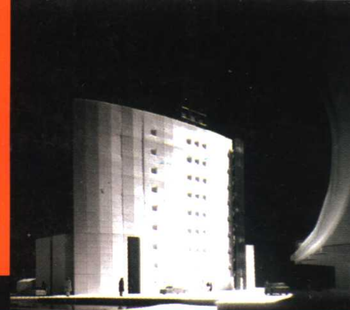
21世纪高等学校土木工程类系列教材

结构力学

（双语教材）

袁文阳 周剑波 编



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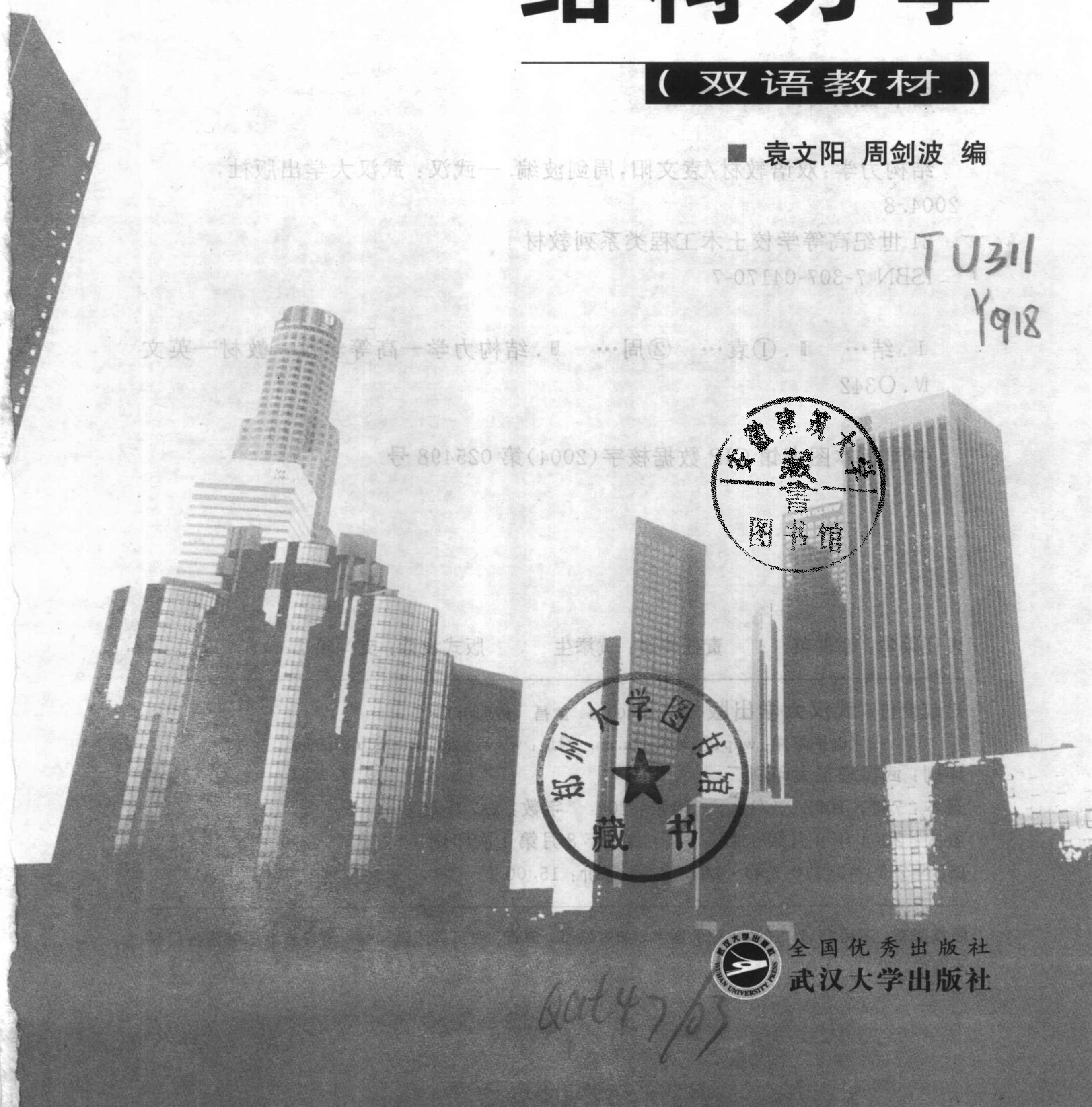

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内容提要

本书是武汉大学"十五"教材计划选定的双语教材，是二十年来结构力学专业英语教材基础上的新成果。全书共13章，基本涵盖了本科结构力学的经典内容，书中附有少量的习题，便于学生自学并促使其阅读更多的参考书以辅助学习。

本书适用于土木、水利等本科专业的结构力学双语教学。

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编者的话

本书被列入武汉大学“十五”规划教材，系武汉大学出版社组织出版的21世纪高等学校土木工程类系列教材之一，在2002年底投入编写。本着勇于探索、有所创新的原则，书中在以下几个方面作了新的尝试和安排：

一、以原结构力学专业英语教材为基础，增加了实质性的解题内容和理论分析，有别于原结构力学专业英语教材的阅读材料性质。

二、参考了大量的国内外同类教材，在编排上尽量与本科结构力学教学的格局相同，并作了比较性的探索，对于同一教学内容，加进了国外教材与本国教材不同的解题方法。

三、把提高学生的英语水平也作为本教材的目的之一，加进了科技英语的口语表达，此外还增加了数学公式和图表的文字表述（这由教师在课堂教学中体现）。

教材建设工作需要长期积累，同时又需要不断总结和翻新。本书作为正式教材出版，还是第一次，其中多有不尽如人意的地方，恳请各方指正。

本书由袁文阳统筹，周剑波选材，历时一年编写完成。陈亚鹏和周艳国参与了校对工作。

感谢武汉大学出版社的李汉保老师、谢群英老师的热情支持和大力协助。

编　　者

2004年3月于珞珈山

Contents

CHAPTER 1
Introduction

1.1 Statics of Structures Defined

By definition*, a structure (especially, an engineering structure) is anything built by man. This covers buildings, bridges power-line supports, storage tanks, railway carriages and wagons, trucks, airplanes, and a multitude of other things. In the narrower sense, a structure is the load-bearing part of a building, bridge, etc.

In this text, we shall treat as a structure any system of interconnected rigid bodies (members).

The requirements that a structure must satisfy may be summed up as follows. Above all, it must be immovable with respect to the ground (or its equivalent) and retain its original geometry throughout its service life. Also, it must be sufficiently strong, stiff, and stable so as to offer adequate resistance to the imposed loads and to keep deformations within safe limits. Finally, it must be economical of materials and inexpensive to erect.

To meet the above requirements the structural engineer must be able to propose a suitable structure, to examine its overall stability and finally, to calculate structural forces and deformations, no matter what materials (elastic or nonelastic), loads (static or dynamic), and calculation techniques are involved or used. This procedure comes under the heading of structural engineering. It widely draws on the techniques and mathematics of strength of materials and the theory of elasticity and plasticity.

The subject dealing with the calculation of reactions (that is forces and moments) and deformations (that is translations and rotations) in structures due to applied loads is known as structural analysis.

The branch of structural analysis concerned with the methods of analyzing structures for strength, stiffness, and stability under loads applied statically is termed *statics of structures*. This will be the subject-matter of the present book.

Statics of structures is closely associated with engineering mechanics and, as already noted,

* See *A dictionary of Civil Engineering* by John S. Scott. — Translator's note.

strength of materials. Strength of materials is, in turn, based on knowledge supplied by engineering mechanics and is concerned with the analysis of structural members for strength, stiffness, and stability. Statics of structures applies the techniques carried over from strength of materials and engineering mechanics to the statical analysis of structures, and serves as the foundation for related subjects in civil engineering.

To sum up, the structural analyst's contribution consists in the choice of optimal structural configurations, preliminary analysis of likely alternatives and final analysis for internal forces, elastic deformations caused by external factors, and for overall stability.

Statics of structures is not concerned with stress-strain relations as such. Nor is it supposed to assign sections to members; both are assumed to be found from strength of materials in the course of design.

It should be clear that statics of structures is an applied science and is primarily a tool for good design rather than an end in itself. This above all implies orientation towards advanced techniques in both analysis and design, and towards economy in both materials.

1.2 Basic Simplifying Assumptions

The basic simplifying assumptions employed in structural analysis cover the structure as a whole. They are as follows:

1. Within certain loading limits, the material of a structure is assumed to be ideally elastic. In other words, once a load has been removed, it leaves behind no deformation.

2. The displacements of various points of a structure, caused by elastic deformation, are assumed to be rather small compared with the size of the structure itself.

This implies that any change in the distribution of forces due to deformation may be ignored when setting up equilibrium equations (that is in finding constraint reactions and or internal forces). The analytical theory based on the premise of small structural deformations is called small deformations theory.

3. Within certain loading limits, the displacements of various points of an elastic structure are assumed to be directly proportional to the forces that cause these displacements. Such structures are referred to as linearly elastic.

4. Linearly elastic structures obey the principle of superposition which is an outcome of Hooke's law. This principle states that:

The forces and the deformations, in a linearly elastic structure, caused by the joint action of loads, are the algebraic sum of the effects of the same loads produced individually, irrespective of the sequence of their application.

1.3 The Structural Model

Real structures are usually much too complex for rational analysis; often, they have to be reduced to simplified models prior to quantitative treatment. This modeling is one of the most important jobs of the analyst and requires experience and judgement so that the resulting model strikes a happy compromise between reality and simplicity. In this book, the numerous "structures" discussed and shown are really only models of the real things.

Basically, a model of a structure is a simplified picture of the main factors governing its behavior under load. The correct choice of a model is a complex and critical task, and depends on the accuracy of analysis required.

As an illustration, consider a single-span railway bridge (Fig. 1.1(a)) which generally consists of two vertical plane trusses joined together by lateral braces and a deck. The deck is assembled from floor beams with their ends fixed to the trusses, and stringers which are connected to and rest on the floor beams. The truss members are rigidly welded or riveted to one another at the ends. The bridge carries a vertical load due to the self-weight of the train, and a horizontal wind load.

(1) two vertical trusses ACC_1A_1 and BDD_1B_1 whose structural models are shown in Fig. 1.1(b);

(2) a horizontal truss CC_1D_1D lying between the top chords of the main vertical trusses and resisting wind loads (its structural model is shown in Fig. 1.1(c));

(3) two lateral supporting frames ACDB and $A_1C_1D_1B_1$ whose structural models are shown in Fig. 1.1(d).

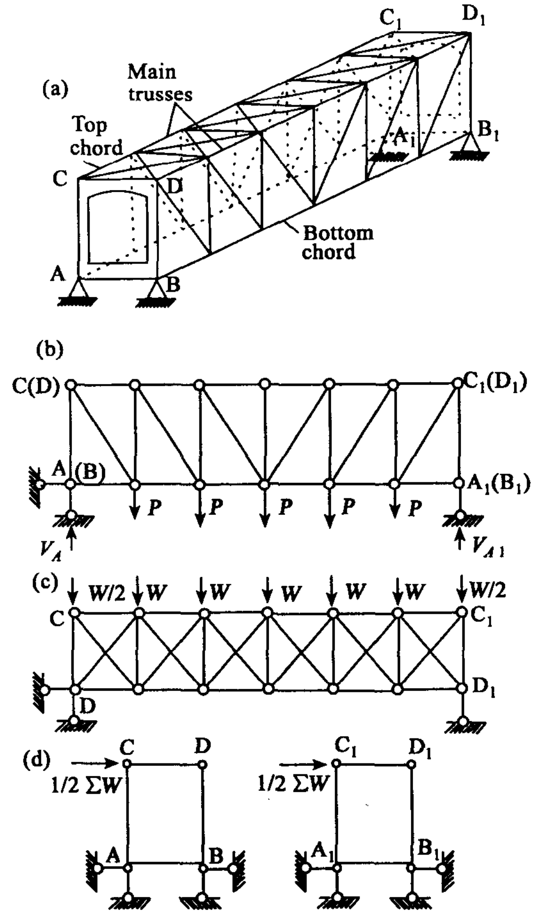

Fig. 1.1

1.4 Classification of Structures

Structures may be classified in various ways:

(1) According as their components lie in a plane or in space, structures may be categorized as:

(a) *Plane structures*. These lie in one plane which also contains their loads (Fig. 1.2). Only plane structures are discussed in this Chapter.

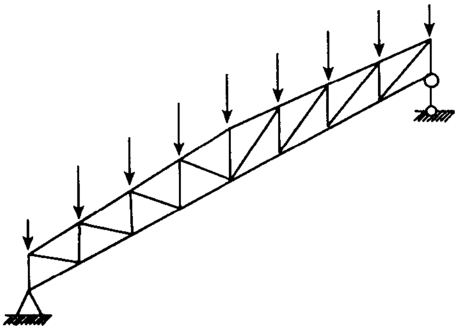

Fig. 1.2

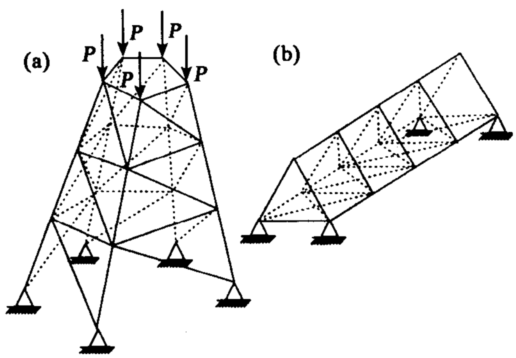

Fig. 1.3

(b) *Space structures*. These lie in space, and loads may act on them along any direction (Fig. 1.3 (a) and (b)). Such structures have only been mentioned to make the discussion complete.

(2) According to the type of their members, structures may further be classed into:

(a) *Framed structures* . These consists of one-dimensional members, that is, those for which one dimension is much larger than the other two. Framed structures include beams, trusses, frames, and arches (Fig. 1.4(a), (b), (c), and (d)).

(b) *Thin-walled* (*two-dimensional*) *structures* . The thickness of such structures is much smaller than the other two dimensions. There are also commonly referred to as plate structures, if their members are plates (Fig. 1.5(a)), or *shell* structures, if their members are shells (Fig. 1.5(b)).

(c) *Massive structures*. For similar reasons, these are also termed three-dimensional structures. They include retaining walls (Fig. 1.6), masonry vaults (Fig. 1.7), dams, and footings analyzed and designed per metre run.

(3) According to the direction of their support reactions, structures may be classed into:

(a) *Thrust-free structures* . When subjected to a vertical load, these develop only vertical supports reactions (Fig. 1.8(a), (b), and (c)).

(b) *Thrust-developing structures* . These develop inclined support reactions which may be resolved into vertical and horizontal components. The latter component is called the thrust. Thrust-developing structure includes arches, vaults, frames (Fig. 1.9(a) and (b)), and arched and cable-stayed trusses (Fig. 1.9(c) and (d)).

(4) According to the manner in which they can be analyzed, structures are divided into: (a) *statically determinate structures* which can completely be analyzed by statics alone; (b) *statically indeterminate structures* which cannot be analyzed by statics alone. For their solution, redundant structures (as statically indeterminate structures are also frequently called) require that the three equations of statics (the equilibrium equations) be supplemented by compatibility equations which take care of their geometry.

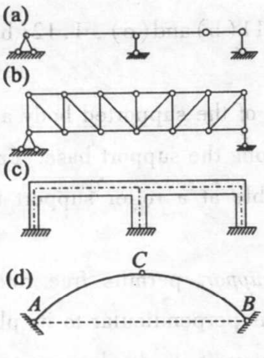

Fig. 1.4

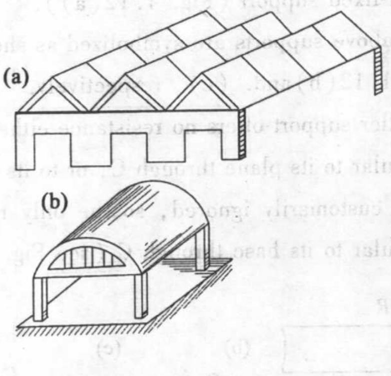

Fig. 1.5

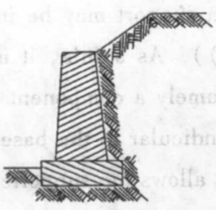

Fig. 1.6

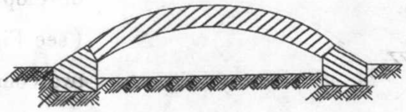

Fig. 1.7

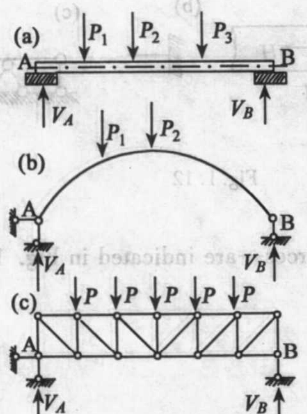

Fig. 1.8

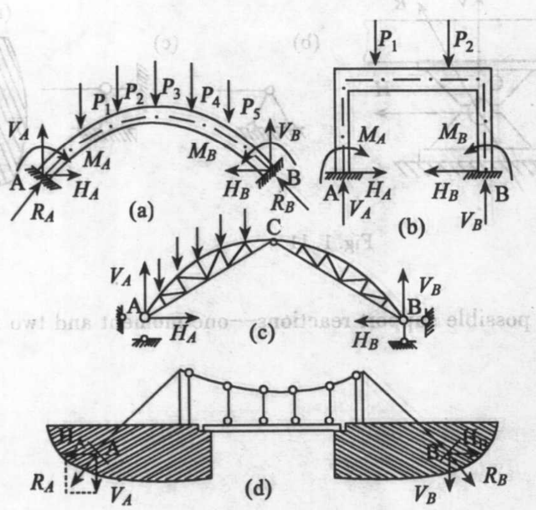

Fig. 1.9

1.5 Supports for Plane Structures

All structures have to be supported suitably. The following three types of support are in common use:

1. A roller support (also called a movable hinged support) (Fig. 1.10(a)).
2. A hinged support (also called an immovable hinged support) (Fig. 1.11(a)).

3. A fixed support (Fig. 1.12(a)).

The above supports are symbolized as shown in Figs. 1.11(b)and(c), 1.12(b) and (c), and Figs. 1.12(b)and. (c), respectively.

A roller support offers no resistance either to the rotation of the supported body about an axis perpendicular to its plane through C, or to its displacement along the support base. Friction at the support is customarily ignored, so the only reaction R possible at a roller support is along the perpendicular to its base through C (see Fig. 1.10(a)).

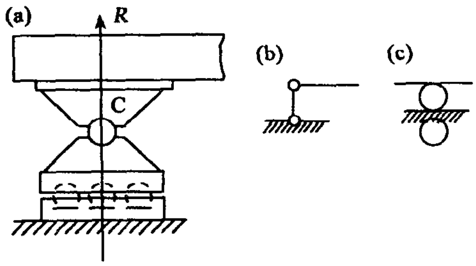

Fig. 1.10

A hinged support permits free rotation of the body about an axis perpendicular to its plane through C, but does not permit its displacement either along or perpendicular to the base. The reaction R developed at such a support may be in any direction (see Fig. 1.11(a)). As a rule, it is resolved into two components, namely a component H along and a component V perpendicular to the base.

A fixed support allows the supported body neither in-plane rotation nor translation in any direction. The three possible support reactions—one moment and two reactive forces—are indicated in Fig. 1.12 (a).

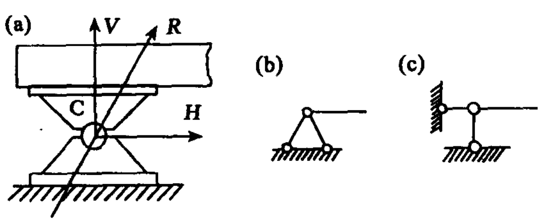

Fig. 1.11

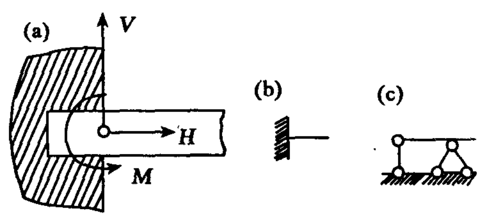

Fig. 1.12

CHAPTER 2

Stability

2.1 Stable and Unstable Structures

As already mentioned in Chapter 1, any structure must retain its original geometry throughout its service life. This requirement is met by what are called stable structures.

To gain insight into this matter, consider a structure made up of three bars hinged to one another at the ends to form a triangle ABC (Fig. 2.1(a)). The geometry of such a triangle will obviously remain unchanged, whatever position it may occupy in space, because three bars of constant length can form only one triangle. If we load the triangle by a force as shown in Fig. 2.1(b), it will nevertheless change its shape, although very insignificantly (see triangle AB_1C_1), —a fact which can be attributed to the elastic deformation of its members alone.

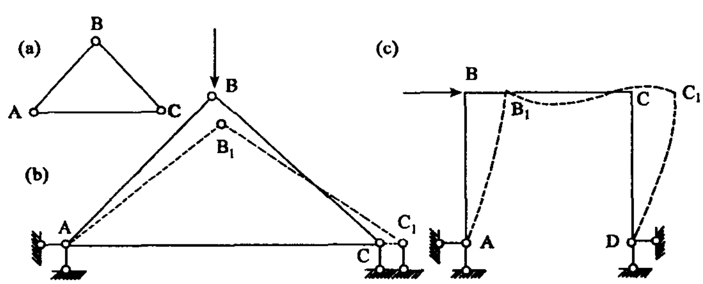

Fig. 2.1

Thus, a structure may be called *stable* if its shape remains unchanged, whatever, the position is in space.

A characteristic feature of a stable structure loaded within reasonable limits is the ability to

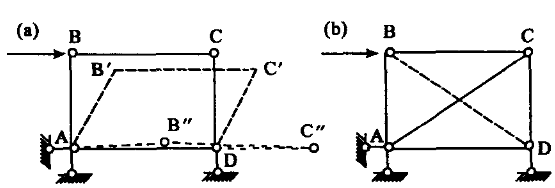

Fig. 2.2

change its shape only insignificantly as a result of elastic deformation of its members. By elastic deformation is meant a change in the size of the constituent members as shown in Fig. 2.1(b), or a change in both the size and shape of the members as shown in Fig. 2.1(c).

A stable structure is amenable to small deformations theory and, as a consequence, to the principle of superposition.

The simplest stable structure is a triangle (sometimes called a basic triangle).

A structure whose shape changes suddenly when its position in space is altered or when it is subjected to a load, however small, is *unstable*.

A characteristic feature of an unstable structure is that any change in its shape is associated with finite displacements of its members without deformation.

As an example, consider the pin-jointed rectangle ABCD shown in Fig. 2.2(a). It is unstable, because even an infinitesimal load will force its members AB, BC, CD, and DA to change their position without any change in length or shape. At first, the loaded rectangle becomes the shape of a parallelogram AB′C′D. Then, its sides collapse, as it were, on one another to form an almost straight line AC″composed of segments AB″, B″C″,C″D, and DA.

If we add a diagonal bar AC (Fig. 2.2(b)) or BD (shown by the dashed line) to the original rectangle, the structure thus derived will be stable.

In practice, use is predominantly made of stable structures fixed to the ground (or its equivalent) so that they will not move, or internally unstable structures attached to the ground so as to form a stable system.

2.2 Arrangement of Truss Members

A detailed discussion of the assembly of trusses has been delayed until this chapter so that the reader will have had some contact with the elementary types. The background should enable him or her to understand the material to follow more easily.

The triangle has been shown to be the basic shape from which trusses are developed because it is the only stable shape. Other shapes such as the ones shown in Figs. 2.3(a) and (b) are obviously unstable and may possibly collapse *underload*. Structures such as these can, however, be made stable by one of the following methods.

1. Addition of members so that the shapes are made to consist of triangles. The structures of Fig. 2.3(a) and (b) are stabilized in this manner in (c) and (d), respectively.

2. Using a member to tie the unstable structure to a stable support. Member AB performs this function in Fig. 2.3(e).

3. Making some or all of the joints of an unstable structure rigid, so they become moment resisting. A figure with moment-resisting joints, however, does not coincide with the definition of a truss (that is, members connected with frictionless pins, and so on).

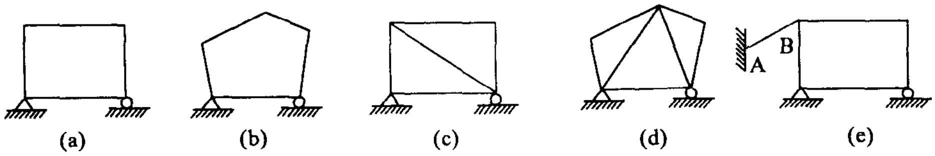

Fig. 2.3

2.3 Statical Determinacy of Trusses

The simplest form of truss, a single triangle, is illustrated in Fig. 2.4(a). To determine the unknown forces and reaction components for this truss, it is possible to isolate the joints and write two equations, $\sum H = 0$ and $\sum V = 0$, for each. From experience obtained before there should be little difficulty in making the necessary calculations.

The single-triangle truss may be expanded into a two-triangle one by the addition of two new members and one new joint. In Fig. 2.4(b), triangle ABD is added by installing new members AD and BD and the new joint D. A further expansion with a third triangle is made in part (c) of

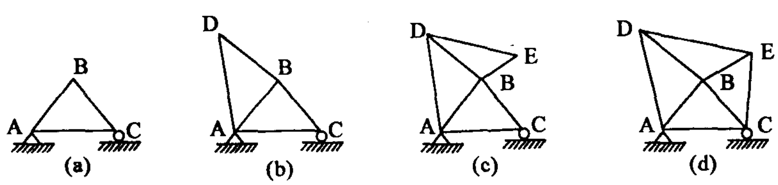

Fig. 2.4

the figure by the addition of members BE and DE and joint E. For each of the new joints, D and E, a new pair of equations is available for calculating the two new-member forces. As long as this procedure of expanding the truss is followed, the truss will be statically determinate internally. Should new members be installed without adding new joints, such as member CE in Fig. 2.4(d), the truss will become statically indeterminate because no new joint equations are made available to find the new member forces.

From the information above an expression can be written for the relationship that must exist between the number of joints and the number of members and reaction components for a particular truss if it is to be statically determinate internally. In the following discussion, m is the number of member, j is the number of joints, and r is the number of reaction components.

If the number of equation available ($2j$) is sufficient to obtain the unknowns, the structure is statically determinate, from which the following relation may be written:

$2j = m + r$

Or as more commonly written,

$m = 2j - r$

Before an attempt is made to apply this equation, it is necessary to have a structure that is stable externally or the results are meaningless; therefore r is the least number of reaction components required for external stability. Should the structure have more external reaction components than necessary for stability (and thus be statically indeterminate externally), the value of r remains the least number of reaction components required to make it stable externally. This statement means that r will equal three for the usual statics equations plus the number of any additional condition equations that may be available.

It is possible to build trusses that have too many members to be analyzed by statics, in which case they are statically indeterminate internally, and m will exceed $2j - r$ because there are more members present than are absolutely necessary for stability. The extra members are said to be redundant members. If m is three greater that $2j - r$, there are three redundant members, and the truss is internally statically indeterminate to the third degree. Should m be less that $2j - r$, there are not enough members present for stability.

A brief glance at a truss will usually show if it is statically indeterminate. Trusses having members that cross over each other or members that serve as the sides for more two triangles may quite possibly be indeterminate. The $2j - r$ expression should be used, however, if there is any doubt about the determinacy of a truss, because it is not difficult to be mistaken. Figure 2.5 shows several trusses and the application of the expression to each. The small circles on the trusses indicate the joints.

Little explanation is necessary for most of the structures shown, but some remarks may be helpful for a few. The truss of Fig. 2.5(e) has five reaction components and is statically indeterminate externally to the second degree; however, two of the reaction components could be removed and leave a structure with sufficient reactions for stability. The least number of reaction components for stability is 3, m is 21, and j is 12; applying the equation $m = 2j - r$ yields:

$21 = 24 - 3 = 21$ statically determinate internally

The truss of Fig. 2.5(j) is externally indeterminate because there are five reaction components and only four equations available. With r equal to 4 the structure is shown to be statically determinate internally. The three-hinged arch of Fig. 2.5(k) has four reaction components, which is the least number of reaction components required for stability; so r equals 4. Application of the equation shows the arch to be statically determinate internally.

In the chapter pertaining to the analysis of statically indeterminate structures it will be seen that the values of the redundants may be obtained by applying certain simultaneous equations. The number of simultaneous equations equals the total number of redundants, whether internal, external, or both. It therefore may seem a little foolish to distinguish between internal and external determinacy. The separation is particularly questionable for some types of internally and externally redundant trusses where no solution of the reactions is possible independently of the member forces, and vice versa.

If a truss is externally determinate and internally indeterminate, the reactions may be obtained by statics. If the truss is externally indeterminate and internally determinate, the reactions are dependent on the internal member forces and may not be determined by a method independent of those forces. If the truss is externally and internally indeterminate, the solution of the forces and reactions will be performed simultaneously. (For any of these situations, it may be possible to obtain a few forces here and there by joints without going through the indeterminate procedure necessary for complete analysis.) This entire subject is discussed in detail in later chapters.

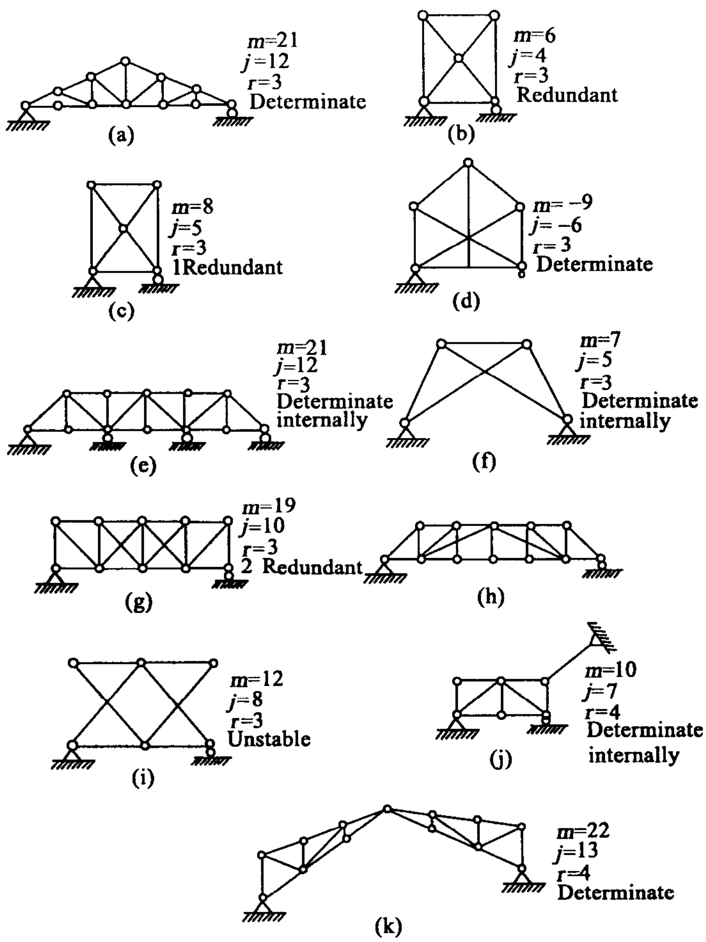

Fig. 2.5

CHAPTER 3
Bending of Beams

3.1 Introduction

A beam is a structural element which is subjected to transverse loads causing *flexure* or *bending*. Additionally, a beam may be required to carry axial force (thrust) and twisting moment (torque). In general, bending moment is accompanied by shear force and the two are related as will be seen later. To understand the behaviour of a beam it is necessary to be able to specify the bending moment and shear force *distributions* in the member. This is done through the drawing of bending moment and shear force diagrams which show the values of these quantities at all sections of the beam. In cases where thrust and torque are also present, distributions of these quantities can also be represented diagrammatically.

The *strength* of a beam will be compared with the magnitudes of the various force actions to which it is subjected and its adequacy assessed. In carrying out this assessment actual (*working*) values of the stresses will be compared with the maximum allowable values. In addition to the various assessments of strength, it is usually necessary to investigate the *stiffness* of the beam and compare actual displacements with those which would be considered limiting values. The term 'displacement' is used in a general sense to include transverse displacements (deflections) and slopes.

In this chapter we consider all these topics, starting with bending moment, shearing force and thrust diagrams and going on to develop the theory of bending which will enable us to calculate stresses and displacements in beams.

3.2 Bending Moment, Shearing Force and Thrust Diagrams

The Bending Moment at a section in a beam is the algebraic sum of the moments of the forces to one side of the section taken about the centroid of the section.

The Shear Force at a section is the algebraic sum of the forces to one side of the section taken perpendicular to the section.

These definitions will be illustrated with reference to the beams shown in Fig. 3.1(a) and (e) in the horizontal beam, Fig. 3.1(a), the section X distant a from the left-hand support is