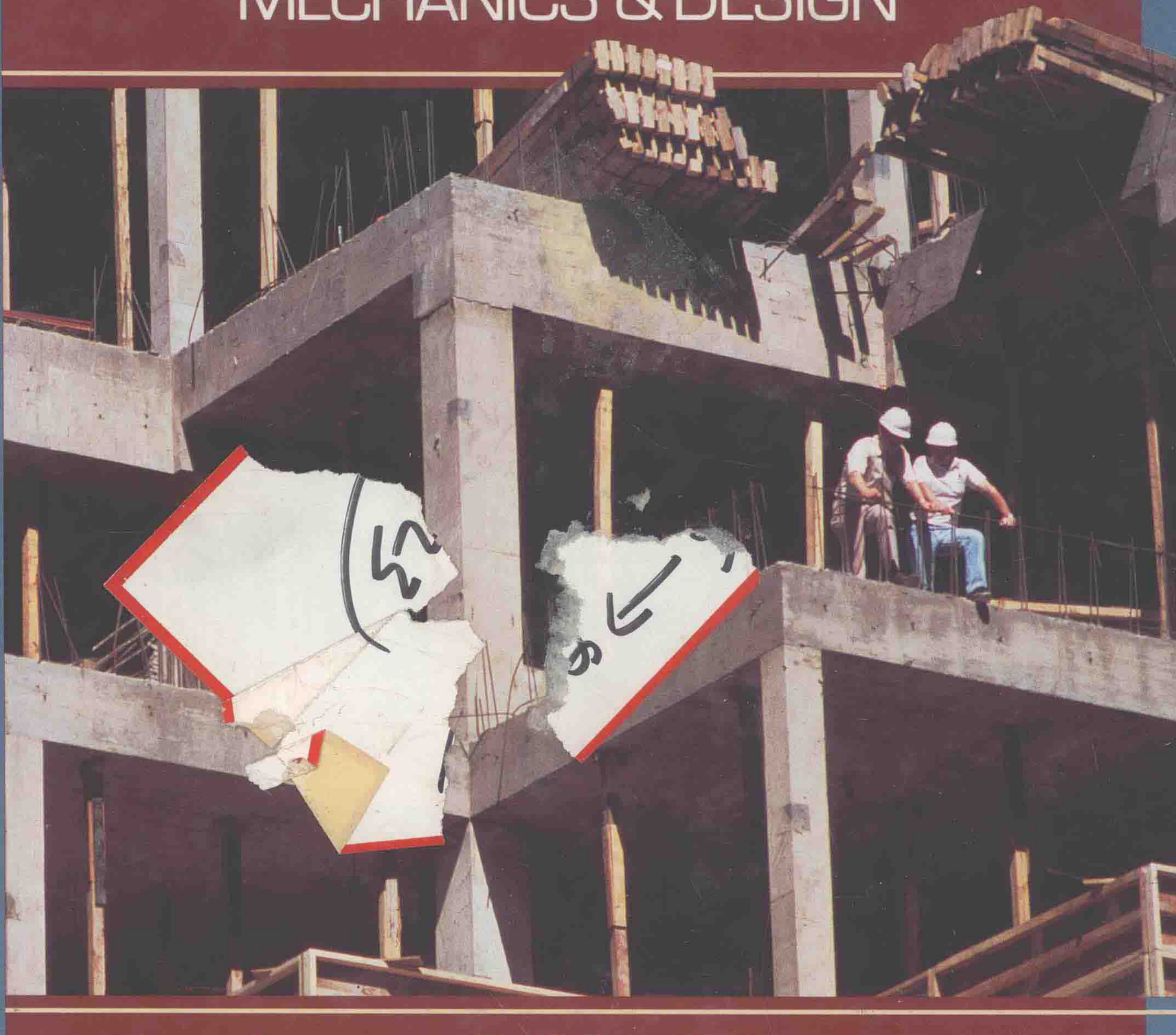
SECOND EDITION

REINFORCED CONCRETE

MECHANICS & DESIGN



James G. MacGregor

REINFORCED CONCRETE
Mechanics and Design

SECOND EDITION

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Preface

Reinforced concrete design is both an art and a science. Since the 1960s, the emphasis on the science has increased as codes became more complex and as computers came to be used to design and detail concrete members. Today, contractors complain that current designs are difficult to build. Designers, faced with the myriad of rules, code clauses, and equations, feel that reinforced concrete design is a mystical science that few understand. This book presents the theory of reinforced concrete as a direct application of the laws of statics and the behavior of reinforced concrete. In addition, it emphasizes that a successful design not only satisfies the design equations, but also is capable of being built at a reasonable price.

The various topics—flexure, shear, columns, and so on—are presented at two levels in this book. Each subject starts with a basic presentation suitable for undergraduate university courses on reinforced concrete. It then moves to more advanced topics not normally found in American textbooks, including, for example, unsymmetrical beams and columns, strain compatibility solutions of beams, $P - \Delta$ analyses of frames, and the design of deep beams and column–beam joints. The latter concepts make this book a useful reference volume in design offices and a suitable text for graduate courses.

Particular emphasis has been placed on the logical order and completeness of the design examples. The examples are done in a step-by-step order and every step is worked out completely from first principles, at least once. Designers used to using design aids will recognize places where they can shorten the calculations. The examples have been chosen to illustrate the effects of unequal spans and other situations normally encountered in design but not in textbooks. Guidance is given in the text and in the examples to help students to make the many judgment decisions required in reinforced concrete design.

Chapter 1 sets the stage for the volume by providing definitions and giving illustrations of the various types of members built from reinforced concrete. A brief history of concrete, reinforced concrete, and codes for reinforced concrete is included.

Chapter 2 continues the introductory material with a discussion of the goals of structural design based, in part, on the limit states design concept. Limit states design is simply the traditional engineering approach of anticipating all of the ways that things can go wrong and taking steps to ensure that they don't. Considerable emphasis is placed on this throughout the book because, since the introduction of strength design in the 1963 ACI Code, concrete structures have become more and more slender and more apt to exhibit excessive cracking, deflections, or vibrations. Chapter 2 also contains a brief introduction to safety theory, a brief review of the loads considered in design, and a discussion of design for economy.

The significant properties of concrete and reinforcement are presented in Chapter 3 as a basis for developing the flexural theory, discussing time-dependent deflections, and so on. This chapter is also intended to serve as a ready reference source for information on the structural aspects of concrete technology.

Chapters 4 through 8 and 11 through 13 deal with the theory and design for various ultimate limit states, such as flexure, shear, anchorage, and so on. In each case, the discussion starts with a review of the behavior of concrete members and uses statics and mechanics to explain this behavior. Practical aspects of design and construction are introduced to explain code limitations and detailing rules. The method of computing the balanced reinforcement ratio in T beams and beams with compression reinforcement has been modified slightly.

Chapter 8 on development has been revised extensively to incorporate the new development and detailing requirements of the 1989 ACI Code. A systematic method of carrying out the development calculations has been used in the examples.

The serviceability limit states, particularly deflection and crack control, are the subject of Chapter 9. The discussion includes the calculation procedures for checking deflections and crack widths, the limits that should be placed on these values, and why.

Chapters 10 and 13 through 15 deal with the design of continuous slabs and beams and two-way slabs. The chapters on two-way slabs have been completely rearranged to improve the order of the topics. Chapter 13 starts with an overview of moments in slabs and the shear strength of two-way slabs and then goes on to present the Direct Design Method with examples. New Secs. 13-11 and 13-12 deal with the calculation of slab deflections. Chapter 14 covers the Equivalent Frame Method. Elastic analysis and a new section on design of reinforcement for the moments from a finite element analysis are presented briefly in Chap. 15. This is followed by Yield Line Theory, a new section on the Strip Method, and a simplified presentation of the Advanced Strip Method with examples.

Footings and load distribution members such as deep beams, corbels, and joints are discussed in Chaps. 16 and 17. Chapter 18 is a new chapter on design for earthquake effects.

Appendix A presents 28 design tables and 14 design charts referred to throughout the book. These are gathered together for easy reference and make it possible to use the text in courses or in an office without the need for a handbook.

A one-semester undergraduate course on reinforced concrete might cover Secs. 2-1 to 2-4 and 2-6 to 2-8 on the basis for design, safety factors, loads, and design for economy; Secs. 3-3, 3-4, and 3-8 on material properties; Chap. 4 and Secs. 5-1 to 5-3 on flexure; Secs. 6-1 to 6-3 and 6-5 on shear; Chap. 8 on anchorage; Secs. 9-1 to 9-5 on serviceability; Chap. 10 on continuous slabs and beams; Secs. 11-1 to 11-5 on columns; and Secs. 14-1 to 16-5 on footings. A subsequent course might cover Chap. 7 on torsion, Secs. 12-1 to 12-6 on slender columns, and Chap. 13 and possibly Chap. 14 on two-way slabs. Chapters 17 and 18 would be optional.

The text makes frequent reference to the 1989 ACI Code and assumes that the reader will have a copy of this code.

Although the foot-pound-second system of units is the main system of units throughout the book, introductory examples in basic topics are repeated completely in SI (metric) units.

My sincere thanks to my friends, colleagues, and reviewers of the text for their suggestions for improvement, discussions of general approach, and other assistance. In particular I wish to thank C. P. Siess; J. E. Breen, who initiated the idea of this book and had many helpful suggestions; R. Green, J. P. Moehle, C. H. Conley, and J. K. Wight, whose comments and critiques of the first edition were invaluable; S. E. Evison and R. J. G. MacGregor, who checked calculations and proofread the various drafts; my wife, who typed the initial drafts; N. Shaw, who typed and changed and rechanged innumerable subsequent drafts; and D. J. MacGregor, who drew many of the figures.

I urge readers who have questions, suggestions for improvements, or clarifications, or who find errors, to write to me. I thank you in advance for taking the time and interest to do so.

I dedicate this book to my wife, Barbara, whose patience and encouragement have made this project possible.

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1

Introduction

1-1 REINFORCED CONCRETE STRUCTURES

Concrete and reinforced concrete are used as building materials in every country. In many, including the United States and Canada, reinforced concrete is a dominant structural material in engineered construction. The universal nature of reinforced concrete construction stems from the wide availability of reinforcing bars and the constituents of concrete, gravel, sand, and cement, the relatively simple skills required in concrete construction, and the economy of reinforced concrete compared to other forms of construction. Concrete and reinforced concrete are used in bridges, buildings of all sorts (Fig. 1-1), underground structures, water tanks, television towers, offshore oil exploration and production structures (Fig. 1-2), dams, and even in ships.

1-2 MECHANICS OF REINFORCED CONCRETE

Concrete is strong in compression but weak in tension. As a result, cracks develop whenever loads, or restrained shrinkage or temperature changes, give rise to tensile stresses in excess of the tensile strength of the concrete. In the plain concrete beam shown in Fig. 1-3b, the moments about O due to applied loads are resisted by an internal tension–compression couple involving tension in the concrete. Such a beam fails very suddenly and completely when the first crack forms. In a *reinforced concrete* beam (Fig. 1-3c), steel bars are embedded in the concrete in such a way that the tension forces needed for moment equilibrium after the concrete cracks can be developed in the bars.

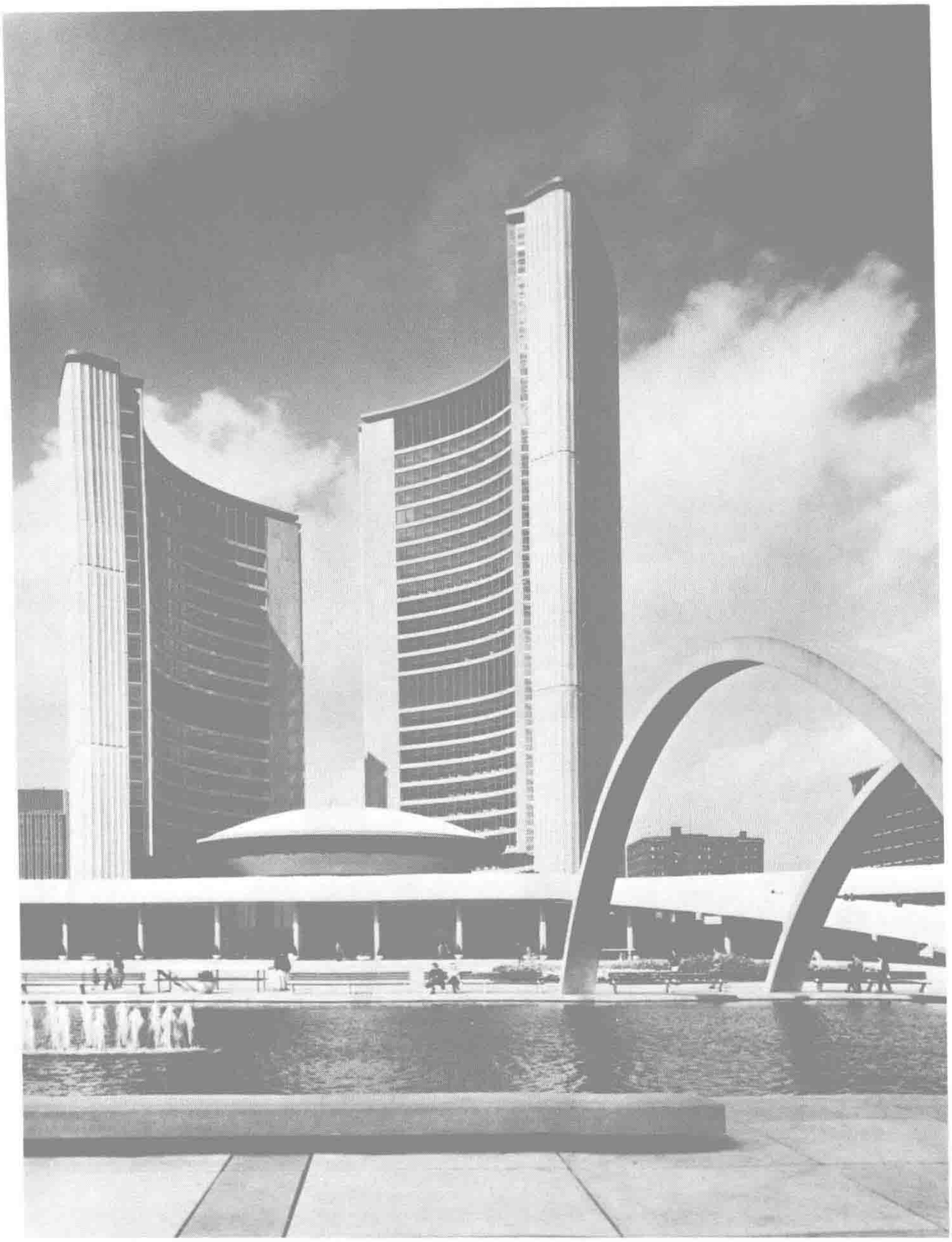

Fig. 1-1
City Hall, Toronto, Canada.

The Toronto City Hall consists of two towers, 20 and 27 stories in height, with a circular council chamber cradled between them. These structures and the surrounding terraces, pools, and plaza illustrate the degree to which architecture and structural engineering can combine to create a living sculpture. This complex has become the trademark and social hub of the city of Toronto. The council chamber consists of a reinforced concrete bowl containing seating for the council, press, and citizens. This is covered by a concrete dome. The wind resistance of the two towers results largely from the two vertical curved walls forming the backs of the towers. The architectural concept was by Viljo Revell, of Finland, winner of an international design competition. Mr. Revell entered into an association with John B. Parkin Associates, who developed the design and also carried out the structural design. The structural design is described in Ref. 1-1. (Photograph used with permission of Neish Owen Rowland & Roy, Architects Engineers, Toronto.)

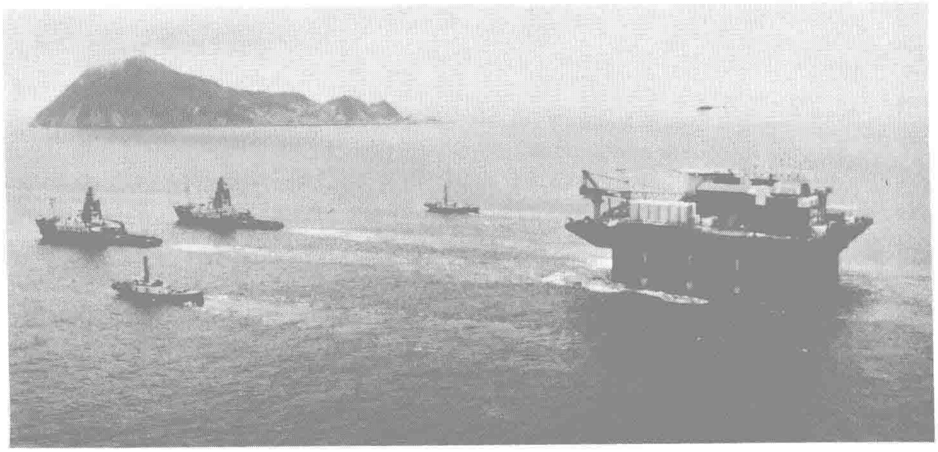

Fig. 1-2
Glomar Beaufort Sea I (CIDS) being towed through the Bering Straits to the Beaufort Sea, Alaska.

This concrete island oil drilling structure consists of a steel mud base, a 230-ft-square cellular concrete segment, and a deck assembly with drilling rig, quarters for 80 workers, and supplies for 10 months. The structure is designed to operate in 35 to 60 ft of water in the Arctic Ocean. Forces from the polar sea ice are resisted by the thick walls of the concrete segment. Design was carried out by Global Marine Development Inc. Engineering and construction support to Global Marine was provided by A. A. Yee Inc. and ABAM Engineers Inc. (Photograph courtesy of Global Marine Development Inc.)

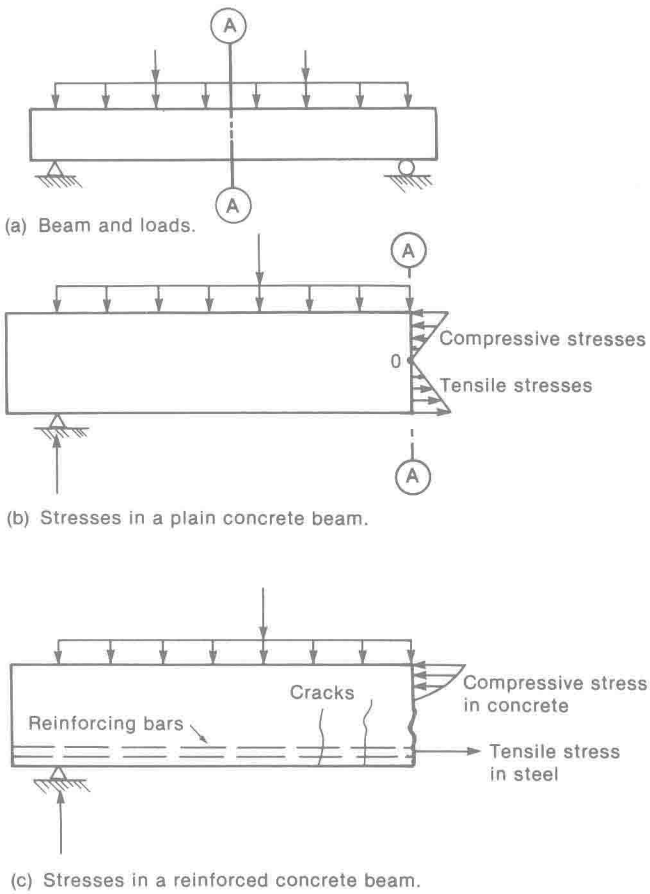

Fig. 1-3
Plain and reinforced concrete beams.

The construction of a reinforced concrete member involves building a form or mold in the shape of the member being built. The form must be strong enough to support the weight and hydrostatic pressure of the wet concrete, and any forces applied to it by workers, concrete buggies, wind, and so on. The reinforcement is placed in this form and held in place during the concreting operation. After the concrete has hardened, the forms are removed.

1-3 REINFORCED CONCRETE MEMBERS

Reinforced concrete structures consist of a series of individual ''members'' that interact to support the loads placed on the structure. The second floor of the building in Fig. 1-4 is built of concrete joist–slab construction. Here a series of parallel ribs or *joists* support the load from the top slab. The reactions supporting the joists apply loads to the beams, which in turn are supported by columns. In such a floor, the top slab has two functions: (1) it transfers load laterally to the joists, and (2) it serves as the top flange of the joists, which act as T-shaped beams that transmit the load to the beams running at right angles to the joists. The first floor of the building in Fig. 1-4 has a slab-and-beam design in which the slab spans between beams, which in turn apply loads to the columns. The column loads are

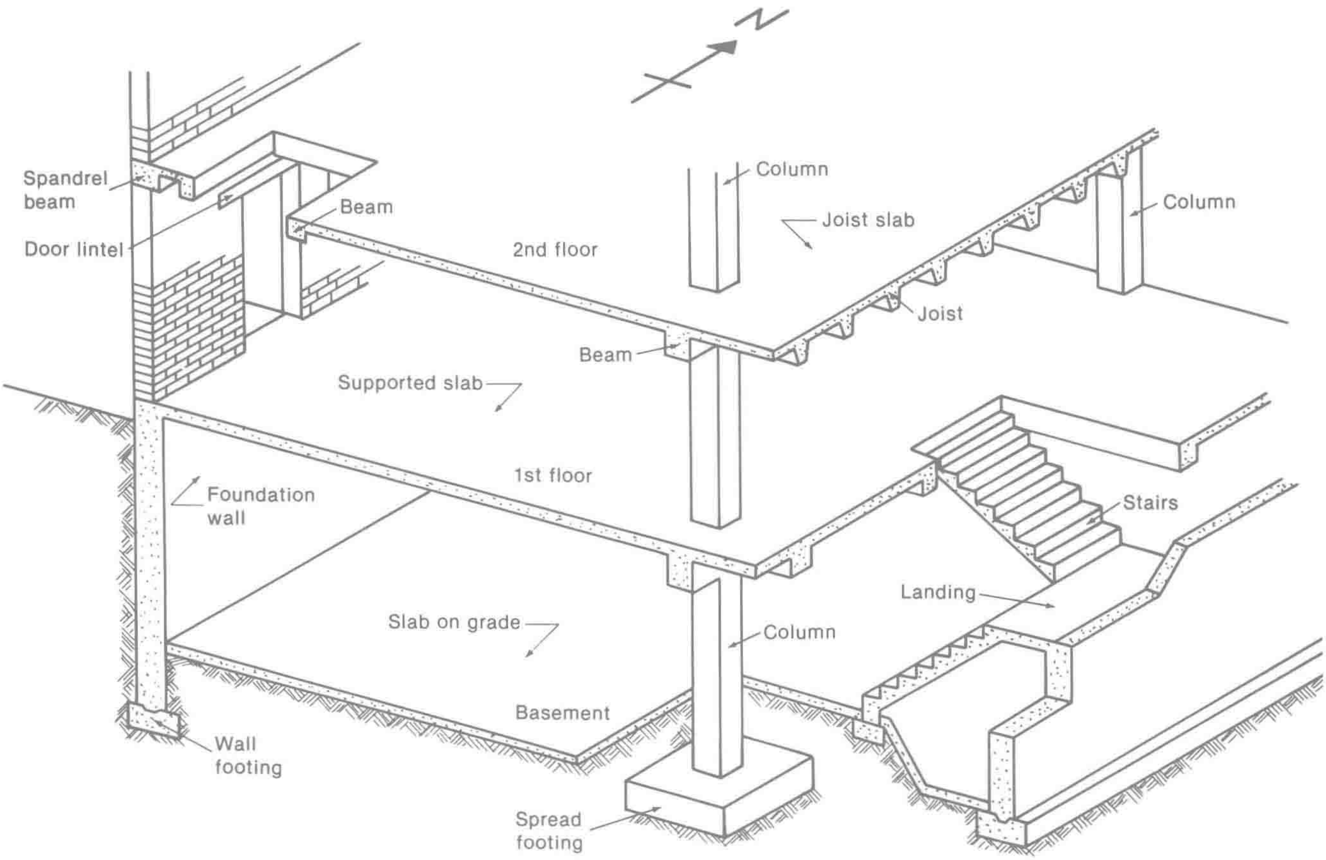

Fig. 1-4
Reinforced concrete building elements. (Adapted from Ref. 1-2.)