Types of Structures and Loads

THEORY OF STRUCTURES

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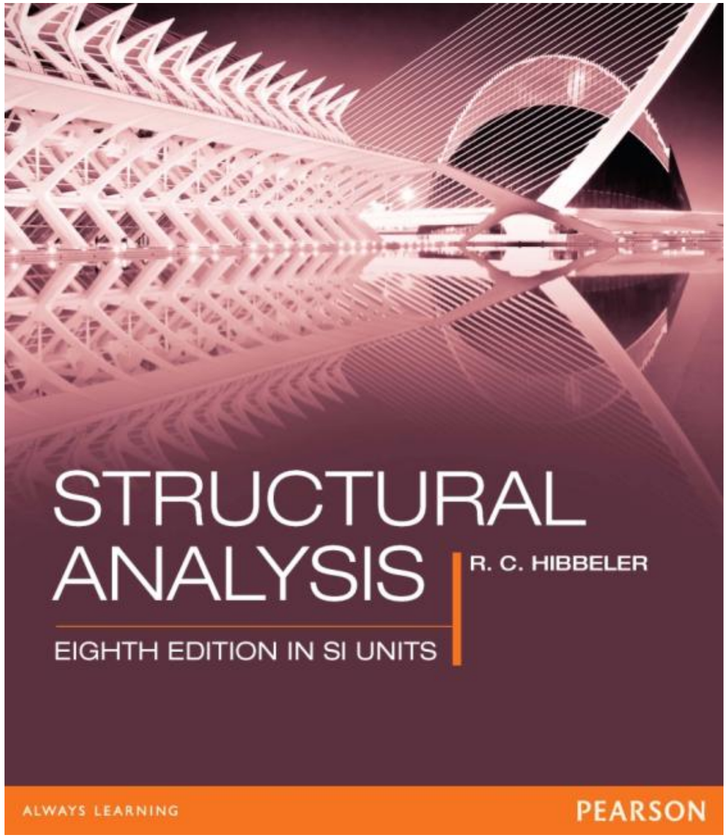


Course Content

- Introduction
- Analysis of Statically Determinate Structures
  - Simple Beams and Frames, Cantilever Beams, Continuous Beams with Hinges, Three-Hinged Arches and Frames, Roof Trusses,
  - Deflections,
- Analysis of Statically Indeterminate Structures
  - Force Method
  - Moment Distribution (Cross) Method

Introduction

A **structure** refers to a system of connected parts used to support a load. Important examples related to civil engineering include

- buildings,
- bridges and
- towers;

and in other branches of engineering,

- ship and aircraft frames,
- tanks, pressure vessels,
- mechanical systems, and
- electrical supporting structures

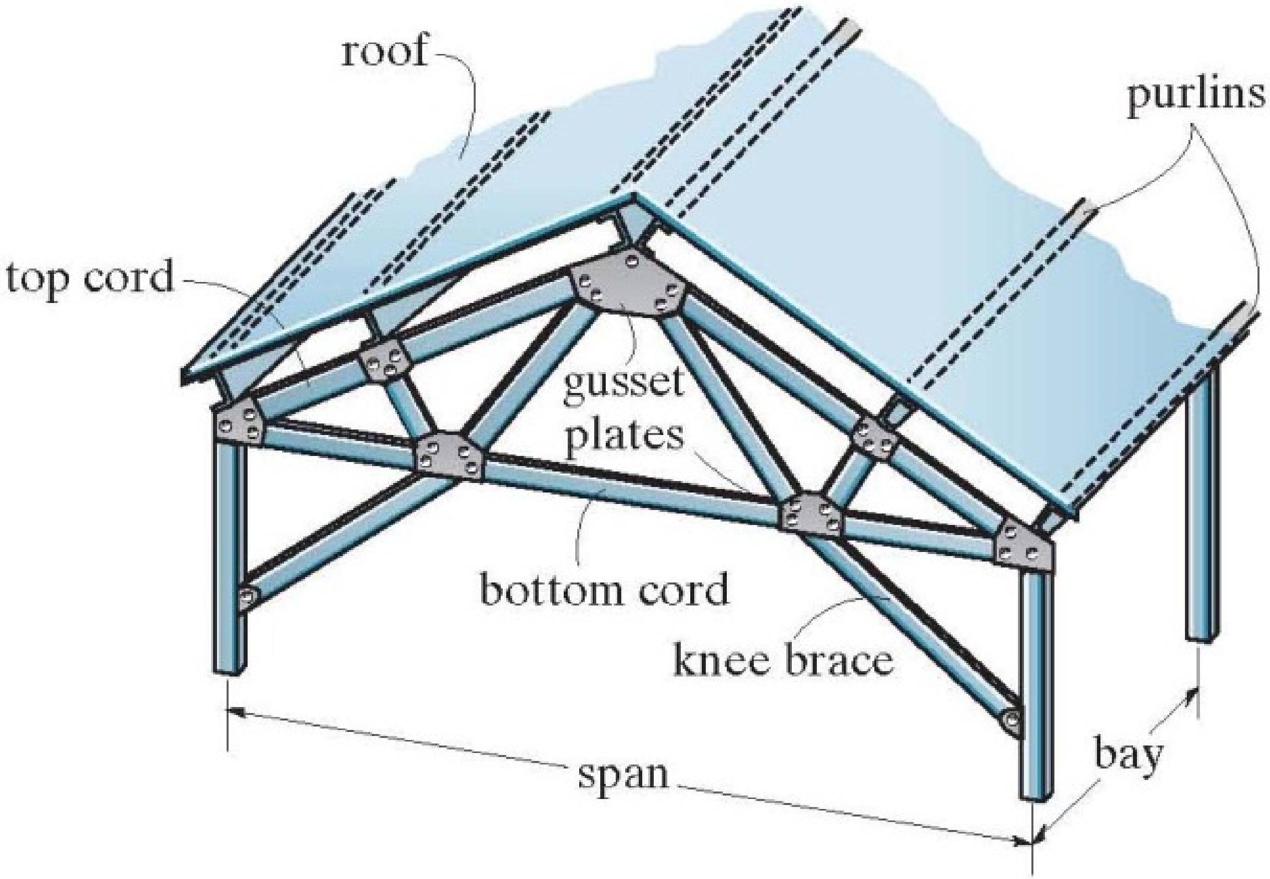
Such structures are composed of one or more solid elements arranged so that the whole structures as well as their components are capable of holding themselves without appreciable geometric change during loading and unloading.

Introduction

- The design of a structure involves many considerations, among which are four major objectives that must be satisfied:
  - The structure must meet the performance requirement (**utility**).
  - The structure must carry loads safely (**safety**).
  - The structure should be economical in material, construction, and cost (**economy**).
  - The structure should have a good appearance (**aesthetics**).

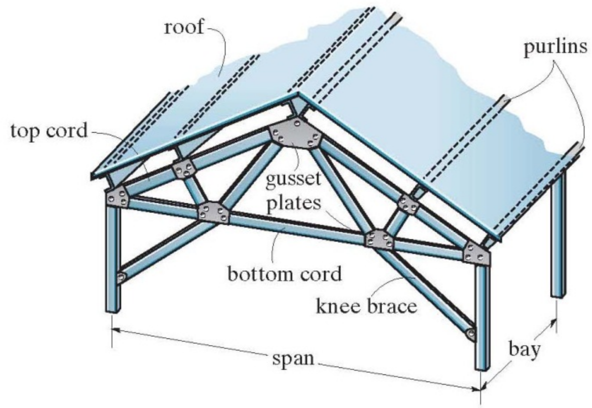
Introduction

- Consider, for example, the roof truss resting on columns shown below.



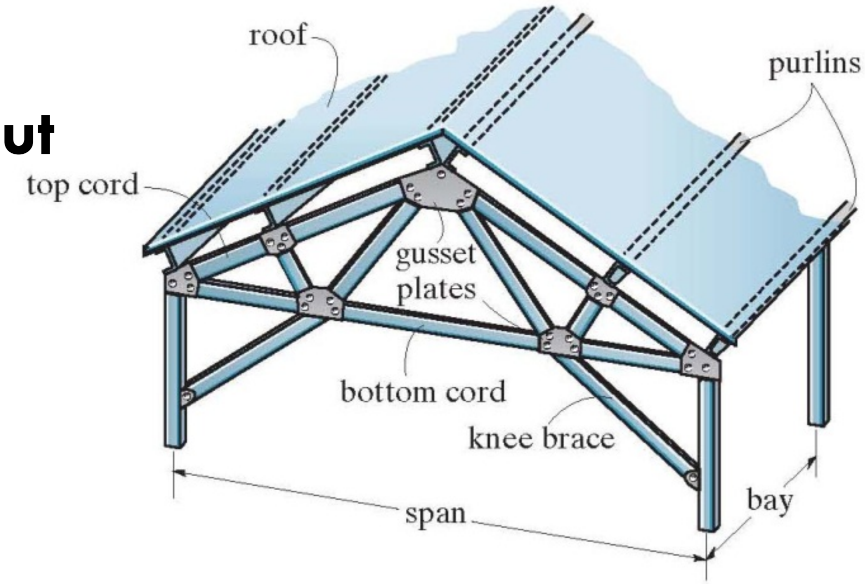
Introduction

- The purposes of the roof truss and of the columns are, on the one hand, to hold in equilibrium their own weights, the load of roof covering and the wind and snow.
- Also to provide rooms for housing a family, for a manufacturing plant, or for other uses.
- During its development the design is generally optimized to achieve minimum expenditure for materials and construction uses.



Introduction

- The complete design of a structure is outlined in the following stages:
  - **Developing a general layout**
  - **Investigating the loads**
  - **Stress analysis**
  - **Selection of elements**
  - **Drawing and detailing**

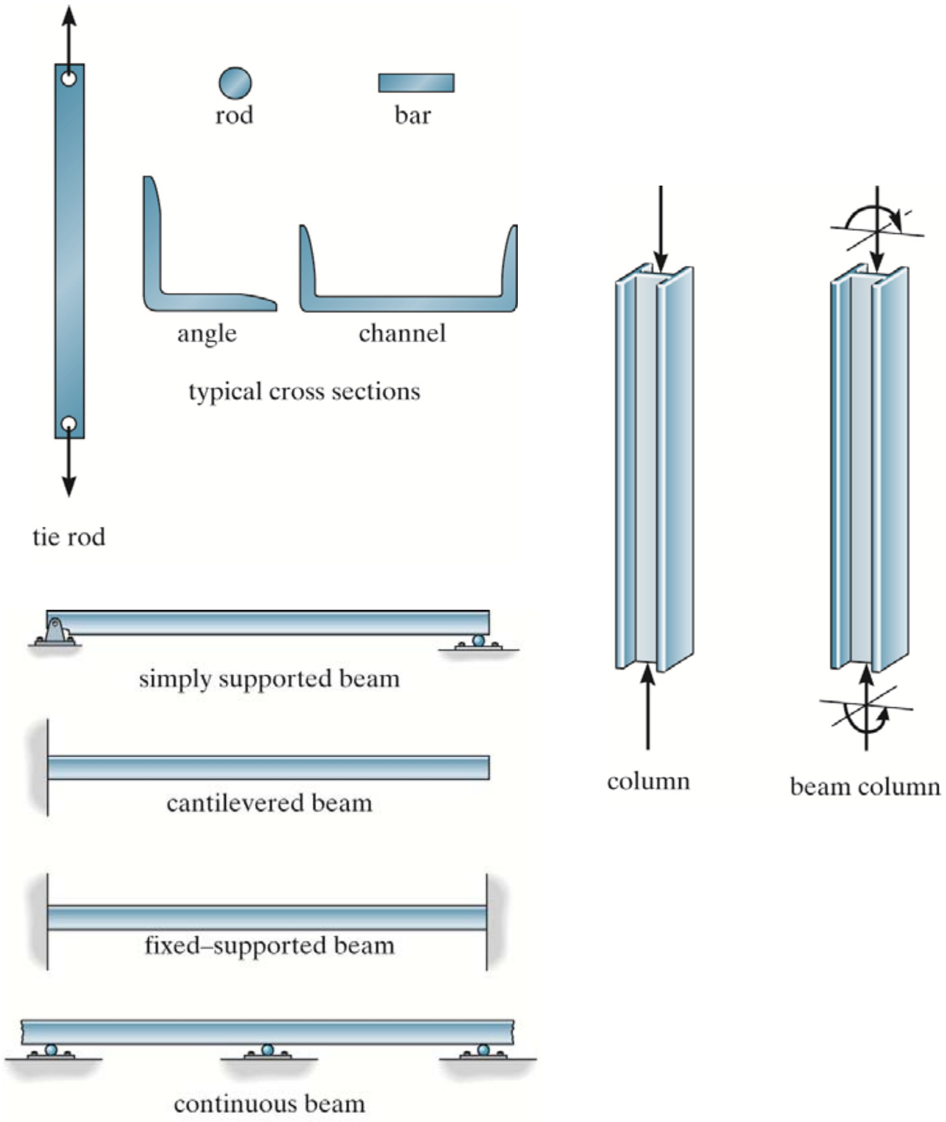


- These five stages are interrelated and may be subdivided and modified
- In many cases they must be carried out more or less simultaneously

Classification of Structures

- Structural elements
  - Tie rods
  - Beams
  - Columns

- Types of structures
  - Trusses
  - Cables & Arches
  - Surface Structures



Loads

Loads

↓

Structural forms

↓

Elements carrying primary loads

↓

Various supporting members

↓

Foundation

Loads

- Design loading for a structure is often specified in codes
  - General building codes
  - Design codes

TABLE 1–1 Codes
General Building Codes
Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-10, American Society of Civil Engineers
International Building Code
Design Codes
Building Code Requirements for Reinforced Concrete, Am. Conc. Inst. (ACI)
Manual of Steel Construction, American Institute of Steel Construction (AISC)
Standard Specifications for Highway Bridges, American Association of State Highway and Transportation Officials (AASHTO)
National Design Specification for Wood Construction, American Forest and Paper Association (AFPA)
Manual for Railway Engineering, American Railway Engineering Association (AREA)

Loads

- Types of load
  - Dead loads
    - Weights of various structural members
    - Weights of any objects that are attached to the structure

TABLE 1–2 Minimum Densities for Design Loads from Materials*

	kN/m^3
Aluminum	26.7
Concrete, plain cinder	17.0
Concrete, plain stone	22.6
Concrete, reinforced cinder	17.4
Concrete, reinforced stone	23.6
Clay, dry	9.9
Clay, damp	17.3
Sand and gravel, dry, loose	15.7
Sand and gravel, wet	18.9
Masonry, lightweight solid concrete	16.5
Masonry, normal weight	21.2
Plywood	5.7
Steel, cold-drawn	77.3
Wood, Douglas Fir	5.3
Wood, Southern Pine	5.8
Wood, spruce	4.5

*Reproduced with permission from American Society of Civil Engineers *Minimum Design Loads for Buildings and Other Structures,* ASCE/SEI 7-10. Copies of this standard may be purchased from ASCE at www.pubs.asce.org.

TABLE 1–3 Minimum Design Dead Loads*

Walls	kN/m^2
100 mm clay brick	1.87
200 mm clay brick	3.78
300 mm clay brick	5.51
Frame Partitions and Walls	
Exterior stud walls with brick veneer	2.30
Windows, glass, frame and sash	0.38
Wood studs 50 × 100 mm unplastered	0.19
Wood studs 50 × 100 mm plastered one side	0.57
Wood studs 50 × 100 mm plastered two sides	0.96
Floor Fill	
Cinder concrete, per mm	0.017
Lightweight concrete, plain, per mm	0.015
Stone concrete, per mm	0.023
Ceilings	
Acoustical fiberboard	0.05
Plaster on tile or concrete	0.24
Suspended metal lath and gypsum plaster	0.48
Asphalt shingles	0.10
Fiberboard, 13 mm	0.04

*Reproduced with permission from American Society of Civil Engineers *Minimum Design Loads for Buildings and Other Structures,* ASCE/SEI 7-10.

Loads

- Live loads
  - Varies in magnitude & location
  - Building loads
    - Depends on the purpose for which the building is designed
    - These loadings are generally tabulated in local, state or national code
    - Uniform, concentrated loads

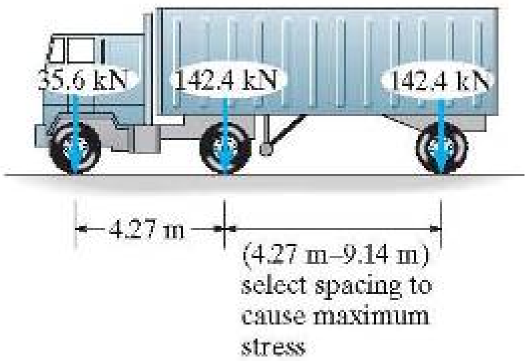
TABLE 1–4 Minimum Live Loads*

Occupancy or Use	Live Load kN/m^2	Occupancy or Use	Live Load kN/m^2
Assembly areas and theaters		Residential	
Fixed seats	2.87	Dwellings (one- and two-family)	1.92
Movable seats	4.79	Hotels and multifamily houses	
Garages (passenger cars only)	2.40	Private rooms and corridors	1.92
Office buildings		Public rooms and corridors	4.79
Lobbies	4.79	Schools	
Offices	2.40	Classrooms	1.92
Storage warehouse		Corridors above first floor	3.83
Light	6.00		
Heavy	11.97		

*Reproduced with permission from *Minimum Design Loads for Buildings and Other Structures*, ASCE/SEI 7-10.

Loads

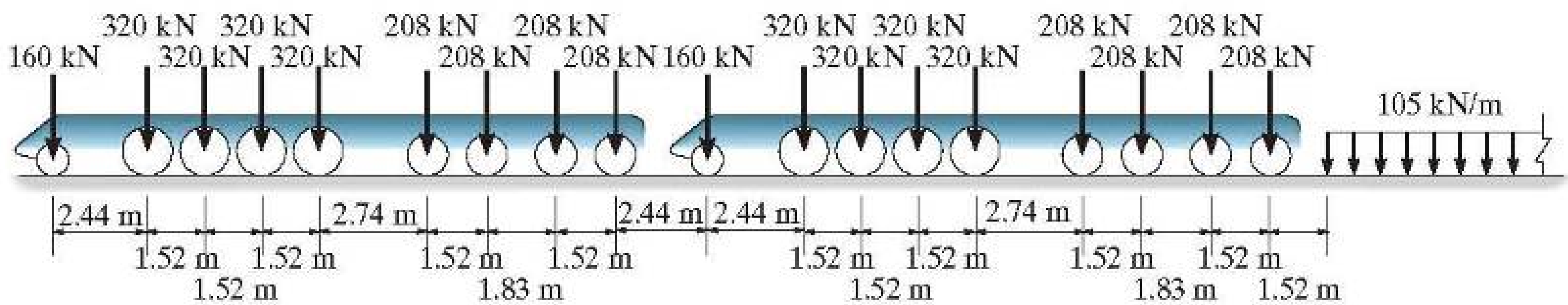
- Highway Bridge loads
  - Primary live loads are those due to traffic
  - Specifications for truck loadings are reported in AASHTO *(American Association of State Highway and Transportation Officials)*
  - For 2-axle truck, these loads are designated with H followed by the weight of truck in tons and another no. gives the year of the specifications that the load was reported



HS 20–44 loading

Loads

- Railway Bridge loads
  - Loadings are specified in AREA
  - A modern train having a 320kN (72k) loading on the driving axle of the engine is designated as an E-72 loading



E-72 loading

Loads

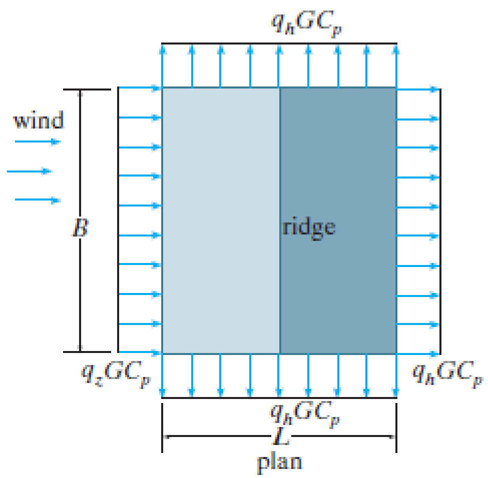
- Impact loads
  - Due to moving vehicles
  - The % increase of the live loads due to impact is called the impact factor, I

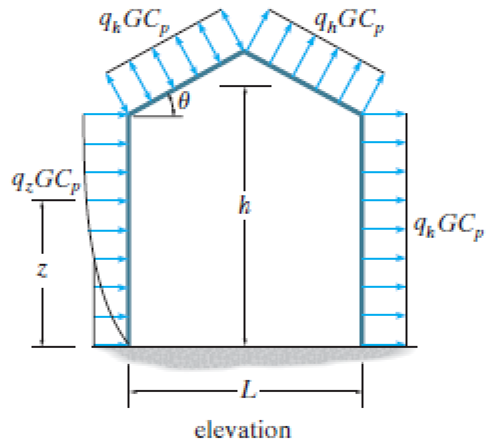
$$I = \frac{15.24}{L + 38.1} < 0.3$$

L = length of the span in m that is subjected to the live load

Loads

- Wind loads
  - Kinetic energy of the wind is converted into potential energy of pressure when structures block the flow of wind
  - Effects of wind depends on density & flow of air, angle of incidence, shape & stiffness of the structure & roughness of surface
  - For design, wind loadings can be treated as static or dynamic approach



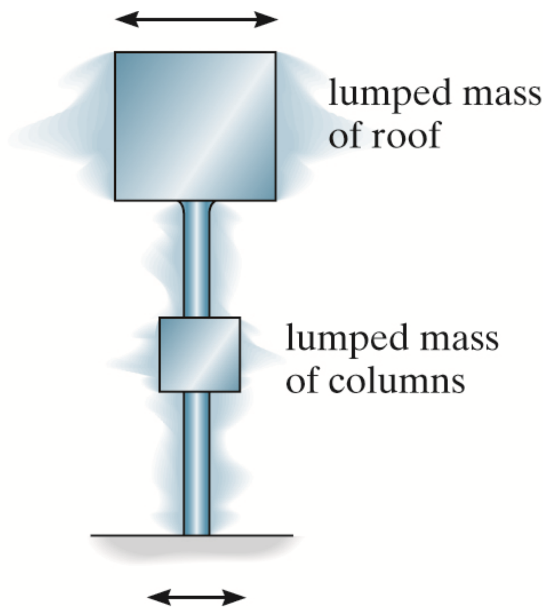


Loads

- Snow loads
  - Design loadings depend on building's general shape & roof geometry, wind exposure, location and its importance
  - Snow loads are determined from a zone map reporting 50-year recurrence interval

Loads

- Earthquake loads
  - Earthquake produce loadings through its interaction with the ground & its response characteristics
  - Their magnitude depends on amount & type of ground acceleration, mass & stiffness of structure
  - Top block is the lumped mass of the roof
  - Middle block is the lumped stiffness of all the building's columns
  - During earthquake, the ground vibrates both horizontally & vertically



Loads

- Earthquake loads
  - The horizontal accelerations create shear forces in the column that put the block in sequential motion with the ground.
  - If the column is stiff & the block has a small mass, the period of vibration of the block will be short, the block will accelerate with the same motion as the ground & undergo slight relative displacements
  - If the column is very flexible & the block has a large mass, induced motion will cause small accelerations of the block & large relative displacement

Loads

- Hydrostatic & Soil Pressure
  - The pressure developed by these loadings when the structures are used to retain water or soil or granular materials
  - E.g. tanks, dams, ships, bulkheads & retaining walls
- Other natural loads
  - Effect of blast
  - Temperature changes
  - Differential settlement of foundation

Structural Design

- Material uncertainties occur due to
  - variability in material properties
  - residual stress in materials
  - intended measurements being different from fabricated sizes
  - material corrosion or decay
- Many types of loads can occur simultaneously on a structure

Structural Design

- Allowable-stress design (ASD) methods include both the material and load uncertainties into a single factor of safety. The many types of loads discussed previously can occur simultaneously on a structure, but it is very unlikely that the maximum of all these loads will occur at the same time. For example, both maximum wind and earthquake loads normally do not act simultaneously on a structure.
- For allowable-stress design the computed elastic stress in the material must not exceed the allowable stress for each of various load combinations. Load combinations specified by the ASCE 7-02 Standard
  - Dead load
  - 0.6 (dead load) + wind load
  - 0.6 (dead load) + 0.7(earthquake load)

Structural Design

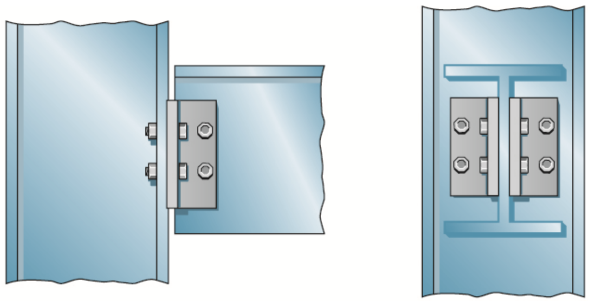
- Ultimate strength design is based on designing the ultimate strength of critical sections
- This method uses load factors to the loads or combination of loads
  - 1.4 (Dead load)
  - 1.2 (dead load) + 1.6 (live load) + 0.5 (snow load)
  - 1.2 (dead load) + 1.5(earthquake load) + 0.5 (live load)

Analysis of Statically Determinate Structures

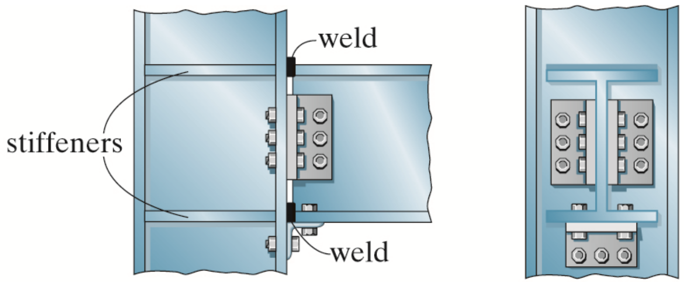
Idealized Structure

- An exact analysis of a structure can never be carried out, since estimates always have to be made of the loadings and the strength of the materials composing the structure.
- It is important to develop the ability to model or idealize a structure so that the structural engineer can perform a practical force analysis of the members
- Support Connections: Structural members are joined together in various ways depending on the intent of the designer. The three types of joints most often specified are
  - Pin connection (allows some freedom for slight rotation)
  - Roller support (allows some freedom for slight rotation)
  - Fixed joint (allows no relative rotation)

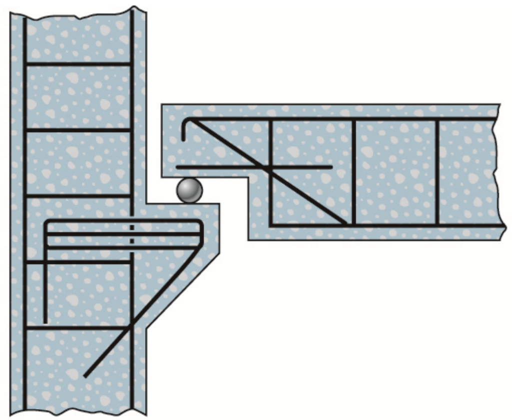
Idealized Structure



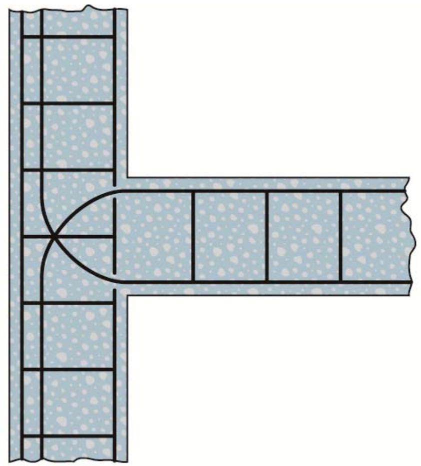
typical "pin-supported" connection (metal)



typical "fixed-supported" connection (metal)



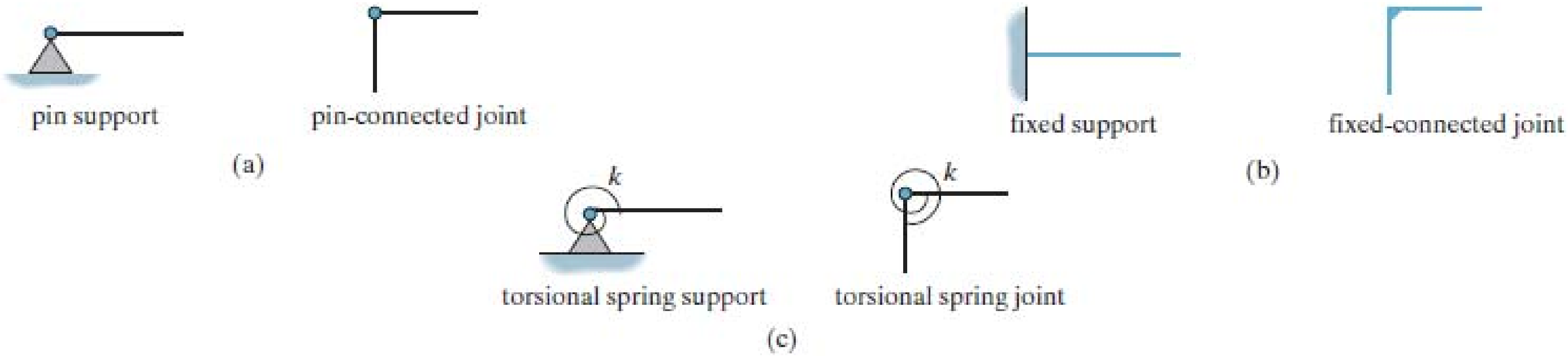
typical "roller-supported" connection (concrete)



typical "fixed-supported" connection (concrete)

Idealized Structure

Idealized models used in structural analysis that represent various support types.



Idealized Structure

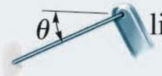
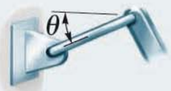
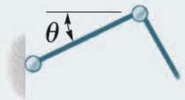
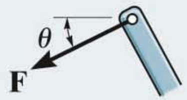
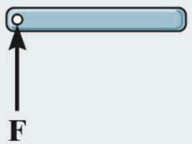
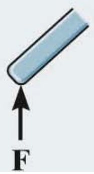
- Support Connections
  - In reality, all connections exhibit some stiffness toward joint rotations owing to friction & material behavior
  - If $k = 0$ the joint is pin and $\rightarrow \infty$, the joint is fixed
  - When selecting the model for each support, the engineer must be aware how the assumptions will affect the actual performance
  - The analysis of the loadings should give results that closely approximate the actual loadings

Idealized Structure

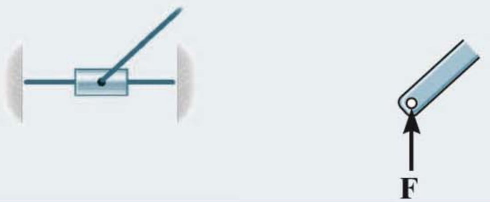
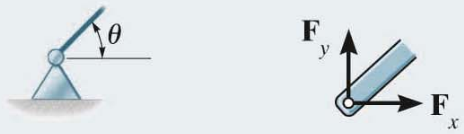
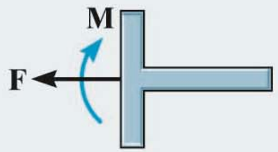
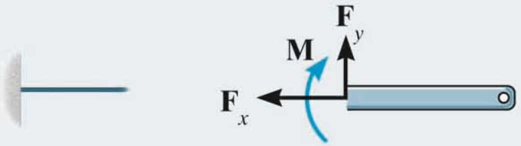
- Support Connections
  - In reality, all supports actually exert distributed surface loads on their contacting members The concentrated forces and moments shown in Table 2–1 represent the resultants of these load distributions.
  - This representation is, of course, an idealization; however, it is used here since the surface area over which the distributed load acts is considerably smaller than the total surface area of the connecting members.

Idealized Structure

TABLE 2–1 Supports for Coplanar Structures

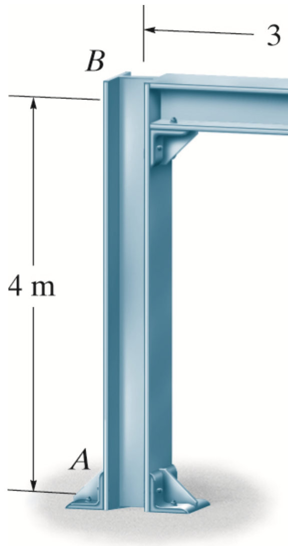
Type of Connection	Idealized Symbol	Reaction	Number of Unknowns
(1)  light cable  weightless link			One unknown. The reaction is a force that acts in the direction of the cable or link.
(2)  rollers 	 		One unknown. The reaction is a force that acts perpendicular to the surface at the point of contact.
 rocker			
(3)  smooth contacting surface			One unknown. The reaction is a force that acts perpendicular to the surface at the point of contact.

Idealized Structure

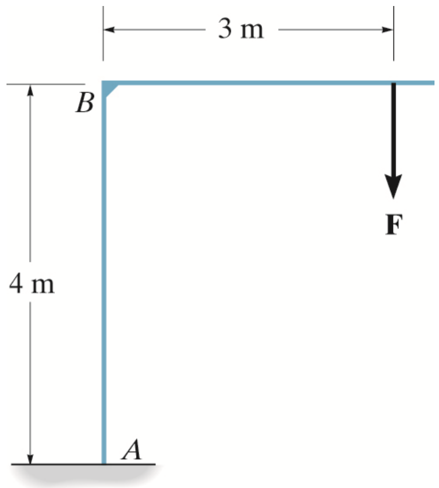
Type	Support	Idealized model / Reaction	Unknowns
(4)	 smooth pin-connected collar		One unknown. The reaction is a force that acts perpendicular to the surface at the point of contact.
(5)	 smooth pin or hinge		Two unknowns. The reactions are two force components.
(6)	 slider  fixed-connected collar	 	Two unknowns. The reactions are a force and a moment.
(7)	 fixed support		Three unknowns. The reactions are the moment and the two force components.

Idealized Structure

- Idealized Structure
  - Consider the jib crane & trolley, we neglect the thickness of the 2 main member & will assume that the joint at B is fabricated to be rigid
  - The support at A can be modeled as a fixed support



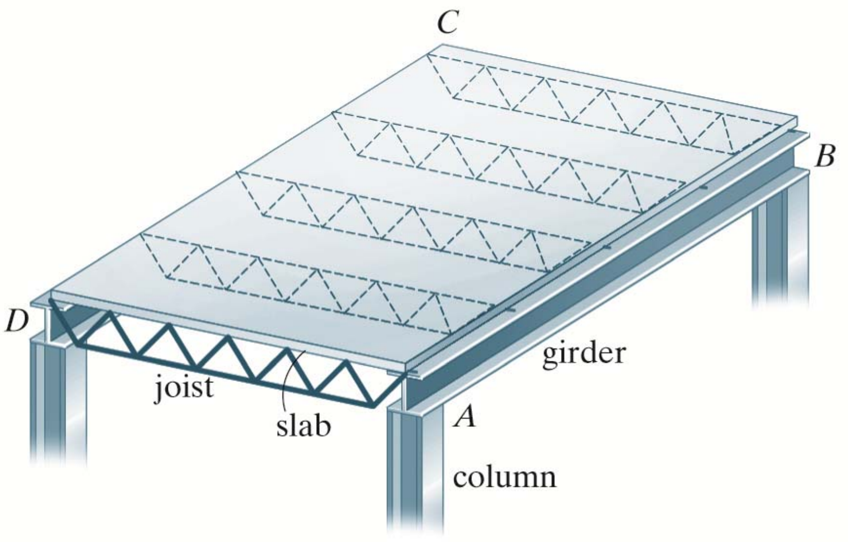
actual structure



idealized structure

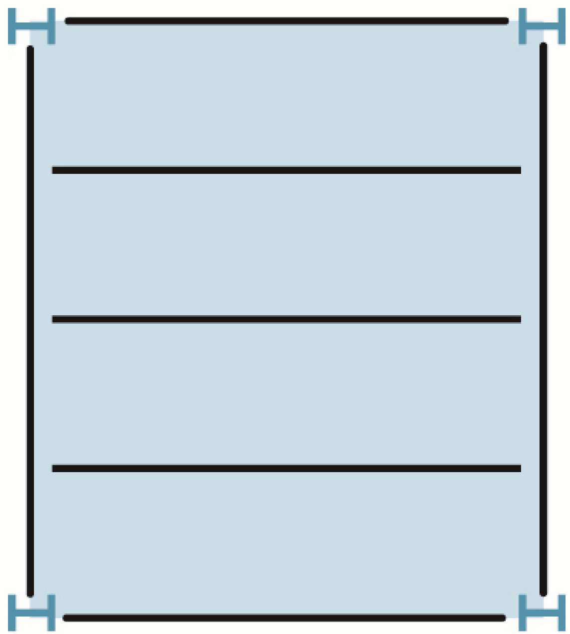
Idealized Structure

- Idealized Structure
  - Consider the framing used to support a typical floor slab in a building
  - The slab is supported by floor joists located at even intervals
  - These are in turn supported by 2 side girders AB & CD



Idealized Structure

- Idealized Structure
  - For analysis, it is reasonable to assume that the joints are pin and/or roller connected to girders & the girders are pin and/or roller connected to columns



idealized framing plan

Idealized Structure

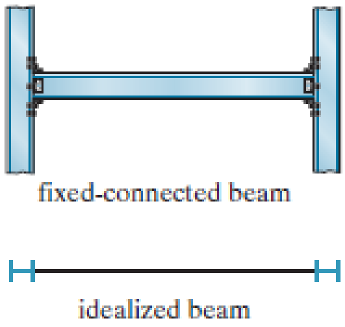


Fig. 2–7

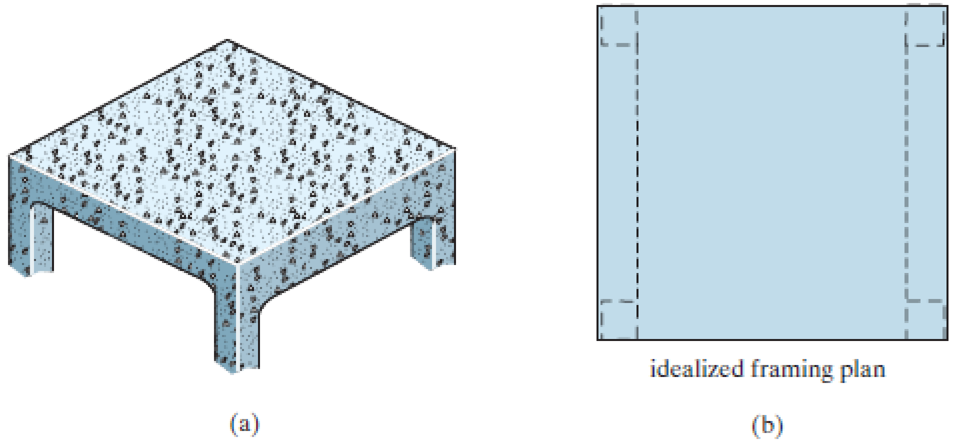


Fig. 2–9

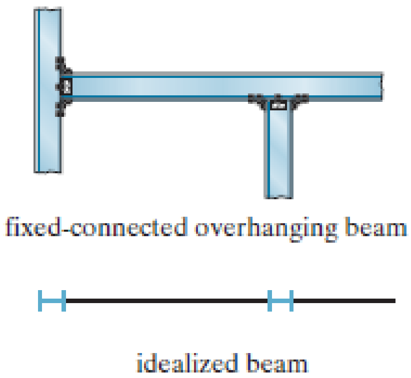


Fig. 2–8

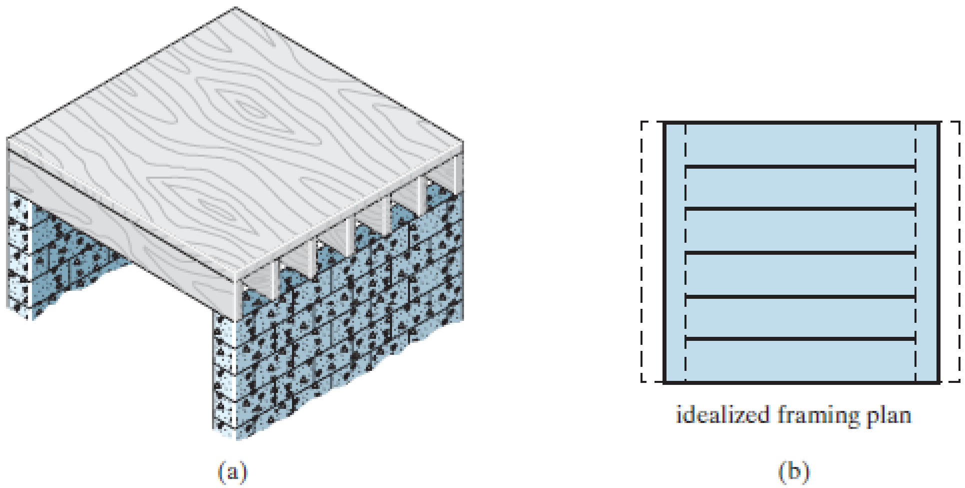


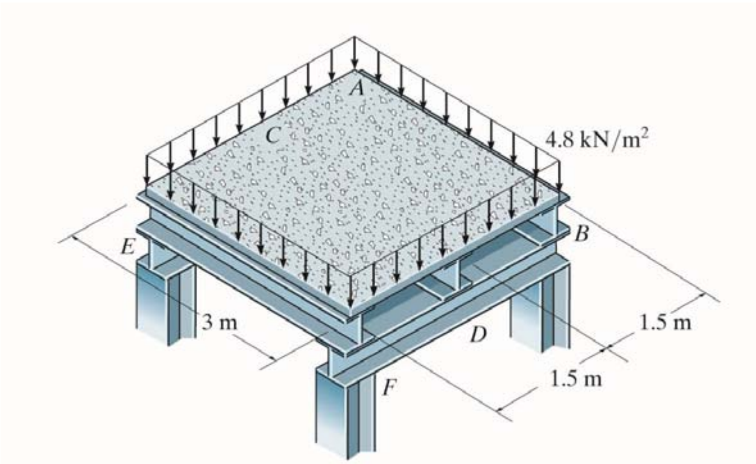
Fig. 2–10

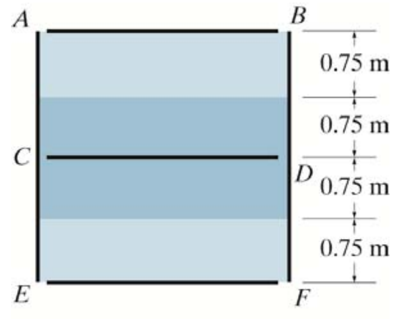
Idealized Structure

- Tributary Loadings
  - There are 2 ways in which the load on surfaces can transmit to various structural elements
    - 1-way system
    - 2-way system

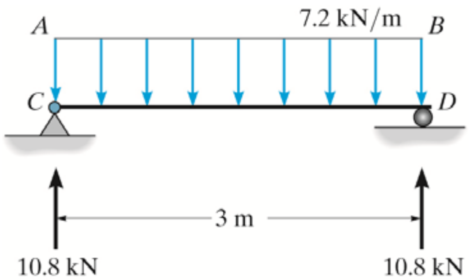
Idealized Structure

- Tributary Loadings
  - 1-way system

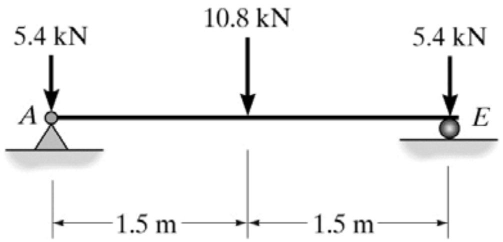




idealized framing plan



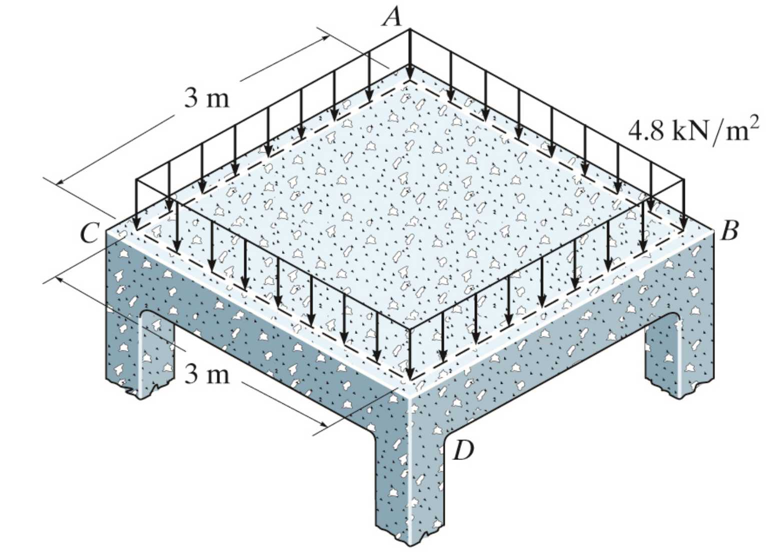
idealized beam

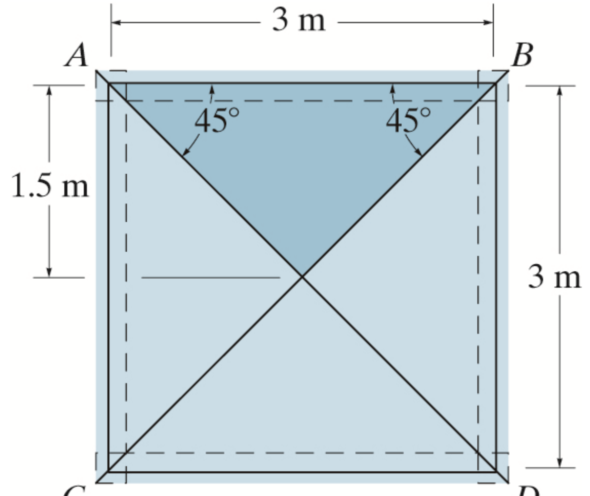


idealized girder

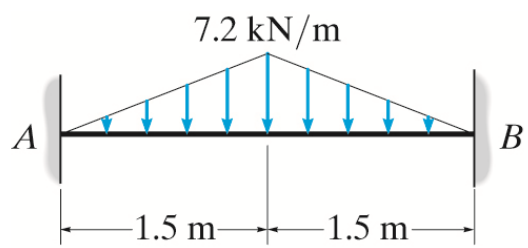
Idealized Structure

- Tributary Loadings
  - 2-way system





idealized framing plan



idealized beam

Example

The floor of a classroom is supported by the bar joists. Each joist is 4.5m long and they are spaced 0.75m on centers. The floor is made from lightweight concrete that is 100mm thick. Neglect the weight of joists & the corrugated metal deck, determine the load that acts along each joist.

Solution

Dead load, weight of concrete slab

$= (100)(0.015)$

$= 1.50 kN / m^2$

Live load $= 1.92 kN / m^2$

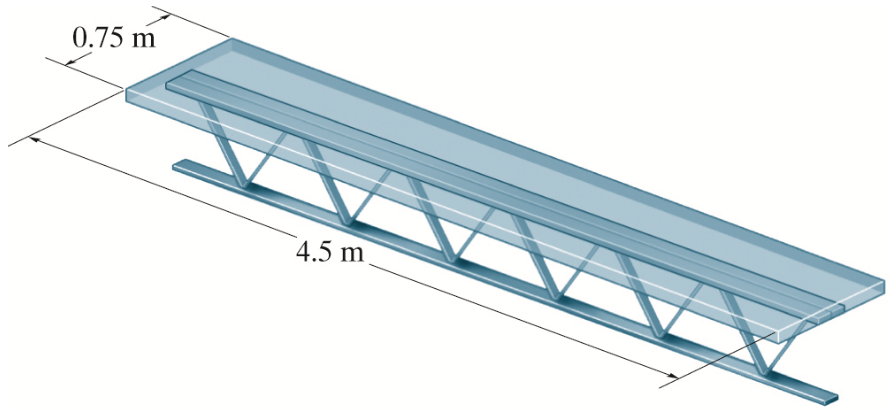
Total load $= 1.50 + 1.92 = 3.42 kN / m^2$

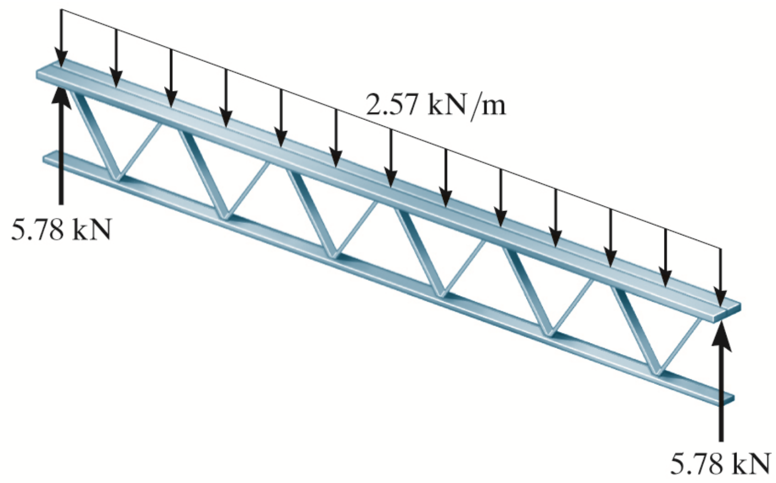
$L_1 = 0.75 m, L_2 = 4.5 m$

$L_1 / L_2 > 2 \Rightarrow$ 1-way slab

Uniform load along its length, w

$= 3.42 kN / m^2 (0.75 m) = 2.57 kN / m$





Principle of Superposition

- The principle of superposition forms the basis for much of the theory of structural analysis. It may be stated as follows:
  - The total displacement or internal loadings (stress) at a point in a structure subjected to several external loadings can be determined by adding together the displacements or internal loadings (stress) caused by each of the external loads acting separately.
- For this statement to be valid it is necessary that a linear relationship exist among the loads, stresses, and displacements.

Principle of Superposition

- 2 requirements for the principle to apply:
  - The material must behave in a linear-elastic manner, so that Hooke's law is valid, and therefore the load will be proportional to displacement.
  - The geometry of the structure must not undergo significant change when the loads are applied, i.e., small displacement theory applies. Large displacements will significantly change the position and orientation of the loads.

Principle of Superposition

- For equilibrium:

$$\sum F_x = 0 \qquad \sum F_y = 0 \qquad \sum F_z = 0$$

$$\sum M_x = 0 \qquad \sum M_y = 0 \qquad \sum M_z = 0$$

- The principal load-carrying portions of most structures, however, lie in a single plane, and since the loads are also coplanar, the above requirements for equilibrium reduce to

$$\sum F_x = 0$$

$$\sum F_y = 0$$

$$\sum M_o = 0$$

Determinacy

- Equilibrium equations provide both the necessary and sufficient conditions for equilibrium
- All forces can be determined strictly from these equations
- No. of unknown forces > equilibrium equations => statically indeterminate
- This can be determined using a free body diagram

Determinacy

- For a coplanar structure

$$r = 3n, \quad \text{statically determinate} \quad \}$$

$$r > 3n, \quad \text{statically indeterminate} \quad \}$$

r = number force and moment reaction components

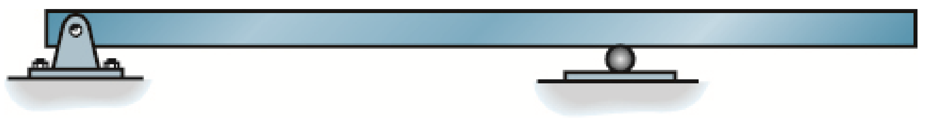
n = number of parts

- The additional equations needed to solve for the unknown equations are referred to as compatibility equations

Example

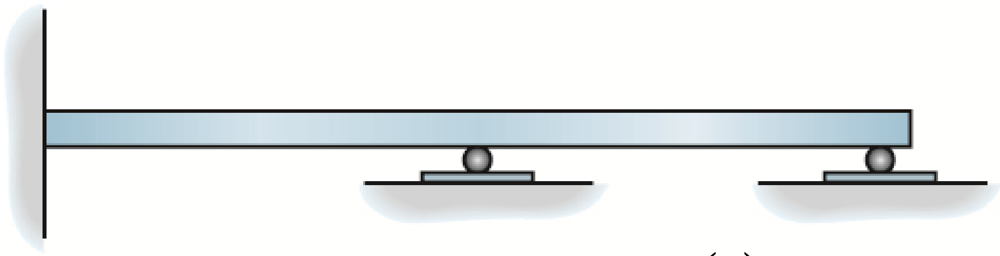
Classify each of the beams as statically determinate or statically indeterminate. If statically indeterminate, report the no. of degree of indeterminacy. The beams are subjected to external loadings that are assumed to be known & can act anywhere on the beams.

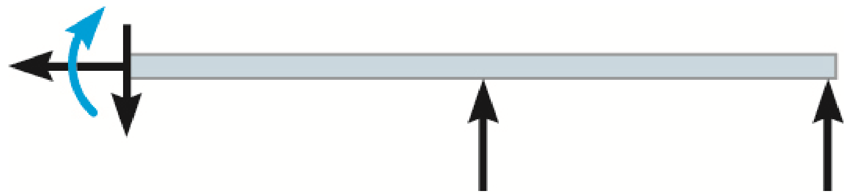
Solution



$$r = 3, n = 1, 3 = 3(1)$$

Statically determinate

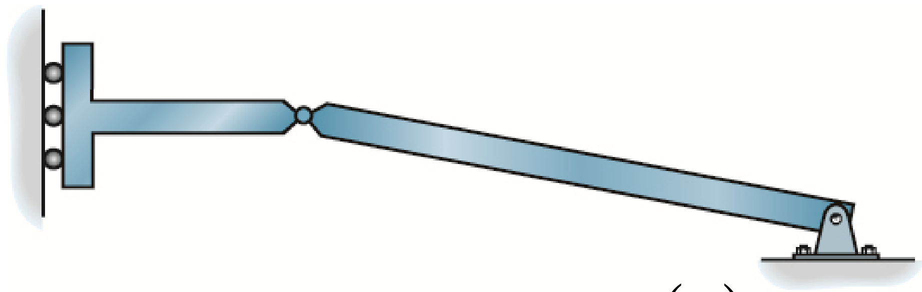




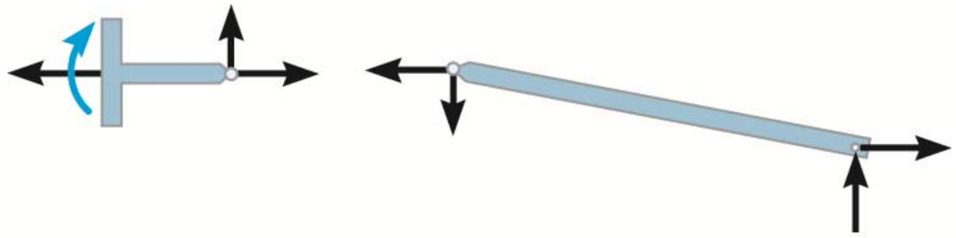
$$r = 5, n = 1, 5 > 3(1)$$

Statically indeterminate to the second degree

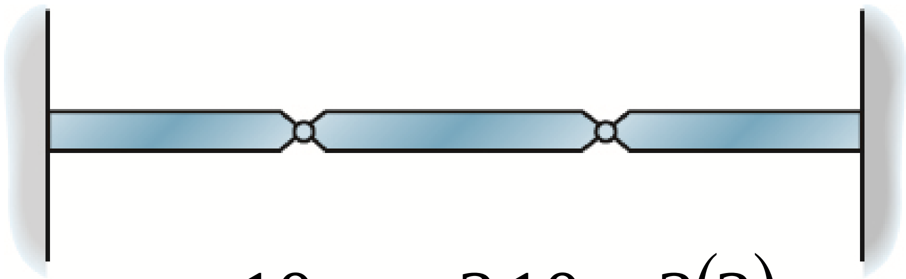
Solution



$$r = 6, n = 2, 6 = 3(2)$$



Statically determinate



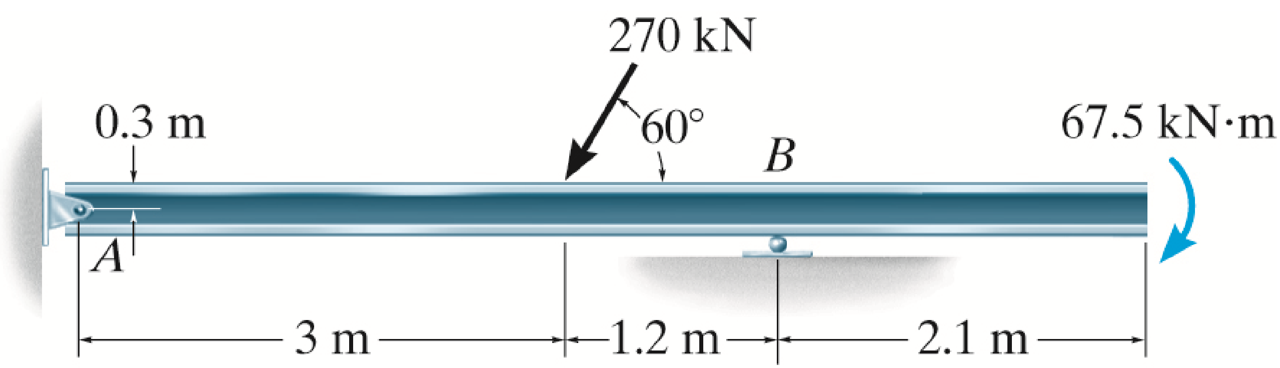
$$r = 10, n = 3, 10 > 3(3)$$

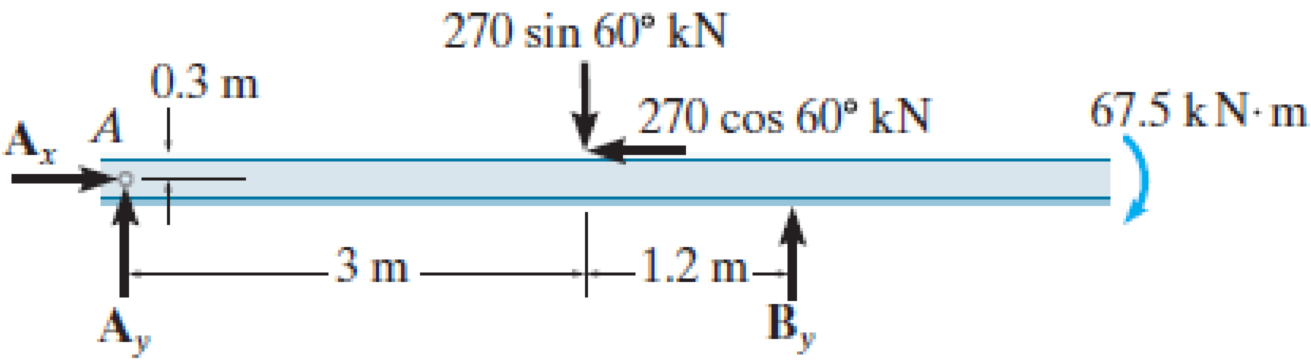
Statically indeterminate to the first degree

Example

Application of the Equations of Equilibrium

Determine the reactions on the beam as shown.





Solution

$\underset{\rightarrow}{+}\sum F_x = 0;\ \ A_x - 270\cos 60^0 = 0$

$A_x = 135\text{kN}$

With anti-clockwise moments in the $+$ direction,

$\sum M_A = 0;\quad -270\sin 60^0(3) + 270\cos 60^0(0.3) + B_y(4.2) - 67.5 = 0$

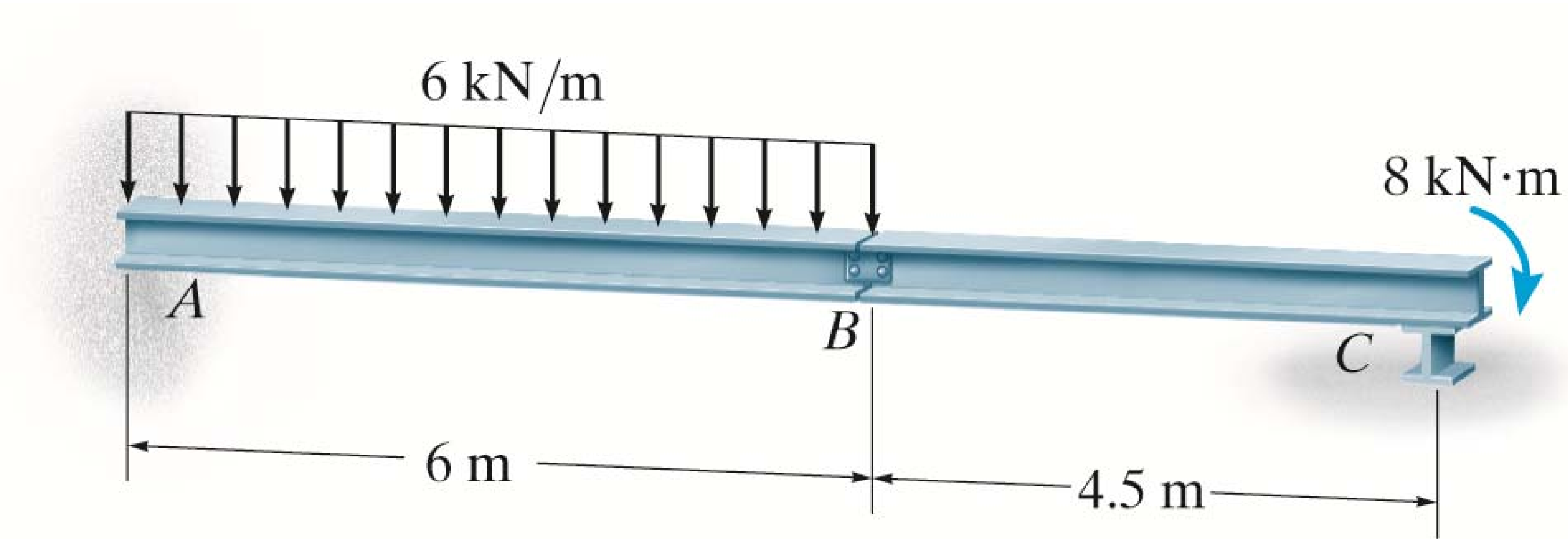
$B_y = 173.4\text{kN}$

$+\uparrow \sum F_y = 0;\quad -270\sin 60^0 + 173.4 + A_y = 0$

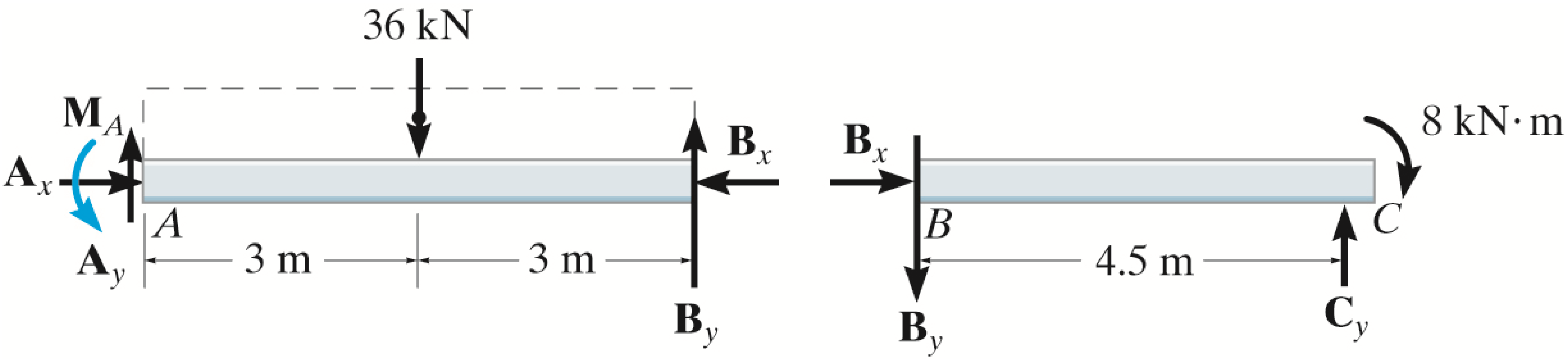
$A_y = 60.4\text{kN}$

Example

The compound beam shown is fixed at A. Determine the reactions at A, B, and C. Assume that the connection at B is a pin and C is a roller.



Solution



36 kN
8 kN·m
$\mathbf{M}_A$
$\mathbf{A}_x$
$\mathbf{A}_y$
$\mathbf{B}_x$
$\mathbf{B}_x$
$\mathbf{B}_y$
$\mathbf{B}_y$
$\mathbf{C}_y$
A
B
C
3 m
3 m
4.5 m

Solution

Segment *BC*:

With anti-clockwise moments in the $+$ direction,

$$\sum M_c = 0; \quad -8 + B_y(4.5) = 0 \quad \Rightarrow B_y = 1.78 \text{ kN}$$

$$+\uparrow \sum F_y = 0; \quad -1.78 + C_y = 0 \quad \Rightarrow C_y = 1.78 \text{ kN}$$

$$\underset{\rightarrow}{+} \sum F_x = 0; \quad B_x = 0$$

Segment *AB*:

With anti-clockwise moments in the $+$ direction,

$$\sum M_A = 0; \quad M_A - 36(3) + (1.78)(6) = 0 \Rightarrow M_A = 97.3 \text{ kN} \bullet \text{m}$$

$$+\uparrow \sum F_y = 0; \quad A_y - 36 + 1.78 = 0 \Rightarrow A_y = 34.2 \text{ kN}$$

$$\underset{\rightarrow}{+} \sum F_x = 0; \quad A_x = 0$$