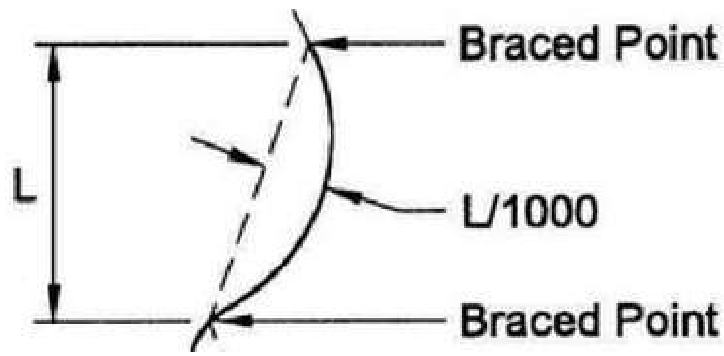
Geometric Imperfections

structural STEEL

DESIGN MODELS: GEOMETRIC IMPERFECTIONS

Member Geometric Imperfections

2016 AISC *Code of Standard Practice* for compression members: out-of-straightness tolerance = $L/1{,}000$



DESIGN MODELS: GEOMETRIC IMPERFECTIONS

Plate Geometric Imperfections

- Plate out-of-flatness ratios are greater than member out-of-straightness ratios
- The ASTM A6 plate tolerance is approximately equivalent to a permissible out-of-flatness of $L/480$
- ASTM A6 is applicable only to manufacturing tolerances and does not address fabrication and erection effects

DESIGN MODELS: GEOMETRIC IMPERFECTIONS

Alan Wood Iron & Steel Company. Philadelphia, PA. (pre-1920)

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Design Models

Buckling

DESIGN MODELS: BUCKLING

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DESIGN MODELS: BUCKLING

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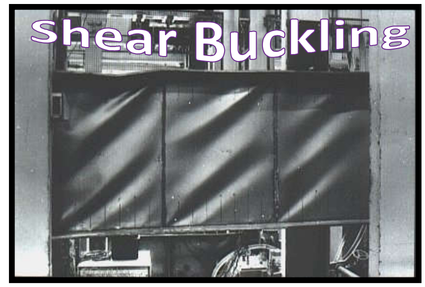
DESIGN MODELS: BUCKLING



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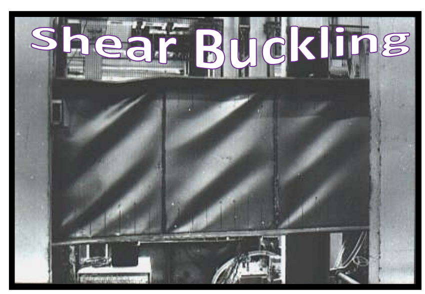
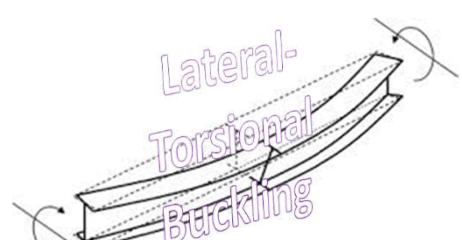
DESIGN MODELS: BUCKLING





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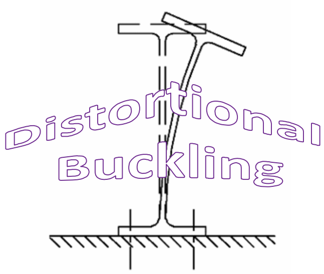
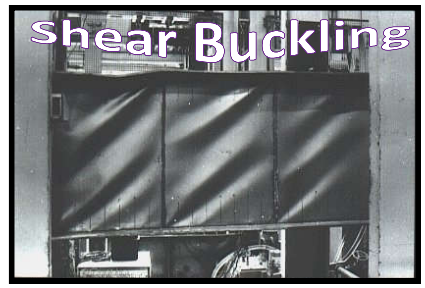
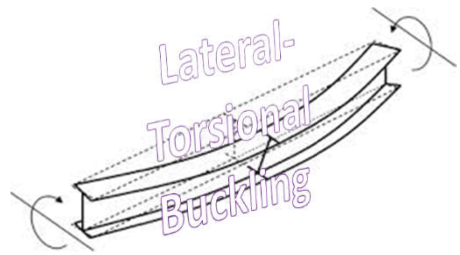
DESIGN MODELS: BUCKLING







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DESIGN MODELS: BUCKLING

Design Model Development

- Identify the primary buckling mode that best fits the buckled shape
- Base the design model on the primary buckling mode
- If needed, consider the effect of secondary buckling modes with empirical factors
- Rectangular connection elements
  - Compression: flexural buckling
  - Flexure: lateral-torsional buckling

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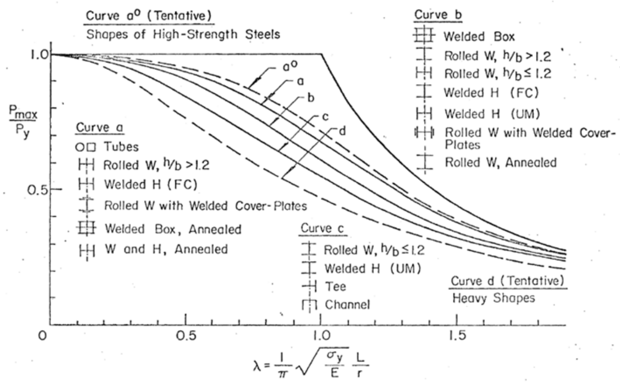
DESIGN MODELS: BUCKLING

Flexural Buckling

The AISC column curve was developed using various shapes

Reidar Bjorhovde [1987]



Bjorhovde, R. (1972), *Deterministic and probabilistic approaches to the strength of steel columns*, Ph.D. dissertation, Lehigh University.

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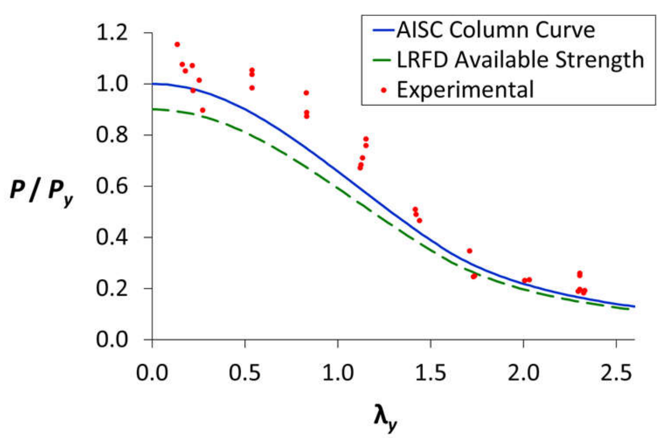
DESIGN MODELS: BUCKLING

Tests on rectangular plate columns compare well with the AISC column curve



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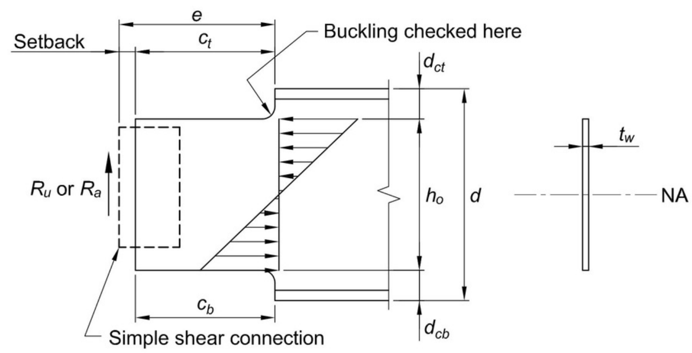
DESIGN MODELS: BUCKLING

Lateral-Torsional Buckling

Cheng et al. (1984) developed design equations for the local strength of double-coped beams by modeling the coped region as a rectangular beam.

Joseph Yura
[1974]



Cheng, J.J., Yura, J.A., and Johnson, C.P. (1984), "Design and Behavior of Coped Beam," Ferguson Lab Report, The University of Texas at Austin.

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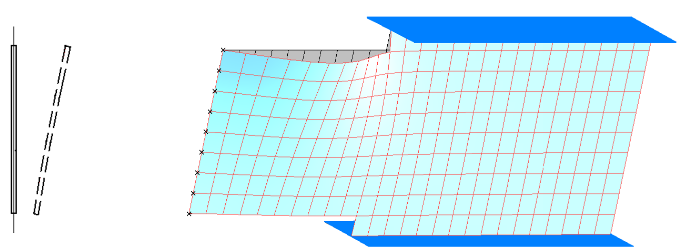
DESIGN MODELS: BUCKLING

The primary buckled shape is characterized by lateral translation and torsional rotation, which is indicative of lateral-torsional buckling.



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Whitmore Zone

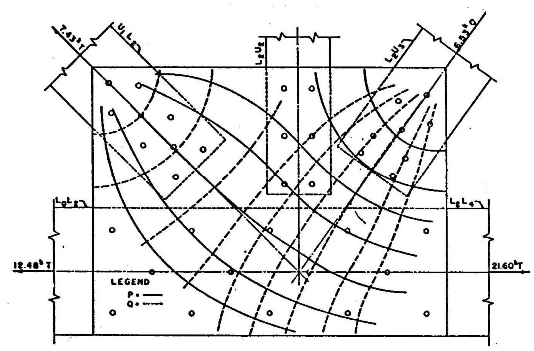
Whitmore Zone

Stress Trajectories

WHITMORE ZONE: STRESS TRAJECTORIES

Whitmore (1952)

- Warren truss joint
- 1/4-scale model
- Experimental/strain gage data
- 1/8 in. thick aluminum plates
- 30° stress trajectory



Whitmore, R.E. (1952), "Experimental Investigation of Stresses in Gusset Plates," University of Tennessee Engineering Experiment Station Bulletin No. 16.

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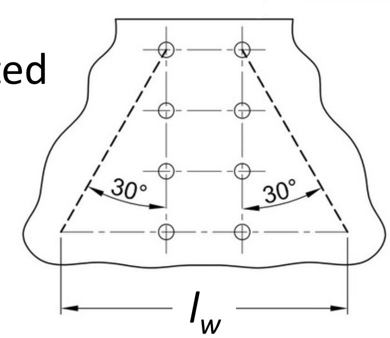
WHITMORE ZONE: STRESS TRAJECTORIES

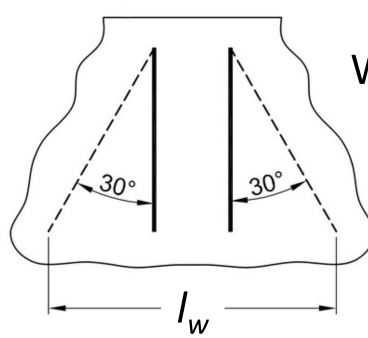
Design: AISC *Manual* Part 9

The effective width, l_w, is based on the Whitmore Section, which is defined by a 30° stress trajectory

Bolted



Welded



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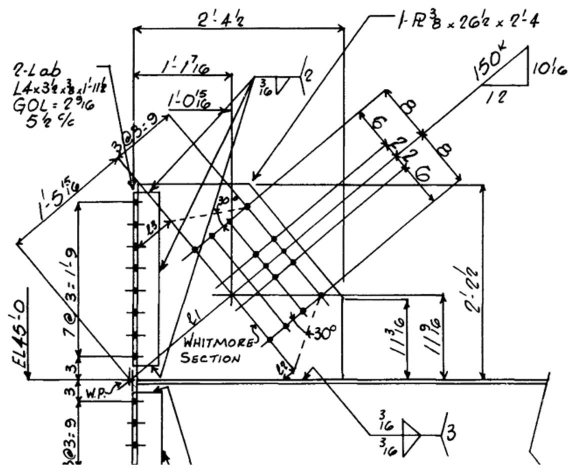
Whitmore Zone

Stability

WHITMORE ZONE: STABILITY

Equivalent Column Model (Thornton, 1984)

- The gusset plate is modeled as a rectangular column
- The column width is defined by the Whitmore Section
- Column curve in AISC *Specification* Section E3



William Thornton [1995]

Thornton, W.A. (1984), "Bracing Connections for Heavy Construction," *Engineering Journal*, AISC.

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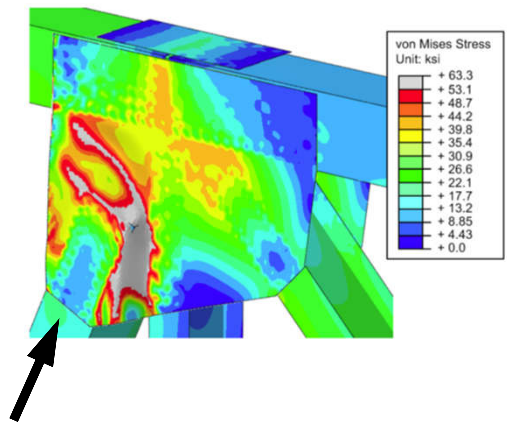
WHITMORE ZONE: STABILITY

White et al. (2013)

- Inelastic FE models
- Yielding at the Whitmore zone

Donald White
[2009]



White, D.W., Leon, R.T., Kim, Y.D., Mentes, Y. and Bhuiyan, M.T.R. (2013), *Finite Element Simulation and Assessment of the Strength Behavior of Riveted and Bolted Gusset-Plate Connections in Steel Truss Bridges*, Final Report Prepared for FHA and NCHRP TRB.

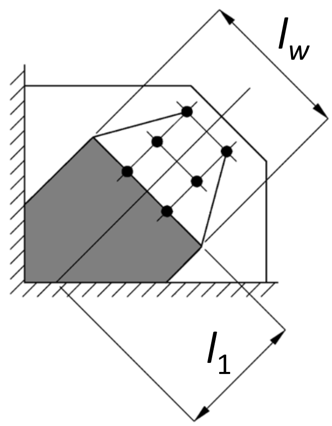
WHITMORE ZONE: STABILITY

Factors Affecting Stability at the Whitmore Zone

- Stress is non-uniform across the Whitmore section
- Frame action forces are neglected
- The Poisson effect is neglected
- The AISC column curve was not developed for plates
- The stress trajectory angle increases with inelastic potential

WHITMORE ZONE: STABILITY

- The out-of-plane restraint provided by the portions of the plate outside the boundaries of the effective width is neglected



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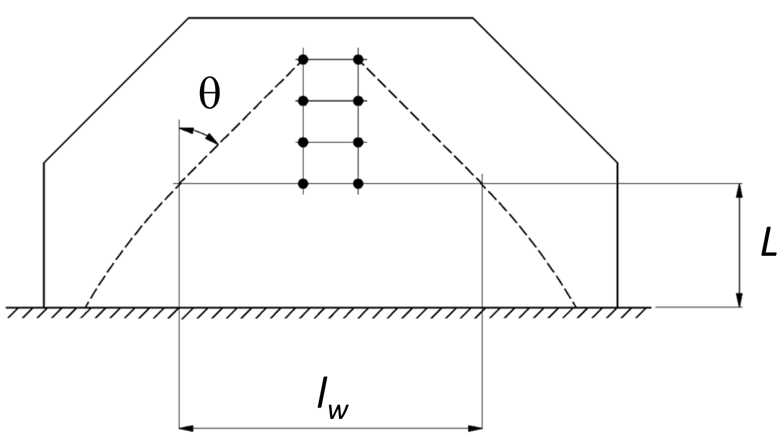
WHITMORE ZONE: STABILITY

- The stress continues to spread out beyond the last fastener



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WHITMORE ZONE: STABILITY

Alan Wood Iron & Steel Company. Philadelphia, PA. (pre-1920)

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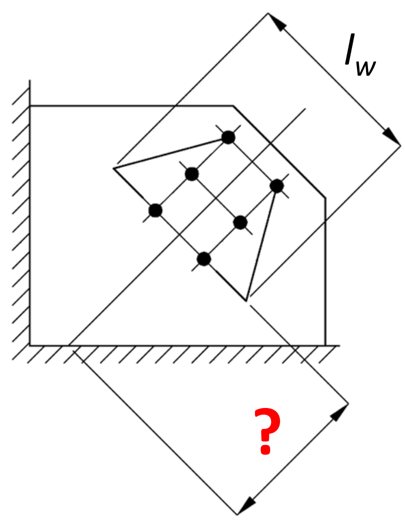
WHITMORE ZONE: STABILITY

Effective Length

$$L_c = KL$$

K = effective length factor = ?

L = unbraced length = ?



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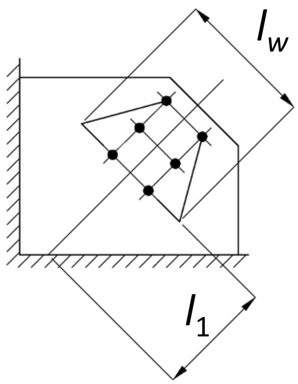
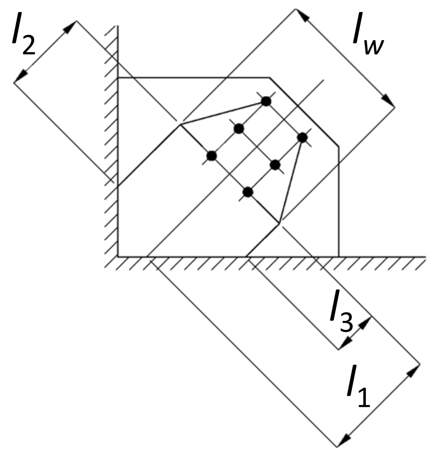
WHITMORE ZONE: STABILITY

Unbraced Length Definitions



$L = l_1$



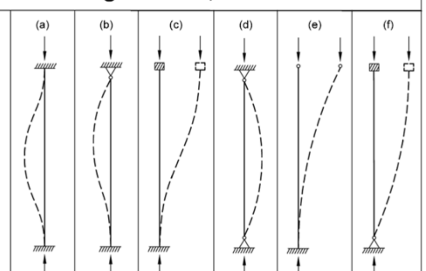
$L = l_{avg} = (l_1 + l_2 + l_3)/3$

WHITMORE ZONE: STABILITY

Effective Length Factors

For columns, effective length factors are selected based on the buckled shape considering the end conditions

TABLE C-A-7.1
Approximate Values of Effective Length Factor, *K*

	(a)	(b)	(c)	(d)	(e)	(f)
Buckled shape of column is shown by dashed line						
Theoretical *K* value	0.5	0.7	1.0	1.0	2.0	2.0
Recommended design value when ideal conditions are approximated	0.65	0.80	1.2	1.0	2.1	2.0
End condition code	Rotation fixed and translation fixed Rotation free and translation fixed Rotation fixed and translation free Rotation free and translation free					

WHITMORE ZONE: STABILITY

For gusset plates, effective length factors are:

- Dependent on the definition of *L*
- Dependent on the gusset plate geometry
- Calibrated with the AISC/AASHTO column curve
- Dependent on ϕ
  - Calibrated to a target reliability index, β, of 4.0 (AISC) or 4.5 (AASHTO)
  - Calibrated at a live-to-dead load ratio, *LL*/*DL*, of 3.0 (AISC) or 6.0 (AASHTO)

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WHITMORE ZONE: STABILITY

For Corner Gusset Plates

Effective lengths				
Reference	***L***	***K***	ϕ	β^a
Thornton (1984)	l_{avg}	0.65	0.85	3.60
Gross and Cheok (1989)	l_{avg}	0.50	0.85	3.18
White et al. (2013)	l_1	0.35	0.75	3.92
AASHTO (2017)	l_1	0.50	0.75	4.76
Current Statistical Analysis	l_1	0.50	0.90	4.01

[a]Based on *LL*/*DL* = 3

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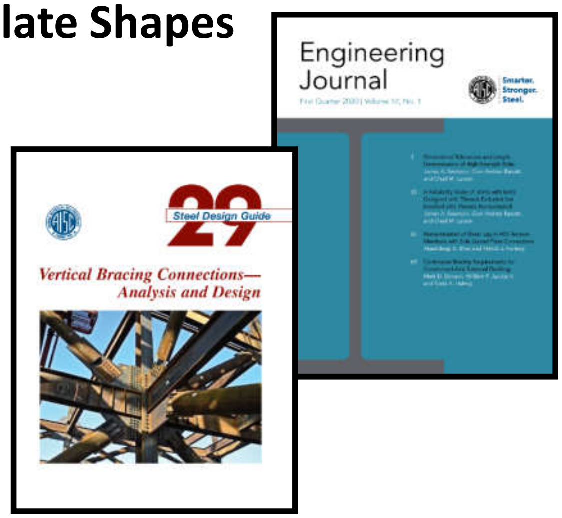
WHITMORE ZONE: STABILITY

For Other Gusset Plate Shapes

Muir and Thornton (2014)

Larry Muir [2014]

William Thornton [1995]



Dowswell (2006, 2012)

Dowswell, B. (2006), "Effective Length Factors for Gusset Plate Buckling," *Engineering Journal*, AISC.
Dowswell, B. (2012), "Effective Length Factors for Chevron Gusset Plates," *Engineering Journal*, AISC.

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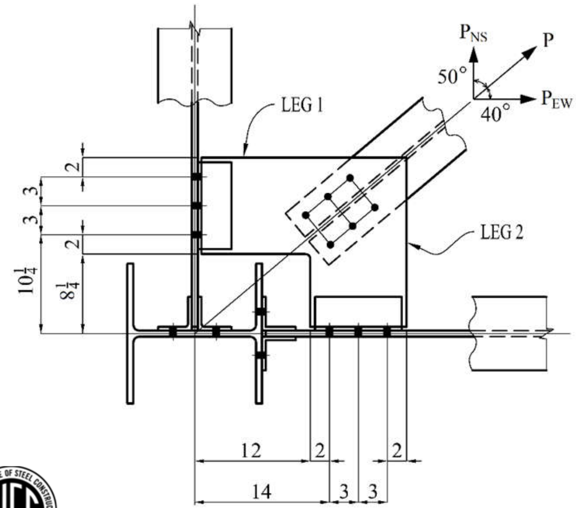
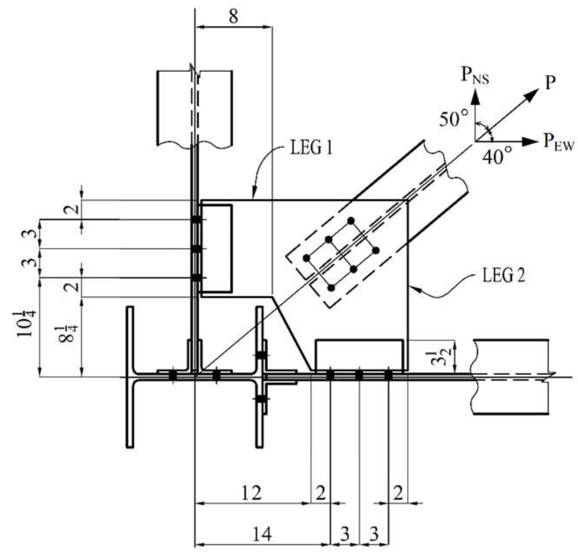
Wrap-Around Gusset Plates

WRAP-AROUND GUSSET PLATES





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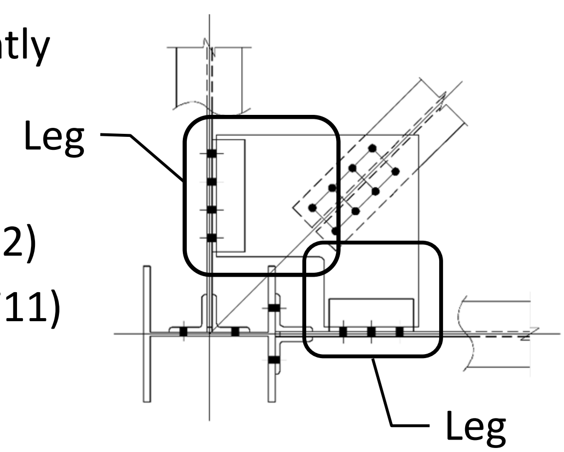
WRAP-AROUND GUSSET PLATES

Design

- Each leg is modeled independently
- Rectangular beam model
- Limit states
  - Shear (AISC *Spec.* Section J4.2)
  - Flexure (AISC *Spec.* Section F11)



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WRAP-AROUND GUSSET PLATES

Required Loads

- Legs are subject to shear and flexure
- Linearly-varying moment diagram
- Maximum moments occur at the reentrant corner

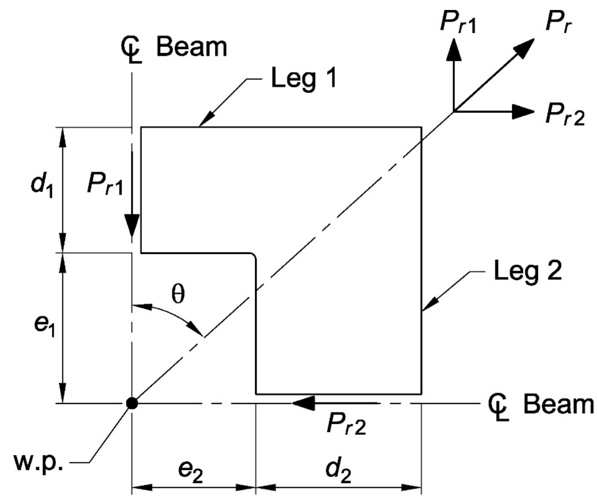

Figure drawn by Eric Bolin

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WRAP-AROUND GUSSET PLATES

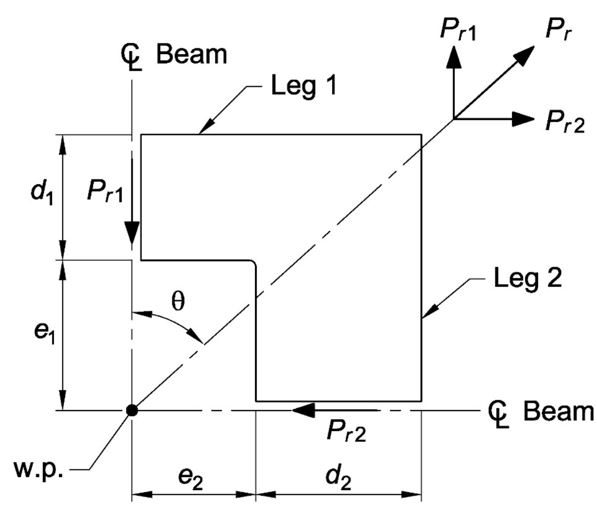
- For Leg 1:

$$M_{r1} = P_{r1}e_2$$

- For Leg 2:

$$M_{r2} = P_{r2}e_1$$

P_{r1}, P_{r2} = force components
e_1, e_2 = cutout dimensions



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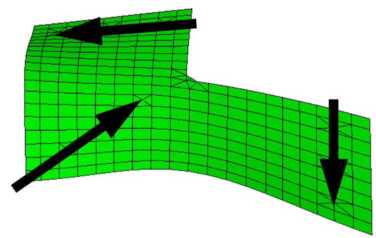
WRAP-AROUND GUSSET PLATES

Stability

The primary buckled shape is characterized by lateral translation and torsional rotation, which is indicative of lateral-torsional buckling.

Design for flexural yielding and lateral-torsional buckling per AISC *Spec.* Section F11.



Specimen 7C

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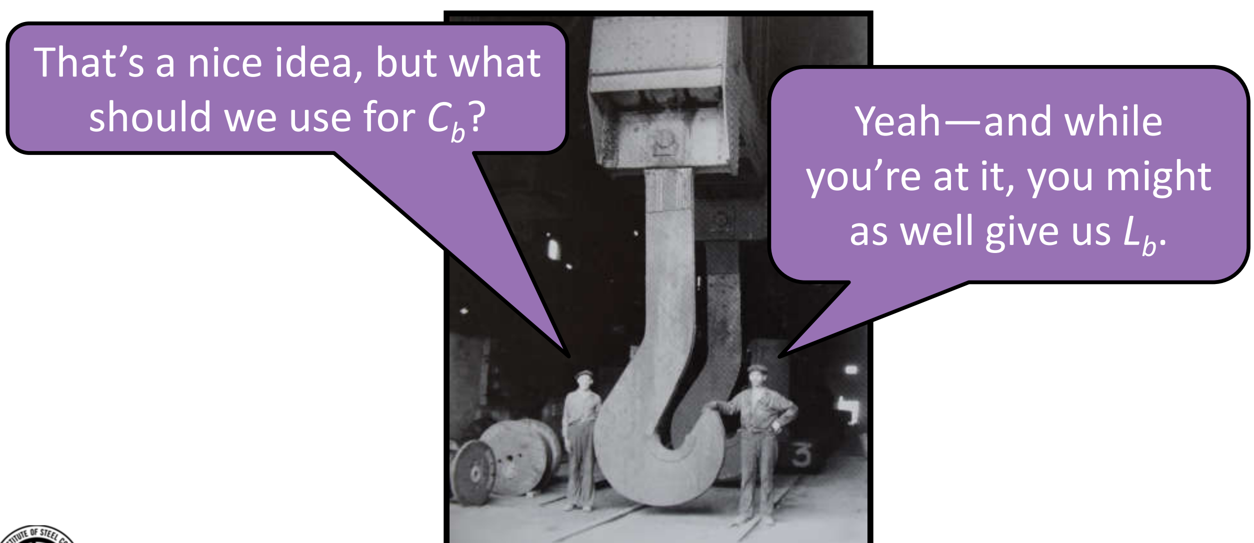
WRAP-AROUND GUSSET PLATES



Otis Steel. Cleveland, OH. H. Grendzinski and Steven Roth

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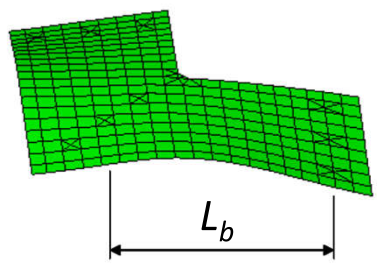
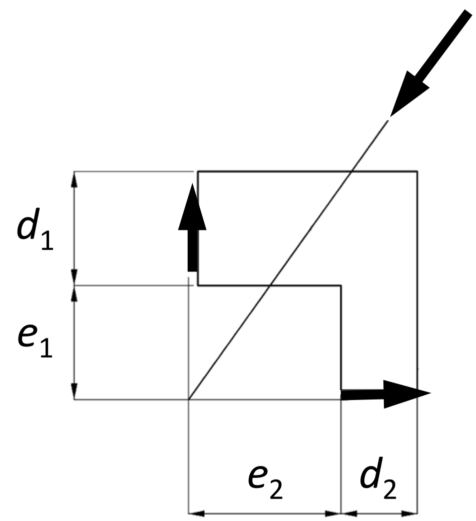
WRAP-AROUND GUSSET PLATES

Brace Compression Loads

$$L_{b1} = e_2 + \frac{d_2}{2} \qquad L_{b2} = e_1 + \frac{d_1}{2}$$

$C_b = 1.00$





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CONCLUSIONS

- Connections can be separated into zones that are designed independently
- Each connection element is modeled as a member with predictable behavior
- Buckling design models for rectangular connection elements are based on the primary buckling mode
  - Compression: flexural buckling
  - Flexure: lateral-torsional buckling

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QUESTIONS?

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