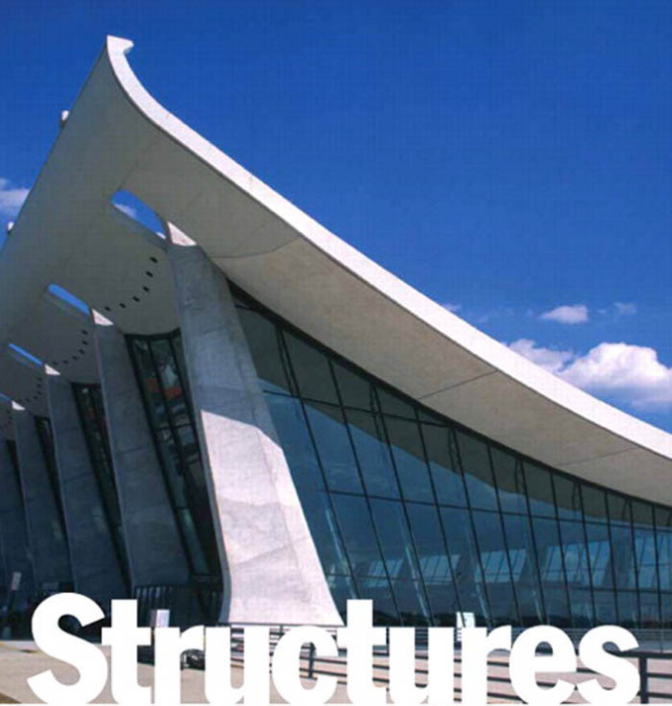

Structures

Seventh Edition

Daniel L. Schodek | Martin Bechthold

STRUCTURES

SEVENTH EDITION

Daniel L. Schodek

Martin Bechthold

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Preface

We are pleased to introduce revised and expanded content coverage to the seventh edition of ***Structures***.

WHAT'S NEW IN THIS EDITION

- Load and resistant factor design approaches are now explained in more depth and are included in the coverage of detailed design approaches for steel and timber beams and columns.
- Coverage of structural system design in Chapter 13 has been expanded and revised.
- All construction and system integration topics have been consolidated in Chapter 15.
- The impact of structural system choices on architectural space and form has been illustrated through many axonometric and perspective views inspired in part by Heino Engel's illustration concepts.
- Several new examples of actual building structures will help students make a better connection between the theory of structures and its actual application to design.
- This edition does not include an accompanying CD. Several structural analysis packages (one was previously included on CD) are available at no or at low cost to academic users. In complex projects, geometrical data can often be extracted directly from three-dimensional digital models for use directly in some type of structural analysis program.

Although the seventh edition has significant changes, especially in its coverage of structural system design, the fundamental goal of this book remains the same—to impart a fundamental understanding of structural behavior to students interested in both designing and analyzing structures. All too often in today's world, we see students trying to use advanced analysis programs without having any real understanding of the basic principles concerning how structures really work. Only with this understanding can new computer-based tools be effectively and sensibly used. For this reason, the book still focuses on presenting an invariant set of physical principles founded in the field of mechanics that designers can use to help understand the behavior of existing structural forms and in devising new approaches. The development of these principles has flowered during the past three centuries to the extent that they are amazingly well established and documented. Some new understandings, of course, continue to occur and likely will always do so. Still, the analytical tools already available to the designer are extensive and enormously powerful. Thus, the real challenge in the field of structures lies not so much in developing new analytical tools but in bringing those in existence to bear in designing and formulating creative structural solutions with the intent of making better buildings.

In this book, we discuss, in an introductory way, the physical principles that underlie the behavior of structures under load. The primary goal of the book, however, is not simply to teach analytical techniques but to explore their role in the design of structures in a building context. Because of this larger goal, the book covers material not only discussed in specialized engineering curricula but also covered in architecture curricula. The traditional hard boundaries between subdisciplines in engineering (e.g., statics and strength of materials) also have been deliberately softened in favor of a more integrative approach.

The book is divided into three major parts. Part I introduces the subject and fundamental concepts of analysis and design. Part II introduces the reader to the primary structural elements used in buildings and discusses their analysis and design. Each chapter in this part is divided into sections that (1) introduce the element considered and explain its role in building, (2) discuss its behavior under load in qualitative terms (an "intuitive" approach), (3) examine its behavior under load in quantitative terms, and (4) discuss methods for designing (rather than just analyzing) the element. Part III contains a unique examination of the principles of structural design because it is a part of the larger building design process. The appendices discuss more advanced principles of structural analysis and cover selected material properties.

The book is intended as a resource for students and instructors who want to design their own curriculum. For those who want to adopt a strictly qualitative approach to the subject, for example, it is possible to read only Chapter 1 in Part I, the sections entitled "Introduction" and "General Principles" in each of the chapters in Part II, and all of Part III. This coverage provides a brief qualitative overview of the field and has a special emphasis on design rather than analysis. For students who already have a background in the analytical aspects of structures, Part III contains summary information that is useful in a design context. Part III can be read independently by such students.

Parts I, II, and III have a certain redundancy in how analytical topics are covered, so students or instructors can integrate the material in the order they see fit. Shear and moment diagrams, for example, are first introduced in an abstract way in Chapter 2. Chapter 4 reintroduces them in connection with the analysis of a specific structural element: the truss. Where to introduce the different presentations, if desired, may be varied by the instructor.

Depending on the reader's needs or the curriculum followed, a reasonable sequence might be an overview (Chapter 1), basic statics (Chapter 2, Sections 2.1 to 2.3), loads and load modeling (Chapter 3), truss analysis and design (Chapter 4), cables and arches (Chapter 5), shear and moment diagrams (Chapter 2, Section 2.4), material properties (Chapter 2, Section 2.6), columns (Chapter 7), beams (Chapter 6), continuous beams (Chapter 8), frames (Chapter 9), plate and grid structures (Chapter 10), membranes and nets (Chapter 11), and shells (Chapter 12). The chapters in Part III on grids, lateral-load resistance approaches, and construction types are often best covered either in parallel or in conjunction with a studio exercise. Other instructors may choose to approach the subject material differently. The book is designed with sufficient flexibility to support different approaches. The material is presented in such a way that a direct cover-to-cover reading also is appropriate.

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The authors are indebted to several people in direct or indirect ways for the approach taken in this book. A large number of academics and professionals have served as reviewers over the many years this book has been in print, and their contributions are greatly appreciated. Many students have taken the time to offer feedback as well, and their contributions are highly valued—they are, after all, the users of this book and have the most insight into what kinds of presentation approaches are most effective. Brendan Kellog and Samuel Moen prepared many of the new illustrations in the book. Each of us would also like to thank our family members for their continued support: Daniel Schodek—Kay and Ben Schodek, Ned Schodek, Johanna Maron and Rowan Daniel Schodek; Martin Bechthold—Marina Sartori, Fosca, Natalia, and Elisa Bechthold. In addition, particular thanks are due to Dorothy Gerring, Pennsylvania College of Technology; Martin Paull, UCLA; and J. S. Rabun, The University of Tennessee, for their assistance with the seventh edition text review.

Daniel L. Schodek
Martin Bechthold
Cambridge, Massachusetts

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I

INTRODUCTORY CONCEPTS

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The three chapters in Part I provide an overview and introduction to structures and their use in buildings. Chapter 1 is a self-contained overview of the field and discusses different ways to classify structural elements and systems. Chapter 2 reviews fundamental principles of mechanics that are generally applicable to the analysis of any structure. Chapter 3 considers the loads that structures must be designed to carry and discusses the structural analysis and design process as it occurs in a building context.

CHAPTER 1

Structures: An Overview

1.1 INTRODUCTION

Definitions are a time-honored way to start any book. A simple definition of a *structure*, in a building context, is "a device for channeling loads that result from the use or presence of the building in relation to the ground." The study of structures involves important and varying concerns, one of which is gaining an understanding of the basic principles that define and characterize the behavior of physical objects subjected to forces. More fundamentally, the study involves defining what a *force* itself is because this familiar term represents an abstract concept. The study of structures also involves dealing with much broader issues of space and dimensionality: *size, scale, form, proportion,* and *morphology* are all terms commonly found in a structural designer's vocabulary.

To begin the study of structures, consider again the definition of a structure in the previous paragraph. Although valuable because it defines a structure's purpose, that definition provides no insight into the makeup or characteristics of a structure: What *is* this device that channels loads to the ground? Using the complex and exacting style of a dictionary editor, a *structure* can be defined as a physical entity having a unitary character that can be conceived of as an organization of positioned constituent elements in space in which the character of the whole dominates the interrelationship of the parts. Its purpose was defined earlier.

It might be hard to believe, but a contorted, relatively abstract definition of this type, which is almost laughable in its academic tone, does have some merit. First, it states that a structure is a *real* physical object, not an abstract idea or interesting issue. A structure is *not* a matter of debate; it is something that is *built* and it is implied that a structure must be dealt with accordingly. Merely postulating that a structure can carry a certain type of load or function in a certain way, for example, is inadequate. A physical device that conforms to basic principles governing the behavior of physical objects must be provided to accomplish the desired behavior. Devising such a structure is the role of the designer.

The expanded definition also makes the point that a structure functions as a whole. This point has fundamental importance, but it can be easily forgotten when one is confronted with a typical building composed of a seemingly endless array of individual beams and columns. In such cases, there is an immediate tendency to think of the structure only as an assembly of individual, small elements in which each element performs a separate function. In actuality, all structures are, and must be, designed primarily to function as an overall system and only secondarily as an array of discrete elements. In line with the latter part of the expanded definition, these elements are positioned and interrelated to enable the overall structure to function as a whole in carrying vertically or horizontally acting loads to the ground. No matter how some individual elements are located and attached to one another, if the resultant configuration and interrelation of all elements does not function as a system and channel all anticipated types of loads to the ground, the configuration cannot be called a structure. The reference to anticipated types of loads is important because structures are normally devised in response to a specific set of loading conditions and function as structures only with respect to those conditions; structures are often relatively fragile with respect to unanticipated loads. A typical building structure capable of carrying normally encountered occupancy and environmental loads cannot, for example, be simply picked up by a corner and transported through space. It would fall apart because its structure was not designed to carry the unique loadings involved. So much for Superman carrying buildings around!

To highlight yet another formal definition, the act of designing a structure also can be defined in complex language, but the result also has value. Designing a structure is the act of positioning constituent elements and formulating interrelations, with the objective of imparting a desired character to the resultant structural entity. The notions that elements are positioned and that relationships exist among these elements are basic to the concept of designing a structure.

Elements can be positioned in various ways to carry loads, and many types of relationships may exist. For example, a block arch is made of carefully positioned elements. A beam may be related to a column simply by resting on top of it, or it may be rigidly attached to the column, with radically different structural actions ensuing. These issues are explored in the remainder of the book.

1.2 GENERAL TYPES OF STRUCTURES

1.2.1 Primary Classifications

Introduction. Fundamental to understanding any field is gaining knowledge of how groups within that field are systematically distinguished, ordered, and named. It also is important to know the criteria or presumed relationships that form the basis for such classifications. This section introduces one method for classifying structural elements and systems: according to their shape and basic physical properties of construction. (See Figure 1.1.) This classification scheme implies that complex structures are the result of only additive aggregations of elements; the scheme is inherently simplistic. In aggregations, only the additive nature of the elements is significant. In structures, it is significant that the elements are also positioned and connected to give the structure certain load-carrying attributes. The simpler classification approach illustrated in Figure 1.1 is useful as an introduction.

Geometry. In terms of their basic geometries, the structural forms at the left in Figure 1.1 can be classified either as *line-forming elements* (or composed of line-forming elements) or as *surface-forming elements*. Line-forming elements can be further distinguished as straight or curved. Surface-forming elements are either planar or curved. Curved-surface elements can be of either single or double curvature.

Strictly speaking, there is no such thing as a line or surface element because all structural elements have thickness. Still, it is useful to classify any long, slender element (such as a column whose cross-sectional dimensions are small with respect to its length) as a line element. Similarly, surface elements also have thickness, but this thickness is small with respect to length dimensions.

Closely coupled with whether an element is linear or surface forming is the material or method of construction used. Many materials are naturally line forming.

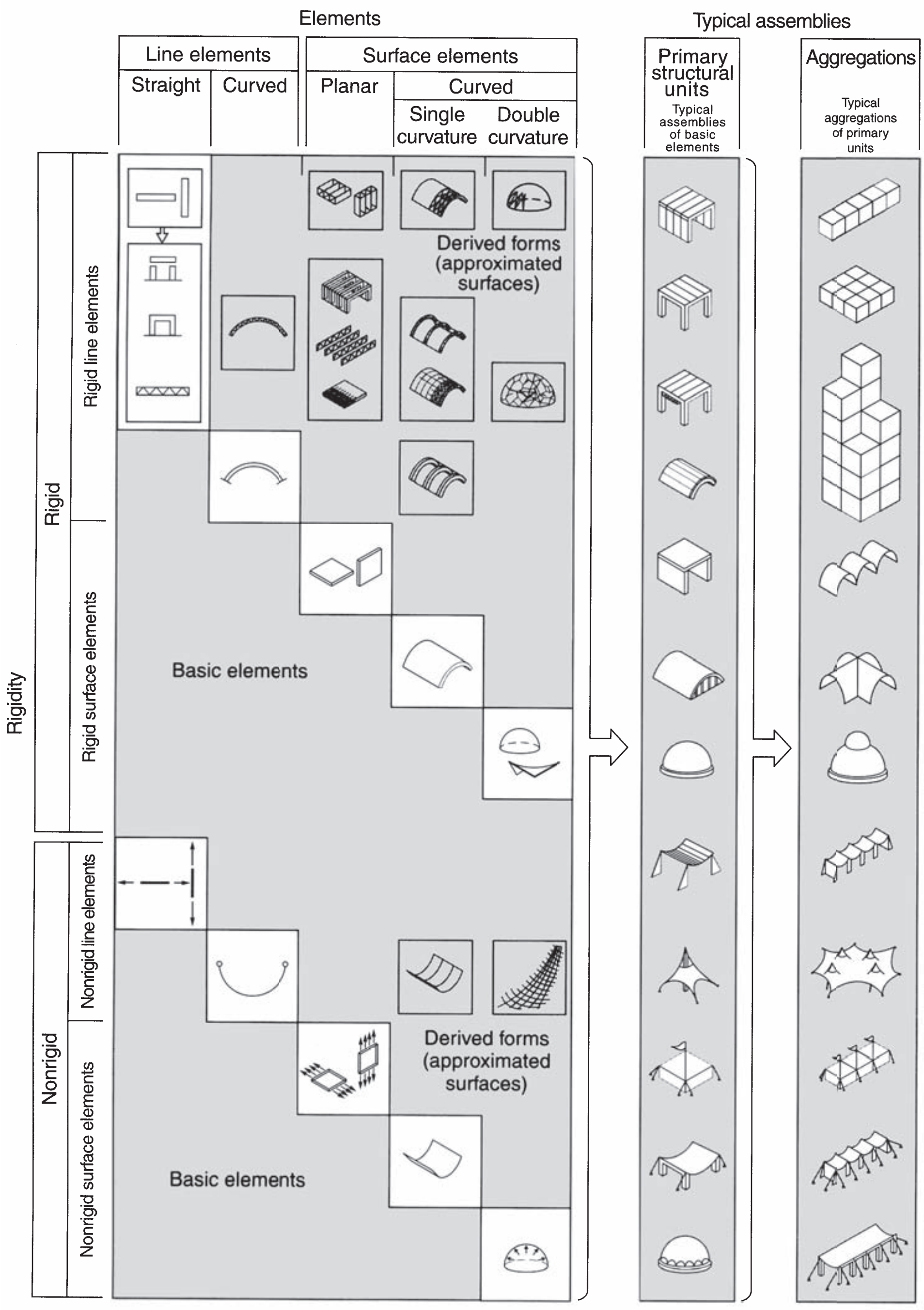
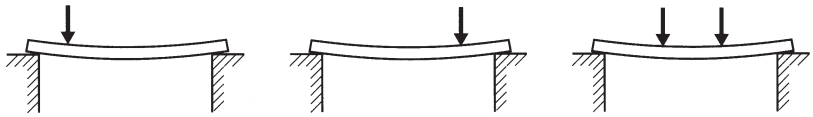


FIGURE 1.1 Classification of basic structural elements according to geometry and primary physical characteristics. Typical primary structural units and other aggregations also are illustrated. The schema is limited and suggests nothing about the importance of properly positioning constituent elements to make feasible structural assemblies.

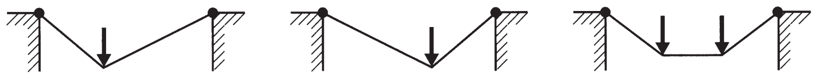
Timber, for example, is inherently line forming because of how it grows. It is possible, however, to make minor surface-forming elements directly from timber (as evidenced by plywood) or larger surface-forming structures by aggregating more elemental pieces. Other materials, such as concrete, can be line forming or surface forming with equal ease. Steel is primarily line forming, but it can also be used to make directly minor surface-forming elements (e.g., steel decking).

Stiffness. Figure 1.1 illustrates a second fundamental classification: the stiffness characteristics of the structural element. The primary distinction is whether the element is rigid or flexible. *Rigid elements*, such as typical beams, do not undergo *appreciable* changes in shape under the action of a load or under changing

FIGURE 1.2 Nonrigid and rigid structures.



(a) Rigid structure (e.g., a beam). The structure is stiff and does not undergo appreciable changes in shape with changes in the loading condition.



(b) Nonrigid or flexible structure (e.g., a cable). The shape of the structure changes with changes in the loading condition.

loads. [See Figure 1.2(a).] However, they are usually bent or bowed to a small degree by the load's action.

Flexible elements, such as cables, assume one shape under one loading condition and change shape drastically when the loading nature changes. [See Figure 1.2(b).] Flexible structures maintain their physical integrity, however, no matter what shape they assume.[1]

Whether an element is rigid or flexible is often related to the construction material used. Many materials, such as timber, are inherently rigid; others, such as steel, can be used to make either rigid or flexible members. A good example of a rigid steel member is the typical beam (an element that does not undergo any appreciable change in shape under changing loads). A steel cable or chain, however, is clearly flexible because the shape that it and similar elements assume under loading is a function of the exact pattern and magnitudes of the load carried. A steel cable thus changes shape with changing loads. Whether a structure is rigid or flexible, therefore, depends *either* on the inherent characteristics of the material used or on the amount and microorganization of the element's material.

Many specific structures that are usually classified as rigid are so only under given loading conditions or under minor variations of a given loading condition. When loading changes dramatically, structures of this type become unstable and tend to collapse. Structures such as arches made by aggregating smaller rigid elements (e.g., blocks) into larger shapes are often in this category.

One-Way and Two-Way Systems. A basic way to distinguish among structures is according to the spatial organization of the system of support used and the relation of the structure to the points of support available. Two primary cases of importance are one- and two-way systems. In a *one-way system*, the structure's basic load-transfer mechanism for channeling external loads to the ground acts in one direction only. In a *two-way system*, the load-transfer mechanism's direction is more complex but involves at least two directions. A linear beam spanning two support points is an example of a one-way system. (See Figure 1.3.) A system of two crossed elements resting on two sets of support points not lying on the same line and in which both elements share the external load is an example of a two-way system. A square, flat, rigid plate resting on four continuous edge supports also is a two-way system: An external load cannot be simplistically assumed to travel to a pair of the supports in one direction only.

The distinction between one- and two-way structural actions is of primary importance in a design context. As is discussed in more detail later, there are

[1]Common English-language connotations of the terms *rigid* and *flexible* are evoked here. In some more advanced structural theory applications, these terms are not used in their literal sense. Rather, distinctions are made among stiffness, strength, and stability.

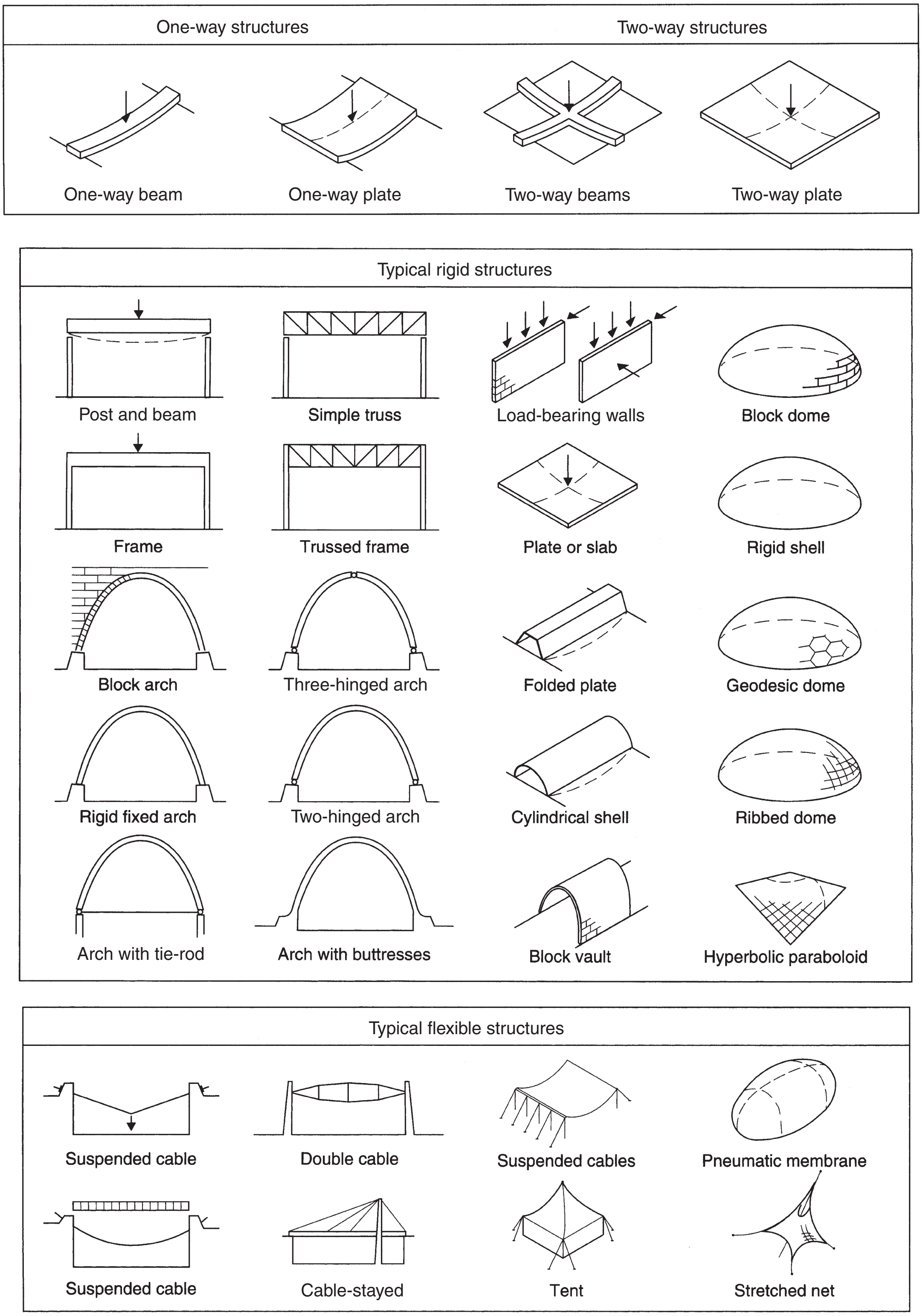


FIGURE 1.3 Types of structural elements.

situations typically involving certain patterns in the support system used that often lead to specific advantages (in terms of the efficient use of materials) in using a two-way system compared to a one-way system. Other patterns in the support system, however, often lead to the converse result. For this reason, it is useful early on to begin distinguishing between one- and two-way systems.

Materials. A common classification approach to structures is by the type of material used (e.g., wood, steel, and reinforced concrete). A strict classification by materials, however, is somewhat misleading and is not adopted here because the principles governing the behavior of similar elements composed of different materials (e.g., a timber and steel beam) are invariant and the differences are superficial. General descriptions have a more intrinsic value at this stage.

As one takes a closer look at structures, however, the importance of materials increases. One reason stems from the close relationship between the nature of the deformations induced in a structure by the action of the external loading and the material and method of construction that is most appropriate for use in that structure. Steel can be used under all conditions. Plain concrete can be used only where the structure is compressed or shortened under the action of the load. Concrete cracks and fails when subjected to tensile forces that elongate the material. Concrete reinforced with steel, however, can be used where elongating forces are present because the steel can be designed to carry those forces. These and other considerations are studied in more detail later in the book.

1.2.2 Primary Structural Elements

Elements. Common rigid elements include beams, columns or struts, arches, flat plates, singly curved plates, and shells having a variety of different curvatures. Flexible elements include cables (straight and draped) and membranes (planar, singly curved, and doubly curved). In addition, several other types of structures (frames, trusses, geodesic domes, nets, etc.) are derived from these elements. Assigning a specific name to an element having certain geometrical and rigidity characteristics is done for convenience only and has its basis in tradition. Naming elements in this way can, however, be misleading because it is easy to assume that if two elements have different names, the way they carry loads also must be different. This is not necessarily so. Indeed, a basic principle that later portions of this book clarify and elaborate on is that all structures have the same fundamental load-carrying mechanism. At this point, however, it is still useful to retain and use traditional names to gain familiarity with the subject.

Beams and Columns. Structures formed by resting rigid horizontal elements on top of rigid vertical elements are commonplace. Often called post-and-beam structures, the horizontal elements (*beams*) pick up loads that are applied transversely to their lengths and transfer the loads to the supporting vertical columns or posts. The *columns*, loaded axially by the beams, transfer the loads to the ground. The beams are bowed or bent as a consequence of the transverse loads they carry (see Figure 1.3), so they are often said to carry loads by *bending*. The columns in a beam-and-column assembly are not bent or bowed because they are subjected to axial compressive forces only. In a building, the possible absolute length of individual beams and columns is rather limited compared with some other structural elements (e.g., cables). Beams and columns are therefore typically used in a repetitive pattern. Simple single-span beams and columns are discussed more extensively in Chapters 6 and 7, respectively. Continuous beams that bear on multiple support points are discussed in Chapter 8. Continuous beams often exhibit more advantageous structural properties than simpler single-span beams supported only at two points.

Frames. The *frame*, illustrated in Figure 1.3, is similar in appearance to the post-and-beam type of structure but has different structural action because of the rigid joints between vertical and horizontal members. This rigidity imparts stability against lateral forces that is lacking in the post-and-beam system. In a framed system, both beams and columns are bent or bowed as a result of the load's action on the structure. As with the post-and-beam structure, the possible lengths of individual elements in a frame structure are limited. Consequently, members are typically formed into a repetitive pattern when they are used in a building. In Chapter 9, we discuss frames in detail.

Trusses. *Trusses* are structural members made by assembling short, straight members into triangulated patterns. The resultant structure is rigid as a result of how the individual line elements are positioned relative to one another. Some patterns (e.g., a pattern of squares rather than triangles) do not necessarily yield a structure that is rigid (unless joints are treated the same way as they are in framed structures). A truss composed of discrete elements is bent or bowed as a whole under the action of an applied transverse loading in much the same way that a beam is bent or bowed. Individual truss members, however, are not subject to bending, but are only either compressed or pulled on. Trusses are explored in depth in Chapter 4.

Arches. An *arch* is a curved, line-forming structural member that spans two points. The common image of an arch is a structure composed of separate, wedge-shaped pieces that retain their position by mutual pressure induced by the load. The shape of the curve and the nature of the loading are critical determinants as to whether the resultant assembly is stable. When shapes are formed by stacking rigid block elements, the resultant structure is functional and stable only when the load's action induces in-plane forces that make the structure compress uniformly. Structures of this type cannot carry loads that induce elongations or any pronounced bowing in the member. (The blocks pull apart and the structure fails.) Block structures can be strong when used properly, as their extensive historical usage attests. The strength of a block structure is due exclusively to the *positioning* of individual elements because blocks are typically either rested one on another or mortared together. (Mortar does not appreciably increase the structure's strength.) The positioning, in turn, depends on the type of loading involved. The resultant structure is thus rigid under only particular circumstances. These issues are discussed more extensively in Chapter 5.

The *rigid arch* is frequently used in modern buildings. It is curved similarly to block arches but is made of one continuous piece of deformed rigid material (Figure 1.3). If properly shaped, rigid arches can carry a load to supports while being subject only to axial compression, and no bowing or bending occurs. The rigid arch can better carry variations in the design loading than its block counterpart made of individual pieces. Many types of rigid arches exist, and they are often characterized by their support conditions (e.g., fixed, two hinged, and three hinged). Arches of this type are discussed in more detail in Chapter 5.

Walls and Plates. Walls and flat plates are rigid, surface-forming structures. A load-bearing wall can typically carry vertically acting loads and laterally acting loads (e.g., wind and earthquake) along its length. Resistance to out-of-plane forces in block walls is marginal. A flat plate is typically used horizontally and carries loads by bending to its supports. Plate structures are normally made of reinforced concrete or steel.

Horizontal plates can also be made by assembling patterns of short, rigid line elements. Three-dimensional triangulation schemes are used to impart stiffness to the resultant assembly. Plate structures are explored in more detail in Chapter 10.

Long, narrow, rigid plates can also be joined along their long edges and used to span horizontally in beamlike fashion. These structures, called *folded plates*, have the potential for spanning fairly large distances. Folded plates are explored in detail in Chapter 10.

Cylindrical Shells and Vaults. Cylindrical barrel shells and vaults are examples of *singly curved-plate* structures. A barrel shell spans longitudinally such that the