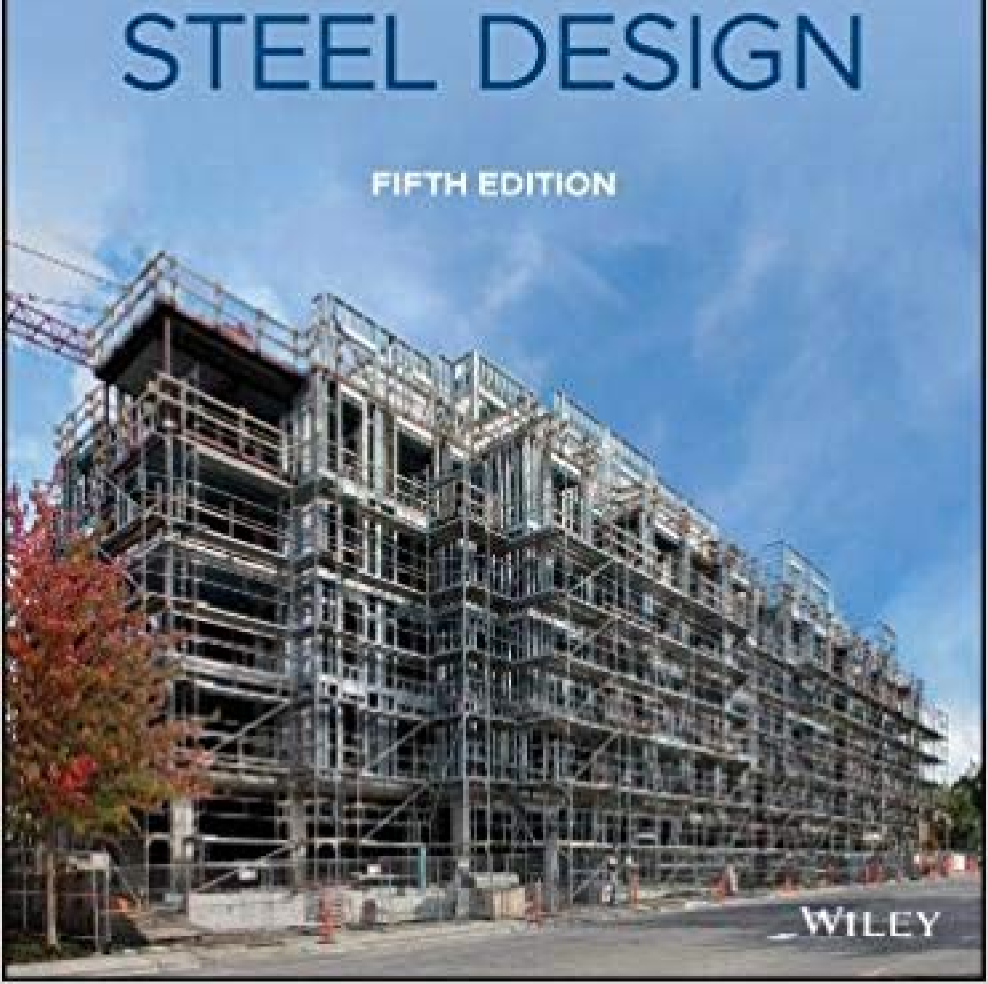
WEI-WEN YU | ROGER A. LABOUBE
HELEN CHEN

COLD-FORMED STEEL DESIGN

FIFTH EDITION



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Fifth Edition

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This edition first published 2020

Edition History
John Wiley & Sons (2e, 1991), John Wiley & Sons (3e, 2000), John Wiley & Sons (4e, 2010)

Registered Office
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA

Editorial Office
111 River Street, Hoboken, NJ 07030, USA

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Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data

Names: Yu, Wei-Wen, author. | LaBoube, Roger A., author. | Chen, Helen, author.
Title: Cold-formed steel design / Wei-Wen Yu and Roger A. LaBoube, Missour University of Science and Tech; Helen Chen, American Iron and Steel Institute.
Description: Fifth edition. | Hoboken : Wiley, 2020. | Includes bibliographical references and index.
Identifiers: LCCN 2019023220 (print) | LCCN 2019023221 (ebook) | ISBN 9781119487395 (cloth) | ISBN 9781119487388 (adobe pdf) | ISBN 9781119487418 (epub)
Subjects: LCSH: Building, Iron and steel. | Sheet-steel. | Thin-walled structures. | Steel—Cold working.
Classification: LCC TA684 .Y787 2020 (print) | LCC TA684 (ebook) | DDC 624.1/821—dc23
LC record available at https://lccn.loc.gov/2019023220
LC ebook record available at https://lccn.loc.gov/2019023221

Cover Design: Wiley
Cover Image: Courtesy of Steel Framing Alliance

Set in 10/12pt TimesLTStd by SPi Global, Chennai, India

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CONTENTS

PREFACE

This fifth edition of the book has been prepared to provide readers with a better understanding of the analysis and design of the thin-walled, cold-formed steel structures that have been so widely used in building construction and other areas in recent years. It is a revised version of the first author's book, *Cold-Formed Steel Design,* fourth edition, published by John Wiley & Sons, Inc. in 2010. All the revisions are based on the 2016 edition of the North American Specification, which incorporated the Direct Strength Method into the main body of the Specification, and reorganized the chapters to be consistent with hot-rolled steel design specification,[1.411] published by American Institute of Steel Construction.

The material was originally developed for graduate courses and short courses in the analysis and design of cold-formed steel structures and is based on experience in design, research, and development of the American Iron and Steel Institute (AISI) and North American design criteria.

Throughout the book, descriptions of the structural behavior of cold-formed steel members and connections are given from both theoretical and experimental points of view. The reasons and justification for the various design provisions of the North American specification are discussed at length. Consequently the text not only will be instructive for students but also can serve as a major source of reference for structural engineers and researchers.

To reflect the change in format and the inclusion of the Direct Strength Method into the main body of the Specification, all chapters have been completely revised according to the reorganized layout of the North American Specification and framing standards.

Chapter 1 includes a general discussion of the application of cold-formed steel structures and a review of previous and recent research. It also discusses the development of design specifications and the major differences between the design of cold-formed and hot-rolled steel structural members. Because of the many research projects in the field that have been conducted worldwide during the past 43 years, numerous papers have been presented at various conferences and published in a number of conference proceedings and engineering journals. At the same time, new design criteria have been developed in various countries. These new developments are reviewed in this chapter. New Sections 1.8 and 1.9 discuss the AISI Specification's design basis for strength and serviceability.

Since material properties play an important role in the performance of structural members, the types of steel and their most important mechanical properties are described in Chapter 2. The mechanical properties of ASTM A1063 steel sheets are added in Table 2.1.

In Chapter 3, the strength of thin elements and design criteria are discussed to acquaint the reader with the fundamentals of buckling modes to be considered in cold-formed steel design, such as local and distortional buckling and post-buckling strength of thin plates, and with the basic concepts used in design. The analytical and numerical approaches for determining local and distortional buckling strengths are discussed in this chapter. This chapter also introduces the definitions of commonly used terms in cold-formed steel design. The concepts of the Effective Width Method and the Direct Strength Method are discussed with the limits of applicability of these methods.

Chapter 4 deals with the design of flexural members. The contents have been reorganized to be consistent with the 2016 edition of the North American Specification. This chapter discusses the flexural member strengths due to global buckling, local buckling interacting with global buckling, and distortional buckling. It also includes new and revised design provisions on inelastic reserve capacity of beams, members with holes, shear strength of webs, web crippling strength and combination with bending, bearing stiffeners in C-section beams, bracing requirements, combination of bending and torsion, and beams having one flange attached to a metal roof system.

The design procedures for compression members are discussed in Chapter 5. The contents have been reorganized to be consistent with the 2016 edition of the North American Specification. This chapter discusses the compressive member strengths due to global buckling, local buckling interacting with global buckling, and distortional buckling. It also includes provisions about the design of built-up members, bracing requirements, and compression members having one flange attached to a metal roof system.

In the 2016 edition of the North American specification, the Direct Analysis Method was introduced to consider the second-order effect in structural analysis. This Direct Analysis Method is discussed in Chapter 6. In addition, revisions have been made on the design of beam–columns using ASD, LRFD, and LSD methods.

Chapter 7 covers the design of closed cylindrical tubes. This revised chapter reflects the rearrangement of design provisions in the North American specification.

Like the member design, the design of connections has been updated in Chapter 8 using the ASD, LRFD, and LSD methods with additional and revised design provisions for bearing strength between bolts and connected parts, combined shear and tension in fasteners, block shear strength, revised design information on screw connections, and power-actuated fasteners.

Because various types of structural systems, such as shear diaphragms and shell roof structures, have become increasingly popular in building construction, Chapter 9 contains design information on these types of structural systems. Revisions are made reflecting the new North American standard of AISI S310 for profiled steel diaphragm panels.

The sectional properties of standard corrugated sheets are discussed in Chapter 10 because they have long been used in buildings for roofing, siding, and other applications. Minor revisions have been made in the chapter.

Steel decks are widely used in building construction. Consequently the updated information in Chapter 11 on their use in steel-deck-reinforced composite slabs and composite beams is timely.

In 2015, the AISI design standards for cold-formed steel framing were consolidated. These standards are specifically applicable for residential and commercial construction. As a result, Chapter 12 has been completely rewritten based on new and consolidated AISI standards.

It is obvious that a book of this nature would not have been possible without the cooperation and assistance of many individuals, organizations, and institutions. It is based primarily on the results of continuing research programs on cold-formed steel structures that have been sponsored by the American Iron and Steel Institute (AISI), the ASCE, the Canadian Sheet Steel Building Institute (CSSBI), the Cold-Formed Steel Engineers Institute (CFSEI) of the Steel Framing Alliance (SFA), the Metal Building Manufacturers Association (MBMA), the Metal Construction Association (MCA), the National Science Foundation (NSF), the Rack Manufacturers Institute (RMI), the Steel Deck Institute (SDI), the Steel Framing Industry Association (SFIA), the Steel Stud Manufacturers Association (SSMA), and other organizations located in the United States and abroad. The publications related to cold-formed steel structures issued by AISI and other institutions have been very helpful for the preparation of this book.

The first author is especially indebted to his teacher, the late Dr. George Winter of Cornell University, who made contributions of pronounced significance to the building profession in his outstanding research on cold-formed steel structures and in the development of AISI design criteria. A considerable amount of material used in this book is based on Dr. Winter's publications.

Our sincere thanks go to Mr. Robert J. Wills, Vice President, Construction Market Development, Steel Market Development Institute (a business unit of the American Iron and Steel Institute), for permission to quote freely from *the North American Specification*, *Commentary*, *Design Manual*, *Framing Standards*, *Design Guides*, and other AISI publications. An expression of appreciation is also due to the many organizations and individuals that granted permission for the reproduction of quotations, graphs, tables, and photographs. Credits for the use of such materials are given in the text.

We are very grateful to Mrs. Christina Stratman for her kind assistance in the preparation of this book. The financial assistance provided by the Missouri University of Science and Technology through the first author's Curators' Professorship and the sponsors for the Wei-Wen Yu Center for Cold-Formed Steel Structures is appreciated.

This book could not have been completed without the help and encouragement of the authors' wives, Yueh-Hsin Yu and Karen LaBoube, and husband, Chunwei Huang, as well as for their patience, understanding, and assistance.

Wei-Wen Yu
Roger A. LaBoube
Hong (Helen) Chen

Rolla, Missouri
March 2019

CHAPTER 1

Introduction

1.1 GENERAL REMARKS

In steel construction, there are two main families of structural members. One is the familiar group of hot-rolled shapes and members built up of plates. The other, less familiar but of growing importance, is composed of sections cold formed from steel sheet, strip, plate, or flat bar in roll-forming machines or by press brake or bending brake operations.[1.1,1.2,1.3*] These are cold-formed steel structural members. The thickness of steel sheet or strip generally used in cold-formed steel structural members ranges from 0.0149 in. (0.378 mm) to about $\frac{1}{4}$ in. (6.35 mm). Steel plates and bars as thick as 1 in. (25.4 mm) can be cold formed successfully into structural shapes.[1.1,1.4,1.314,1.336,1.345]

Although cold-formed steel sections are used in car bodies, railway coaches, various types of equipment, storage racks, grain bins, highway products, transmission towers, transmission poles, drainage facilities, and bridge construction, the discussions included herein are primarily limited to applications in building construction. For structures other than buildings, allowances for dynamic effects, fatigue, and corrosion may be necessary.[1.314,1.336,1.345,1.417]

The use of cold-formed steel members in building construction began in about the 1850s in both the United States and Great Britain. However, such steel members were not widely used in buildings until around 1940. The early development of steel buildings has been reviewed by Winter.[1.5–1.7]

*The references are listed at the back of the book.

Since 1946 the use and the development of thin-walled cold-formed steel construction in the United States have been accelerated by the issuance of various editions of the "Specification for the Design of Cold-Formed Steel Structural Members" of the American Iron and Steel Institute (AISI).[1.267,1.345] The earlier editions of the specification were based largely on the research sponsored by AISI at Cornell University under the direction of George Winter. It has been revised subsequently to reflect the technical developments and the results of continuing research.[1.267,1.336,1.346,1.416,1.417]

In general, cold-formed steel structural members provide the following advantages in building construction:

1. As compared with thicker hot-rolled shapes, cold-formed light members can be manufactured for relatively light loads and/or short spans.
2. Unusual sectional configurations can be produced economically by cold-forming operations (Fig. 1.1), and consequently favorable strength-to-weight ratios can be obtained.
3. Nestable sections can be produced, allowing for compact packaging and shipping, as well as for developing efficient structural applications.

Figure 1.1 Various shapes of cold-formed sections.[1.1]

4. Load-carrying panels and decks can provide useful surfaces for floor, roof, and wall construction, and in other cases they can also provide enclosed cells for electrical and other conduits.
5. Load-carrying panels and decks not only withstand loads normal to their surfaces, but they can also act as shear diaphragms to resist force in their own planes if they are adequately interconnected to each other and to supporting members.

Compared with other materials such as timber and concrete, the following qualities can be realized for cold-formed steel structural members[1.8,1.9]:

1. Lightness
2. High strength and stiffness
3. Ease of prefabrication and mass production
4. Fast and easy erection and installation
5. Substantial elimination of delays due to weather
6. More accurate detailing
7. Nonshrinking and noncreeping at ambient temperatures
8. Formwork unneeded
9. Termite proof and rot proof
10. Uniform quality
11. Economy in transportation and handling
12. Noncombustibility
13. Recyclable material

The combination of the above-mentioned advantages can result in cost savings in construction (www.buildsteel.org).

1.2 TYPES OF COLD-FORMED STEEL SECTIONS AND THEIR APPLICATIONS

Cold-formed steel structural members can be classified into two major types:

1. Individual structural framing members
2. Panels and decks

The design and the usage of each type of structural member have been reviewed and discussed in a number of publications.[1.5–1.75,1.267–1.285,1.349,1.358,1.418]

1.2.1 Individual Structural Framing Members

Figure 1.2 shows some of the cold-formed sections generally used in structural framing. The usual shapes are channels (C-sections), Z-sections, angles, hat sections, I-sections, T-sections, and tubular members. Previous studies have indicated that the sigma section (Fig. 1.2*d*) possesses several advantages, such as high load-carrying capacity, smaller blank size, less weight, and larger torsional rigidity as compared with standard channels.[1.76]

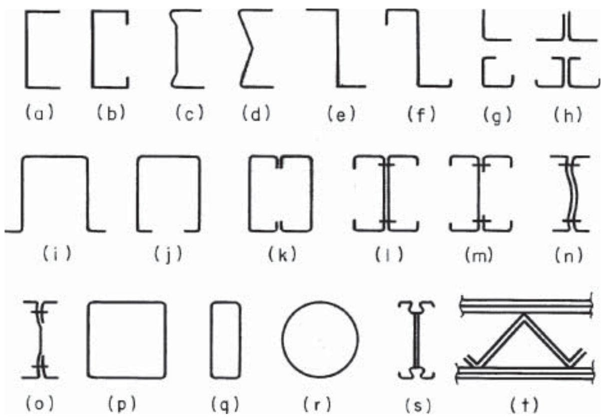

Figure 1.2 Cold-formed sections used in structural framing.[1.6]

In general, the depth of cold-formed individual framing structural members ranges from 2 to 16 in. (50.8 to 406 mm), and the thickness of material ranges from 0.0329 to 0.1180 in. (0.836 to 2.997 mm). In some cases, the depth of individual members may be up to 18 in. (457 mm), and the thickness of the member may be $\frac{1}{2}$ in. (12.7 mm) or thicker in transportation and building construction. Cold-formed steel plate sections in thicknesses of up to about $\frac{3}{4}$ or 1 in. (19.1 or 25.4 mm) have been used in steel plate structures, transmission poles, and highway sign support structures.

In view of the fact that the major function of this type of individual framing member is to carry load, structural strength and stiffness are the main considerations in design. Such sections have commonly been used as primary framing members in buildings having multiple stories in height.[1.278] In 2000, the 165-unit Holiday Inn in Federal Way, Washington, utilized eight stories of axial load bearing cold-formed steel studs as the primary load-bearing system.[1.357] Figure 1.3 shows a mid-rise construction building. Cold-formed steel for mid-rise construction has become popular for these buildings that typically may range from 4 to 12 stories high. Chapter 12 provides additional discussion of cold-formed steel applications for low- and mid-rise construction. Additional information may also be obtained at www.buildsteel.org. In tall multistory buildings the main framing is typically of heavy hot-rolled

Figure 1.3 Building composed entirely of cold-formed steel sections. Courtesy of Don Allen.

shapes and the secondary elements may be of cold-formed steel members such as steel joists, studs, decks, or panels (Figs. 1.4 and 1.5). In this case the heavy hot-rolled steel shapes and the cold-formed steel sections supplement each other.[1.264]

As shown in Figs. 1.2 and 1.6–1.10, cold-formed sections are also used as chord and web members of open web steel joists, space frames, arches, and storage racks.

1.2.2 Panels and Decks

Another category of cold-formed sections is shown in Fig. 1.11. Historically, these sections are generally used for roof decks, floor decks, wall panels, siding material, and bridge forms. Recently, profiled deck has been used for shear wall. Some deeper panels and decks are cold formed with web stiffeners.

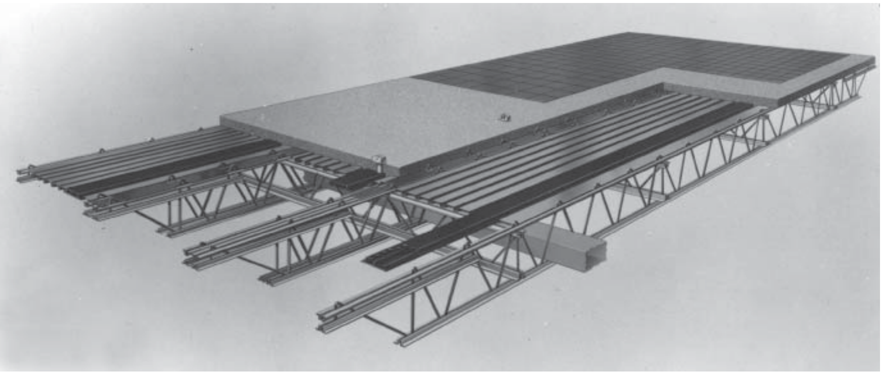

Figure 1.4 Composite truss–panel system prefabricated by Laclede Steel Company.

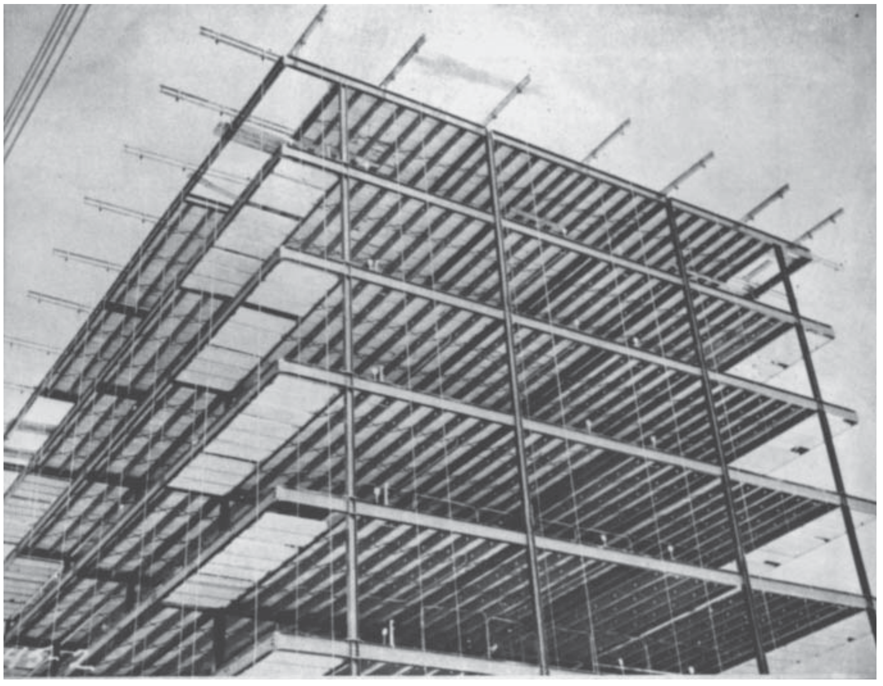

Figure 1.5 Cold-formed steel joists used together with hot-rolled shapes. Courtesy of Stran-Steel Corporation.

The depth of panels generally ranges from 9/16 to $7\frac{1}{2}$ in. (14.2 to 191 mm), and the thickness of materials ranges from 0.018 to 0.075 in. (0.457 to 1.91 mm). This is not to suggest that in some cases the use of 0.012-in. (0.305-mm) steel-ribbed sections as load-carrying elements in roof and wall construction would be inappropriate.

Steel panels and decks not only provide structural strength to carry loads, but they also provide a surface on which flooring, roofing, or concrete fill can be applied, as shown in Fig. 1.12. They can also provide space for electrical conduits, or they can be perforated and combined with sound absorption material to form an acoustically conditioned ceiling. The cells of cellular panels are also used as ducts for heating and air conditioning.

In the past, steel roof decks were successfully used in folded-plate and hyperbolic paraboloid roof construction,[1.13,1.22,1.26,1.30,1.34,1.35,1.72,1.77–1.84] as shown in Figs. 1.13 and 1.14. One of the world's largest cold-formed steel primary structures using steel decking for hyperbolic paraboloids, designed by Lev Zetlin Associates, is shown in

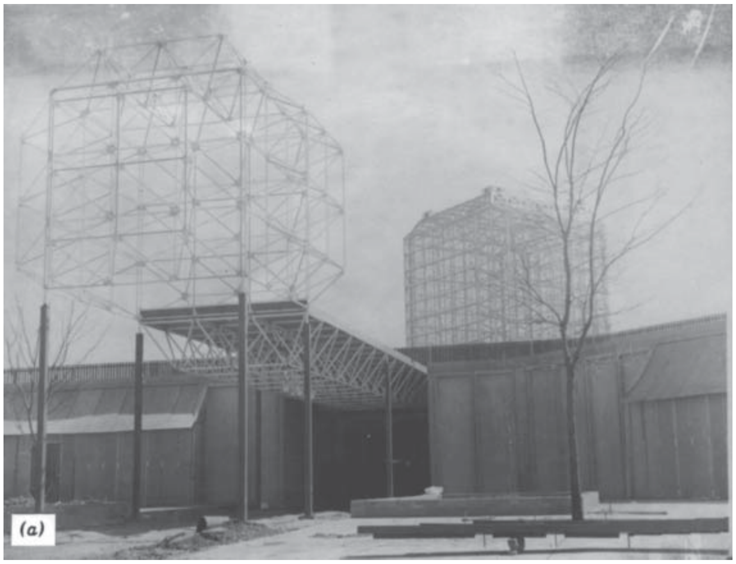

Figure 1.6 Cold-formed steel sections used in space frames. Courtesy of Unistrut Corporation.

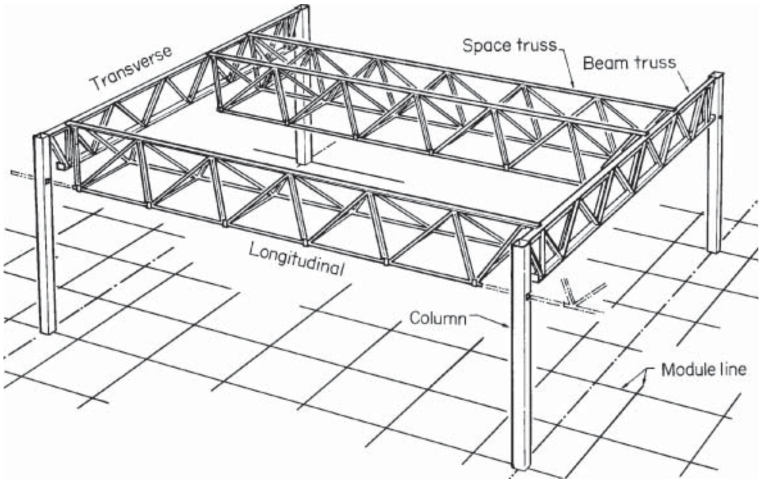

Figure 1.7 Cold-formed steel members used in space grid system. Courtesy of Butler Manufacturing Company.

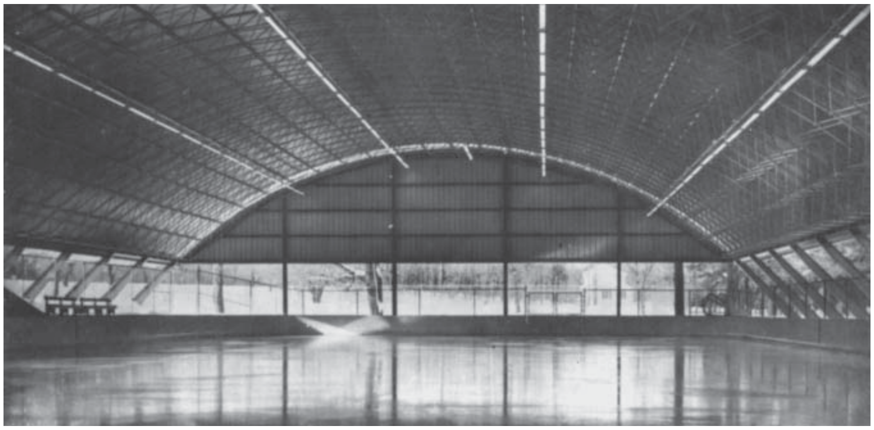

Figure 1.8 Cold-formed steel members used in a 100 × 220 × 30-ft (30.5 × 67.1 × 9.2-m)triodetic arch. Courtesy of Butler Manufacturing Company.

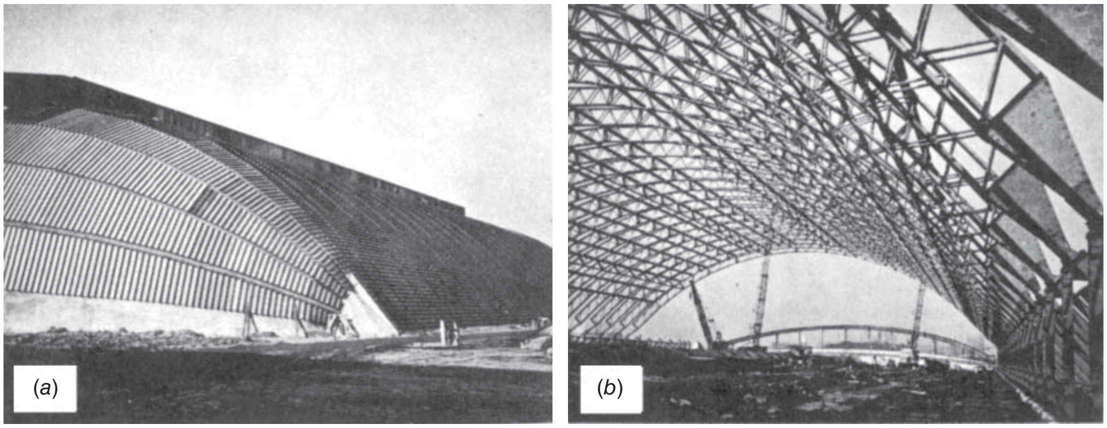

Figure 1.9 Hangar-type arch structures using cold-formed steel sections. Courtesy of Armco Steel Corporation.[1.6]

Fig. 1.15.[1.82] Roof decks may be curved to fit the shape of an arched roof without difficulty. Some roof decks are shipped to the field in straight sections and curved to the radius of an arched roof at the job site (Fig. 1.16). In other buildings, roof decks have been designed as the top chord of prefabricated open web steel joists or roof trusses (Fig. 1.17).[1.85,1.86] In Europe, TRP 200 decking (206 mm deep by 750 mm pitch) has been used widely. In the United States, the standing seam metal roof has an established track record in new construction and replacement for built-up and single-ply systems in many low-rise buildings.

Figure 1.11 also shows corrugated sheets, which are often used as roof or wall panels and in drainage structures. The use of corrugated sheets as exterior curtain wall panels is illustrated in Fig. 1.18*a*. It has been demonstrated that corrugated sheets can be used effectively in the arched roofs of underground shelters and drainage structures.[1.87–1.89]

The pitch of corrugations usually ranges from $1\frac{1}{4}$ to 3 in. (31.8 to 76.2 mm), and the corrugation depth varies from $\frac{1}{4}$ to 1 in. (6.35 to 25.4 mm). The thickness of corrugated steel sheets usually ranges from 0.0135 to 0.164 in. (0.343 to 4.17 mm). However, corrugations with a pitch of up to 6 in. (152 mm) and a depth of up to 2 in. (50.8 mm) are also available. See Chapter 10 for the design of corrugated steel sheets based on the AISI publications.[1.87,1.88] Unusually deep corrugated panels have been used in frameless stressed-skin construction, as shown in Fig. 1.18*b*. The self-framing corrugated steel panel building proved to be an effective blast-resistant structure in the Nevada tests conducted in 1955.[1.90]

Figure 1.10 Rack structures. Courtesy of Unarco Materials Storage.

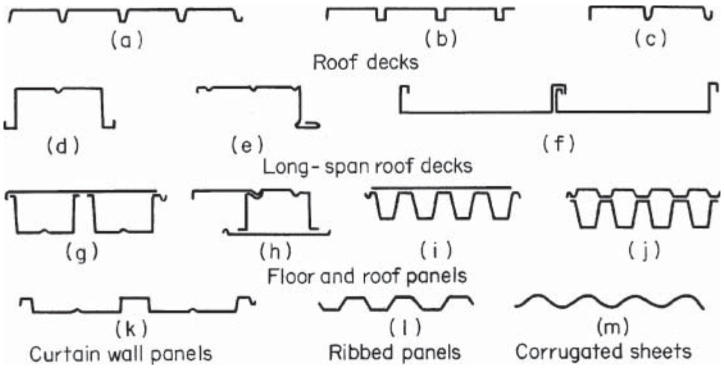

Figure 1.11 Decks, panels, and corrugated sheets.

Figure 1.19 shows the application of standing seam roof systems. The design of beams having one flange fastened to a standing seam roof system and the strength of standing seam roof panel systems are discussed in Chapter 4.

In the past four decades, cold-formed steel deck has been successfully used not only as formwork but also as reinforcement of composite concrete floor and roof slabs.[1.55,1.91,1.103] The floor systems of this type of composite steel deck-reinforced concrete slab are discussed in Chapter 11.

1.3 METAL BUILDINGS AND INDUSTRIALIZED HOUSING

Single-story metal buildings have been widely used in industrial, commercial, and agricultural applications. Metal

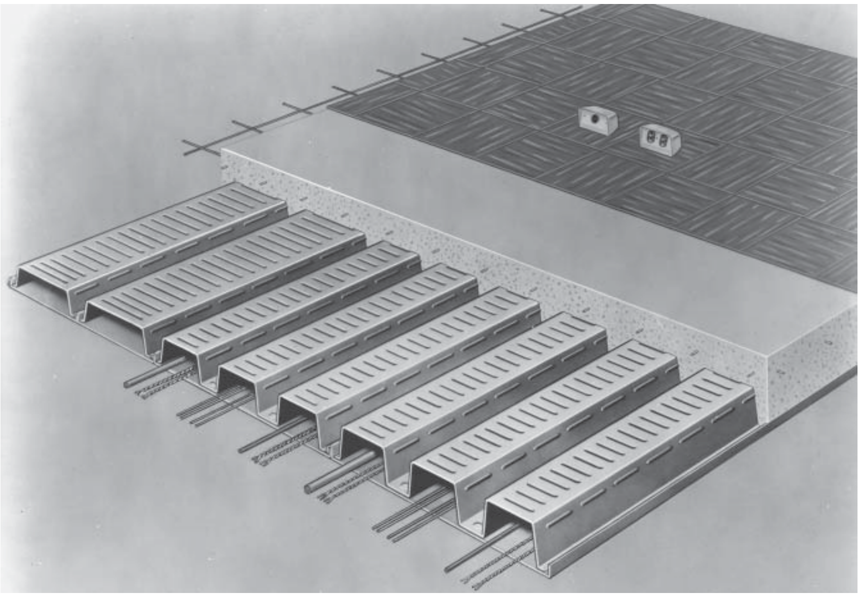

Figure 1.12 Cellular floor panels. Courtesy of H. H. Robertson Company.

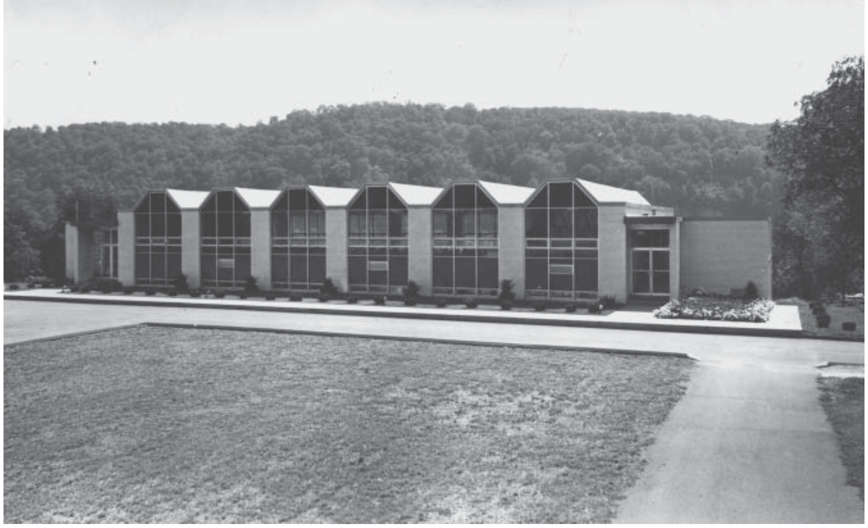

Figure 1.13 Cold-formed steel panels used in folded-plate roof. Courtesy of H. H. Robertson Company.

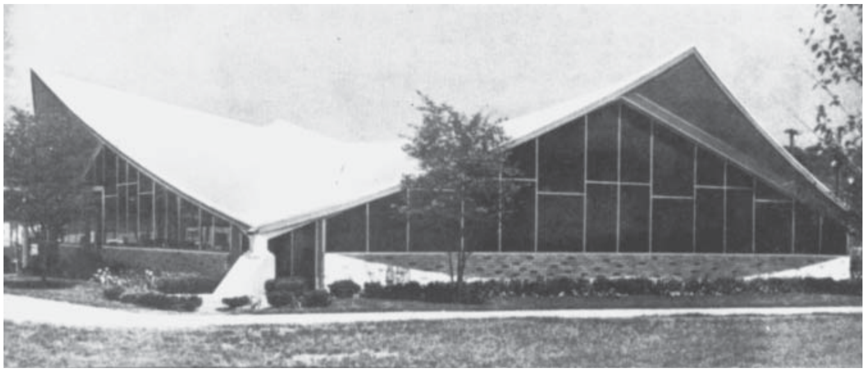

Figure 1.14 Hyperbolic paraboloid roof of welded laminated steel deck. Reprinted from *Architectural Record,* March 1962. Copyright by McGraw-Hill Book Co., Inc.[1.79]

Figure 1.15 Super bayhangar for American Airlines Boeing 747s in Los Angeles.[1.82] Courtesy of Lev Zetlin Associates, Inc.

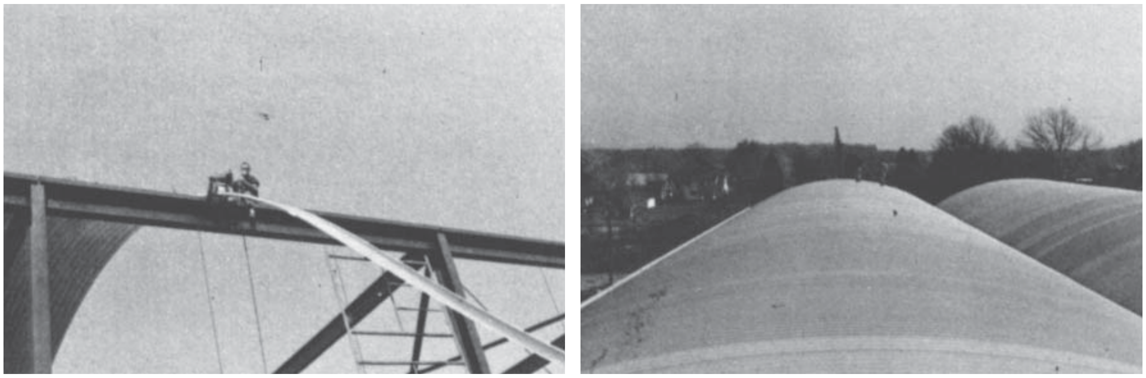

Figure 1.16 Arched roof curved at job site. Courtesy of Donn Products Company.

Figure 1.17 Steel deck is designed as the top chord of prefabricated open web steel joists. Courtesy of Inland-Ryerson Construction Products Company.

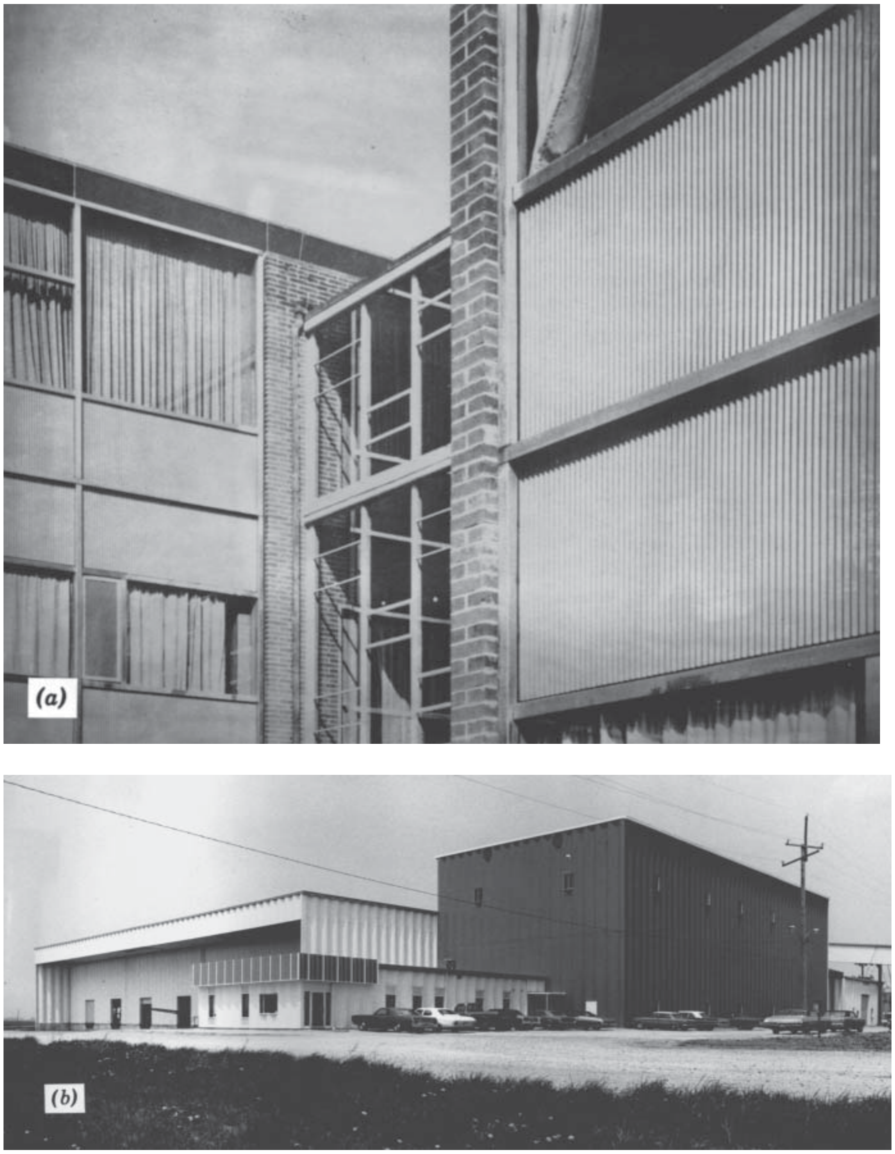

Figure 1.18 (*a*) Exterior curtain wall panels employing corrugated steel sheets.[1.87] (*b*) Frameless stressed-skin construction. Courtesy of Behlen Manufacturing Company.

building systems have also been used for community facilities such as recreation buildings, schools, and churches.[1.104,1.105] Metal buildings provide the following major advantages:

1. Attractive appearance
2. Fast construction
3. Low maintenance
4. Easy extension
5. Lower long-term cost

In general, smaller buildings can be made entirely of cold-formed sections (Fig. 1.20), and relatively large buildings are often made of welded steel plate rigid frames with cold-formed sections used for girts, purlins, roofs, and walls (Fig. 1.21).

The design of pre-engineered metal buildings is often based on the *Metal Building Systems Manual* issued by the Metal Building Manufacturers Association (MBMA).[1.360] The 2012 edition of the MBMA manual is a revised version of the previous manual. The new manual includes (a) load

Figure 1.19 Application of standing seam roof systems. Courtesy of Butler Manufacturing Company.

application data [International Building Code (IBC) 2006 loads], (b) crane loads, (c) serviceability, (d) common industry practices, (e) guide specifications, (f) AISC-MB certification, (g) wind load commentary, (h) fire protection, (i) wind, snow, and rain data by U.S. county, (j) a glossary, (k) an appendix, and (l) a bibliography. In addition, MBMA also has published the *Metal Roof Systems Design Manual*.[1.361] It includes systems components, substrates, specifications and standards, retrofit, common industry practices, design, installation, energy, and fire protection.Additional information may be located at www.mbma.com.

The design of single-story rigid frames is treated extensively by Lee et al.[1.107] In Canada the design, fabrication, and erection of steel building systems are based on a standard of the Canadian Sheet Steel Building Institute (CSSBI).[1.108]

Industrialized housing can be subdivided conveniently into (1) panelized systems and (2) modular systems.[1.109,1.278] In panelized systems, flat wall, floor, and roof sections are prefabricated in a production system, transported to the site, and assembled in place. In modular systems, three-dimensional housing unit segments are factory built, transported to the site, lifted into place, and fastened together.

In the 1960s, under the School Construction Systems Development Project of California, four modular systems of school construction were developed by Inland Steel Products Company (modular system as shown in Fig. 1.17), Macomber Incorporated (V-Lok modular component system as shown in Fig. 1.22), and Rheem/Dudley Buildings (flexible space system).[1.110]

In 1970 Republic Steel Corporation was selected by the Department of Housing and Urban Development under the Operation Breakthrough Program to develop a modular system for housing.[1.111] Panels consisting of steel facings with an insulated core were used in this system.

Building innovation also includes the construction of unitized boxes. These boxes are planned to be prefabricated of room size, fully furnished, and stacked in some manner to be a hotel, hospital, apartment, or office building.[1.25,1.112] For multistory buildings these boxes can be supported by a main framing made of heavy steel shapes.

In the past, cold-formed steel structural components have been used increasingly in low-rise buildings and residential steel framing. Considerable research and

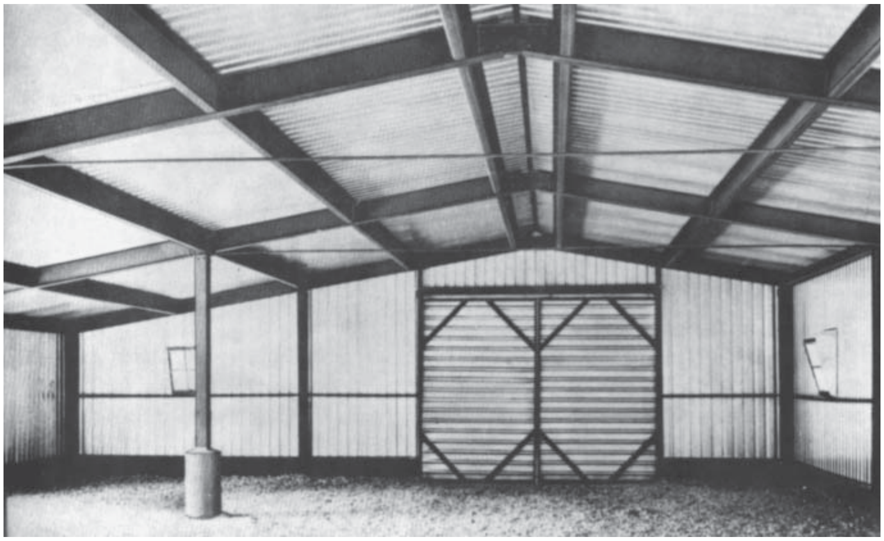

Figure 1.20 Small building made entirely of cold-formed sections. Courtesy of Stran-Steel Corporation.[1.6]

Figure 1.21 Standardized building made of fabricated rigid frame with cold-formed sections for girts, purlins, roofs, and walls. Courtesy of Armco Steel Corporation.

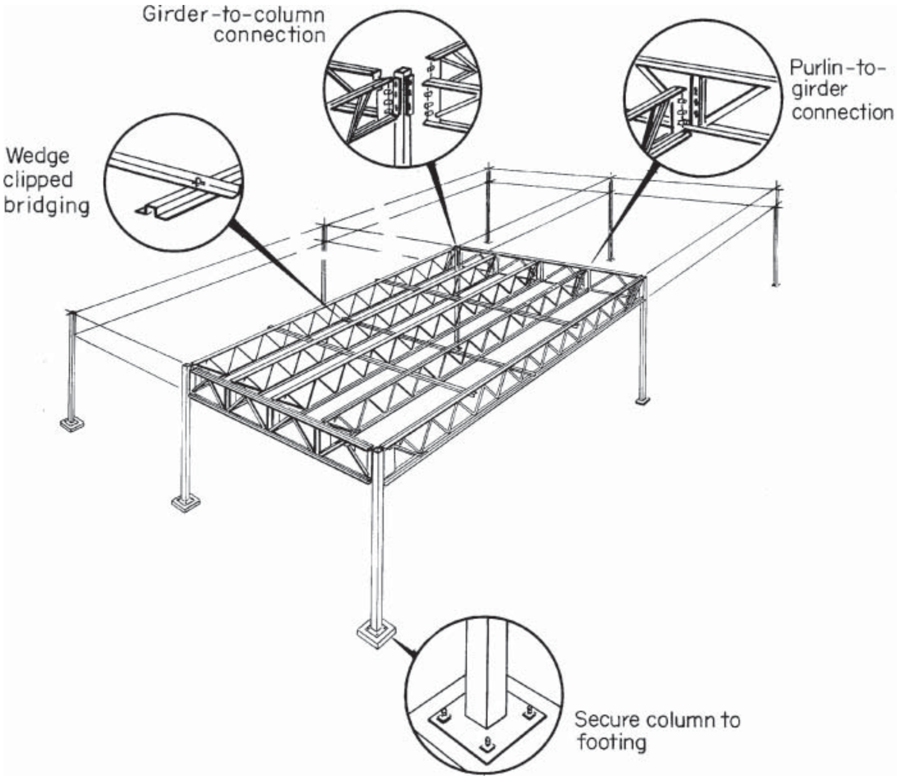

Figure 1.22 V-Lok modular component system. Courtesy of Macomber Incorporated.

development activities have been conducted continuously by numerous organizations and steel companies.[1.21,1.25,1.27,1.28,1.113–1.116,1.280–1.301] In addition to the study of the load-carrying capacity of various structural components, recent research work has concentrated on (1) joining methods, (2) thermal and acoustical performance of wall panels and floor and roof systems, (3) vibrational response of steel decks and floor joists, (4) foundation wall panels, (5) trusses, and (6) energy considerations. Chapter 12 provides some information on recent developments, design standards, and design guide for cold-formed steel light-frame construction.

In Europe and other countries many design concepts and building systems have been developed. For details, see Refs. 1.25, 1.140–1.143, 1.117, 1.118, 1.268, 1.270, 1.271, 1.273, 1.275, 1.290, 1.293, and 1.297.

1.4 METHODS OF FORMING

Three methods are generally used in the manufacture of cold-formed sections such as illustrated in Fig. 1.1:

1. Cold roll forming
2. Press brake operation
3. Bending brake operation

1.4.1 Cold Roll Forming[1.1,1.119]

The method of cold roll forming has been widely used for the production of building components such as individual structural members, as shown in Fig. 1.2, and some roof, floor, and wall panels and corrugated sheets, as shown in Fig. 1.11. It is also employed in the fabrication of partitions, frames of windows and doors, gutters, downspouts, pipes, agricultural equipment, trucks, trailers, containers, railway passenger and freight cars, household appliances, and other products. Sections made from strips up to 36 in. (915 mm) wide and from coils more than 3000 ft (915 m) long can be produced most economically by cold roll forming.

The machine used in cold roll forming consists of pairs of rolls (Fig. 1.23) which progressively form strips into the final required shape. A simple section may be produced by as few as six pairs of rolls. However, a complex section may require as many as 15 sets of rolls. Roll setup time may be several days.

The speed of the rolling process typically ranges from 20 to 300 ft/min (6 to 92 m/min). The usual speed is in the range of 75–150 ft/min (23–46 m/min). At the finish end, the completed section may be cut to required lengths by an automatic cutoff tool without stopping the machine. Maximum cut lengths are usually between 20 and 40 ft (6 and 12 m). The flat sheet may be cut to length prior to the rolling process.

As far as the limitations for thickness of material are concerned, carbon steel plate as thick as $\frac{3}{4}$ in. (19 mm) can be roll formed successfully, and stainless steels have been roll formed in thicknesses of 0.006–0.30 in. (0.2–7.6 mm). The size ranges of structural shapes that can be roll formed on standard mill-type cold-roll-forming machines are shown in Fig. 1.24.

The tolerances in roll forming are usually affected by the section size, the product type, and the material thickness. The following limits were given by Kirkland[1.1] as representative of commercial practice, but do not necessarily represent current industry tolerances:

Piece length, using automatic cutoff	$\pm\frac{1}{64}-\frac{1}{8}$ in. (0.4–3.2 mm)
Straightness and twist	$\pm\frac{1}{64}-\frac{1}{4}$ in. (0.4–6.4 mm) in 10 ft (3 m)
Cross-sectional dimensions	
Fractional	$\pm\frac{1}{64}-\frac{1}{16}$ in. (0.4–1.6 mm)
Decimal	±0.005–0.015 in. (0.1–0.4 mm)
Angles	±1°–2°

Table 1.1 gives the fabrication tolerances as specified by the MBMA for cold-formed steel channels and Z-sections to be used in metal building systems.[1.360] All symbols used in the table are defined in Fig. 1.25. The same tolerances are specified in the standard of the CSSBI.[1.108] For light steel framing members, the AISI framing standard S240-15[1.400,1.432] includes manufacturing tolerances for structural members. These tolerances for studs and tracks are based on the American Society for Testing and Materials (ASTM) standard C955-11. See Table 1.2 and Fig. 1.26. For additional information on roll forming, see Ref. 1.119.

1.4.2 Press Brake

The press brake operation may be used under the following conditions:

1. The section is of simple configuration.
2. There is a small required quantity.

The equipment used in the press brake operation consists essentially of a moving top beam and a stationary bottom bed on which the dies applicable to the particular required product are mounted, as shown in Fig. 1.27.

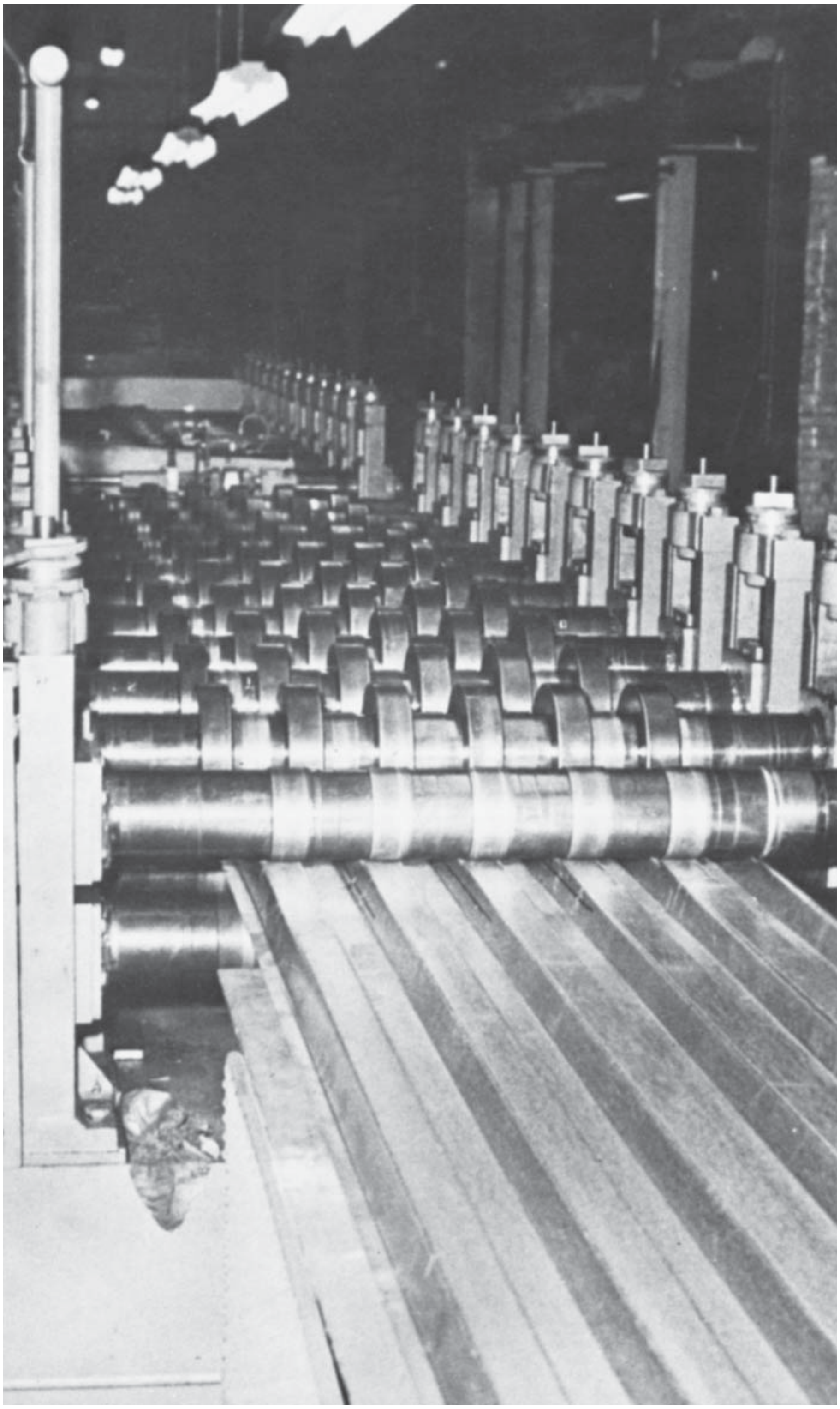

Figure 1.23 Cold-roll-forming machine.

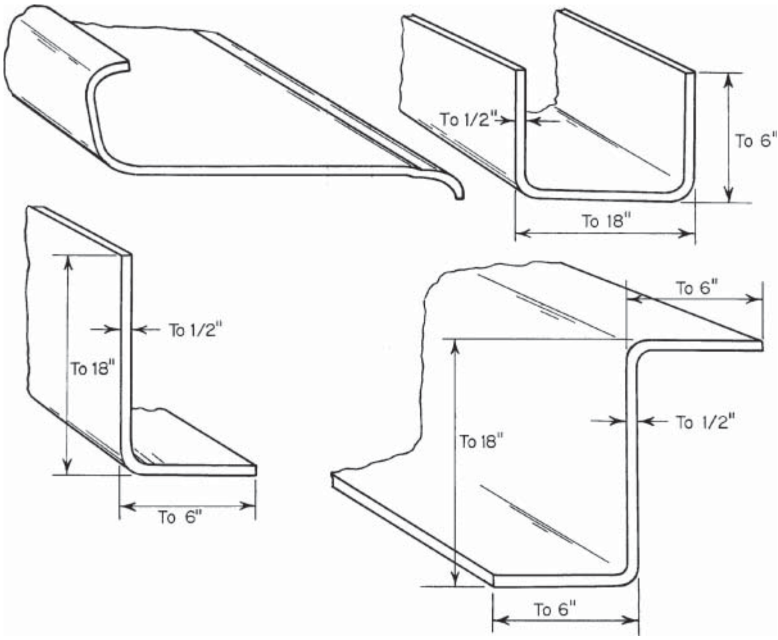

Figure 1.24 Size ranges of typical roll-formed structural shapes.[1.1]

Table 1.1 MBMA Table on Fabrication Tolerances[1.360]

Dimension	Tolerances, in. +	Tolerances, in. −
Geometry		
D	$\frac{3}{16}$	$\frac{3}{16}$
B	$\frac{3}{16}$	$\frac{3}{16}$
d	$\frac{3}{8}$	$\frac{1}{8}$
θ_1	3°	3°
θ_2	5°	5°
Hole location		
E_1	$\frac{1}{8}$	$\frac{1}{8}$
E_2	$\frac{1}{8}$	$\frac{1}{8}$
E_3	$\frac{1}{8}$	$\frac{1}{8}$
S_1	$\frac{1}{16}$	$\frac{1}{16}$
S_2	$\frac{1}{16}$	$\frac{1}{16}$
F	$\frac{1}{8}$	$\frac{1}{8}$
P	$\frac{1}{8}$	$\frac{1}{8}$
L	$\frac{1}{8}$	$\frac{1}{8}$
Chamber, C	$\frac{1}{4}\left(\frac{\text{L.ft}}{10}\right)$, in.	
Minimum thickness t	$0.95 \times$ design t	

Note: 1 in. = 25.4 mm.

Simple sections such as angles, channels, and Z-sections are formed by press brake operation from sheet, strip, plate, or bar in not more than two operations. More complicated sections may take several operations.

It should be noted that the cost of products is often dependent upon the type of the manufacturing process used in production. Reference 1.120 indicates that in addition to the strength and dimensional requirements a designer should also consider other influencing factors, such as formability, cost and availability of material, capacity and cost of manufacturing equipment, flexibility in tooling, material handling, transportation, assembly, and erection.

1.5 RESEARCH AND DESIGN SPECIFICATIONS

1.5.1 United States

1.5.1.1 Research During the 1930s, the acceptance and development of cold-formed steel members for the construction industry in the United States faced difficulties due to the lack of an appropriate design specification. Various building codes made no provision for cold-formed steel construction at that time.

Since cold-formed steel structural members are usually made of relatively thin steel sheet and come in many different geometric shapes in comparison with typical hot-rolled sections, the structural behavior and performance of such thin-walled, cold-formed structural members under loads differ in several significant respects from that of

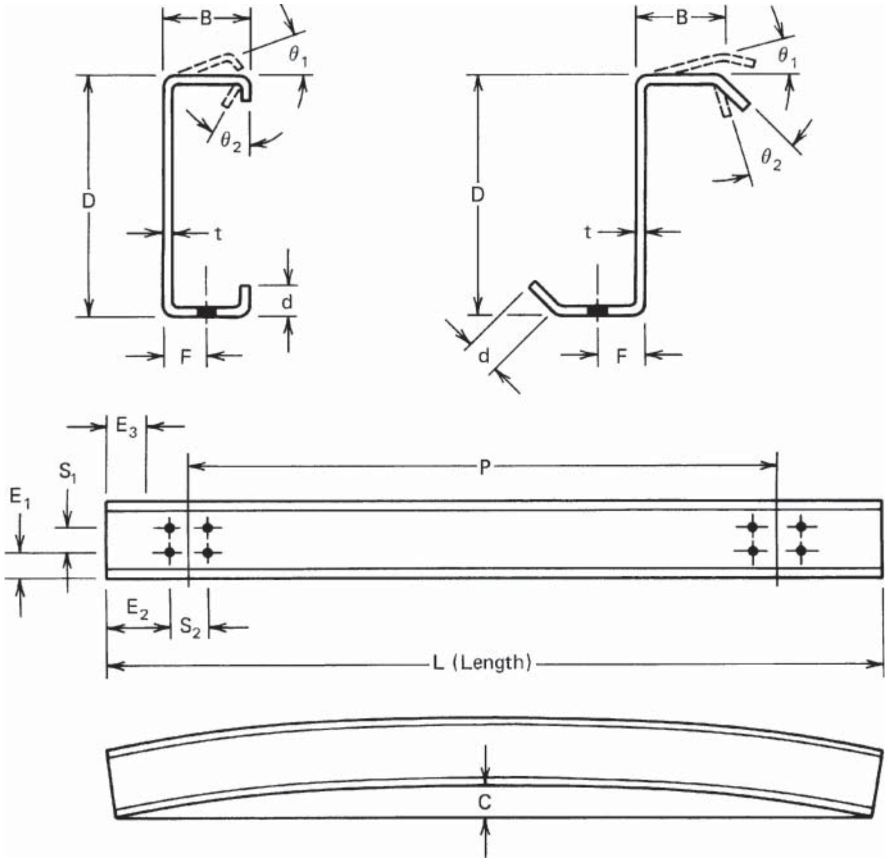

Figure 1.25 Symbols used in MBMA table.[1.360]

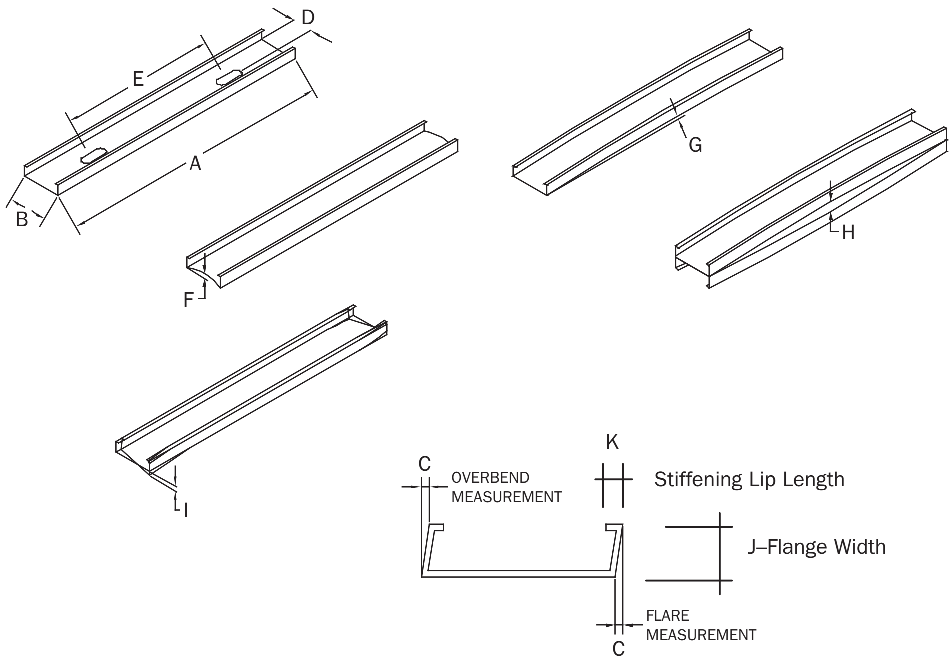

Figure 1.26 Manufacturing tolerances.[1.400,1.432]

Table 1.2 ASTM C 955-11 Manufacturing Tolerances for Structural Members[1.400,1.432]

Dimension[a]	Item Checked	Studs, in. (mm)	Tracks, in. (mm)
A	Length	+3/32 (2.38) –3/32 (2.38)	+1/2 (12.7) –1/4 (6.35)
B[b]	Web Depth	+1/32 (0.79) –1/32 (0.79)	+1/32 (0.79) +1/8 (3.18)
C	Flare Overbend	+1/16 (1.59) –1/16 (1.59)	+0 (0) –3/32 (2.38)
D	Hole Center Width	+1/16 (1.59) –1/16 (1.59)	NA NA
E	Hole Center Length	+1/4 (6.35) –1/4 (6.35)	NA NA
F	Crown	+1/16 (1.59) –1/16 (1.59)	+1/16 (1.59) –1/16 (1.59)
G[c]	Camber	1/8 per 10 ft (3.13 per 3 m)	1/32 per ft (2.60 per m) 1/2 max (12.7)
H[c]	Bow	1/8 per 10 ft (3.13 per 3 m)	1/32 per ft (2.60 per m) 1/2 max (12.7)
I	Twist	1/32 per ft (2.60 per m) 1/2 max (12.7)	1/32 per ft (2.60 per m) 1/2 max (12.7)
J	Flange Width	+1/8 (3.18) –1/16 (1.59)	+1/4 (6.35) –1/16 (1.59)
K	Stiffening Lip Length	+1/8 (3.18) –1/32 (0.79)	NA

[a]All measurements are taken not less than 1 ft (305 mm) from the end. See Fig. 1.26 for symbol definitions.
[b]Outside dimension for *stud*; inside for *track*.
[c]1/8 inch per 10 feet represents L/960 maximum for overall camber and bow. Thus, a 20-foot-long member has 1/4-inch permissible maximum; a 5-foot-long member has 1/16-inch permissible maximum.

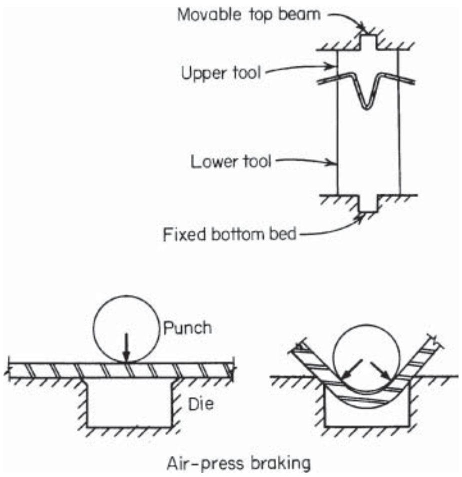

Figure 1.27 Press braking.[1.2,1.16]

heavy hot-rolled steel sections. In addition, the connections and fabrication practices which have been developed for cold-formed steel construction differ in many ways from those of heavy steel structures. As a result, design specifications for heavy hot-rolled steel construction cannot possibly cover the design features of cold-formed steel construction completely. It soon became evident that the development of a new design specification for cold-formed steel construction was highly desirable.

Realizing the need for a special design specification and the absence of factual background and research information, the AISI Committee on Building Research and Technology (then named the Committee on Building Codes) sponsored a research project at Cornell University in 1939 for the purpose of studying the performance of light-gage cold-formed steel structural members and of obtaining factual information for the formulation of a design specification. Research projects have been carried out continuously at Cornell University and other universities since 1939.

The investigations on structural behavior of cold-formed steel structures conducted at Cornell University by Professor George Winter and his collaborators resulted in the development of methods of design concerning the effective width for stiffened compression elements, the reduced working stresses for unstiffened compression elements, web crippling of thin-walled cold-formed sections, lateral buckling of beams, structural behavior of wall studs, buckling of trusses and frames, unsymmetrical bending of beams, welded and bolted connections, flexural buckling of thin-walled steel columns, torsional–flexural buckling of concentrically and eccentrically loaded columns in the elastic and inelastic ranges, effects of cold forming on material properties, performance of stainless steel structural members, shear strength of light-gage steel diaphragms, performance of beams and columns continuously braced with diaphragms, hyperbolic paraboloid and folded-plate roof structures, influence of ductility, bracing requirements for channels and Z-sections loaded in the plane of the web, mechanical fasteners for cold-formed steel, interaction of local and overall buckling, ultimate strength of diaphragm-braced channels and Z-sections, inelastic reserve capacity of beams, strength of perforated compression elements, edge and intermediate stiffeners, rack structures, probability analysis, and C- and Z-purlins under wind uplift.[1.5–1.7,1.31,1.121,1.122,1.133–1.136]

The Cornell research under the direction of Professor Teoman Pekoz included the effect of residual stress on column strength, maximum strength of columns, unified design approach, screw connections, distortional buckling of beams and columns, perforated wall studs, storage racks, load eccentricity effects on lipped-channel columns, bending strength of standing seam roof panels, behavior of longitudinally stiffened compression elements, probabilistic examination of element strength, direct-strength prediction of members using numerical elastic buckling solutions, laterally braced beams with edge-stiffened flanges, steel members with multiple longitudinal intermediate stiffeners, design approach for complex stiffeners, unlipped channel in bending and compression, beam–columns, cold-formed steel frame design, and second-order analysis of structural systems and others.[1.220,1.273,1.302–1.308,1.346,1.362,1.363]

In addition to the Cornell work, numerous research projects on cold-formed steel members, connections, and structural systems have been conducted at many individual companies and universities in the United States.[1.121.1.143,1.267,1.302–1.305,1.309,1.311,1.346,1.362–1.366,1.419–1.423] Forty-three universities were listed in the first edition of this book published in 1985.[1.352] Research findings obtained from these projects have been presented at various national and international conferences and are published in the conference proceedings and the journals of different engineering societies.[1.43,1.117,1.118,1.124–1.132,1.144–1.147,1.272–1.276,1.302–1.308,1.367–1.377]

Previously, the ASCE Committee on Cold-Formed Members conducted surveys of current research on cold-formed structures and literature surveys.[1.133–1.134,1.135,1.136,1.139–1.141] Thirty-eight research projects were reported in Ref. 1.136. In Ref. 1.141, about 1300 publications were classified into 18 categories. These reports provide a useful reference for researchers and engineers in the field of cold-formed steel structures.

In 1990, the Center for Cold-Formed Steel Structures was established at the University of Missouri–Rolla to provide an integrated approach for handling research, teaching, technical services, and professional activity.[1.312] In 1996, the Center for Cold-Formed Steel Structures conducted a survey of recent research. Reference 1.309 lists 48 projects carried out in seven countries. In October 2000, the center was renamed the Wei-Wen Yu Center for Cold-Formed Steel Structures (CCFSS) at the Fifteenth International Specialty Conference on Cold-Formed Steel Structures.[1.378]

1.5.1.2 AISI Design Specifications As far as the design criteria are concerned, the first edition of "Specification for the Design of Light Gage Steel Structural Members" prepared by the AISI Technical Subcommittee under the chairmanship of Milton Male was issued by the AISI in 1946.[1.5] This allowable stress design (ASD) specification was based on the findings of the research conducted at Cornell University up to that time and the accumulated practical experience obtained in this field. It was revised by the AISI committee under the chairmanships of W. D. Moorehead, Tappan Collins, D. S. Wolford, J. B. Scalzi, K. H. Klippstein, S. J. Errera, and R. L. Brockenbrough in 1956, 1960, 1962, 1968, 1980, 1986, 1996, 2001, 2007, 2012, and 2016 to reflect the technical developments and results of continuing research.

In 1991, the first edition of the load and resistance factor design (LRFD) specification[1.313] was issued by AISI under the chairmanship of R. L. Brockenbrough and the vice chairmanship of J. M. Fisher. This specification was based on the research work discussed in Ref. 1.248. In 1996, the AISI ASD Specification[1.4] and the LRFD Specification[1.313] were combined into a single specification[1.314] under the chairmanship of R. L. Brockenbrough and the vice chairmanship of J. W. Larson. The revisions of various editions of the AISI Specification are discussed in Ref. 1.267. In Ref. 1.315, Brockenbrough summarized the major changes made in the 1996 AISI Specification. See also Ref. 1.316 for an outline of the revised and new provisions. In 1999, a supplement to the 1996 edition of the AISI Specification was issued.[1.333,1.335]

The AISI Specification has gained both national and international recognition since its publication. It has been accepted as the design standard for cold-formed steel structural members in major national building codes. This design standard has also been used wholly or partly by most of the cities and other jurisdictions in the United States having building codes. The design of cold-formed steel structural members based on the AISI Specification has been included in a large number of textbooks and engineering handbooks.[1.13,1.149–1.158,1.269,1.277,1.318–1.320,1.350–1.358,1.412]

1.5.1.3 North American Specifications The above discussions dealt with the AISI Specification used in the United States. In Canada, the Canadian Standards Association (CSA) published its first edition of the Canadian Standard for Cold-Formed Steel Structural Members in 1963 on the basis of the 1962 edition of the AISI Specification with minor changes. Subsequent editions of the Canadian Standard were published in 1974, 1984, 1989, and 1994.[1.177,1.327] The 1994 Canadian Standard was based on the limit states design (LSD) method, similar to the LRFD method used in the AISI specification except for some differences discussed in Section 1.8.3.1

In Mexico, cold-formed steel structural members have always been designed according to the AISI specification. The 1962 edition of the AISI design manual was translated into Spanish in 1965.[1.201]

In 1994, Canada, Mexico, and the United States implemented the North American Free Trade Agreement (NAFTA). Consequently, the first edition of *North American Specification for the Design of Cold-Formed Steel Structural Members* (NAS) was developed in 2001 by a joint effort of the AISI Committee on Specifications, CSA Technical Committee on Cold-Formed Steel Structural Members, and Camara Nacional de la Industria del Hierro y del Acero (CANACERO) in Mexico.[1.336] It was coordinated through the AISI North American Specification Committee chaired by R. M. Schuster. This 2001 edition of the North American Specification was accredited by the American National Standard Institute (ANSI) as an American National Standard (ANS) to supersede the AISI 1996 Specification and the CSA 1994 Standard with the approval by CSA in Canada and CANACERO in Mexico.

The North American Specification provides an integrated treatment of ASD, LRFD, and LSD. The ASD and LRFD methods are for use in the United States and Mexico, while the LSD method is used in Canada. This first edition of the North American Specification contained a main document in Chapters A through G applicable for all three countries and three separate country-specific Appendices A, B, and C for use in the United States, Canada, and Mexico, respectively.

The major differences between the 1996 AISI Specification and the 2001 edition of the North American Specification were discussed by Brockenbrough and Chen in Refs 1.339 and 1.341 and were summarized in the *CCFSS Technical Bulletin*.[1.338]

In 2004, AISI issued a Supplement to the 2001 Edition of the North American Specification that provides the revisions and additions for the Specification.[1.343,1.344] This supplement included a new Appendix for the design of cold-formed steel structural members using the direct-strength method (DSM). This new method provides alternative design provisions for determining the nominal axial strengths of columns and flexural strengths of beams without using the effective widths of individual elements. The background information on DSM can be found in the Commentary of Ref. 1.343 and Chapters 3 through 6.

The first edition of the North American Specification was revised in 2007.[1.345] It was prepared on the basis of the 2001 Specification,[1.336] the 2004 supplement,[1.343] and the continued developments of new and revised provisions. The major changes in the 2007 edition of the North American specification were summarized in Refs. 1.346–1.348. In this revised Specification, some design provisions were rearranged with editorial revisions for consistency. The common terms used in the Specification were based on the Standard Definitions developed by a joint AISC–AISI Committee on Terminology.[1.380] In addition to Appendix 1 on the DSM, Appendix 2 was added for the second-order analysis of structural systems. For the country-specific design requirements, Appendix A is now applicable to the United States and Mexico, while Appendix B is for Canada. Subsequent editions of the North American specification have been issued in 2012[1.416] and 2016.[1.417] The major changes to these specification editions are summarized by Refs. 1.424–1.426.

The North American specification has been approved by the ANSI and is referred to in the United States as AISI S100. It has also been approved by the CSA and is referred to in Canada as S136.

1.5.1.4 AISI Design Manuals In addition to the issuance of the design specification, AISI published the first edition of the *Light Gauge Steel Design Manual*[1.5] in 1949, prepared by the Manual Subcommittee under the chairmanship of Tappan Collins. It was subsequently revised in 1956, 1961, 1962, 1968–1972, 1977, 1983, 1986, 1996, 2002, 2008, 2013, and 2018.[1.349,1.427,1.428]

The 2002 AISI Design Manual was based on the 2001 edition of the North American Specification.[1.336,1.340]

It included the following six parts: I, Dimensions and Properties; II, Beam Design; III, Column Design; IV, Connections; V, Supplementary Information; and VI, Test Procedures. Design aids (tables and charts) and illustrative examples were given in Parts I, II, III, and IV for calculating sectional properties and designing members and connections. Part I also included information on the availability and properties of steels that are referenced in the Specification. It contains tables of sectional properties of channels (C-sections), Z-sections, angles, and hat sections with useful equations for computing sectional properties. The development of this 2002 AISI Design Manual was discussed by Kaehler and Chen in Ref. 1.342.

Following the issuance of the 2007 edition of the Specification, AISI revised its Design Manual in 2008[1.349] on the basis of the second edition of the North American Specification.[1.345] As for previous editions of the Design Manual, the data contained in the AISI design manual are applicable to carbon and low-alloy steels only. They do not apply to stainless steels or to nonferrous metals whose stress–strain curves and some other characteristics of structural behavior are substantially different from those of carbon and low-alloy steels. For the design of stainless steel structural members, see Ref. 1.429.

It should also be noted that at the present time there are standardized sizes for studs, joists, channels, and tracks produced by the light-steel framing manufacturing companies as defined by the AISI *North American Standard for Cold-Formed Steel Framing—Product Data*.[1.379] The design aids for those frequently used members are included in the AISI Design Manual. Except for the AISI designated sections, the sections listed in the tables of Part I of the AISI design manual are not necessarily stock sections with optimum dimensions. They are included primarily as a guide for design.

In some other countries, the cold-formed steel shapes may be standardized. The standardization of shapes would be convenient for the designer, but it may be limiting for particular applications and new developments.

1.5.1.5 AISI Commentaries Commentaries on several earlier editions of the AISI design specification were prepared by Professor Winter of Cornell University and published by AISI in 1958, 1961, 1962, and 1970.[1.161] In the 1983 and 1986 editions of the Design Manual, the format used for the simplified commentary was changed in that the same section numbers were used in the Commentary as in the Specification. For the 1996 edition of the Specification, the AISI Commentary, prepared by Wei-Wen Yu, contained a brief presentation of the characteristics and the performance of cold-formed steel members, connections, and systems.[1.310] In addition, it provided a record of the reasoning behind and the justification for various provisions of the AISI Specification. A cross reference was provided between various provisions and the published research data.

The Commentary on the 2001 edition of the North American Specification[1.337] was prepared on the basis of the AISI Commentary on the 1996 Specification with additional discussions on the revised and new design provisions. In the Commentary on the 2007 and subsequent editions of the North American Specification, comprehensive discussions with extensive references are included for the new provisions, particularly for Appendices 1 and 2. For details, see Refs. 1.346, 1.430, and 1.431.

In Refs. 1.62, 1.73, and 1.174, Johnson has reviewed some previous research work together with the development of design techniques for cold-formed steel structural members.

1.5.1.6 Other Design Standards and Design Guides In addition to the AISI Design Specifications discussed in Sections 1.5.1.2 and 1.5.1.3, AISI also published "Overview of the Standard for Seismic Design of Cold-Formed Steel Structures—Special Bolted Moment Frames"[1.381,12.47] and the ANSI-accredited North American standards for cold-formed steel framing, including (a) general provisions, (b) product data, (c) floor and roof system design, (d) wall stud design, (e) header design, (f) lateral design, (g) truss design, and (h) a prescriptive method.[1.387] These standards have been developed by the AISI Committee on Framing Standards since 1998. In 2015, the AISI Committee on Framing Standards merged the framing standards into a single document, *North American Standard for Cold-Formed Steel Structural Framing,* AISI S240.[1.432] A companion specification, the *North American Standard for Cold-Formed Steel Framing—Nonstructural Members,* AISI S220[1.433] was introduced. The uses of these standards for residential and commercial construction are discussed in Chapter 12. Furthermore, AISI also published numerous design guides: *Direct Strength Method (DSM) Design Guide*,[1.383] *Cold-Formed Steel Framing Design Guide*,[1.384,1.434] *Steel Stud Brick Veneer Design Guide*,[1.385,1.435] *A Design Guide for Standing Seam Roof Panels*,[1.386] and others. In addition, the Cold-Formed Steel Engineers Institute (CFSEI) has developed and published numerous technical notes and design guides on a broad range of design issues (www.cfsei.org).

In the past, many trade associations and professional organizations had special design requirements for using cold-formed steel members as floor decks, roof decks, and wall panels,[1.103,1.162,1.330–1.332] open web steel joists,[1.163] transmission poles,[1.45,1.48,1.164,1.321,1.322,1.323] storage racks,[1.165,1.166,1.407–1.410] shear diaphragms,[1.167–1.169,1.388,1.389]