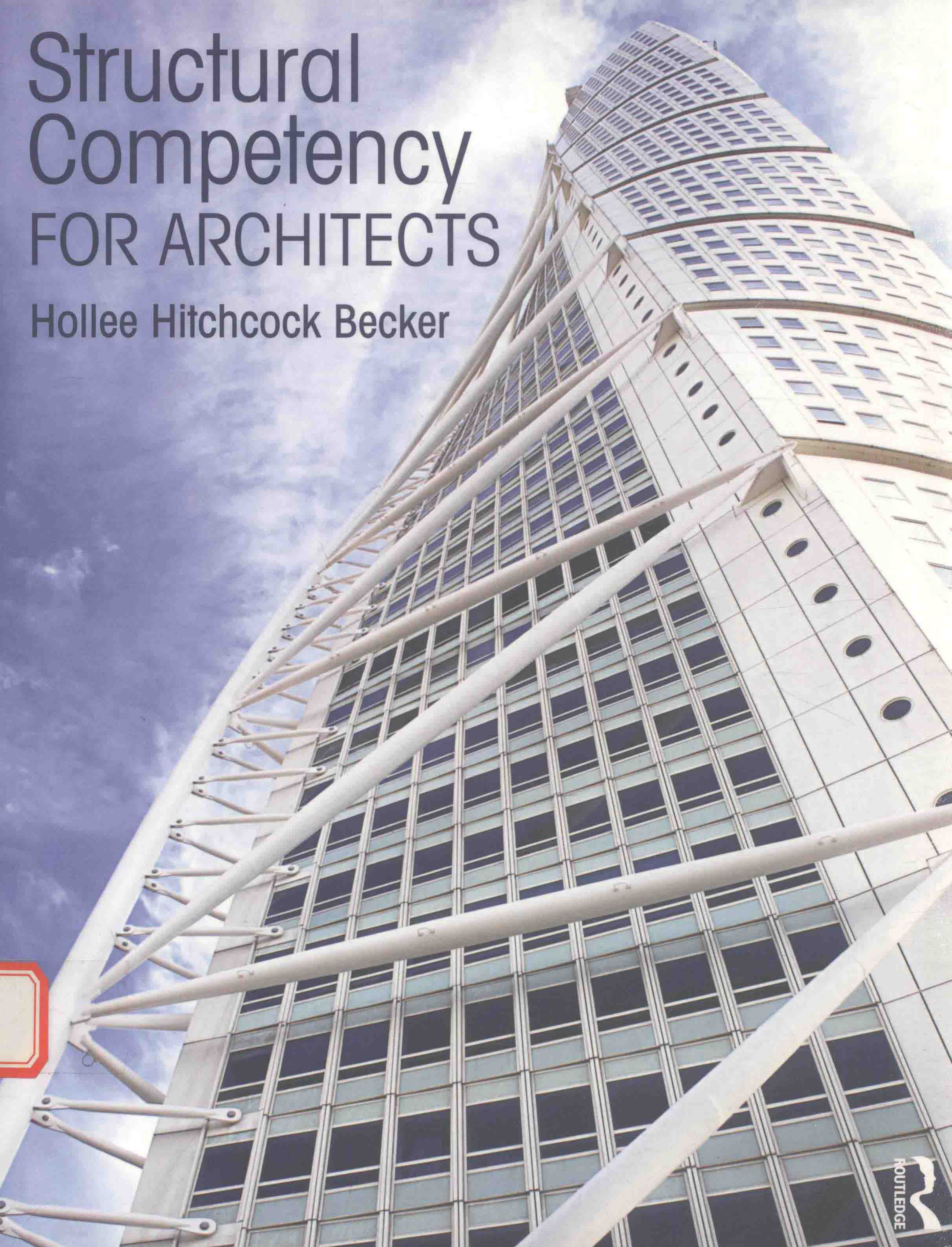
# Structural Competency FOR ARCHITECTS

Hollee Hitchcock Becker



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# Introduction

A structure is an assembly of interrelated components that serve a common purpose. Structure may present itself with a hierarchy of components as in the structure of a corporation or rely on the patterns and relationships between similar components as in the structure of molecules. In Architecture, structure is a system of interrelated components that is capable of supporting itself and transferring all loads safely to the ground.

Architects and indeed all designers should understand structures in order to communicate effectively with contractors and consultants or to design component sizes. But the most important reason to understand structures is to express the design intent or concept through the structure. Only by understanding how different structural types and materials behave will the structural system become fully integrated with the design intent.

In this book, the basic concepts of statics and strength of materials are presented first, followed by discussion of structural systems. This order allows the reader to understand how components of various systems behave in terms of the stresses they receive. After discussion of structural types, design methods for components for specific materials of wood, steel and concrete are presented.

If chemical and heat reactions are ignored, there are five basic ways to physically break an object:

1. Tension—pulling
2. Compression—pushing, crushing, squeezing
3. Flexure—bending
4. Shear—chopping, cutting, slicing, punching through
5. Torsion—twisting.

Other types of failure are a refined definition based on these basic five types. Metal fatigue, for example, is caused by the repeated bending in alternating opposite directions.

Try this experiment: Collect five identical pieces of chalk, five identical rubber bands and five identical paper clips. Test each of the three objects for tension, compression, flexure, shear and torsion by trying to break one of the identical objects by pulling, another by crushing, etc. What is noticed about the behavior of chalk compared to rubber?

The forces and reactions in tension, compression, flexure, shear and torsion are determined by statics. Statics is the physical state in which all components are at rest and in equilibrium. How or when or if a component will fail under a particular force or stress depends on the properties of the material from which it is made; the strength of the material.

This book is intended to be a simple explanation of the structural problems architecture students, designers and architects may encounter whether designing in steel, wood, concrete or an alternate material.

# Contents



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Part I

# Statics and Strength of Materials

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one

# Finding Reactions

Newton's Three Laws of Motion:

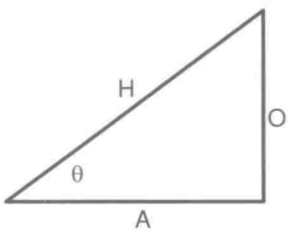
1. A body at rest will remain at rest and a body in motion will continue uniformly in a straight line unless acted upon by a force.
2. F = ma: that is, the rate of change of momentum (mv) is equal to the force producing it and in the direction of that force.
3. Every force acting upon a body at rest has an equal and opposite reaction.

Newton's third law of motion is the basis for static structural analysis. For a structure to remain static, that is, at rest and not in motion, the sum of all forces must equal zero. This means that any force applied to a component must be resisted by that component with an equal and opposite force. In order to do that, the structural component will internalize the force and transfer it to a support or another component of the structural system. The force will be transferred from component to component until it reaches the ground.

## 1.1 Vectors

It is important to understand basic trigonometric functions in order to work with vectors.

Below is a quick review.




1.1
Basic trigonometric functions

Basic trigonometric functions:

$\sin\theta = O/H$ , $\cos\theta = A/H$ and $\tan\theta = O/A$

$O = H\sin\theta$ and $A = H\cos\theta$

### 1.1.1 Vectors

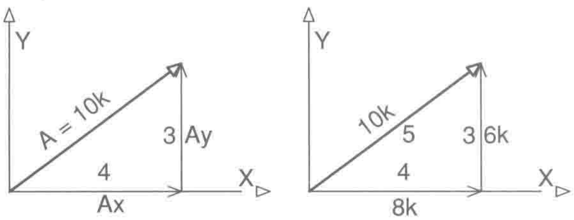
Loads or forces in architecture are described in terms of vectors. There are three necessary components that define a vector:

1. Origin or starting point
2. Direction
3. Magnitude.

The origin is the point of contact. Vector direction is expressed by its x and y relationships. Normal convention for vector direction is that a vector moving to the right is +X, a vector moving to the left is –X, a vector moving up is +Y and a vector moving down is –Y.

A vector direction can be expressed by its x and y relationships or by its angle from an axis. When a vector is expressed in terms of rise and run the ratio of the X and Y components to the full vector magnitude are equal to the ratio of the rise and run of the direction to the hypotenuse they create. This is important to remember, because it allows the vector components or magnitude to be found when only partial information is available.

**Example 1-1: Find the X and Y components of the force vector A = 10k with a rise/run of $\frac{3}{4}$.**

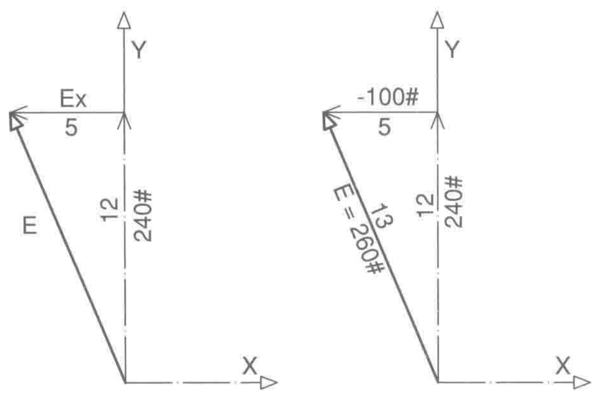



**1.2**
Vector components defined by rise and run

$$\frac{10k}{5}=\frac{A_y}{3}=\frac{A_x}{4}\ldots A_x=\left(\frac{10k}{5}\right)(4)=8 \text{ and } A_y=\left(\frac{10k}{5}\right)(3)=6k$$

Notice that vector components are tip to tail; directed so that they form an alternate route from the origin to the endpoint, indicating component directions.

**Example 1-2: Find magnitude of vector E if $E_y$ = 240.**




**1.3**
Vector magnitude defined by rise/run

1. Determine the hypotenuse of the triangle:

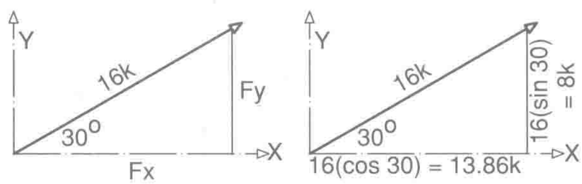
$$H=\sqrt{(5^2+12^3)}=13$$

2. Use ratios to determine the vector component E:

$$\frac{E}{13}=\frac{240\#}{12}=\frac{-E_x}{5}\ldots E=\left(\frac{240\#}{12}\right)(13)=260$$

**Example 1-3: When a vector is expressed in terms of its angle relative to an axis, use trigonometric functions to determine the components.**

The 16K force is in a direction 30° above the positive y. Because sin30° and cos30° are known, the ratio of sine or cosine to the whole is equal to the ratio of $F_y$ or $F_x$ to the vector force F = 16k.




**1.4**
Vector components defined by angle

$$\frac{F_x}{\sin 30}=\frac{16k}{1}\ldots F_x=16k(\sin 30)=16k(0.5)=8k$$

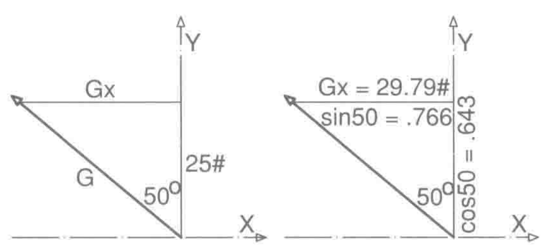
$$\frac{F_y}{\cos 30}=\frac{16k}{1}\ldots F_y=16k(\cos 30)=16k(0.866)=13.86k$$

If the vector direction is expressed in terms of the angle from the Y-axis, the results will be the same.

$$\frac{F_x}{\cos 60}=\frac{16k}{1}\ldots F_x=16k(0.5)=8k$$

$$\frac{F_y}{\sin 60}=\frac{16k}{1}\ldots F_y=16k(0.866)=13.86k$$

**Example 1-4: The ratios of sine and cosine can be used to find a vector force magnitude when only the angle from an axis and one of the components are known.**




**1.5**
Vector magnitude defined by angle

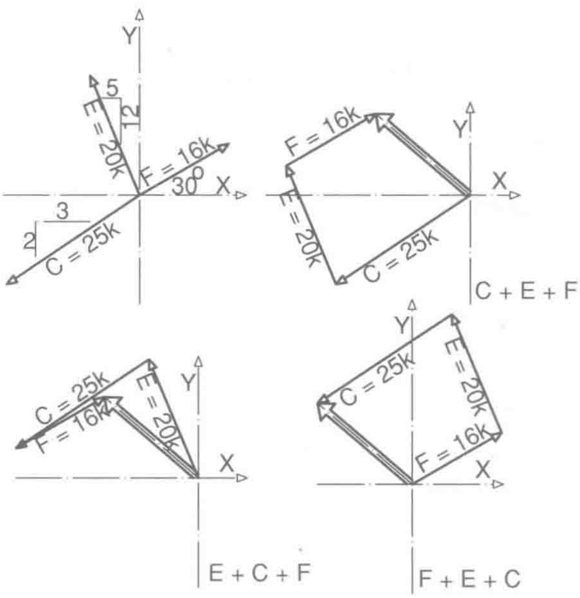
Find magnitude of force G and the horizontal component $G_x$ if the vector G is directed 50° left of the positive Y-axis and the vertical component $G_y$ = 25#.

$$\frac{G}{1}=\frac{25\#}{\cos 50}=\frac{25\#}{0.643}=38.89\#$$

$$\frac{25\#}{\cos 50}=G_x \sin 50 \ldots G_x=(25\#)\left(\frac{0.766}{0.643}\right)=29.79\#$$

## 1.1.2 Adding Vectors

The sum of vectors passing through a common point is called a resultant vector. Vectors traveling through a common point may be added graphically by connecting vectors tip to tail, in any order, starting at the origin, then finding the resultant vector by drawing a line from the origin to the endpoint. The independence of order is demonstrated in Figure 1.6 by adding three vectors in different orders. The resultant vector is always the same. Although an easy way to check an answer, it is only as accurate as the scale of drawing.




1.6
Graphically added vectors

To add vectors mathematically:

1. Break each vector into X and Y components.
2. Sum X direction components; sum Y direction components.
3. Find magnitude of resultant vector by using Pythagorean's theorem.

$$F=\sqrt{(\Sigma f_x)^2+(\Sigma f_y)^2}$$

4. Find direction of the resultant vector relative to the X-axis by using:

$$\tan^{-1}\left(\frac{f_y}{f_x}\right)$$

**Example 1-5: Adding vectors.**

Add the three vectors in Figure 1.6:

1. Find vector components:

$$C_x=\left(\frac{25k}{\sqrt{13}}\right)(-3)=-20.80k$$

$$C_y=\left(\frac{25k}{\sqrt{13}}\right)(-2)=-13.87k$$

$$E_x=(20k)\left(\frac{-5}{13}\right)=-7.69k$$

$$E_y=(20k)\left(\frac{12}{13}\right)=-18.46k$$

$$F_x = 16\cos 30 = 13.86k$$

$$F_y = 16\sin 30 = 8.00k$$

2. Sum the X components and sum the Y components.

$$\Sigma f_x = -20.8 - 7.69 + 13.86 = -14.63k$$

$$\Sigma f_y = -13.78 + 18.46 + 8.00 = 12.59k$$

3. Resultant magnitude:

$$R=\sqrt{(14.63^2+12.59^2)}=19.30k$$

4. Resultant direction:

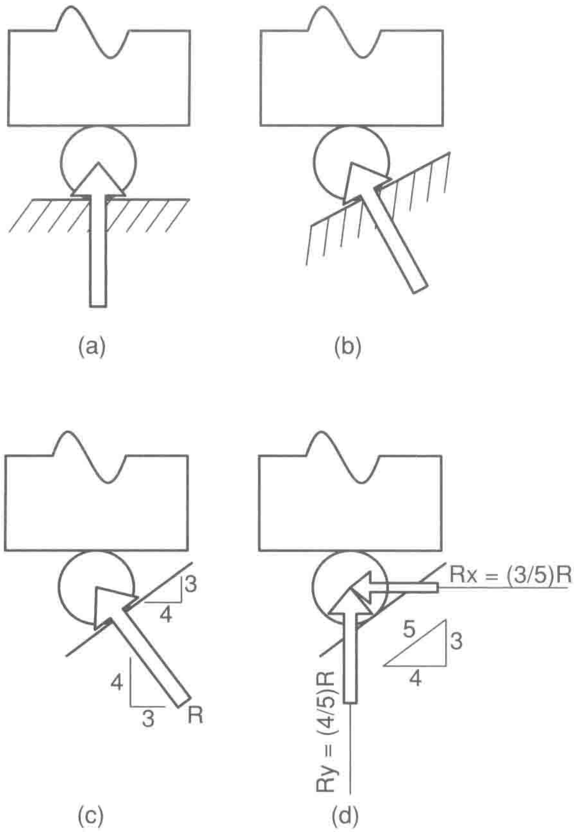
$$\theta=\tan^{-1}\left(\frac{12.59}{-14.63}\right)=-40.71 \text{ or } 40.71°$$

above the negative X-axis.

# 1.2 Supports

There are three basic types of supports to consider: rollers, pins and fixed connections.

Rollers: The reaction is a force through the roller center perpendicular to the surface on which the roller sits, whether horizontal (a) or at an angle (b).




**1.7**
Roller support

If the slope of the reaction surface is in terms of a rise (Y) over a run (X), then the slope of the reaction vector, which is perpendicular to the surface, has a rise (X) over a run (Y). Knowing this, the reaction vector components can be calculated.

If the roller support rests on a surface with a rise/run of $\frac{3}{4}$, the slope of the vector R is $\frac{4}{3}$.

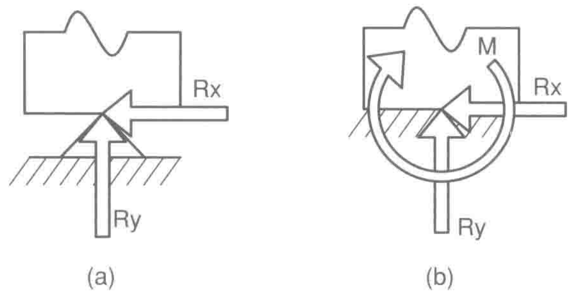
1. Determine the hypotenuse of the triangle:

$$h = \sqrt{3^2 + 4^2} = 5$$

2. Use ratios to determine the vector components $A_x$ and $A_y$:

$$\frac{R}{5} = \frac{R_y}{4} = \frac{R_x}{3} \ldots R_x = \left(\frac{R}{5}\right)(3) = 0.6R \text{ and } R_y\left(\frac{R}{5}\right)(4) = 0.8R$$

Pinned support: The reaction is a force through the pin in a direction opposite to the resultant of forces applied to the pin. It is important to remember that both pins and rollers are free to rotate. Because of this they do not transfer any rotational force called a moment through the support.



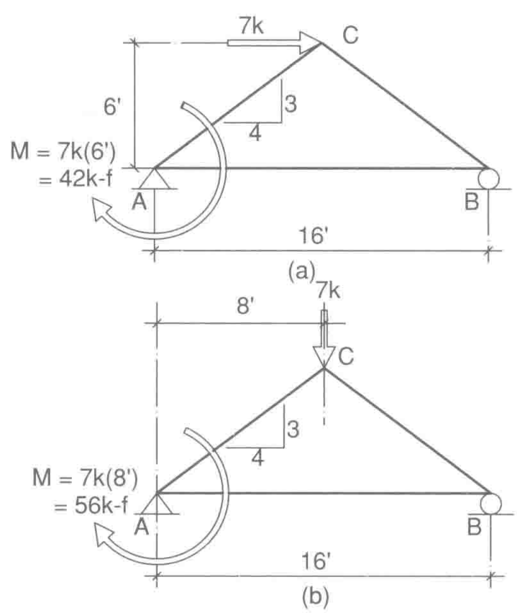

**1.8**
Pinned support (a) and fixed support (b).

Fixed support: A fixed support has a reaction in a direction opposite to the resultant of forces applied. Unlike a pinned support, a fixed support resists rotation and has a moment reaction equal to the moment applied to the support, but in an opposite direction.

## 1.3 Moments

Moment: $M_A = F(d)$

A moment about some point A is caused by a force, F, acting at a perpendicular distance, d, to the point. The units for a moment are: kip-feet (k-f), kip-inches (k-in), pound-feet (lb-ft) or pound-in (lb-in). Convention for the direction of moment is positive for a clockwise rotation and negative for a counter-clockwise rotation.




**1.9**
Direction affects moment

The rigid frame in Figure 1.9 has a horizontal 7k force applied at point C. The perpendicular distance between the line of that force and point A is 6′.

$$M_A = f(d) = 7k(6') = 42k\text{-}f$$

The rotation is clockwise, which is considered positive, therefore $M_A = 42k\text{-}f$.

The moment about point B ($M_B$) is also 42k-f because the perpendicular distance between the line of force and Point B remains 6′. The direction is still clockwise.

By rotating the 7k (b) applied at point C, the moment about point A ($M_A$) changes because the perpendicular distance between the line of the force and point A changes.

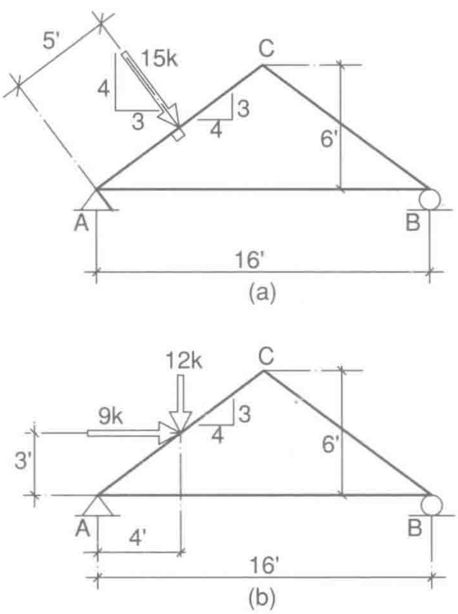
$$M_A = 7k(8') = 56k\text{-}f \text{ clockwise} = 56k\text{-}f$$

$$M_B = 7k(8') = 56k\text{-}f \text{ counter-clockwise} = -56k\text{-}f$$

The direction of a moment can be easily shown by holding a pencil loosely at the point of rotation and pushing in the direction of the applied force. The pencil will rotate in the direction of the moment.

**Example 1-6: Summing moments.**

The 15k force is applied perpendicular to and at the center of the AC leg. Find the moment about point A and B.




1.10
Summing moments

$M_A$ can be solved easily because the force is perpendicular to the leg AC.

$$\Sigma M_A = 0 = 15k(5') = 75k\text{-}f$$

The 15k must be broken into components to solve for $M_B$.

$$15k\left(\frac{4}{5}\right) = 12k\downarrow \text{ and } 15k\left(\frac{3}{5}\right) = 9k\rightarrow$$

$$\Sigma M_B = 0 = -12k(12') + 9k(3') = -117k\text{-}f$$

counter-clockwise

## 1.4 Reactions

Structure transmits loads to the ground through a series of reactions to applied forces. Before any component can be designed to handle the transfer of applied loads, the reactions at the support(s) must be found.

To solve for reactions:

1. Identify the unknowns
2. Break all forces into X and Y components
3. Sum the forces and moments at the supports:

$$\Sigma M = 0,\ \Sigma f_y = 0,\ \Sigma f_x = 0$$

### 1.4.1 Concentrated Loads

A concentrated load is a load that is applied at a single point. It is handled as a vector with magnitude (force in lb or K), direction and origin (the point at which it is applied).

**Example 1-7: Finding reactions.**

1. Identify the unknowns: The support at point A is a pin and therefore may have a reaction in the X and Y directions ($A_x$ and $A_y$). A pin cannot resist rotation and therefore has no moment transfer. The support at point B is a roller and therefore the only reaction is a force perpendicular to the support surface ($B_y$). The free body diagram (b) shows applied forces and unknown reactions.
2. Break all forces into X and Y components: The applied force is a horizontal force; it does not have a Y component.
3. Sum the forces and moments at the supports: Start by summing the moments about a pin.

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