Structural Design For the Stage

Lesson 3

Beam Design and Load Analysis

1

Beam Stress

- Beams are structural members which are subject to tangential loads
  - Tangential load = load perpendicular to the axis of member
  - Causes bending
- When we analyze beams, we do not look at compressive and tensile stresses.
- We can treat bending stress a whole with its own design value

2

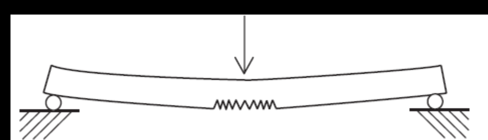
Beams

- Beams fail in three ways:
  - Bending
  - Horizontal shear
  - Vertical shear

3

Beams

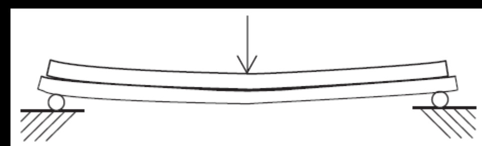
- Bending failure:
  - The fibers of the beam literally pull apart.
  - Beam failure is likely due to long spans
- The orientation of the board affects its resistance to stress
  - A 2x4 oriented on edge will resist bending better than an 2x4 lain flat.



4

Beams

- Horizontal shear
  - When top and bottom fibers slide past each other in the middle of the beam's cross section.
  - Short beams are more likely to fail due to horizontal shear
  - For solid shapes, horizontal shear is not dependent on shape.
  - Failure to horizontal shear would be a crack in the middle of the beam, often following the grain of the lumber



5

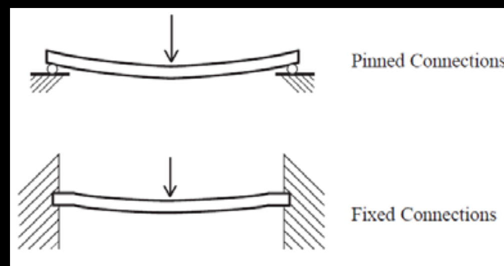
Beams

- Vertical Shear:
  - In this mode, the beam looks to be sliced cleanly through.
  - The slice typically is close to a support.
  - For this failure mode, extreme loading conditions must be present.

6

Beam Connections

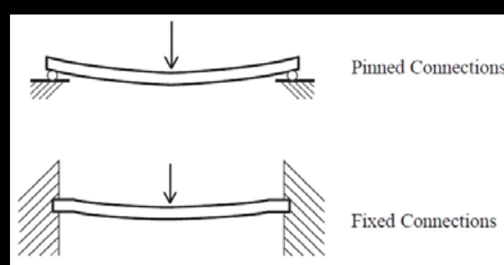
- We define fixity of a beam's connections as how it will respond to a load
- A beam resting on top of a wall will flex differently than a beam whose ends are embedded in concrete for example.
- Engineers call these pinned and fixed connections.



7

Beam Connections

- A Pinned connection resists one force with one direction and sense.
  - In theory, it offers no resistance to rotational movement.
- A Fixed connection supports a force in any direction and sense.
  - In theory, it offers complete resistance to any movement because its ends cannot move



8

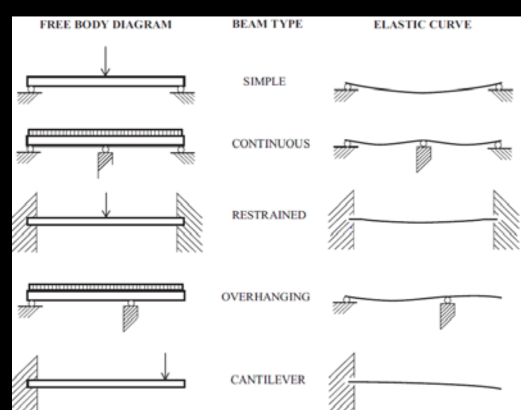
Beam Connections

- How we approach designing a beam depends upon its fixity
- In reality, most connections are between these two conditions.
  - A leg bolted to a platform will offer some resistance to rotation, but not the equivalent to a fixed connection.
- To simplify our calculations, most connections we will do are anayized as if fixed or pinned to make the calculations easier.
- For theatre, most of our connections are pinned, and we will learn how to calculate on pinned connections.
- Pinned calculations will be conservative—the reality is our fixity will be stronger when bolted than we calculate

9

Types of Beams

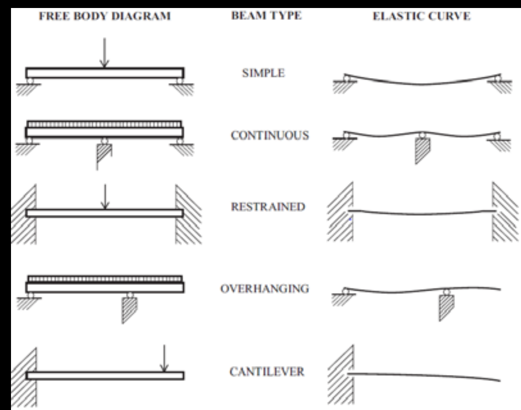
- There are five types of beams used in theatrical design.
- We define type type by the pattern of supports and connections between the beam and supports.



10

Types of Beams

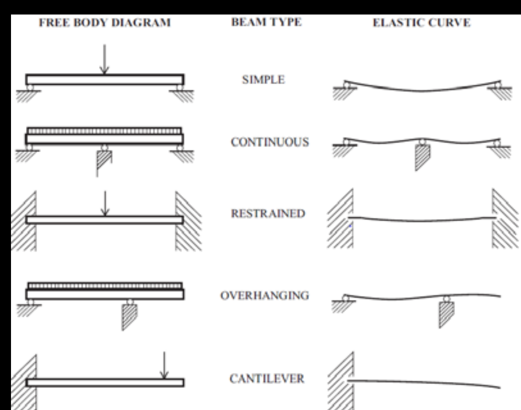
- A simple beam is the most common type of beam. Supported at both ends by a pinned connection.
- A continuous beam is a beam with three or more supports.
- A restrained beam is a beam supported at both ends with fixed connections.
  - Uncommon in scenery but common in theatre rigging systems



11

Types of Beams

- An overhanging beam has pinned connections and one end overhanging a support.
  - A double overhanging beam is a special case in which both ends overhang the supports.
- A cantilever beam has only one fixed support and is distinctly different from an overhanging beam
- Real world beam configurations are combinations of these five types.
  - A pipe batten is a continuous bema with a double overhang.



12

Beam terminology

- We use a few phrases to define beams:
- Joists are small beams which are used in repetitive systems such as floors.
- Rafters are a special type of joist used in sloping roofs within a repetitive system.
- Girders are large beams which support smaller beams such as joists.

13

Check point

- What are three types of beam failure?
- What is the difference between a pinned and fixed connection
- What are the five types of beams?
- Define Joist, Rafter, and Girder

14

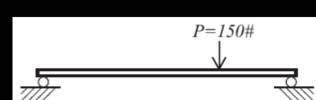
Analyzing the load

- There are two types of loads on beams.
- Dead loads are permanent loads such as the weight of the flooring material
- Live loads are temporary loads such as the weight of furniture or an actor walking across the deck.
- Some loads can last a long time and still be considered a live load
  - Furniture
  - Snow on a roof of a house
- Beams may be subject to either or both types of loads.

15

Analyzing the load

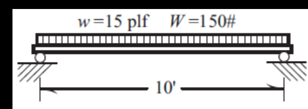
- Point Loads are loads that are specific and concentrated into a small area.
- We represent point loads by drawing an arrow indicated the load and direction
- We label the arrow with a upper case P and magnitude of the load.



16

Analyzing the load

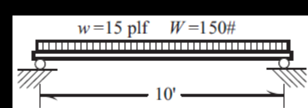
- Distributed Loads are loads that are general and spread evenly over the entire area.
- We represent this as a hatched rectangle
- We label distributed loads in two ways:
  - Lowercase w and the weight Per Linear Foot (PLF)
  - Uppercase W and the total weight

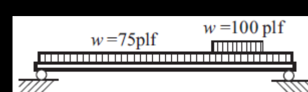


17

Analyzing the load

- When there is more than one distributed load across the platform they are combined.
- When there is a partially distributed load they are stacked and drawn wih weight





18

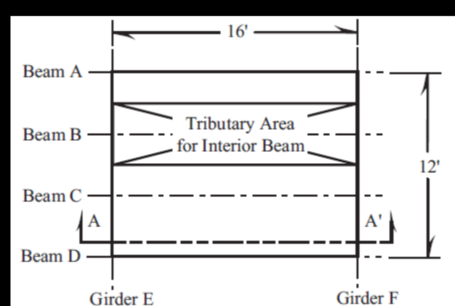
Identifying Live/Dead loads

- After identifying the types of loads and the magnitudes of each load we must assign the loads to beams.
- This seams simple, but requires attention.
- A distributed load evenly covers the beam.
- A point load between two beams are assumed to share the load equally. What happens if the point is one foot away from the beam and three feet from the next? (the closer beam supports 75% of the weight)

19

Identifying Live/Dead loads

- We use the concept of the tributary area to determine what is supported by a beam.
- Beam B carries anything in the area of its tributary area.
- This is helpful for dead/live loads that are expressed in PSF. We can calculate the square footage and convert this to PLF



20

Checkpoint

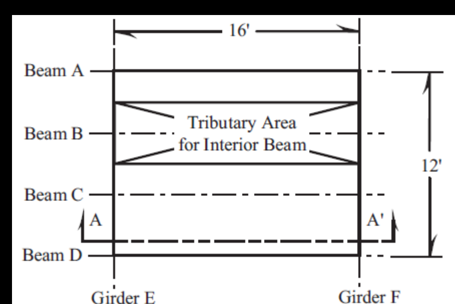
- What are distributed loads?
- What are point loads?

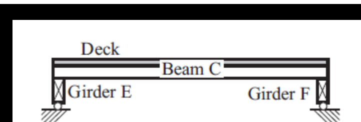
- What is dead weight?
- What is live weight?

21

Example 1a:

- A deck is constructed of 4'x4' stressed skin platforms with 24' of 5/4 x 2" framing and 5/8" plywood skins and covered by ½" MDF. Beams are on 4'-0" centers and span 16'-0"
- Determine the loading on Beams A, B, C, D

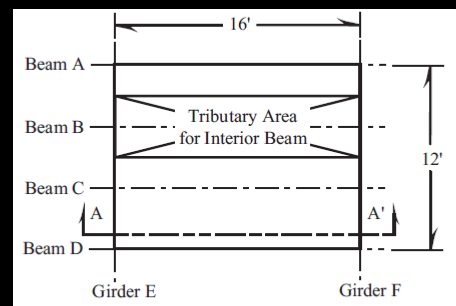


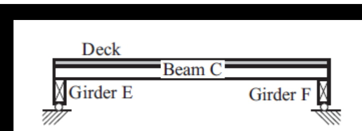


22

Example 1a:

- We start this by figuring out the weight per square foot:
  - 5/8” ply = 3.0 psf/in; 5/4 lumber = 35 lb/ft^3 ; MDF = 2.16 psf





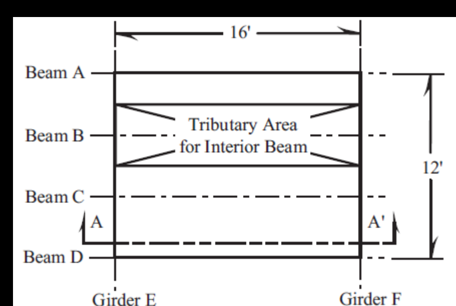
- Calculate the plywood weight:
- $(3.0\frac{psf}{in})(0.625")(32\ ft^2) = 60\#$
  - .625” = 5/8” decimal
  - 32 ft^2 = front and back of stress skin platform

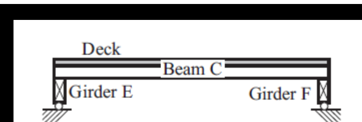
23

Example 1a:

- Calculate weight of framing: (Weight for wood is usually in by the cubic foot. Calculate how many cubic inches are in the material

$$1.25"(2")(24')(12\ in/ft) = 720\ in^3$$





- Convert to cubic feet

$$\frac{720\ in^3}{1728\ in^3} = 0.4167\ ft^3$$

- Calculate weight of frame:

$$0.4167\ ft^3(35\ lb/ft^3) = 14.58\#$$

24

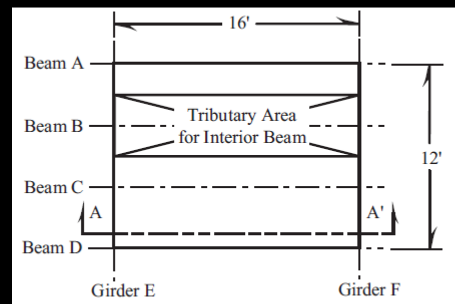
Example 1a:

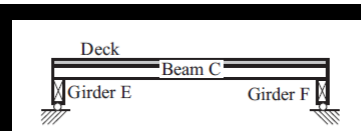
- Calculate how much a triscut weighs:

$$Deadload = \frac{W_{ply} + W_{5/4x2}}{16sqft}$$

$$\frac{60\# + 14.58\#}{16\ sqft} = 4.66\ psf$$

Add the weight of the ½” MDF to the calculation to achieve a total weight of 6.82psf. To make the math easier, we can round UP to 7psf (*Why not down?)*





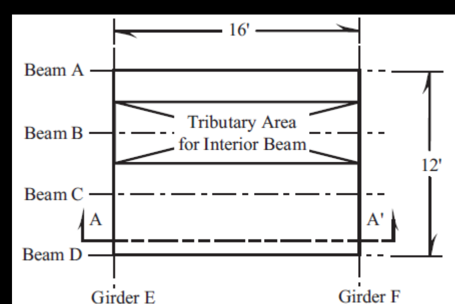
25

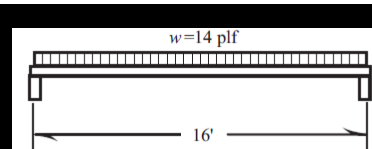
Example 1a:

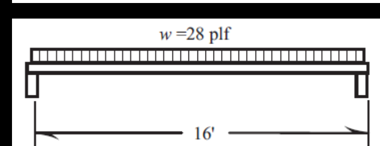
- Now calculate for the tributary area for each beam.
- Beams A + D have the same area
- Beams B + C have the same area

- Calculate AD (7PSF x 2’) = 14 plf
- Calculate BC (7psf x 4’) = 28 plf

- Create the diagrams

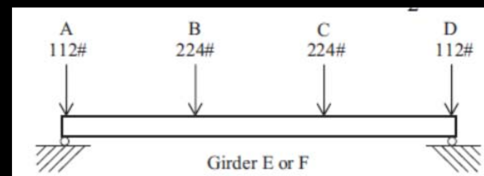






26

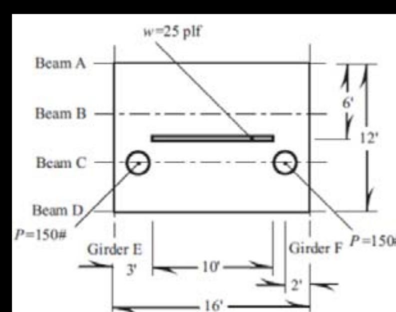
Example 1b:

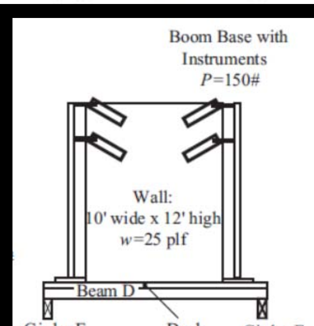


- What is the loading on girders E and F
- Each girder will support ½ the weight of each beam.
- These loads will be point loads.
- Point load for beams A and D = $\frac{14\ plf\ (16')}{2} = 112\#$
- Point load for beams B and C = $\frac{28\ plf\ (16')}{2} = 224\#$

27

Example 1c:



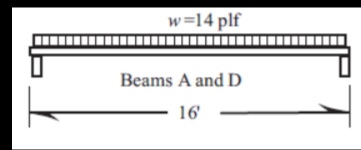


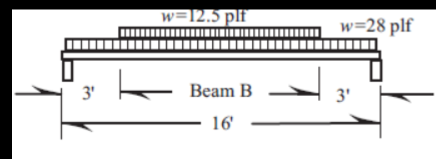
- The same stage now contains a wall and two booms on the deck as shown. The wall is 10’-0” long and weighs 25 plf and is centered between beams B and C.
- The booms are 2’-0” from each edge center on Beam C and weigh 150# each.
- How does this affect loading of beams and girders?

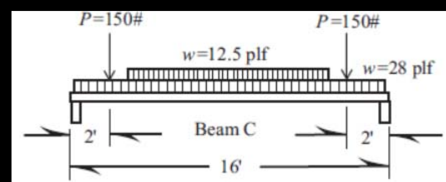
28

Example 1c:

- Start by adjusting our beam loading diagrams:
  - Note wall on Beams B and C shows a distributed load that is centered and dimensioned
  - Note that the booms on Beam C are shown as point loads and dimensioned







29

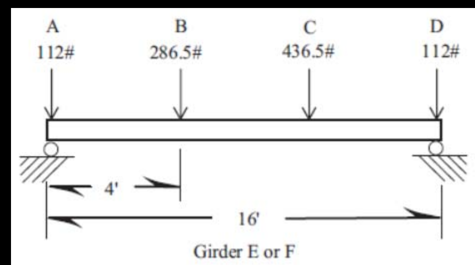
Example 1c:

- Point load for beams A and D = $\frac{14\ plf\ (16')}{2} = 112\#$
- Point load for beams B = $\frac{28\ plf\ (16')+12.5\ plf(10')}{2} = 286.5\#$
- Point load for beams C = $\frac{28\ plf\ (16')+12.5\ plf(10')+150\#+150\#}{2} = 436.5\#$
- Note:
  - Sign (+/-) represents the sense of the force
  - Why do we multiply PLF by 10’ or 16’
  - Why do we divide everything by 2?

30

Example 1c:

- New solution for Girder E & F:



- Note:
  - What does the circle represent under the beam?
  - What do the arrows represent on A, B, C, D?

31

Live Loads

- In the above example, only dead loads were considered, with no accounting for actors on the deck.
- Analyzing a person walking on the floor would be tedious if we had to analyze for every possible scenario where someone could stand.
- To deal with this problem, structural engineers designate a uniformly distributed live load rating.
- Typical home design uses 40 psf over the entire floor.
- While low, it would be unusual for the load over every square foot to exceed 40 psf. (a person might take up 6 square feet for example)

32

Live Loads

- A 12’x15’ room for example would have a load capacity of 7,200 lbs.
- If an average person weighs 175 pounds, it would take 42 people to exceed the total live load of capacity.

- It is common practice to assign a live load based on the intend use of the structure.
  - Bleachers and grandstands use 100 psf
  - Stage floors use 150 psf
  - Table in appendix G shows multiple values

33

Live Loads

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34

Live Loads

- We will commonly use 50psf as a standard for theatre decks.
- This is 10# more than normal house floors.
- To simplify calculations, we assume the 50psf includes the weight of the beam and decking.

- Always remember that if the load is unusual, the live load should be changed to reflect it.
  - E.g. a cast of 30 will be standing on the downstage edge of a set at curtain call.

35

Example 1d:

- Assuming a 50 psf live load rating is applied to the deck from 1a, wht is the loading?

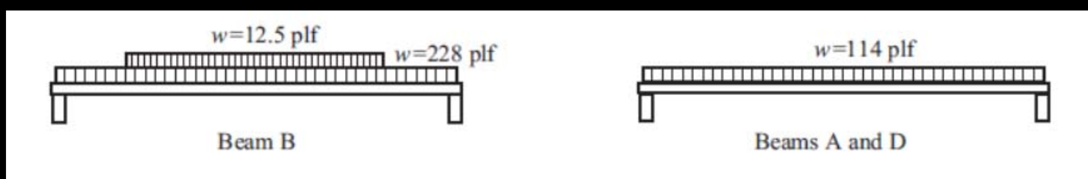
- Beams A and D = (50 ps)(2') = 100 plf
- Beams B and C = (50 psf)(4') = 200 plf

- Total Load $_{\text{A and D}}$ = Dead load + Live Load = 14 plf + 100 plf = 114 plf
- Total Load $_{\text{B and C}}$ = Dead loa**Entertainment Rigging: A Practical Guide**
- d + Live load = 28 plf + 200 plf = 228 plf

36

Example 1d:

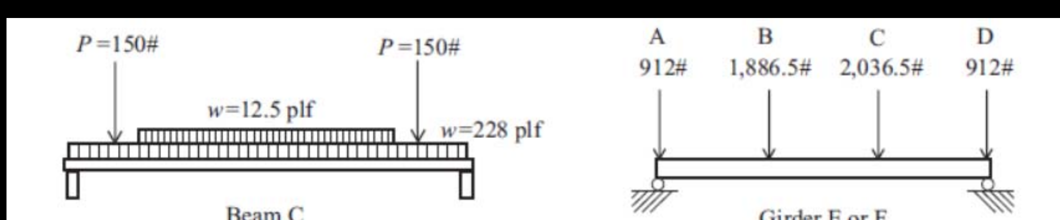
- Girder Loading:
- Point load for beams A and D = $\frac{114\ plf\ (16')}{2} = 912\#$
- Point load for beams B = $\frac{228\ plf\ (16')+12.5\ plf(10')}{2} = 1886.5\#$



37

Example 1d:

- Girder Loading:
- Point load for beams C = $\frac{228\ plf\ (16')+12.5\ plf(10')+150\#+150\#}{2} = 2,036.5\#$



38

Checkpoint

- What are live loads?
- How do we determine live loads on surfaces?

39

Assignment

40