DESIGN OF STEEL STRUCTURES

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I dedicate this book to the memory of my parents, Jurjis and Sabat Abu-Saba, who did not have the privilege to go to school. Yet they believed in the power of knowledge and provided us, their children, with the opportunity to learn and grow.

The infinite spans the human mind.
The spirit spins free of space and time.
The joy and sadness of life are a wink
In the eternal flow.
The stream cascades and meanders
To merge and be lost in the greater sea.

Elias G. Abu-Saba
November 6, 1994

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Preface

This book is intended for classroom teaching in architectural and civil engineering at the graduate and undergraduate levels. Although it has been developed from lecture notes given in structural steel design, it can be useful to practicing engineers. Many of the examples presented in this book are drawn from the field of design of structures.

Design of Steel Structures can be used for one or two semesters of three hours each on the undergraduate level. For a two-semester curriculum, Chapters 1 through 8 can be used during the first semester. Heavy emphasis should be placed on Chapters 1 through 5, giving the student a brief exposure to the consideration of wind and earthquakes in the design of buildings. With the new federal requirements vis a vis wind and earthquake hazards, it is beneficial to the student to have some understanding of the underlying concepts in this field. In addition to the class lectures, the instructor should require the student to submit a term project that includes the complete structural design of a multi-story building using standard design procedures as specified by AISC Specifications. Thus, the use of the *AISC Steel Construction Manual* is a must in teaching this course. In the second semester, Chapters 9 through 13 should be covered. At the undergraduate level, Chapters 11 through 13 should be used on a limited basis, leaving the student more time to concentrate on composite construction and built-up girders.

Chapters 6, 11, 12, 13, and 14 can be used for a graduate course. As a prerequisite for the graduate course, the student must have a minimum of three credit hours in the design of steel structures. The instructor will go into more depth in the presentation of Chapters 6, 11, 12, and 13. The student should be required to submit a term project using rigid frames in multi story buildings. Chapter 14 provides a simple method which can easily be computerized, allowing the student the facility of designing medium- to high-rise buildings using steel frames. U. S. customary units are used throughout, although some examples are presented with S. I. units. To help students convert from U. S. units to S. I. units, tables of conversion are provided in Chapter 1.

The allowable stress design method (ASD) is used predominantly in this book. To help the student appreciate the load and resistance factored design method (LRFD), the text includes discussions and examples utilizing this method.

Fundamental principles of steel design are presented in logical order to encourage the student to tackle the problem of design with a more general perspective. Tables, graphs and other design aids are introduced to help facilitate the design process. The selection of sections in the design of composite construction is made easier by a short-cut approach, thus eliminating the tediousness of the trial-and-error method.

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The author expresses his appreciation to the hundreds of students who have attended his classes at North Carolina Agricultural and Technical State University. Without them this book could not have been materialized.

Finally, the author wishes to thank his wife, Dr. Mary Bentley Abu-Saba, for her continued support and encouragement.

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1

Introduction

1.1 INTRODUCTION

Conversion Factors

The building industry in the United States is gradually adopting the new metric-based system referred to as SI units (for System International). For many years, the Congress of the United States has tried to legislate the use of the metric system without success. At present, scientific and technical periodicals and journals in this country are requiring the use of both systems in their publications. In this book, illustrations and example problems use both the SI and U.S. systems. Table 1.1 lists the standard units for both systems.

To help the reader make the transition from one system to another, conversion factors are provided in Table 1.2.

Design Philosophy

The design of structures is a creative process. At the same time, the structural designer must have a basic understanding of the concepts of solid mechanics and be able to work harmoniously with the architect who is in charge of the project, the contractor who will perform the construction, and the owner who will bear the cost of the project and use it. The principal goals of the structural designer are to provide a safe and reliable structure that will serve the function for which it was intended, an

TABLE 1.1 Units of Measurement

Name of Unit	Abbreviation	Use
	U.S. System	
Length		
Foot	ft	Large dimensions, building plans, beam spans
Inch	in.	Small dimensions, size of member cross sections
Area		
Square feet	ft^2	Large areas
Square inches	$in.^2$	Small areas, properties of cross sections
Volume		
Cubic feet	ft^3	Large volumes, quantities of materials
Cubic inches	$in.^3$	Small volumes
Force, Mass		
Pound	lb	Specific weight, force, load
Kip	k	1000 lb
Pounds per foot	lb/ft	Linear load as on a beam
Kips per foot	k/ft	Linear load as on a beam
Pounds per square foot	lb/ft^2 or psf	Distributed load on a surface
Kips per square foot	k/ft^2 or ksf	Distributed load on a surface
Pounds per cubic foot	lb/ft^3 or pcf	Relative density, weight
Stress		
Pounds per square inch	$lb/in.^2$ or psi	Stress in structures
Kips per square inch	$k/in.^2$ or ksi	Stress in structures
	SI System	
Length		
Meter	m	Large dimensions, building plans, beam spans
Millimeter	mm	Small dimensions, size of member cross sections
Area		
Square meter	m^2	Large areas
Square millimeter	mm^2	Small areas, properties of cross sections

Name of Unit	Abbreviation	Use
Volume		
Cubic meter	m^3	Large volumes, quantities of materials
Cubic millimeter	mm^3	Small volumes
Mass		
Kilogram	kg	Mass of materials
Kilograms per cubic meter	kg/m^3	Density
Force (Load on Structures)		
Newton	N	Force or load
Kilonewton	kN	1000 N
Stress		
Pascal	Pa	Stress or pressure ($1 \text{ Pa} = 1 \text{ N/m}^2$)
Kilopascal	kPa	1000 Pa
Megapascal	MPa	1,000,000 pascal
Gigapascal	GPa	1,000,000,000 pascal

economical structure that can be built and maintained within the specified budget, and a structure that is aesthetically acceptable.

Design Loads

Design loads for buildings include dead and live loads. Dead loads consist of the weight of all permanent constructions, including fixed equipment that is placed on the structure. In bridges, it includes the weight of decks, sidewalks, railings, utility posts and cables, and the bridge frame. Live loads are dynamic and vary in time. They include vehicles, snow, personnel, movable machinery, equipment, furniture, merchandise, wind and earthquake forces, and the like. Once a building frame has been selected on the basis of dead and live loads, a check must be made using a combination of these loads. In some regions, a check must include the seismic forces. Member sizes may have to be modified from the initial selection to meet the wind and seismic forces.

Live load tables are provided by almost all building codes. In unusual cases, the design load intensity is established to the satisfaction of a building official. However, the actual distribution of the live load for maximum effect is the responsibility of the design engineer. Table 1.3 lists live load intensities for various occupancies.

TABLE 1.2 Conversion Factors for Measurement Units

To Convert from U.S. Units to SI Units, Multiply by	U.S. Units	SI Units	To Convert from SI Units to U.S. Units, Multiply by
25.4	in.	mm	0.03937
0.3048	ft	m	3.281
645.2	in.^{2}	mm^2	1.550×10^{-3}
16.39×103	in.^{3}	mm^3	61.02×10^{-6}
416.2×103	in.^{4}	mm^4	2.403×10^{-6}
0.09290	ft^2	m^2	10.76
0.02832	ft^3	m^3	35.31
0.4536	lb (mass)	kg	2.205
4.448	lb (force)	N	0.2248
4.448	k (force)	kN	0.2248
1.356	ft-lb (moment)	N-m	0.7376
1.356	k-ft (moment)	kN-m	0.7376
1.488	lb/ft (mass)	kg/m	0.6720
14.59	lb/ft (force)	N/m	0.06853
14.59	k/ft (force)	kN/m	0.06853
6.895	lb/in.^{2} (force/unit area)	kPa	0.1450
6.895	k/in.^{2} (force/unit area)	MPa	0.1450
0.04788	lb/ft^2 (force/unit area)	kPa	20.93
47.88	k/ft^2 (force/unit area)	MPa	0.02093
16.02	lb/ft^3 (density)	kg/m^3	0.6242

1.2 STRUCTURAL STEEL AND ITS PROPERTIES IN CONSTRUCTION

Historically, the use of steel in construction for commercial buildings has been widely adopted in the United States. The availability of steel makes it much easier to use. In addition, steel has many characteristics that make it more advantageous than concrete. Structural steel takes less time to erect. The combination of high strength, light weight, ease of fabrication and erection, and many other favorable properties makes steel the material of choice for construction in this country. These properties will be discussed briefly in the following paragraphs.

High Strength

The strength of a construction material is defined by the ratio of the weight it carries to its own weight. When compared with other building

TABLE 1.3 Minimum Uniformly Distributed Live Loads

Occupancy or Use	Live Load (lb/ft^2)
Apartments (see residential)	
Armories and drill rooms	150
Assembly halls and other places of assembly	
Fixed seats	60
Movable seats	100
Balcony (exterior)	100
Bowling alleys, poolrooms, and similar recreational areas	75
Corridors	
First floor	100
Other floors, same as occupancy served except as indicated	
Dance halls	100
Diningrooms and restaurants	100
Dwellings (see residential)	
Garages (passenger cars)[a]	100
Grandstands (see reviewing stands)	
Gymnasiums, main floors and balconies	100
Hospitals	
Operating rooms	60
Private rooms	40
Wards	40
Hotels (see residential)	
Libraries	
Reading rooms	60
Stackrooms	150
Manufacturing	125
Marquees	75
Office buildings	
Lobbies	100
Offices	80
Penal institutions	
Cell blocks	40
Corridors	100
Residential	
Multifamily Houses	
Corridors	60
Private apartments	40
Public rooms	100
Dwellings	
First floor	40
Second floor and habitable attics	30
Unhabitable attics	20

[a] Floors shall be designed to carry 150% of the maximum wheel load anywhere on the floor.

(cont'd.)

TABLE 1.3 (*cont'd.*)

Occupancy or Use	Live Load (lb/ft²)
Hotels	
Corridors serving public rooms	100
Guest rooms	40
Private corridors	40
Public rooms	100
Public corridors	60
Reviewing stands and bleachers[b]	
Schools	
Classrooms	40
Corridors	100
Sidewalks, vehicular driveways, and yards subject to trucking	250
Skating rinks	10
Stairs' fire escapes and exitways	100
Storage warehouse	
Heavy	250
Light	125
Stores	
Retail	
First floor, rooms	100
Upper floors	75
Wholesale	125
Theaters	
Aisles, corridors, and lobbies	100
Balconies	60
Orchestra floors	60
Stage floors	150
Yards and terraces, pedestrians	100

[b] For detailed recommendations, see American Standard Places of Outdoor Assembly, Grandstands and Tents, Z20.3 1950, or the latest revision thereof approved by the American Standard Association, Inc., National Fire Protection Association, Boston, MA.

Source: Minimum Uniformly Distributed Live Loads ASCE 7-88 (Formerly ANSI A58.1), Table 2, p. 4.

materials, steel is considered to have a high strength ratio. This is important in the construction of long-span bridges, tall buildings, and buildings that are erected on relatively poor soil.

Strength and ductility are the two properties that make steel suitable for building structures that otherwise could not have been possible. The strength of steel provides buildings with a minimum number of columns and relatively small members. Its ductility relieves overstressing in certain

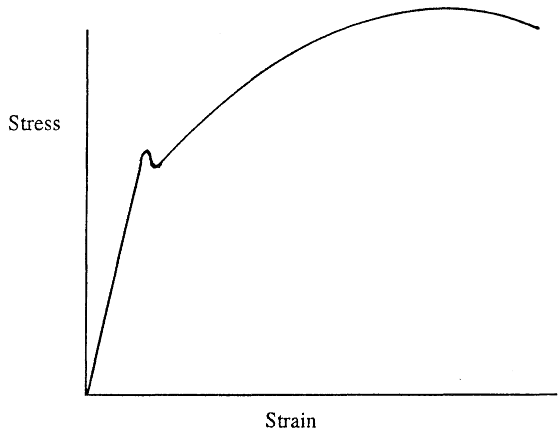

Figure 1.1 Typical stress–strain curve.

members in a given structure by allowing redistribution of stresses due to yielding.

A typical stress–strain diagram for structural steel is shown in Figure 1.1. If we look at this diagram, it can be observed that steel obeys Hooke's law up to the first yield. In this region, stress is directly proportional to strain. Beyond this point, steel experiences a plastic condition momentarily and then enters into the strain-hardening state. At failure, the strain ranges from 150 to 200 times the elastic strain. During strain hardening, the stress continues to increase to a maximum and then drops slightly before failure. At the end of the strain-hardening state, the cross section of the tension specimen is reduced. This characteristic is referred to as *necking*.

1.3 APPLICATIONS

The diagram shown in Figure 1.2 represents a typical interior panel of a library stack room's framing system. It has a reinforced concrete floor slab $4\frac{1}{2}$ in. thick. Tiling weighs 1 lb/ft^2, and ceiling loads are equivalent to 10 lb/ft^2.

Example 1.1

(a) Determine the uniform load on a typical beam and express it in pounds per linear foot.

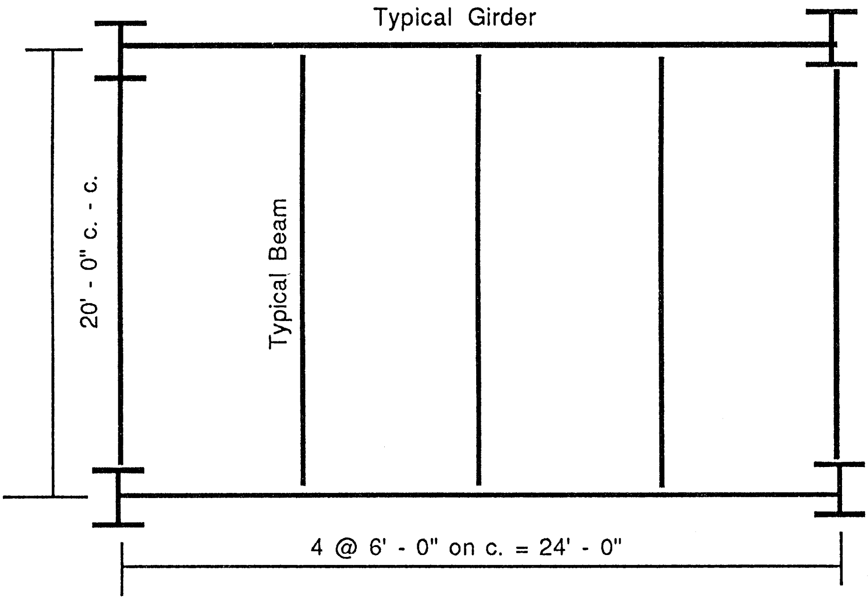

Figure 1.2 Floor plan: typical interior bay.

(b) Assuming that the typical beam and its fireproof coating weighs 50 lb/linear ft, find the concentrated loads on a typical girder.

(c) Show the loading system on the members in **(a)** and **(b)**.

(d) Do part **(a)** and **(b)** using the SI measurement units.

Solution

Typical Beam

In Figure 1.3a, the strip that is 1 ft × 6 ft represents the tributary area for the loading per linear foot on the beam shown in Figure 1.3b. Thus, the uniform load from each load component will be equal to the intensity of that load component times the tributary area. Calculation of the loads on the beam is presented as follows.

Dead Loads

Slab	$1 \times 6 \times 4.5 \times \frac{1}{12} \times 150$	$= 337.5$ lb/ft
Ceiling load	$1 \times 6 \times 10.0$	$= 60.0$
Tiling load	$1 \times 6 \times 1$	$= 6.0$
Subtotal		$=$ **403.5 lb / ft**

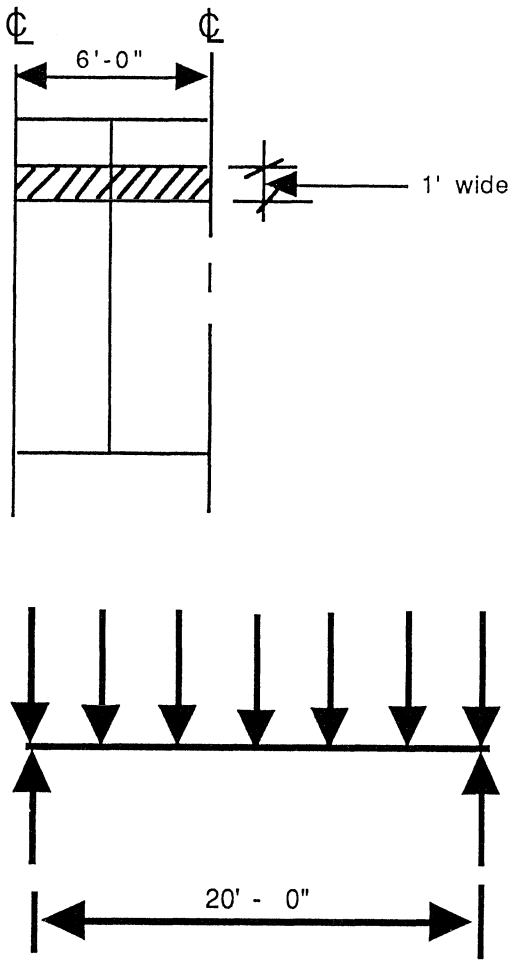

Figure 1.3 Typical beam. (a) Loading strip; (b) simply supported beam.

Live Loads

From Table 1.3, the intensity of the live load is 150 lb/ft^2. Thus, the uniform live load on the beam is calculated as follows:

Live load	$1 \times 6 \times 150$	= 900.0 lb/ft
Total (dead + live)		**= 1303.5 lb / ft**

The intensity of the uniform load on the typical beam shown in Figure 1.4 is therefore found to be 1303.5 lb/ft.

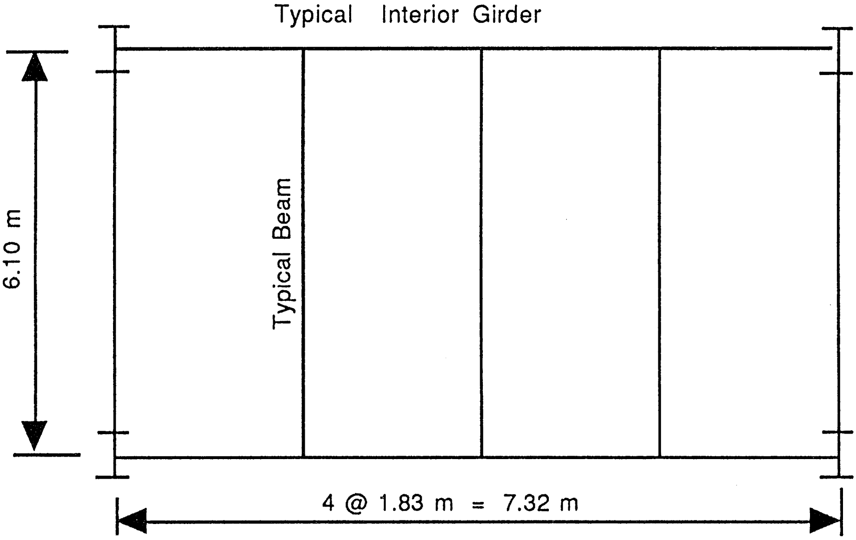

Figure 1.4 Typical interior girder with concentrated loads from typical beams.

Concentrated Loads on Typical Interior Girder

Calculate reaction R at the end of the beam

$$R = (DL + LL) \times \frac{L}{2} + \frac{1}{2} \times \text{weight of beam}$$
$$= 1303.5 \times \frac{20}{2} + \frac{1}{2} \times 20 \times 50$$
$$= 13{,}035 + 500$$
$$= 13{,}535 \text{ lb}$$

Or expressed in kips, $R = 13.58$ k.

Since an interior girder shown in Figure 1.5 supports typical beams on both sides, the reaction on the girder is double the reaction from one beam. Hence, the concentrated loads on the girder will have the magnitude P of

$$P = 13.54 \times 2$$
$$= 27.1 \text{ k}$$

Example 1.2

SI Measurement Units

Repeat the above problem using the SI measurement units showing the floor plan, typical beam, and girder. From Table 1.2, all measurements are

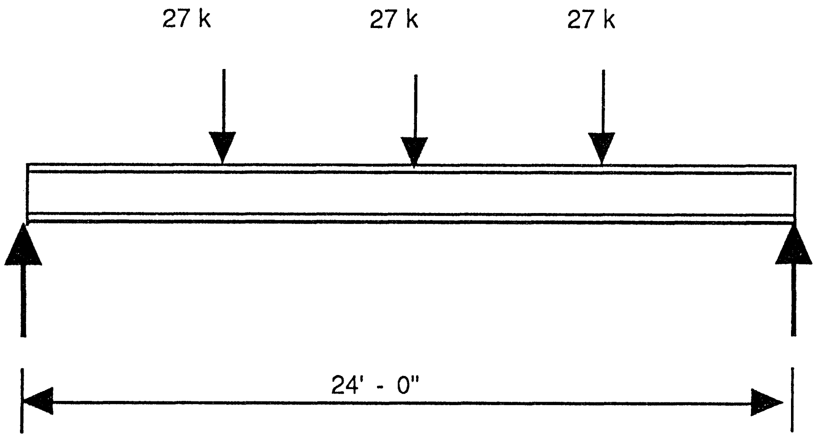

Figure 1.5 Floor plan: typical interior bay in SI units.

converted into SI units. A summary of the results for the above problem is shown below.

Loads	U.S. Units (lb/ft)	Conversion Factor	SI Units (N/m)
		Dead Loads	
Slab	337.5	14.59	4924
Ceiling	60.0		875
Tiling	6.0		88
Subtotal	403.5		5887
		Live Load	
Floor	900.0		13,131
		Weight of Beam	
Beam plus coating	50.0		730
		Total Uniform Load on Beam Including Its Weight	
	1303.5		19,748

Determine the reaction at the end of the beam.

	U.S. Units (lb)	Conversion Factor	SI Units (N)
Reaction at end of beam R	13,535	4.448	60,204
		Concentrated Loads on Girder	
$P = 2R$	27,070		120,408
$P/1000$	27.1 k		120.4 kN

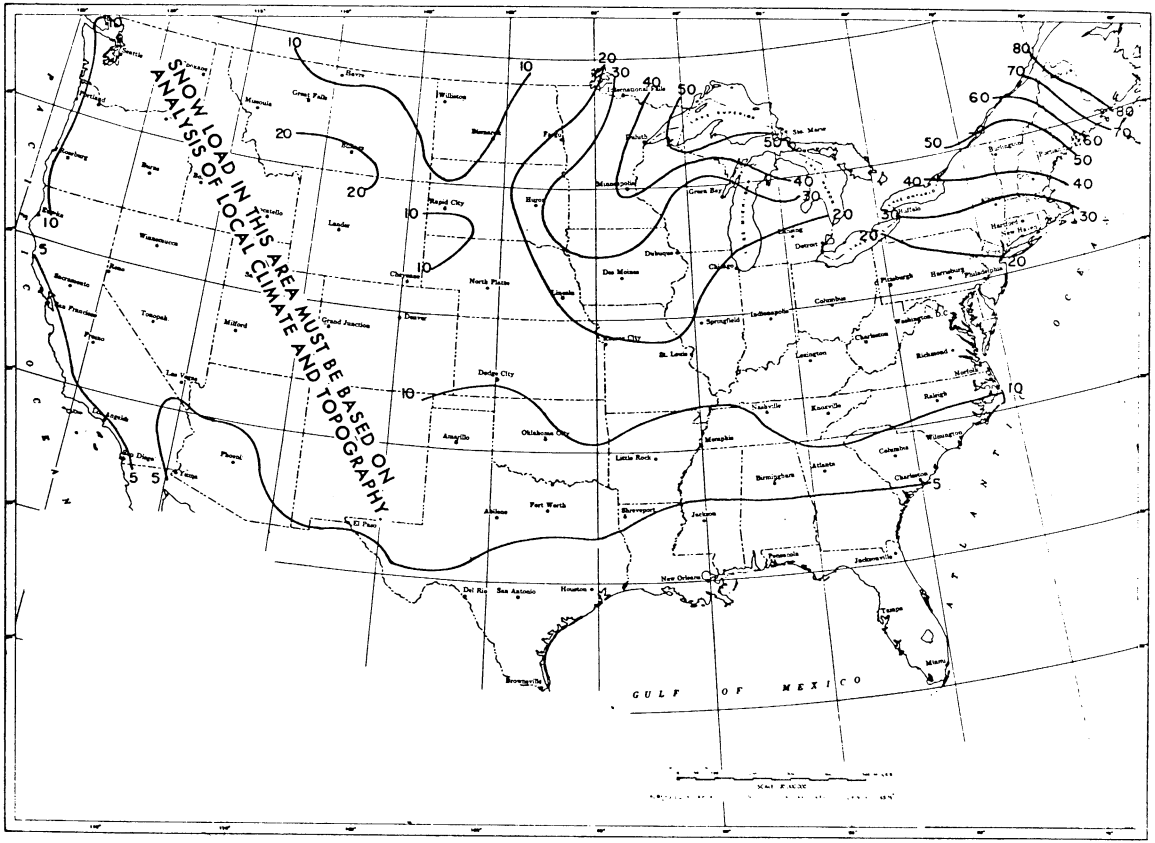

Figure 1.6 Snow load in pound-force per square foot on the ground, 5-year mean recurrence interval.

1.4 LOADS, LOAD FACTORS, AND LOAD COMBINATIONS

In 1986, the AISC introduced the first edition of a manual for steel construction using the load and resistance factor design method (LRFD). It will not be long before designers for steel construction are expected to use this method in preference to the allowable strength method currently in use. LRFD proportions the various members in a given structural system so that no single member or part may exceed the applicable limit state when the structure is subjected to all appropriate factored load combinations. The design strength of each structural member or assemblage must exceed the required strength based on the factored nominal loads.

The following nominal loads are considered in the design of steel structures:

D = dead load due to the weight of the structural element and permanent features on the structure

L = live load due to occupancy and movable equipment

L_r = roof live load

W = wind load

S = snow load (see Figure 1.6 for snow loads in the United States)

E = earthquake load

R = load due to initial rainwater or ice exclusive of the ponding contribution

The required strength of the structure and its elements must be determined from the appropriate critical combination of factored loads listed below:

$$1.4D \tag{1.1}$$

$$1.2D + 1.6L + 0.5(L_r, S, \text{or } R) \tag{1.2}$$

$$1.2D + 1.6(L_r, S, \text{or } R) + (0.5L \text{ or } 0.8W) \tag{1.3}$$

$$1.2D + 1.3W + 0.5L + 0.5(L_r, S, \text{or } R) \tag{1.4}$$

$$1.2D + 1.5E + (0.5L \text{ or } 0.2S) \tag{1.5}$$

$$0.9D - (1.3W \text{ or } 1.5E) \tag{1.6}$$

Exception: The load factor on L in combinations (1.3), (1.4), and (1.5) shall equal 1.0 for garages, areas occupied as places of public assembly, and all areas where the live load is greater than 100 lb/ft^2.