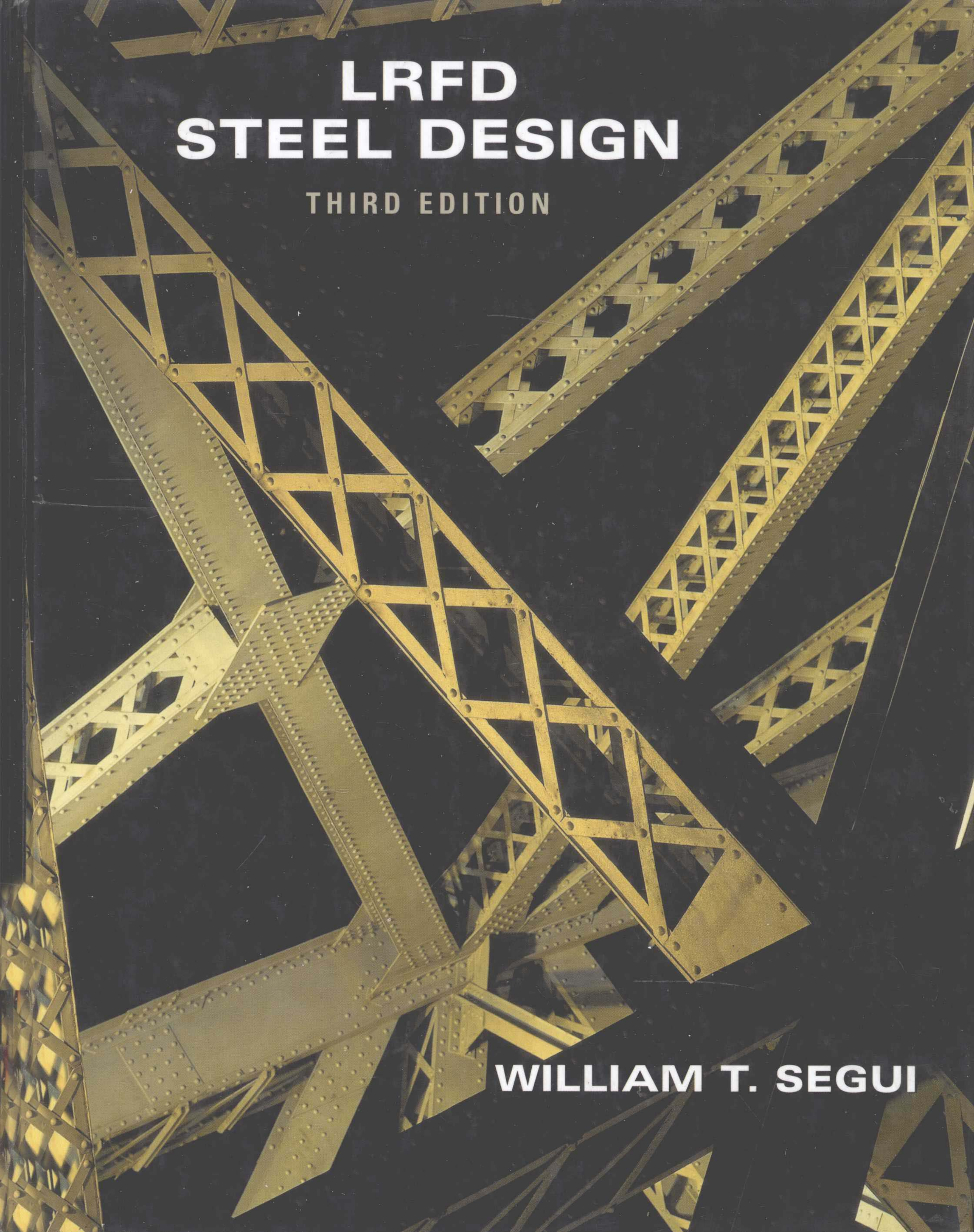
LRFD STEEL DESIGN

THIRD EDITION



WILLIAM T. SEGUI

LRFD Steel Design

Third Edition

William T. Segui
The University of Memphis

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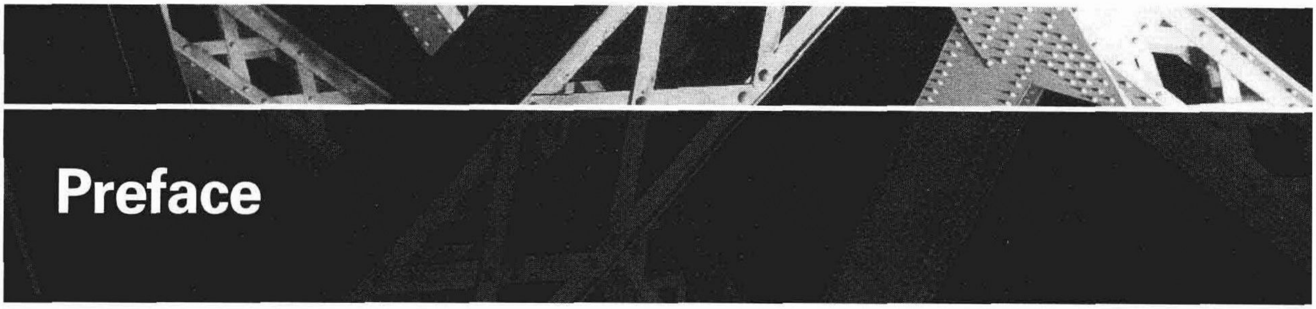

Preface

LRFD Steel Design is a basic textbook in structural steel design for undergraduate civil engineering students at the junior or senior level. Its primary function is that of a textbook, although practicing civil engineers who need a review of current practice and the current AISC Specification and Manual will find it useful as a reference. Students using this book should have a background in mechanics of materials and analysis of statically determinate structures. New sections have been added,

This new, third edition of the textbook has been prompted by recent changes in the AISC Specification and Manual. AISC issued the Specification in 1999 and the LRFD Manual of Steel Construction—Third Edition at the end of 2001. The Manual has undergone the most sweeping change, with the two volumes of the previous edition combined into one volume. New sections have been added, and all numerical values are now given to three significant figures. There is a new design aid for tension members. Beam design aids are now given for channel shapes as well as W-shapes. Since the preferred steel for W-shapes is now ASTM A992, all design aids for beams and columns use a yield stress for 50 ksi for W-shapes, and 36 ksi steel is no longer included for W-shapes. There is no longer a separate section for composite beams and columns; those topics are now included in the beam and column sections. A new procedure, complete with design aids, is given for the design of beam–columns.

The Specification now uses a dual system of units. All equations have been nondimensionalized where possible, and where it is not possible, values are given in U.S. customary units followed by the SI version in parentheses. Load factors and load combinations are no longer given in the Specification. For those, the designer must refer to ASCE-7. Other changes include a new section on stability bracing and ew bolt bearing strength provisions.

The third edition of *LRFD Steel Design* incorporates these AISC and other changes. New examples are given throughout the book, and many examples and other material have been rewritten for improved clarity. Most of the problems for assignment are new or modified. There is a new section devoted to the design of floor and roof systems, and the coverage of deflections has been expanded. Chapter 6, Beam–Columns, includes a brief treatment of stability bracing. Chapter 7, Simple Connections, has been extensively revised. The AISC approach to shear plus tension in bolts, using the "three line" approximation, is emphasized (rather than the direct application of the elliptical interaction equation.) The approach to computation of bolt bearing strength has been slightly modified, as has the computation of fillet weld strength. In addition, the direction of load on fillet welds is now accounted for.

In Chapter 8, Eccentric Connections, the section on moment-resisting connections has been revised, with an expanded discussion of partially restrained connections.

Depending on the level of competence of the student, *LRFD Steel Design* can be used for one or two courses of three semester hours each. A suggested two-course sequence is as follows: a first course covering Chapters 1 through 7 and a second course covering Chapters 8 through 10, supplemented by comprehensive design assignments. This division of topics has been used successfully for several years at The University of Memphis.

The emphasis of this book is on the design of building components in accordance with the provisions of the AISC LRFD Specification and LRFD Manual of Steel Construction. Although the AASHTO and AREA Specification are referred to occasionally, no examples or assigned problems are based on these documents.

Prior to the introduction of the Load and Resistance Factor Design Specification by AISC in 1986, the dominant design approach for structural steel was allowable stress design. Although load and resistance factor design is emphasized by the American Institute of Steel Construction, allowable stress design is still in use, and students should have some familiarity with it. To that end, Appendix B provides a brief introduction to that topic.

It is absolutely essential that students have a copy of the Manual of Steel Construction. In order to promote familiarity with it, material from the Manual is not reproduced in this book so that the reader will be required to refer to the Manual. All notation in *LRFD Steel Design* is consistent with that in the Manual, and AISC equation numbers are used in tandem with sequential numbering of other equations according to the textbook chapter.

U.S. customary units are used throughout, with no introduction of SI units. Although the AISC Specification now used a dual system of units, the steel construction industry is still in a period of transition.

As far as design procedures are concerned, the application of fundamental principles is encouraged. Although this book is oriented toward practical design, sufficient theory is included to avoid a "cookbook" approach. Direct design methods are used where feasible, but no complicated design formulas have been developed. Instead, trial and error, with "educated guesses," is the rule. Tables, curves, and other design aids from the Manual are used, but they have a role that is subordinate to the use of basic equations. Assigned problems provide practice with both approaches, and where appropriate, the required approach is specified in the statement of the problem.

In keeping with the objective of providing a basic textbook, a large number of assigned problems are given at the end of each chapter. Answers to selected problems are given at the back of the book, and an instructor's manual with solutions is available.

I would like to express my appreciation to the following people who have reviewed the proposal for this edition and provided helpful comments: William L. Bingham, North Carolina State University; Gary R. Consolazio, University of Florida; Walter Gerstel, University of New Mexico; Udaya B. Halabe, West Virginia University; Marvin Halling, Utah State University; Thomas H. Miller, Oregon State

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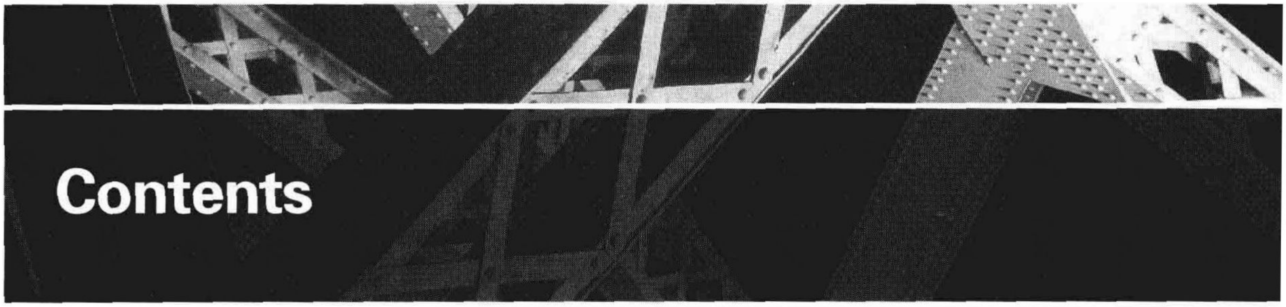
I would greatly appreciate learning of any errors that users of this book discover. I can be contacted at wsegui@memphis.edu.

William T. Segui



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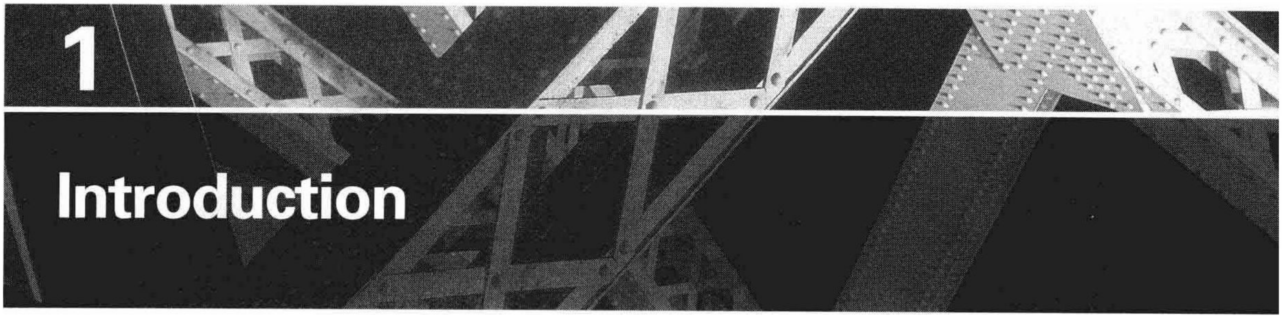


1 Introduction

1.1 STRUCTURAL DESIGN

The structural design of buildings, whether of structural steel or reinforced concrete, requires the determination of the overall proportions and dimensions of the supporting framework and the selection of the cross sections of individual members. In most cases the functional design, including the establishment of the number of stories and the floor plan, will have been done by an architect, and the structural engineer must work within the constraints imposed by this design. Ideally, the engineer and architect will collaborate throughout the design process to complete the project in an efficient manner. In effect, however, the design can be summed up as follows: The architect decides how the building should look; the engineer must make sure that it doesn't fall down. Although this distinction is an oversimplification, it affirms the first priority of the structural engineer: safety. Other important considerations include serviceability (how well the structure performs in terms of appearance and deflection) and economy. An economical structure requires an efficient use of materials and construction labor. Although this objective can usually be accomplished by a design that requires a minimum amount of material, savings can often be realized by using more material if it results in a simpler, more easily constructed project. In fact, at the present time, materials account for one-third or less of the cost of a typical steel structure, whereas labor costs can account for 60% or more.

A good design requires the evaluation of several framing plans — that is, different arrangements of members and their connections. In other words, several alternative designs should be prepared and their costs compared. For each framing plan investigated, the individual components must be designed. To do so requires the structural analysis of the building frames and the computation of forces and bending moments in the individual members. Armed with this information, the structural designer can then select the appropriate cross section. Before any analysis, however, a decision must be made on the primary building material to be used; it will usually be reinforced concrete, structural steel, or both. Ideally, alternative designs should be prepared with each.

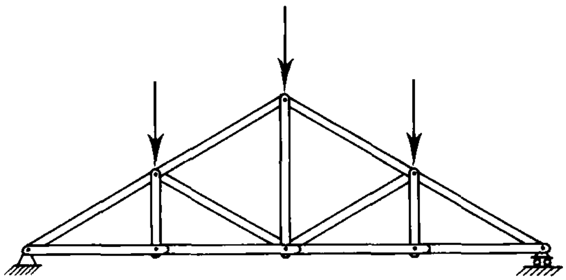
The emphasis in this book will be on the design of individual structural steel members and their connections. The structural engineer must select and evaluate the overall structural system in order to produce an efficient and economical design but cannot do so without a thorough understanding of the design of the components (the "building blocks") of the structure. Thus component design is the focus of this book.

Before discussing structural steel, we need to examine various types of structural members. Figure 1.1 shows a truss with vertical concentrated forces applied at the joints along the top chord. In keeping with the usual assumptions of truss analysis — pinned connections and loads applied only at the joints — each component of the truss will be a two-force member, subject to either axial compression or tension. For simply supported trusses loaded as shown — a typical loading condition — each of the top chord members will be in compression, and the bottom chord members will be in tension. The web members will either be in tension or compression, depending on their location and orientation and on the location of the loads.

Other types of members can be illustrated with the rigid frame of Figure 1.2a. The members of this frame are rigidly connected by welding and can be assumed to form a continuous structure. At the supports, the members are welded to a rectangular plate that is bolted to a concrete footing. Placing several of these frames in parallel and connecting them with additional members that are then covered with roofing material and walls produces a typical building system. Many important details have not been mentioned, but many small commercial buildings are constructed essentially in this manner. The design and analysis of each frame in the system begins with the idealization of the frame as a two-dimensional structure, as shown in Figure 1.2b. Because the frame has a plane of symmetry parallel to the page, we are able to treat the frame as two-dimensional and represent the frame members by their centerlines. (Although it is not shown in Figure 1.1, this same idealization is made with trusses, and the members are usually represented by their centerlines.) Note that the supports are represented as hinges (pins), not as fixed supports. If there is a possibility that the footing will undergo a slight rotation, or if the connection is flexible enough to allow a slight rotation, the support must be considered to be pinned. One assumption made in the usual methods of structural analysis is that deformations are very small, which means that only a slight rotation of the support is needed to qualify it as a pinned connection.

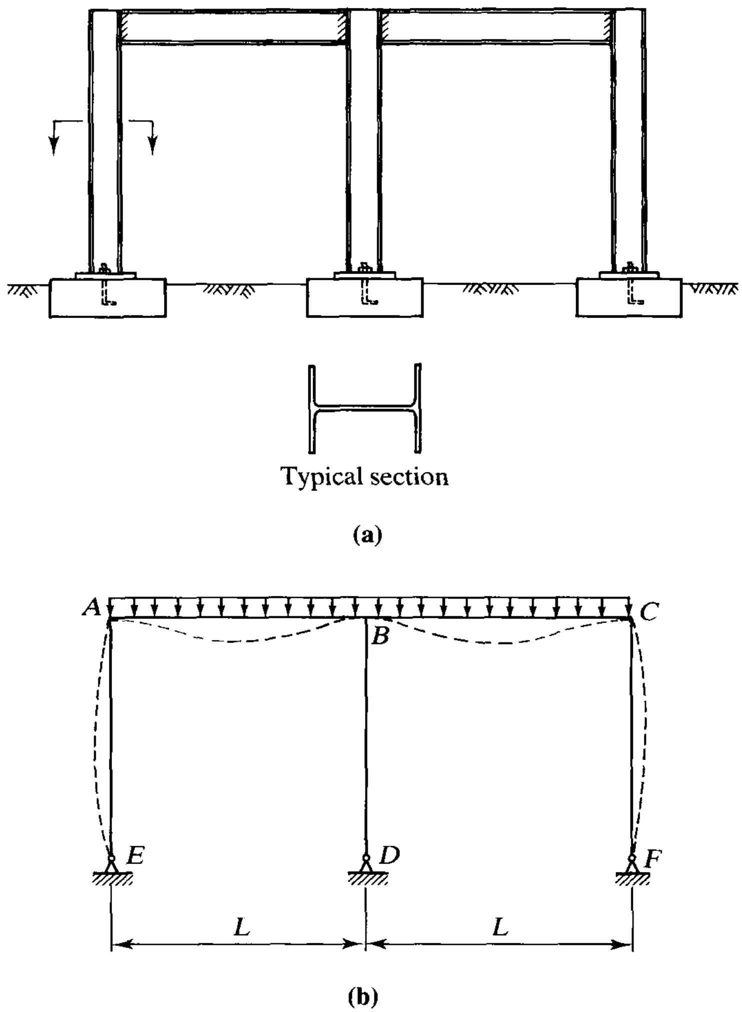
Once the geometry and support conditions of the idealized frame have been established, the loading must be determined. This determination usually involves apportioning a share of the total load to each frame. If the hypothetical structure under consideration is subjected to a uniformly distributed roof load, the portion carried by one frame will be a uniformly distributed line load measured in force per unit length, as shown in Figure 1.2b. Typical units would be kips per foot.

FIGURE 1.1



For the loading shown in Figure 1.2b, the frame will deform as indicated by the dashed line (drawn to a greatly exaggerated scale). The individual members of the frame can be classified according to the type of behavior represented by this deformed shape. The horizontal members *AB* and *BC* are subjected primarily to bending, or flexure, and are called *beams*. The vertical member *BD* is subjected to couples transferred from each beam, but for the symmetrical frame shown, they are equal and opposite, thereby canceling each other. Thus member *BD* is subjected only to axial compression arising from the vertical loads. In buildings, vertical compression members such as these are referred to as *columns*. The other two vertical members, *AE* and *CF*, must resist not only axial compression from the vertical loads but also a significant amount of bending. Such members are called *beam-columns*. In reality, all members, even those classified as beams or columns, will be subjected to both bending and axial load, but in many cases, the effects are minor and can be neglected.

FIGURE 1.2



In addition to the members described, this book covers the design of connections and the following special members: composite beams, composite columns, and plate girders.

1.2 LOADS

The forces that act on a structure are called *loads*. They belong to one of two broad categories: *dead load* and *live load*. Dead loads are those that are permanent, including the weight of the structure itself, which is sometimes called the *self-weight*. In addition to the weight of the structure, dead loads in a building include the weight of nonstructural components such as floor coverings, partitions, and suspended ceilings (with light fixtures, mechanical equipment, and plumbing). All of the loads mentioned thus far are forces resulting from gravity and are referred to as *gravity loads*. Live loads, which can also be gravity loads, are those that are not as permanent as dead loads. They may or may not be acting on the structure at any given time, and the location may not be fixed. Examples of live loads include furniture, equipment, and occupants of buildings. In general, the magnitude of a live load is not as well defined as that of a dead load, and it usually must be estimated. In many cases, a structural member must be investigated for various positions of a live load so that a potential failure condition is not overlooked.

If a live load is applied slowly and is not removed and is reapplied an excessive number of times, the structure can be analyzed as if the load were static. If the load is applied suddenly, as would be the case when the structure supports a moving crane, the effects of impact must be accounted for. If the load is applied and removed many times over the life of the structure, fatigue stress becomes a problem, and its effects must be accounted for. Impact loading occurs in relatively few buildings, notably industrial buildings, and fatigue loading is rare, with thousands of load cycles over the life of the structure required before fatigue becomes a problem. For these reasons, all loading conditions in this book will be treated as static, and fatigue will not be considered.

Wind exerts a pressure or suction on the exterior surfaces of a building, and because of its transient nature, it properly belongs in the category of live loads. Because of the relative complexity of determining wind loads, however, wind is usually considered a separate category of loading. Because lateral loads are most detrimental to tall structures, wind loads are usually not as important for low buildings, but uplift on light roof systems can be critical. Although wind is present most of the time, wind loads of the magnitude considered in design are infrequent and are not considered to be fatigue loads.

Earthquake loads are another special category and need to be considered only in those geographic locations where there is a reasonable probability of occurrence. A structural analysis of the effects of an earthquake requires an analysis of the structure's response to the ground motion produced by the earthquake. Simpler methods are sometimes used in which the effects of the earthquake are simulated by a system of horizontal loads, similar to those resulting from wind pressure, acting at each floor level of the building.

Snow is another live load that is treated as a separate category. Adding to the uncertainty of this load is the complication of drift, which can cause much of the load to accumulate over a relatively small area.

Other types of live load are often treated as separate categories, such as hydrostatic pressure and soil pressure, but the cases we have enumerated are the ones ordinarily encountered in the design of structural steel building frames and their members.

1.3 BUILDING CODES

Buildings must be designed and constructed according to the provisions of a building code, which is a legal document containing requirements related to such things as structural safety, fire safety, plumbing, ventilation, and accessibility to the physically disabled. A building code has the force of law and is administered by a governmental entity such as a city, a county, or, for some large metropolitan areas, a consolidated government. Building codes do not give design procedures, but they do specify the design requirements and constraints that must be satisfied. Of particular importance to the structural engineer is the prescription of minimum live loads for buildings. Although the engineer is encouraged to investigate the actual loading conditions and attempt to determine realistic values, the structure must be able to support these specified minimum loads.

Although some large cities have their own building codes, many municipalities will modify a "model" building code to suit their particular needs and adopt it as modified. Model codes are written by various nonprofit organizations in a form that can be easily adopted by a governmental unit. Three national code organizations have developed model building codes: the *Uniform Building Code* (International Conference of Building Officials, 1997), the *Standard Building Code* (Southern Building Code Congress International, 1999), and the *BOCA National Building Code* (BOCA, 1999) (BOCA is an acronym for Building Officials and Code Administrators.) These codes have generally been used in different regions of the United States. The *Uniform Building Code* has been essentially the only one used west of the Mississippi, the *Standard Building Code* has been used in the southeastern states, and the *BOCA National Building Code* has been used in the northeastern part of the country.

A unified building code, the *International Building Code* (International Code Council, 2000), has been developed to eliminate some of the inconsistencies among the three national building codes. This was a joint effort by the three code organizations (ICBO, BOCA, and SBCCI). These organizations will continue to function, but the new code replaces the three regional codes.

Although it is not a building code, ASCE 7-98, *Minimum Design Loads for Buildings and Other Structures* (American Society of Civil Engineers, 2000) is similar in form to a building code. This standard provides load requirements in a format suitable for adoption as part of a code. The *International Building Code* incorporates much of ASCE 7-98 in its load provisions.

1.4 DESIGN SPECIFICATIONS

In contrast to building codes, design specifications give more specific guidance for the design of structural members and their connections. They present the guidelines and criteria that enable a structural engineer to achieve the objectives mandated by a building code. Design specifications represent what is considered to be good engineering practice based on the latest research. They are periodically revised and updated by the issuance of supplements or completely new editions. As with model building codes, design specifications are written in a legal format by nonprofit organizations. They have no legal standing on their own, but by presenting design criteria and limits in the form of legal mandates and prohibitions, they can easily be adopted, by reference, as part of a building code.

The specifications of most interest to the structural steel designer are those published by the following organizations.

1. **American Institute of Steel Construction (AISC):** This specification provides for the design of structural steel buildings and their connections. It is the one of primary concern in this book, and we discuss it in detail (AISC, 1999).
2. **American Association of State Highway and Transportation Officials (AASHTO):** This specification covers the design of highway bridges and related structures. It provides for all structural materials normally used in bridges, including steel, reinforced concrete, and timber (AASHTO, 1996, 1998).
3. **American Railway Engineering and Maintenance-of-Way Association (AREMA):** The AREMA *Manual of Railway Engineering* covers the design of railway bridges and related structures (AREMA, 2001). This organization was formerly known as the American Railway Engineering Association (AREA).
4. **American Iron and Steel Institute (AISI):** This specification deals with cold-formed steel, which we discuss in Section 1.6 of this book (AISI, 1996).

1.5 STRUCTURAL STEEL

The earliest use of iron, the chief component of steel, was for small tools, in approximately 4000 B.C. (Murphy, 1957). This material was in the form of wrought iron, produced by heating ore in a charcoal fire. In the latter part of the eighteenth century and in the early nineteenth century, cast iron and wrought iron were used in various types of bridges. Steel, an alloy of primarily iron and carbon, with fewer impurities and less carbon than cast iron, was first used in heavy construction in the nineteenth century. With the advent of the Bessemer converter in 1855, steel began to displace wrought iron and cast iron in construction. In the United States, the first structural steel railroad bridge was the Eads bridge, constructed in 1874 in St. Louis, Missouri (Tall, 1964). In 1884, the first building with a steel frame was completed in Chicago.

The characteristics of steel that are of the most interest to structural engineers can be examined by plotting the results of a tensile test. If a test specimen is subjected