Night School 23: Topics on Industrial Building Design and Design of Non-building Structures

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AISC Night School

Session 8 – Non-building Buildings, Part 2
August 11, 2020

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AISC Live Webinars

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AISC Live Webinars

Course Description

Non-building Structures, Part 2
August 11, 2020

This session will focus on the design of plate structures. Basic geometry, stiffener layouts, design references, loads, details and analysis will be discussed. The session will also look at buckling of cyclindrical shells, flat plates subjected to out-of-plane loads, and review the design of stiffeners.

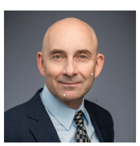
AISC Live Webinars

Learning Objectives

- Identify various plate and shell structures and design resources for each.
- List loads and load considerations for the design of various plate and shell structures.
- Describe the critical limit state of buckling in cylindrical shells.
- List the applicable design considerations for stiffener design of plate and shell structures.

Night School 23: Industrial Structures

Session 8 – Non-building Structures, Part 2
August 11, 2020



Bo Dowswell, P.E., PhD, Arc International LLC

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Plate and Shell Structures

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Plate and Shell Structures

- Introduction
- Loads
- Buckling of cylindrical shells
- Analysis
- Stiffener design

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Plate and Shell Structures

Introduction

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Introduction

Structure Type Identified by Function

- Fluid storage: tanks
- Bulk solids storage/handling: silos, bins, hoppers, chutes, stacking tubes
- Gas transport/modification: stacks, ducts, pollution control equipment
- Support structures: tubular conveyor galleries, sign structures, wind turbines

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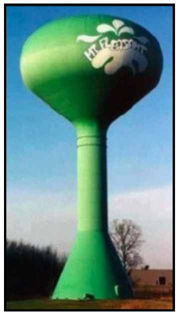
Introduction

Tanks



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Introduction

Silos, Bins, Hoppers

14

Introduction

- Gaylord, E.H. and Gaylord, C.N. (1984), *Design of Steel Bins for Storage of Bulk Solids*, Prentice-Hall.
- Rotter, J.M. (2001), *Guide for the Economic Design of Circular Metal Silos*, Spon Press.
- CEN (2007), *Silos*, Eurocode 3, Design of Steel Structures, Part 4-1, EN 1993-4-1, European Committee for Standardization.
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Introduction

Stacks

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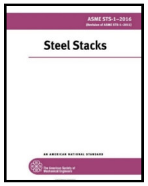

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Introduction

Industrial Ducts

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Introduction

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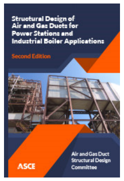

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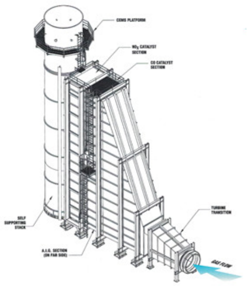
Introduction

Pollution Control Equipment



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Introduction

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Introduction

Tubular Conveyor Galleries

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Introduction

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- Troitsky, M.S. (1982), "Tubular Conveyor Galleries," *Engineering Structures*, Vol. 4, No. 2.

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Plate and Shell Structures

Loads

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Loads

General

- Wind
- Seismic
- Dead
- Live
- Maintenance loads

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Loads

Tanks

- Fluid pressure

Stacks

- Vortex shedding vibrations perpendicular to the wind direction
- Ovalizing wind vibrations

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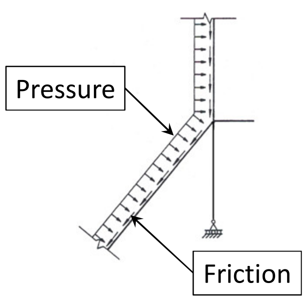
Loads

Bulk Solids Storage

- Material pressure
- Material friction
- Dynamic impact
- Material expansion



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Loads

Chutes

- Material pressure
- Material friction
- Dynamic impact

Tubular Conveyor Galleries

- Belt pull force during operation, startup and shutdown
- Thermal load

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Loads

Industrial Ducts

- Pressure
- Thermal load caused by gas temperature
- Ash/dust weight

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Plate and Shell Structures

Buckling of Cylindrical Shells

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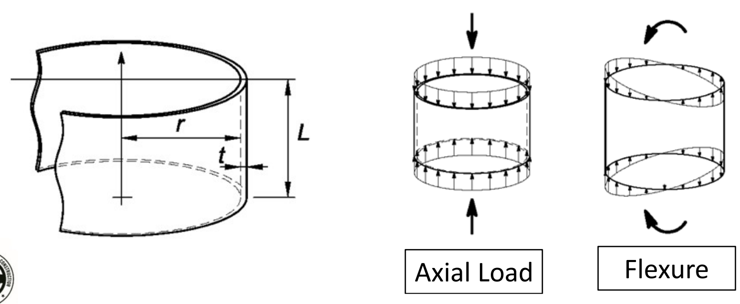
Buckling of Cylindrical Shells

Buckling is the critical limit state of cylindrical shells with high *r*/*t* ratios subjected to compressive membrane stresses.



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Buckling of Cylindrical Shells

Behrooz, F.T., Omidi, M. and Shokrieh, M.M. (2017), "Experimental and Numerical Investigation of Buckling Behavior of Composite Cylinders with Cutout," *Thin-Walled Structures*, Vol. 116.

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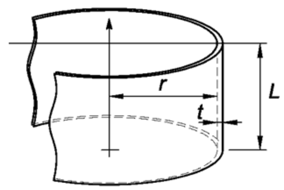
Buckling of Cylindrical Shells

The theoretical buckling stress (classical elastic critical stress) of a perfect cylindrical shell subjected longitudinal compression is

$$\sigma_{cl} = \frac{E}{\sqrt{3\left(1-\nu^2\right)}}\frac{t}{r} = 0.605E\frac{t}{r}$$



E = modulus of elasticity

r = radius

t = thickness

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Buckling of Cylindrical Shells

Capacity reduction (knockdown) factors must be applied to the critical stress to address these effects:

- Geometric imperfections
- Inelasticity
- Interaction of buckling modes

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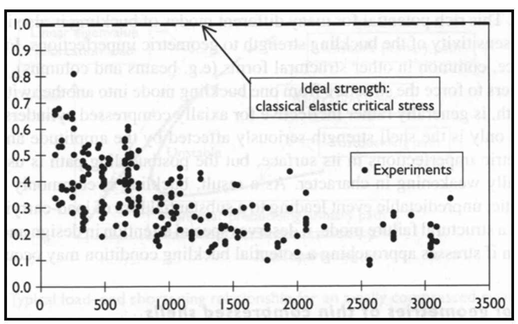
Buckling of Cylindrical Shells

Buckling Stress Ratio, σ_l/σ_{cl}



r/t

Teng, J.G. and Rotter, J.M. (2004), Buckling of Thin Metal Shells, Spon Press.

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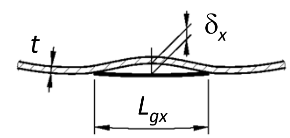
Buckling of Cylindrical Shells

Geometric Imperfections

- Knockdown factors are have been developed for various types of structures with different levels of fabrication quality
- The document that was used to calculate the buckling strength should also be used to determine the tolerances



Geometric Imperfection Tolerance

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Buckling of Cylindrical Shells

Further Information:

- API (2004a), *Bulletin on Stability Design of Cylindrical Shells*, API Bulletin 2U, Third Edition, American Petroleum Institute, June.
- ASME Code Cases N-284 and N-530 (and others)
- CEN (2007), *Strength and Stability of Shell Structures*, Eurocode 3, Design of Steel Structures, Part 1-6, EN 1993-1-6, European Committee for Standardization.

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Buckling of Cylindrical Shells

- Ziemian, R.D. (2010), *Guide to Stability Design Criteria for Metal Structures*, Sixth Edition, John Wiley & Sons.
- ECCS (2008), *Buckling Strength of Steel Shells-European Design Recommendations*, 5th Edition, European Convention for Constructional Steelwork.
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Plate and Shell Structures

Analysis

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Analysis

AISC *Specification* Section A1

The *Specification* applies to "…structural steel buildings and other structures, where other structures are defined as structures designed, fabricated and erected in a manner similar to buildings, with building-like vertical and lateral load resisting elements."

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Analysis

The available strengths in the AISC *Specification* were not developed to be compared to the results from finite element models built with plate, shell or solid elements.

The safety factors (ASD) and resistance factors (LRFD) were calibrated to provide a specific target reliability when compared with required loads calculated using truss and beam elements in the structural analysis model.

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Analysis

The analysis of plate and shell structures can be performed with finite element models, equations or a combination of the two methods.

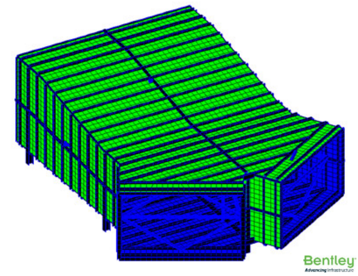

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Plate and Shell Structures

Analysis

Finite Element Models

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Finite Element Models

Generally, three methods are used to model plate and shell structures:

1. Coarse mesh
   - Large plate elements are used to distribute the applied loads to the stiffeners and supports
   - Stiffeners can be designed within the software
   - Plate stresses are not required to be accurate because the plates are designed manually

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Finite Element Models

2. Fine mesh
   - Mesh refinement is required for accurate plate stresses
   - Required plate stresses are determined within the software
   - Available plate stresses are calculated manually
   - For further information, see API (2004b) and Spyrakos (1994)
3. Advanced analysis
   - The strength is determined within the software
   - For further information, see CEN (2007) and ECCS (2008)

API (2004b), *Design of Flat Plate Structures*, API Bulletin 2V, Third Edition, American Petroleum Institute, June.
Spyrakos, C.C. (1994), *Finite Element Modeling in Engineering Practice*, Algor, Inc. Publishing Division.

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Finite Element Models

Stiffeners are usually modeled with offset beam elements. This modeling technique captures the stiffener moment caused by loads that are applied in the plane of the plate (for example, thermal expansion/contraction).

- The offset is the distance from the plate centerline to the stiffener centroid
- The offset can be modeled with rigid links or an "offset" command in the software

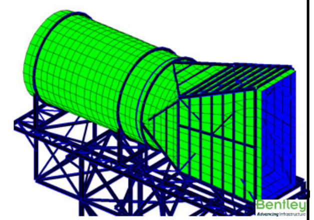

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Plate and Shell Structures

Analysis

Plate/Shell Stresses

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Plate/Shell Stresses

- Stress concentrations and end effects can cause high local stresses in plate/shell finite element models
- "It is not necessary to evaluate every location just because stresses are computed there. It is important for the analyst to focus on the failure locations based on the flow of the loads and the stress magnitudes" (Hollinger and Hechmer, 2000)
- An appropriate design model will allow higher stresses in areas when the strength is not compromised

Hollinger, G. and Hechmer, J. (2000), "Three-Dimensional Stress Criteria—Summary of the PVRC Project," *Journal of Pressure Vessel Technology*, American Society of Mechanical Engineers, Vol. 122, February, pp. 105-109.

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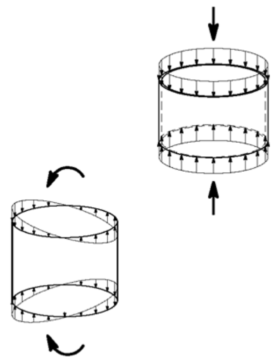
Plate/Shell Stresses

Membrane Stress

Normal stress that is uniformly distributed across the plate thickness

- Remote from discontinuities
- Example: global bending and axial stresses in a cylindrical structure



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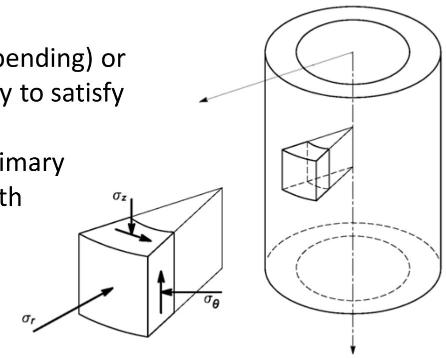
Plate/Shell Stresses

Primary Stress

Any normal (membrane or bending) or shear stress that is necessary to satisfy the laws of equilibrium

- Results in failure if the primary stress exceeds the strength
- Not self-limiting



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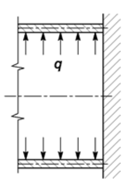
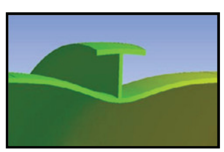
Plate/Shell Stresses

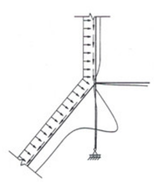
Secondary Stress

A stress caused by constraint.

- Minor distortion caused by local yielding and relieve the stresses without failure
- Self-limiting







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Plate/Shell Stresses

Local Primary Membrane Stress

Membrane stress at a discontinuity such as an opening or a support.

- Local yielding causes a redistribution of stresses to adjacent parts of the structure
- Excessive distortion can limit proper stress redistribution
- A stressed region can be considered local for a distance is equal to or less than l_s

$$l_s = \sqrt{rt}$$

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Plate/Shell Stresses

Peak Stress

Sum of primary and secondary stresses

- Caused by stress concentrations at local discontinuities
- Causes only minor distortions
- Considered only as a potential source of fatigue cracking or brittle failure

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Plate/Shell Stresses

Allowable Plate/Shell Stresses

- Primary membrane stress: F_c
- Primary normal stress (membrane plus bending): $1.5F_c$
- Local primary membrane stress: $1.5F_c$
- Peak stress: $3F_c$

F_c = available stress

ASME *Boiler and Pressure Vessel Code*, American Society of Mechanical Engineers.

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Plate/Shell Stresses

For tension stresses, F_c is the minimum of the available yield strength, F_{cy}, and the available rupture strength, F_{cu}.

$F_{cy} = \phi_y F_y$ (LRFD), F_y/Ω_y (ASD)

$F_{cu} = \phi_u F_u$ (LRFD), F_u/Ω_u (ASD)

For compressive primary membrane stresses, F_c is the available buckling strength from the appropriate code/document.

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Plate and Shell Structures

Analysis

Combined Models

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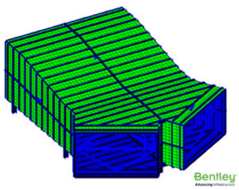
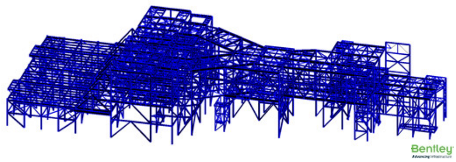
Combined Models

For elevated plate structures that are supported by steel structures, separate finite element models are usually developed for each structure. Deformation compatibility between the two models is an important design consideration.





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Combined Models

Generally, two methods are used to model the interface between the plate structure and the support structure.

- Separate models, where the support loads from the plate/shell structures are added to the support structure
- Combined models, where the plate/shell models are imported into the support-structure model

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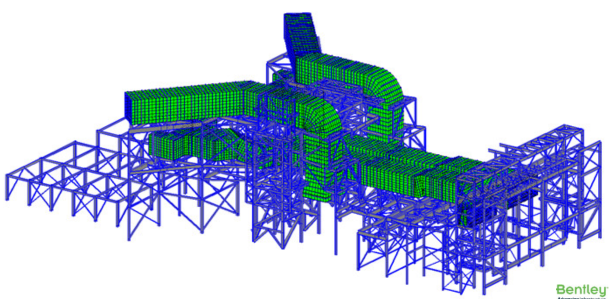
Combined Models

Combined models often reveal support loads that are significantly different from the separate models.



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Combined Models

The accuracy of separate models can be increased by using spring supports in the plate/shell model based on the stiffness of the support-structure model.

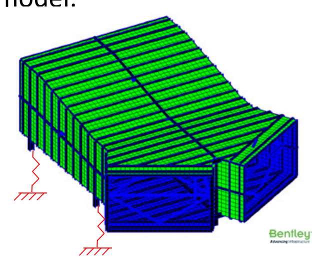

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Plate and Shell Structures

Stiffener Design

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Stiffener Design

Flat-Plate Stiffeners

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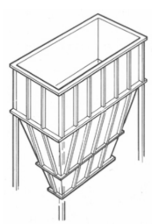
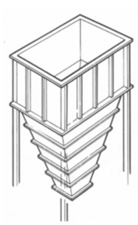
Stiffener Design

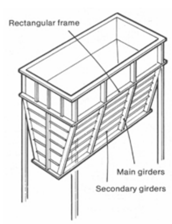
Rectangular Hopper Stiffeners



Vertical stiffeners



Horizontal stiffeners



Two-way stiffeners

AWRA (1984), *Design and Construction of Welded Steel Bins*, AWRA Technical Note 14, Australian Welding Research Association.

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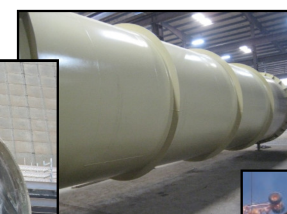
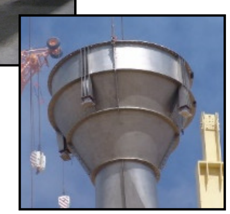
Stiffener Design

Ring Stiffeners





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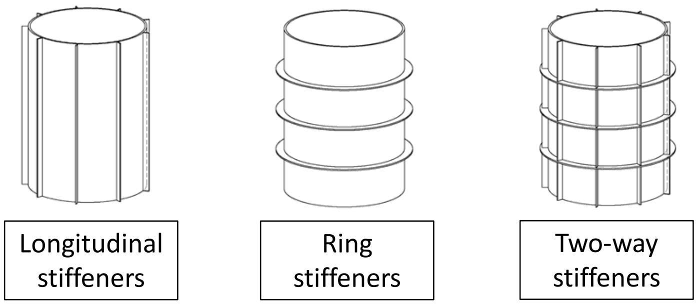
Stiffener Design

Shell Stiffeners



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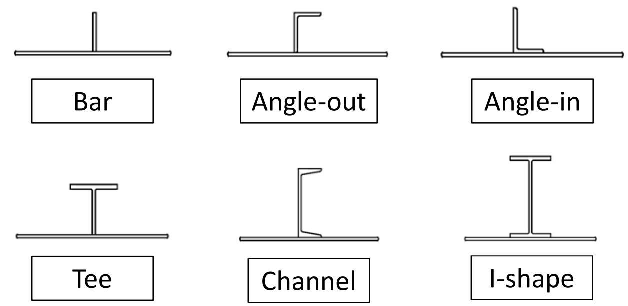
Stiffener Design

Common Shapes



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Stiffener Design

AISC *Specification* Section A1

The *Specification* applies to "…structural steel buildings and other structures, where other structures are defined as structures designed, fabricated and erected in a manner similar to buildings, with building-like vertical and lateral load resisting elements." Therefore, the AISC *Specification* is not applicable to stiffener design in plate and shell structures.

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Plate and Shell Structures

Stiffener Design

Effective Plate Width

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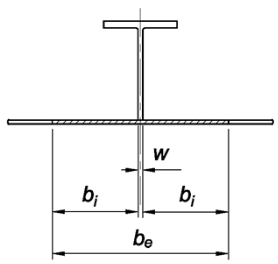
Effective Plate Width

A portion of the plate can be assumed to act compositely with the stiffener, increasing the sectional properties.



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Effective Plate Width

The effective width is dependent on:

- For stiffeners subjected to flexure, the effective width can be limited by shear lag
- When the attached plate is subjected to axial or flexural compression, the effective can be limited by local buckling
- For stiffeners subjected to flexural compression, the smallest of the two limits for shear lag and local buckling is applicable

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Effective Plate Width

Design Values

- A wide range of effective width equations are available with varying degrees of complexity
- The effective width used in design varies, depending on the applicable design document

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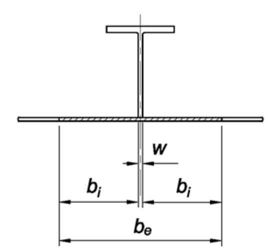
Effective Plate Width

Simple Design Guidelines

- ASME STS-1-2016: $b_e = 16t$
- Blodgett (1966): $b_e = 24t$
- Bleich (1952): $b_e = 30t$
- NAAMM (1992): $b_e = 32t$
- Lambert (1968): $b_e = 40t$



Blodgett, O.W. (1966), *Design of Welded Structures*, The James F. Lincoln Arc Welding Foundation.
Lambert, F.W. (1968), *The Theory and Practical Design of Bunkers*, The British Constructional Steelwork Association.
NAAMM (1992), *Metal Stairs Manual*, AMP 510-92, National Association of Architectural Metal Manufacturers.

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Plate and Shell Structures

Stiffener Design

Effective Plate Width: Shear Lag

Effective Plate Width: Shear Lag

When limited by shear lag, the effective width is dependent on the length between flexural inflection points.

- For flat-plate stiffeners, the effective width is dependent on the span and the shape of the moment diagram
- For ring-stiffeners, the effective width is dependent on the radius of curvature and the bending mode

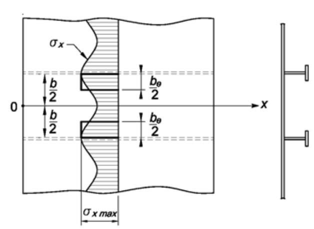
Effective Plate Width: Shear Lag

For flat-plate stiffeners and longitudinal stiffeners at cylindrical shells (AISC *Specification* Section I3.1a; Bleich, 1952; CEN, 2006):

b_e = Span/4 $\leq b$

b = stiffener spacing

b_e = effective width



Bleich, F. (1952), *Buckling Strength of Metal Structures*, McGraw-Hill.
CEN (2006), *Design of Steel Structures-Part 1-5: Plated Structural Elements*, EN1993-1-5, European Committee for Standardization.

Effective Plate Width: Shear Lag

More accurate methods for flat-plate stiffeners are in API (2004), Paik and Thayamballi (2003) and Heins (1976)

API (2004), *Design of Flat Plate Structures*, Bulletin 2V, Third Edition, American Petroleum Institute, June.
Heins, C.P. (1976), *Applied Plate Theory for the Engineer*, Lexington Books.
Paik, J.K. and Thayamballi, A.K. (2003), *Ultimate Limit State Design of Steel-Plated Structures*, John Wiley & Sons.

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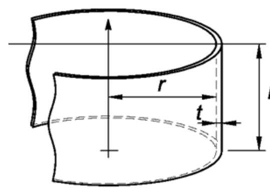
Effective Plate Width: Shear Lag

For ring stiffeners

$$b_e = 1.56\sqrt{rt}$$

r = radius

t = thickness



At cone-cylinder junctions and splices with different plate thicknesses, see Rotter (2001).

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Plate and Shell Structures

Stiffener Design

Effective Plate Width: Local Buckling

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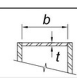
Effective Plate Width: Local Buckling

Case 8 in AISC *Specification* Table B4.1a is conservative for flat-plate stiffeners.

TABLE B4.1a
Width-to-Thickness Ratios: Compression Elements
Members Subject to Axial Compression

Case	Description of Element	Width-to-Thickness Ratio	Limiting Width-to-Thickness Ratio λ_r (nonslender/slender)	Examples
8	All other stiffened elements	b/t	$1.49\sqrt{\frac{E}{F_y}}$	

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Effective Plate Width: Local Buckling

Using Case 8, solve for b to determine the effective width

$$b_e = 1.49t\sqrt{\frac{E}{F_y}}$$

t = plate thickness

E = modulus of elasticity

F_y = specified minimum yield stress

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Effective Plate Width: Local Buckling

A more accurate method uses AISC *Specification* Section E7 with k = 4.0 in the classical plate buckling equation, resulting in an elastic buckling stress of

$$F_{el} = k\frac{\pi^2 E}{12\left(1-\nu^2\right)\left(b/t\right)^2} = 3.62E\left(\frac{t}{b}\right)^2$$

In this case, the limiting width-to-thickness ratio is $\lambda_r = 1.90\sqrt{\frac{E}{F_y}}$

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Effective Plate Width: Local Buckling

Using C_1 = 0.22 in *Specification* Eqn. E7-3, the effective width is

When $\lambda \le \lambda_r\sqrt{\frac{F_y}{F_{cr}}}$ $\quad b_e = b$

When $\lambda > \lambda_r\sqrt{\frac{F_y}{F_{cr}}}$ $\quad b_e = 1.9t\sqrt{\frac{E}{F_{cr}}}\left(1-0.42\frac{t}{b}\sqrt{\frac{E}{F_{cr}}}\right)$

F_{cr} = critical stress for global buckling of the stiffener. F_{cr} can also be defined as the compression stress in the plate, or conservatively, F_y can be used.

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Plate and Shell Structures

Stiffener Design

Global Buckling

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Global Buckling

Generally, the strength of stiffeners can be calculated according to AISC *Specification* Chapters E, F and H for stiffeners subjected to axial compression and flexure.

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Plate and Shell Structures

Stiffener Design

Global Buckling: Flat-Plate Stiffeners

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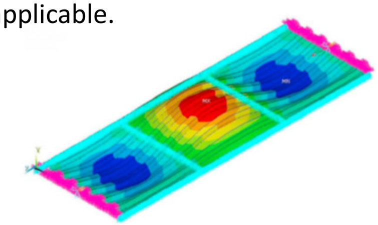
Global Buckling: Flat-Plate Stiffeners

Out-of-Plane (Flexural) Buckling

For out-of-plane buckling of stiffeners subjected to axial compression, the flexural buckling equations in AISC *Specification* Section E3 are applicable.



Haffar, M.Z., Kovesdi, B. and Adany, S. (2019), "On the Buckling of Longitudinally Stiffened Plates, Part 2: Eurocode-Based Design for Plate-Like Behavior of Plates with Closed-Section Stiffeners," *Thin-Walled Structures*, Vol. 145.

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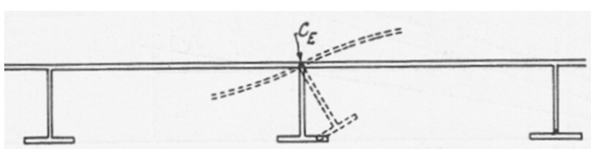
Global Buckling: Flat-Plate Stiffeners

Stiffener Tripping

For stiffeners subjected to axial compression, the plate restrains flexural buckling in the plane of the plate. However, constrained-axis buckling can occur, where the stiffener buckles about an enforced axis of rotation.

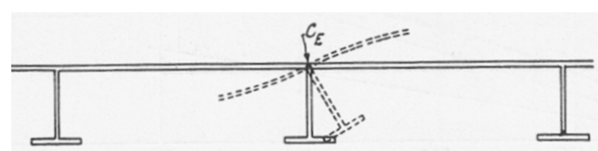


Bleich, F. (1952), *Buckling Strength of Metal Structures*, McGraw-Hill.

87

Global Buckling: Flat-Plate Stiffeners

- Plate axial resistance restrains translation
- Plate flexural resistance partially restrains torsional rotational of the stiffener



Bleich, F. (1952), *Buckling Strength of Metal Structures*, McGraw-Hill.

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Global Buckling: Flat-Plate Stiffeners

There are several ways to design for in-plane buckling:

1. Neglect the bracing provided by the plate.
2. Assume the plate restrains only lateral translation. In this case, the limit state will be constrained-axis buckling, which is discussed on Slides 44-50 of Session 3.
3. Design the member using the plate for both lateral and torsional stability bracing. In this case, AISC *Specification* Section F12 is applicable, where F_{cr} is determined by analysis (finite element buckling analysis or calculations)

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Global Buckling: Flat-Plate Stiffeners

For further information on stiffener tripping, refer to:

- API (2004), *Design of Flat Plate Structures*, Bulletin 2V, Third Edition, American Petroleum Institute, June.
- ABS (2004), *Guide for Buckling and Ultimate Strength Assessment for Offshore Structures*, American Bureau of Shipping, April.
- Bleich, F. (1952), *Buckling Strength of Metal Structures*, McGraw-Hill.

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Global Buckling: Flat-Plate Stiffeners

Stiffeners Subjected to Flexure

For stiffeners subjected to flexure, the lateral-torsional buckling equations in AISC *Specification* Chapter F are applicable.

- Plate axial resistance restrains translation
- Plate flexural resistance partially restrains torsional rotational of the stiffener

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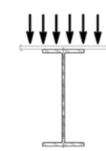
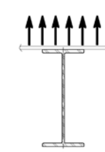
Global Buckling: Flat-Plate Stiffeners

Conservative design assumptions:

- Full bracing when the connected flange is subjected to compression



- No bracing when the non-connected flange is subjected to compression



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Global Buckling: Flat-Plate Stiffeners

For I-shaped stiffeners with continuous lateral bracing at the tension flange subjected to a uniform suction load, C_b can be calculated according to AISC *Specification* Section F1 Commentary Figure C-F1.5.

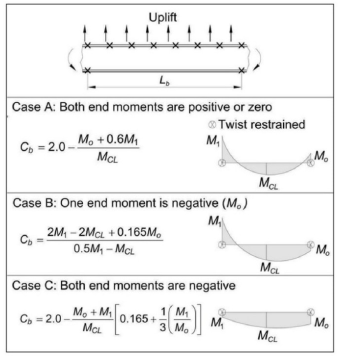

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Plate and Shell Structures

Stiffener Design

Global Buckling: Ring Stiffeners

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Global Buckling: Ring Stiffeners

AISC Design Guide 33 can be used to design curved members as equivalent straight members.

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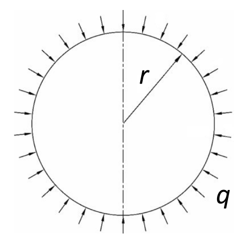
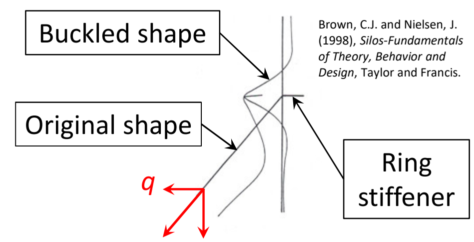
Global Buckling: Ring Stiffeners

In-plane buckling of a ring stiffener at a silo cone-cylinder junction





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Global Buckling: Ring Stiffeners

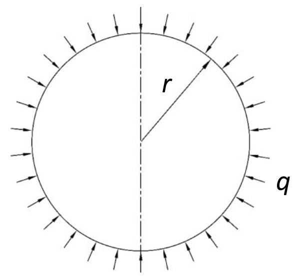
For ring stiffeners subjected to a uniform line load, *q*, the critical buckling load for in-plane buckling is

$$q_{cr} = \frac{3EI_i}{r^3}$$

E = modulus of elasticity

I_i = in-plane moment of inertia

r = centroidal radius



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Global Buckling: Ring Stiffeners

- To account for geometric and material imperfections, the stiffener can be designed as an equivalent straight column
- The flexural buckling provisions in AISC *Specification* Section E3 can be used with a modified effective length, L_c
- The required axial load in the equivalent column is $P_r = qr$
- L_c is determined by setting the elastic column-buckling load ($\pi^2 EI/L_c^2$) equal to the ring-buckling load

$$L_c = \frac{\pi r}{\sqrt{3}} = 1.81r$$

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Plate and Shell Structures

Conclusions

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Conclusions

- Design loads should be calculated with the best available code or document
- For cylindrical shells, the buckling strength is dependent on the geometric imperfection tolerances
- For plate elements, the maximum mesh size is dependent on the required accuracy of the stresses
- Flat-plate stiffeners are typically designed with the provisions in the AISC *Specification*
- Ring stiffeners can be designed with AISC Design Guide 33

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Session 8
the End

Thank you!

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Quiz 8 Issued: August 13
Final Exam Issued: August 18
Deadline for Quiz 8 and Final Exam: September 8
Certificates Issued: September 11

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Access to the quiz

Information for accessing the quiz will be emailed to you by Thursday. It will contain a link to access the quiz. EMAIL COMES FROM NIGHTSCHOOL@AISC.ORG.

Quiz and attendance records

Posted Thursday mornings. www.aisc.org/nightschool -- Click on Current Course Details.

Reasons for quiz

- EEU – You must take all quizzes and the final exam to receive EEU.
- PDHs – If you watch a recorded session, you must pass quiz for PDHs.
- REINFORCEMENT – Reinforce what you learn tonight. Get more out of the course.

Note: If you attend the live presentation, you do not have to take the quizzes to receive PDHs

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Night School Resources

Find all your handouts, quizzes and quiz scores, recording access, and attendance information all in one place!

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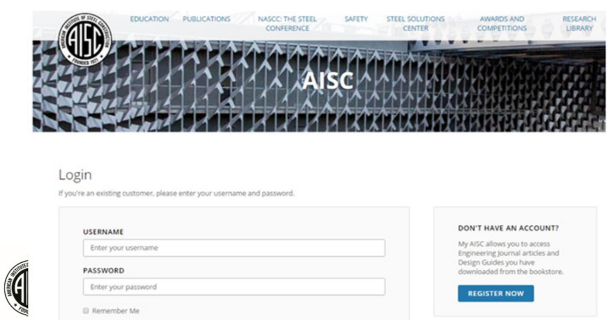

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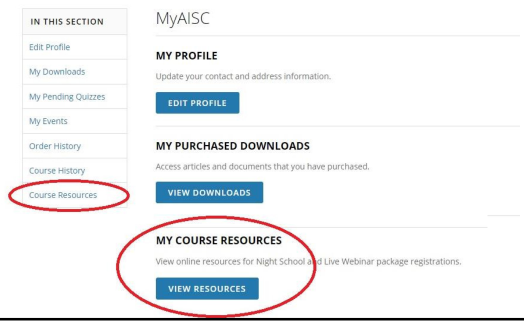

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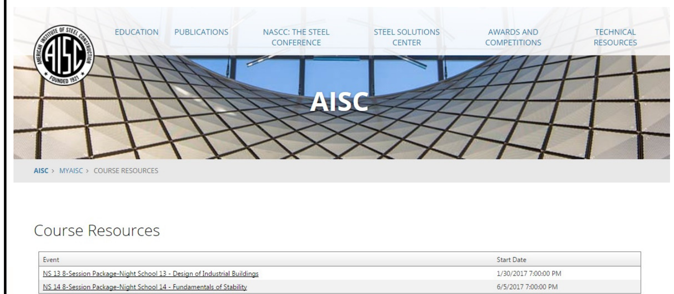

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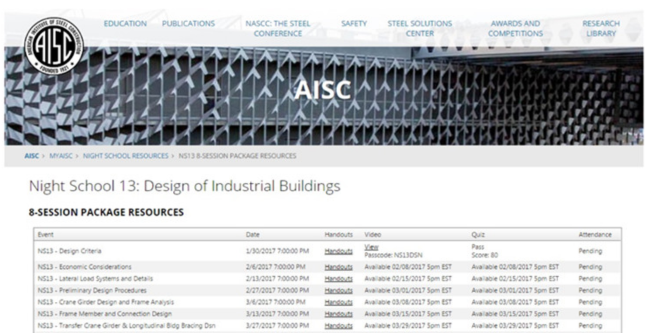

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Night School Resources

- Weekly "quiz and recording" email.
- Weekly updates of the master quiz and attendance record, found at www.aisc.org/nightschool23. Scroll down to Quiz and Attendance records.
  - Updated on Thursday mornings.

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Night School Resources

- Webinar connection information
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