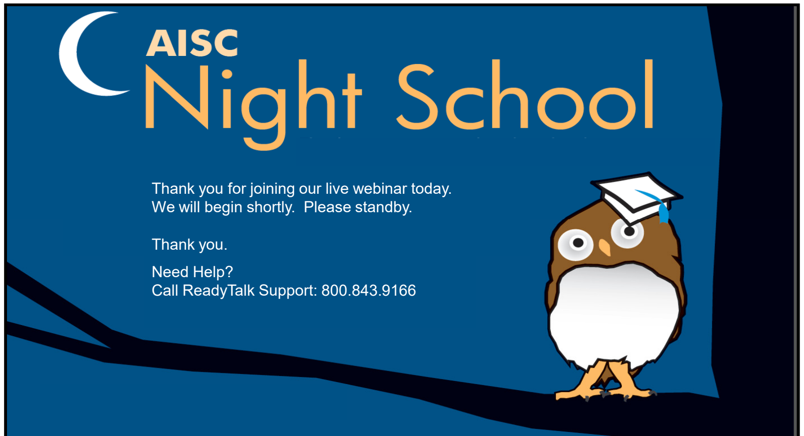

Classical Methods of Structural Analysis

Louis F. Geschwindner

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Session Description

20.1 Introduction and Basic Concepts
June 3, 2019

The session will start with a brief discussion of the history of structural analysis in order to place into context the development of classical methods of analysis and to illustrate how they have influenced approaches currently used. Such topics as equilibrium, superposition, first- and second-order analysis, determinate and indeterminate structures, shear and moment diagrams, and deflected shapes will be reviewed. AISC specification requirements will also be discussed.

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Learning Objectives:

- Describe how the development of classical methods of structural analysis has influenced current approaches.
- Evaluate the differences between determinate and indeterminate structures.
- Describe the connection between classical methods and the AISC Specification analysis requirements.
- Derive shear and moment diagrams for different structural situations.

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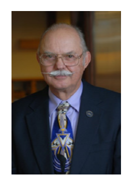
Night School 20
Classical Methods of Structural Analysis

Session 1: Introduction and Basic Concepts
June 3, 2019



Louis F. Geschwindner, PE, PhD
Professor Emeritus, Penn State University,
Former Vice President, AISC, and
Senior Consultant, Providence Engineering
State College, Pensylvania

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Classical Methods of Structural Analysis:
How we did it before computers

Night School 20
Lesson 1
Introduction and Basic Concepts

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Night School 20

- Introduce classical methods of analysis that may be useful in the design of steel structures.
- Emphasize understanding structural behavior to support improved design.
- Use deflection calculations to analyze indeterminate structures.
- Review direct and approximate methods of indeterminate structural analysis.

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Night School 20

1.	Introduction to Basic Concepts	6/3/2019
2.	Strain Energy and Real Work	6/17/2019
3.	Deflections by Virtual Work	6/24/2019
4.	Moment Areas and Elastic Weights	7/8/2019
5.	Indeterminate Structures and the General Method	7/15/2019
6.	Indeterminate Structures by Slope Deflection	7/22/2019
7.	Approximate Methods and Moment Distribution	7/29/2019
8.	Classical Approaches applied to Second-order Analysis	8/5/2019

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Lesson 1
Introduction and Basic Concepts

- Brief History of structural analysis
- Equilibrium
- Determinate vs. indeterminate structures
- Elastic vs. inelastic analysis
- Small deflections vs. large deflections
- 1^{st}-order vs. 2^{nd} – order analysis
- Superposition
- AISC 360 analysis requirements
- Shear and Moment diagrams
- Deflected shapes
- Unit loads, pattern loading and influence lines
- Introduction to Consistent Deflections.

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Structural Engineering

"The art of modeling materials that we do not wholly understand, into shapes that we cannot precisely analyze, so as to withstand forces we cannot really assess, in such a way that the community at large has no reason to suspect the extent of our ignorance!"

A. R. Dykes, IStructE

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Structural Analysis

- The process used to determine how a structure responds to specific loads or actions.
- Based on a mathematical model of the structure of interest.
- Results measured by establishing forces and deformations throughout the structure.

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Structural Analysis

- A mathematical model is used to predict the behavior of a real structure. The model is based on:
  - Engineering mechanics theory
  - Laboratory research
  - Model and field experimentation
  - Experience
  - Engineering judgment

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Structural Analysis

- All methods of structural analysis are founded on a series of basic assumptions.
- The assumptions were developed in detail early in the structural engineers academic studies.
- Often, these basic assumptions have been forgotten by the time the student has moved on to the next structures course.
- It should be helpful to remember that we did not always know what we know today.

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History

- Archimedes (287 – 212 BC)
  - His treatise *On the Equilibrium of Planes* established him as the founder of statics.
- Leonardo da Vinci (1452 – 1519)
  - Introduced the concept of the moment of a force.
- Galileo Galilei (1564 – 1642)
  - Originated mechanics of materials.
  - Discussed the problem of the cantilever beam.
    - Not correctly solved until 1855

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History

- Robert Hooke (1635 – 1703)
  - Hooke's Law – Elasticity.
- Sir Isaac Newton (1642 – 1727)
  - Laws of motion, law of universal gravitation, and infinitesimal calculus.
- Johann Bernoulli (1667 – 1748)
  - Introduced principle of virtual velocities (basis of virtual work).

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History

- Leonhard Euler (1707 – 1783)
  - Column buckling.
- Louis Marie Henri Navier (1785 – 1836)
  - First text book in mechanics of engineering.
  - This was the first systematic treatment of the theory of structures.
- Squire Whipple (1804 – 1888)
  - First rational analysis of the jointed truss.

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History

- 1863 – Ritter
  - Method of sections.
- 1864 – Maxwell
  - 1st treatment of indeterminate structures.
  - "Theory of Reciprocal Deflections," sometimes known as Maxwell – Betti Reciprocal Theorem.
  - Graphical truss analysis – Maxwell Diagram
- 1868 – Mohr
  - Lead to Conjugate Beam

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History

- 1873 – Green
  - Moment Area
- 1874 – Mohr
  - Consistent Deflections using Virtual Work
- 1886 – Müller Breslau
  - Influence line was a deflected shape
- 1915 – Maney
  - Slope-Deflection Method

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History

- 1924 Hardy Cross
  - Began teaching moment distribution
  - Revolutionized the analysis of continuous frames
- Last 50 years
  - Merging of earlier methods into modern matrix and finite element formulations.

We will be looking at methods that are close to 100 years old and older.

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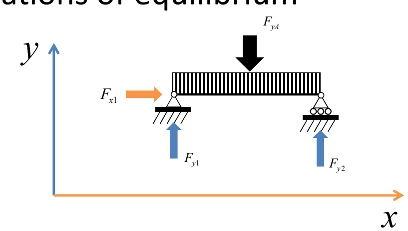
Equilibrium

- The most important equation in structural engineering, T=C.
- In a planer system there are three independent equations of equilibrium

$$\Sigma F_x = 0$$
$$\Sigma F_y = 0$$
$$\Sigma M_z = 0$$



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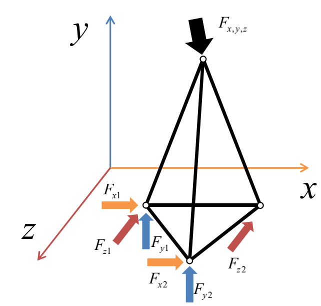
Equilibrium

- In a three dimensional system there are six independent equations of equilibrium

$$\Sigma F_x = 0 \quad \Sigma M_x = 0$$
$$\Sigma F_y = 0 \quad \Sigma M_y = 0$$
$$\Sigma F_z = 0 \quad \Sigma M_z = 0$$



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Determinate vs. Indeterminate

- Determinate
  - Number of unknowns = number of equations
    - Equations of equilibrium
    - Condition equations
  - Forces and moments independent of member properties
- Indeterminate
  - Number of unknowns > number of equations
    - Equilibrium, condition, other equations
  - Forces and moments dependent on relative member properties

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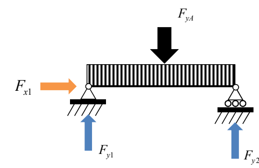
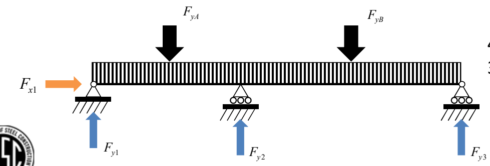
Determinate vs. Indeterminate

- Determinate



3 unknowns
3 equations of equilibrium

- Indeterminate



4 unknowns
3 equations of equilibrium

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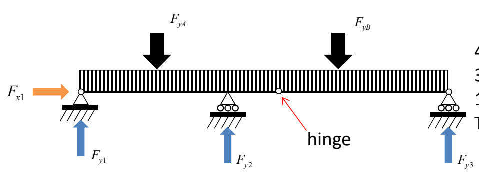
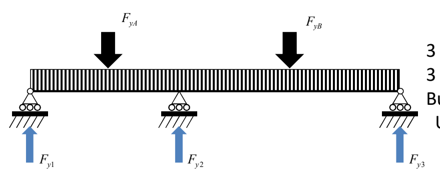
Stable vs. Unstable



4 unknowns
3 equations of equilibrium
1 condition equation (hinge)
Thus:
Stable and determinate



3 unknowns
3 equations of equilibrium
But:
Unstable

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Elastic vs. Inelastic

- Elastic
  - Stress is proportional to strain.
  - Material follows Hooke's Law.
- Inelastic
  - Stress is not proportional to strain.
  - Some of the material yields while other portions do not.

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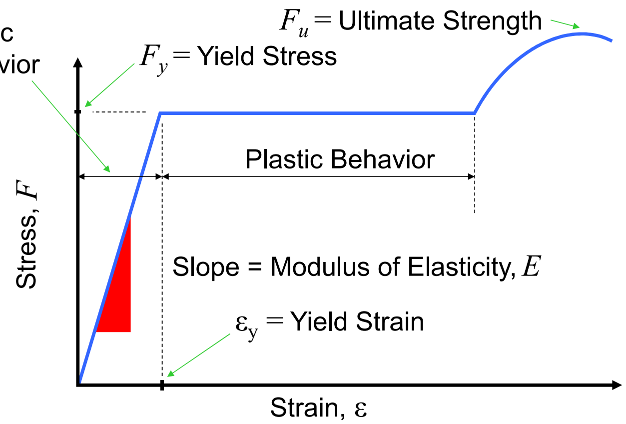
Steel as a Material



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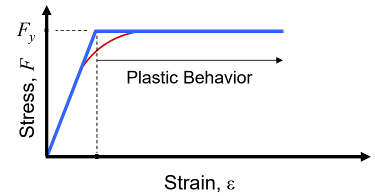
Compression Members

Inelastic behavior results from the presence of residual stresses in the rolled shape. This will have an impact on column strength that will be shown later.



Stub column test where actual residual stresses impact stress-strain curve

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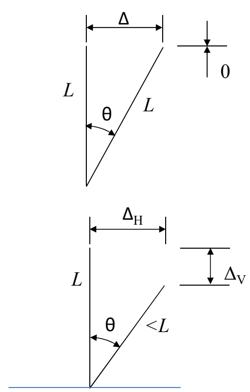
Small Deflection vs. Large Deflection

- Small
  - 1st order
  - $\sin\theta = \tan\theta = \theta$
- Large
  - 2nd order
  - $\sin\theta \neq \tan\theta \neq \theta$
  - Cable structures



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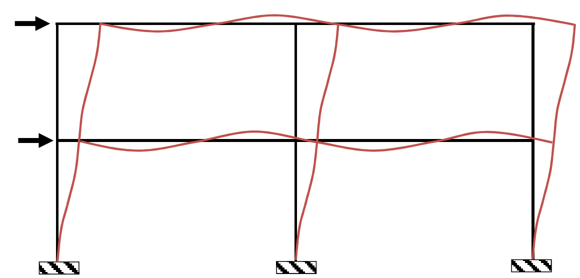
Small Deflection vs. Large Deflection

- Frame structure



Force-deformation relations are formulated as linear equations.

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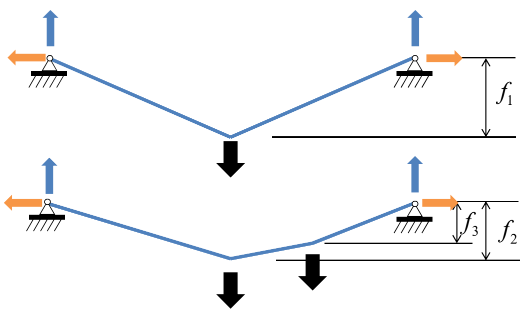
Small Deflection vs. Large Deflection

- Cable structure



Force-deformation relations can not be formulated as linear equations.

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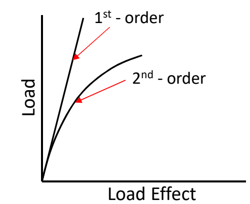
1st-order vs. 2nd-order

- 1st-order analysis
  - Deformations and rotations are small enough (infinitesimally small) as to not impact analysis results.
- 2nd-order analysis
  - Deformations and rotations are large and will influence analysis results.



The deformations in each of these cases are about the same magnitude, they are just accounted for differently.
Ignored vs. considered.

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1st-order vs. 2nd-order

- 1st order analysis
  - Equilibrium formulated about undeformed geometry
  - Beam-column ignores impact of axial load on moment
- 2nd order analysis
  - Equilibrium formulated about final displaced geometry
  - Beam-column includes impact of axial load on moment

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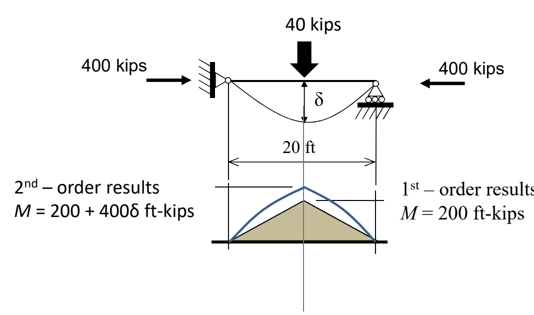
1st-order vs. 2nd-order

Beam with axial force



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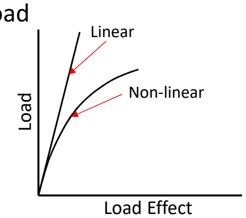
Linear vs. Non-linear

- Linear
  - Effects of load proportional to load
  - Elastic material
  - Superposition applicable
- Non-linear
  - Effects of load not proportional to load
  - Geometric nonlinearities
  - Elastic-plastic material
  - Inelastic material
  - Superposition not valid



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Superposition

- Requirements
  - Elastic behavior
  - Small deflections
- The Principle of Superposition:

"If the displacements of, and stresses at, all points of a structure are proportional to the loads causing them, then the total displacements and stresses resulting from the application of several loads will be the sum of the displacements and stresses caused by these loads when applied separately."

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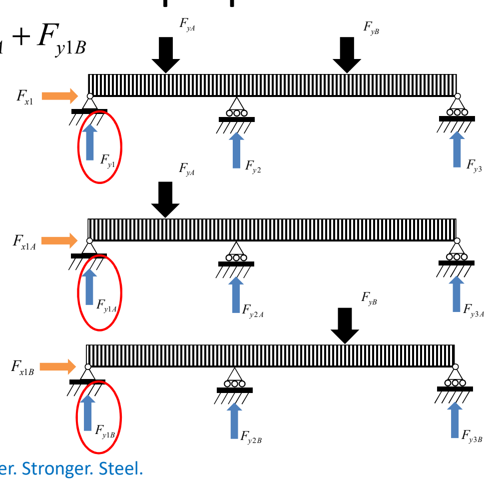
Superposition

$$F_{y1} = F_{y1A} + F_{y1B}$$



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History

- Question to consider
  - Which came first?
    - Understanding Equilibrium
    - Understanding Gravity

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Polling Question

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B3.3 Required Strength

"The required strength of structural members and connections shall be determined by structural analysis for the applicable load combinations as stipulated in Section B2."

"Design by elastic or inelastic analysis is permitted. Requirements for analysis are stipulated in Chapter C and Appendix 1."

We will be looking at methods of elastic analysis.

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- B2. Loads and Load Combinations
  - The loads, nominal loads and load combinations shall be as stipulated by the applicable building code.
  - In the absence of a building code, the loads, nominal loads and load combinations shall be those stipulated in *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE/SEI 7)

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C1. General Stability Requirements

- Stability shall be provided for the structure as a whole and for each of its elements. The effects of all of the following on stability of the structure and its elements shall be considered:
  a) flexural, shear and axial member deformations…
  b) second-order effects,
  c) geometric imperfections,
  d) stiffness reduction due to inelasticity; and
  e) uncertainty in stiffness and strength.

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- We will be using elastic analysis according to Section B3.3 to determine the impact of the loads defined in Section B2.
- The requirements of Section C1 go beyond the results of an elastic analysis but those requirements can be accommodated with a properly executed elastic analysis.

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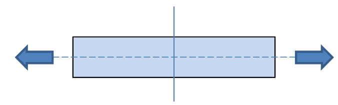
Axial Force, Shear Force and Bending Moment

- **Axial Force, *F*:** *at any transverse cross section of a straight beam, the algebraic sum of the components acting <u>parallel to the axis</u> of the beam of all loads and reactions applied to the portion of the beam on either side of that cross section.*



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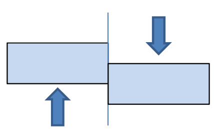
Axial Force, Shear Force and Bending Moment

- **Shear Force, *V*:** *at any transverse cross section of a straight beam, the algebraic sum of the components acting <u>transverse to the axis</u> of the beam of all loads and reactions applied to the portion of the beam on either side of the cross section.*



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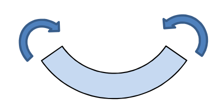
Axial Force, Shear Force and Bending Moment

- **Bending Moment, *M*:** *at any transverse cross section of a straight beam, the algebraic sum of the moments acting, taken <u>about an axis</u> passing through the centroid of the cross section, <u>normal to the plane of loading</u>, of all loads and reactions applied to the portion of the beam on either side of the cross section.*



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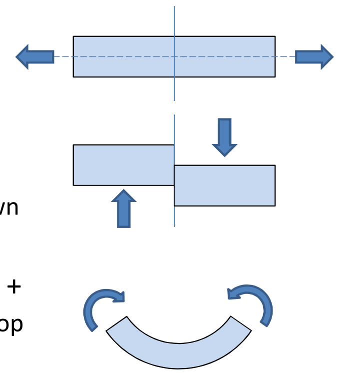
Axial Force, Shear Force and Bending Moment

- Sign Convention
  - Axial Tension, +
  - Shear, +
    - left up – right down
  - Bending Moment, +
    - Compression on top



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Shear and Moment Diagrams

- Plots of the shear force and bending moment at each cross section of the beam.
- Values determined through use of free body diagrams.
- Shapes determined by understanding relationships between load, shear and moment.

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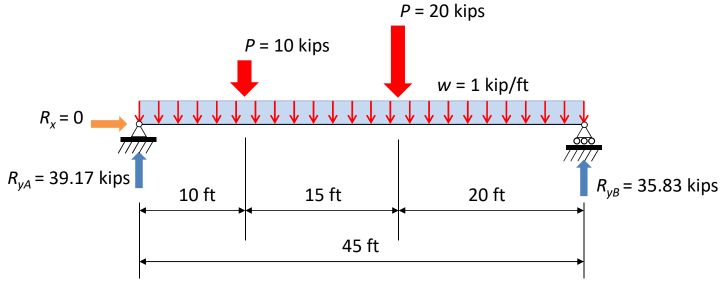
Shear and Moment Diagrams



Reactions found by applying equations of equilibrium

$$\Sigma F_x = 0$$
$$\Sigma F_y = 0$$
$$\Sigma M_z = 0$$

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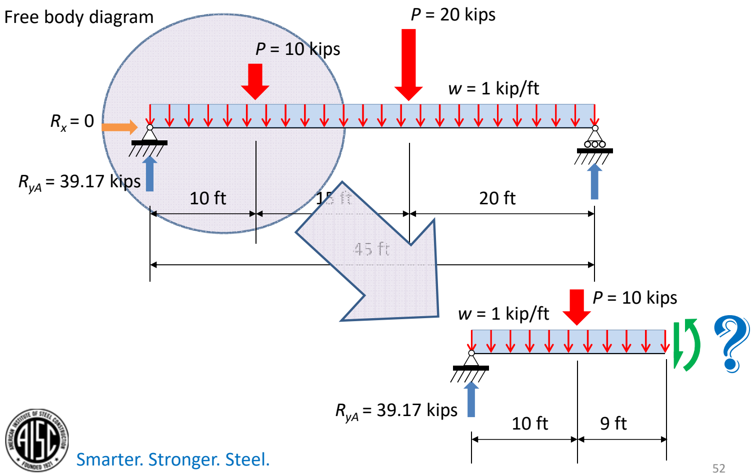
Shear and Moment Diagrams



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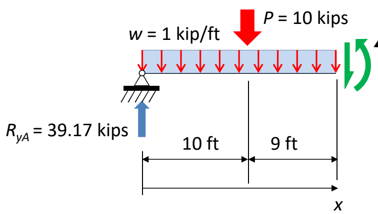
Shear and Moment Diagrams



$$\Sigma F_y = 0$$
$$39.17 - 1.0(19.0) - 10.0 - V_x = 0$$
$$V_x = 10.17 \text{ kips}$$

$$\Sigma M_z = 0$$
$$39.17(19) - 10.0(9.0) - 1.0(19.0)\left(\frac{19.0}{2}\right) - M_x = 0$$
$$M_x = 473 \text{ ft-kips}$$

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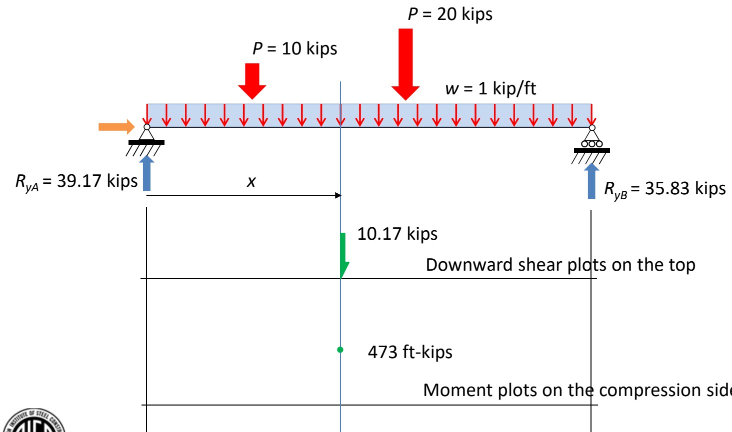
Shear and Moment Diagrams



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Shear and Moment Diagrams

- Applying the equations of equilibrium is a straight forward process.
- Determination of shear and moment values at any particular point is rarely an issue for the engineer.
- Sketching the shear and moment diagrams, before knowing all the values is a valuable tool for analysis and design.

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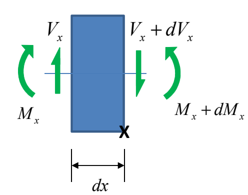
Shear and Moment Diagrams

- What is the relationship between the shear diagram and the moment diagram?



From moment equilibrium,

$$M_x + dM_x = M_x + V_x dx$$

Then

$$\frac{dM_x}{dx} = V_x$$

The slope of the moment diagram is the value of the shear

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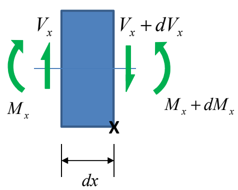
Shear and Moment Diagrams

- What is the relationship between the shear diagram and the moment diagram?



Also,

$$dM_x = V_x dx$$

which leads to

$$\int_{M_A}^{M_B} dM_x = M_B - M_A = \int_{x_A}^{x_B} V_x dx$$

So we see that the change in moment is the area of the shear diagram

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Shear and Moment Diagrams

- The same could be shown for the relationship between the load diagram and the shear diagram.
  - The slope of the shear diagram is equal to the magnitude of the load
  - The change in shear is the area of the load.

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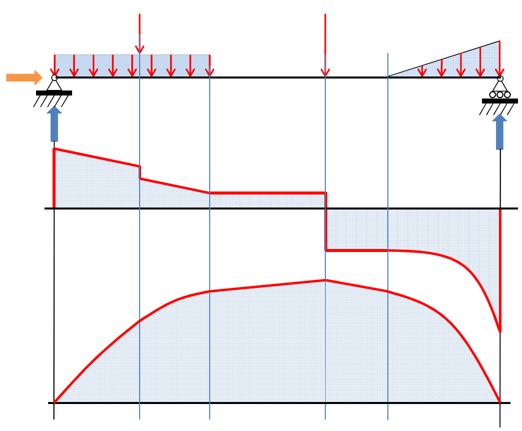
Shear and Moment Diagrams



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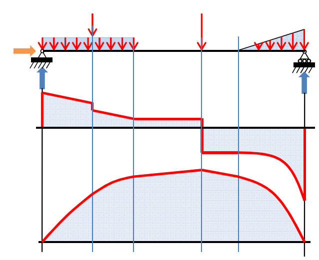
Shear and Moment Diagrams



Characteristics

- Uniform load → sloping shear, curved moment
- Concentrated load → abrupt change in shear, point in moment
- No load → no change in shear, straight line moment
- Triangular load → parabolic shear, 3rd -order moment curve
- Zero shear → relative maximum moment

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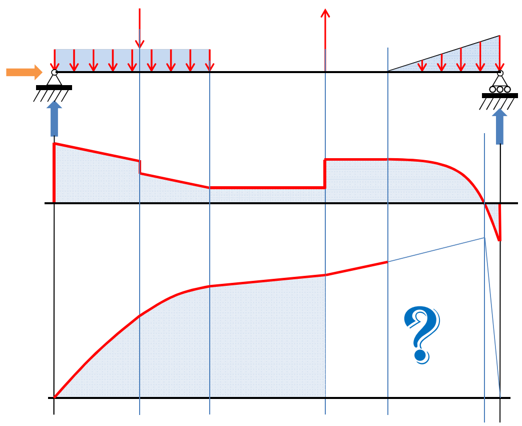
Shear and Moment Diagrams



I am trying to draw this but something isn't working right, why?

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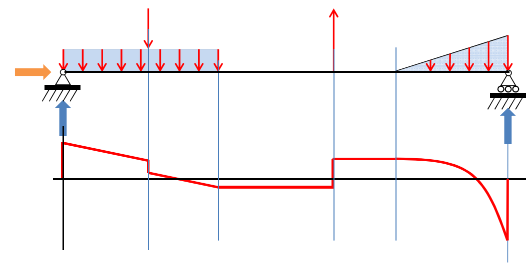
Shear and Moment Diagrams



Equilibrium requires that the reactions change, thus the base line of the diagram must move but the shape we developed is correct.

Now it can be seen that there are 3 points of relative maximum moment, like on a two span continuous beam.

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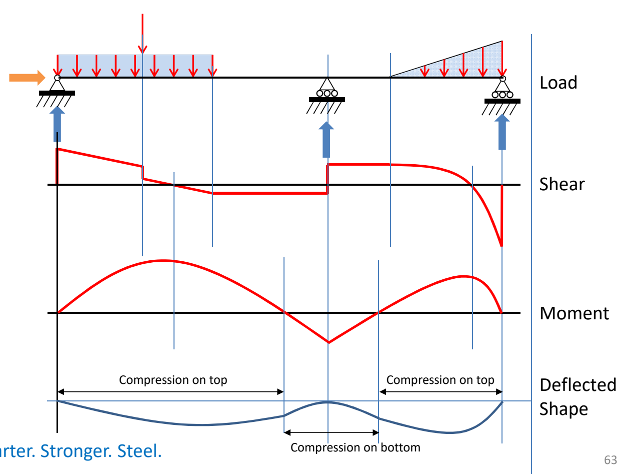
Shear and Moment Diagrams



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Deflected Shape

- No matter what the loading, the deflected shape for a continuous beam will be a smooth curve.
- The moment diagram will always tell us which side of the beam is in compression.
- Although it is difficult to draw accurate deflected shapes, it is easy to draw an approximate deflected shape using what we know already.

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Use of Unit Loads

- From the principle of superposition, we know that we can analyze a structure for loads independently and then add the results together.
- Based on this, we can analyze the structure for a 1 kip or 1 kip/ft load and then multiply by an appropriate constant to get the results for the actual loading.

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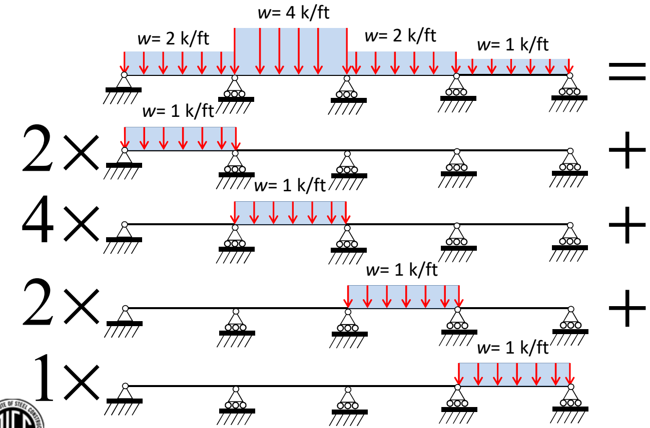
Use of Unit Loads



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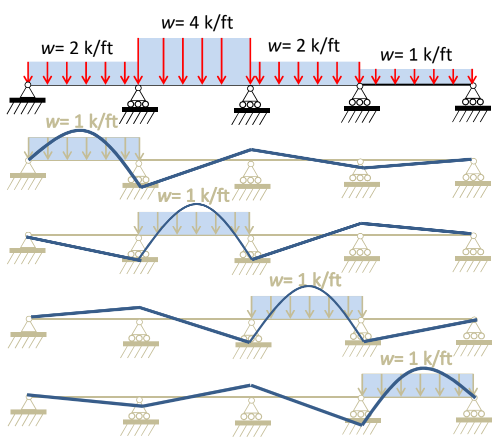
Use of Unit Loads



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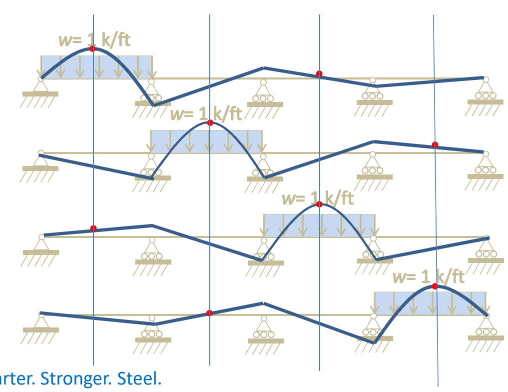
Use of Unit Loads

Which loads are combined to get the worst case positive moment at the center of the span?



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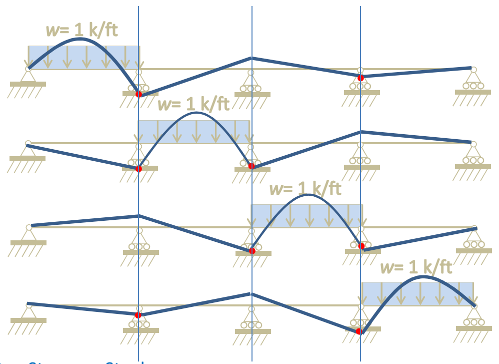
Use of Unit Loads

Which loads are combined to get the worst case negative moment at the supports?



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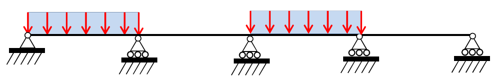
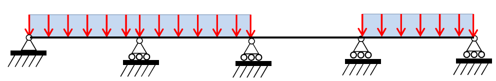
Use of Unit Loads

- So what patterns do we see?
  - For positive moments, the span of interest and every alternate span.



  - For negative moments, the spans adjacent to the support of interest and alternate spans.



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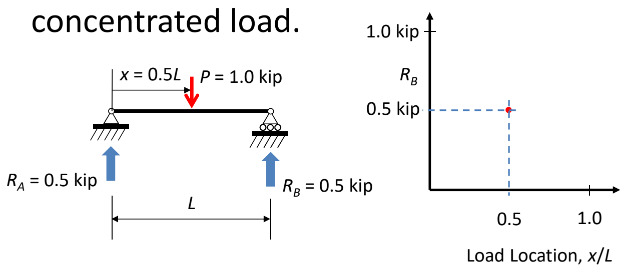
Use of Unit Loads

- Consider a simple beam with a unit concentrated load.



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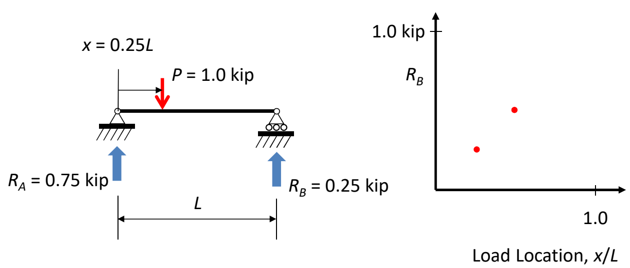
Use of Unit Loads

- Move the load to the left



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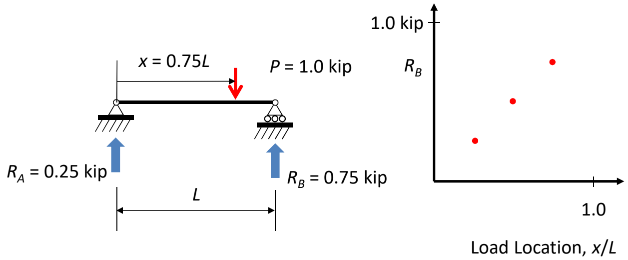
Use of Unit Loads

- Move the load to the right



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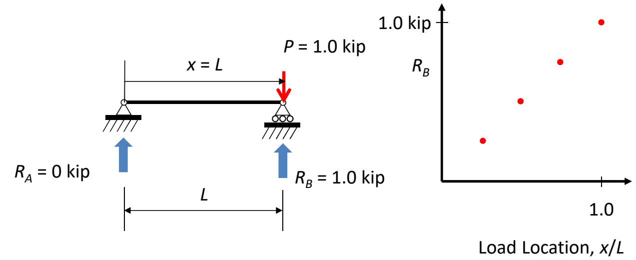
Use of Unit Loads

- Move the load above the right support



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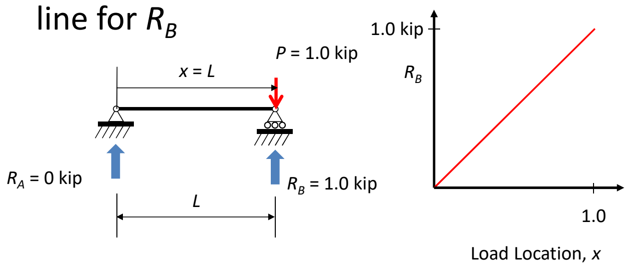
Influence Lines

- Connect the dots and you have the influence line for R_B



Using the influence line you can determine the reaction at B for any location and any load magnitude. For a uniform load the area under the line gives the reaction.

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Influence Lines

- Some loads may be located at any position on a structure.
- It is essential to know where to position that load to cause the maximum influence.
- With bridges this is a common consideration.
- With buildings it is not as common an issue.
- However, influence lines may still be useful for building applications.

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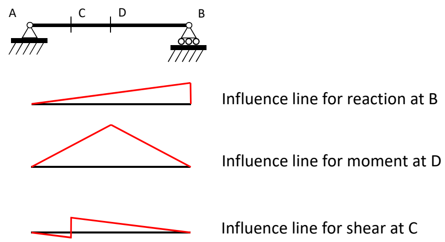
Influence Lines

- Definition: *a curve whose ordinate at any point equals the value of some particular function due to a unit load acting at that point.*



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Influence Lines

- Müller-Breslau principle: *If an internal stress component, or reaction component, is considered to act through some small distance and thereby to deflect or displace a structure, the curve of the deflected or displaced structure will be, to some scale, the influence line for the stress or reaction component.*

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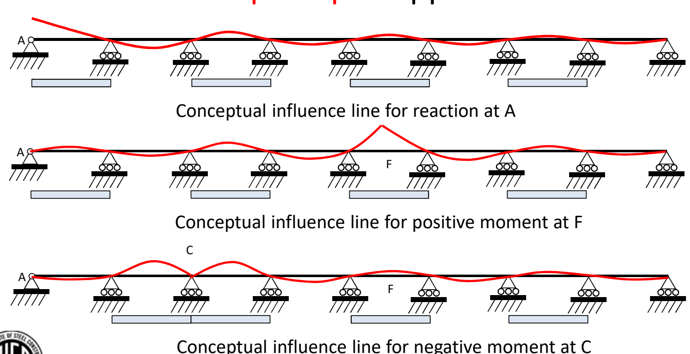
Influence Lines

- Müller-Breslau principle: application



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Deflections

- We have seen how understanding deflections and deflected shapes is important for understanding influence lines.
- There are many other reasons that conceptual or computed deflections are important/useful.
- One of those reasons is their role in the analysis of indeterminate structures.

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Deflections

- Maxwell's "general method" also known as Consistent Deformations or Consistent Deflections
  - The approach uses deformation compatibility equations in addition to the equilibrium equations when there are more unknowns then may be determined through equilibrium.

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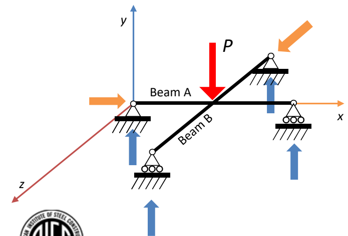
Deflections

- Consistent Deflections example
  - Consider two simple beams of unequal spans and stiffness that cross at their mid-spans and support a concentrated load at that point, as shown



There are 6 unknowns and 6 equations of equilibrium. However, there are too many unknowns in the y direction for the reactions to be determined with just these equations. An additional independent equation must be found.

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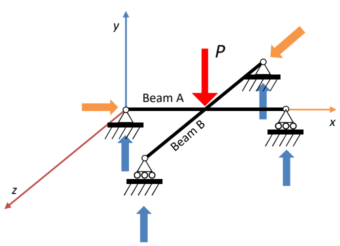
Deflections



The additional equation can be found by considering the condition at the intersection of the beams. At this location, the deflections must be "consistent" meaning here, the same. Thus,

$$\Delta_A = \Delta_B$$

and $\Delta_A = \dfrac{P_A L_A^3}{48EI_A} \quad \Delta_B = \dfrac{P_B L_B^3}{48EI_B}$

from which $\dfrac{P_A L_A^3}{48EI_A} = \dfrac{P_B L_B^3}{48EI_B}$

yielding $P_A = P_B\left(\dfrac{L_B^3}{48EI_B}\left(\dfrac{48EI_A}{L_A^3}\right)\right) = P_B\left(\dfrac{L_B^3 I_A}{L_A^3 I_B}\right)$

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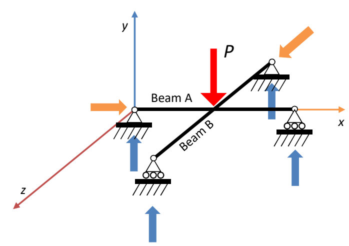
Deflections



From this equation we are able to determine the relationship between the amount of load carried by Beam A and Beam B.

$$P_A = P_B\left(\frac{L_B^3 I_A}{L_A^3 I_B}\right)$$

If the span and moment of inertia are the same for each beam, then they each carry the same amount of load, $P_A = P_B$.

If Beam A has twice the moment of inertia as Beam B, $I_A = 2I_B$, then , $P_A = 2P_B$.

Using the remaining equations of equilibrium, all 4 *y*-axis reactions may be determined for any relationship of beam properties.

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Deflections

- We may conclude from this discussion of deflections that there will be value in looking at various ways to determine deflections.
- In addition to deflections we will also discuss ways to determine rotations and any other deformation that might be useful to us.

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Deflections

- Question to consider
  - What deformations must be included in analysis according to AISC 360-16?
    - Flexure only
    - Flexure plus shear
    - Only deformations in members
    - All deformations affecting stability

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Polling Question

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Summary

- Considered the basic principles and behavioral assumptions needed to better understand structural analysis.
- Looked at the influence deflections play in our ability to understand structural behavior.
- Began to see how calculating deflections will allow us to solve the condition equations necessary when the equations of equilibrium are not sufficient.

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Lesson 2

- Strain Energy and Real Work
  - Develop an understanding of strain energy.
  - Develop the principles of real work.
  - Consider Maxwell's Law of Reciprocal Deflections.
  - Use these principles to calculate rotations and deflections for structures with various loadings.
  - Assess the issues that lead to the introduction of virtual work.

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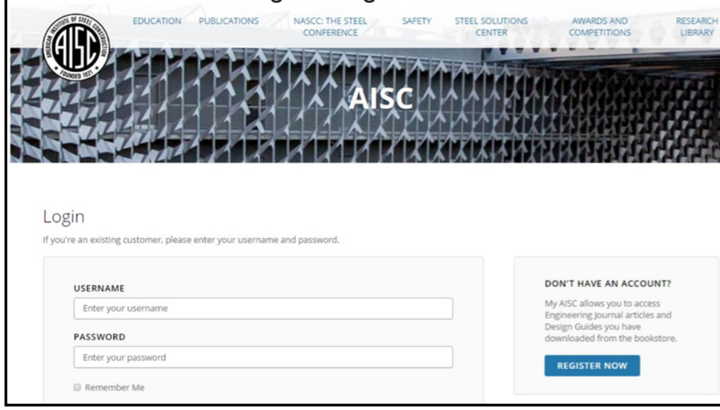

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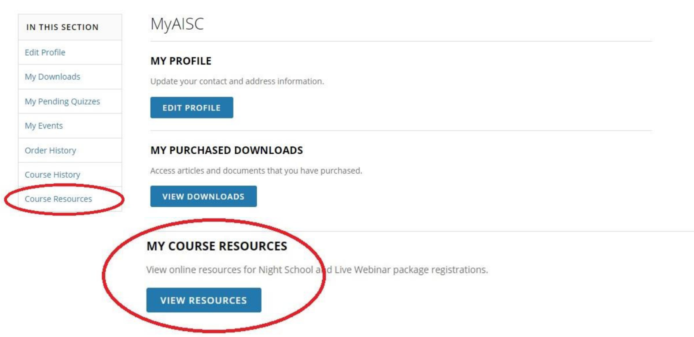

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