INDUSTRIALIZED AND AUTOMATED BUILDING SYSTEMS

A MANAGERIAL APPROACH

ABRAHAM WARSZAWSKI

SECOND EDITION

E & FN SPON
An imprint of Routledge

Industrialized and Automated Building Systems

To my wife Margalit, my children Alon, Roni, Kobi, Ofra,
and their spouses

Industrialized and Automated Building Systems

Abraham Warszawski
Technion-Israel Institute of Technology

E & FN SPON
Taylor & Francis Group

London and New York

First published 1999 by E & FN Spon
11 New Fetter Lane, London EC4P 4EE

Simultaneously published in the USA and Canada
by Routledge
29 West 35th Street, New York, NY 10001

E & FN Spon is an imprint of the Taylor & Francis Group

This edition published in the Taylor & Francis e-Library, 2005.

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication data
A catalogue record for this book has been requested

ISBN 0-203-22369-1 Master e-book ISBN

ISBN 0-203-27785-6 (Adobe eReader Format)
ISBN 0 419 20620 5 (Print Edition)

Contents

Preface

There is a general feeling that the vast gains in productivity and quality, realized in the 20th century in manufacturing industries, have not been matched by similar progress in building construction. This book reflects my deep belief that a significant remedy to this problem can be attained only with industrialization and automation replacing manual labor in all phases of the building process.

The slow advent of industrialization in building and its failure to establish itself as a clearly preferable alternative to the old, traditional methods, was partly due to objective reasons—the dispersion and diversity of construction projects. But it also stemmed to a large extent from lack of an integrated approach and a comprehensive managerial view of the process. Decisions concerning technologically advanced building methods—in design, construction technology, management, and economics—require a thorough understanding of the prevailing constraints in each of these domains and of their mutual interdependence. It is the purpose of this book to provide a framework for such interdisciplinary knowledge which can be later augmented by a more specific study in each particular field.

This book approaches industrialization and automation from a management viewpoint, that is, from the point of view of the person who is in charge of the overall selection, design, implementation, and operation of the building system. It is ultimately management's understanding and support of the innovative technologies which determine their success when competing with traditional methods. For this purpose, the book covers the various aspects of industrialization—technological, managerial, and economical. It also deals with the use of information technologies in production and construction onsite. Such a comprehensive approach is also useful to other parties involved in the building realization process —architects, engineers, producers, and builders—who want to perform efficiently within a coordinated professional effort of an industrialized project. They are referred in each chapter to specific sources, in their particular fields of interest.

This new edition of *Industrialization and Robotics in Building* is retitled, revised, and updated to take into account the growing role of automation in the industrialized building process—in its design, production, and construction. This most significant change, which has taken place since the book was first published in 1990, is amply described and discussed in this second edition.

The contents of this book are based on my lectures over the past 20 years at the Technion-Israel Institute of Technology, the State University of North Carolina, the University of Texas at Austin, and Hong Kong University. The material is drawn from my experience as a consultant in Israel and other countries, from my research work at the Technion-Israel Institute of Technology and the Carnegie-Mellon University of Pittsburgh, and from the information generously supplied to me by many companies and institutions in various countries. A large part of the new material in this edition is based on our research program in building automation at the National Building Research Institute of the Technion, I.I.T., and especially on the development project of the interior finishing robot which is described here, and the various studies of automated planning and design in building.

The book can be divided into three parts. The first part includes general information about heavy concrete-based prefabrication—typical systems, their components, performance requirements, design, and production methods—the type that is currently the core of industrialization efforts in most countries. The second part deals with managerial aspects of prefabrication—plant organization, production scheduling, cost estimating, quality control, and long-range economic planning. The third part deals with automation and information technologies in design, production, and construction onsite.

This book can be used as a text for a graduate or an undergraduate curriculum in civil engineering and architecture studies. It will be relevant also to studies in building surveying and construction.

The assignments at the end of each chapter are a very important part of these courses. Some of them involve a progressive development of an industrialized building system through various design and planning stages. They require a considerable amount of work on the part of the student, and deserve additional time in class for presentation and discussion, when completed.

The book may be used also by practitioners who wish to get acquainted with the subject of industrialization and automation, without a rigid institutional framework. The text is arranged in a modular fashion—each chapter dealing with a separate subject. This makes it easier for readers who want to become acquainted, through self-tutoring, with selected aspects of the subject, without going over the whole text.

Acknowledgements

I wish to express my deep gratitude to all persons who assisted me in the preparation of both editions of this book. Above all, I wish to thank Professors Bohdan Lewicki, Chanoch Jaegermann, Yehoshua Dayan, and Oded Shmueli, who read large parts of the manuscript and offered me their advice, and to Professor Rachel Becker, who wrote Chapter 4.

Special thanks are due to colleagues who collaborated with me in research studies of various aspects of automation and prefabrication in building: Dr. Y. Rosenfeld, Dr. R.Navon, Dr. H.Argaman, Dr. I.Shohet, Eng. U.Zaicek, Eng. A. Yavnai, Professor A.Bentur, Dr. M.Puterman, Dr. A.Retik, Dr. R.Sacks and Dr. E.Ishai. Their contribution is duly acknowledged.

I am grateful to Engineers A.Peres and J.Warszawski for their useful comments.

Also, I wish to acknowledge with gratitude the information and assistance which I received from numerous parties. Not all of the information has been explicitly mentioned in the book but all of it assisted me very much in its writing. Thanks are due in this context to the following (in alphabetical order):

Austria: Ainedter Industrie Automation (AIA) Co., Avermann Co., Filmoser Co.

Belgium: Danilith Co., Decomo Co., Delmulle Co., Federation of the Cement Industries, Kerkstoel 2000 +Co.

Canada: National Research Council, Ce Fer Designs Co., Modern Mosaics Co.

Denmark: Prof. H.Nissen, Mr. M., Kjeldsen, Building Center of Denmark, The Danish Precast Concrete Federation, Hojgaard and Schultz Co., Larsen Nielsen Co., Modulbeton Co.

Finland: Prof. A.Sarja, Association of the Concrete Industry, Elematic Co., Induco Co., Parma Co., Partek Co., VTT.

France: Gibat Co., National Syndicate of Reinforced Concrete and Industrialized Techniques, Ministry of Environment, Ministry of Education, Center of Studies and Research of Precast Concrete (CERIB), Otep Co., Outinord Co., Potain Co., PPB Co., Rector Co., SARET Co.

Germany: Association of German Concrete and Precast Elements Industries, Anliker Co., Arbau Co., Baumann Bautechnik Co., ISW at the University of Stuttgart, Kaiser Omnia Co., Liebherr Co., Lissmac Co., Milz Co., Modern Technik Co., Putzmeister Co., Rudolph Co., Syspro Co., Schworer Co., Unitechnik Co.—Cieplick & Poppek, Vollert Co., Weckenmann Co.

Hungary: Prof. G.Sebestyen, Dr. G.Kunszt, BVM Co.

Israel: Eng. A.Alweyl, Arch. R.Alweyl, Prof. A.Bentur, Dr. M.Benbassat, Arch. H.Brand, Eng. N.Chitron, Dr. A.Churchman, Prof. G.Herbert, Eng. M.Pazner, Dr. M.Puterman, Ministry of Construction and Housing, Ashtrom Co., Eshed Robotec Co., Fabcon Co., Modan Co., Ramet Co., Sibus Rimon Co., Spancrete Co., Yuval Gad Co.

Italy: Bima Co., Cadillon Co., Car-Mix Co., Fiori Co., Sacma Co., Silla Co., Tamburini Co., Tecnocemento Co., Zanussi Edilizia Co.

Japan: Prof. Y.Hasegawa, Prof. Y.Tamura, Prof. N.Kano, Fanuc Co., Fujita Co., Kajima Co., Kawasaki Co., Komatzu Co., Kumagai Gumi Co., Misawa Co., Mitsubishi Co., Nachi Co., Ohbayashi Co., Shimizu Co., Taisei Co., Takenaka Co.

Netherlands: Prof. N.T.Habraken, Association of Precast Concrete Manufacturers, CVK Elementen Co., Grimbergen Co.

Poland: Prof. T.Bilinski, Prof. K.Cieszynski, Center of Building Research and Design (COBPBO).

South Africa: Industrialized Building Association.

Spain: Arch. R.Bofil, Institute of Eduardo Torroja, Institut de Technologia de la Construccio de Catalunya.

Switzerland: Dr. T.Koncz, Swiss Association of Professionals of Precast Concrete, Peikert Co., Variel Co., Wey Co.

United Kingdom: Atcost Co., Blatcon Co., Costain Dow Mac Co., Crendon Co., Cement and Concrete Association.

United States: Allen Engineering Co., ATLSS Engineering Research Center, Lehigh University, Prof. R.Carr, Mr. J.Engelberger, Office of Housing and Urban Development (HUD), Carnegie-Mellon University, University of Texas at Austin, Advance Research and Robotics Inc., Arnold Stone Co., Blakeslee Prestress Co., Dillon Co., Jacobus Technologies Inc., Odetics Co., Prestressed Concrete Institute, Polaroid Co., Prab Co., Puma Co., Reiss Co., Telerobotics Co., Unimation Co., Viking System Co., Zachary Co.

Yugoslavia: Institute for Materials Testing of Serbia, Institute of Technical Sciences of Serbia.

Conversion factors

SI (metric) to other units

To convert from	**To**	**Multiply by**
	Length	
millimeter (mm)	inch	0.0393
meter (m)	foot	3.2808
meter (m)	yard	1.0936
kilometer (km)	mile (statute)	0.6215
	Area	
square millimeter (mm^2)	square inch	0.00155
square meter (m^2)	square foot	10.7642
square meter (m^2)	square yard	1.19603
	Volume (capacity)	
cubic meter (m^3)	gallon	264.2008
cubic meter (m^3)	cubic foot	35.3107
cubic meter (m^3)	cubic yard	1.3079
cubic meter (m^3)	liter	1,000
	Force	
newton (N)	kilogram-force	0.1019
newton (N)	kip-force (1000 lb)	0.0002248
newton (N)	pound-force (lb)	0.2248
kilonewton (kN)	kip-force	0.2248
	Pressure or stress (force per area)	
pascal (Pa)	kilogram-force/square meter	0.1019
megapascal (MPa)	kip-force/square inch (ksi)	0.1450
pascal (Pa)	newton/square meter (N/m^2)	1.000
pascal (Pa)	pound-force/square foot (lb/ft^2)	0.02088
kilopascal (kPa)	pound-force/square inch (lb/in.^{2})	0.1450
	Bending moment or torque	
newton-meter (N•m)	inch-pound force	8.8507
newton-meter (N•m)	foot-pound force	0.7375
newton-meter (N•m)	meter-kilogram force	0.1019
newton-meter (N•m)	meter-ton force	0.0001019
	Mass	
gram (g)	ounce-mass (avoirdupois)	0.03528

To convert from	**To**	**Multiply by**
kilogram (kg)	pound-mass (avoirdupois)	2.2045
kilogram (kg)	ton (metric)	0.001
kilogram (kg)	ton (short, 2000 lb)	0.011
gram (g)	kilogram	0.001
	Mass per volume	
kilogram/cubic meter (kg/m^3)	pound-mass/cubic foot	0.06242
kilogram/cubic meter (kg/m^3)	pound-mass/cubic yard	1.6855
kilogram/cubic meter (kg/m^3)	pound-mass/gallon	0.008345
	Temperature	
degrees Celsius (°C)	degrees Fahrenheit (°F)	t_F=1.8t_c+32
	Energy	
	Heat	
megajoule (MJ)	British thermal unit (Btu)	947.817
megajoule/kilogram (MJ/kg)	British thermal unit/pound (Btu/lb)	429.923
megajoule/square meter (MJ/m^2)	British thermal unit/square foot (Btu/ft^2)	88.055
square meter•degree Celsius/watt ($m^{2\cdot}$°C/W)	square foot•hour•degree Fahrenheit/British thermal unit (ft^2•hr•°F/Btu)	5.678
watt (W)	British thermal unit/hour (Btu/hr)	3.412
watt/meter•degree Celsius (W/$m^{2\cdot}$°C)	British thermal unit•foot/hour•square foot•degree Fahrenheit (Btu.ft/hr•ft^2•°F)	0.578
watt/square meter•degree Celsius (W/m^2•°C)	British thermal unit/hour•square foot•degree Fahrenheit (Btu/hr•ft^2°F)	0.176

Chapter 1
Industrialization and Automation in Building

1.1
Introduction

It is the basic tenet of this book that a radical improvement of productivity and quality in building construction can be attained only through intensive industrialization and automation of the building process.

Recent innovations in the building process should be viewed in the general context of the technological progress of human society over time. In this respect Toffler [6] identifies three major technological "waves" which advanced human society over a period of ten millennia from the most primitive level to its present state. Although initially focusing on technological production processes, these waves were accompanied by deep social and economic changes.

The first wave, the establishment of agricultural civilization, consisted in the settling of formerly nomadic societies in permanent settlements. The population in these settlements could satisfy much better its basic needs by employing orderly agricultural techniques, and devote part of its effort toward improvement of living standards in terms of shelter and various consumption goods. One of the main results of this revolution was the erection of permanent buildings made from wood, stone, bricks, earth, and other indigenous materials for a population which formerly lived in tents or caves. Building as a distinctive craft, and later as several specialized crafts, also emerged from this development.

The second wave, industrial civilization, resulted from the development of machines propelled by artificial energy—first by steam and later by electricity and oil. The industrial revolution, which started at the beginning of the 18th century with the invention of the steam engine, enabled substitution of human effort by stronger, faster, and more precise machine work. It also enabled the introduction of efficient and well-controlled processes for production of various new materials and products. The considerable capital investment in machines and other industrial facilities which was necessary had to be justified by the creation of large factories, each with a large output of standardized products.

The industrial revolution affected the building sector in many ways. Perhaps its most important effects were the introduction of structural steel and reinforced concrete as main building materials in the second half of the 19th century, and later, in the 20th century, the industrialization of work on a building site, making the most of mechanized materials handling equipment and of large prefabricated building components. However, for reasons which will be discussed later in this chapter, the potential for industrialization on site was realized only to a limited extent.

The third wave, the information revolution, which started in the second part of the 20th century, draws from the use of computers for storing, processing, and transmitting information, and for automated control of industrialized processes. Computerized control makes production more efficient in terms of materials use.

Figure 1.1 The Temple of Amon in Luxor

It also makes it feasible to cater by diversification to individual tastes, without significantly increasing the production cost.

The information revolution had a considerable effect on design work in building and on some aspects of its administration and control. Its effect on the construction process onsite is still very limited, mainly due to lack of a sufficient industrialized base.

The most important task of technological progress in building is therefore to increase the extent of industrialization onsite with a view to its subsequent automation, wherever feasible.

The industrialization of building is most effective when as many as possible of the building components are prefabricated in a plant with appropriate equipment and efficient technological and managerial methods. Comprehensive prefabricated elements that are produced in the plant considerably reduce both the amount of work onsite and dependence on the skill of available labor, on the weather, and on various local constraints.

Production of large building components offsite is not a novel concept. Famous structures of the ancient world—in Egypt, Greece, and Italy (see Figs. 1.1 and 1.2)—were erected with prefabricated stone components such as pillars, slabs, and porticos, some of them weighing 5, 10, and even 100 tons. These components were sometimes hauled from quarries tens or hundreds of kilometers to their erection sites.

The transportation and erection of large components required, in the absence of machines, an enormous amount of human labor and superior organizational and logistic effort. It was therefore applied only in monumental buildings, such as temples and palaces, and justified by the architectural effect of volume, size and ornament obtained in this manner. The remaining mass of structures, mostly dwellings, were built with "conventional" methods that were much easier to execute. These methods used local materials—timber, clay, and stones often cut or molded into small work pieces such as bricks, blocks, and logs— which could conveniently be handled by one or two workers. The selection, adaptation, placement, jointing, and finishing of these pieces resulted in whole walls, floors, stairs, and other building segments. The efficiency and quality of this conventional process depended entirely on the skill of individual workers.

Application of prefabrication for other than architectural reasons—for example, economy, speed, or quality of construction—was made feasible with the general advent of mechanized production and transportation methods in the 19th century. Prefabricated components, mostly of timber and cast iron, were

Figure 1.2 The temple of Hephaestus in Athens

used in residential and public buildings. One of the most prominent examples of an advantageous use of the prefabrication potential was during the Crimean War in the years 1854–1855. Over a period of 2 months about 1400 barrack units were prefabricated in England, shipped to the war area (5000km away), and erected there to provide shelter for the English and French troops. Each unit was made of timber structure and walls and could house 20–25 soldiers. Another famous application was in the construction of the Crystal Palace in London. This large structure (90,000 m^2) was assembled for the London exhibition in 1851 from a very large number of cast iron, modular skeleton and window components. In the second part of the 19th century several British manufacturing enterprises already specialized in the production of cast iron building elements—panels, gratings, stairs, balconies, columns, beams—and others which could be ordered from standard catalogues for various types of residential and public buildings. These and other early applications of prefabrication are described in Refs. [2–5, 8] and other sources.

In the course of the 19th century, reinforced concrete established itself as one of the major building materials. It had some distinctive advantages over other prevalent materials: its main ingredients—sand, gravel, and water—were inexpensive and available almost anywhere. Its production process was relatively simple. It could be molded into any shape and with proper processing yield an attractive exterior surface. It was strong, durable, and resistant to weather, wetness, and various mechanical effects. For these reasons concrete components could compete successfully with stone, in monumental and architectural buildings, with timber and bricks in housing, and with steel in bridges and other heavily loaded structures. The use of high-strength prestressed concrete increased even further its range of applications. One of the first applications of precast concrete components was by W.H.Lascelles in England in 1878 [3]. Lascelles employed thin precast concrete plates attached to timber posts for use in walls and attached to concrete joists for use in floors of residential cottages.

The full realization of precast concrete potential for prefabrication was made possible with the development of specially adapted transportation and erection equipment immediately after World War II. Only then did precast concrete establish itself as a viable alternative to the conventional building methods. The urgent demand for housing in the period following World War II and the active involvement of the

Figure 1.3 The Marne la Vallée housing project near Paris (Bofil)

public authorities in its supply created a very favorable environment for the proliferation of comprehensive prefabricated building systems. Such systems, consisting of prefabricated slabs, vertical structural elements, exterior walls, and partitions, stairs, and sanitary units, could offer a large output of building in a short time with reasonable quality. At the same time prefabrication also offered a wealth of architectural shapes and finishes—like those presented in Figs. 1.3–1.6— which could hardly be attained with any other technology.

The demand for prefabricated building systems was at its peak in the 1950s, 1960s, and early 1970s in eastern Europe, where prefabrication became the predominant building technology, and also in many countries of western Europe where it was extensively used in the construction of new cities, new neighbourhoods near existing cities, and large public housing projects. The interest in concrete-based prefabrication methods also grew in the United States, which until that time was mainly involved in prefabrication of lightweight "mobile" houses. The U.S. government initiated, in the early 1970s, a large-scale innovation project —Operation Breakthrough—in which it actively assisted in the development of a large number of building systems.

The demand for comprehensive prefabricated building systems subsided in the late 1970s, especially in western Europe and the United States (in eastern Europe it subsided with the political changes of the early 1990s), with the urgent need for mass housing in the urban areas largely satisfied. These systems found themselves at a disadvantage while competing with conventional building methods for small and diversified building projects. In the remaining large projects prefabrication was in hard competition with another mode of building industrialization—monolithic walls and slabs cast onsite in room-size steel molds. Prefabrication focused more and more on production of selected components— decorative exterior walls and prestressed modular slabs which were used mainly in public and industrial buildings.

The failure on the part of designers and producers to think in terms of systems rather than individual elements, and their failure to make system building more attractive and efficient given the present circumstances of fragmented and diversified demand, made prefabrication less competitive than existing methods. This initiated the vicious circle of lesser demand, hence a higher cost per unit, still less demand, and so on. The need for a system approach and its efficient management is expanded in the following sections of this chapter.

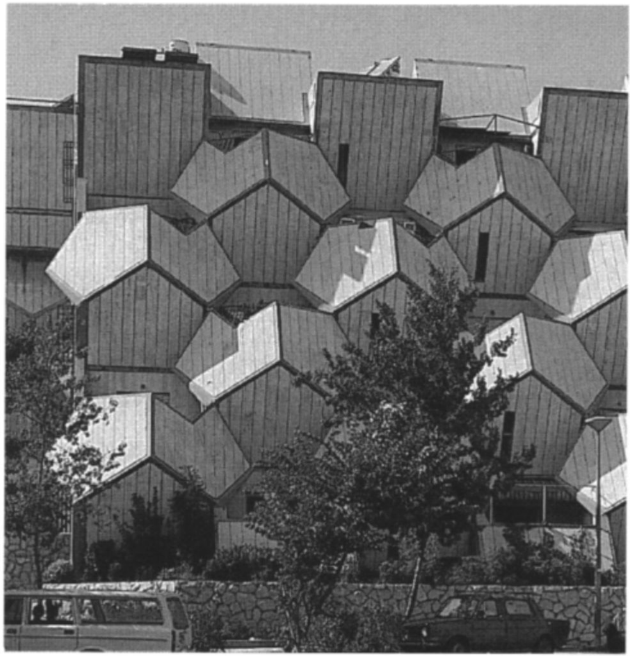


Figure 1.4 The Ramot project in Jerusalem (Heker)

Figure 1.5 The Habitat project in Montreal (Safdie)

Furthermore, it is now possible to automate the industrialized building process with the aid of new information technologies. The use of computer tools in design and robots in production of elements gives the new methods a competitive edge in most building markets. This point will also be discussed.

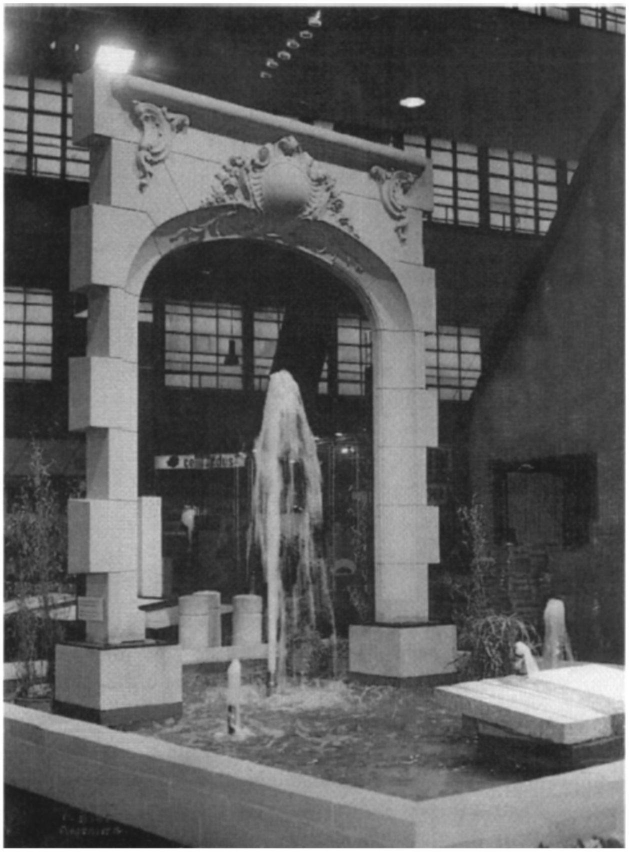


Figure 1.6 The Conrad Hotel, Brussels (Decomo Co.)

1.2
The nature of industrialization

The industrial revolution marked the passage from a handicraft economy to one dominated by industry and machine manufacture. It originated with the introduction of machines, steam power, and new ways of making steel and iron in the 18th century. It received a tremendous boost in the late 19th century with the invention of electric power, the internal combustion machine, petroleum fuel, and chemical synthetics, and it culminates today with the advent of electronics, atomic power, and computers. Each of these stages increased productivity and improved the performance and quality of the product.

In this book we define an *industrialization process* as an investment in equipment, facilities, and technology with the purpose of increasing output, saving manual labor, and improving quality.

The following features are considered prerequisites to a successful industrialization process:

1 *Centralization of Production.* Utilization of expensive equipment and facilities is feasible only with production performed at a single location (for a particular region). The process will thus use the

economies of scale with respect to capital investment, management, and auxiliary services. From this central location the product is shipped to the various consumer areas.

2 *Mass Production.* The investment in equipment and facilities associated with an industrialization process can be justified economically only with a large production volume. Such volume allows a distribution of the fixed investment charge over a large number of product units without unduly inflating their ultimate cost.

3 *Standardization.* Production resources can be used in the most efficient manner if the output is standardized. Then the production process, machinery, and workers' training can best be adapted to the particular characteristics of the product.

4 *Specialization.* Large volume and standardization allow a high degree of labor specialization within the production system. The process can be broken down into a large number of small homogeneous tasks. Workers continuously engaged in any of them can perform at the higher productivity level attained with specialization.

5 *Good Organization.* Centralization of production, high volume, and specialization of work teams requires a sophisticated organization capable of a high quality of planning, coordination, and control functions with respect to production and distribution of the products.

6 *Integration.* To ensure optimal results, a very high degree of coordination must exist between design, production, and marketing of the product. This can be ensured in the most efficient way within an integrated system in which all these functions are performed under a unified authority.

A high degree of industrialization, as characterized by these features, can be found today not only in the production of all types of consumer and capital goods but also in agriculture, medicine, education, and various types of service-industries.

The automation which computer control gives to many stages of production adds new dimensions to the industrialized process. Large production series, standardization, and specialization are no longer prerequisites for the feasibility of industrialization.

While large volumes of production are still essential to the feasibility of an investment, production no longer has to be uniform. There is a growing demand for a smaller series of diversified products which are better suited to the individual tastes of various customer groups and even of individual customers. If a company wants to survive in the competitive market it must cater to this type of diversified demand. Automation of production makes this feat possible at a minimum additional cost.

Automated features in both the design and the production of products make the proficiency of workers in execution of individual tasks less important. More sophisticated production tools and automated production control shift the emphasis from worker specialization in individual activities to their understanding of the whole process and its underlying technology.

1.3

Special features of the building process

After discussing the general attributes of an industrialized process, we proceed to examine their implications with reference to building systems. A building system was defined earlier as all work components necessary for a particular type of building together with their execution techniques and procedures.

We must first consider the major differences between construction and a typical manufacturing process. These differences, summarized in Table 1.1, were the main cause of the slow advent of industrialization in building. We will now discuss some of them in more detail.

Table 1.1 Main features of construction versus manufacturing industries

Manufacturing	*Construction*
All the work performed at one permanent location	Work dispersed among many temporary locations
Short to medium service life of a typical product	Long service life of a particular product
High degree of repetition and standardization	Small extent of standardization; each project has distinctive features
Small number of simplified tasks necessary to produce a typical product	Large number of tasks requiring a high degree of manual skills necessary to complete a typical construction project
All tasks performed at static workstations	Each task performed over large work area with workers moving from one place to another
Workplace carefully adjusted to human needs	Rugged and harsh work environment
Comparatively stable workforce	High turnover of workers
Unified decision-making authority for design, production, and marketing	Authority divided among sponsor, designers, local government, contractor, and subcontractors

Distinctive nature of projects

The distinctive nature of every building project results from different needs, habits, and preferences of eventual users, different surroundings in which buildings are erected, and different perceptions of designers of an optimal solution for a particular combination of a user and an environment. The question of whether higher standardization should always be sought, even at a cost of a somewhat less effective functionality, higher monotony, and consequently lower satisfaction of an individual user (or group of users), is still very much debated among sponsors (both private and public), designers, and contractors. The prevailing trend, at least in the developed countries, seems to advocate standardization only as long as it does not affect the overall quality and aesthetics of a particular solution. The great challenge of industrialization in building—both from the architectural and technological viewpoints—consists of how to standardize the requirements from individual building components and still ensure maximum design freedom with respect to the final building product. It appears that new production techniques employing computer-aided design and manufacturing will permit considerable diversification of output without affecting construction feasibility. These possibilities are discussed later in this book.

Dispersion of construction activity

The dispersion of construction activity, even with a fairly standardized demand, is inevitable at present because considerable parts of the building project— infrastructure, foundations, erection, and finishing—can feasibly be carried out at the present state of technology only onsite. The problem of industrialization in building is therefore how to increase, as much as possible, the share of construction work that can be performed at an offsite centralized facility and how to benefit from the better equipment and organization available there.

Work environment

The physical hardship of construction work, rugged ambient conditions, and the need to move continuously from one location to another are inherent features of the onsite conventional construction process. Those parts of construction work which can be performed in a prefabrication plant would certainly benefit from a more hospitable and effective workplace.

Complexity of building process

A construction process, for most types of building, involves some 20–30 different skilled trades. This complexity is caused by the multitude of functions which most buildings perform. A typical building must provide shelter, adaptable thermal and acoustic conditions, locomotion between its different levels, water and power supply, disposal of wastes, illumination, communication with the outside world, and other more specific functions, for example, cooking, recreation, storage, sports activities, and various industrial processes. Each of these functions may vary with particular constraints of space, location, and usage. This proliferation of functions results in a large number of works that must be coordinated and adapted to each other in the finished project. The success of industrialization depends therefore on the extent that these different works can be combined in comprehensive assemblies, adapted to their multipurpose functions. The most far-reaching solution under this principle is the fabrication of a whole building, or its sizable parts, as a single unit, with all necessary fixtures and finish works completed in the plant. Such an approach, although sometimes employed in practice, may complicate to a large degree the production and especially the transportation and erection process. A more flexible alternative consists in dividing the building into several types of major components—exterior walls, floor slabs, and vertical walls—each of them of the largest manageable size within the transportation and erection constraints, and containing as much as possible of fixtures and finish works. An exterior wall, for example, prefabricated as an assembly, may include exterior and interior finish, thermal insulation, windows—painted and glazed—electrical outlets, and even a heating unit or an air conditioner.

Long service life

Building projects are formally expected to function at least 50 years, but their actual service life is much longer. Such a long life cycle has an important implication with regard to several aspects of building performance. The most obvious is quality. An inferior building cannot be discarded or withdrawn by a manufacturer for repairs; it will therefore continue to plague the users, and possibly the envi ronment, over its entire life span. The quality of building is therefore of paramount importance and should be ensured with appropriate design and careful control during construction. Another important aspect has to do with the altering patterns of the building's use, due to the dynamics of family growth that change with time, life-styles, and living standards. The ideal solution to these problems could be a "flexible" building that can be adapted, by easy modification of its components, to changing user requirements or special maintenance needs.

Divided authority

The distinctive nature of every building project necessitates, for its procurement process, an individual input from several factors that in many cases act independently of each other: performance requirements from the sponsor, design attributes from the designer, and construction constraints from the contractor. A divided authority necessarily reduces the overall efficiency of a solution, when compared with an integrated system that could utilize, in a most effective manner, the potential of design and construction, in view of user needs and market conditions. The need to integrate design and construction is much more evident in an industrialized than in a conventional building system. A production based on fixed facilities and involving large setup costs is by its nature less adaptable to design variations than onsite construction using mostly manual labor. Two solutions can be applied in practice to overcome this difficulty. One is to unify design, production, and marketing functions under a single entrepreneur within a so-called “closed” building system. Such a system, developed with an imaginative design and based on a thorough market study, will offer building alternatives attractive enough to a sufficient portion of potential clients. Another solution, following an “open system” approach, confines itself to production of standard “catalogue” components very much in the same way as standardized structural steel profiles, asbestos sheets, nuts, and bolts. Such standardized building components (e.g., floor slabs, beams) can then be incorporated into building plans by any designer acquainted with their shapes and dimensions. Both approaches are discussed extensively in other parts of the book.

1.4
Industrialized building systems

A building system can be defined as a set of interrelated elements that act together to enable the designated performance of a building. In a wider sense it may also include various procedures—technological and managerial—for the production and assembling of these elements for this purpose.

The main features of an industrialized building system, as they emerge from the discussion in the previous section, may be summarized as follows:

1 As many as possible of the building elements are prefabricated offsite, at a central facility, where specialized equipment and organization can be established for this purpose.
2 The various building works are incorporated into large prefabricated assemblies with minimum erection, jointing and finishing work onsite.
3 Materials and component handling onsite is extensively mechanized; in concrete work, large standard steel forms, ready-mixed concrete, and concrete pumps are used.
4 Design, production, and erection onsite are strongly interrelated. They must be viewed therefore as parts of an integrated process which has to be planned and coordinated accordingly.
5 Automation may be introduced into the building realization process in order to reduce human involvement and improve quality in design, production, and construction onsite.

The benefits of industrialized systems, their limitations, and the ways to cope with them are discussed in the next section.

1.5
The benefits and limitations of industrialized building systems

The benefits of industrialization were presented as its raison d’être in the previous sections. When applied to a building process, these benefits are:

1. Saving in manual labor onsite (up to 40–50% of the input in conventional construction), especially in skilled trades such as formwork, masonry, plastering, painting, carpentry, tiling, and pipelaying (electrical and water supply).
2. Faster construction process, that is, earlier completion of building projects.
3. Higher quality of components attainable through careful choice of materials, use of better production tools—in batching and casting—and strict quality control.

These benefits, if realized, should have resulted, despite the required investment, in definite economic gains due to lower labor costs, faster turnover of working capital, and saving in life-cycle costs of the finished buildings.

Despite these benefits, the share of industrialized building in the total output is not increasing in most countries, as expected, mainly due to the following reasons:

1. Volatility of the building market and a general decline in demand for large public housing projects in most developed countries made an investment in production facilities more risky when compared with conventional laborintensive methods. This was particularly true in several European countries with an abundant supply of cheap imported labor.
2. The excessive tendency toward repetitiveness and standardization in public projects, where industrialization was most widely applied, resulted in monotonous "barracklike" complexes that very often turned into dilapidated slums within several years. The unfortunate image of industrialized dwellings as socially inferior housing solutions was further reinforced by production defects in building components, which are quite frequent in the initial stages of prefabrication. Such defects—resulting from lack of technical expertise and poor quality control—caused aesthetic and functional faults, such as cracks, blemishes, moisture penetration, and poor thermal insulation in completed buildings.
3. Industrialized systems were considered very rigid with respect to changes which might be required in the building over its economic life. This was true especially when small span "room size" prefabrication was employed.
4. The technology, organization, and design of prefabricated building systems never became an integral part of the professional knowledge of engineers and architects, obtained as other subjects through a regular academic education. The academic curriculum seldom includes courses that present, in a thorough and methodological manner, the potential and the problems associated with industrialization in building. As a result, there is a natural tendency among designers and builders to prefer familiar conventional solutions, perhaps with occasional utilization of single prefabricated elements.

It seems that the first three factors can no longer be considered valid in view of the technological progress in this field and the experience gained with industrialized building, especially over the last three decades of its application. The various available alternatives of industrialization allow selection of a system that under effective management and rational utilization procedures, need not impose a significant financial burden on its users.

Furthermore, aggressive marketing is today an essential function in any type of production activity and a marketing effort aimed at securing sufficient demand for building sytems should not be an exception.

There is also no pressing need today for standardization and repetitiveness "at all costs." Automated design and production procedures allow for use of almost custom-made components for each individual project without prohibitive additional costs. The abundance and variety of shapes and finishes available today, with the advance in precasting technology, exceed by far those normally offered in conventional building. Experience accumulated with prefabrication and modern quality control methods practically assure a product quality much superior to what can be attained with available construction labor supply. The weakness of existing industrialized systems is still in their cumbersome connections and jointing methods, which are also very sensitive to errors and sloppy work. These can no doubt be improved with an appropriate development effort.

It also appears that considerable flexibility with regard to changes may be attained if careful attention is given to location of the "rigid" elements of the building, i.e. the structural supports and the service systems.

Paradoxically, the last factor—lack of sufficient acquaintance with industrialization among building professionals—has always provided, and still does, the greatest impediment to its successful application in practice. The tendency to view industrialization as mere utilization of premanufactured components disregards the system approach, which is absolutely essential to realization of its advantages over conventional construction methods. Development or selection of an industrialized system must always consider the following aspects:

1 Physical performance—stability, strength, thermal and acoustic requirements, fire resistance, maintainability, and insulation.
2 Architectural design—aesthetics, functionality, versatility, and flexibility.
3 Technology—selection of materials, production methods, and connecting, jointing, and finishing techniques.
4 Management—planning and coordination of production, transportation, and erection, and quality control.
5 Economics—forecasting of demand—its scope and characteristics and the selection of the most profitable method and optimal location and size of the production plant in accordance with this demand.
6 Marketing—advertising, sales engineering, and effective contracting for projects.

The knowledge essential for examination of these features can be acquired only through an orderly learning process.

This book presents, from a managerial viewpoint, the material necessary for rational planning or selection of an industrialized building system. It may be used as a text for teaching a course on industrialization in architectural and civil engineering curricula. It may also be used by practitioners in these fields who wish to become acquainted with the subject without a rigid institutional framework. It cannot be used however as a "manual" from which an optimal instant solution to a particular problem can be extracted.

The principles of industrialization reviewed very briefly in the preceding sections, and thoroughly explored in the subsequent chapters, can be applied to any type of building and to different construction materials. They will be explored in this book with specific applications to concrete-based construction where industrialization has been most widely employed to date. Similar principles may be applied also to lightweight prefabrication methods, although the production there is closer in nature to regular manufacturing processes.

Chapters 2–11 deal with various aspects of industrialization of the building process, and constitute the first two parts of the book.

The first part (Chapters 2, 3, 4 and 5) reviews the prevalent alternatives of industrialized building systems, their design procedures, performance specifications and production methods. In the second part—Chapter 6 deals with the organization of a prefabrication plant, Chapters 7, 8, and 9 present production planning, cost estimating, and quality management methods, and Chapters 10 and 11 are concerned with the economic implications of industrialized building.

1.6

Automated building systems

The implementation of industrialization in building cannot be examined today without consideration of the impact of information technologies on the design, production, and assembling onsite of prefabricated elements.

Automation of a mechanized system, in the context examined here, means referring all, or certain, aspects of control of the system to a computer-driven device. The device can instruct the machine (or machines) to perform a preprogrammed sequence of operations and modify the instructions on the basis of the feedback received from the machine's performance.

In general, the benefits of mechanization and automation are saving of manual labor, elimination of strenuous, dirty, and dangerous work, and improvement of quality. A very important benefit of automation is the flexibility it gives to an otherwise rigid mechanized process.

Any type of mechanized building activity can be automated. Many building activities which are still performed manually must first be mechanized and only then can they be automated. The decision of whether to mechanize/automate a building activity, and to what extent, should depend on a feasibility analysis—the expected benefits of the change vs. the additional costs to be incurred.

In this book we will examine the general nature of automation in building and then focus our attention on the merits of an *industrialized automated* system which employs automation in the production of building elements in the prefabrication plant and in performing the remaining works on site. The concept of automation in building can be further expanded into an *automated building realization system,* which also includes the design activities. The elements of such a system will be briefly reviewed here and examined further in Chapter 16.

Automation in design

Computer-aided drafting and computer-aided engineering analysis have already been well established for some time, as part of a regular professional practice. Drafing is made more efficient by creation and manipulation of standard entities: geometric forms and building details. These can be created, copied, adapted, and joined to produce a desired, preconceived architectural drawing. The drawings can be checked for consistency, updated when required, stored, and retrieved, using appropriate computer software.

Computer software is also available for an analysis of the performance of various building systems (structural, mechanical, environmental), and for checking that they conform to accepted codes and standards.

It is the higher-level design work—the allocation of spaces, location of supports, and in the case of prefabrication, the shaping of elements and subsequent generation of production drawings—which is now being delegated to knowledge-based computer programs.

Automation of production in plant

Automation in plant is driven by information received from the design stage. Production activities which can be automatically controlled in plant include: forming of molds for prefabrication, preparation of reinforcement and its placement in the molds, mixing and placement of concrete, placement or shaping of exterior finish, quality inspection, curing of concrete, and handling of components between processes.

Automation of construction onsite

Prefabricated components can be assembled, jointed and finished onsite using construction robots. Robots are machines which can be programed to perform various construction tasks either autonomously, or in tandem with human operators. Prefabricated building components can be assembled at a desired location by an automated crane. Subsequently, different finishing operations—jointing, painting, tiling etc.—can be performed by single function or multifunctional robots. Because of the particular nature of the building environment the building robots have to be mobile and be able to interact with the environment through appropriate sensors.

A considerable amount of industrialization is essential for automation of the production or erection process; there is nothing to automate if the building work is done manually. And vice versa, highly mechanized systems must be automated in order to cope economically with diversified orders.

The third part of the book (Chapters 12–16) deals with the application of automation to industrialized building.

Chapter 12 describes automation in prefabrication plants. Chapter 13 explains the general principles of industrial robotics, Chapter 14 explores their applications to robotization of construction work onsite, and Chapter 15 deals with the implementation of robotization. Chapter 16 examines future trends in the application of industrialization and automation to the building process.

1.7

Summary and conclusions

Industrialization entails investment in equipment, facilities, and technology in order to increase output, save manual labor, and improve quality. The main attributes to industrialization are centralization of production, large volume, standardization of products, specialization of workers, efficient organization of production and distribution, and unified authority over all stages of the process.

The construction process differs from manufacturing in several important features, which impede the progress of industrialization in this sector. These include uniqueness of every project, dispersion of production, changing workplace, complexity of product, rugged environment, and divided authority over the process.

Eventual industrialization of the building process will maximize the share of components manufactured in a plant, focus prefabrication on large comprehensive assemblies, improve the technology of jointing and connection onsite, emphasize effective quality control, provide a flexible and versatile design of systems and components, and strive toward efficient coordination among design, prefabrication, and erection onsite.

The benefits of industrialization in building are a saving in skilled labor onsite, a faster construction process, and better quality of the product. In order to realize these benefits, it is necessary to educate architects and engineers in a system approach that integrates design, technology, management, economics, and marketing of industrialized building.

Automation seems to be a natural and essential extension of the industrialization process, if the provision of individual solutions to each customer is to be made feasible.

Assignments

1.1 Give three examples of building systems with prefabricated components; each using a different material. Specifically, refer to the following components: structural framing, floors, exterior walls and partitions.

1.2 To what extent is prefabrication applied, in the various types of buildings (residential, commercial, industrial, etc.) in your region? Give some typical examples of application.

1.3 Identify a fully or partially prefabricated building being erected in your vicinity. Describe the technology employed in the execution of main building works. Could you suggest some ideas on how to increase the extent of industrialization in this particular building?

1.4 Based on a short bibliographical survey (e.g., Ref. 1), describe the main features of the U.S. "mobile homes" system. What are the main advantages and limitations of this building solution?

1.5 Based on a short bibliographical survey, describe and discuss two examples of application of prefabricated concrete components before World War II.

1.6 Based on a short bibliographical survey, describe the objectives and the results of Operation Breakthrough in the United States.

References

1. A.J.Bernhardt, *Building Tomorrow: The Mobile Manufactured Housing Industry,* MIT Press, Cambridge, MA, 1980.
2. H.Gilbert, *Pioneers of Prefabrication: The British Contribution in the Nineteenth Century,* Johns Hopkins University Press, Baltimore, 1978.
3. A.E.J.Morris, *Precast Concrete in Architecture,* The Whitney Library of Design, London, 1978.
4. B.Russel, *Building Systems Industrialization and Architecture,* Wiley, New York, 1981.
5. B.J.Sullivan, *Industrialization in the Building Industry,* Van Nostrand, New York, 1980.
6. A.Toffler, *The Third Wave,* Bantam Books, New York, 1981.
7. U.S. Department of Housing and Urban Development, *Operation Breakthrough— Feedback,* U.S. Government Printing Office, Washington, DC, 1972.
8. R.B.White, *Prefabrication Industry and Its Development in Great Britain,* HMSO, London, 1965.

Chapter 2
Building Systems and Components

2.1
Introduction

A building system was defined earlier as all work components necessary for a particular type of building together with their execution procedures and techniques. Building systems can be classified in different ways, depending on the particular interest of their users or producers. A frequent basis for such classification is the construction technology. In this manner four major groups can be distinguished: systems with (1) timber, (2) steel, (3) cast in situ concrete, and (4) precast concrete as their main structural and space-enclosing material. Various composite solutions are also prevalent, for example, steel framing with concrete or timber floor slabs, cast in situ concrete beams and columns with precast concrete slabs, and precast concrete framing with brick masonry.

This book deals with precast concrete systems. These systems may employ different types of precast elements. For the sake of their presentation here, the systems are classified according to the geometrical configuration of their main framing components as follows:

1 Linear or skeleton (beams and columns) systems.
2 Planar or panel systems.
3 Three-dimensional or box systems.

This classification facilitates an acquaintance with the main types of precast components; however, it is not always precise or exhaustive. Many systems employ components belonging to different geometrical groups. They will be discussed within their most appropriate context.

A different group of industrialized building systems, which combines cast in situ framing elements with precast slabs, walls, or facades, is also explored.

The design of buildings erected from precast elements must consider the following requirements:

- An orderly transfer of vertical loads from horizontal (floor slabs, beams) to vertical (columns, walls) elements, and from them to foundations.
- Lateral stability: the capacity of the structure to withstand horizontal loads. In buildings, this capacity is usually attained through floor slabs acting as horizontal diaphragms which transfer the loads to appropriate vertical elements—cores (stairs/elevator) or frames. The vertical elements can be monolithic, or made of precast elements with appropriately designed connections between them. The floor slabs, made of precast elements, must have special ties so that they act as diaphragms.

- Integrity of the structure: its ability to act as a unified whole by appropriate connections between members. Each connection must be designed in light of this requirement.
- Strength of individual precast elements—to withstand loads introduced to them during their erection and service.

Structural design meeting these requirements is regulated by national codes (e.g. BS 8110 in the UK, ACI 318 in the USA, DIN 1045 in Germany). Other performance requirements for prefabricated systems are reviewed in Chapter 4.

2.2
Linear systems

Linear systems, as defined here, use as their main structural elements columns, beams, frames, or trusses made of plain or prestressed concrete. Their important feature is the capacity to transfer heavy loads over large spans. For this reason they are used in the construction of bridges, parking lots, warehouses, industrial buildings, sport facilities, and so on.

General principles

Typical systems of linear components for industrial and agricultural buildings are shown in Fig. 2.1. They are composed of structural frames, spaced at equal distances, thereby creating modular "cells" that can be repeated a desired number of times in longitudinal direction or sideways. The span *(L)* of these frames varies between 10 and 30 m, depending on the building's purpose and various architectural considerations. The spacing *(S)* between them varies, in most cases, between 5 and 10m. The height (H) of columns varies between 4 and 10m.

Different variants of the structural scheme allow for the most convenient partitioning of the frame into connected precast elements. A rectangular frame is usually composed of two columns and a horizontal beam, connected so as to attain stability in the frame plane. For this purpose the columns may be fixed at the bottom, and the beam is freely supported [Fig. 2.1 (a)], which makes it easier for assembling (the connection at the top does not have to transfer moments and is therefore simpler). They may be hinged at the bottom and transfer moments at the top [Fig. 2.1(b)] which does not involve the foundations in the transfer of moments. Pitched frames can be composed of 2, 3, or 4 parts [Fig. 2.1(c), (d), (e)], depending on their dimensions and the transportation and erection conditions.

Stability of the frames system in the longitudinal direction can be obtained by bracing with steel diagonals, or by attaching the frame to rigid building components, for example staircases or solid walls.

Single frames can be extended sideways into as many bays as necessary, or upwards, for multistory buildings, as shown in Fig. 2.1f. Attention must be paid to their lateral stability either by introduction of rigid connections at the corners, by bracing with diagonals, or by attaching the multiframe to a rigid building component.

The roof may be supported directly on the frames, when precast slabs or Tee beams are used for this purpose. It may also be supported on a precast joist system, when the roof material—corrugated steel, asbestos, or thin concrete plates —requires smaller spans between supports.

Examples of linear systems for industrial buildings are shown in Fig. 2.2.

Linear structural systems of widely spaced beams and columns give the user (or the designer) a considerable flexibility in partitioning the layout, by means of removable partitions, into functional spaces

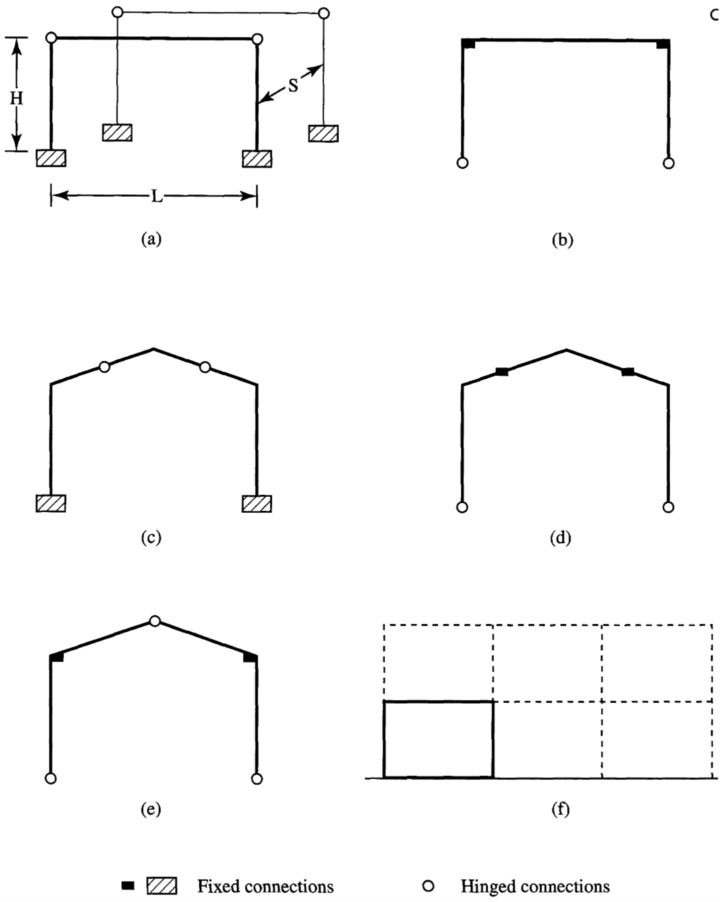


Figure 2.1 Typical schemes of industrial linear systems

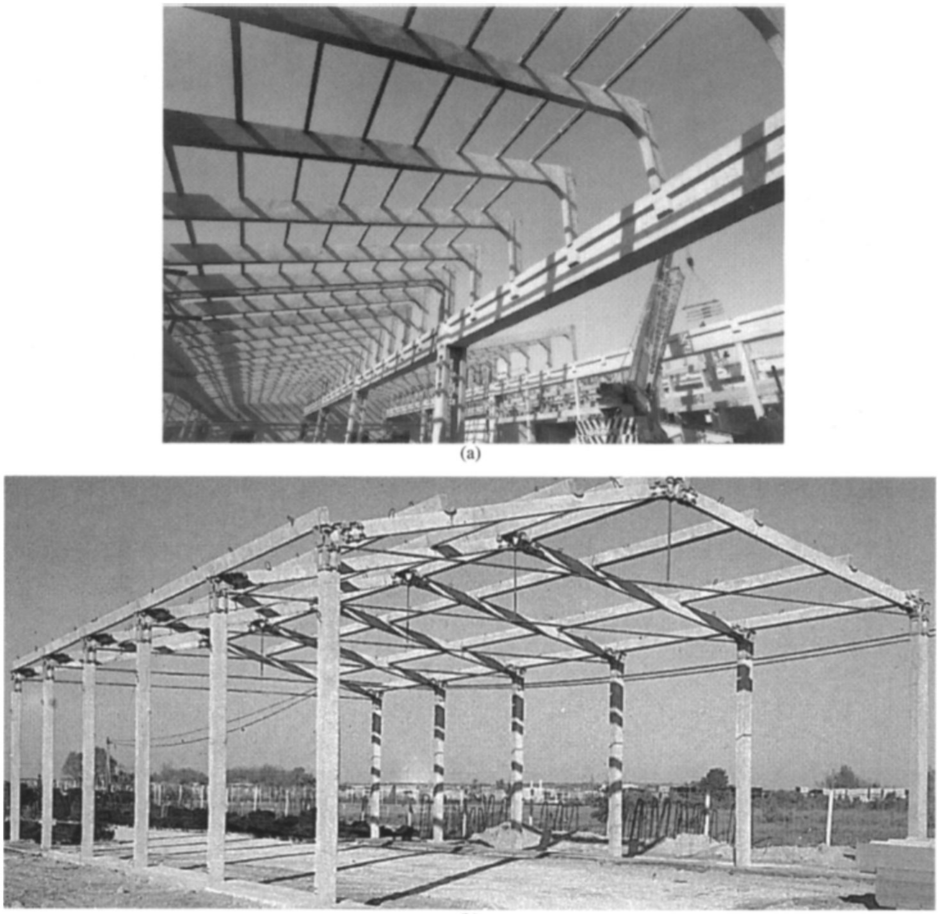
that can be adjusted to the particular needs of each user. They can also be easily modified with changing requirements in the future. The skeletons are therefore often used, together with prefabricated enclosures and space dividers, for public buildings—schools, offices, hospitals, and other single-story or multistory structures. They consist of a grid of columns and beams which support plain or prestressed floor slabs. The spacing between columns in multistory public buildings is in the range of 6–12 m, and the story height varies between 2.80 and 4.50 m.

Two examples of linear systems for public buildings are shown in Fig. 2.3— one used for garages (Fig. 2.3a) and the other for multistory offices (Fig. 2.3b).

A general description of linear systems and their methods of analysis and design are included in Refs. [9, 10].

Elements and connections

Typical linear elements are shown in Fig. 2.4. Beams (a)–(c) are used as a direct support to floor slabs. The width of rectangular beams (a) is usually at least 300 mm, and their width-to-height ratio ranges from 1:1 to 1:3. Beams (b) and (c) have additional ledges 150–200 mm wide for slab support on one or both sides. Beam



(a)

(b)

Figure 2.2 Examples of linear systems for industrialized buildings: (a) industrial hall; (b) light agricultural shed

(d) is used for large spans: its varying height and recessed flanges allow an optimal adaptation of material to the imposed stresses. Joists (e) and (h) are used to support lightweight roofing and girders (f) and (g) are used in bridges and other heavily loaded structures. Columns (i) may be several stories high and include corbels to support beams on each story. Columns (j) are mostly used in industrial buildings. Block (k) and formed (l) footings are mostly used in industrial buildings. The dimensions of the various beams and girders used in skeletal systems depend on their span, the loads applied, their materials, and special architectural and economic considerations. Their height-to-span ratio is, in most cases, in the range of 1:10 to 1:20. Prefabricated beams of the length exceeding 5–6 m are usually prestressed. Tables and nomograms for selection of linear elements are given in Refs. [2, 3, 15, 17] and other sources.

The main methods of load transfer between supported and supporting members—beam to girder, column to column, or column to footing—are the following:

1 Through steel plates or angles. The steel elements embedded in both connected members are welded or bolted to each other in a similar manner as in steel structural members. Welding severely restrains

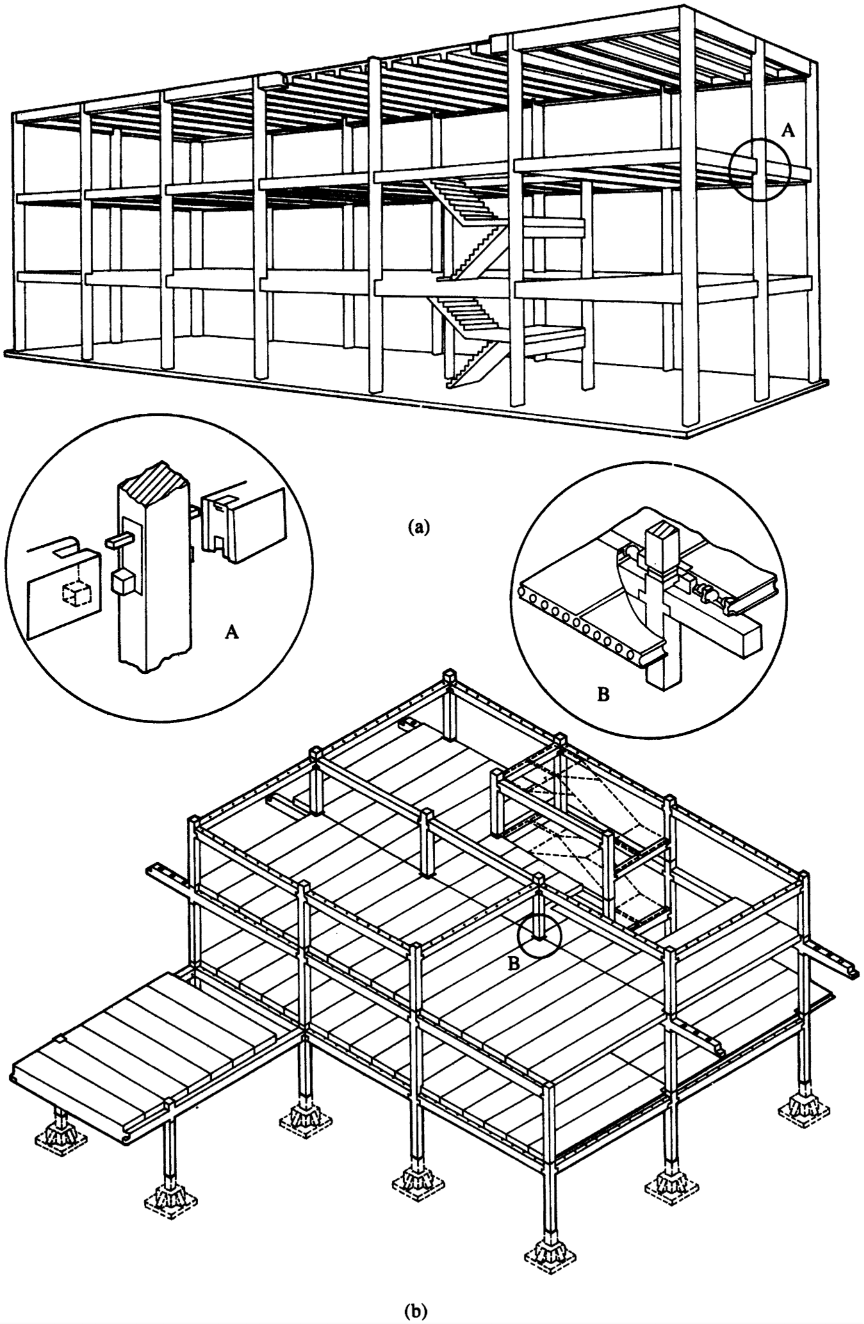


Figure 2.3 Examples of linear systems for public buildings: (a) multistory car park; (b) office building

any possible movement of a supported member caused by temperature changes or other effects, and may in such cases introduce additional stress to the structure.

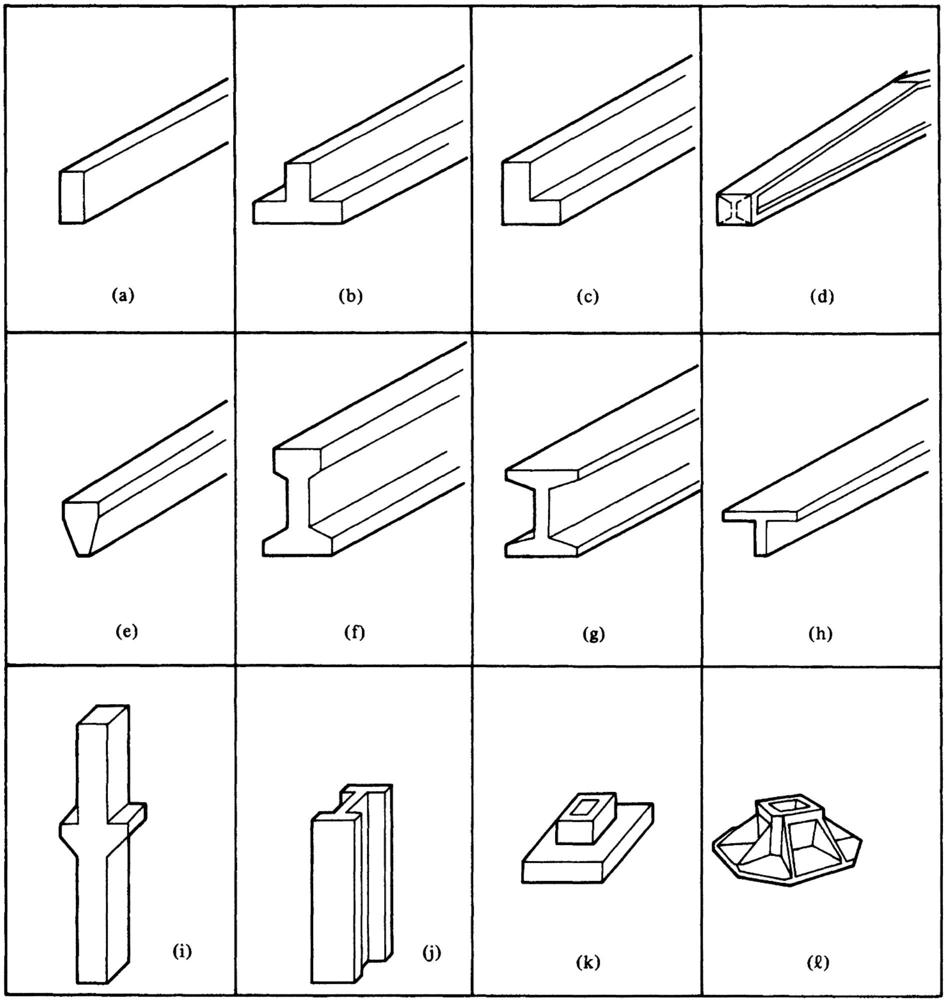


Figure 2.4 Typical linear prefabricated elements: (a)-(d) beams; (e), (h) joists; (f), (g) girders; (i), (j) columns; (k), (l) footings

2 Through bearing pads, made of elastomeric materials (neoprene), laminated fabric, synthetic fibers, and other materials. Such pads allow a certain measure of freedom of movement to supported members.

3 Through concrete grout. The grout, which is 20–30 mm thick and consists of a 1:3 cement-to-sand mix with a stiff consistency, is spread on a concrete bearing to provide a uniform load distribution over the connected surface.

The bearing area is calculated, in each case, according to the loads to be transferred and the permissible stresses in the various materials. Typical connections recommended by PCI and other sources [2, 10, 11, 17] are shown in Fig. 2.5. Connections between column and footing are shown in (a) and (b). Connection (a) between column and cast in situ footing uses a steel base plate anchored to a column and bolted to bars in the footing. A connection similar to (c) may be also employed for this purpose. Connection (b) is used for a column and a precast footing. Connection in columns can use a bolted support (c) or welding between steel fixtures (plates or angles), embedded in both members, as shown in Fig. 2.3(b). Connections between a beam and a column as shown in (d) and (e) can use a dowel-sleeve entry or welding of steel fixtures anchored to connected elements. A dowel-sleeve connection can be also used for beam or girder (f) or column on girder support. The hidden connection (e) may be preferred for aesthetic reason, and is applied in residential and office buildings. A corbel supported connection (d) is preferred structurally and is mostly applied in industrial buildings.

A moment-bearing connection between precast elements can be obtained by welding of tension bars or profiles protruding from one element to bars or plates anchored in the other, as shown in a detail in Fig. 2.3(a).

The various methods for attaching structural plates, angles, and other inserts to precast elements are shown in Fig. 2.6. The inserts can be attached with regular bolts into receptacles as shown in Fig. 2.6(a) or directly into predrilled holes with expansion bolts as shown in Fig. 2.6(b). They can be anchored in concrete with headed studs [Fig. 2.6(c)] or welded to rebars [Fig. 2.6(d)]. Such inserts can transfer tension or shear forces between connected members. An analysis of connections of linear elements is included in Refs. [11, 14, 15] and other sources.

It was already noted that linear precast concrete framing systems are similar in nature to their steel counterparts. They can transfer heavy loads over large spans and allow a considerable freedom in utilization of free space between columns. They must be used, in most buildings, in conjunction with other space-enclosing or space-dividing elements—built onsite or prefabricated.

2.3

Planar systems

Probably the most widely used types of prefabricated system are those employing planar or panel-shaped elements for floor slabs, vertical supports, partitions, and exterior walls. Unlike linear systems, which are mainly employed as structural framing, planar systems also fulfill interior and exterior space enclosure func tions. They may be prefabricated with a considerable amount of finish work— exterior finish, thermal insulation, electrical conduits and fixtures, plumbing, door and window frames, and others—and therefore significantly reduce the content and amount of skilled labor onsite. Planar systems are therefore most often used in residential buildings, offices, schools, hotels, and similar buildings with moderate loads and large amounts of finish works.

General principles

Several examples of planar system solutions applied to a typical residential building are shown in Fig. 2.7. Figure 2.7(a) shows a system of floor slabs supported on parallel bearing walls referred to often as *cross walls*. Relatively short spans (3–4 m) typical of homes and small hotel rooms allow for the economical use of *room-size* floor components. The size of these slabs, as their name implies, can be determined from the planned room outlines, so that their joints are not seen by the user. This is an aesthetic and often a functional advantage. On the other hand, room-size components necessarily impose a rigidity with respect to possible changes in interior location of supporting walls.

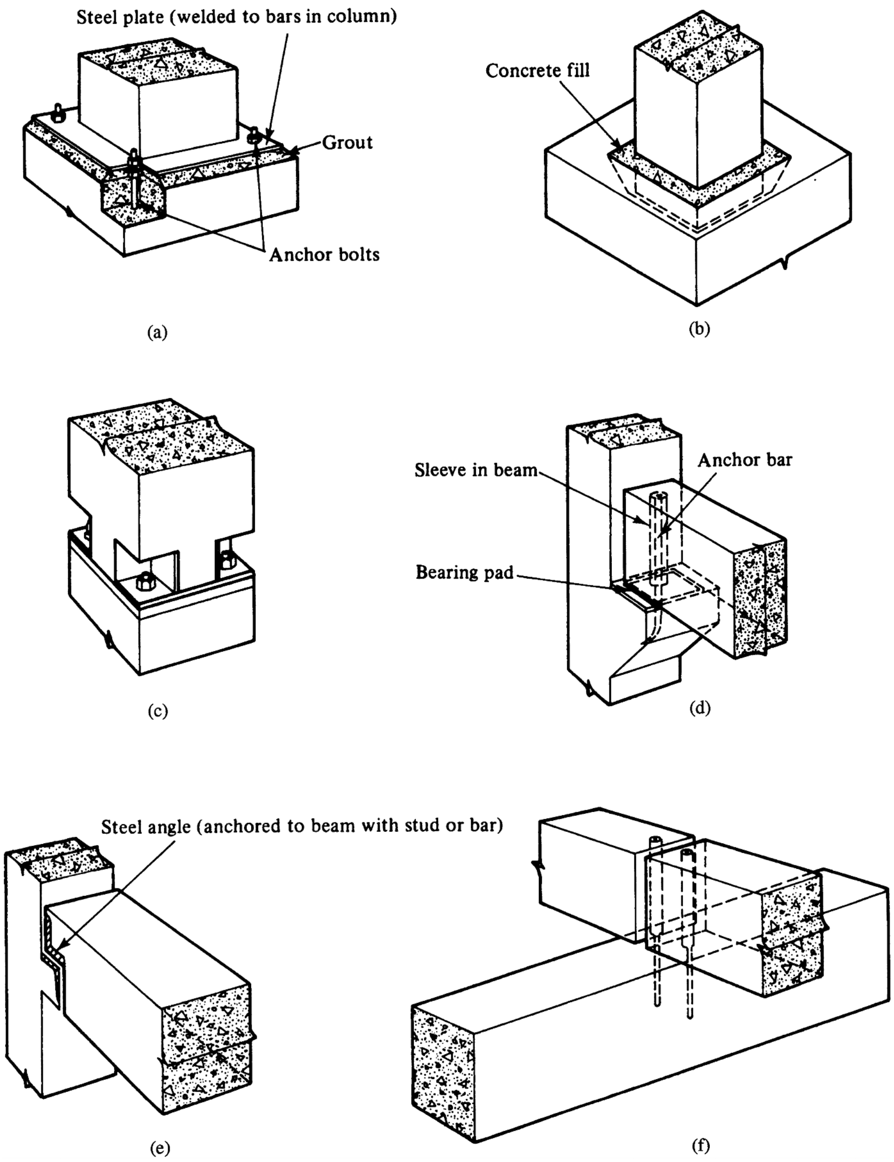
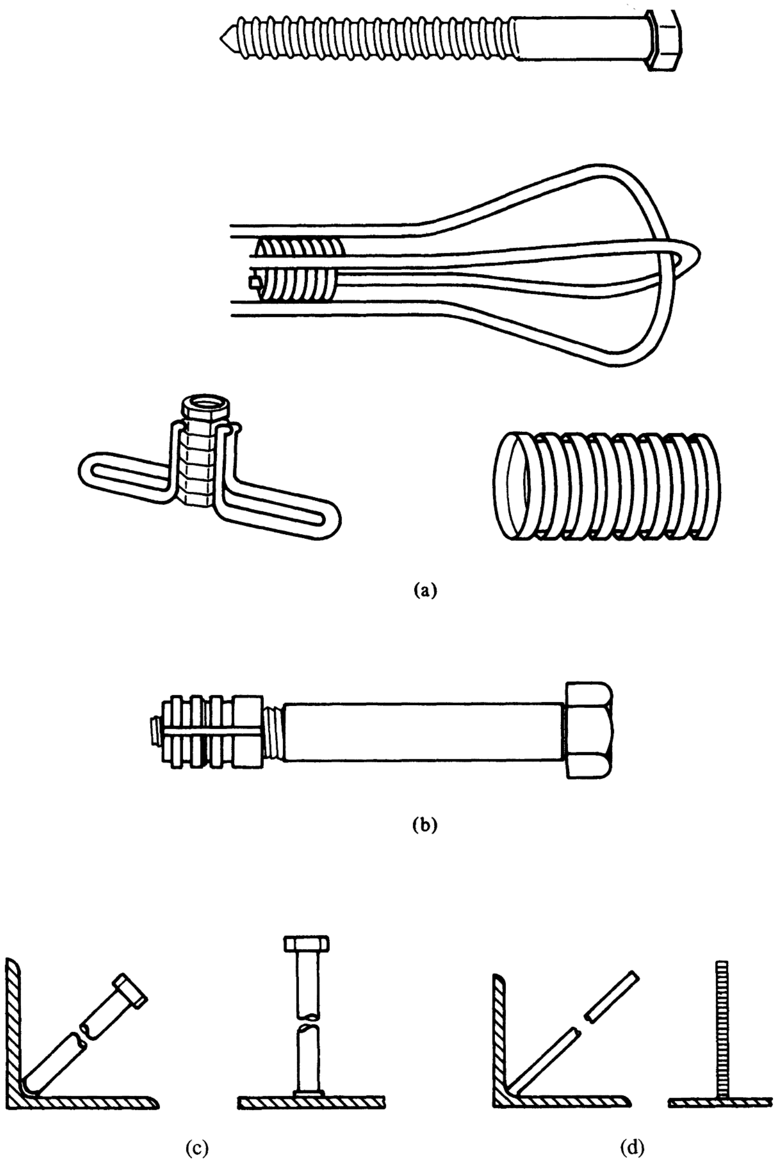


Figure 2.5 Typical connections between linear elements: (a), (b) column to footing; (c) column to column; (d), (e) beam to column; (f) beam to girder

The necessary lateral stability in planar systems is attained by monolithic structural elements, mostly interior cores, and by special jointing provisions, prescribed by the structural codes.

Figure 2.7(b) shows a system of modular slabs supported on cross walls. Such slabs require less labor input in production and, due to their special configuration, as explained later, are more economical in terms of material for larger spans. Consequently, they allow wider spacing (7–10 m) of supports and, as shown for this particular layout, complete freedom of partitioning inside a given dwelling layout. Figure 2.7(c) shows the same type of slabs supported on exterior walls which allows even more freedom in interior partitioning


(a)

(b)

(c)

(d)

Figure 2.6 Connection inserts and fasteners: (a) bolt and receptacles; (b) expansion bolt; (c) headed struts; (d) welding to bars

of the total building. On the other hand, the width of these slabs, mostly 1.20 m (in special cases 2.40 and 2.70 m), precludes the hiding of joints, which was possible in the case of room-size slabs.

Figure 2.7(d) shows a "hybrid" system, which uses, in the same building, linear elements for structural supports and planar elements for partitions and space enclosure. The advantage of this system with respect to flexibility of design was already mentioned before. However, adaptations of linear to planar elements, especially beams and columns to walls, may pose some architectural inconvenience.

The dimensions of planar components are determined by their support system, by the layout of enclosed spaces, and by other architectural design features. They must also conform to the width and height transportation constraints and the lifting capacity of erection equipment. The weight of planar precast components usually does not exceed 50–80 kN, which allows their erection with cranes of a 800–1200 kN•m lifting capacity, assuming that the required reach does not exceed 15–20 m. The weight of components may be reduced by using, for their production, lightweight concrete, as explained in Chapter 5. The main components of a planar system are presented in the following sections.

Floor slabs

Horizontal slab components are used in intermediate building floors, flat roofs, ground floors, landings, and platforms. Several types of precast elements are used for this purpose:

Room-size panels

Room-size panels conform to room outline underneath them, as shown in Fig. 2.7(a). The thickness of room-size slabs, required for structural reasons, depends on their supporting conditions and the superimposed load. A typical 3–4 m room span requires, under a moderate load, a slab thickness not in excess of 120–130mm (acoustical considerations may necessitate, for such thickness, special types of flooring). Solid slabs 180–200mm thick may be used for spans of up to 5.50m. The width of a room-size slab is limited by traffic regulations in various countries to 3.60m (or even 2.40m) if slabs are transported horizontally. If they are transported in a vertical position, their width may reach 4m, and on especially adapted trailers even 5 m.

Slabs are usually supported along edges on bearing walls or beams as shown in Fig. 2.8(a), (b). The length of support should be at least 60mm, allowing for positioning and production tolerances. This length may be reduced to a minimum if a temporary support is provided until attaining later a monolithic connection, as in Fig. 2.8(d). A moment connection can be attained by splicing or welding of top reinforcement, as in Fig. 2.8(c).

The main advantages of room-size slabs are as follows:

- They are very easy to manufacture even under field conditions.
- They utilize room-width (3.00–4.00m) spaced supports and therefore are relatively economical in terms of their concrete and steel usage.
- The joints between slabs are invisible to the user and are therefore preferable from the aesthetic viewpoint.
- They also do not require, for this reason, concrete topping or special structural connections to ensure a common action of adjacent panels.

The limitations of room size panels are as follows:

- Their production requires more labor than the production of standard modular units.
- They require more design work.
- They are limited to relatively short spans.

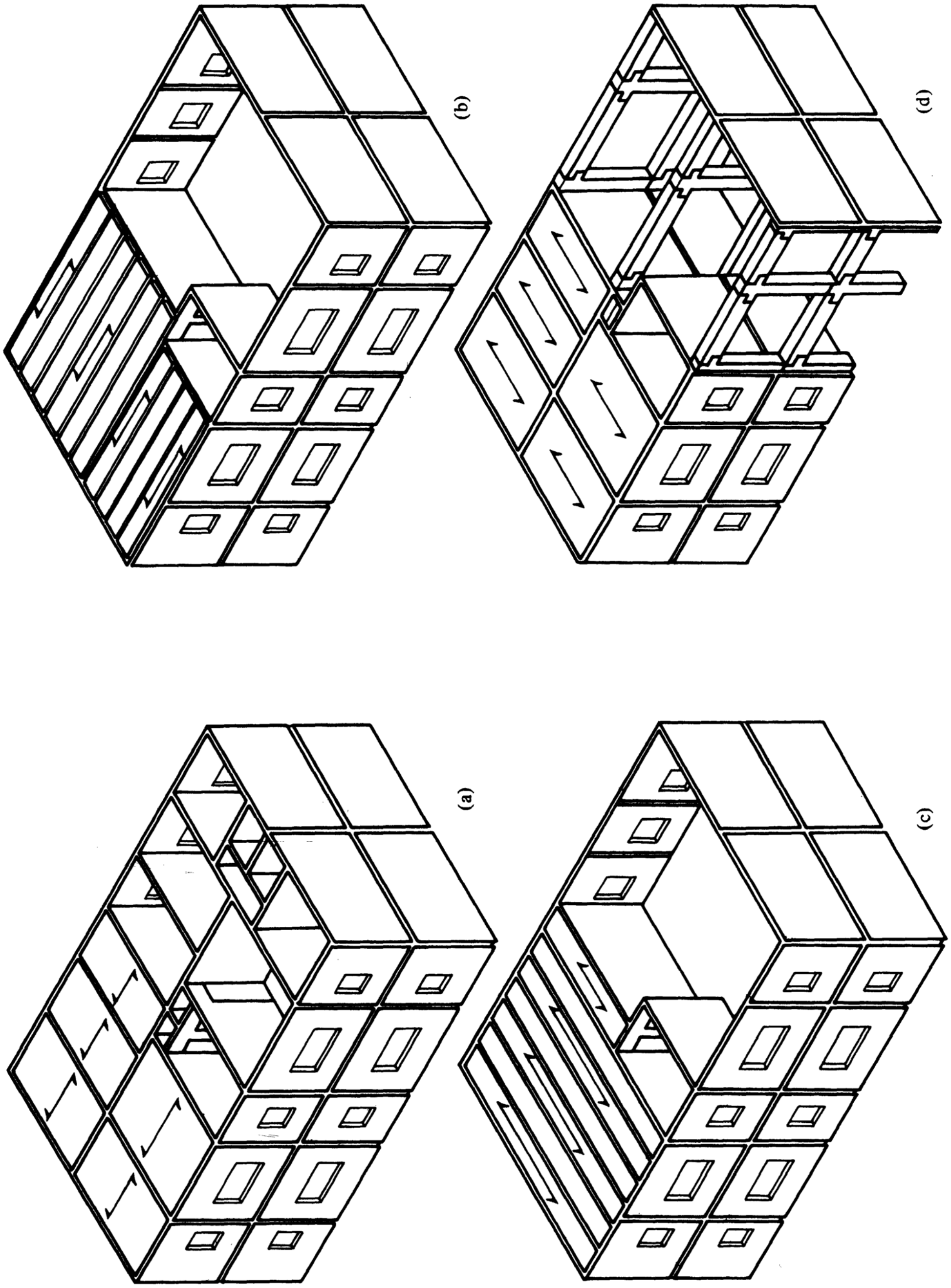
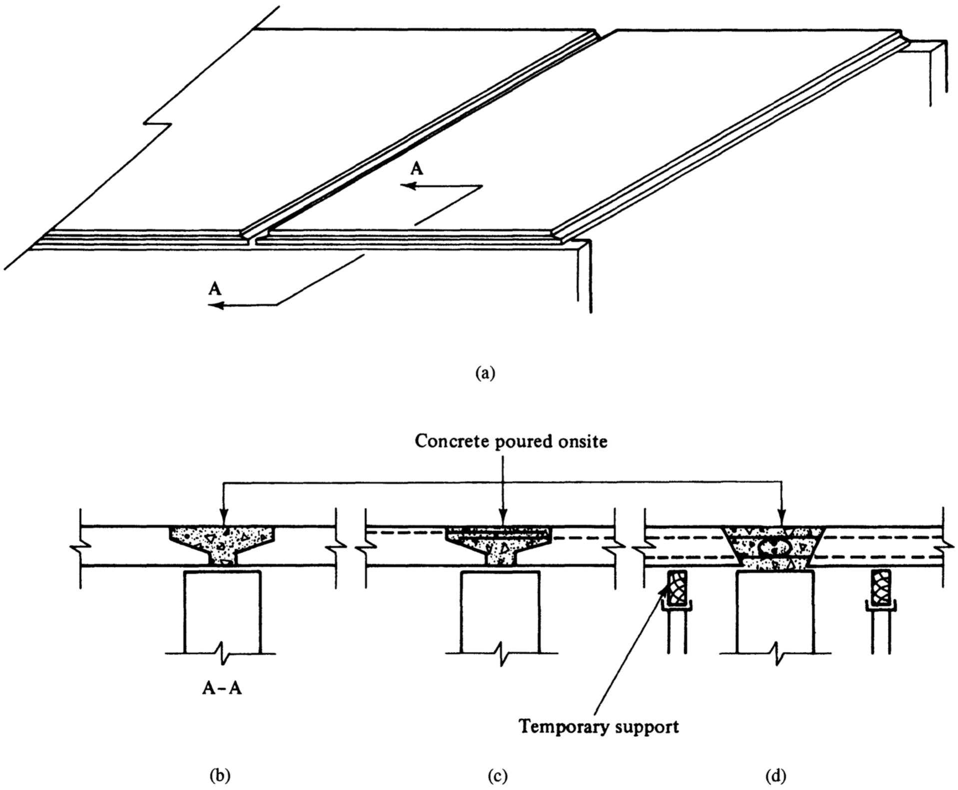


Figure 2.7 Different systems of planar elements: (a) room-size slabs on cross walls; (b) modular slabs on cross walls; (c) modular slabs on exterior walls; (d) slabs on beams and columns

- Their use limits the possibility of future changes. Since they are supported on interior space dividers



(a)

(b) (c) (d)

Figure 2.8 Room-size slab: (a) view, (b) section; (c) moment connection; (d) with temporary support

(walls, partitions), any change in location of these elements may cause serious structural problems.

Modular hollow core slabs

These are shown in Fig. 2.9. Their most common width is 1.20m, although 0.60, 0.90, 2.40 and 2.70 m widths are also available. The hollow core slabs are usually prestressed, although in some systems nonprestressed slabs are also used for spans of up to 6.50m. The prestressed slabs shown in Fig. 2.9(c) and (d) can be used for spans of up to 15.00 m and a thickness of up to 300 mm. In spans exceeding 6–7 m the prestressed elements require, in various codes, a 50 mm "topping" with a reinforcing mesh, to ensure their uniform and monolithic performance. In general, the economical thickness of prestressed hollow core slabs used for residential and office buildings is about 1/30–1/45 of their span. The prestressed hollow core slabs are mostly used in public and commercial buildings, where large open spaces are needed or where users require frequent changes in interior space layout. In such cases they may be supported on exterior walls, as in Fig. 2.7(c) or on columns-beams framing, as in Fig. 2.7(d). When used in dwellings, they are mostly supported on interdwelling cross walls, as in Fig. 2.7(b). The reduced weight of hollow core slabs (about 65% of a solid slab) allows for more economical utilization of materials. The core may be used for transfer of electrical conduits and plumbing pipes. The uniform shape and dimensions of these elements allow a very labor efficient, albeit capital-intensive, production process. The joints between elements, which cannot