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Mechanics of Materials

An Introduction to Engineering Technology

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Preface

There has been a need for a textbook in mechanics of materials for students in 2- or 4-year technology programs in engineering, architecture, or building construction. In addition, students in vocational schools and technical institutes will find in this book the fundamentals of statics and strength of materials that will be vital in school and in their professional lives.

This text provides the necessary information required for students of the aforementioned programs to successfully grasp important physical concepts. The material has been written in a simple way, with only some knowledge of college algebra and trigonometry required; no special engineering background or knowledge of calculus is necessary for understanding this text.

I have taught statics and strength of materials in the engineering program at Texas State Technical College-Harlingen for the past 15 years, and I have presented the material here in the same way that I would present it in the classroom. Each topic is followed by examples so the student can learn the problem solving methods and apply them in real-world problems. The student will also see a set of practice problems at the end of each topic. At the end of each chapter, there is a summary with a set of review questions and problems.

Doing the homework will give the student a much deeper understanding of the variety of concepts and encourage him/her to continue studying this fascinating branch of engineering. It goes without saying that the material in this text could also be a valuable reference for those individuals seeking state licensing in professional engineering. The students taking this class must not just read the book; they should take it as a serious and important text, concentrating on each chapter, working on the problems carefully, analyzing each problem, and trying to relate them to real-world situations or problems they are currently facing on the job site. This is how to learn engineering science. They always say that mastery of technical ideas often means hard work and concentration. Those who are not afraid of a challenge can excel!

I have organized the chapters in a simple way so the student can easily read and understand the material. I have avoided using difficult language. In fact, the book is based on the simplest educational process; I believe that in writing such a technical book this method must be followed. In Chap. 1, I introduce the basic fundamentals, definitions in mechanics of materials, and the metric and English systems of units.

I have shown examples and also included some questions and problems for the student to work on. Working on engineering problems requires a firm understanding of how to do unit conversions, because the unit conversion is the building block of engineering science. In Chap. 2, I cover force systems on structures, force components, equilibrium of forces, and the free body diagram.

Chapter 3 discusses force moments, principle of moments, moment equations for equilibrium, and application of force moments in engineering. Numerous example problems are introduced and solved throughout this chapter. Chapter 4 covers the centroid of an area, and Chap. 5 discusses the moment of inertia of an area, and many example problems are solved throughout this chapter to clarify this important concept.

Stress and strain are introduced in Chap. 6, and numerous real-world problems are solved in all the sections of the chapter. Chapter 7 covers torsion in circular sections, and discusses how to calculate the transmission of power through a rotating shaft. In Chap. 8, I explain the shear and bending moment in a beam and show many example problems for which the student might find applications in structural engineering and building construction.

Chapter 9 discusses bending stresses in beams and covers the resisting moment and flexure formulas for beams. In Chap. 10, I explain the columns and slenderness ratio for compression members. Steel and timber columns are also discussed in this chapter with example problems.

There are two appendices in this book, A and B. Appendix A shows the beam diagrams and formulas for helping the students to solve the homework problems. Appendix B provides information about the centroids and properties of areas. The students are encouraged to refer to any updated strength of materials or engineering texts to extract more information about the standard steel or timber, if necessary. Author decided not to include the tables of properties from the other current sources, because they may lack data or may be outdated.

In closing, my academic experience teaching mathematics, physics, and engineering courses for 27 years at colleges and universities in Texas, and also my practice as a professional engineer were the primary impetus for writing this book. This book will hopefully show how the fundamental concepts of mechanics of materials can be applied to real-world problems.

I wish to extend my thanks to the staff and faculty at Texas State Technical College-Harlingen, who provided me guidance, encouragement, and support. Finally, I am grateful to my loving son Reza, for his help and encouragement in making this book possible.

I have tried to produce an error-free book, but no doubt some errors still remain. Please let me know of any that you find. Comments, suggestions, and criticisms are always welcome from readers.

Harlingen, TX, USA Parviz Ghavami

Contents

Author Bios

Parviz Ghavami was born on January 10, 1943 in Iran. He obtained his early and secondary education in Esphahan. He continued his education towards a university degree and received a Master of Science degree in mechanical engineering. He stayed in the engineering field from 1965 to 1978, and worked as a design engineer and senior project engineer for overseas industries both in Iran and abroad.

Leaving Iran in 1978 to pursue further graduate studies in The United States, Dr. Ghavami obtained a Master of Science degree in mechanical engineering at the University of Portland, OR in August 1979. From 1979 until 1983, he worked as a project design engineer for consulting firms in Fort Collins, CO, and Norman, OK.

In August 1984 he joined the faculty of the Mathematics and Science Department at Texas State Technical College in Harlingen, where he taught mathematics, physics, and engineering courses. Meanwhile, in 1989, he accepted an adjunct faculty position with the University of Texas at Brownsville, TX where he taught mathematics, physics, and engineering courses.

In May1997, he received his Master of Science degree in mathematics at the University of Texas-Pan American. In May 2000, Dr. Ghavami was licensed by the Texas Board of Professional Engineers with a specialization in mechanical and civil engineering.

In May 2003, Dr. Ghavami received a Doctor of Education degree in Administration and Supervision at the University of Houston. Finally, he received his Master of Science degree in civil engineering at Texas A&M University at Kingsville in May 2011.

In the last 15 years, Dr. Ghavami, as president of Ghavami Consulting, has done a great number of projects for the construction industry in residential and commercial structural and mechanical engineering design and construction.

Dr. Ghavami enjoys traveling around the world. His hobbies are reading, gardening, listening to music, cooking, and translating science/science fiction books. In addition to his native language, Farsi, Dr. Ghavami also reads, writes, and speaks German and Russian.

1 Introduction

Overview

The importance of a thorough knowledge of fundamentals in any field cannot be overemphasized. Fundamentals have always been stressed in the learning of new skills, whether it be football or physics. Similarly, the science of mechanics is founded on basic concepts and forms the groundwork for further study in the design and analysis of machines and structures.

Learning Objectives

Upon completion of this chapter, you will be able to define the fundamental terms used in mechanics of materials, and the English or metric systems of units for different problems. You will also be able to differentiate vector and scalar quantities and identify the significance rule of these quantities in the field of mechanics of materials. Your knowledge, application, and problem solving skills will be determined by your performance on the chapter test.

Upon completion of this chapter, you will be able to:

- *Define mechanics of materials*
- *Define the fundamental terms used in mechanics*
- *Identify the main differences in the metric and English systems of units*
- *Define vector and scalar quantities with some examples*

1.1 Mechanics of Materials

Mechanics is defined as the study of the effects of forces on bodies. Statics is the study of bodies that are at rest or moving with constant velocity while subjected to force systems. When the changes of shape of the body and the internal state of the body due to the effects of external force systems become important, the study is

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then known as mechanics of materials or strength of materials. It is essential that the following basic terms be understood, since they continually recur in all phases of this technical study.

1.2 Trigonometry

To analyze the forces and work on problems in mechanics of materials or any type of engineering problems, the student must have a thorough understanding of algebraic and trigonometric functions and formulas. Solution of mechanics of materials problems requires such mathematical principles.

1.3 Metric and English Systems of Units

Units are used to define the size of physical quantities. Meter, kilogram, second, newton, and Kelvin are, respectively, units of length, mass, time, force (weight), and temperature in the metric system (SI). Foot, slug, second, pound, and degrees Rankin are, respectively, units of length, mass, time, force (weight), and temperature in English system.

The metric system (SI) offers major advantages relative to the English system. For example, the metric system uses only one basic unit for length, the meter, whereas, the English system uses many basic units for length such as inch, foot, yard, mile, etc. Also, because the metric system is based on multiples of 10, it is easier to use and learn.

The metric system of units, today, has been adopted all over the world. However, the United States is making progress toward the adoption of SI units in order to sell American products more easily on the world market. Therefore, information about the conversion factors is provided between the SI and the English system of units.

1.4 Fundamental Terms

Mass

Mass is a measure of the quantity of matter. It is related to the inertia of the body and is usually considered a constant. The unit of mass in the metric system is the kilogram.

Force

This term is applied to any action on a body which tends to make it move, change its motion, or change its size and shape. A force usually produces acceleration. The unit of force in the metric system is the newton (N) and in the English system, the pound (lb).

Example 1.1 Convert 75 lb to newtons.
(75 lb) (4.45 N/1 lb) = 334 N.

Example 1.2 Convert 150,000 newtons to pounds (lb)
(150,000 N) (1 lb/4.45 N) = 3.37×10^4 lb

Pressure
Pressure is the external force per unit area. It is calculated by dividing the total external force acting on a cross-sectional area of a body or substance. The unit of pressure in the metric system is N/m^2 (Pa), and in the English system, lb/in.^{2} (psi).

Example 1.3 Find the pressure, in metric units, that a hollow cast-iron column exerts on its foundation shown in Fig. 1.1.

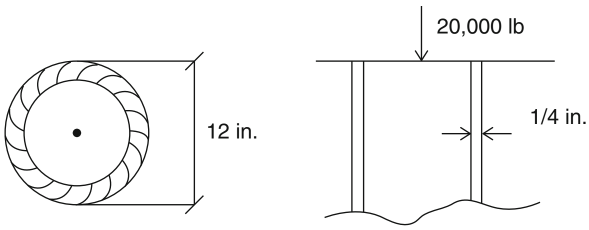


Fig. 1.1

Solution Outside diameter (OD) = 12 in.
Inside diameter (ID) = 12 − 2(0.25) = 11.5 in.
Area of the column (A) = $\pi/4(12^2 - 11.5^2)$ = 9.23 in.^{2}
Pressure (P) = Force/Area = 20,000 lb/9.23 in.^{2} = 2,167 lb/in.^{2} (psi)
Using conversion factors: 1 kPa = 1,000 N/m^2 = 0.145 lb/in.^{2}
(2,167 psi) (1 kPa/0.145 psi) = 14,944.83 kPa

Density
This term may refer either to weight or mass density. Weight density is the weight per unit volume of a body or substance. The unit of weight density in the metric system is N/m^3 and in the English system, lb/ft^3. Mass density is the mass per unit volume of a body or substance. The unit of mass density in the metric system is kg/m^3 and in the English system, slug/ft^3.

Weight
Weight is the force with which a body is attracted toward the center of the earth by gravitational pull. The unit of weight in the metric system is the newton (N), and in the English system, the pound (lb).

Example 1.4 Find the weight of a wooden block 20 cm × 15 cm × 10 cm. Assume the weight density of wood to be
$D = 227\ \text{N/m}^3$.
Find the volume of the block:
$V = \text{width} \times \text{depth} \times \text{length} = 10\ \text{cm} \times 15\ \text{cm} \times 20\ \text{cm} = 3{,}000\ \text{cm}^3$
Using conversion factors: $1\ \text{cm}^3 = 10^{-6}\ \text{m}^3$
$(3{,}000\ \text{cm}^3)\ (10^{-6}\ \text{m}^3/1\ \text{cm}^3) = 0.003\ \text{m}^3$
Find the weight of the block:
$W = \text{VD} = 0.003\ \text{m}^3 \times 227\ \text{N/m}^3 = 0.681\ \text{N}$.

Load
This term is used to indicate that a body of some weight is applying a force against some supporting structure or part of a structure. For example, a load weighing 100 lb is applied on a beam supported at two ends. Or, a beam itself can be considered a certain load on part of a structure.

Example 1.5 A brick wall 6 in. thick and 8 ft high supports a roof load equal to 1,500 lb/ft of wall. If the reinforced concrete footing of the wall is 1.7 ft deep and 2.5 ft wide, find the pressure between the footing and the soil (Fig. 1.2) (consider 1 ft of the wall).

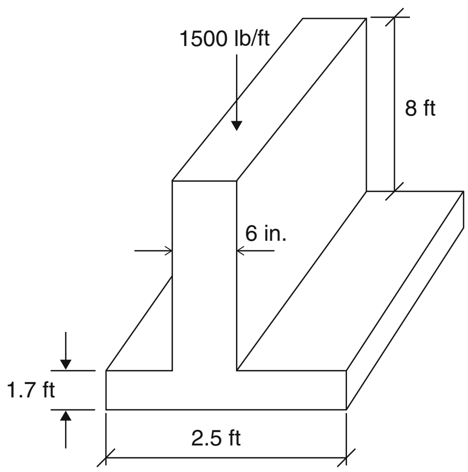


Fig. 1.2

Solution Weight per unit volume (from the table of structural materials) for brick and concrete are:

$120\ \text{lb/ft}^3$ (brick)
$150\ \text{lb/ft}^3$ (concrete)

Load on one linear foot of wall:

$$\begin{array}{lcr} 1.\,\text{Roofload} & = & 1{,}500\ \text{lb} \\ 2.\,\text{Brickwall} = (6/12\ \text{ft})(1\ \text{ft})(8\ \text{ft})\left(120\,\text{lb/ft}^3\right) & = & 480\ \text{lb} \\ 3.\,\text{Footing} = (1.7\,\text{ft})(2.5\,\text{ft})(1\,\text{ft})\left(150\,\text{lb/ft}^3\right) & = & \underline{638\ \text{lb}} \\ \text{Total load} & & 2{,}618\ \text{lb} \end{array}$$

P = force/area = 2,618 lb/2.5 ft × 1 ft = 1,047 lb/ft^2.

Moment

The tendency of a force to cause rotation about an axis through some point is known as *moment*. Moment (M) of a force (F) about a given point (O), is the product of the force and its perpendicular distance r from the line of action between the force and point O.

The point or axis of rotation is called the *center of moments*. The perpendicular distance between the line of action and the center of rotation is called the *moment arm*.

This can be formulated as:

$$M = F \times r$$

$$\text{Moment of Force} = \text{Magnitude of Force} \times \text{Moment Arm}$$

The unit of moment in the metric system is N-m, and in the English system, inch-pounds (in.-lb) or foot-pounds (ft-lb).

Example 1.6 A 10 ft beam has a load of 600 lb at a distance of 2 ft from the left end of the beam. Calculate the moment of load about each end point (Fig. 1.3).

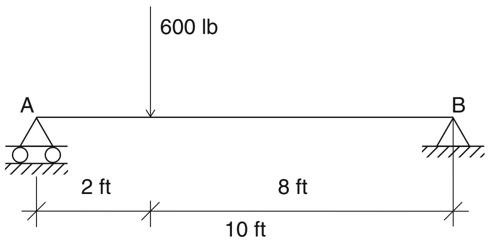


Fig. 1.3

Solution Moment of force = 600 lb × 2 ft = + 1,200 ft-lb
Moment of force = 600 lb × 8 ft = −4,800 ft-lb
Notice the sign of moment clockwise (+) and counterclockwise (−).

Example 1.7 Convert 10.94 in.-lb to newton-meters.
Using conversion factors: 1 lb = 4.45 N, and 1 in. = 0.0254 m
1 in.-lb = 0.0254 m × 4.45 N = 0.1130 N-m
Therefore, (10.94 in.-lb) (0.1130 N-m/in.-lb) = 1.24 N-m

Couple

Couple is a pair of parallel forces equal in magnitude and opposite in direction. Their only effect is to produce a moment. The only motion a couple can cause is rotation (Fig. 1.4). Note that the moment of a couple is equal to the product of one of its forces F and the perpendicular distance d between the forces

$$M = F \times d$$

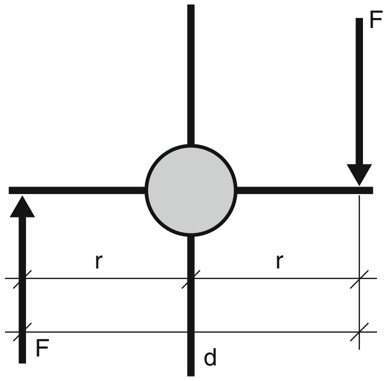


Fig. 1.4

Vector

In general, any quantity that has direction and magnitude is a vector quantity. Examples include force, weight, displacement, velocity, and acceleration, etc.

Scalar

Scalar quantities are quantities that have magnitude only. They are complete without a direction. Examples include mass, density, area, volume, distance, speed, time, temperature, work, power, etc.

1.5 Vector Operations

1.5.1 Multiplication and Division of Vectors by a Scalar

When a vector is multiplied by a scalar quantity, its magnitude will be changed. Depending on the positive or negative values of the scalar, the magnitude of the vector will be increased or decreased. In the same manner, we use this operation if we divide a vector by any positive or negative scalar quantity.

1.5.2 Addition of Vectors

There are two common graphical methods for finding the geometric sum of vectors.

Polygon method
Parallelogram method

Polygon Method
This method is mostly used in applications dealing with the addition of more than two vectors. Use a ruler and protractor to measure the size (magnitude) and direction of the vector. Measurements must be done to proper scale. Continue this process for each vector until you find the magnitude and direction of the resultant vector (Fig. 1.5).

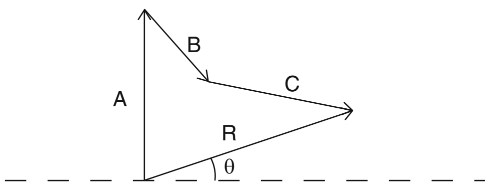


Fig. 1.5

Note that the resultant vector will be drawn with its tail at the origin (starting point) and its tip joined to the tip of the last vector. Also, the order in which the vectors are added together has no effect in obtaining the resultant of the vector.

Parallelogram Method
In the parallelogram method, the resultant of only two forces will be obtained, and the lines of actions of these two forces pass through a common origin. The two forces form the sides of a parallelogram whose diagonal will be represented as the resultant of the two forces (Fig. 1.6). In the parallelogram method, vectors **A** and **B** do not depend upon the order in which they are added. The addition of two vectors is *commutative*, and we write

$$\mathbf{A} + \mathbf{B} = \mathbf{B} + \mathbf{A}$$

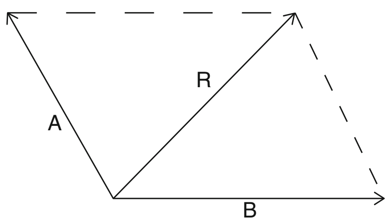


Fig. 1.6

1.5.3 Subtraction of Vectors

Subtraction of vectors **A** and **B** is obtained by adding to **A** the negative vector **B** (−**B**). We write

$$\mathbf{A} - \mathbf{B} = \mathbf{A} + (-\mathbf{B})$$

In graphical representation, **A** − **B** is constructed by connecting the tail of (**A**) to the head of (−**B**).

Subtraction is a special case of addition; therefore, vector addition rules can be applied to vector subtraction.

Example 1.8 A car is pulled out by two cables as shown (Fig. 1.7). If cable *A* is exerting 1,200 lb, find the force exerted by cable *B* needed to move the car straight out. Use trigonometric laws to work on the problem.

(Assume that the resultant of forces is directed along the axis of the car.)

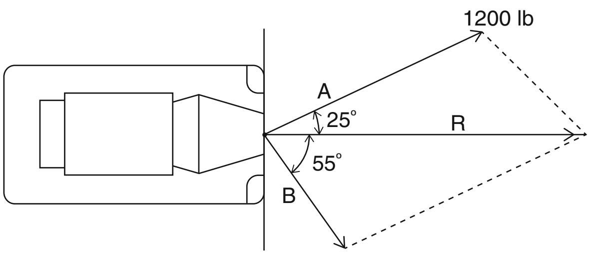
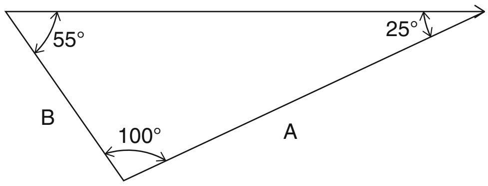


Fig. 1.7

Solution Use a triangle rule. Note that the triangle rule, in fact, is half of the parallelogram rule mentioned earlier. Notice that the resultant of the forces must be perpendicular to the front of the car to keep the car straight.

Using the triangle rule, the force on cable *B* can be calculated using the law of sines. We write

$$1,200\,\text{lb}/\text{sine}\,55^\circ \;\; = B/\sin 25^\circ$$
$$B = 619 \text{ lb}$$



Chapter Summary

1. The subject of mechanics of materials is concerned with the behavior of deformable bodies under the influence of external loads.
2. Fundamental terms such as mass, force, weight, load, density, pressure, moment, and couple are used in our subject of interest.
3. We presented the metric (SI) and English systems of units both used in engineering problems.

   You have learned the major distinction between metric and English systems of units and the advantages of the metric over the English system in our technological world.
4. The concepts of vector and scalar quantities, and how they are applied in mechanics of materials were covered. Vectors have magnitude and direction, whereas scalars are only identified by magnitude.
5. Since the vectors have magnitude and direction, they may not be added in the usual manner. For this purpose, both the polygon and parallelogram methods were presented.

Review Questions

1. What is *mechanics of materials*?
2. What is a *force*?
3. What is a *load*?
4. What is the *moment of a force*?
5. What are the major advantages of the metric system?
6. What is a major distinction between *scalar* and *vector* quantities?
7. Name some examples of scalar and vector quantities in mechanics of materials.
8. Can vectors be added or subtracted the same way as scalars? Why?
9. What method can be applied to add a number of vectors?
10. What method can only be used for the addition of two vectors?

Problems

1. Convert 12.3 ft to SI units.
2. Convert 25.6 lb to kilograms.
3. Convert 875 in.-lb to newton-meters.
4. Convert 6,000 psi to newtons per square meter.
5. Convert 3.45 lb/ft^2 to Pascals (N/m^2).
6. Convert 950 N.m to foot-pounds.
7. Convert 3.5 $in.^3$ to mm^3.
8. Convert 560 ft^2 to m^2.
9. Convert lb/ft to N/m.
10. Convert 1.6×10^9 kPa to MPa.

11. Find the moment of the forces in Fig. 1.8 about the given points:
    (a) 50,000-N force about point B,
    (b) 8,000-N force about point A, and
    (c) 10,000-N force about point A.

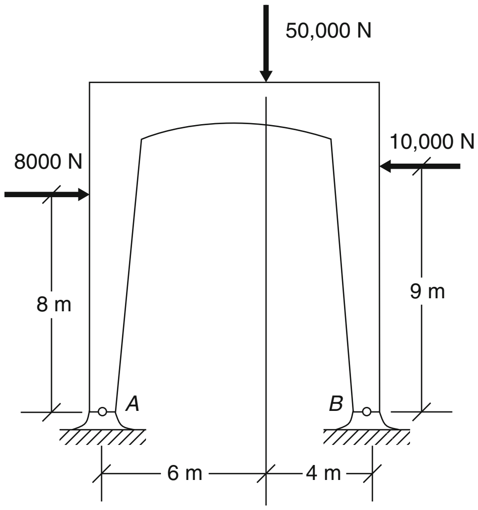


Fig. 1.8

12. State which of the following are scalars and which are vectors.
    (a) Weight
    (b) Energy
    (c) Volume
    (d) Speed
    (e) Momentum
    (f) Distance
13. Represent graphically (a) a force of 10 lb in a direction 30° north of east, (b) a force of 50 N in the direction 60° east of north.
14. Find the magnitude and direction of the resultant of the vectors **A** and **B** which are at right angles. (hint: use the Pythagorean theorem.)
    (a) $A = 15$ N, $B = 20$ N
    (b) $A = 150$ lb, $B = 250$ lb
    (c) $A = 1{,}500$ N, $B = 3{,}500$ N
15. Add the given vectors in Fig. 1.9 by drawing the appropriate resultant. Use the parallelogram in (c) and (d).

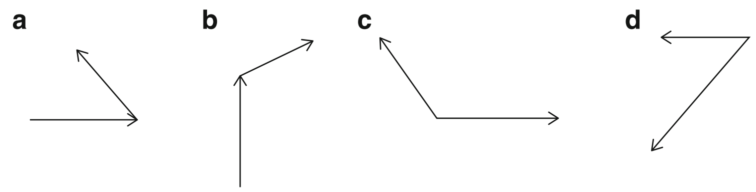


Fig. 1.9

16. Using the polygon method, add the vectors in Fig. 1.10 (choose appropriate scale).

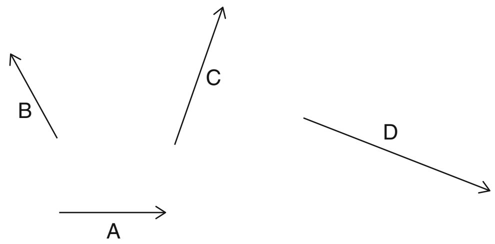


Fig. 1.10

17. Using the parallelogram law and also trigonometric rules, find the resultant of the forces on the structure shown (Fig. 1.11).

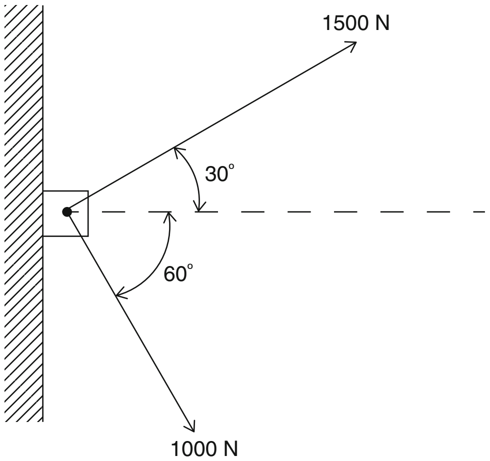


Fig. 1.11

18. Find the resultant of forces on the hook shown (Fig. 1.12) (hint: use the law of cosines.)

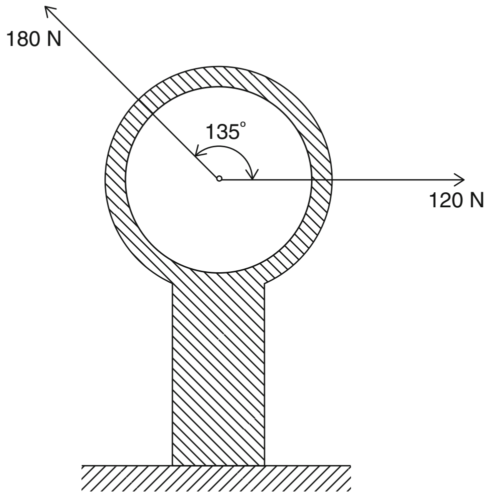


Fig. 1.12

19. Using the component method, find the resultant of the concurrent forces shown in Fig. 1.13 on the structural members A, B, and C.

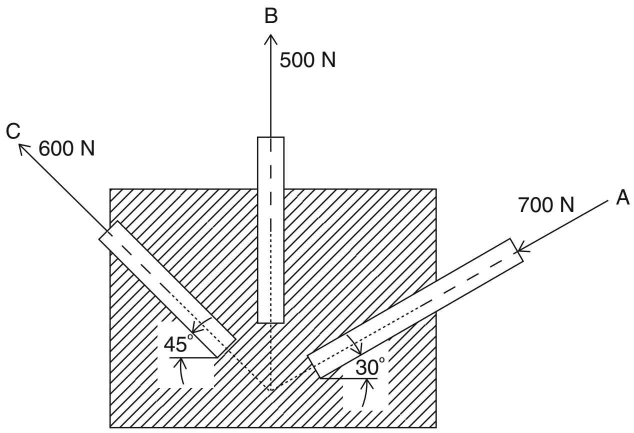


Fig. 1.13