Technological Rules and Constraints Affecting
Design of Precast Concrete Housing

by

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ABSTRACT

Precast concrete technology is of great importance in multifamily housing. This technology provides the possibility to the industrialize housing construction and thus enhance the availability and quality of houses. With regard to the design process of precast concrete housing, architectural and technological concepts have to be woven into housing systems by iterative processes. Although precast concrete technology is an offshoot of reinforced concrete technology, its structural nature and construction process is not the same: its identification with the concept of industrialization makes this technology quite different from cast-in-place concrete. In other words, the processes of precasting, of transportation and handling, and of the erection of precast concrete building systems give significant advantages to housing systems, but they pose technological constraints to as well.

This thesis investigates the technological rules and constraints of precast concrete structural systems which provide technological approaches to precast concrete housing systems. First, the methodology of the considerations of structural systems is introduced. Second, the technological rules and constraints of precasting, transportation, and construction methods are discussed in detail. Then, the technological rules and constraints of three typical structural systems, including unbraced frame, braced frame, and large panel, are examined.

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Acknowledgments

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Chapter 1

Introduction

Research and development of precast concrete housing systems in this country was brisk in the '60s and '70s, stimulated by European forerunners as well as by the trend of modernism in architecture. Since then the recognition of this technology has shifted from conceptual and systematic projects to practical and partial applications. Some applications of this technology have proven successful and grown sophisticated, such as precast prestressed concrete slabs or precast concrete claddings. On the other hand, the more creative applications in the context of architectural and technological concepts, the so-called "systems approach", seems to be attracting neither architects nor engineers.

This somewhat fixed nature of present applications could blind designers to the potential of breakthrough accompanied by an improvement in sub-technologies. By studying the nature of precast concrete with regard to its technological aspects, it can be understood that the best use of this technology is not the replacement of cast-in-place concrete structures with precast materials, nor the mass production of monotonous houses. Differences in the economical dimension of a frame span between precast concrete structures and cast-in-place concrete structures, or variations in finished surface and shapes of external precast concrete walls, may result in a different design.

1.1 Scope of Thesis

The primary objective of this thesis is to clarify the impact of precast concrete technology on the design of multifamily housing. This impact can be defined broadly as the design limitation inherent to precast concrete - - or as a constraint - - a limitation imposed by the design process. Rules and constraints play varying roles in the manufacturing, transportation, and construction process, as well as in the chosen structural system. Throughout the thesis, the relationship between issues of technology and design is considered.

To study the technological aspects of precast concrete housing systems, their structural systems must first be classified in the context of their elements as well as in the way they work. Therefore the discussion of the rules and constraints over precast

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concrete housing systems generally is organized according to (1) the structural form of the system (structural system), and (2) the types of loads the system must bear. The reminder of this introductory chapter discusses the classification of housing systems according to the types of structural systems and loads.

Chapters 2, 3, and 4 present the rules and constraints associated with precasting, transportation and construction methods, respectively.

Chapters 5, 6, and 7 discuss the three major structural system types identified in the next section: Unbraced frame structural system, braced frame structural system, and large panel structural system. Each of the chapters on structural limitation in the design is subdivided according to load type.

1.2 Classification by Structural System Type

Table 1-1 classifies precast concrete housing systems in terms of elements, structural systems, and lateral load support systems. To make the structural difference clear, housing systems are first classified according to the elements that make their structural systems: (1) column and beam, (2) Large panel, and (3) box unit. These three element types are then divided into five groups according to their structural system types. Then the five structural system types are sub-divided into several groups according to their lateral load supporting systems, to show how each structural system types attains stability against applied loads. Although there are hybrid systems that comprise different types of structural systems, such as a combination of moment-resisting frame structure and large panel structure or large panel structure and self-supporting box unit, they are omitted from the table.

In this thesis, the considerations of structural systems deal with three types of systems: the unbraced frame structural system, the braced frame structural system, and the large panel structural system. The box unit system is excepted from the consideration of structural rules and constraints. This is because the box unit system is of less importance in the housing market in the U.S. due to the limited size and weight that can be transported on road.

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Precast concrete elements	Structural system types	Lateral load support
Column and beam	Unbraced frame system	Moment-resisting frame
		Column base
	Braced frame system	Frame filled with block wall / Diagonal brace
		Shear wall
		Core / Hull core
Large panel	Large panel system	Shear wall
		Core
Box unit	Self-supporting box unit system	Box
	Supported box unit system	Shear wall
		Moment resisting frame

(Table 1-1)   Classification of precast concrete housing systems

1.3 Classification by Load Type

The PCI Design Handbook lists the following primary considerations which must be made in a preliminary analysis of the total structure:[1]

(1) framing dimensions,

(2) span to depth ratios,

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[1]PCI Design Handbook. Chicago: Precast / Prestressed Concrete Institute. 1985. p. 3-4

(3) lateral load resisting systems,

(4) control of volume change deformations and resistant forces, and

(5) connection concepts.

Items 2 and 4 above can be eliminated. This is because span to depth ratios, which determine the depth of horizontal framing members, do not significantly affect the design of housing systems directly. With regard to the control of volume change deformations and resistant forces, the volume change must be examined for long span structures or tall columns, which are rarely applied to housing. However, the PCI Architectural Precast Concrete says of the thermal effect on a structure, "Evaluate thermal movements as they might affect requirements for joints, connections, reinforcement and compatibility with adjacent materials."[2]

1.3.1. Framing dimensions

This issue is dealt with as "Dimensions" and "Articulations"[3] in Chapter 5 to 7. The PCI Design Handbook explains the framing dimensions as "When possible, bays should be laid out to fit the module of the components selected. . . Width of wall and deck units may be limited by over-the-road hauling regulations. It is often feasible to cast wall panels in multi-story units, and economy is achieved with fewer pieces to handle."[4] In Chapters 4 to 7, articulations of precast concrete members and the optimal dimensions of building systems in terms of the structural rationality and economics are discussed as well. This is because the method of articulation greatly affects manufacturing, transportation, and construction, as well as the way the load is carried at their connections.

1.3.2. Lateral load resisting systems

This issue is dealt with as "lateral load resisting systems" and "vertical load resisting systems" in Chapters 5 to 7. A lateral load resisting system can be built by both precast concrete members and cast-in-place concrete members. Lateral load resisting systems can also work concurrently as architectural elements, such as enclosures, separating walls, or service cores. Regardless of the kinds of members which organize a structural system, the lateral load resisting system is one fundamental part of the

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[2] Architectural Precast Concrete, Second Edition. Chicago: Precast / Prestressed Concrete Institute. P. 159
[3] The term "articulation" represents the division of a structural system in to parts in the order of manufacturing, transportation, and assembly, keeping the functions of the structural system intact.
[4] PCI Design Handbook. p. 3-5.

structural system, dictating the outline of a building system as well as its floor plan. The coherence between a lateral load resisting system and a floor plan is indispensable for a building system.

No matter what the structural system of a multifamily house is, it must be designed for both vertical and lateral loads. Hence, vertical load resisting systems have to be examined. Compared to the rules and constraints of lateral resisting systems, those of vertical load resisting systems are relatively simple because vertical loads usually work parallel to the corresponding systems, such as columns and/or walls, while lateral loads work at right angles to the corresponding systems like cantilevers. The constraints of maximum height are discussed in the context of the vertical load resisting system and the lateral load resisting system. Suspended structures might be one of the alternatives in terms of vertical load resisting systems. However, such a structure is highly unusual in housing, and is omitted from discussion here.

1.3.3. Connections

This issue is dealt with in the sections "Connections" in Chapters 5 to 7. The rules of connections are discussed in the context of articulations and tolerances, load carrying, and details. Although typical details of connections are shown in each chapter, the details of connections have huge varieties. The PCI, Architectural Precast Concrete notes that:

> "Individual precasters have developed connections over the years which they
> favor, because they suit their particular production and/or erection techniques.
> Connections should comply with local codes. They may also be subject to
> functional requirements such as recessing for flash floors and/or exposed ceilings.
> These conditions lead to a variety of connections, nearly always custom-designed
> for each project and often defying any grouping or classification as 'standard'
> connections."[5]

For this reason, in Chapter 5 to 7, the rules and constraints of connections are considered from the viewpoint of the required structural performances, and then typical details are shown.

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[5] Architectural Precast Concrete, Second Edition, pp. 186

1.3.4. Transfer of Loads

Throughout this thesis, the relationship between structural members and applied loads is treated in terms of the structural issue of how to sustain a house's internal and external loads. For this reason, each of the factors above - - framing dimensions and articulations, lateral and vertical load resisting systems, and connections - - are dealt with in the context of the transfer of loads.

Table 1-2 classifies loads in terms of the levels of transfer of loads, starting from the primary loads and preceding to those that exist at connections. Note that primary loads, which are applied to the whole structural system, are distributed to each structural member, and that those loads which exist at each member dictate the required performances of connections.

Level of load transfer	Structural function	Load types
Level 1 Loads applied to a structural system as a whole	Vertical and lateral load resisting systems	Vertical load (dead load / live load) Lateral load (wind load / seismic load)
Level 2 Loads applied to structural members	Framing dimension and articulation	Compressive load Tensile load Shear load Bending moment Torque
Level 3 Loads applied to connections	Connections	Compressive load Tensile load Shear load Bending moment

(Table 1-2) Classification of the loads

Since the breakdown in the table is aimed at presenting an organic consideration of structural systems, the order of the levels do not necessarily correspond with a sequence in the design process of a structural system. However, each level might correspond to the following design requirements:

(a) Level 1 / Volume and shape of the house.

(b) Level 2 / Framing dimensions that accord with a floor plan.

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The articulation of structural members that facilitate transportation and handling, the sequence of construction, as well as structural rationality.

(c) Level 3 / Connections that enhance the constructability and aesthetics of the house.

1.4. Classification by Structural Rules

Table 1-3 is a matrix showing the locations of the structural rules in Chapters 5 to 7 in terms of structural system types and the level of load carrying. This matrix is used mainly in Chapters 5 to 7 on the rules and constraints of each structural system type. Since the rules and constraints of precasting, transportation, and construction methods are mostly common to all structural system types and the levels of load carrying, they are not considered within a specific structural type unless there is some special consideration unique to that system.

		Structural System Type		
		Unbraced frame structural system	Large panel structural system	Braced frame structural system
Level of Load Transference and Structural Function	**Level 1** Vertical and lateral load resisting systems	5.1	6.1	7.1
	Level 2 Framing dimensions and articulations	5.2	6.2	7.2
	Level 3 Connections	5.3	6.3	7.3

(Table 1-3)   Matrix of the structural rules
Each number corresponds to the chapter number in this thesis.

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Chapter 2
Precasting Rules and Constraints

2.1. Introduction

The PCI Design Handbook describes precast concrete as "both a construction method and a construction material."[1] As a material, the advantages of precast concrete can be attributed mostly to its manufacturing process. With regard to the quality of the pieces, the PCI Architectural Precast Concrete notes that "Since working conditions and inspection in a plant are superior to field conditions and less dependent on climatic factors, operations demanding high quality standards are most efficiently and economically performed in the plant."[2] Phillips and Sheppard note that "By placing the forms on a vibrating table or with the use of external vibrators placed on the forms, a higher degree of consolidation is obtained which, along with lower water cement ratio and higher cement contents results in higher strength and truer surfaces and corners."[3] However, the advantages of precast concrete as a material cannot be ascertained without understanding the rules and constraints of the manufacturing process. In this chapter, these rules and constraints of factory precasting are discussed in terms of: (1) cost and quantity, (2) shape and size, and (3) on-site precasting.

2.2. Cost and Quantity

Because of the initial cost for preparing molds, the cost and quantity of precast concrete pieces relate to each other closely. Barch, M. G. in Precast Exposed Concrete Finishes, notes that "Obviously, the cost of a mould will affect the cost of the product formed therein. Re-use factor must be considered as well as first cost. First cost of a steel mould, for instance, is high, but if a large number of uses is required, its high re-use potential will compensate for this."[4] As a nature of the manufacturing process, the cost of each piece goes down as the number of repetitive uses of a mold increases. Also, repetitive production leads to the empirical rationalization the whole manufacturing

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[1]PCI Design Handbook. p. 2.

[2]Architectural Precast Concrete. Second Edition. p. 198.

[3]Phillips, W, R. , & Sheppard, D. A. Plant Cast Precast concrete and Prestressed concrete: a Design Guide. Illinois: PCI. 1980. pp. 2.

[4]Barch, M. B. Precast Exposed Concrete Finishes: The Architects' Journal Information Library, 26 March 1969. pp. 814.

process to some degree in terms of a productivity of labor, such as re-bar work or handling. For these reasons, the large scale of a project and a good amount of demand in a market are advantageous for reducing the cost of precasting. Even if construction projects are fragmented, standardized pieces may obtain the same effect by spreading in a market. However, the cost of a piece itself does not directly affect the total construction cost of a project. This is because regardless of whether the making of a piece is expensive, the piece could still reduce the total construction cost if it eliminates a great amount of on-site work. For example, a highly prefabricated precast concrete piece in which many components of a house, such as piping, windows, or finishing, are already fixed may eventually reduce the total construction cost.

It follows from what has been said that there are different approaches to making a good use of precast concrete in terms of the economy of precasting:

    (a) Simple members: make a piece for versatile use, such as hollow-core slabs or Tee slabs

    (b) Articulated members: make a piece by dividing a structural system by a certain systematic method so that both repetitive precasting and constructability are enhanced, and

    (c) Integrated members: make a piece by integrated articulation, including structural and non-structural elements.

In general, the greater the amount of on-site work shifted to a factory work, the greater the reduction in labor costs. This improves the working conditions of construction, but requires more initial costs for facilities and management. It can also be said that an integrated member tends to deprive a piece of its versatile use in an existing housing market, and as a result, the cost reduction of repetitive manufacturing cannot be expected. To overcome this trade-off relationship and make the most of the advantages of precast concrete in terms of both materials and method, the standardization of pieces represents a good solution. The standardization of the articulated members and the integrated members might correspond to the systems approach which is called "kit of parts" and "factory made module", respectively in terms of precasting. A great variety in these kinds of approaches can be seen in prototypical projects (Figures 2-1, 2-2)
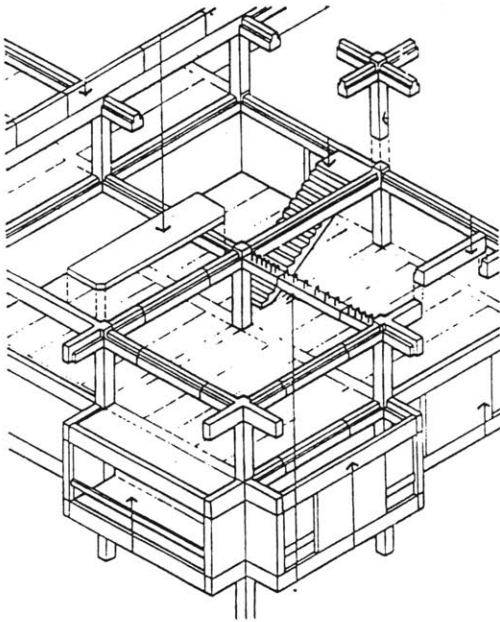
(Figures 2-1)   Source; <u>répertoire des systémes de construction industrialisés en habitation.</u>
An example of "Kit of parts" (Componoform project).
A structural system is divided into standardized precast concrete pieces.
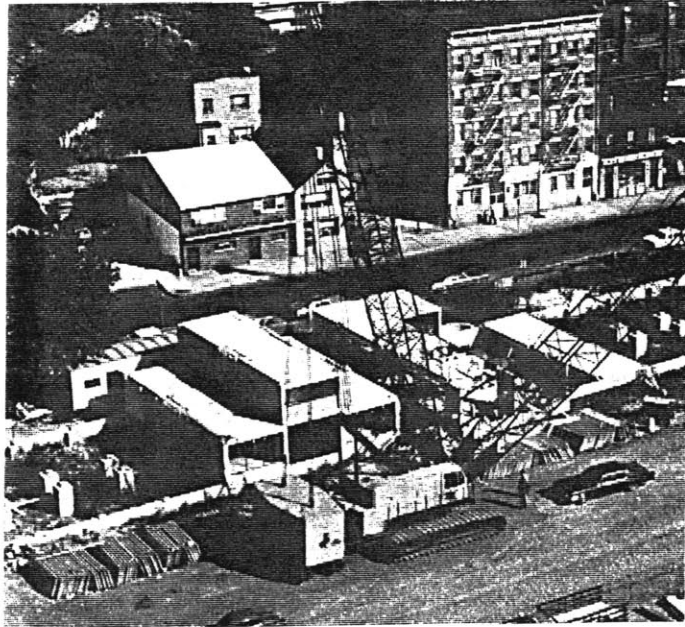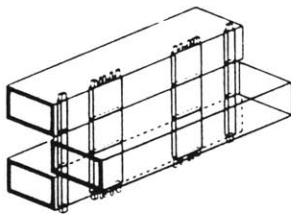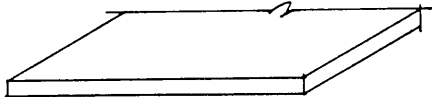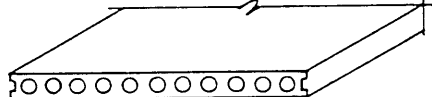

(Figures 2-2)   Source; <u>Feed back: Operation Breakthrough.</u>
An example of "factory made module" (Shelley System).
"The precast box module is totally prefinished within the finishing production area before it leaves for the site." This system is 10% to 20 % less costly than conventional construction. Delivery rate is 1,000 - 2,000 dwelling units / years for each factory. Transportation limitation is approximately 200 miles from production plant.

2.2.1. Simple members

Simple members for versatile uses, such as single tees, double tees, flat slabs, and planks, are standardized and available from the stock of precasters. These pieces are used not only for slabs, but also for walls. They are standardized in terms of their sizes, which is one foot along the length and some variation in width depending on precasters. Because most of these are prestressed during the manufacturing process, they attain high flexural load capacity by being thinner and lighter. Flat slabs and planks are sometimes used for multi-story houses, while tees are not commonly used because of their depth (12 to 48 inches) and because their span (12 to 112 feet) is often too long for houses.

The standard precast concrete pieces have the advantages of availability and low cost. The PCI Design Hand Book notes that "Whenever possible the designer should attempt to use the standard shapes and sizes available in the region of the jobsite. This will reduce the product cost due to the savings in mold costs."[5] Some attention to the design of the floor plan is required in terms of modules to adopt standard slabs since cutting each piece to fit in is costly. According to the PCI Design hand book, flat slabs and hollow core planks have the following approximate size ranges:[6]

|	Approximate Size Ranges		
	Width	Depth	Span
CHANNEL SLAB			
FLAT SLAB	8' – 12'	3" – 6"	14' – 22' (35' with shoring)
HOLLOW CORE PLANK	40" – 8'	6" – 12"	16' – 42'

2.2.2. Articulated members

Because the sizes of a bay, the story-height, and the dimension of a structural piece differ for each house, most structural members of a precast concrete housing system have to be customized rather than use standardized pieces. The customized pieces require both the cost for formwork and the time for preparations. Although the preparation of

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[5]PCI Design Handbook. p. 5.

[6]PCI Design Handbook. p. 5.

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precast concrete pieces can usually be started well ahead of the time of assembly because of the duration of other kinds of work, such as a site preparation and foundation works, a detailed consideration of the application of precast concrete at the early stage is indispensable to make the most of the cost efficiency of repetitive production.

Phillips, W, R. , & Sheppard, D. A., in Plant Cast Precast concrete and Prestressed concrete: a Design Guide, note that, "Due to steam or controlled curing methods, precast concrete can be cast in the afternoon, cured at elevated ambient temperatures seven to ten hours during the night, the units removed from the forms the next morning and the form readied for reuse the same day."[7] Since a mold can produce no more than one piece a day by usual operations, more molds are required when the preparation time is not long enough. Molds are usually made with steel shuttering on steel platforms for repetitive use (Figure 2-3). With regard to the material of the molds, Phillips and Sheppard point out that ". . . finished wood and fiberglass forms may be used up to 50 times with minor rework; concrete and metal forms have practically unlimited service lives." For these reasons, the cost of molds depends on the number of pieces produced by a mold and the length of preparation time. A wood and fiberglass mold and concrete mold are shown in Figures 2-4 and 2-5.
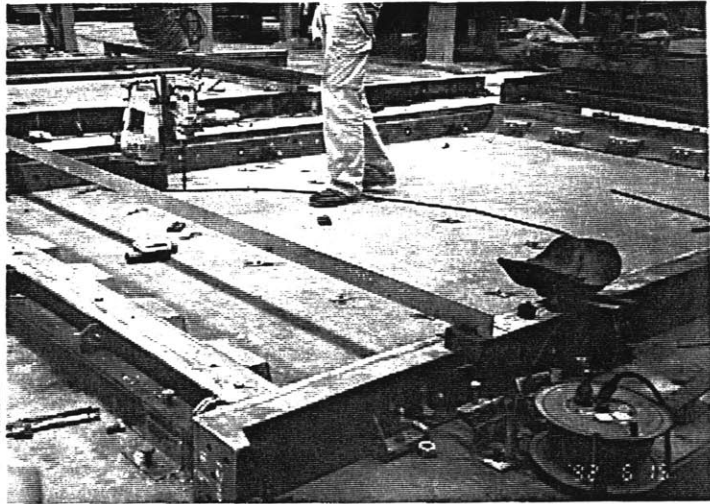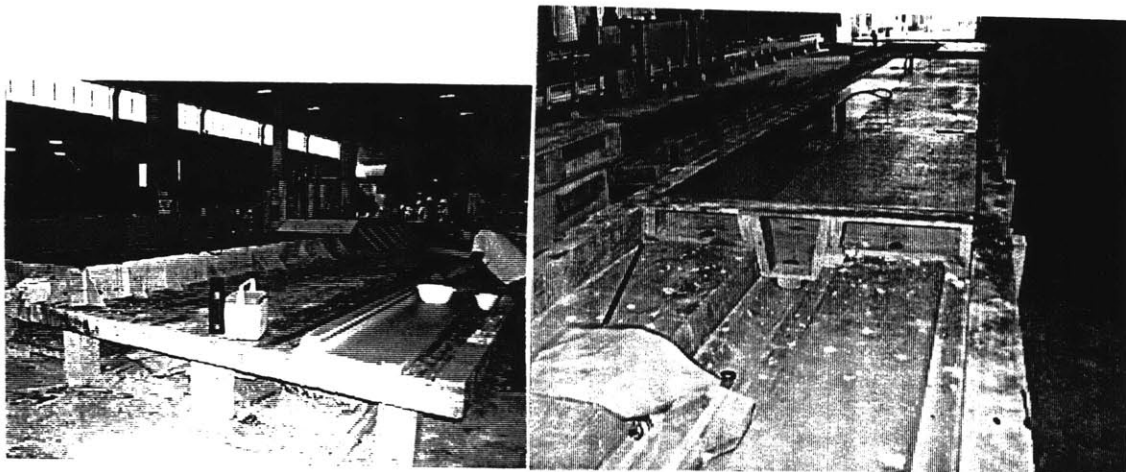

(Figure 2-3)   Source; personal file
Making of a steel mold on a steel platform.
Shutterings are fixed to platform by bolting. A worker is drilling holes for Shutterings of an opening of a wall.

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[7]Phillips, W, R. , & Sheppard, D. A. p. 3.
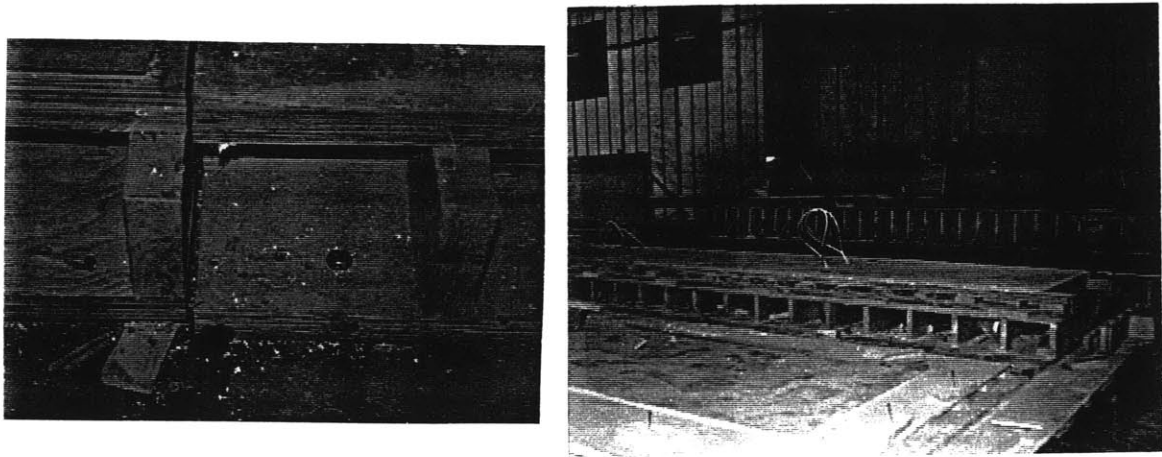
(Figure 2-4)   Source; personal file
A wood and fiberglass mold

(Figure 2-5)   Source; personal file
A concrete mold.
left: Making of a plaster model of precast concrete spandrel to make their concrete mold.
right: A concrete mold for ornamental pieces.

Phillips and Sheppard point out that "a project should be of a certain minimum size in order to spread out certain fixed costs such as plant set-up, mold costs and erection mobilization costs over a sufficient broad base to make the use of precast concrete economically viable. Minimum project sizes are those that would generate 10,000 square

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feet of architectural precast concrete panels, 15,000 square feet of prestressed concrete deck members, or 1000 lineal feet of standard prestressed or precast concrete components, such as girders, columns or piling."[8]   With regard to multifamily houses, such a minimum project size is approximately equivalent to 15 units of 1,000 square feet of floor area each.

2.2.3. Integrated members

The economy of precasting can be enhanced not only by repetitive production but also by adding other work processes within the precasting process.   For example, elements of service infrastructure, such as conduits, piping, or ducts, can be embedded in a piece during the precasting process (Figure 2-6).   Window installations and external finishes done with precasting can reduce the cost of on-site jobs as well as the cost of scaffoldings around a house under construction provided that the accuracy of dimensional coordination can be assured in casting(Figure 2-7).   For this reason, the economics of precasting cannot be determined solely by the unit price of the pieces.   In some cases of precast concrete curtain walls for high-rise buildings, panes are also installed during the precasting process.   However, considering the sequence of construction, this method is not practical for load-bearing panels because glass is vulnerable to fresh concrete and the fire of welding work, as well as to transportation and handling.
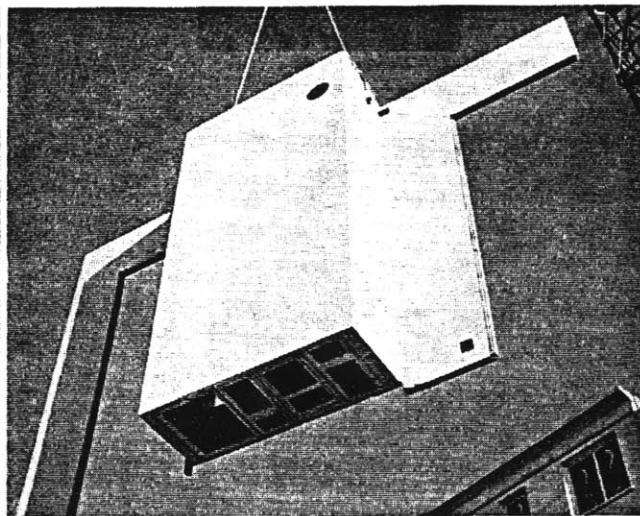
(Figure 2-6)   Source; Diamant, R, M, E. Industrialized Building 3.
Precast partition wall with ventilation ducts

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[8]Phillips, W, R. , & Sheppard, D. A. p. 3.
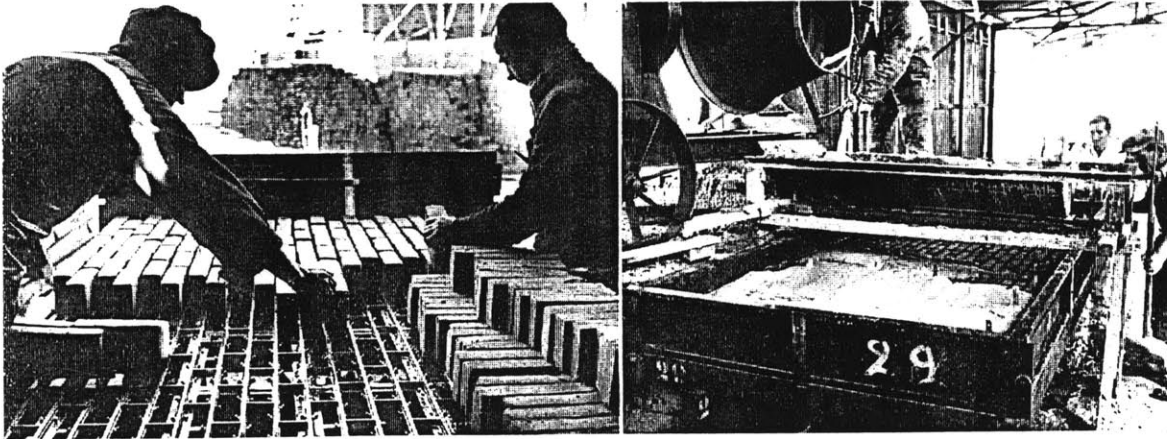
(Figure 2-7)   Source; Diamant, R, M, E. Industrialized Building 1.
Placing bricks on a metal grid to make a external wall

Box units can be manufactured in a precaster and installed with fittings and finishes already inside. However, such a highly prefabricated piece calls for a large scale project or a sufficient market to make the plant set-up and management costs pay off. For example, in the case of the Shelley system (Figures 2-2), the delivery rate of a factory is 1,000 - 2,000 (dwelling units / years), while economical transportation is confined to 200 miles from a factory.[9]

2.3. Shape and size

While some rules and constraints govern the shape to be precast, size is not a constraint of precasting because the maximum size of a piece is dictated by the constraints of transportation. Generally, planer shapes are easy to precast and three dimensional shapes are difficult and costly.

2.3.1. Panel

Panels are cast by either horizontal casting (Figure 2-8) or vertical casting (Figure 2-9). Barch notes that "The advantages of horizontal casting include the wide range of possible finishes, ease of positioning reinforcement, insulating and similar elements, and also generally greater control over finishing treatments."[10] On the other hand, in terms of

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[9]U.S. Department of Housing and Urban Development. Feed back: Operation Breakthrough. 1973.

[10]Barch, M. B. p. 803.

vertical casting, he writes "Vertical casting has major advantages for internal wall units which require a smooth surface on both sides. The two largest faces are formed against the mould so that trowelling and other hand-smoothing operations are required only along the narrow top edge of unit."[11]
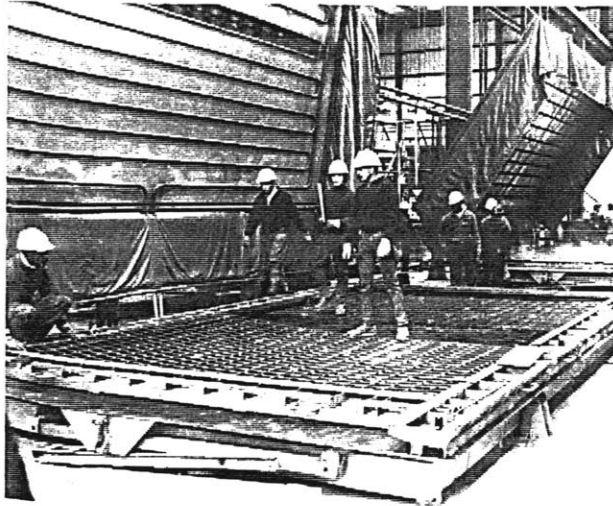
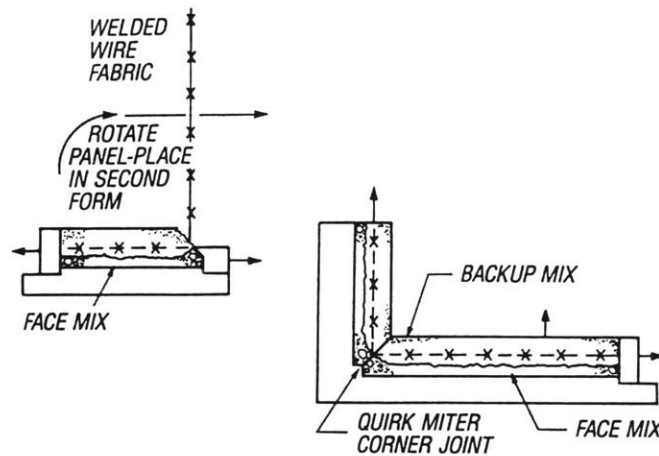(Figure 2-8)   Source; Diamant, R, M, E. Industrialized Building 1.
Horizontal casting
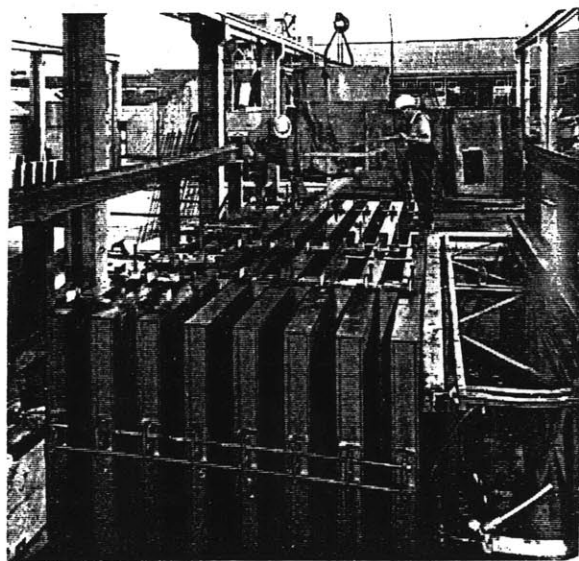
(Figure 2-9)   Source The Architects' Journal Information Library, 26 March 1969. p.804
Vertical casting by battery molds

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[11]Barch, M. B. p. 804.

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Horizontal casting can produce more elaborate panel-finishes by placing many other materials before pouring fresh concrete in a mold. For example, stones, color concrete, bricks, and tiles can be included as facade materials. Compared to vertical casting, where a drift of fresh concrete inside molds has some impact on installed material, in horizontal casting facilitates, conduits or recesses for fittings, as well as steel devices for connections, such as anchor plates or sleeves, can be installed with precision. Panels with large returns, such as external walls at corners or slabs with balcony-ends, are made by either two-stage precasting (Figure 2-10) or vertical casting (Figure 2-11).

(Figure 2-10)   Source; Architectural Precast Concrete, Second Edition.
Two-stage precasting gives wide choice of surface finishes which is not possible at vertical casting.
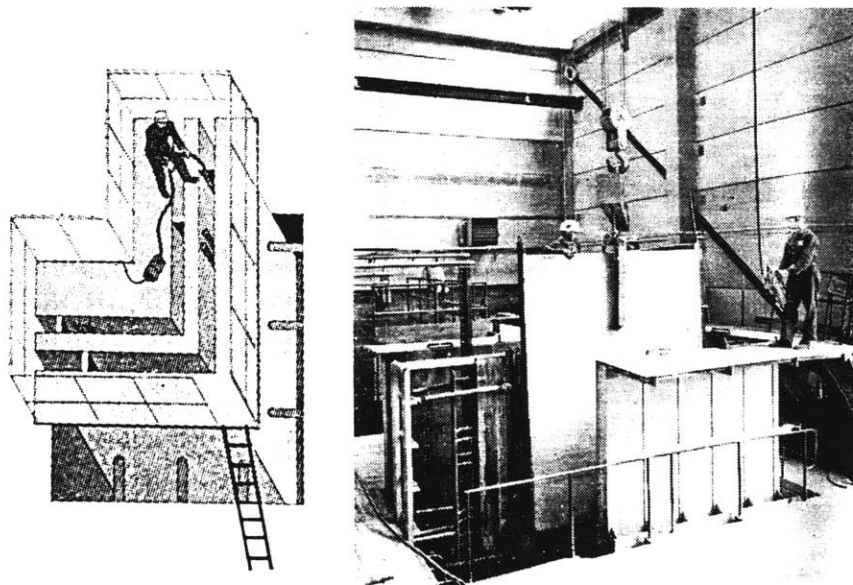
(Figure 2-11)   Source; Diamant, R, M, E. Industrialized Building 3.
Vertical casting of panels with large return. An L-shaped casting battery makes two units at the same time.

2.3.2. Columns and beams

If a piece has a linear or plane shape, either columns or beams can be cast as easily as panels by placing shutterings on a platform. On the other hand, three-dimensional connections or projections make the precasting process more difficult. Edward Allen, in Fundamentals of Building Construction, explains this fact as follows:

"If corbels are required on three sides, box frames are set atop the upper side of the column as it lies in the bed. For corbels on the fourth side, steel plate inserts are cast into the bottom of the column in the bed, to which reinforcing bars are welded after the column is removed from the bed. The corbels on the fourth side are then cast around the reinforcing bars in a separate operation."[12]

With regard to a three dimensional piece of a moment-resisting frame, the condition is even more difficult than what Allen describes, since, for structural reasons, a welded connection is not allowed. For this reason, this kind of piece must be made by two-stage precasting or by preparing a special mold to cast the piece at once.

2.3.3. Box

Precasting of a monolithic box unit has been developed in the (former) Soviet Union, European countries and the U.S., with the aim of achieving a higher level of industrialization of housing construction. With regard to the precasting, there are many kind of techniques, but generally they have a high initial cost for molds and limited versatility of productions. The International Symposium on Box-unit Construction, III-1[13] shows two kinds of precasting techniques commonly used in the (former) Soviet Union, which are "the cassette technique" (Figure 2-12) and "the movable-core technique" (Figure 2-13). The movable-core technique is different in that its inner mold moves vertically during the casting process so that a higher degree of consolidation of concrete can be attained.

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[12]Allen, Edward. Fundamentals of Building Construction. N.Y.: John Wiley & Sons. 1985. pp. 530.
[13]The International Symposium on Box-unit Construction: III-1. Hungarian Institute for Building Science. May 23-25, 1973. p. 10-1
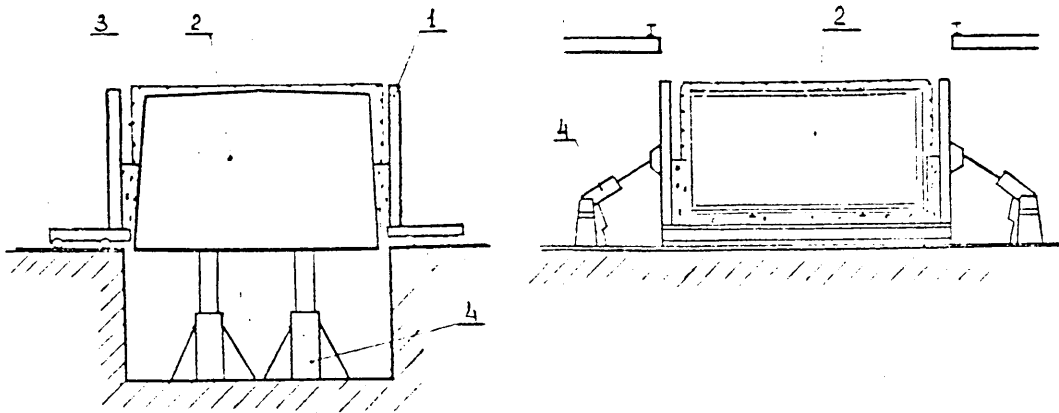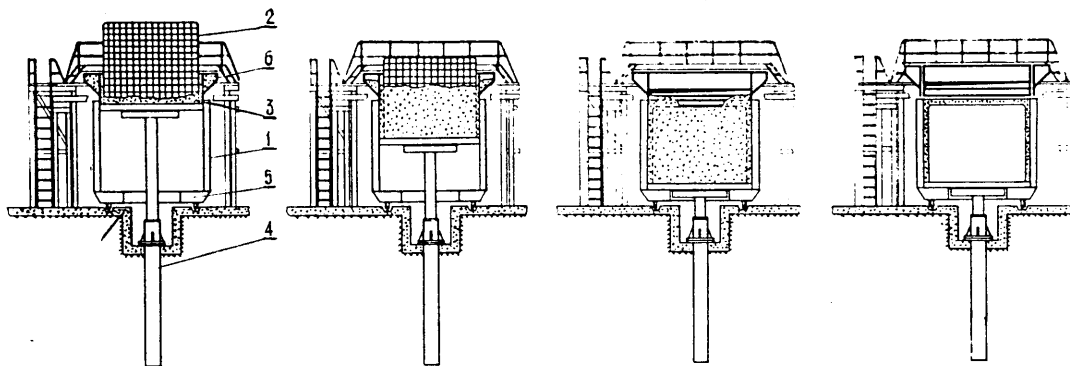
1- the external board, 2 - the core, 3 - concrete,
4 - the hydro-cylinder,

(Figure 2-12)   Source; The International Symposium on Box-unit Construction, III-1
The cassette techniques

1 - the external board, 2 - the core, 3 - concrete,
4 - the hydro-cylinder, 5 - a cart, 6 - vibro-hoppers

(Figure 2-13)   Source; The International Symposium on Box-unit Construction, III-1
The movable-core technique

In the U.S. presently, monolithic box units are produced mainly for infrastructure work, such as storage tanks and telecommunication systems vaults, where the mold consists of an inner mold which is folded inward as well as an outer mold which is unfold outward (Figure 2-14). With regard to the precasting for housing systems (Figure 2-15), the high initial cost for molds and the lack of versatility for various shapes as well as the dimensional constraints of transportation (Chapter 3) create economical constraints. However, a sufficient market or a large project may make this method feasible. For

example, Technoform, a single family house project constructed from box precast concrete on which International Form Corporation, Florida, has recently embarked, calls for sales of at least 150 units to make the investment for their steel frame pay off.[14]
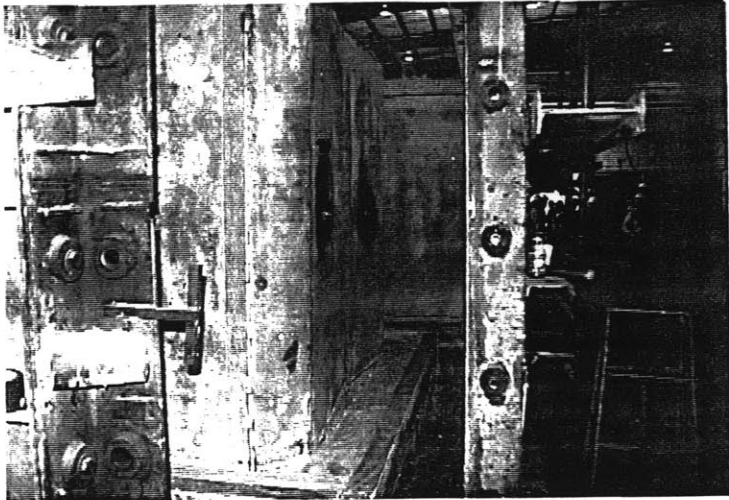
(Figure 2-14)   Source; personal file
A telecommunication systems vault
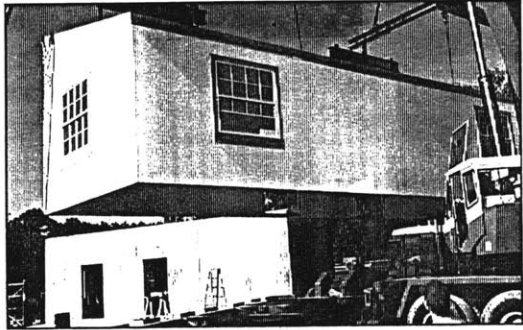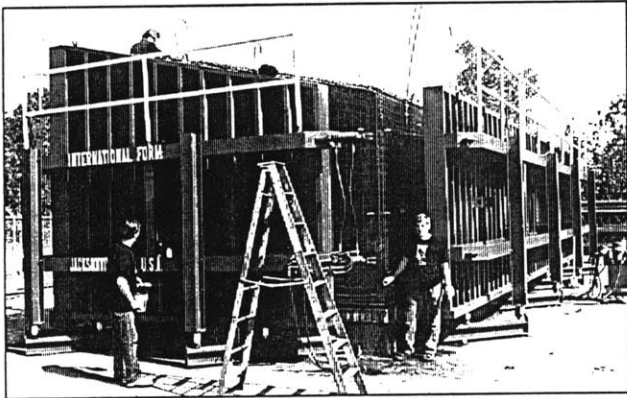
(Figure 2-15)   Source; Catalogue. Homes of many Forms. International form corporation
Technoform Project. Tow pieces of box units make an individual detached house.

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[14]Personal interview, Vice president John S. Diperna, September 12, 1993.
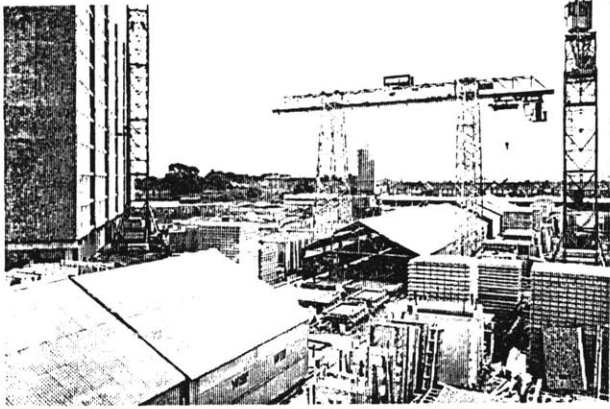
2.4. On-site precasting

On-site precasting is a realistic alternative when a housing project needs large numbers of precast concrete pieces or when a construction site is a great distance from the nearest precaster. Although this method seemingly violates the concept of precast concrete, it has the following advantages:

(1) The dimensional constraints of transportation can be avoided. For example, precast concrete slabs could be made the size of full span in both directions, while they are usually divided into several pieces. In this case, the labor and time for assembly can be curtailed and the reinforcement between slabs eliminated.

(2) In the cases that there are no precasters within a close area, transportation cost can be reduced by on-site precasting. Production machinery is moved to an other job after completion.

(3) The output of the pieces can be flexible for a change of time schedule or details. In other words, management and inspection of precasting can be facilitated.

On-site precasting requires the cost to set up a temporary factory and a large space inside or adjacent to the construction site. The facility of precasting could be simplified compared to that in a factory, due to its limited kinds of production. Although molds and handling facilities are indispensable, the size of the whole facility depends on the climate. When a site is located in a tropical area, there is no need for fully enclosed working space. Thus, a production plant can be moved rather than stay in a fixed location. Diamant, in the Industrialized Building 3, explains in the section of the 'Wates' project (Figure 2-7 to 2-8), which is an on-site precasting system, that the minimum scale of housing projects for adopting the on-site precasting is as follows: "It is considered that this technique is viable economically for the building of 250 dwellings in high-rise blocks and 300 dwellings in low-rise developments."[15]

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[15]Diamant, R, M, E. Industrialized Building 3. Great Britain: Iliffe Books Ltd. 1968. pp. 25.

(Figure 2-16) (Figure 2-17)   Source; Diamant, R, M, E. <u>Industrialized Building 3.</u>
Left; An on-site precasting factory. Right; A tower block built using the Wates system
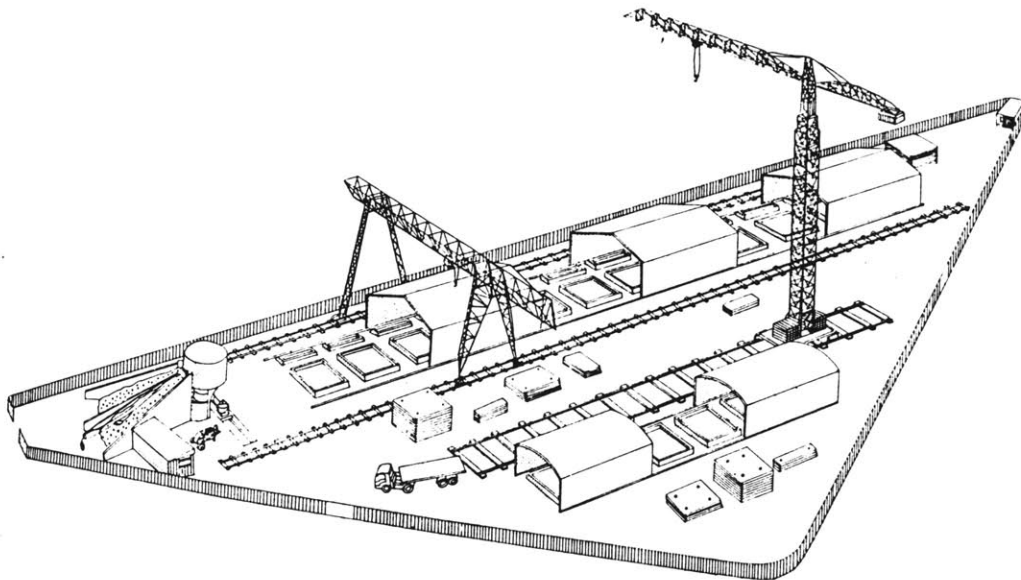
(Figure 2-18)   Source; Diamant, R, M, E. <u>Industrialized Building 3.</u>
The layout of a factory

Chapter 3
Transportation Rules and Constraints

3.1. Introduction

The purpose of this section is to consider the transportation of precast concrete pieces in terms of rules and constraints. The rules of transportation can be divided into three areas: (1) size and weight of the pieces, (2) transportation costs, (3) shape of pieces, and (4) Type of transportation.

3.2. Size and weight of pieces

The physical limits on the size and weight of precast concrete pieces during transportation is a critical constraint that affects building systems ; because far larger and heavier pieces could be manufactured and handled except for the transportation process. Although there are several means of transportation, road, rail, water, and even helicopter, the discussion is limited to truck transportation because, in most cases, both rail and water transportation must be accompanied by truck transportation, and its rules are the most restrictive.

The maximum size and weight of precast concrete pieces that can be transported depend on local regulations which differ from state to state. According to Phillips and Sheppard, the limits in California for which no permits are required are:[1]

Width -   12 feet
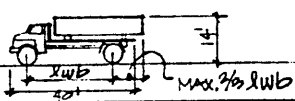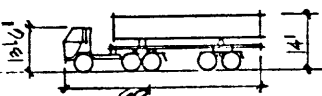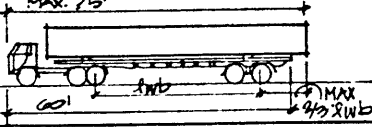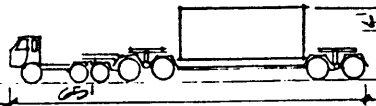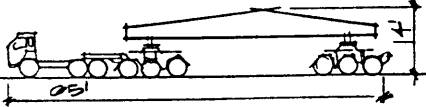
Load height - 14 feet measured from the surface on which the vehicle stands.

Load length - The load upon any combination of vehicles shall not exceed 75 feet measured from the front extremity of the vehicle or load to the rear extremity of the last vehicle or load.

Weight -   Maximum gross weight ranges from 34,000 pounds to 80,000 pounds according to the distance between the axles of a vehicle; the load on any one axle shall not exceed 20, 000 pounds.

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[1]Phillips, W, R. , & Sheppard, D. A. p. 37-44

Some relaxation of these limits can be obtained by acquiring special permits. But it must be noted that one cannot always make the most of these limits when the construction site is located along a secondary road. In specific areas, then, local conditions, such as electrical wires, bridges, or tunnels, dictate the rules for each case. Also, the level of traffic congestion affects the time and cost requirements of transportation. Typical types of vehicles are shown in Figure 3-1.

TRANSPORT VEHICLE		COMPONENT			VEHICLE			MAX PPC WT. TONS ≠	SPECIAL PROVISIONS
		ℓ	w	h	ℓ	w	h		
(truck diagram)	TRUCK	*	8'-4"	14'	40'	8'	13'6	23/25	NONE
	OVER WIDTH OR LENGHT								PERMISSION
(semi diagram)	SEMI NO OVERHANG	*	8'-4"	14'	60'	8'	13'6	40	
	OVERWIDTH								PERMISSION
(semi w/ overhang diagram)	SEMI W/ OVERHANG	*	8'-4"	14'	60'	8'	13'6	40	
	OVERWIDTH								PERMISSION
(low loader diagram)	LOW LOADER	*	8'-4"	14'	65'	8'	13'6	40	
	OVERWIDTH								PERMISSION
(with drawbar diagram)	WITH DRAWBAR	*	8'-4"	14'	65'	8'	13'6	40	
	SPECIAL TRANSPORTS			14'		13'6			PERMISSION NEEDED

* LENGHT VARIES SUBJECT TO THE VEHICLE AND ITS WHEELBASE
≠ VERIFY WEIGHT W/ TABLE AND DEPT. OF MOTOR VEHICLES.

(Figure 3-1) Source: Plant Cast Precast concrete and Prestressed concrete: a Design Guide
Maximum loads of typical types of vehicles

The constraints of transportation not only restrict the maximum size and weight of pieces, but also affect the economical size and weight of pieces. The PCI Design Handbook points out this issue, following the statement about the limit of size and weight of loads, that "These restrictions add to the cost of precast units, and should be compared with savings realized by combining smaller units into one large unit. When possible, a precast unit, or several units combined, should approximate the usual payload

of 20 tons. For example, an 11 ton unit may not be economical, because only one can be shipped per load, while two 10 ton units could be shipped on one load."[2]

Although a house may consist many different shapes and sizes of pieces, the idea of combining different types of pieces up to the maximum load is not always practical because pieces that arrive out of the sequence raise handling costs and cause storage problems. It can also be presumed that bulky shapes, such as three dimensional connections of columns and beams or walls with angles, might fail to take advantage of the weight limit because of the lower density of loads. This issue will be dealt with in the discussion of shapes (section 3.3).

Because pieces are subjected to dynamic forces during transportation, the stress on them is sometimes more significant during transportation than after erection. For this reason, pieces with large projections or openings have to be strengthened temporarily by ties or braces during transportation (Figure 3-2).
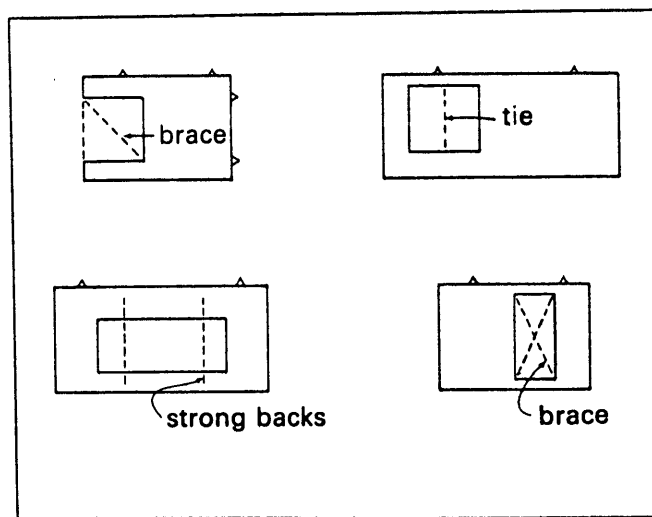
(Figure 3-2)   Source: PCI Design Handbook
Methods of temporary strengthening of panels with significant openings.

The constraints on size and weight are critical issues in the design of housing systems because the larger pieces are preferable in terms of the structural and methodological rationality of building systems. Generally, from the view point of the on-site construction process, the less fragmented the pieces, the less labor and time; thus

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[2]PCI Design Handbook, p. 5-17

costs may be reduced on site. Also, the reduced numbers of connections caused by the lower fragmentation could enhance the rigidity of the whole structure.

The limits of size affect the design of precast concrete box unit systems in a different way since the restricted maximum width of boxes is critical for the planning of housing. Although box unit systems are one of the most industrialized housing systems in a factory-made process provided that they are installed with infills, such as partitions, kitchens, bathrooms, the limited volume of each box it somewhat awkward. To get rid of this constraint, setting an on-site plant of precast concrete instead of transporting the precast concrete box from remote plants could be one of the alternatives. For example, the project of 'HABITAT 67' in Montreal, in which each box was 38 feet long, 10 feet high, and 17 feet 6 inches wide, was carried out by making precast concrete boxes on the construction site.[3]

3.3. Transportation costs

No matter how a piece of precast concrete is transported, it can incur substantial transportation costs which may reduce the feasibility of a building system. Also, the market might be limited if the transportation cost soars in remote areas. To examine this issue, the ratio of transportation cost to total construction cost was estimated, taking an example of a 4 to 7 story multifamily house with a cast-in-place column and beam structure, where only the floor slabs and roof slabs are built by precast planks. All the unit prices and construction costs are taken from the Means building construction cost data 1994 [4] and the Means square foot costs 1994.[5] The costs are calculated on a cost pre-square foot basis.

The Means building construction cost data 1994 mentions the transportation costs of precast concrete slabs in its appendix: "Hauling costs run from $.45 per S.F. for short hauls to $.85 for 50 mile hauls."[6] According to the Means square foot costs 1994, the total construction costs per square foot for a 4 to 7 story apartment with moderate

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[3]The Architectural Forum. July-August 1972. p.93.
[4]Means Open Shop Building Construction Cost Data 1994. Massachusetts: R.S. Means Company, Inc.. 1993.
[5]Means square foot costs 1994. Massachusetts: R.S. Means Company, Inc.. 1993.
[6]Means Open Shop Building Construction Cost Data 1994. pp. 446.

finishing runs between $75 to $85. Assuming the total area of planks is almost the same as the total area of the building (assuming the additional amount of planks for the roof slab is equivalent to the total amount of openings on the floor slabs, such as staircases and piping spaces), the transportation costs for the planks over a short distance of 50 miles are around 0.5% and 1% of the total construction cost.

The example above does not show the ratio of transportation cost for further distances. In another example, Director Antony Herrey and Assistant Professor William A. Litle, Massachusetts Institute of Technology, showed the relationship between the distance and cost of transportation based on the building system that they developed.[7] They concluded that "For a distance of 100 miles we determined that the cost to transport the box for a lightweight modular box system apartment building is about 1% of the total development cost. This cost increases only to about 4% for a distance of 500 miles. These results led us to conclude that the siting of a factory should be based more upon insuring good access to suppliers and to labor than upon the cost of transporting the finished boxes."[8]

In a real project, a difference of 1% or even less in construction cost is critical. In bidding, an error of this amount could be fatal. However, it must be noted that this 1% of transportation cost does not mean the 1% higher total construction cost because we can expect some cost reductions from other aspects, such as the elimination of formworks and re-bar works. Turning again to the estimation of a 4 to 7 story apartment, the cost per square foot of precast planks, including job overhead, and that of cast-in-place concrete slabs are $6.43 and $7.69 respectively according to the Means square foot costs 1994.[9]

To make the most of precast concrete technology, two different points of view must be understood with regard to transportation cost. One is the cost in relation to technology alternatives, such as cast-in-place concrete slabs and precast concrete slabs, which take place after the blueprint has already been determined. In this case, the main issue is a simple cost comparison between the application of two materials or methods. The other point of view, which is more important for designing building systems, is the cost in relation to technology alternatives and their impacts. An example is the

[7] Herrey, A, and Litle, W. A. Industrialized Housing Feasibility Study. M.A.: Massachusetts Institute of Technology. October 1972.

[8] Herrey, A, and Litle, W. A. p. 7.

[9] Means square foot costs 1994.

transportation costs versus the reduction of job overhead caused by the shorter work duration or reduced labor costs.

There is another point of view to consider in the transportation cost, which could be called the "potential transportation cost," in terms of energy efficiency. Not only precast concrete but also conventional cast-in-place concrete requires a certain amount of transportation costs for re-bars, formworks, and fresh concrete. As a matter of fact, cast-in-place concrete calls for truck mixers moving between a construction site and fresh concrete plants while the fresh concrete used in precast concrete plants is readied in the same plant. Also, cast in place concrete requires a much greater amount of formwork and support devices, all of which have to be transported. For this reason, the total amount of transportation cost, regardless of whether or not it is itemized in the list of estimations, could be higher with cast-in-place concrete. Therefore, in most cases, it would be safe to say that we can not know which is the more energy effective method in terms of transportation unless we examine the whole process, from the procurement of raw materials to the final delivery to construction sites.

3.4. Shape

The shapes of precast concrete pieces relate to both size and weight as well as the cost of transportation. As mentioned before, bulky shapes may fail to make the most of the limits of size and/or weight, and raise the transportation costs. This inefficiency may happen with three dimensional shapes, such as "tree" columns, walls with angles, and box-shaped pieces. Two studies of the relationship between the shape and the efficiency of transportation are given for tree column and box units.

3.4.1. Tree columns

Although a precast "tree" column has some advantages, such as structural rigidity at the column-to-beam connections, and a reduction of the number of joints, it is typically a bulky shape. The following is a trial calculation on an ideal column and beam piece which consists of an uninterrupted 4 story column and beams at four directions (Figure 3-1). The length of each part is derived from the maximum size that can be transported. The density of precast concrete is 150 lb./ft^3.
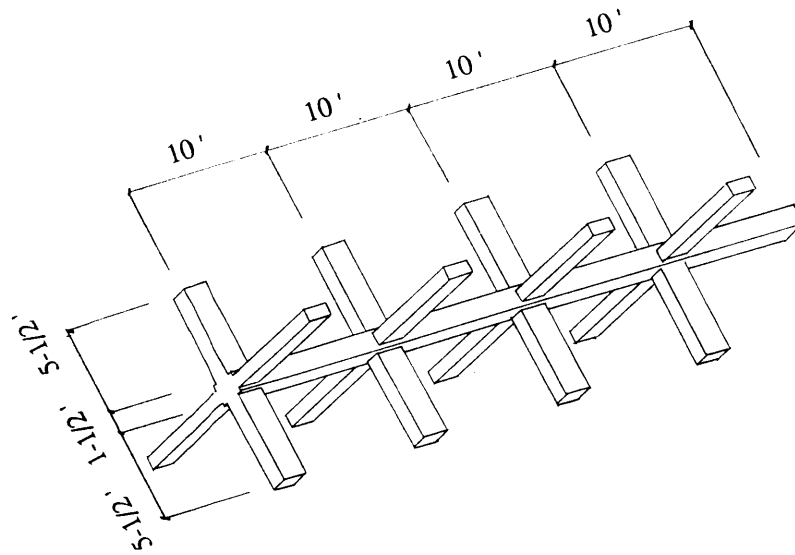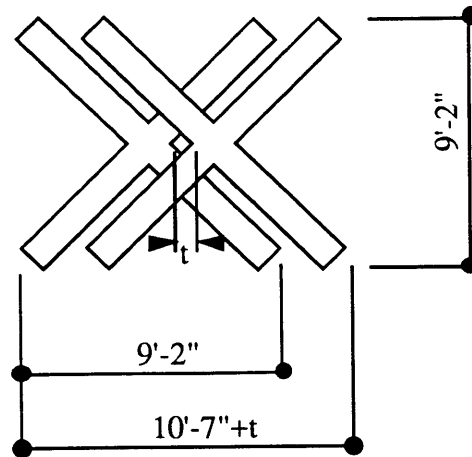
(Figure 3-1)
Tree columns

Column

      Length: 40 (ft.)

      Cross section: 1.5 (ft.) by 1.5 (ft.)

Beam

      Length: 5.5 (ft.)

      Depth / width: 1.5 (ft.) / 1.0 (ft.)   .

Total volume: 222.0 (ft^3)

Total weight: 33,300 (lb.)

The total weight of this piece is much lighter than the maximum weight of 70,000 lb. (presuming that 10,000 lb. out of the maximum gross weight of 80,000 lb. is the weight for an empty vehicle). However, this result does not necessarily show the inefficiency of the transportation since the space underneath the tree column could be stuffed with other small pieces, or another tree column could be loaded upon or beside the first, making the total weight 66,600 (lb.) in this case (Figure 3-2).

(Figure 3-2)
Two tree columns side by side

3.4.2. Box

The following is a trial calculation on an ideal precast concrete box unit which is the maximum size that can be transported. The box has 3 inch walls and 4 inch slabs - - the same thickness as for 'Habitat Puerto Rico'.[10] Both ends are open (Figure 3-3).
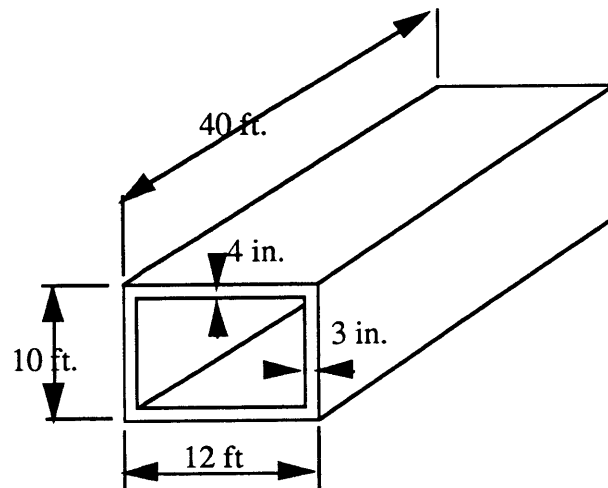
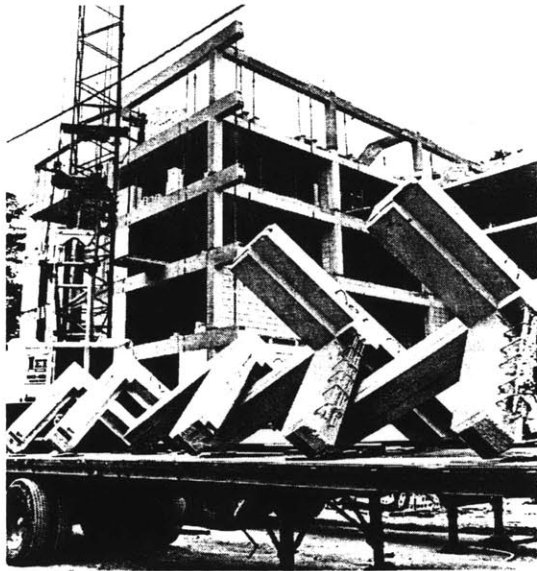(Figure 3-3)
Precast concrete box unit

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[10] 'Habitat Puerto Rico'. Project, Moshe Safdie. 1969.

|	walls	Slabs
Length:	40 (ft.)	40 (ft.)
Width:	10 (ft.)	12 (ft.)
Thickness:	0.25 (ft.) *2	0.33 (ft.) *2
volume:	200 (cft.)	320 (cft.)
weight:	30,000 (lb.)	48,000 (lb.)
Total weight:		78,000 (lb.)

The total weight of this piece is a little heavier than the maximum weight of 70,000 (lb.), however, a box 5 feet shorter in length weighs 68,250 (lb.). It follows from what has been shown that the bulky shape of the box unit does not necessarily result in inefficiency of the transportation.

Although these are somewhat idealized examples, even those with seemingly bulky pieces are not critically inefficient in terms of transportation. The comparison between the maximum volume and weight of the load that can be transported is another consideration of the efficiency of transportation. Presuming that the maximum dimension of the load is 12 ft. in width, 10 ft. in height, and 50 ft. in length, the enclosed volume is 6000 ft^3. On the other hand, given a load limit of 70,000 lb. and a concrete density of 150 lb./ft^3, the maximum solid concrete volume is 467 ft^3. This implies that in any case, we can use only 8% of the maximum allowable volume during transportation.[11] For this reason, it can be said that bulky shapes need not result in inefficient transportation. The dimensional constraints of the loads are more likely critical than the weight constraints (Figures 3-4), (Figure 3-5).

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[11]Morse-Fortier, Len. Professor, Massachusetts Institute of Technology, Building Technology Group.

(Figure 3-4)   Source; the <u>Architectural Plus</u>. July - August. 1974.
Componoform project in Cambridge, Massachusetts
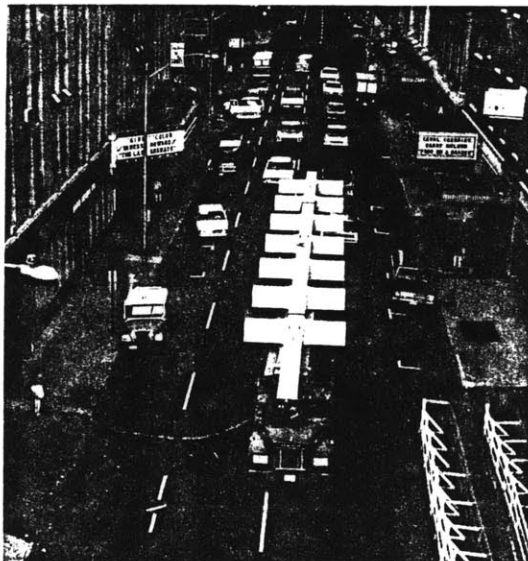
(Figure 3-5)   Source; <u>Fundamentals of Building Construction.</u>
Transportation for a parking garage in New Haven

Chapter 4

The Rules and Constraints of Construction Methods

4.1. Introduction

In this Chapter, the impacts of different construction methods on the design of precast concrete structural systems are discussed. Although the construction process involves many complex issues, the main subjects that relate directly to the design of structural systems include: sequences of erection, lifting and handling, and tolerance of pieces. Each of these issues is affected by construction cost and duration, site condition, and the dimensions of the building. Generally, construction methods in each case are determined by their cost and duration. However, the iterative steps of the design process between construction methods and structural design have great importance in the improvement of the productivity of structural systems.

4.2. Cost

Precast concrete building systems are of great importance in the enhancement of the availability and habitability of housing. Since construction methods are justified by total construction cost, a cost comparison between a precast concrete house and a cast-in-place concrete house may be helpful in clarifying the impact of the alternatives of construction methods on housing systems. In general, the advantages of precast concrete in construction methods are as follows: elimination of most site formwork, fewer scaffoldings, speed of construction, and quality control.

A pamphlet, Toda Technics: Toda-Rahmen Precast Concrete Method, issued by Toda Corporation, Japan, shows a cost comparison between a precast concrete multifamily house and a cast-in-place concrete multifamily house, based on a project which was carried out using a precast concrete braced frame structural system (Figures 4-1 and 4-2).[1]

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[1]Toda Technics: Toda-Rahmen Precast Concrete Method (a pamphlet). Toda Corporation. Japan. May, 1992.

(Figures 4-1) Source: <u>Toda Technics: Toda-Rahmen Precast Concrete Method</u>
The multifamily house constructed by the precast concrete braced frame structural system (7 stories, 99,000 ft^2.) Beams, slabs, and external walls are precast, while columns are cast-in-place.
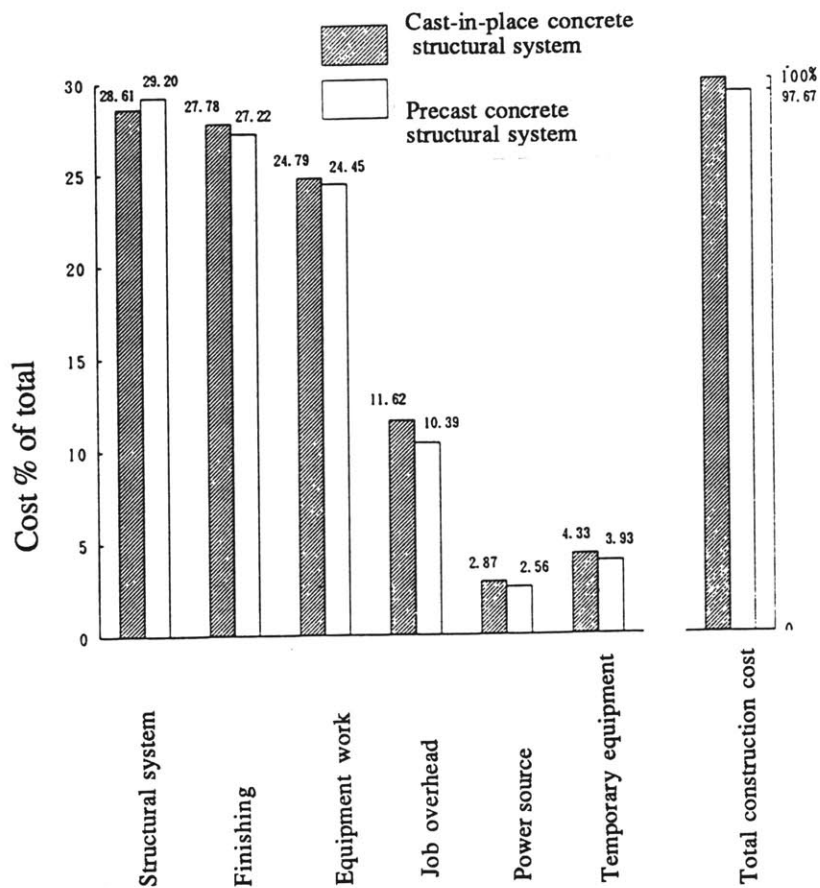

(Figures 4-2) Source: <u>Toda Technics: Toda-Rahmen Precast Concrete Method</u>
Cost comparison between two medium-rise multifamily houses constructed by precast concrete and cast-in-place concrete respectively. The vertical axis shows the construction cost by percentages against the total construction cost by cast-in-place concrete. The data of total construction cost is not available.

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With regard to the construction of a precast concrete multifamily house, Figure 4-2 shows that the cost of the structural system is higher than that of cast-in-place concrete, however, other costs are lower than those of cast-in-place concrete, leading to a lower total construction cost for this precast concrete building. Further, since the cost of a structural system greatly depends on the degree of the standardization of pieces in terms of dimensions and connections, as well on varying conditions, such as site condition, site location, and given construction duration, it cannot be concluded that precast concrete will always lead to higher structural system costs. With regard to the cost of finishing work, the smooth surfaces of precast concrete have obvious advantages. The cost reduction of equipment work comes from the fact that precast pieces incorporate electrical boxes, conduits, and sleeves for piping. A remarkable cost effect of the precast concrete building system can be seen in job overhead and equipment costs. These cost reductions can be attributed to the shorter duration of on-site work, which is 10 and a half months for the precast concrete building system and 13 months for the cast-in-place concrete building system in this case. This example makes it clear that the short duration of on-site work should be given great importance in precast concrete construction methods. As mentioned in Chapter 2, early preparation for precasting is also indispensable for obtaining both short duration and low precasting cost.

4.3. Sequence

The sequences of assembly are dictated by the order of lifting and connecting. The order of lifting is greatly affected by the condition of a construction site. When the choice of lifting equipment is limited by site conditions, such as narrow space around the building or close proximity of adjacent buildings, sufficient lifting capacity and necessary crane reach may not be available. In such cases, articulations of precast concrete pieces might be more fragmented to ease lifting and connecting and the articulation might be changed to deal with a restricted sequence of assembly. For example, if the approach of a crane is limited to one side of a building and other sides are adjacent to other buildings, the erection will be forced to begin at the rear side and proceed to the front bay by bay since a construction sequence by story could impede the reach of the cranes. In this case, multi-story articulations of vertical structural members may be advantageous because of construction speed and less requirement for lateral supports (Figure 4-3). The effects of the overlapping working position of lifting and foundation work, which may cause conflict or may call for an expensive temporary platform for a crane, should be taken into account.

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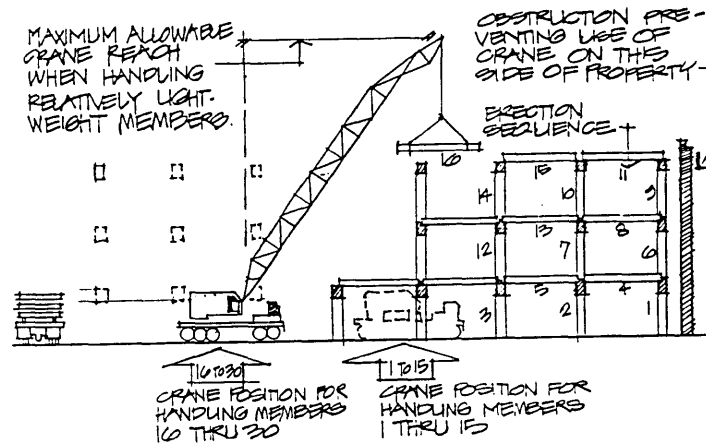
(Figure 4-3)   Source: Plant Cast Precast concrete and Prestressed concrete: a Design Guide
The erection of precast concrete frame structure by bay.
This erection process can be employed by the frame structures with mechanical connection (this structural system calls for structural bracing) or those with multi-story columns. Phillips and Sheppard describes this sequence that ". . . erecting a stack of precast members required to complete a vertical portion of the structure without moving the crane, and then moving to the next crane set-up point where the operation is replaced."[2]

A precast concrete frame structure with mechanical connections can be erected bay by bay with temporary tightening, a significant advantage over a precast concrete frame structure with monolithic cast-in-place connections which must be erected floor by floor (Figure 4-4). In such a structure, the vertical structural members cannot be erected until the lower floor is cast and functioning to support the columns to be erected next (Figure 4-5). Additionally, certain areas on each floor have to be cast-in-place at the same time. Since cast-in-place concrete work requires a certain amount of equipment and preparation, the construction sequence becomes fragmented, necessarily increasing overall duration, increasing total construction costs. Considering the connection details, which have to be cast or grouted before erection of the next floor, the erection of a large panel structure should also proceed by story.
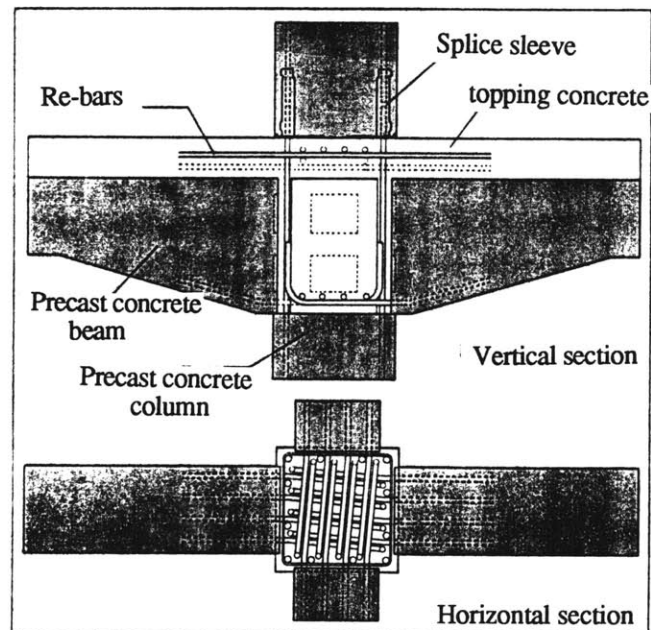
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[2]Phillips, W, R. , & Sheppard, D. A. p. 50.

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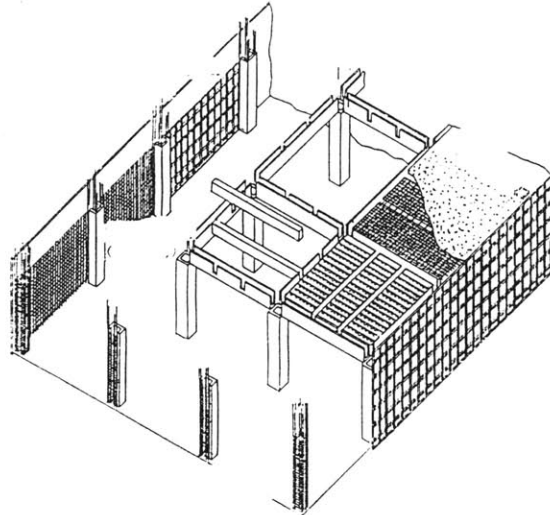
(Figure 4-4)   Source: Toda-Rahmen Precast Concrete Method
The erection of precast concrete frame structure by story.
Precast concrete shell slabs, beams, and columns constitute monolithic structure by being cast at the same time. The election of upper floor cannot be started until the concrete is cured.

(Figure 4-5)   Source: Toda-Rahmen Precast Concrete Method
A connection detail of a cast-in-place connection of frame structure.

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Considering the concept of precast concrete, which is a method of the industrialization of reinforced concrete structural systems, it might be said that the smaller the amount of cast-in-place concrete the greater expectation of the cost reduction by easy assembly. However, cast-in-place concrete elements sometimes constitute a critical part of the whole structural system that cannot be substituted by precast concrete; for example, where monolithic joints are called for at regions of high stress, and topping concrete on a slab is required to support high service loads and to provide a flat floor surface. For this reason, the sequence of the erection and articulation of a structural system should be considered in relation to lifting condition and connection designs so that integration of precast concrete and cast-in-place concrete is facilitated.

4.4. Tolerances

Tolerance is required for both precasting and assembly of precast concrete pieces to absorb dimensional deviations. While dimensional deviations of precasting are caused by production method, equipment, formwork, workmanship, and quality control, those of assembly are caused by human error as well as the limits imposed by measuring instruments and placement techniques.[3] These variations eventually lead to need for tolerance at connections, where design tolerances are considered by means of the combinations of maximum and minimum deviations of both precasting and assembly. The Design and Construction of Large-Panel Concrete Structures: Report 2. depicts the relationships between actual, specified, and coordinating dimensions as shown in Figure 4-6.

The Design and Construction of Large-Panel Concrete Structures: Report 2. describes the relationship between the assembly tolerances and connection design as follows:

> "Lack of fit may result in costly on-site modification and adjustment, and impairment of the load-bearing capacity of the structure. . . Tolerances are determined by the requirement of the entire construction process considering technology and economics of currently used methods of precasting, setting-out and assembly. The most influential factor affecting tolerances appears to be connection type--more accuracy is required for bolted connections than for grouted connections."[4]

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[3]Design and Construction of Large-Panel Concrete Structures: Report 2. p. 64.

[4]Design and Construction of Large-Panel Concrete Structures: Report 2. p. 62.
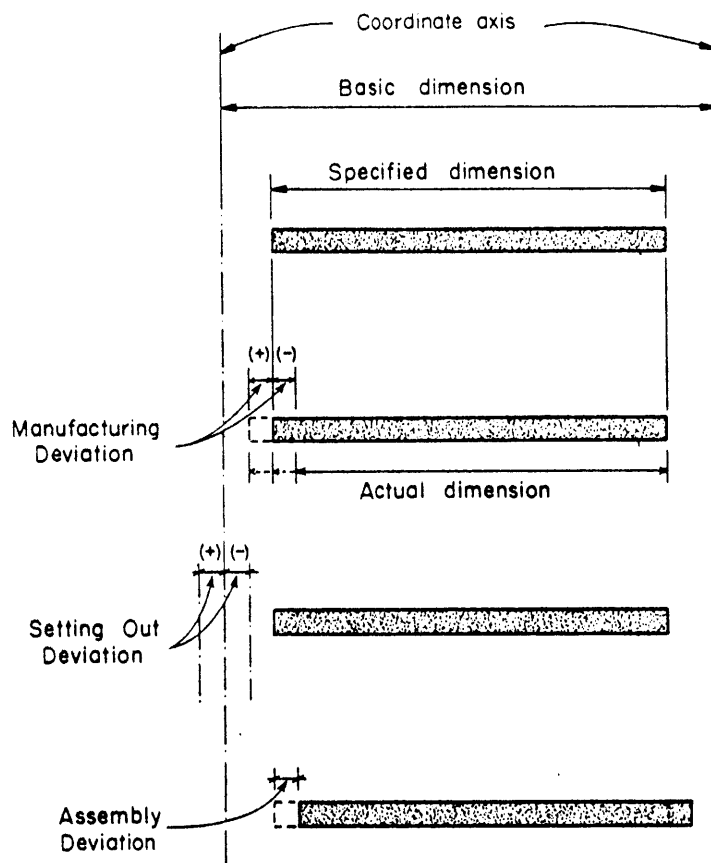
(Figure 4-6)   Source: Design and Construction of Large-Panel Concrete Structures: Report 2.
Panel size deviation
The deviations affects connections are considered as the combinations of maximum and minimum deviations of both precasting and assembly. This figure shows, in addition to the two kinds of deviations, setting out deviation, which is the variations in the positions of supports.

With regard to the relationship between tolerances and articulations, it can be said that articulated pieces can take advantage of tolerances by canceling their precasting deviations at each connection if they have a connection design that facilitates positional adjustment, whereas large pieces, such as multi-story columns, call for much more attention to maintaining precasting and assembly tolerances.[5] This alternative between articulated and less articulated pieces is more important for vertical members because these pieces are erected before the assembly of horizontal members and provide their support, when setting out deviations have to be taken into account.

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[5]manufacturing tolerances are usually fixed regardless of the size of the size of pieces.

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Chapter 5

Rules and Constraints of

Unbraced Frame Structural System

5.1. Introduction

This Chapter, and Chapters 6 and 7 discuss the structural rules and constraints of precast concrete structural systems that dictate the design of housing systems according to the structural classifications of Chapter 1. The scope of the study is limited to structural issues; this includes the structural performance of the whole building, its members, and its connections. Non-structural precast concrete, found in such objects as curtain wall panels or ornamental pieces, is outside the scope of this section.

The considerations proceed according to the level of load transfer as shown in Table 1-2, reproduced here as Table 5-1.

| Level of load transfer	Structural function	Load types
Level 1 Loads applied to a structural system as a whole	Vertical and lateral load resisting systems	Vertical load (dead load / live load) Lateral load (wind load / seismic load)
Level 2 Loads applied to structural members	Framing dimension and articulation	Compressive load Tensile load Shear load Bending moment
Level 3 Loads applied to connections	Connections	Compressive load Tensile load Shearing load Bending moment

(Table 5-1) Classification of the loads transfer
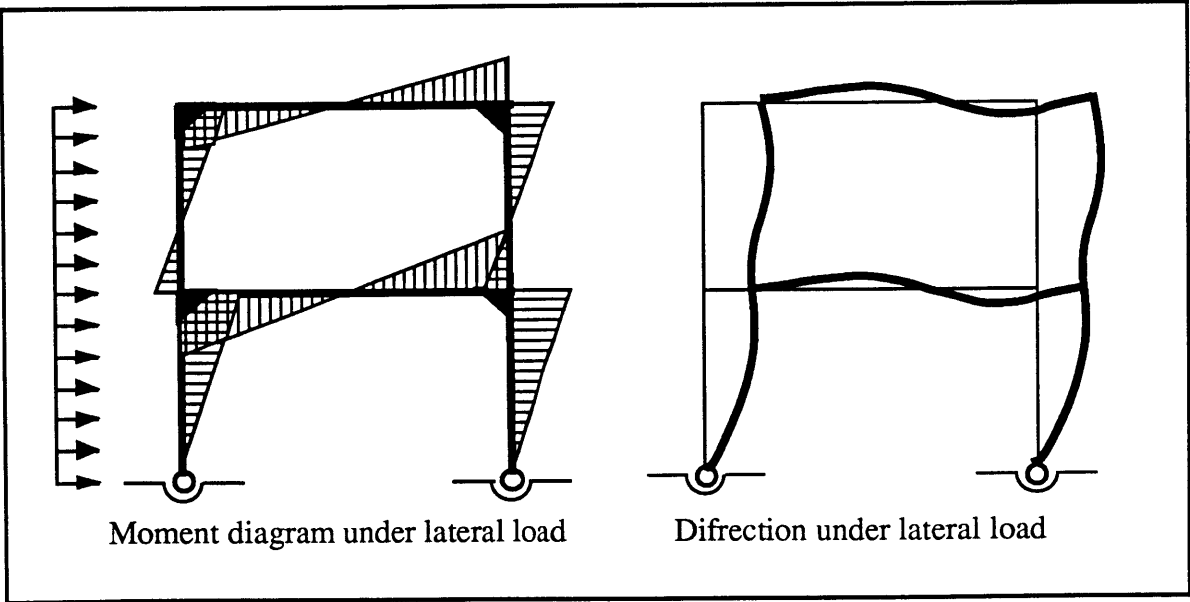
5.2. Unbraced frame structural systems at Level 1

The PCI design handbook notes that ". . . in some structures, adequate shear walls interfere with the function of the building, or are more expensive than alternate solutions. In these cases, the lateral stability of the structure depends on the moment-resisting capacity of either the column bases, a beam-column frame, or both."[1] This is the case for

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[1] PCI Design Handbook. p. 3-43.

unbraced frame structural systems. Accordingly, consideration of the braced frame structural systems is divided into two structural systems: (1) the "column base structural system" (Figure 5-1); and (2) the "moment-resisting frame structural system" (Figure 5-2), also called "beam-column frame structure" in the PCI Design Handbook.

Moment diagram under lateral load   Difrection under lateral load
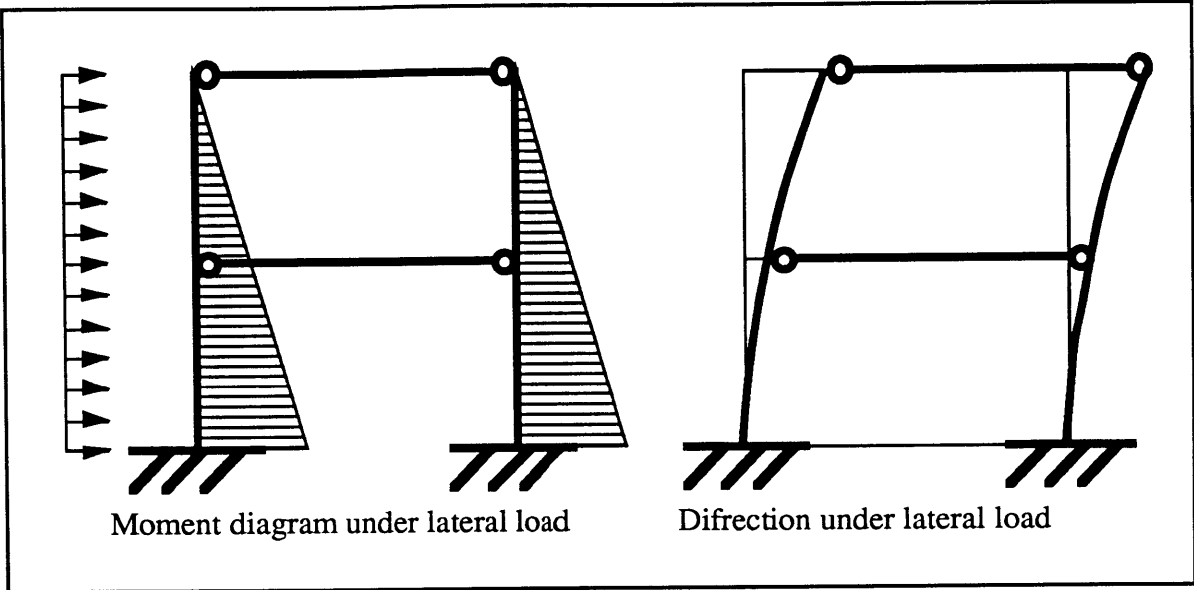
(Figure 5-1)   Column base structure

Moment diagram under lateral load   Difrection under lateral load

(Figure 5-2)   Moment-resisting frame structure

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5.2.1 Column base structural system

According to the PCI Design Handbook, "Single-story and some low-rise buildings without shear walls may depend on the fixity of the column base to resist lateral loads. The ability of a spread footing to resist moments caused by lateral loads is dependent on the rotational characteristics of the bases." [2] The columns and beams have simple connections which do not resist bending moments.

The column base structure is used typically in parking garages which have cast-in-place or precast concrete columns, precast prestressed concrete slabs (Tees) and precast prestressed beams. In houses, this relatively vulnerable structure pays off only if infills and enclosures have to be separated from the structures for the purpose of designing an open system house. A housing complex on Genterstrasse in Munich, Germany, (Figures 5-3 to 5-5) is such a project.
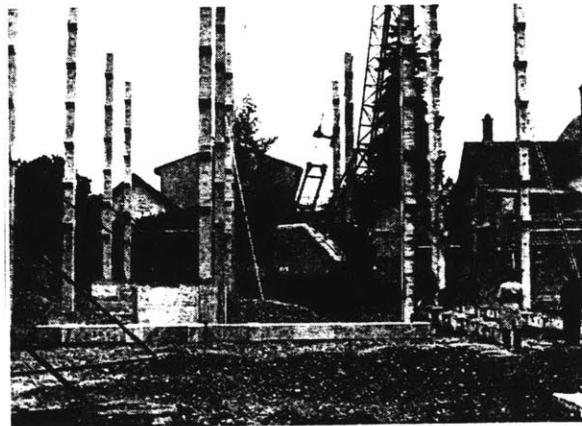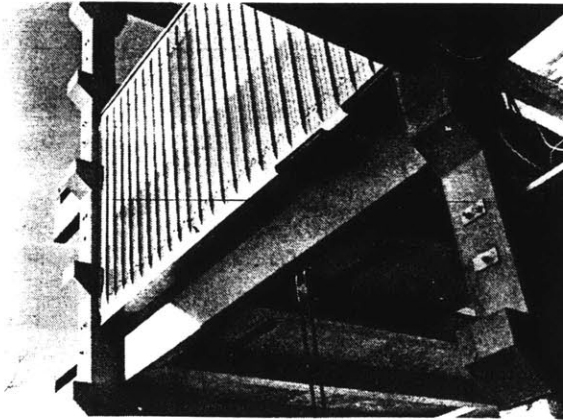

(Figure 5-3)   Source; Werk. March, 1971.
Election of columns
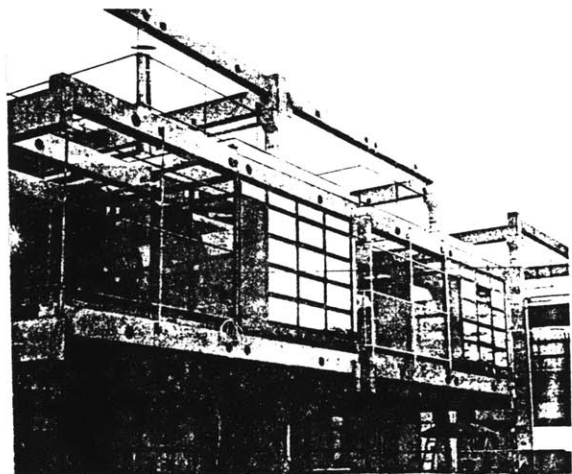
(Figure 5-4)
Facade
Absence of structural walls at the perimeter gives free arrangement of internal and external walls.

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[2]PCI Design Handbook. p. 3-43.

(Figure 5-5)
Connection between columns and beams.
Beams rest on corbels of columns.

Pin connections between columns and beams facilitate the application of prestressed beams and planks and make a long span structure possible. However, a long span is not always advantageous for the structure of housing. Foster notes that "For example, the cost of infilling panels of bricks or blocks at the separating wall positions, to provide the necessary degree of fire resistance and sound insulation, must be added to the cost of the reinforced concrete frames to make it comparable with the box frame."[3]

The maximum height of this structural system is limited to low-rise housing. Since a column is analogous to a vertical cantilever fixed on the ground, the height of the house depends primarily on the applied lateral load as shown in Figure 5-1.

5.2.2 Moment-resisting frame structural system

The moment-resisting frame structural system of precast concrete is structurally equivalent to that of cast-in-place concrete. Because the connections between precast concrete pieces have to be as rigid as in a monolithic structure, this is more difficult to achieve in precast.

Although a moment-resisting frame structure resists lateral loads better than a column base structure, its application is confined to low to medium-rise housing, without additional lateral load resisting systems. Mainstone notes that "This was because the

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[3]Foster, J. S. p. 223.

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large shear forces that might arise near the base from wind loads could be resisted only most inefficiently by the beams and columns both acting primarily in bending - while columns were simultaneously carrying high axial compressions."[4]

With regard to the maximum height of this structural system, it is interesting to see the differences of the recognition in various countries. For example, Elliott, of the Department of Civil Engineering, University of Nottingham, United Kingdom, says that "Unbraced frames are practical only up to three stories and braced frames up to about 20 stories."[5] On the other hand, Englekirk, California, says that "Joints in regions of high stress do not appear to concern Japanese engineers as much as they do engineers in the United States. This is evidenced by the fact that Japanese engineers have constructed frame buildings up to 24 stories using precast beams and cast-in-place columns. . . Recent American experience in areas of comparable seismicity is limited and typically does not use precast components to the extent used by the Japanese."[6]

The Japanese high-rise frame structure described above has cast-in-place columns. When both columns and beams are precast concrete, the maximum height of such a structure is around 10 stories. In the U.S., although some houses up to seven stories might have been built with a precast concrete frame structure, relatively strict building codes have limited practical applications of this structure. It must be noted that these differences in maximum building heights are caused by the varying building codes that restrict the technical applications in each country, rather than by actual technical limitations.

Moment-resisting structural systems are advantageous for the design of open systems[7], where shear walls have to be eliminated from floor plans. Figures 5-6 to 5-8 show a recent open-system housing project, "Next 21", in Japan. The structure above the third floor is constructed by precast concrete moment-resisting frame with no structural walls. Several architects designed individually assigned areas based on a module (0.3 m

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[4]Mainstone, Rowland. p. 270.

[5]Eliott, K. S. (1992). The Design of Modern Precast Concrete Multistory Framed Structures in the United Kingdom. PCI Journal, May-June 1992, p. 32.

[6]Englekirk, R. E. p. 80.

[7]The term "open system" can be defined as the system that is possible to accommodate the wide range of plan options.
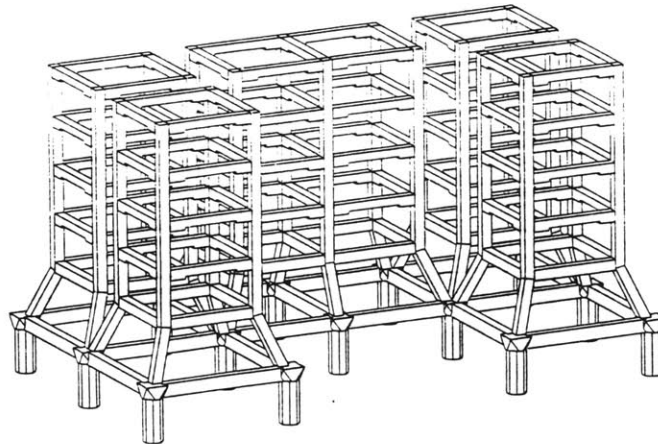
by 0.3m). External walls are designed so that they can be changed when a renovation takes place in the future.
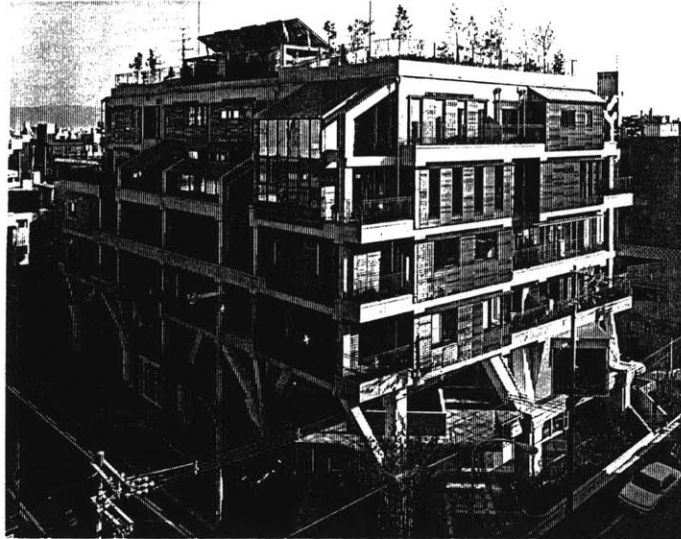
(Figure 5-6)   Source; <u>Nikkei architecture.</u> January, 1994.
Facade
Fenestrations are chosen from ready-made products which match the module so that renovations are facilitated.

(Figure 5-7)
Skeleton
80% of the structural system was built by precast concrete pieces, including columns, beams, and slabs. First and second floors have a different frame dimension to provide a community zone. As a result, the small volume of frame work at the first and second floors were built by cast-in-place concrete.

Precast concrete shell slab

Precast concrete shell beam

Precast concrete column

Infills

External walls
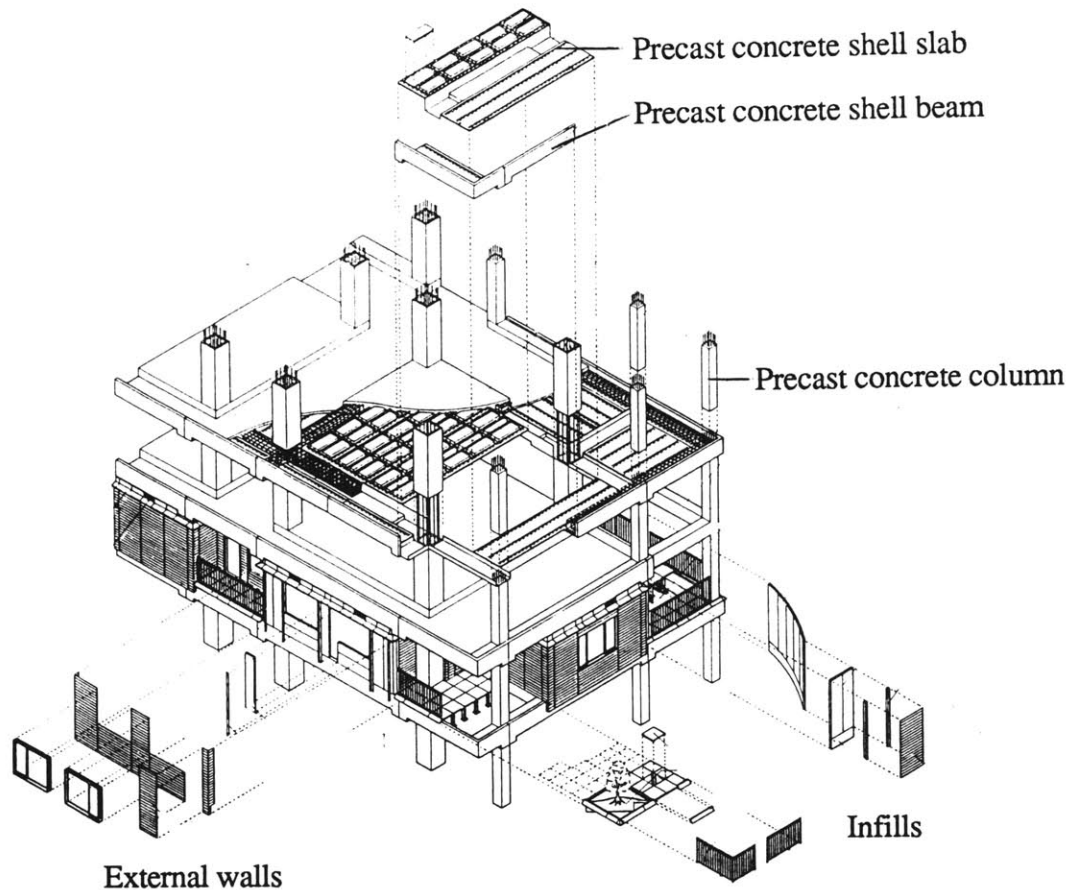
(Figure 5-8)　Source; GA Japan, no. 06. Jan. - Feb., 1994.
Components
In this project, different architects designed infills of houses at their allotted areas, according to the module. Infrastructures are arranged so that they do not disturb the module.

5.3. Unbraced frame structural systems at Level 2

5.3.1 Dimensions

(1) The dimensions of the column base structural system

Due to the pin connections between the horizontal structural members and columns, the column base structures can be easily combined with prestressed beams and/or planks, which can span a much longer distance than usual reinforced concrete. For example, some of the standard precast prestressed concrete planks and beams can span a maximum of 50 feet. However, the practical maximum lengths of spans in a column base structure house are limited by the following constraints:

(a) Since the capacity to resists lateral load depends on the stability of footings and the rigidity of the connection between columns and footings, the increased amount of lateral load caused by the longer spans cannot be complemented by an increase in the flexural rigidity of the columns themselves.

(b) The deflection of planks may make the installation of infills difficult, especially when a plank spans more than one apartment unit. The PCI Design Handbook indicates that "Non-structural components attached to members which could be affected by camber variations, such as partitions or folding doors, should be placed with adequate allowance for error."[8]

(2) The dimensions of the moment-resisting frame structural system

Since the principle of a precast concrete moment-resisting frame structure is the same as that of cast-in-place frame structures in that they must be monolithic, as shown in section 4.3, the dimensions of columns and beams of both structures should be equivalent. However, in terms of the dimensions of pieces, these two structures are different in that precast concrete structures should consist as much as possible of pieces of the same dimensions to enhance the economy. For this reason, the dimensions of columns and beams might not be reduced as the number of stories increases, while this reduction is common for cast-in-place reinforced concrete structures. Even a partial modification could be difficult because the size of each part relates to every other part, as in the case of the cross section of a column and the length of a beam.

On the other hand, unlike column base structures, this structure is incompatible with precast prestressed concrete members for the following two reasons: (1) precast prestressed concrete beams are pin ended; they are difficult to connect to columns in a monolithic way, and (2) the application of precast prestressed concrete beams causes structural complications. Foster points out that "When applied to complete monolithic structures prestressing presents complications in design and construction. For wide span, freely supported beams are generally considered preferable to continuous beams in order to avoid similar complications."[9]

5.3.2 Articulations

The articulation of the pieces has to be designed with the following considerations.

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[8]PCI Design Handbook. p. 4-43.

[9]Foster, J. S. p. 226.

(a) stress at connections,

(b) transportation, and

(c) construction methods (Lifting / Sequence / Tolerance).

Since the stress on the whole structure is not uniform at every point, the required load capacity of connections varies in both amount and types according to the location. Basically, connections should be located at the points where the bending stress is minimal. However, this rule is not always a primary criterion of the articulation when other factors are given priority and the stress at connections turns out to be in a reasonable range.

As discussed in Chapter 3, the rules and constraints of transportation can be understood as the maximum volumetric dimensions, maximum weights, and cost efficiency of transportation. The need to lift pieces also limits the maximum weight that can be used economically. Although some equipment is capable of lifting a piece which is much heavier than what can be transported, the location of a construction site and the cost of lifting equipment might limit the maximum weight of a piece, and which would affect the numbers and position of articulations.

The maximum size of a piece is also limited by handling requirements during precasting and erection. The PCI Design Handbook indicates that "The loads and forces on precast and prestressed members, especially wall panels, during production, transportation, or erection will frequently be more critical than in-place loads. This is because concrete strengths are lower and support points and orientation are usually different."[10]

The installation of a large piece calls for special attention to avoid undesirable stress (Figure 5-9), or for additional reinforcement of the piece which requires additional costs. Although the number of temporary supports might be affected by the means of articulation and the number of pieces, usually it does not affect the total construction cost significantly. This is because temporary supports are required to adjust the position of each piece in any case and can be removed as soon as the connections are fixed, whereas the temporary supports at cast-in-place concrete structure have to be left in position during the curing time of concrete, which usually takes three weeks.

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[10]PCI Design Handbook. p. 5-2
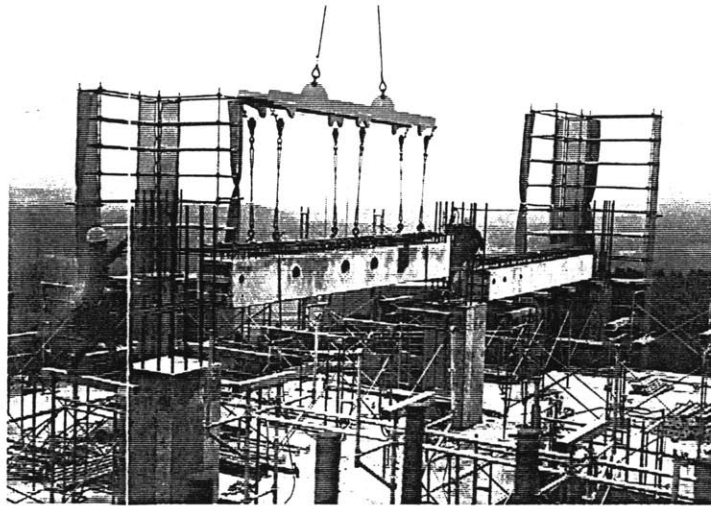
(Figure 5-9)   Source; Toda Technics: <u>Toda-Rahmen Precast Concrete Method</u>
A lifting of a precast concrete beam at a construction of a hotel in Japan.
A spreader beam is used for lifting long span and/or heavy pieces.

In this thesis, the word "tolerance" refers to the space between precast concrete pieces that absorbs the minor errors of the pieces and assembly works. This tolerance relates to the sequence of assemblies and the detail of connections. For instance, the installation of a precast concrete beam between multi-story precast concrete columns requires a considerable tolerance and desirable connections because of the variations of the inside measurements between the columns (Figure 5-10).
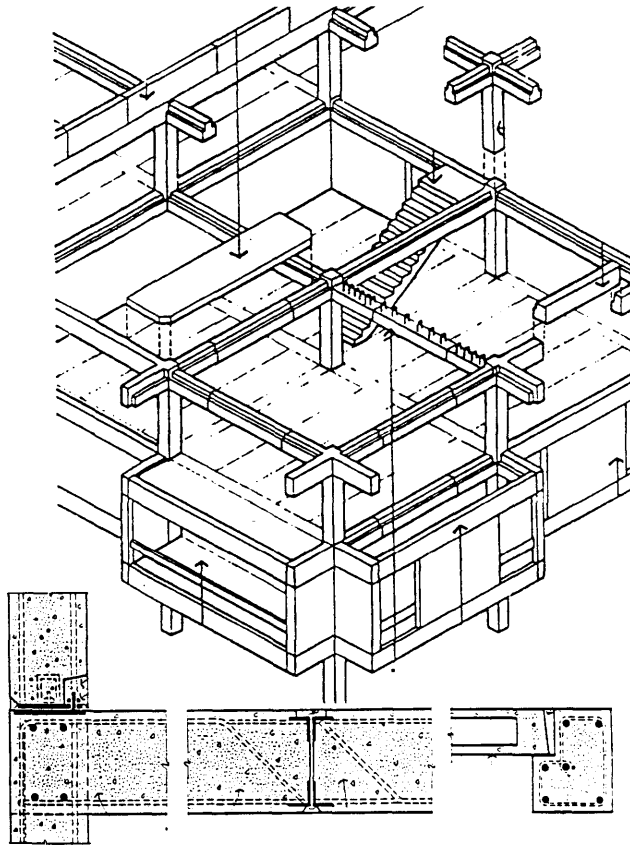
1

(Figure 5-10)   Source; répertoire des systémes de construction industrialisés en
habitation.
A detail of connection between a tree column and intermediate beam at Componoform project.
The nominal tolerance of a welding connection calls for an accurate erection of tree columns.

(1) Articulation of the column base structural system

As shown in Figure 5-11, each column of the column base structure is monolithic. Although there are ways to connect several pieces of a precast concrete column in line to make longer columns, these connections cannot be recommended as a result of their tight tolerance. Because even a minute bend at any connection may be a critical defect which could cause buckling, it seems reasonable that the columns of the column base structure cannot be articulated.

As mentioned in section 4.1.1, the maximum height of the column base structural system is limited to low-rise housing due to its lateral load resisting capacity. As far as the maximum height being limited to low-rise structures, articulation of columns is not required because the maximum length of precast concrete pieces that can be transported is about 75 feet, which is usually long enough for a 7 story dwelling.
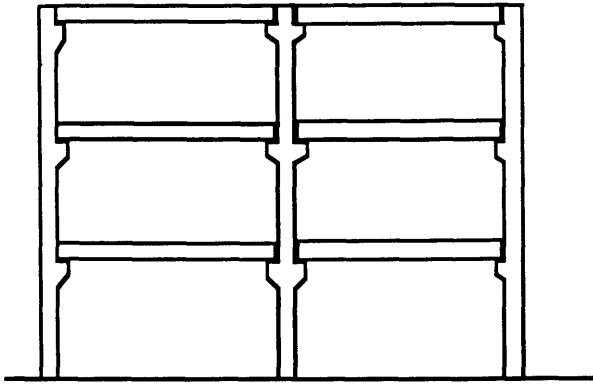
(Figure 5-11)   Articulation of column base structure

(2) Articulation of moment-resisting frame structural system

Compared to the column base structural system, the moment-resisting frame structural system can have a much greater variation in articulations, and each of them shows a clear contrast in terms of transportation, construction methods, and the detail of connections. Articulations can be classified into the following two groups according to the positions of connections.
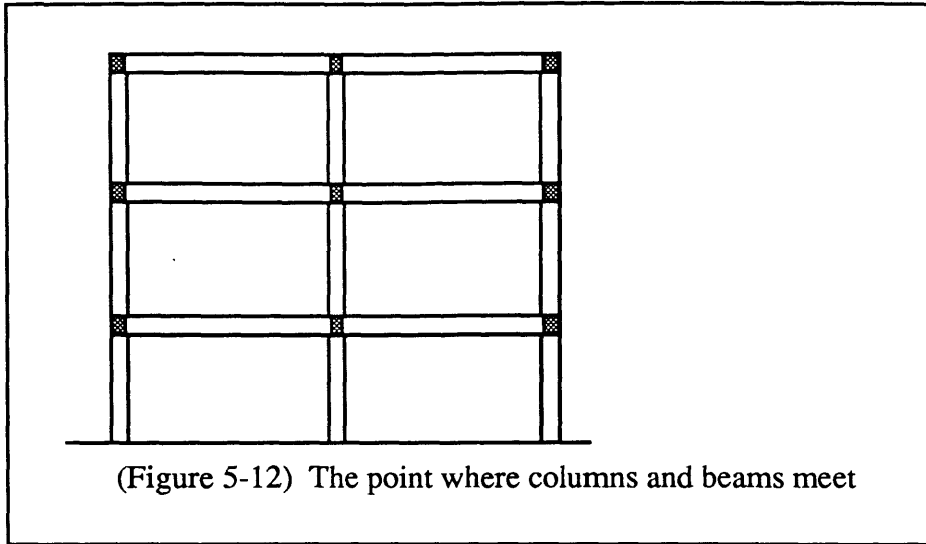
(a) Articulation-A:

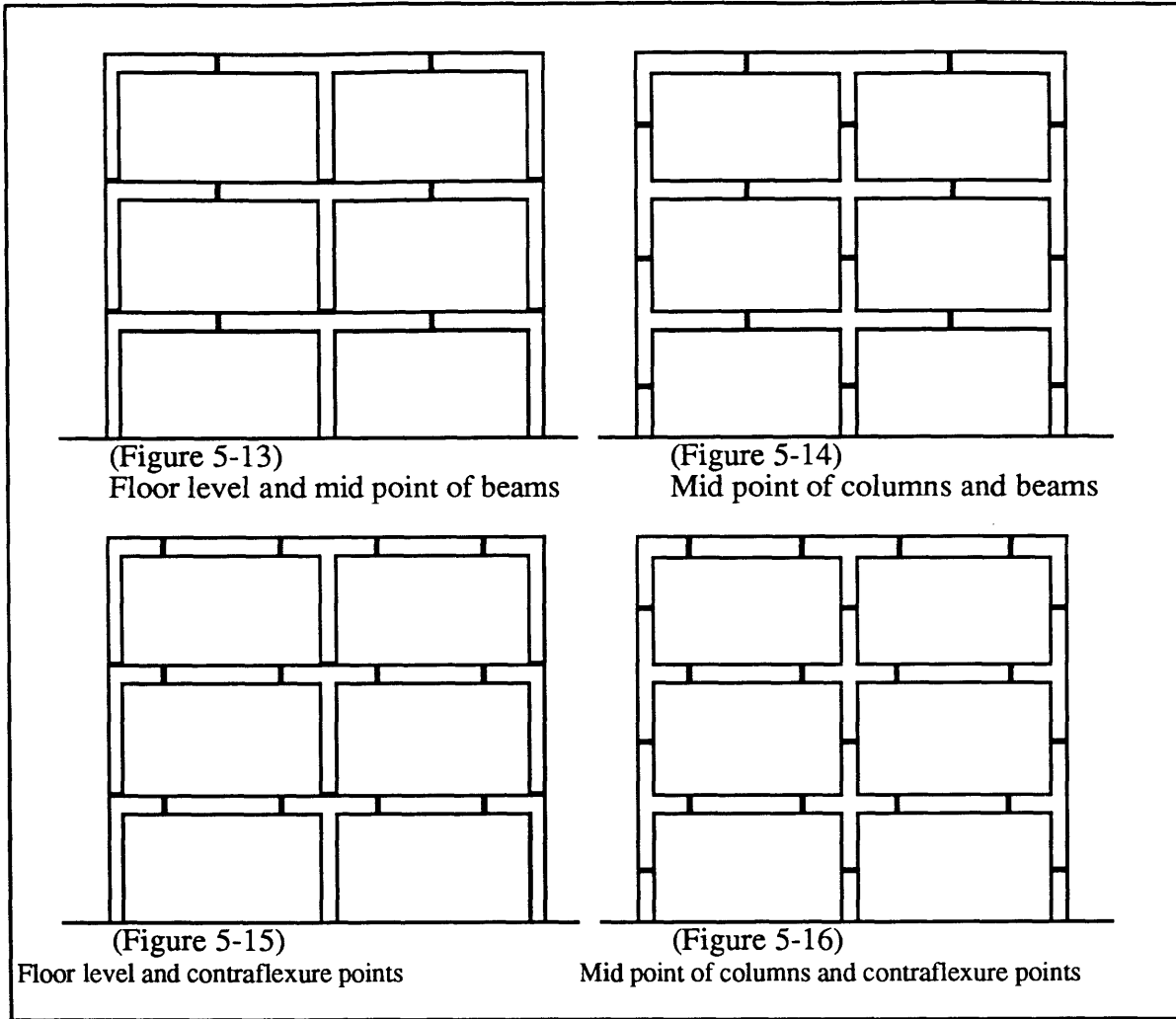The articulation at the point where columns and beams meet (Figure 5-11).

(b) Articulation-B:

The articulation at the intermediate points or at the middle point of columns and/or beams (Figures 5-13 to 5-16).
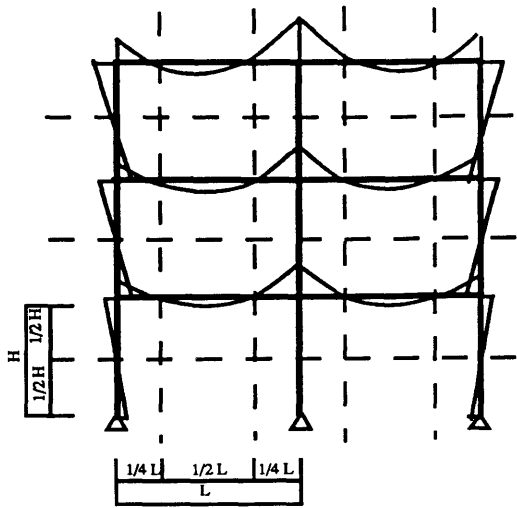
Articulation-A

(Figure 5-12) The point where columns and beams meet

(Figure 5-13)
Floor level and mid point of beams

(Figure 5-14)
Mid point of columns and beams

(Figure 5-15)
Floor level and contraflexure points

(Figure 5-16)
Mid point of columns and contraflexure points

(a) Stress at connections

Figures 5-17 and 5-18 are simplified moment diagrams of moment-resisting frame structures in terms of vertical and lateral loads. Figure 5-17 shows that inflection points, points on structural members where bending moment does not exist, are around one quarter of the way from both ends for beams and at the center for columns. Figure 5-18 shows that bending moments caused by lateral loads are minimal around the center of each member. The shearing load of each structural member is the same at any point along it. When structural pieces are articulated at the inflection points (as shown at Figure 5-16), the stress on the connections is minimal.
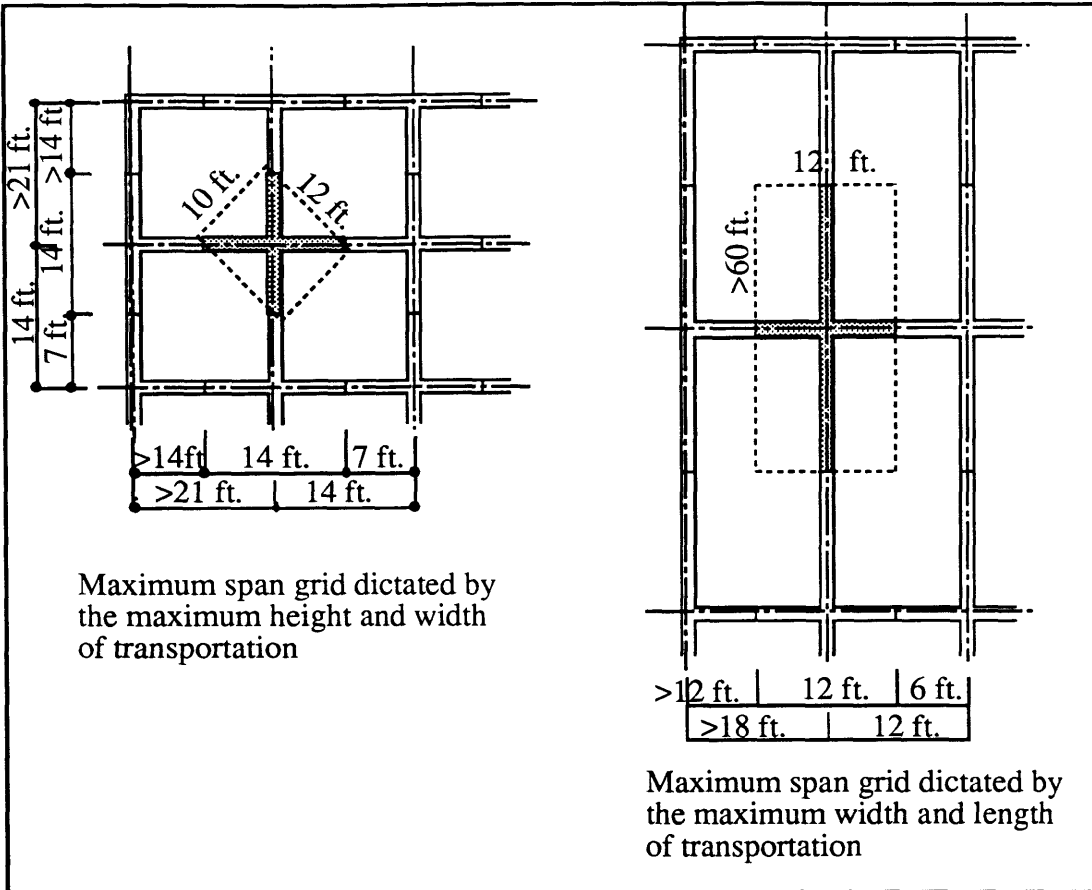
(Figure 5-17)
Moment under vertical load
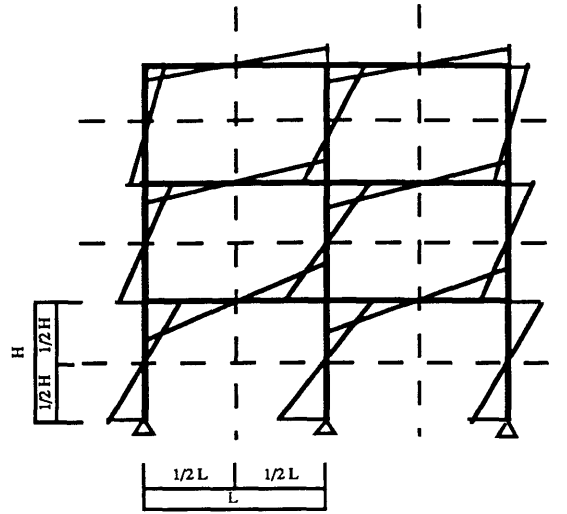
(Figure 5-18)
Moment under lateral load

(b) Transportation

The linear shape of the pieces in Articulation-A apparently has an advantage over the volumetric shapes of the pieces in Articulation-B with regard to the constraints of transportation and handling. In Articulation-B, the articulations at the midpoints of the beams (Figure 5-13, 5-14) have the most disadvantageous shapes for transportation. Under the constraint of the maximum size of transportation, which is approximately 10 ft. 12 ft. 60 ft. (assuming that a hauling vehicle occupies 15 ft. of the maximum total length 75 ft.), the maximum floor span grid may limited to 14 ft. by 14 ft. when the load height and width are used, or to 12 ft. by less than 75 ft. when load width and length are applied (Figure 5-19). These approximate calculations do not suggest the size of span grid, but prove that these articulations are feasible in terms of transportation.

Left diagram labels:
>21 ft. | >14 ft | >14 ft
14 ft. | 14 ft.
14 ft | 7 ft
10 ft. | 12 ft.

>14ft | 14 ft. | 7 ft.
>21 ft. | 14 ft.

Maximum span grid dictated by
the maximum height and width
of transportation

Right diagram labels:
12 ft.
>60 ft.

>12 ft. | 12 ft. | 6 ft.
>18 ft. | 12 ft.

Maximum span grid dictated by
the maximum width and length
of transportation

(Figure 19)
Maximum span grid of middle point articulations
in terms of transportation constraints

(c) Construction methods (Lifting / Sequence / Tolerance)

Lifting is not a technical constraint of the maximum possible weight that can be lifted, but is a constraint of economics that results from many parameters such as the location of a building, the scale and shape of the building, weight of pieces, and the speed of erection. For this reason, desirable lifting equipment, and thus a desirable articulation in terms of lifting, may differ with every project. For example, when the location of a construction site does not allow a crawler crane to approach from both sides of a house, large pieces at the far side may not be economically lifted.

The precast concrete pieces in Articulation-A can be either solid or void. Void precast concrete columns and beams are called "precast shell units" (Figures 5-20, 5-21). They are filled with cast-in-place concrete after being set in position. This method is favorable for making precast concrete pieces lighter and also for attaining monolithic

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joints, although the amount of cast-in-place increases. On the other hand, each piece in Articulation-B, which is mostly larger than that of Articulation-A, cannot be void because of the difficulties of manufacturing and constructing. For this reason, Articulation-B makes the pieces much heavier than those of Articulation-A. The application of Articulation-B requires careful consideration of its feasibility in terms of lifting.
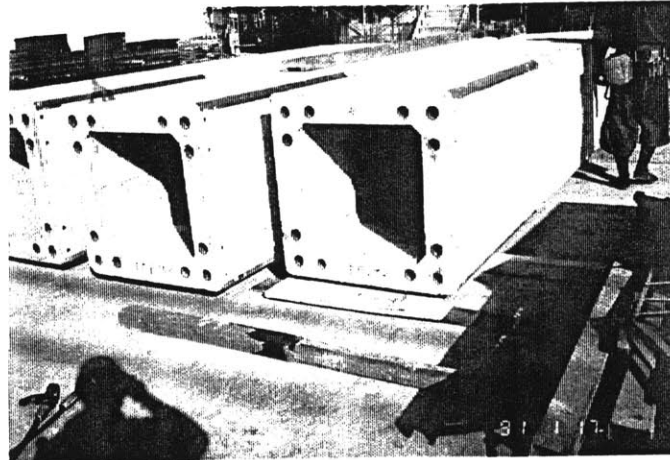
(Figure 5-20)   Toda Technics: <u>Toda-Rahmen Precast Concrete Method</u>
Precast concrete shell columns
Re-bars are joined by splice sleeves which are seen at the bottom of the pieces.
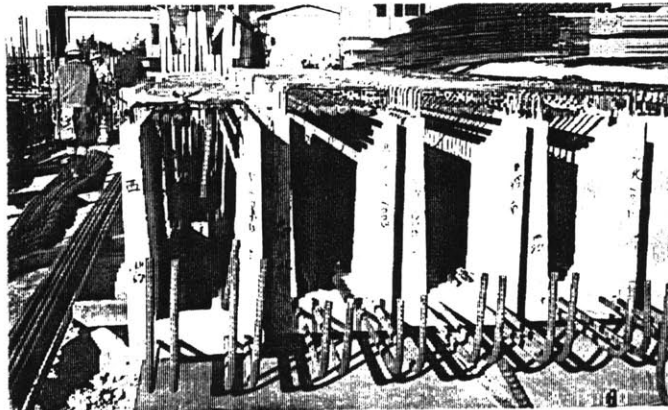

(Figure 5-21)   Toda Technics: <u>Toda-Rahmen Precast Concrete Method</u>
Precast concrete shell beams
End of bottom re-bars are fixed into the connection right above a precast concrete shell column.

Sequence / Tolerance

The tolerance between pieces is important for the facilitation of assemblies as well as for avoiding the accumulation of errors. While each piece in Articulation-A, which

always has linear shape, has two connections at each end, most of the pieces in Articulation-B have more than two connections. In other words, while Articulation-A requires a two-dimensional adjustment, Articulation-B calls for a three-dimensional adjustment. Multi-story columns require more tolerance between columns and beams as well as considerations of the sequence of assembly (Figure 5-22).
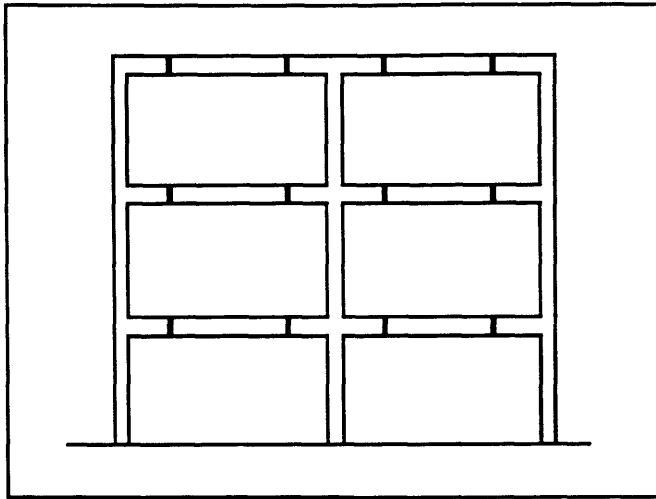
(Figure 5-22)
Multi-story column.

Articulation-A has enough tolerance because of its cast-in-place connections. When the connections of Articulation-B are located at contraflexure points they can be designed to resist mainly for shearing, compression, and tension, such as welded or bolted connections (Figure 5-23). However, those connections must be designed to cope with tolerances which are tighter than cast-in-place connections.
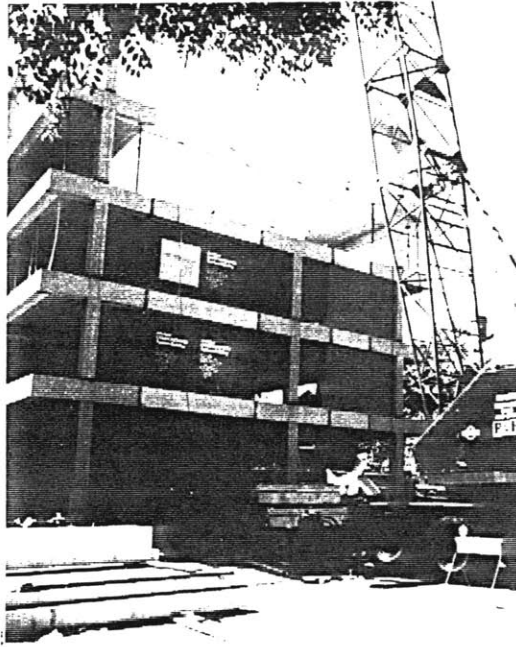
(Figure 5-23)   Source; <u>Industrialized Housing Feasibility Study</u>.
Componoform project
A construction of multi-family house in Cambridge, Massachusetts, in 1969, which shows an example of moment-resisting frame structure by 'tree' columns. In this case, the frame is articulated at the intermediate points of beams and the bottom of columns at each story.

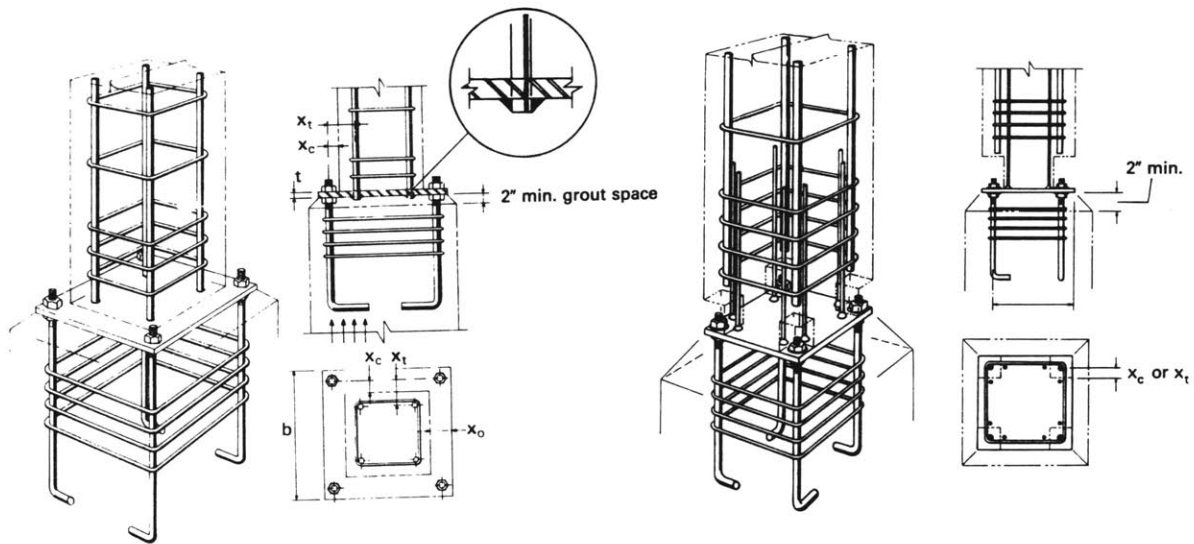## 5.4. Unbraced frame structural systems at Level 3

5.4.1 Connections of the column base structural system

(a) Base to column connections of the column base structural system

Since the lateral loads on a column base structure are resisted by the stability of footings, the stress is the highest at the connection between the columns and footings. There are two types of connections in this area: the connections of a foot of column directly grouted in a footing (Figure 5-24), and the connections that are fixed by a base plate and anchor bolts (Figure 5-25). When precision is required, the latter type of connections is preferable.
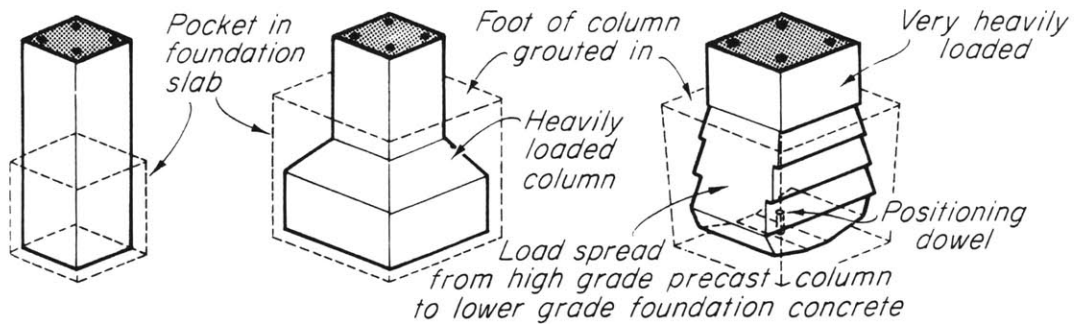
(Figure 5-24)   Source; <u>Structure and Fabric Part 2.</u>
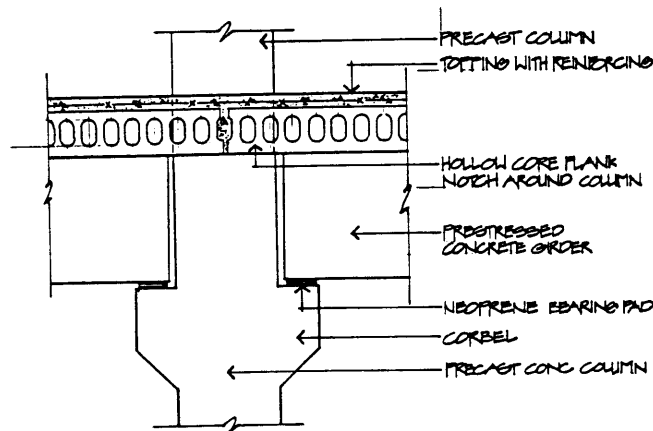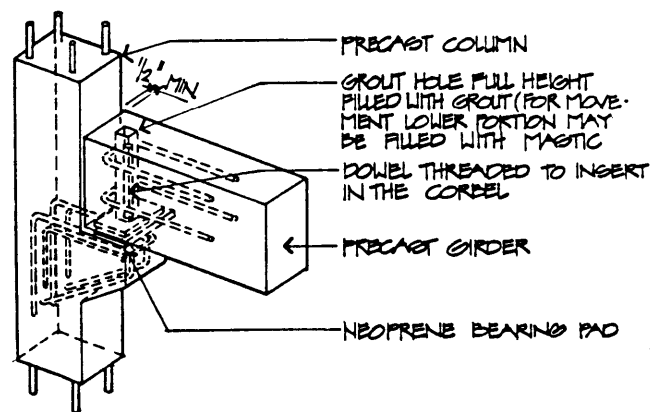Base to column connections

(Figure 5-25)   Source; <u>PCI Design Handbook.</u>
Base to column connections by a base plate and anchor bolts

(b) Column to beam connections of the column base structural system

With regard to the column to beam connections of the column base structural system, there are two design criteria to be satisfied. One is that they have to be pin connections so that the bending moment of the beams will not be transferred to the columns. To make a pin connection, the beams cannot be secured tightly against lateral loads at multiple points of different heights. Another criterion is that the connections

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have to provide tolerances for the lateral movements of the beams. Phillips and Sheppard suggest that "Special attention should be paid to the design and detailing of corbels and ledges, due to the high stress concentrations at these critical interfaces. Floating neoprene bearing under girders assure relief of creep and shrinkage movement stress."[11]

In order to make the above connections conform to the conditions, most of the connections comprise projections of columns, such as corbels, ledges and steel hangers on which the edges of the beams rest, as well as fasteners that prevent the beams from slipping off (Figures 5-26 and 5-27).

(Figure 5-26)   Source; Structure and Fabric Part 2.
Beam to column connection by a corbel.

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[11]Phillips, W, R. , & Sheppard, D. A. p. 408.
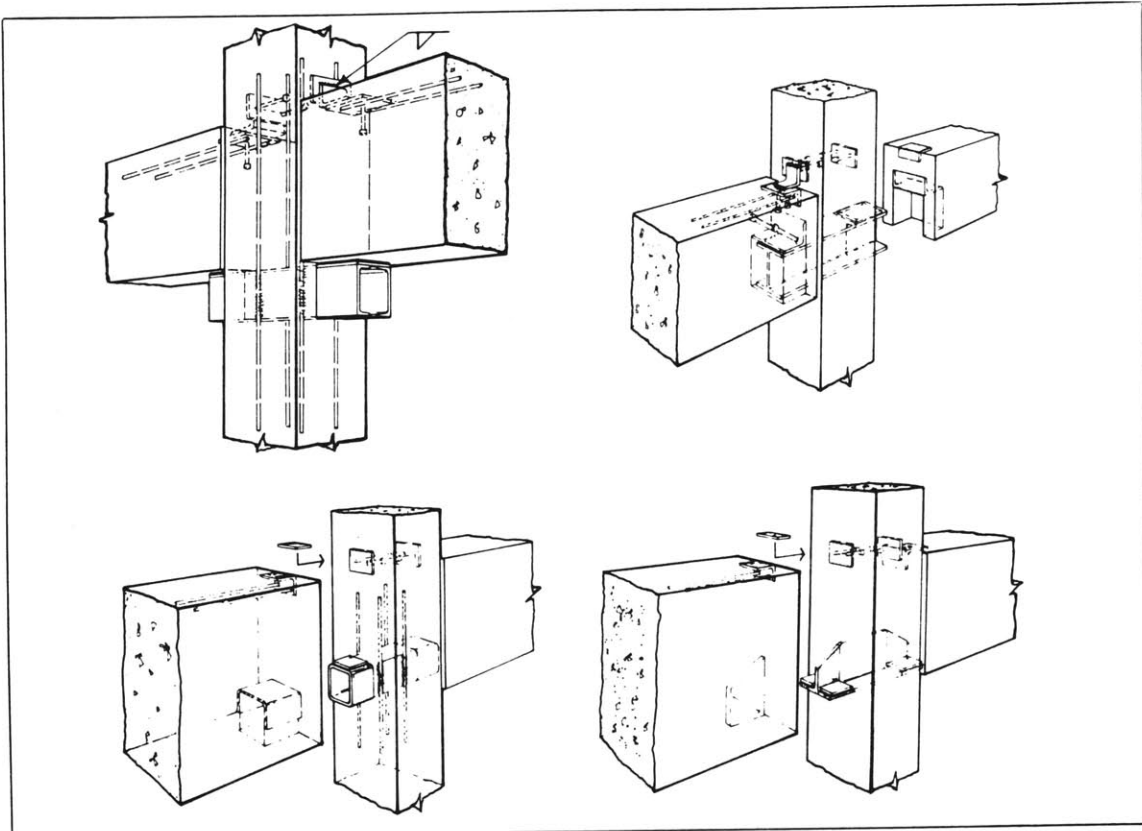
(Figure 5-27)   Source; PCI Design Handbook.
Structural steel haunches

While the function of a moment-free connection is simple, an inconsistency between the floating nature of beams and the carrying of lateral load from beams to column makes the connection design difficult. Although pin connections between column and beam generally facilitate the use of precast prestressed beams which have a long span, increasing floor areas which raise the amount of lateral seismic load may be troublesome. Since the lateral load capacity is determined by the stability of bases against rotation in the ground, increasing the section areas of columns does not necessarily raise the lateral

rigidity of the structural system. Thus, this structural system calls for a careful examination of the load capacity of the connections and of the frame dimension.

5.4.2 Connections of the moment-resisting frame structure

The following is a principal rule of the connection of the precast concrete moment- resisting frame structure: When a connection is located in regions of high stress, it has to show a ductile property at its yield point, which is attained only by monolithic connections. Phillips and Sheppard describe this issue, noting, ". . . the connections are required to be monolithic near points of maximum stress, capable of development to cause the building to act as a single, integral unit, and detailed to eliminate brittle type failures."[12] The consideration of this rule is also important regarding the articulations of the frame (discussed in section 4.2) and the design of the connections.

According to Englekirk, "In the United States neither code nor practice accepts connectors or splices in beams or columns of ductile frames if post yield deformations are likely."[13] This means that no mechanical connections can be accepted as ductile connections and they are thus inappropriate for column to beam connections. This constraint on the applications of mechanical connections could result in the articulation of pieces at the middle of a beam rather than the panel zone (the area where column and beam contact). Phillips and Sheppard note regarding the moment frame structure that "All precast or combined precast concrete systems use detailing conforming to the ductile moment-resisting frame provisions of the Code. The most frequently used method employs single unit or 'tree' columns with extended reinforcing spliced to field placed longitudinal bars at non critical locations."[14]

With regard to the connections at a panel zone, which is supposed to be a critical location, cast-in-place connections are commonly adopted. Phillips and Sheppard indicate that ". . . a ductile moment-resisting frame is possible through the use of precast shell units and poured in place concrete."[15] Also, the PCI Design Handbook suggests the following connection design criteria in terms of ductility: "In connections, ductility is

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[12]Phillips, W, R. , & Sheppard, D. A.   p. 11.

[13]Englekirk, R. E.   p. 79.

[14]Phillips, W, R. , & Sheppard, D. A.   p. 17.

[15]Phillips, W, R. , & Sheppard, D. A.   p. 3.

achieved by designing so that steel devices yield prior to concrete failure."[16] Typical details of the moment-resisting connections are shown in Figures 5-28 to 5-31. Among them, the alternative is dictated by the required capacities against various types of loads specific to each case. The characteristics of each type of moment-resisting connection are understood by comparing them with cast-in-place reinforced concrete structures which might have the utmost load capacity with the same dimension.
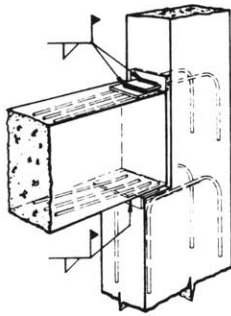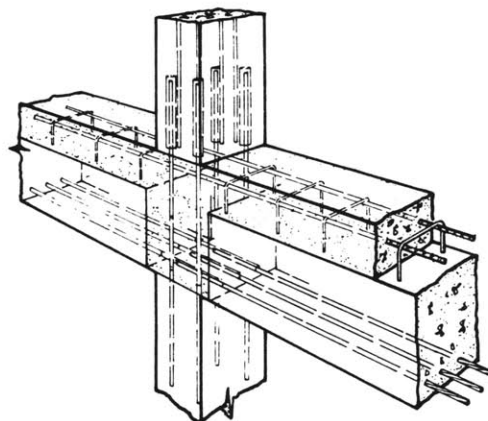
(Figure 5-28)
Moment-resisting connection of
a multi-story column
with a corbel and welding
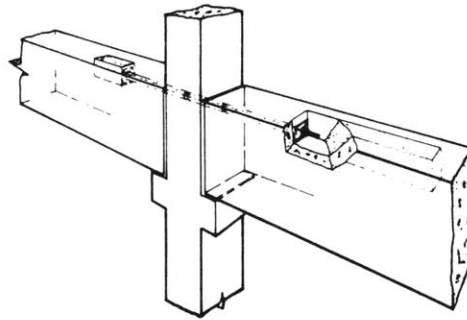
(Figure 5-29)
Moment-resisting connection of
a multi-story column
with a corbel and post tensioning
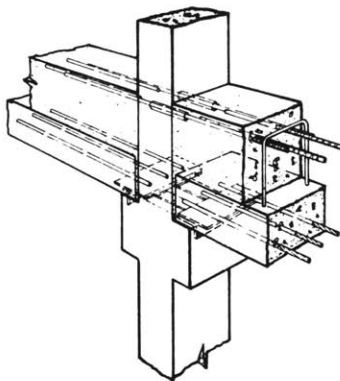
(Figure 5-30)
Moment-resisting connection of
a multi-story column
with a corbel and cast-in-place concrete

(Figure 5-31)
Moment-resisting connection of
a single-story column
with cast-in-place concrete (monolithic connection)

Source, Figures 5-28 to 31; PCI Design hand book

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[16]PCI Design Handbook, p. 6-4.

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To attain ductility, the details of cast-in-place connections must be in accordance with theories of the transfer of loads in cast-in-place reinforced concrete structural systems. Allen explains the basic theory of cast-in-place reinforced concrete structure as follows: "The basic theory of concrete reinforcing is extremely simple: Put the steel where there is tension in a structural member and let the concrete resist the compression. . . . But there are some important exceptions: Steel is used to resist some of the compression in concrete columns and in beams whose height must be reduced for architectural reasons."[17]

With regard to the bending moment in a connection, the re-bars sustain the tensile load at the top of a beam and both re-bars and concrete sustain the compressive load at the bottom (Figure 5-32). Concerning the shearing load, both re-bars and concrete can resist shearing to some extent, but yielding is caused slantwise, where the addition of stirrups help to resist diagonal tensions (Figure 5-33).
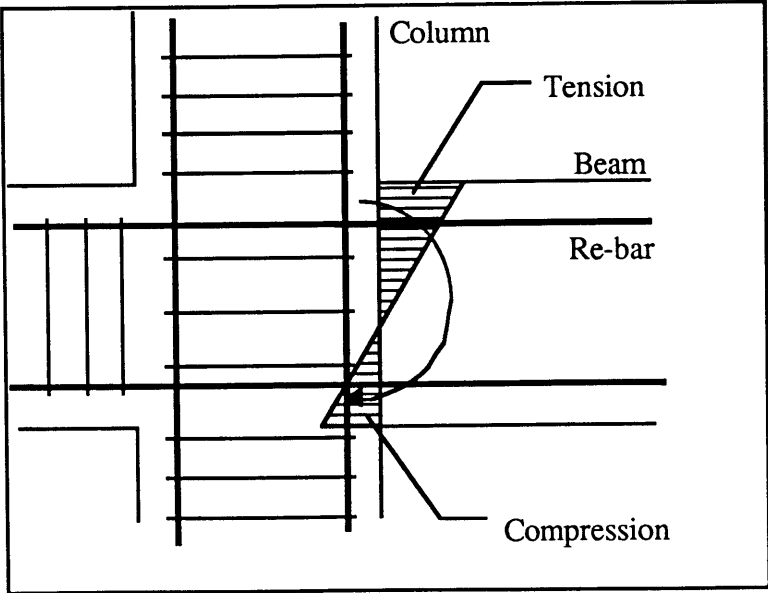
(Figure 5-32)

A bending moment around a beam-to-column connection works as a tensile load and compressive load.

17Allen, Edward. p. 442.

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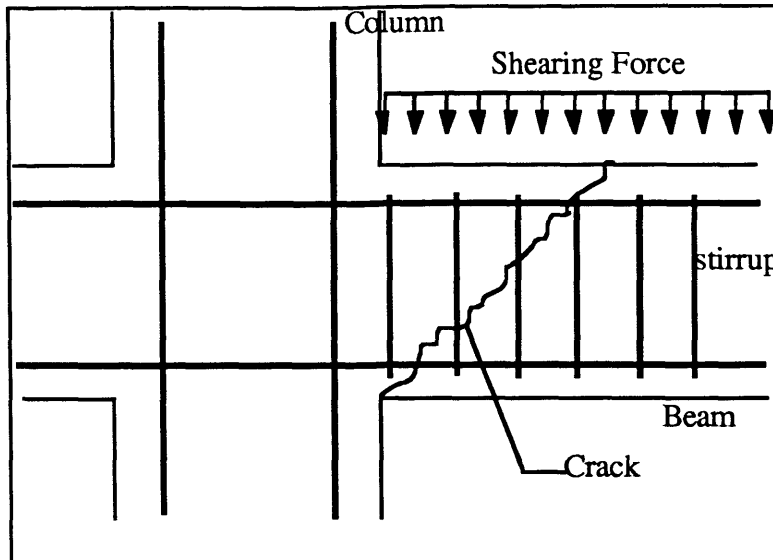
(Figure 5-33)

A Shearing force on a beam
is distributed to re-bars
(stirrup) as tensile loads.

The PCI Design Handbook notes about shear friction theory that, "Use of the shear-friction theory is recognized by Sect. 11.7 of ACI 318-83, which states that shear friction is 'to be applied where it is appropriate to consider shear transfer across a given plane, such as an existing or potential crack, an interface between dissimilar materials, or an interface between two concrete pieces cast at different times.'. . .Ductility is achieved by placing reinforcement across this anticipated crack so that the tension developed by the reinforcing bars will provide a force normal to the crack. This normal force in combination with 'friction' at the crack interface provides the shear resistance."[18] What the passages above make clear are as follows:

(a) The tension of re-bars plays a critical role in sustaining shearing loads at the point cracks are likely.

(b) Shear friction is not expected between two plane precast concrete surfaces.

With regard to the second rule above, beams which have mating keys connected by post tensioning can sustain shearing load (Figure 5-34). However, this method is difficult for frame structure in terms of tolerance of pieces and the sequence of assembly.

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[18]PCI Design Handbook. p. 6-18.
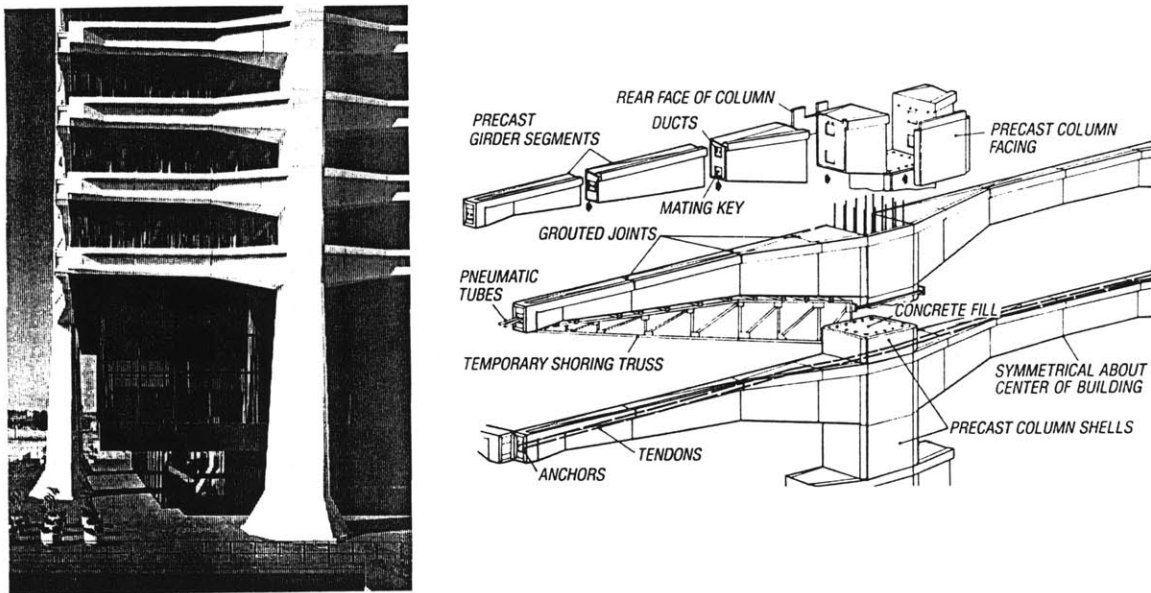
(Figure 5-34)   Source; <u>Architectural Precast Concrete, Second Edition,</u>
Beam assembly of Jacksonville's New Tower (29 stories, 430 ft. in height).
Beams were built by precast concrete pieces by post tensioning.

According to the previous considerations concerning moment-resisting connections, the connection in Figure 5-28 must have a high capacity for vertical loads, but the welded connection is not allowed at critical locations. At the connections in Figures 5-29 and 5-30, the ineffectiveness against the negative bending moment caused by the absence of anchors at the bottom of the beams makes them inappropriate for high lateral loads. However, the continuity of the column might allow it to be combined with a column base structure. At the connection in Figure 5-29, an insufficient amount of stirrups around the ends of the tendons may reduce the capacity for shearing loads. The connection in Figure 5-31 is almost comparable with cast-in-place connections. However, the splice sleeve joints at the bottom of the columns may need to be qualified by practice.

Despite the large amount of cast-in-place concrete, the connection in Figure 5-31 is the most common and practical for the following reasons: (1) the continuity of the re-bars at the top and bottom of the beams makes it a rigid and ductile connection; (2) cast-in-place concrete and the topping concrete are poured at the same time, which makes the slab and beam monolithic and also saves labor cost; and (3) the reduced weights of

precast concrete beams facilitate the lifting works, particularly when U-shaped precast shell beams are adopted. Typical details of a cast-in-place connection are shown in Figures 5-35 and 5-36.
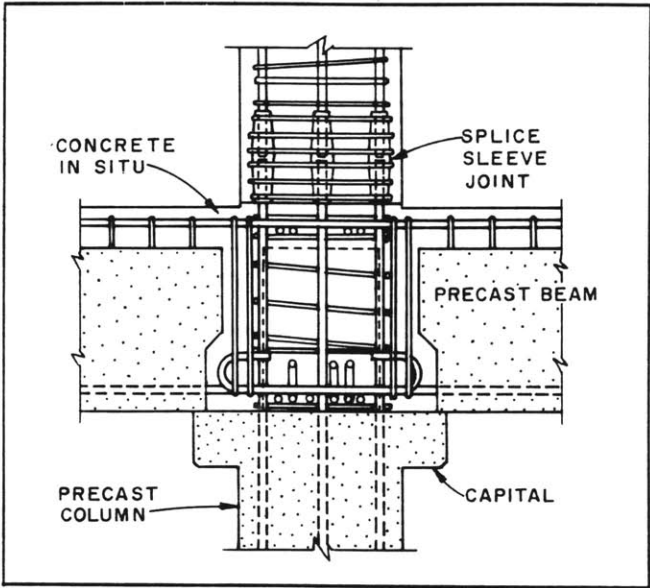
(Figure 5-35)   Source; PCI Journal, March-April 1987,
Detail of a cast-in-place connection.
A capital at the top of column should provide temporary support to a beam, but it does not work for a structural system. These capitals tend to be eliminated recently as shown in the next figure.
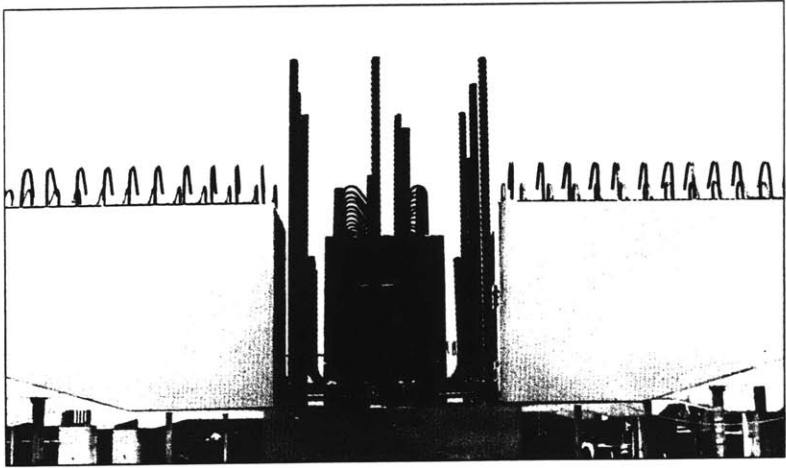
(Figure 5-36)   Source; Toda Technics: Toda-Rahmen Precast Concrete Method
Cast-in-place connection

As a whole, the applications of moment-resisting connections must conform to the provisions of the Codes. But it must be noted that the connections of the precast concrete pieces, which are critical parts of precast concrete structures, can be improved. Allen points out that "Joint design is the area in which precast concrete technology is developing most rapidly. Many new joining systems are patented each year, and as grouts and adhesives develop further there will be further simplifications and improvements of many kinds in precast concrete framing details."[19]

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[19]Allen, Edward. p. 535.

Chapter 6

Rules and Constraints of Braced Frame Structural System

6.1. Introduction

In this thesis, the term "braced" refers to the lateral load support systems that include shear walls, frames filled inside with brick or block walls, and diagonal braces. Since both moment-resisting frames and pin-frames can be braced, the braced frame structural system contains one or two orthogonal braces to provide lateral rigidity. In this sense, the braced frame structural system is widely variable in its combinations of frame (either pin frame or moment resisting frame), kind of braces, and direction of bracing (Figure 6-1).
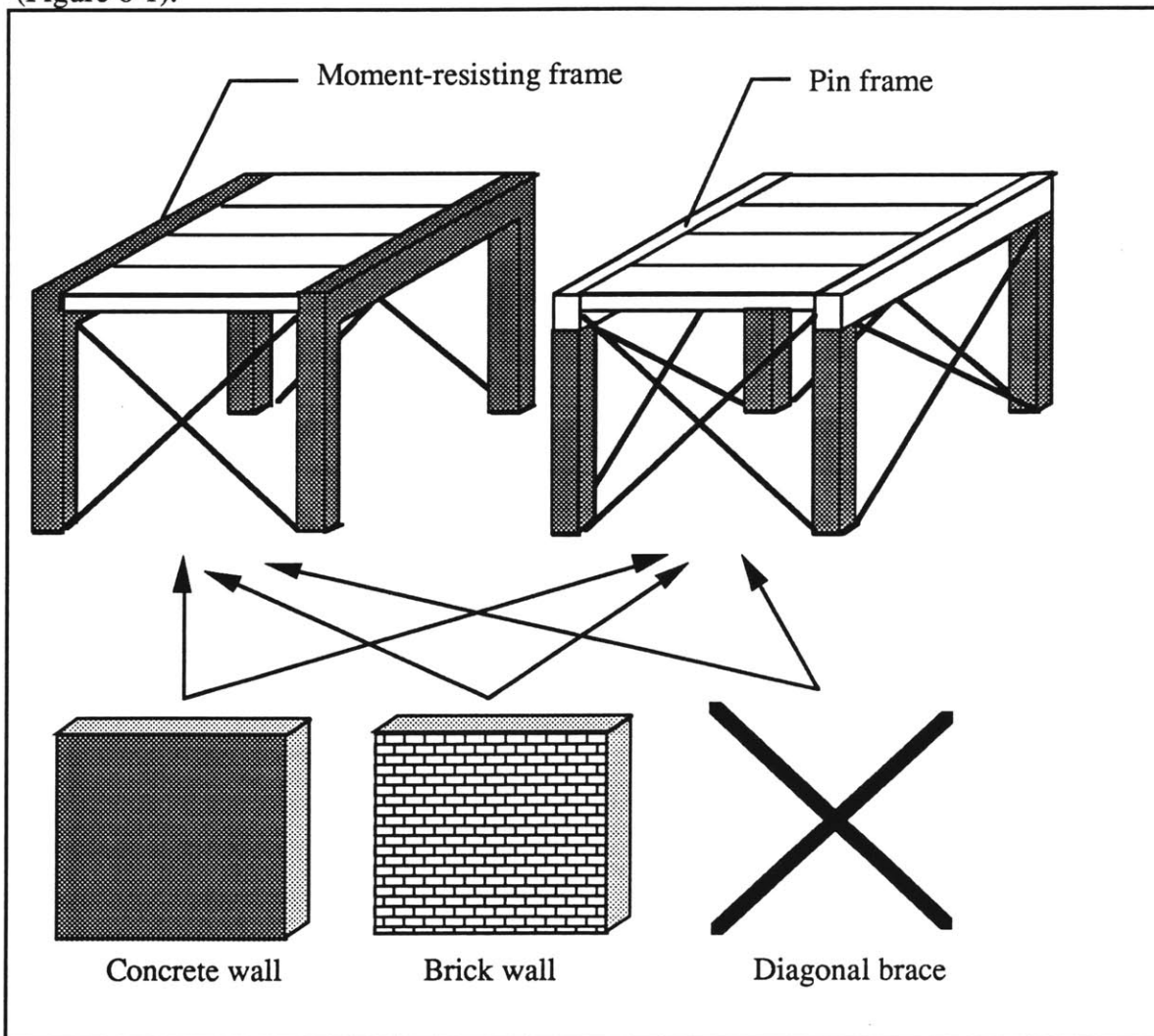
(Figure 6-1)   The combinations of braced frame structure

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Compared with the unbraced frame structural system, the braced frame structural system has higher lateral load stability, longer frame spans, and lower construction cost, which make it advantageous for medium to high-rise office buildings. This structural system is not commonly used in the construction of low to medium-rise multifamily houses. This might be because a dimensional incompatibility between large frame spans and a required floor area of each apartment would cause an uneconomical redundancy of superstructure and of concrete separating walls.

Separating walls, which divide each floor into several apartments, have to provide sound insulation and fire protection. For this reason, separating walls are usually made with either concrete, brick, or block , regardless of their functions (structural or non-structural), while partitions inside houses are made by light walls. Thus, the large span of the braced frame structural system is not necessarily advantageous for multifamily houses. As shown in Chapter 2, a hollow core plank can span some 40 feet without intermediate support. This means that such planks, combined with braced frames, can make a hollow space which will accommodate several apartments. However, if apartments are divided by concrete separating walls at the same position throughout every floor, a load-bearing wall structure would make more sense.
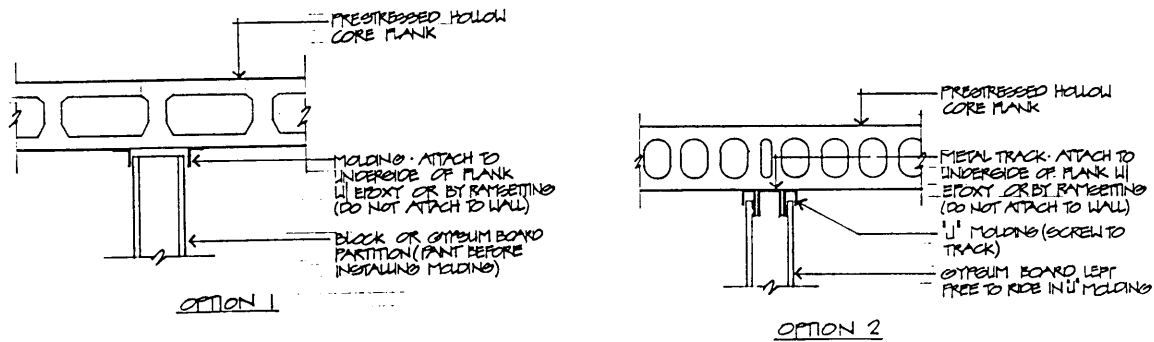
6.2. Braced frame structural system at Level 1

Phillips and Sheppard note that "When hollow core planks are used in housing or motel applications where the underside of the plank forms the finished ceiling, partition attachment details should allow for movement of the plank due to temperature changes and creep and shrinkage effects on camber and plank self weight deflection."[1] To attain fire and sound protection, separating walls of houses have to reach to the bottom of the upper slab, where joints with clearance for movement are required (Figure 6-2). Although fire protection can be attained not only by concrete walls but also by dry walls, the latter are less effective for sound insulation. The ACI Code suggests the maximum permissible computed deflection of the precast prestressed slabs that support non structural elements likely to be damaged by large deflections as L / 480 (L = span)[2].

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[1]Phillips, W, R. , & Sheppard, D. A.. p. 344.
[2]Ghosh, S.K. and Rabbat, B. G. (Eds.). Notes on ACI 318-89: Building Code Requirements for Reinforced Concrete. 1990. Portland Cement Association. p. 8-3.

However, virtual limitations must be examined considering the densely located partitions in a house as well as its infrastructure, such as piping or electricity.

(Figure 6-2)   Source: Plant Cast Precast concrete and Prestressed concrete: a Design Guide
Partition attachment details.

Two primary advantages of braced frames are inherent in if combined with structural system: (1) their large span and (2) their high maximum building height. The long span of precast prestressed concrete beams and slabs is facilitated by pin connections between columns and beams, which call for bracing.

With regard to high-rise housing, a braced frame structure, especially that with a moment-resisting frame, can make a more rigid structural system compared to the unbraced frame structural system or the large panel structural system. By bracing a moment-resisting frame, both lateral rigidity and low dead load resistance can be enhanced. This approach can be seen in two typical high-rise building systems: hull-core systems and equal span grid systems (Figures 6-5, 6-6). It must be noted that these structural systems are basically different from long span structural systems in that they are considered as subsets of the moment-resisting frame structures.

In terms of a structural system for open system houses, the wider span of the braced frame structural system may seem preferable to the shorter span of the moment-resisting frame. However, the length of a frame span might be dictated by architectural dimensions rather than by the economy of the structure, because the position of columns

implies a module by supporting separating walls and other infills. Also, the arrangement of pipe shafts for kitchens and bathrooms, which should be kept away from any regions of large deflections, is dictated by the module. For all these incompatibilities, if a housing system is designed so that a super structure and infills are physically separated, the long span and high rigidity of the braced frame structure provide a good support system. For example, the "Townland" system (Figure 6-3), part of Operation Breakthrough, uses a huge uninterrupted space to make several stories of platforms and builds individual houses within.

By dealing with infills within each floor, impacts of floor deflections on infills can be avoided and the large inner spaces can be put to good use. Services could be provided from a core, which is located around columns or combined with them, through the platforms. Ceilings and partitions are supported by the same platform and thus, damages caused by deflections are not likely. Although this kind of system causes a significant redundancy of superstructure and infills, it may be one of the possible alternatives, considering the dimension of inner space provided by a braced frame structural system accompanied by precast prestressed concrete slabs - - up to 40 feet for hollow core slabs, and up to 75 feet using tee slabs in a transverse.[3] This separation of a structural system and infills supports dramatic alteration of each apartment viable and thus especially advantageous for multifamily houses which change owners periodically.

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[3]According to the PCI design Handbook, these numbers are 40 ft. and 100 ft. respectively. The 75 ft. figure cited above is the maximum length that can be shipped by road transportation.
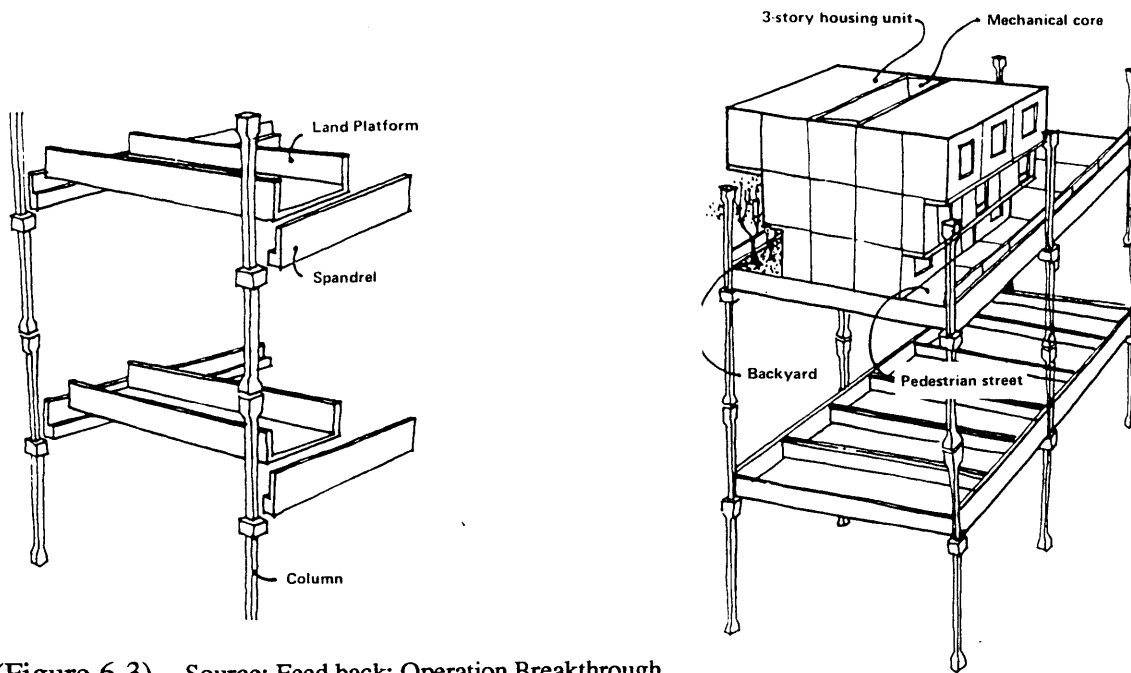
(Figure 6-3)   Source: Feed back: Operation Breakthrough

"The superframe, or 'Supported Land System' (SLS), consists of precast concrete components making up the elevated platforms (Figure A). Infill, for the purpose of the BREAKTHROUGH dimension, is two- and three-story dwelling units that use a number of factory-built parts (Figure B)."[4]   Although not depicted, diagonal braces or shear walls would be necessary to support the super structure.

In the remainder of this chapter, a long span braced frame structural system is considered as a possible application in a housing system. Then, the hull-core system and the equal span grid system are discussed. Since high vertical and lateral stresses induced in the structural system of high-rise multifamily houses pose strict structural constraints, such as configurations of braces or length of frame spans, variations in plans are limited. However, the constructability of precast concrete building systems is of great importance in high-rise multifamily houses.

(1) Long span structural systems

Elliott suggests that the following design stages have to be considered for brace framed structures:[5]

(1) horizontal diaphragm action in the precast floor slab,

(2) transfer of horizontal load from the floor slab to the vertical bracing elements,

(3) transfer of load to the foundation, and

(4) component and joint design.

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[4]U.S. Department of Housing and Urban Development. Feed back: Operation Breakthrough. 1973. p. 205

[5]Eliott, K. S. (1992). The Design of Modern Precast Concrete Multistory Framed Structures in the United Kingdom. PCI Journal, May-June 1992, p. 44.

He also notes regarding the transfer of loads and stability that: "The problem is to ensure adequate ultimate strength and stiffness, but more importantly to ensure that the failure mode is ductile. . . This is not to say that precast frames are designed as 'energy sinks,' but simply that load paths are directed away from the mechanical connections toward the under-reinforced precast components and in situ tie beams."[6] This description makes it clear that a braced frame structure has to be designed to carry the lateral loads from the slabs to the braces without causing stresses at the beam-to-column connections that are designed as pin connections.

Since a building has to resist lateral forces from all directions, rectangular buildings must have a lateral load resisting system for each of the two orthogonal directions. It is important that each lateral load resisting system employ either bracing, moment-resisting frames, or their combination. These wide choices of bracing in terms of locations and methods create a variety of braced frame structures.

With regard to the long span of the braced frame system, schematic structural designs are shown in Figure 6-4. In figure (a), lateral loads are resisted by the moment-resisting frame in the longitudinal direction and by braces in the transverse direction. In figure (b), the frame has pin connections and is braced in both of the orthogonal directions. In figure (c), pin frames are placed only in the transverse direction while lateral loads are supported by braces in both of the orthogonal directions. The dimensions in each case might be dictated by the possible length of precast prestressed concrete slabs and the number of stories. Figures (b) and (c), where the frames have pin connections, can employ precast prestressed concrete beams, while the longitudinal span of figure (a) is limited by the lateral load resistance of connections. Each of the three figures can be duplicated to comprise a larger structural system.

In general, as discussed in Chapter 4, monolithic connections of the moment-resisting frame are complex and costly. The PCI Design Hand Book recommends designing a precast concrete frame structure with simple pin connections and shear walls if an economical structure is desired, noting that ". . . it is most desirable when designing

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[6]Eliott, K. S. (1992). p. 44.

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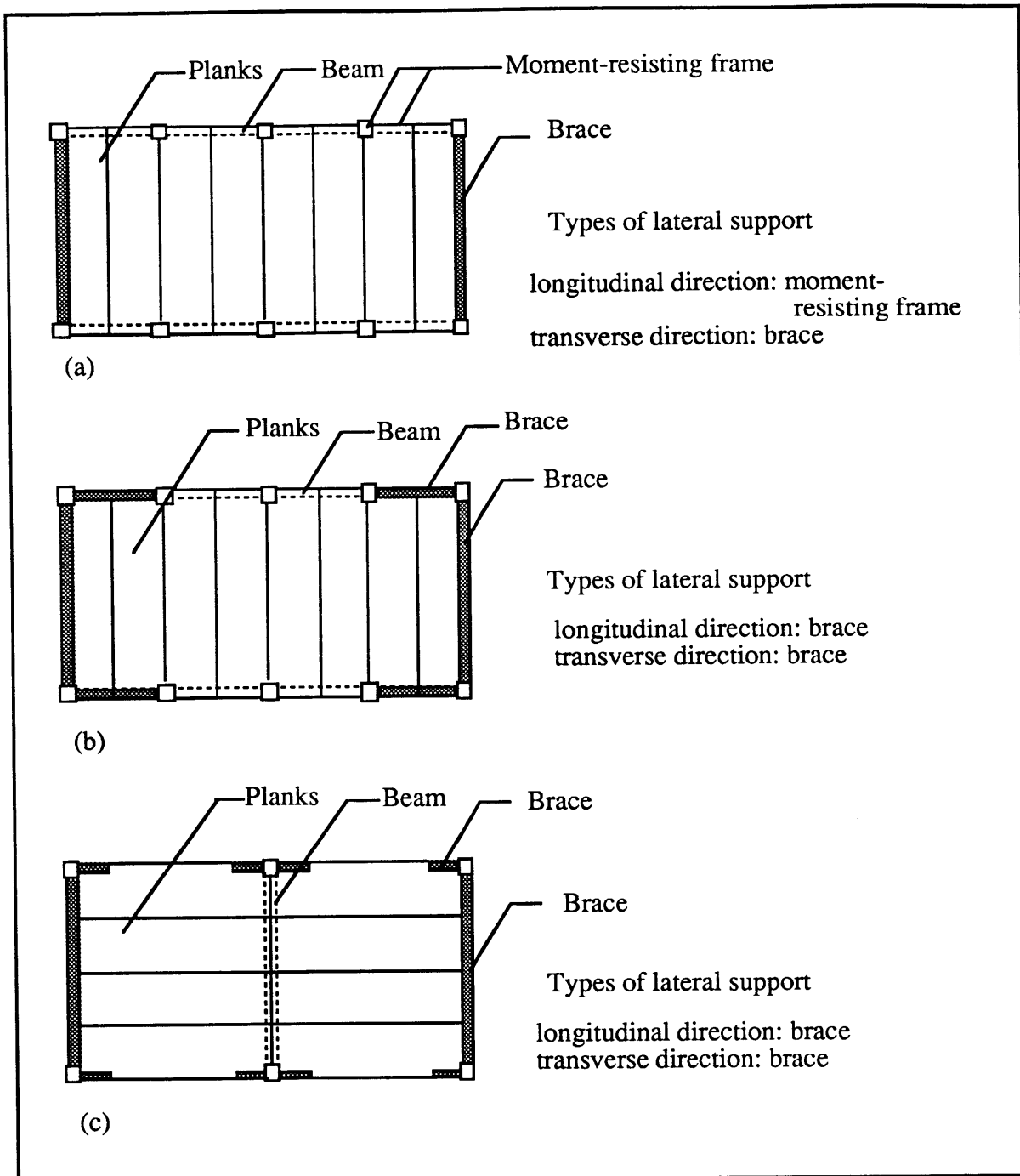
(Figure 6-4) Schematic designs of long span braced frame structural systems

precast, prestressed concrete structures to have connections which allow lateral movement and rotation, and achieve lateral stability through use of floor and roof diaphragms and shear walls."[7] However, the application of moment-resisting frames in

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[7]PCI Design Handbook, p. 3-43.

one direction is still a useful alternative to make an open end. The transfer of loads in each of the three schematic designs shown in the Figure 6-4 are considered in the following section (4.3).

(2) High-rise structural systems

In terms of maximum building height, Elliott, from a study based on a case in Great Britain, indicates that "Structures exceeding three stories or 33 ft (10 m) in height should certainly be designed as braced."[8] He also says that the braced frame structure can be built up to about 20 stories.[9] While his descriptions are of the braced frame with pin connections[10], the braced frame with moment-resisting frame can attain higher maximum height by constructing the hull-core system or the equal span system.
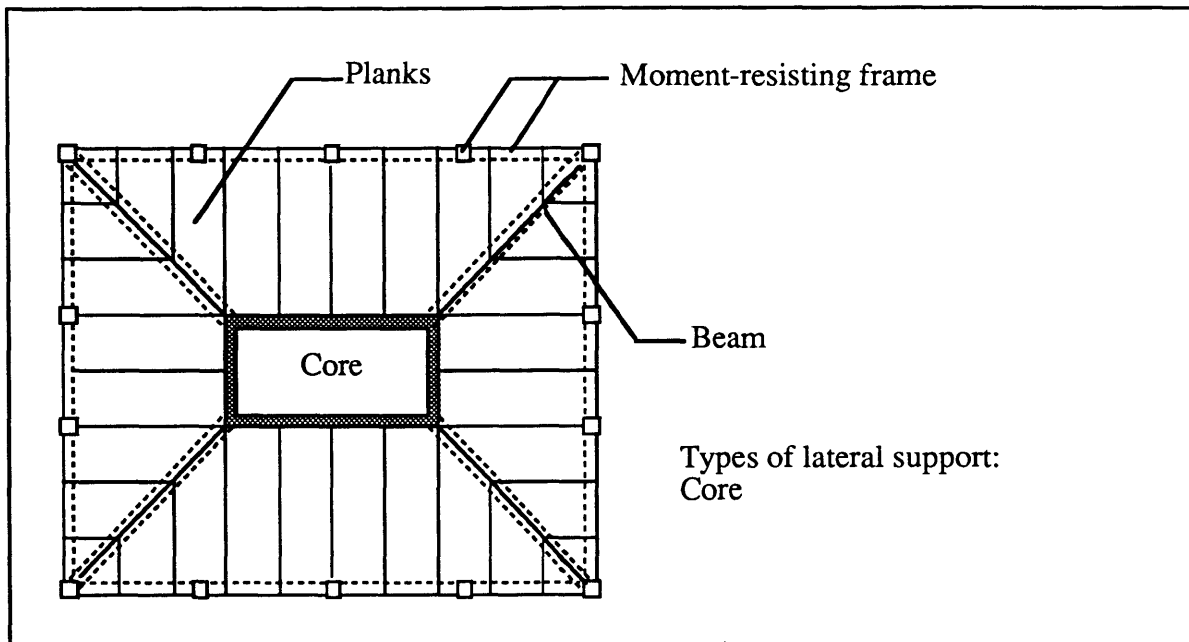

(Figure 6-5) Schematic design of hull-core system

The hull-core system (Figure 6-5) is one of the most effective structural systems since a structural core resists lateral loads in both of the orthogonal directions, and its symmetrical configuration decreases the possibility of torsion. Although the absence of structural cross walls make the structural system suitable for office buildings, large

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[8]Eliott, K. S. (1992). p. 34.

[9]Eliott, K. S. (1992). p. 32.

[10]Although the information is limited, 20 to 30 stories might be thought of as maximum for the braced pin frame structural systems.

uninterrupted inner spaces are not necessarily advantageous for multifamily houses, as previously stated. Foster notes the outline of this kind of structure as follows: "A development of this for very tall buildings, known as the 'hull-core' system, utilises (sic) a rigid or braced framework for the perimeter structure to form stiff walls interacting with each other to produce an external annular structure, called the hull."[11] Even though a structure may have a symmetrical floor section, turbulent wind will cause a torsional moment as the building's height increases. For this reason, torsional rigidities as well as symmetrical configurations are required for these types of structures.

Beam

Brace

Types of lateral support:
moment-resisting frame
and braces
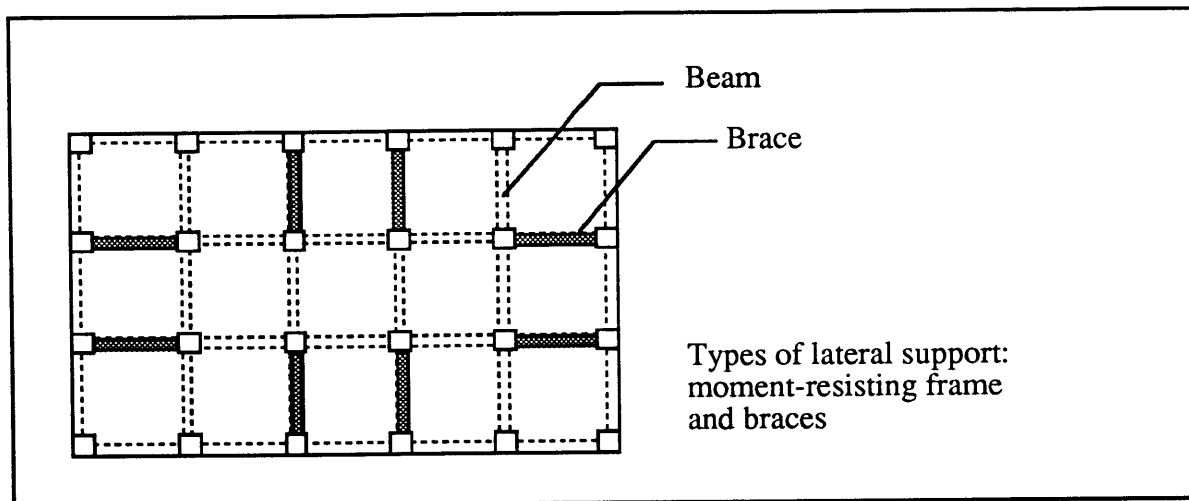
(Figure 6-6) Schematic design of the equal span grid system

Alternatively, the equal span grid system consists of moment-resisting frame and braces (Figure 6-6). The spans do not have to be the same in both directions. However, uniform spans make for an equal distribution of applied loads and identical dimensions of the pieces, and as a result the economy of precasting can be improved. Compared to the hull-core structural system, this system has many columns and braces. The braces can be concrete shear walls which also make good separating walls. This structural system has become common in Japan (Figure 6-7), due to the diffusion of precast shell pieces (column, beam, and slab) which facilitate lifting as well as making monolithic connections, and also due to the development of high strength concrete.[12]

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[11]Foster, J. S. Structure and Fabric Part 2. Great Britain: B T Batsford Limited. 1977. p. 197.

[12]"Recent collaborative R & D project in Japan on innovative reinforced concrete has attained the use of the concrete of 600 kg/cm^2 (8,300 psi) for commercial use. Now 1,000 kg/cm^2 (13,750 psi) has come close to practical use. . .40 to 50 story high-rises can be built by 600 kg/cm^2, while feasibility of construction by 1,000 kg/cm^2 is an issue of economy." (Trans. from Nikkei Architecture 31, January 1994., Japan.)
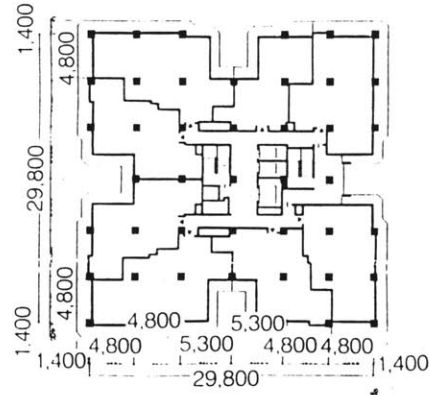
(Figure 6-7)   Source: Monthly Building Engineering Magazine, January 1994. p.80.
A multifamily house in Kawasaki, Japan. An example of a high-rise housing built by the equal span grid system (30 stories, 285 ft.). This project uses precast shell beam and slab. The strength of concrete is 420 kg/cm^2 (5775 psi.).

While the structural core of the hull-core system and the braces of the equal span grid system have to be constructed by cast in place concrete shear walls to avoid the accumulation of lateral displacement at each floor, the application of precast concrete columns, beams, and slabs has great advantages because of the elimination of horizontal formworks (set up, stripping, and lifting temporary materials) at elevated work places. It must also be noted that the rigid behavior of a reinforced concrete structure under cyclical lateral loads is preferable to the flexible behavior of a steel structure, which causes an uncomfortable swaying movement at the highest stories.
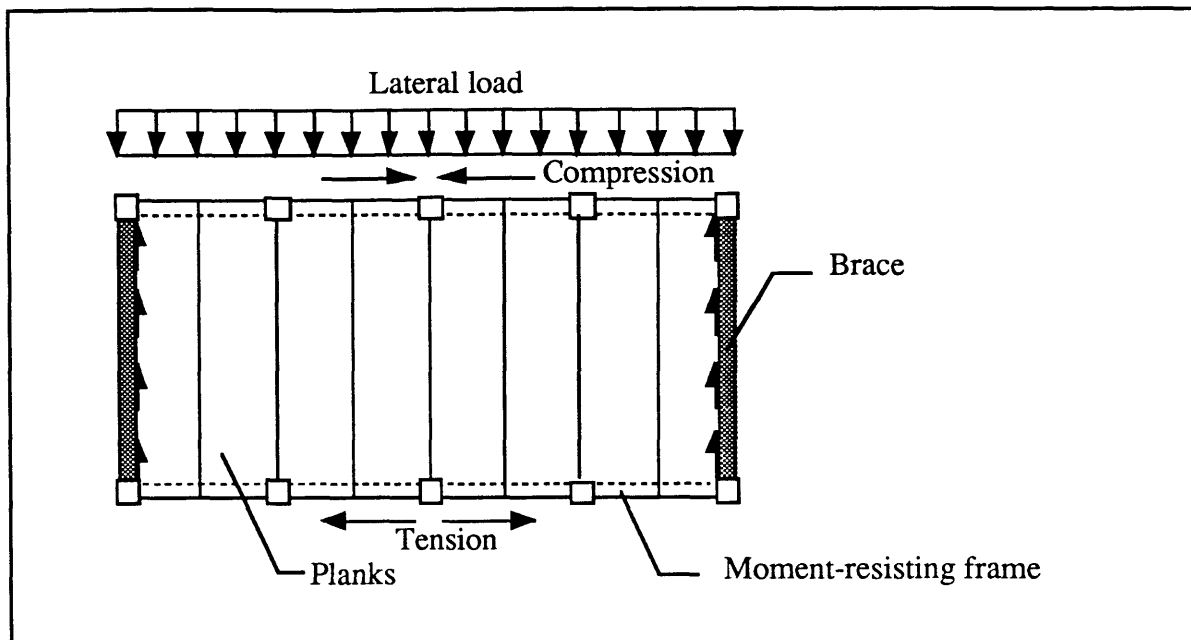

6.3. Braced frame structural system at Level 2

6.3.1 Dimension

(a) Long span structural system

The PCI Design Hand Book explains the functions of slabs and braces as follows: "The diaphragm is analyzed by considering the roof or floor as a deep horizontal beam, analogous to a plate girder or I-beam. The shear walls or structural frames are the supports for this analogous beam. Thus the lateral loads are transmitted to these supports

as reaction. As in a beam, tension and compression are induced in the chords or 'flanges' of the analogous I-beam."[13] This conceptualization is shown in Figure 6-8.


(Figure 6-8)   Reference: the PCI Handbook
Moment-resisting frame with braces
Lateral loads and reactions at the long span braced frame structural system

The structural system in Figure 6-8 has braces in the transverse direction and moment-resisting frames in the longitudinal direction. The transverse lateral load is carried from the slab to the braces by diaphragm action in the slab. As previously explained, the lateral load also causes tension and compression in the longitudinal direction. However, the PCI Design Handbook notes that "Stresses are usually quite low, and only as many bars or weld plates as required should be used."[14] Details are shown in the next section (6.3). Additional transverse braces are required as the structure expands in the longitudinal direction. Lateral load in the longitudinal direction is resisted by moment-resisting frames which consist of elements in the same plane. These two dimensional frames facilitate the precasting of beam and column units.

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[13]PCI Design Handbook. p. 3-27.

[14]PCI Design Handbook. p. 3-29.
An example of the computation of this chord force is shown in the Design and Construction of Large-Panel Concrete Structures: Report 4. (U.S. Department of Housing and Urban Development, Office of Policy Development and Research. October 1977.) , which indicates that the chord forces can be sufficiently resisted by the connections between slabs.

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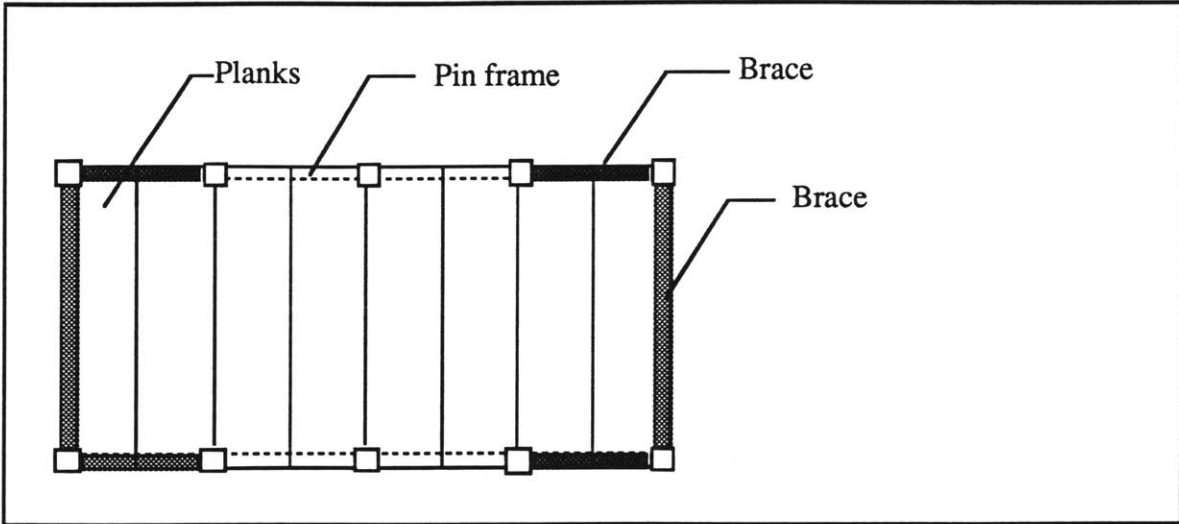
(Figure 6-9)
Pin frame with braces

The structural system in Figure 6-9 has pin connections between columns and beams and braces in both orthogonal directions. The transfer of the lateral load in the transverse direction is the same as that shown in Figure 6-8. The lateral load in the longitudinal direction is resisted by braces. Since the load capacity of braces can be controlled by their thickness and by the frame at the periphery, the proportion of braced to unbraced bays in the longitudinal direction can be varied, with floors planned for a desired dimension.
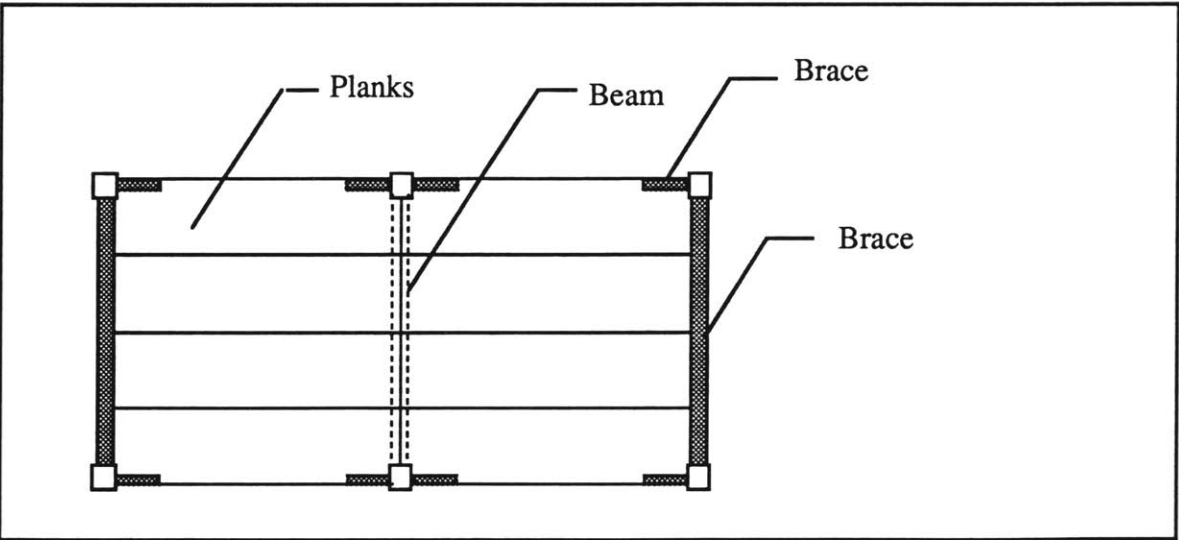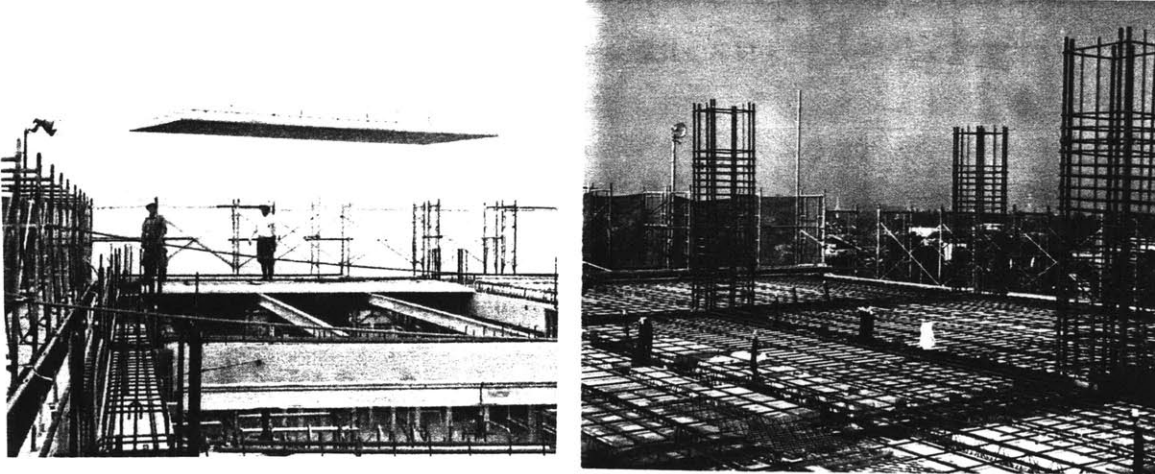

(Figure 6-10)
Pin frame with braces

When planks are placed in the longitudinal direction, supporting frames are required in the transverse direction (Figure 6-10). These frames can be either braced, as shown in the figure, or moment-resisting, which is equivalent to a duplicated form of the system shown in Figure 6-8. To make openings, longitudinal braces have to be shear walls with openings, or partial shear walls beside the columns. Although this configuration has a long span in both of the orthogonal directions, some structural inefficiencies occur in that (1) the absence of frames in the longitudinal direction makes bracing difficult, and (2) the long transverse beams support high dead load and service load, possibly causing substantial deflection. Comparing the previous three configurations, economical structures can be attained most easily when precast prestressed concrete slabs are parallel to shear walls.

(b) High-rise

In the hull-core system shown in Figure 6-5, slab members are simply supported by a core at the center and frames at the perimeter, thus creating uninterrupted inner space. The length of slab members is a function of building height, the proportion of the core area to the total floor area, as well as the span of the beams at the perimeter. On the other hand, in the equal span grid system, which is basically a hybrid of moment-resisting frame structural system and braced frame structural system, spans are usually limited to 6 m (20 ft.).[15] For this reason, precast solid slabs or precast shell slabs are commonly used to take advantage of two-way action rather than precast prestressed concrete slabs (Figures 6-11, 6-12).

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[15]Monthly Building Engineering Magazine, Japan. January 1994. p. 80.

(Figure 6-11) Source: Toda Technics: Toda-Rahmen Precast Concrete Method
Setting precast concrete shell slabs (left) and two-way reinforcement (right).

(Figure 6-12) Source: Kenchiku Gijyutu. Japan. December 1992.
Construction of a high-rise multifamily buildup by the equal span grid system. (31 stories, 340 ft.
Kagawa, Japan).

6.3.2 Articulations

With regard to the articulations of frames, as mentioned above, either moment-resisting frames or pin frames are adopted in braced frame structures. Each of the frames

has a different possibility for articulation because of the required functions at the connections between columns and beams.

When the frame has to have moment rigidity, as in the scheme shown in Figures 6-4 (a) and 6-5, the alternative methods are either to cast-in-place beam to column connections, or to deliver "beam and column units" with mechanical joints. In the braced frame structural system, the articulations of the beam and column unit are different from those of the moment-resisting structural system (discussed in Chapter 5) in that the former are comprised of elements within a single vertical plane and these planes do not have projections of beams normal to that plane. The lack of these projections facilitates precasting, transportation, and handling, and as a result, multi-column units (Figure 6-13) are added as alternatives.
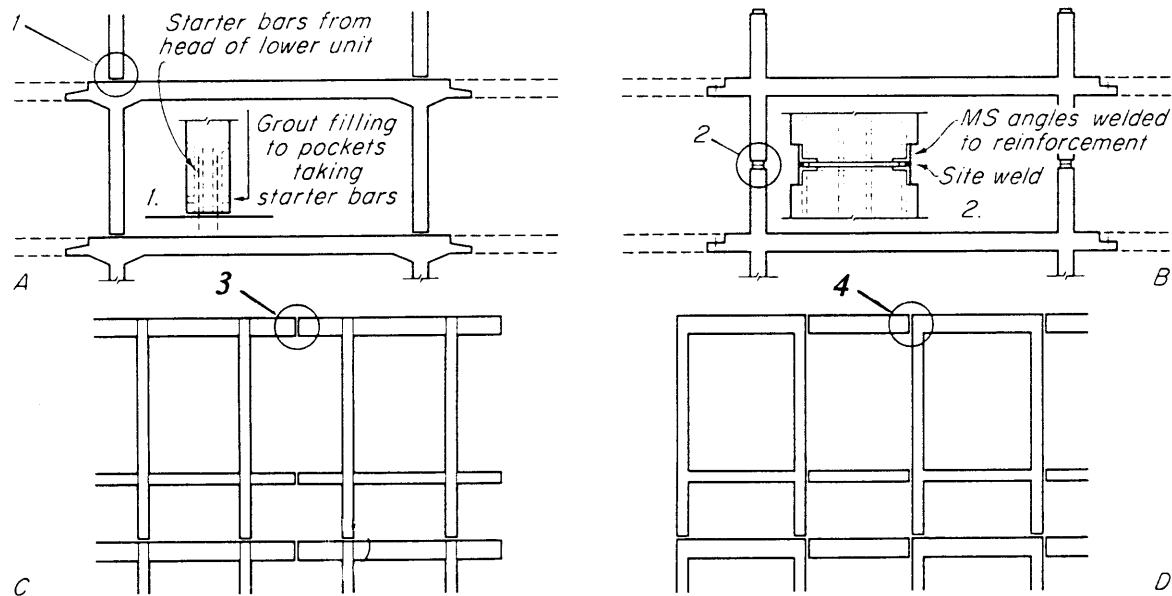
(Figure 6-13)   Source: Foster, J. S. Structure and Fabric Part 2.
The articulations of beam and column units (elevations). Connection details 1 and 2 are shown in the figures. Details 3 and 4 are shown in Figure 6-18.

Foster describes the beam and column units as follows. "These can be formed in various ways but each type consists essentially of a pair or more of columns linked by a beam and so formed that beam and column connections do not occur at the same point, thus overcoming the difficulties of assembly which arise when they do coincide. A pair of columns linked by a beam is easier to brace temporarily while the joints are being

made than separate columns. Such units are, therefore, easier and quicker to erect than separate beams and columns."[16]

When moment rigidity is not required for a frame, as in the scheme shown in Figures 6-4 (b) and (c), the frame is articulated at beam to column connections to simplify the precasting, transportation, and handling. Although the pieces are more fragmented than in beam to column units, greater tolerance at connections facilitates erection. For this reason, multi-story columns with corbels or structural steel haunches as shown in Figure 5-11 can be employed.

6.4. Braced frame structural system at Level 3

1. Slab to slab connections

The connections between adjacent precast concrete slab panels play a critical role in making pieces work together as a diaphragm to resist shear forces (as shown in Figure 6-8). Precast concrete slabs have two variations: (a) precast prestressed concrete slabs, such as hollow core slabs or solid flat slabs, with no composite topping, and (b) these slabs with composite topping.

(a) Precast prestressed concrete slabs without composite topping:

The PCI Design Hand Book notes that "In floors or roofs without composite topping, the shear transfer between members is usually accomplished by weld plates or grout keys, depending on the members."[17] Typical details are shown in Figure 6-14.

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[16]Foster, J. S. pp. 218-9.
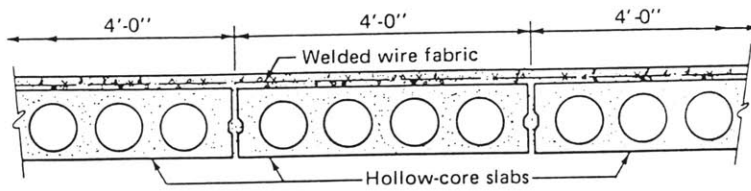
[17]PCI Design Handbook. p. 3-27.
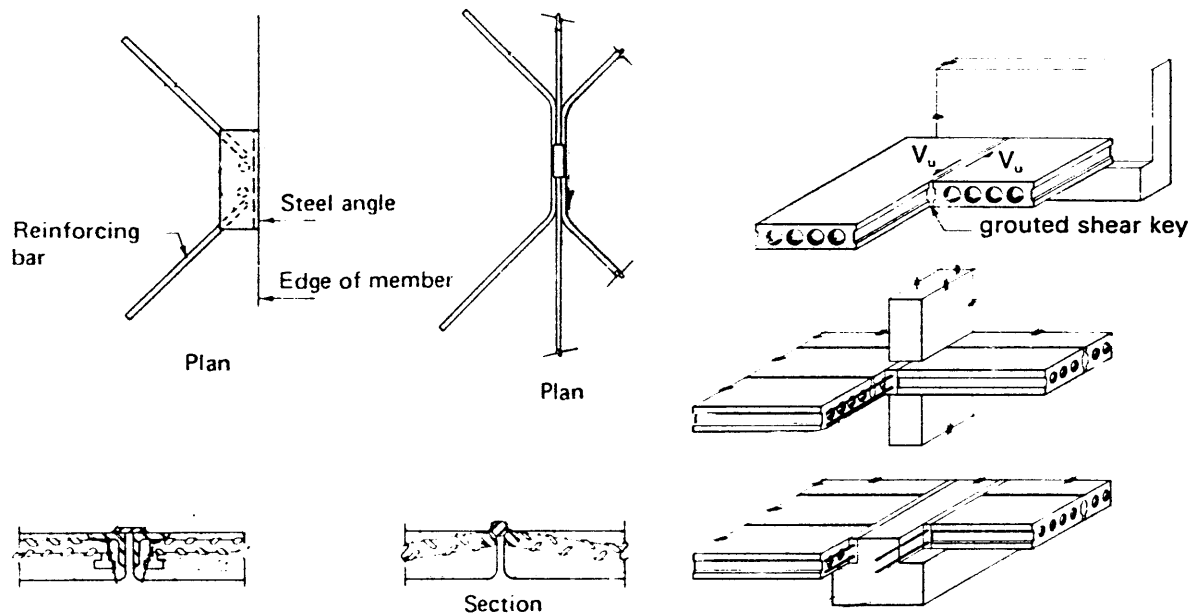
(Figure 6-14)   Source: PCI Design Handbook
Connections between slabs when composite topping concrete is not used
Welded plates (left) and grout keys (right)

With regard to housing, the absence of topping could be troublesome because of the camber of precast prestressed concrete pieces. While the errors of floor surface level could be neglected in some of the commercial buildings which have large inner spaces without infill walls, such a tolerance is limited in houses. In other words, the high density of infills and service infrastructures requires demands that floors be level. This issue is very important when infills are standardized and an open system is employed.

(b) Precast prestressed concrete slabs with composite topping:

Composite topping concrete is poured onto the pieces after placing welded wire fabric (Figures 6-15, 16). Composite topping not only connects adjacent pieces but also adds to the vertical load capacity of the slab. In addition, monolithic connections between slab and beam as well as slab and shear walls are facilitated by embedding dowels for those beams and shear walls into the concrete topping. (Figures 6-17, 18)

(Figure 6-15)   Source: <u>PCI Design Handbook</u>
Hollow-core slabs with composite topping. Usual thickness of topping concrete is 2 in.


(Figure 6-16)   Source: Toda Technics: <u>Toda-Rahmen Precast Concrete Method</u>
Concrete casting

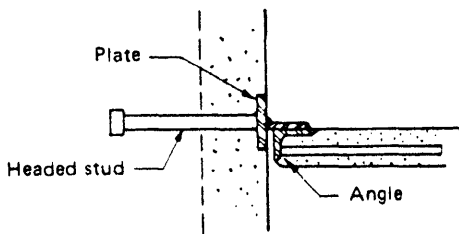## 2. Slab to beam / slab to brace connections

Since the transfer of lateral load can be induced between slabs and braces (braced frames or shear walls) as well as between slabs and moment-resisting frames, these connections have to resist horizontal shear forces. Dowels are commonly used to ensure the shear load capacities of the connections (Figures 6-15, 16, and 17).
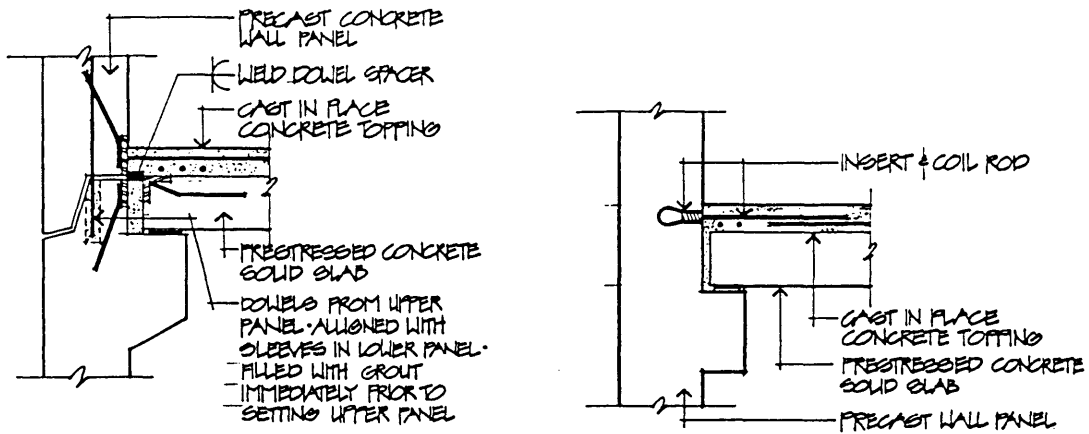
(Figure 6-17) Source: Plant Cast Precast Concrete and Prestressed concrete: A Design Guide.
Slab to wall connections of planks.
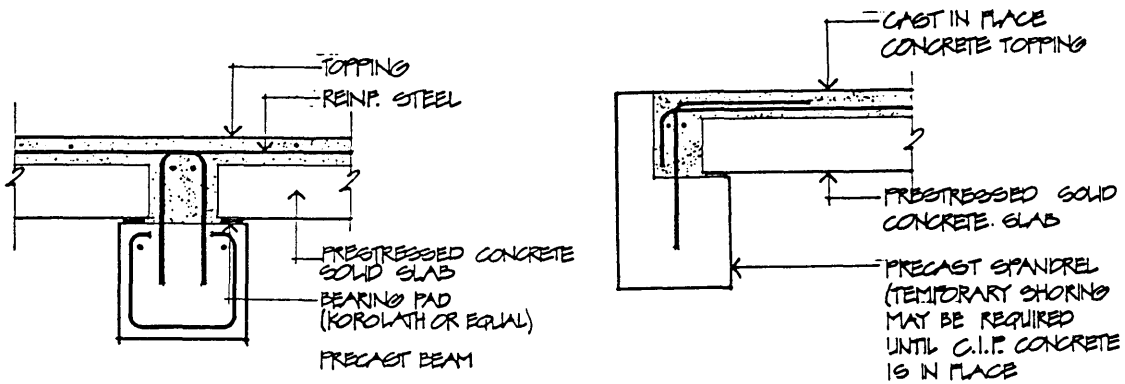
(Figure 6-18) Source: Plant Cast Precast Concrete and Prestressed Concrete: A Design Guide.
Slab to beam connections of planks

(Figure 6-19) Source: PCI Design Handbook
Slab to wall connection without topping concrete

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3. Frame connections

When lateral rigidity is required for a certain part of a frame, this part has to be built by moment-resistive connections or "beam and column unit", which could be either single column or multi column. The details of moment-resistive connections were shown in Chapter 5. Although examples of the connections between each 'beam and column unit' are shown in Figure 6-20, "standard" details cannot be suggested because the 'beam and column unit' is not a popular method at this time.
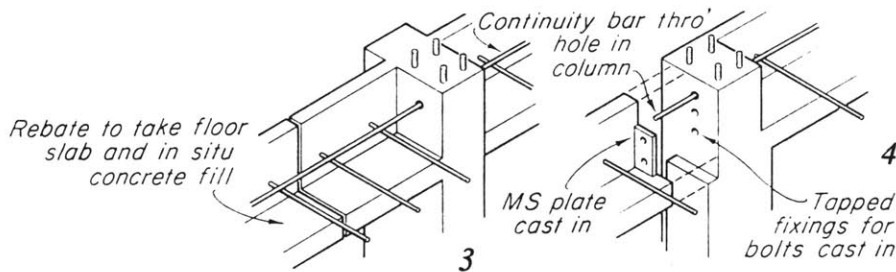
(Figure 6-20)   Source: Foster, J. S. Structure and Fabric Part 2.
Connections of beam and column units which correspond to the frames shown in Figure 6-13.

The connection between beam and column units represents an area for which further research is required to enhance the constructability of precast concrete frame structures. Mechanical connections which have enough tolerance for assembly or cast-in-place connections with no fuss might be useful (Figure 6-21).
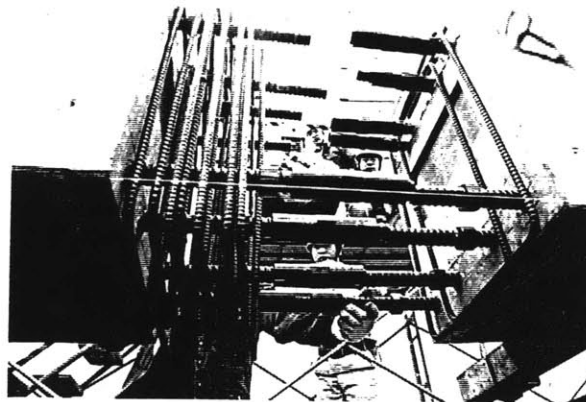
(Figure 6-21)   Source: Toda Technics: Toda-Rahmen Precast Concrete Method
Screw joint at a beam to beam connection

Chapter 7

Structural Rules and Constraints of

Large Panel Structural Systems

7.1. Introduction

The large panel structural system can be defined as the system that consists of precast concrete load-bearing wall panels and precast concrete slabs. Precast concrete slabs include precast prestressed concrete slabs, precast solid slabs, and precast concrete shell slabs. This structural system has been most commonly employed in the construction of low to medium-rise multifamily housing (1 to 11 stories). This may be because structural walls provide the fire resistance and sound insulation required at the separating walls and because manufacturing the pieces and assembling them on site is relatively easy compared to using frame structural systems. However, considerations in this thesis are not confined to the common applications of this structural system; it is intended as an exploration of possible applications of precast concrete technology to all types of multifamily houses.

From the structural viewpoint, the nature of this system can be represented by fragmentation and the vertical uniformity of each floor, since these walls work as lateral supports as well as vertical supports. On the other hand, from the architectural point of view, the configurations and dimensions of structural walls cannot be dealt with without considering zones and/or infill modules. Full consideration of the architectural implications of large panel systems is beyond the scope of this thesis. For this reason, the configurations and dimensions of this structural system are discussed only with regard to its structural rationality, with no consideration of their implications for infill strategies.

7.2. Large panel structural system at Level 1

Since a load-bearing panel provides a lateral support as well as a vertical support, the lateral rigidity of a structural system can be attained relatively easily by interconnecting walls and slabs. The most effective lateral support system is designed by locating panels in both orthogonal directions with a symmetrical arrangement as well as

with vertical continuity. These rules concerning the arrangement of walls are crucial in taller buildings because of the possibility of torsion under lateral loads.

The Design and Construction of Large-panel Concrete Structures: Report 2, a research document published by the U.S. Housing and Urban Department, notes that "Where the center of rigidity of the resisting elements and the center of mass of the structure do not coincide, torsion will be introduced into the structure. Because torsion due to lateral loads can produce significant stress, particularly in peripheral elements, a more or less symmetrical arrangement of the principal lateral load resisting elements should always be attempted."[1] However, for low to medium-rise buildings, the possibility of torsion is less significant and so the location of walls is not always symmetrical. It should also be added that structural symmetry does not necessarily coincide with geometrical symmetry. The primary concern is for establishing coincident centroids of mass and resistance.

Mainstone notes the constraints in planning large panel structural systems as follows: ". . . the walls should not only be fairly closely-shaped and as unbroken as possible in plan but should also be distributed and aligned fairly symmetrically about the principal axes. They should, moreover, be as continuous as possible from top to bottom of the building. In other words, their plan should repeat from floor to floor and should be a reasonably efficient one if read as the cross-section of a large built-up beam."[2] He says, following the above, that the load-bearing wall structural system is not suitable for high-rise housing because of the small variety of floor plans at different levels which is likely to be imposed by the vertical continuity of load-bearing walls.[3] The uniformity of each floor in terms of the dimensions of the apartments is a characteristic of this structural system. However, great variations in each apartment could be attained if the design process included variations of infill, as well as the presence of openings in structural walls.

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[1]U.S. Department of Housing and Urban Development, Office of Policy Development and Research. Design and Construction of Large-Panel Concrete Structures: Report 2. (1976). p. 8.

[2]Mainstone, Rowland. p. 272.

[3]Mainstone, Rowland. p. 272.

Gyula Sebestyén, in the _Large-Panel Buildings_[4], classifies the large panel structural system with regard to the arrangement of load-bearing walls as: (a) longitudinal spine walls, (b) cross walls, and (c) combined spine walls and cross walls (Figure 7-1).
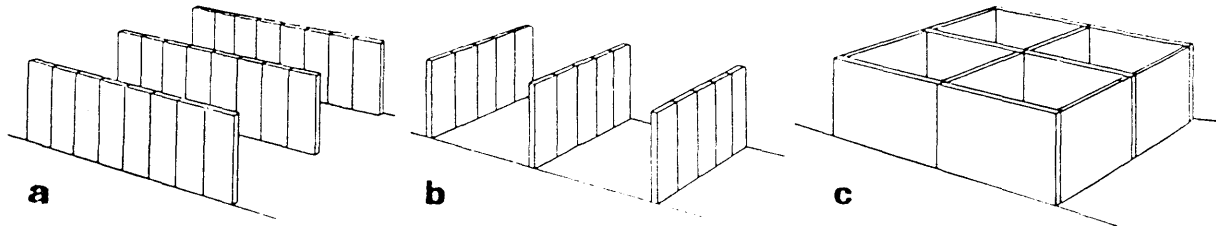

(Figure 7-1) Source; Sebestyén, Gyula. _Large-Panel Buildings._
Classification of load-bearing walls made with large precast units
a. Longitudinal spine walls   b. cross-walls   c. combined spine walls and cross-walls

Sebestyén explains the longitudinal spine wall system and cross wall system as follows: "Owing to the smaller spans, load-bearing cross-wall systems require less reinforcing steel than buildings that contain load-bearing longitudinal walls. On the other hand, with load-bearing cross-wall systems, the amount of walling required is greater. Some walls can be replaced by lintels. The quantity of walling required depends not only on the load-bearing system used but also on the following factors: (i) in the case of load-bearing cross wall construction, on the material and the thickness of the external (non-load-bearing) walls, (ii) on the effect of the party walls upon the amount of walling, i.e. on whether party walls and load-bearing walls can be combined."[5]

Considering the required functions of multifamily housing, the cross wall system provides walls that serve as party walls (separating walls) which provide both fire resistance and sound insulation. On the other hand, the longitudinal spine wall system tends to deprive external walls of sufficient openings which are indispensable for each apartment. For this reason, the longitudinal spine wall system is not commonly employed by housing projects. Schematic designs of the three systems are shown in Figures 7-2 to 7-4.

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[4]Sebestyén, Gyula. _Large-Panel Buildings._ (A. Frankovszky, Trans.) Budapest: Publishing House of the Hungarian Academy of Science. 1965. p. 50.
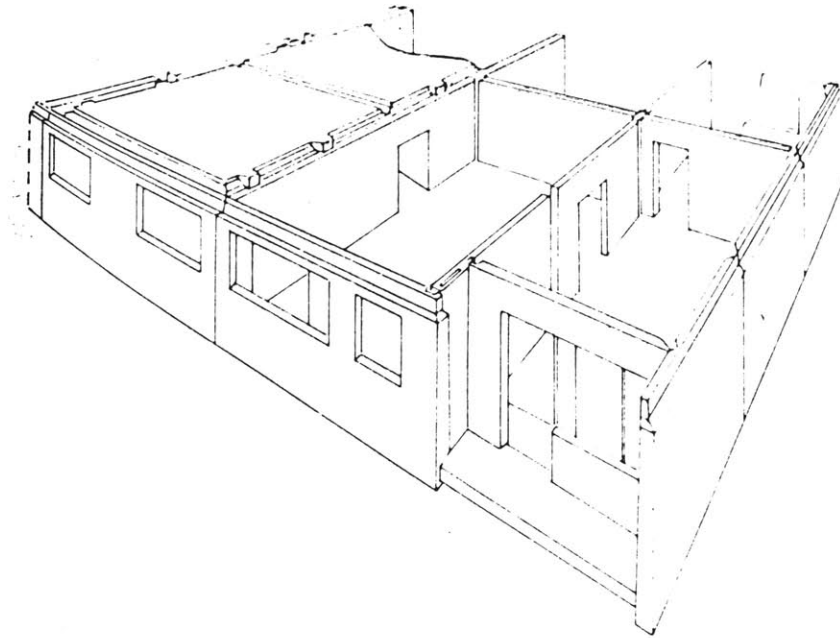
[5]Sebestyén, Gyula. p. 49.
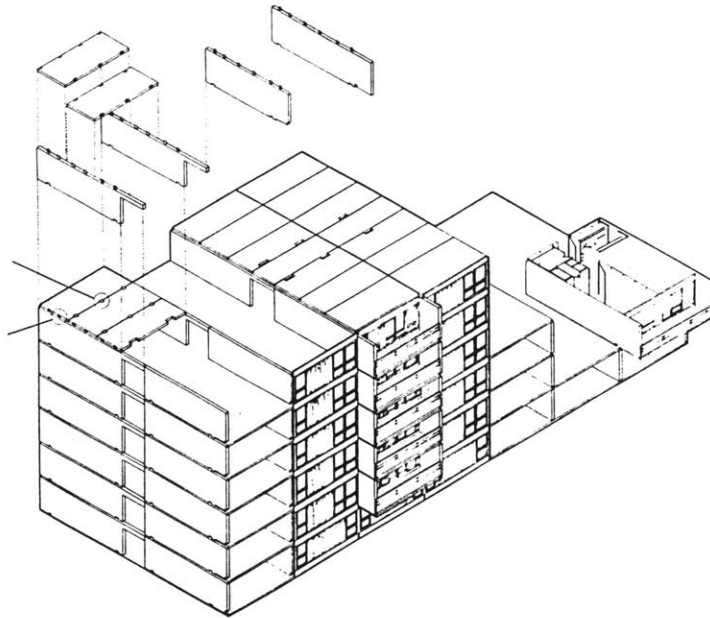
(Figure 7-2)   Source: <u>Feedback: Operation Breakthrough</u>
Cross wall system (Descon / Concordia system, an project at Operation breakthrough)

(Figure 7-3)   Source: Habraken, N. J., <u>Variations: The systematic Design of support.</u>
Spine wall system

(Figure 7-4)   Source: Diamant, R, M, E. <u>Industrialized Building 1.</u>
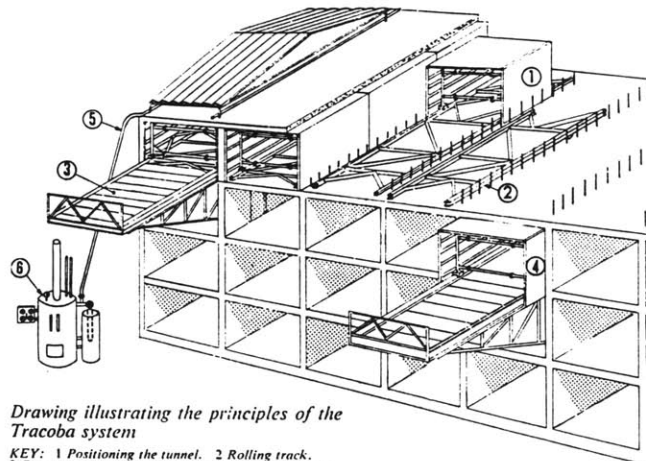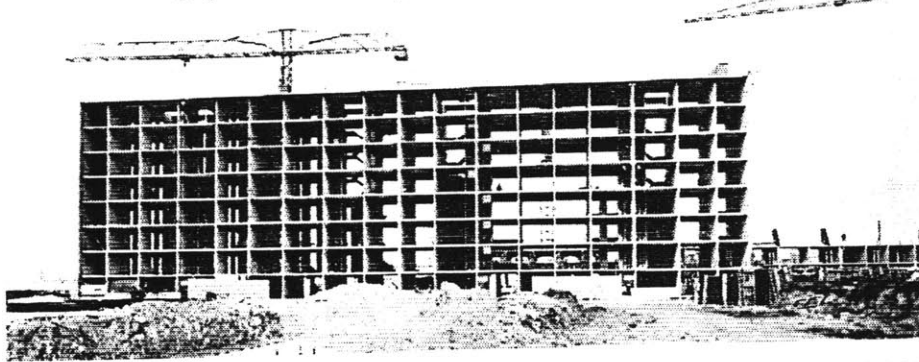Mixed system (Tracoba system, France)

With regard to the combined spine walls and cross walls (mixed system), each floor is divided into smaller spaces. However, the increased number of structural walls allows more openings in both directions. If fixed dimensions for each room are preferred, or if high lateral rigidity of the whole structure is required, this structural system may be advantageous. Also, using structural walls in both of the orthogonal directions permits the application of two-way slabs, which transfer load in both directions to the walls.

The <u>Design and Construction of Large-panel Concrete Structures: Report 2</u>, notes that, regarding the cross wall system, "Since current connection details make frame action between adjacent slab spans and between slabs and walls almost impossible, lateral resistance of Large Panel buildings is provided economically only by cantilever action of the stacks of wall panels in their own planes. Therefore, where possible, longitudinal spine walls or segments should be used to improve the stability of the longitudinal direction."[6] (Figure 7-5) In this sense, neither a complete cross wall system nor a complete spine wall system are feasible. Although cast-in-place load-bearing wall structural systems sometimes have only cross walls, they have to be distinguished from large panel structural systems in that they have monolithic connections between slabs and walls which resist lateral loads by a frame function (Figure 7-6).

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[6]<u>Design and Construction of Large-Panel Concrete Structures: Report 2.</u> (1976). p. 58

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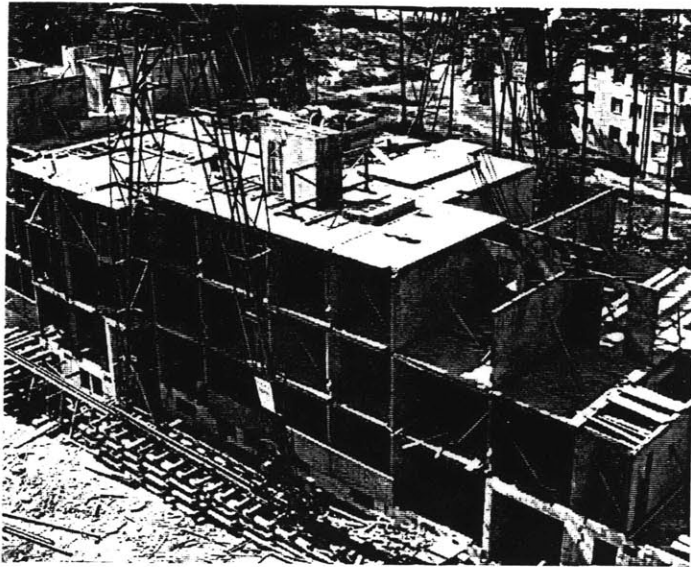
(Figure 7-5)   Source: Diamant, R, M, E. Industrialized Building 1.
Large panel structural system with cross walls and longitudinal walls

Drawing illustrating the principles of the
Tracoba system
KEY: 1 Positioning the tunnel. 2 Rolling track.
3 Gangway for releasing the tunnel. 4 Tunnel in the

(Figure 7-6)   Source: Diamant, R, M, E. Industrialized Building 1.
A cast-in-place wall structure by a slip-form method, called 'Tracoba'. Cross walls and slabs make
frame function, which resists longitudinal lateral loads.

Sebestyén, notes that "Large precast units can be used for single-storey houses
and for two to six-storey or even taller buildings. Up to a height of six storeys, load-

bearing wall construction is suitable, but for taller buildings load-bearing frames are usual."[7]   Although the information about the maximum height of this structural system is limited, most of the precedents show that is has been practically adapted to nearly high-rise buildings of up to 25 stories (Figure 7-7).[8]   However, in spite of high lateral load rigidity, the maximum height is lower than that of braced frame structures because of the high dead load of the total structural system.
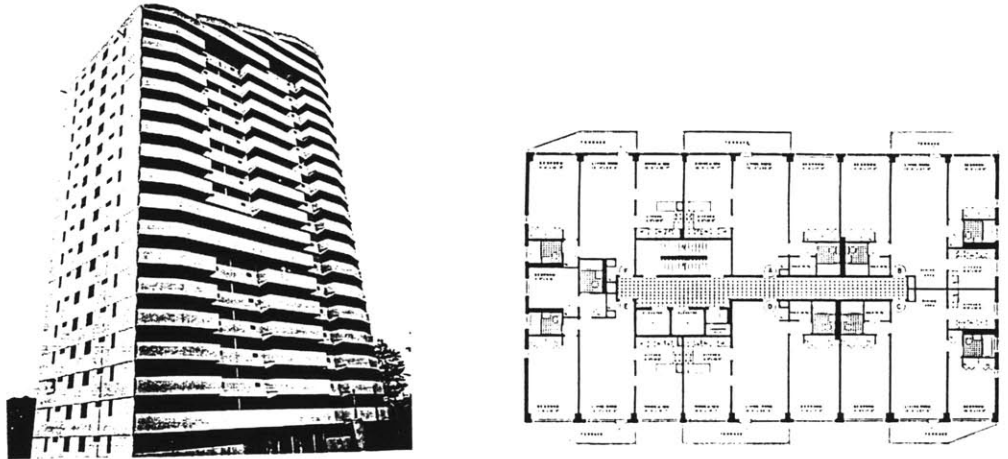
(Figure 7-7)   Source: Feed back: Operation Breakthrough. 1973.
20-story, 110-unit high-rise multifamily house employed by the cross wall system under construction in   Yonkers, New York.

## 7.3. Large panel structural system at Level 2

7.3.1 Dimension

From a structural point of view, it must be noted that the cross-wall system and the spine wall system usually employ planks as their slabs, while the mixed system is justified by employing two-way slabs. In general, priority may be given to one of the two directions in the arrangement of wall panels to accommodate precast prestressed planks (Figure 7-8). However, as discussed previously, both the cross-wall system and the spine wall system call for additional load-bearing panels in the secondary direction. The wall panels in the secondary direction are provided in various ways, such as by staircases, service cores, or as part of the external walls.

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[7]Sebestyén, Gyula. p. 52.
[8]According to the Feed back: Operation Breakthrough (1973), the high-rise multifamily houses carried out by CAMCI Inc. based on a French large panel structural system, "Tracoba" has the maximum 26 stories.

When spans are enlarged, construction costs for the structure go down since the reduced costs for wall panels per square foot exceed the additional costs for increasing the depth of planks or installing reinforcements. However, economy cannot be measured only by the cost of the structure since structural walls could supply the functions of separating walls or external walls.[9] The dimension of inner space and the locations of walls in secondary directions are usually dictated by architectural concepts about multifamily housing rather than by structural economy.

(a) Cross Wall System   (b) Spine Wall System
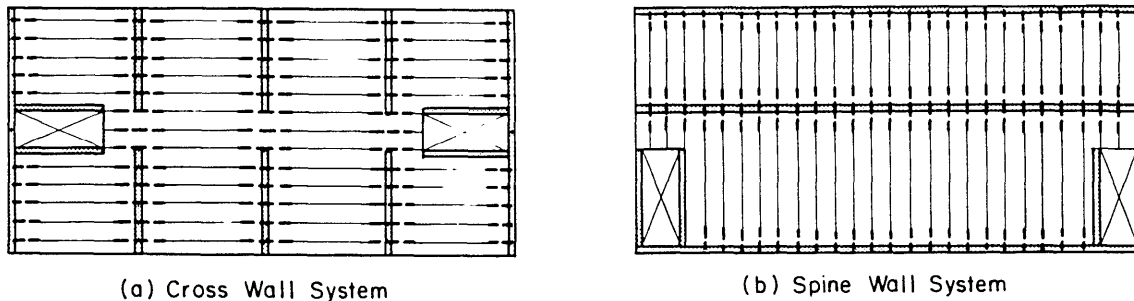
(Figure 7-8)   Source: Design and Construction of Large-Panel Concrete Structures: Report 2.
The cross wall system (left) and the spine wall system (right) accommodate planks.

7.3.2 Articulations

With regard to the articulation of load-bearing wall panels, the PCI. Architectural Precast Concrete notes that in commercial buildings, such as office buildings : "In multi-story buildings, the load-bearing wall panels can be several stories in height up to the maximum transportation length, or one-story high and connected at every floor level. The architectural requirements generally govern. The variety of shapes and surface finishes commonly associated with cladding are possible, . . . By extending load-bearing panels vertically through several stories, complex connection details are minimized, and consequently the economic advantages of load-bearing wall panels are increased."[10]

This description is of load-bearing wall panels of commercial buildings that are located at the perimeters of the buildings (Figure 7-9) where wall to slab connections occur at one side of these panels. Although these concepts of multi-story structural walls

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[9]Moghadam, H. R. A Cost Study of an American Precast Panel System. Thesis Civil Engineering.
   1977. Massachusetts Institute of Technology.
[10]Architectural Precast Concrete. Second Edition. p. 46-7

are worth considering, attention must be paid to the difference between commercial buildings and multifamily houses. First, the cross-wall system and the mixed system, which are commonly employed in multifamily houses, have interior structural wall panels, which call for wall to slab connection on both sides of the walls. Second, the external walls of the spine wall system have wall to slab connections at one side, which makes multi-story structural walls feasible, but the dimensional constraints of these pieces eliminates the possibility for balconies.

Before turning to the variations in the articulations of large panel structural systems, the structural effects of the articulations must be clarified. While multi-story load-bearing panels could rationalize the process of assembly, the increment of lateral load rigidity by means of a flexural continuity in a lateral support system, which is advantageous for frame structures, cannot be expected in large panel structural systems. This is because lateral loads are resisted by the shearing load capacity of the walls that is parallel to the loads, but is not resisted by the flexural capacity of the walls that are perpendicular to the lateral loads (Figure 7-10).

When connected adequately, single-story panels are equivalent to multi-story load-bearing panels as lateral support systems. Englekirk notes that "In the United States neither code nor practice accepts connectors or splices in beams or columns of ductile frames if post yield deformations are likely. On the other hand, joints in precast wall panels are accepted regardless of whether or not they possess any ductility."[11] Because the connections between large panels are relatively easy (shown in section 6.3), their articulations mostly depend on precasting, transportation, and assembly, rather than on structural considerations.

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[11]Englekirk, R. E. p. 79.
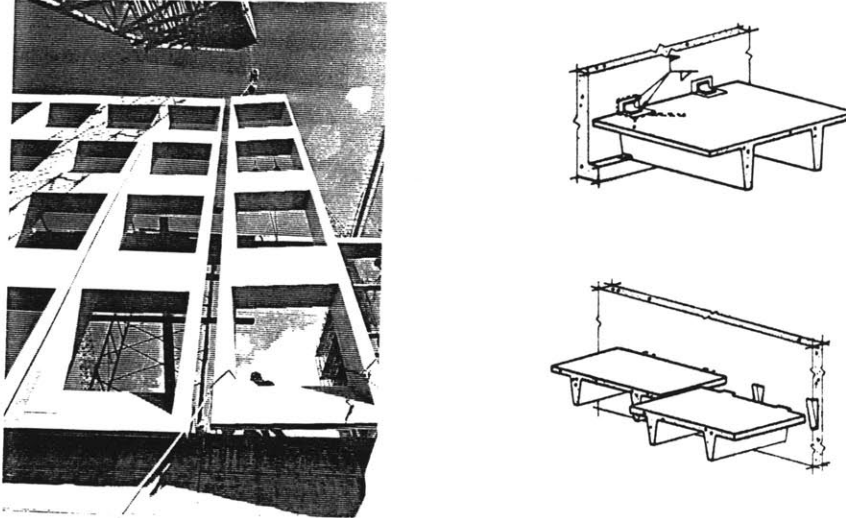
(Figure 7-9) Source: <u>Architectural Precast Concrete, Second Edition</u>
Assembly of multi-story external load-bearing wall panels at an office building (left).
Connections between multi-story external load-bearing wall panels and tee slabs call for corbels or
pockets on the panels(right).
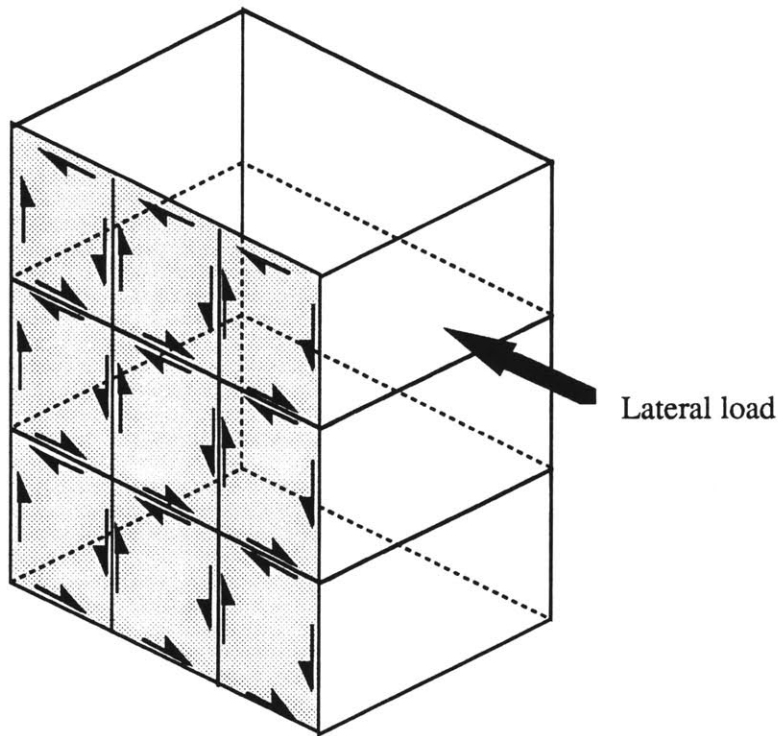
(Figure 7-10)
The relationship between lateral load and shear action of panels

With regard to the articulations of slabs and walls, the following four types are possible: (a) L-shaped unit, (b) Multistory wall, (c) Multi-bay slab, and (d) Single-story

wall (Figures 7-11). Because of the constraints of transportation and handling, neither a T-shaped nor cross-shaped unit is practical.

a. L-shaped unit

b. Multi-story panel

c. Multi-bay slab

d. Single-story panel
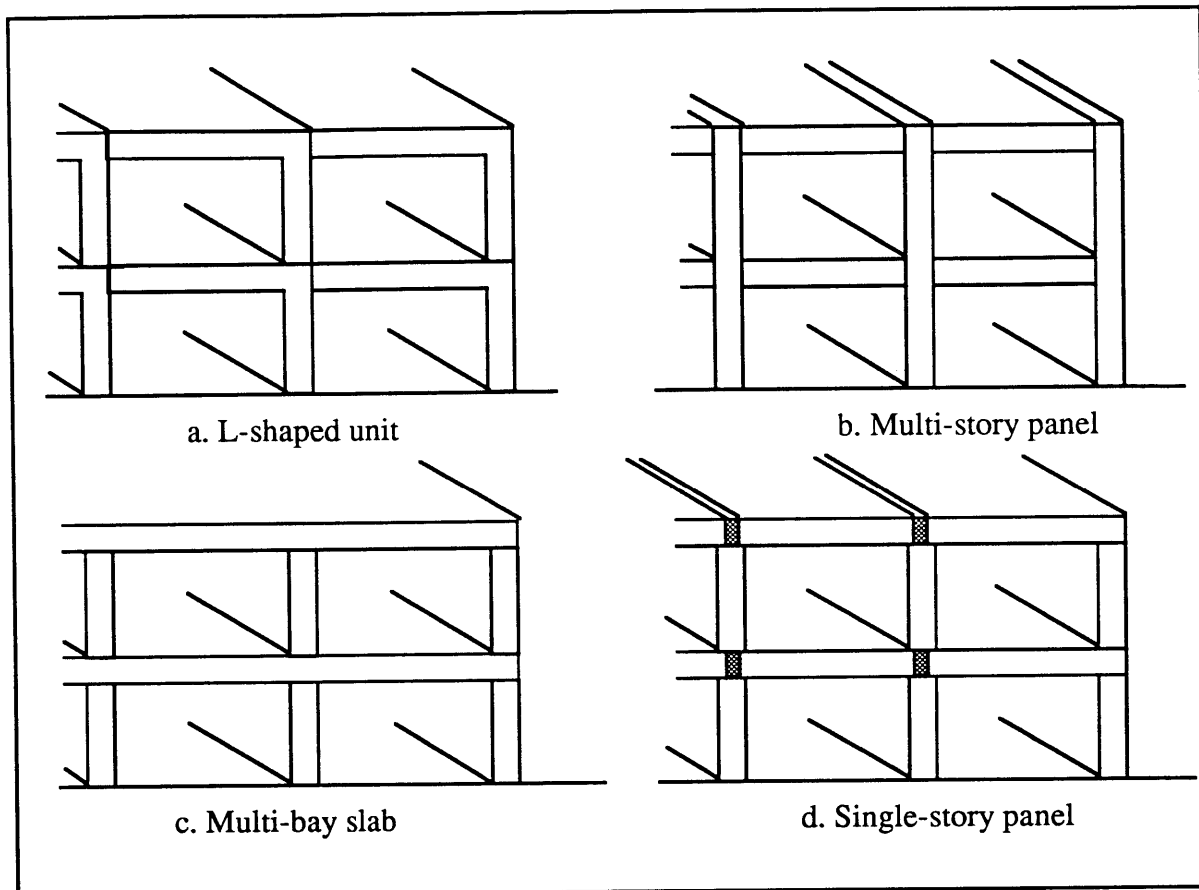
(Figure 7-11)
Articulations of slabs and walls

(a) L-shaped unit

The L-shaped unit consists of a wall and slab connected monolithically. Therefore, a structural system attains moment rigidity by frame action in one direction. The 'Angle-Unit system' in Sweden (Figure 7-12) shows an example of an L-shaped unit system. Although the pieces seem bulky, the constraints of manufacturing and transportation are overcome by a vertical casting mold (Figure 7-13) and a shape that can be nested together. For all these advantages, this method is not commonly used. Disadvantages include high initial costs for manufacturing and handling devices (Figure 7-14) as well as limited dimensional versatility.
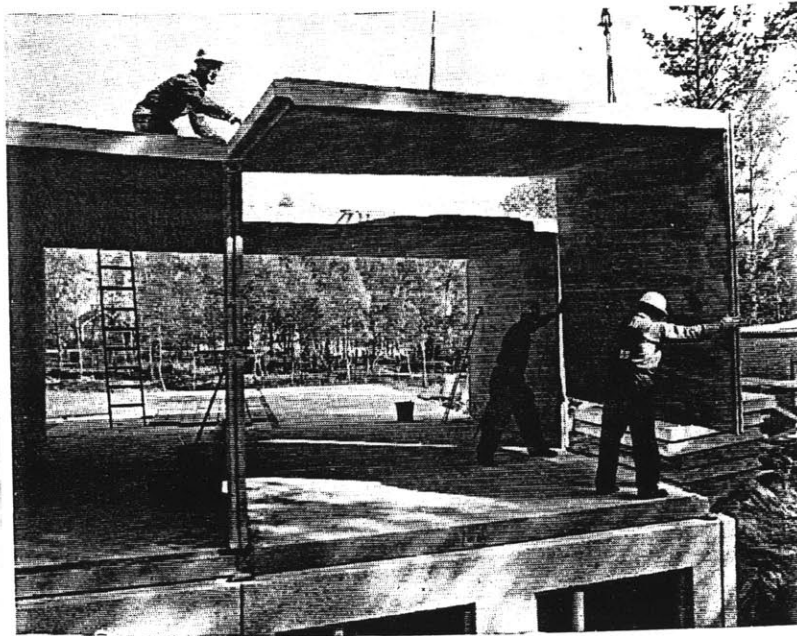
(Figure 7-12)   Source: Diamant, R, M, E. Industrialized Building 1.
Assembly of the angled unit
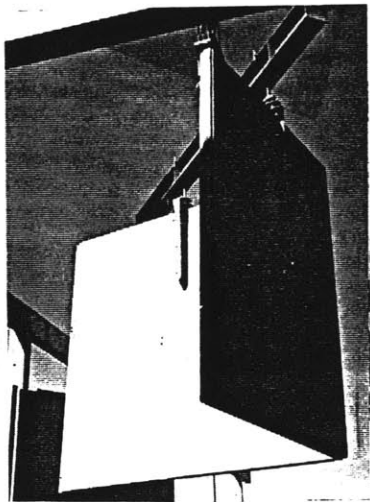
(Figure 7-13)
The L-shaped casting battery
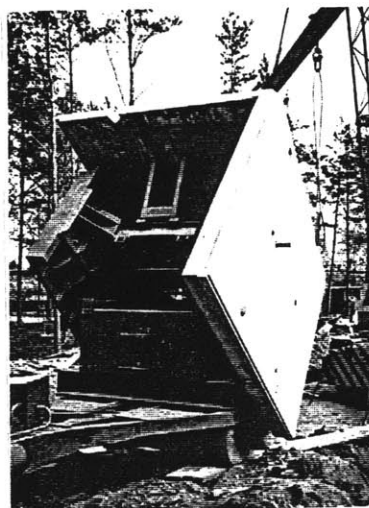
(Figure 7-14)
A handling device on site which turns the unit through
90 degrees so that the floor section assumes a
horizontal position

(b) Multi-story panel

     While commercial buildings usually employ the spine wall system to obtain
uninterrupted inner spaces, multifamily houses are mostly constructed by the cross wall

system or the mix system. To provide as much light and ventilation as possible, load-bearing panels for multifamily housing are located inside the building rather than on its perimeter. However, multi-story panels as interior walls may cause some difficulties in precasting where corbels have to be cast at the mid points on the both sides of a panel.

(c) Multi-bay slab

although the assembly of slabs is as simple as putting them in position, it poses major difficulties. The enlargement of slab pieces makes lifting troublesome because lifting a horizontal member is far more difficult than lifting a vertical member (Figure 7-15). On the other hand, a complete interruption in load-bearing wall panels makes their connection difficult, and so multi-bay slabs may be impractical.
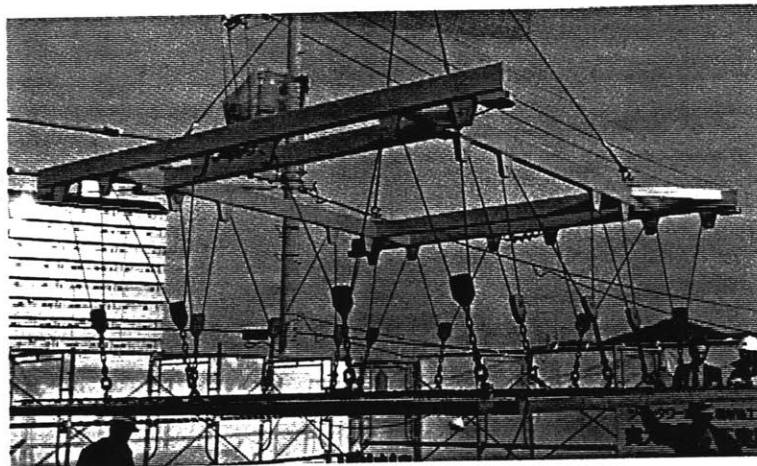
(Figure 7-15) Source: Toda Technics: Toda-Rahmen Precast Concrete Method
Lifting large slab pieces requires high equipment costs.

(d) Single-story wall.

A combination of single-story panels and single-bay slabs is the most common articulation in multi-family housing. In general, in large panel structural systems, a fragmented articulation does not diminish the rigidity of the structure. Increasing the numbers of connections can be dealt with relatively easily with sleeve joints or by welding. For these reasons, constructability is enhanced by simple articulations rather than by large unit pieces.

7.4. Large panel structural system at Level 3

(a) Slab to slab connections

The primary function of slab to slab connections is to transfer a shear load so that a diaphragm can carry lateral loads to structural walls. The methods of connection depend on the types of slab members as well as the design loads. When the cross wall system or the spine wall system is employed in a house, slab pieces span in one direction, thus planks are usually used (Figure 6-14). In the case that wall panels constitute the mixed system, slab pieces are supported in both orthogonal directions. In these cases, precast solid slabs or precast shell slabs might be used.
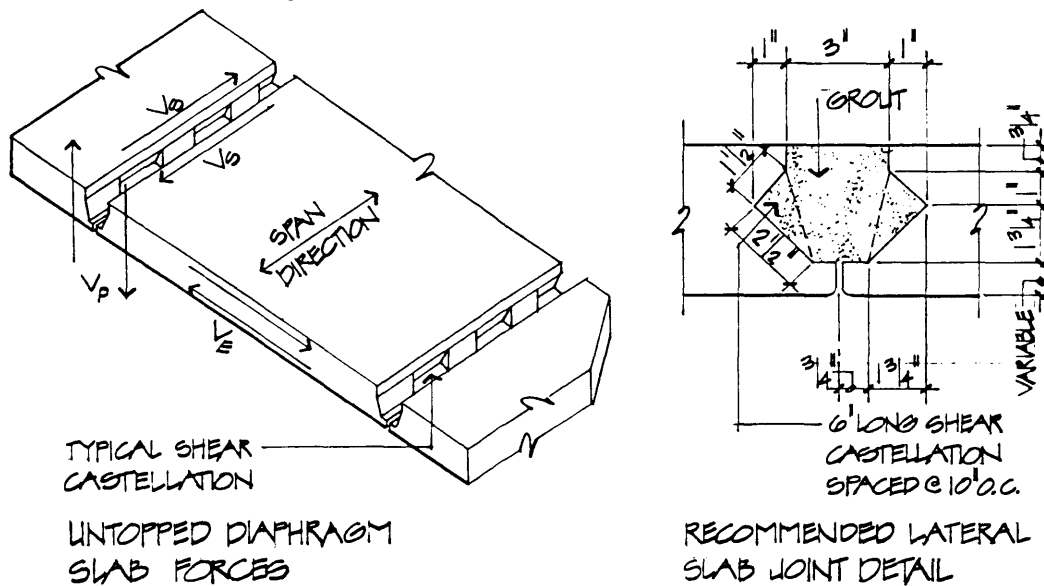
Structural concrete topping is useful for connecting planks as well as for increasing their load capacity by exploiting flexural continuity over structural walls (Figure 7-16). The Design and Construction of Large-Panel Concrete Structures: Report 2 notes that "Wherever a sizable negative moment capacity is required, a composite structural topping reinforced over the supports offers a relatively simple solution."[12] A detail of structural topping concrete was shown in the previous chapter (Figure 6-15). Precast shell slabs also attain flexural continuity with cast-in-place concrete (Figure 6-11).

Continuous Composite   Simple Span Non-Composite
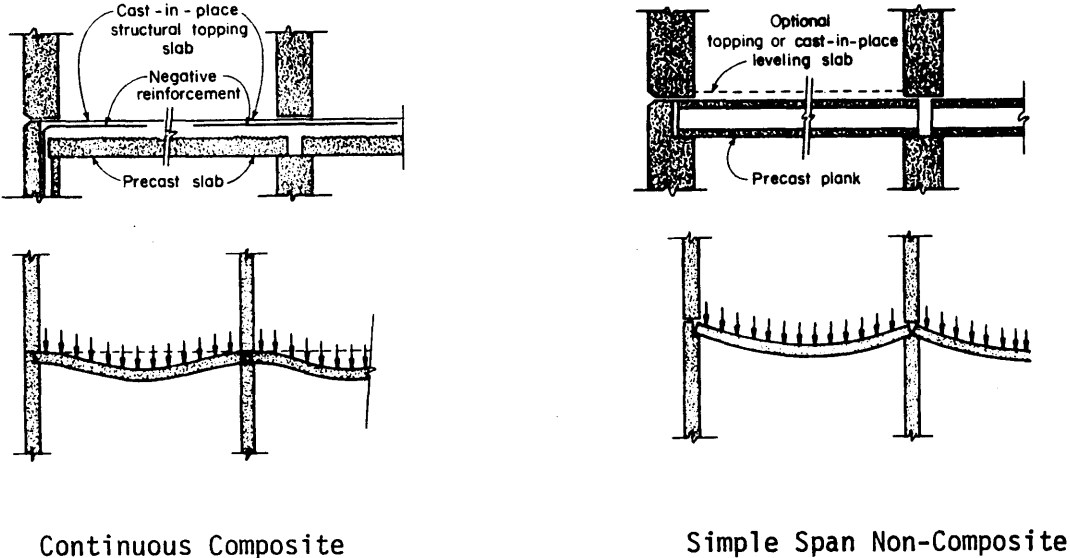
(Figure 7-16)   Source: Design and Construction of Large-Panel Concrete Structures: Report 2
Structural concrete topping develops flexural continuity over the supports.

When solid slabs are employed, their connections should be grouted so that the advantages of solid slabs are not impaired. If great shear loads are expected, shear castellations should be used (Figure 7-17).

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[12]Design and Construction of Large-Panel Concrete Structures: Report 2. p. 71.

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TYPICAL SHEAR
CASTELLATION

UNTOPPED DIAPHRAGM
SLAB FORCES

6' LONG SHEAR
CASTELLATION
SPACED @ 10' O.C.

RECOMMENDED LATERAL
SLAB JOINT DETAIL

(Figure 7-17) Source: Plant Cast Precast concrete and Prestressed concrete: a Design Guide.
Connection between solid slabs. Shear castellation carry shear-friction by being grouted.

(b) Slab to wall connections / wall to wall horizontal connections

Horizontal connections occur at each floor level, where vertical load from a load-bearing wall panel and shear load from slabs are carried to the wall at lower floors. With regard to the connection between upper and lower load-bearing wall panels, vertical loads are supported by the compressive strength of the panels themselves, and mechanical connections, such as weld plates, grouted splice sleeves, and post-tensioning, are used to provide shear resistance (Figure 7-18). The tolerances in both the vertical and horizontal directions have to be taken into account to enhance precision and constructability.

interior joint   exterior joint
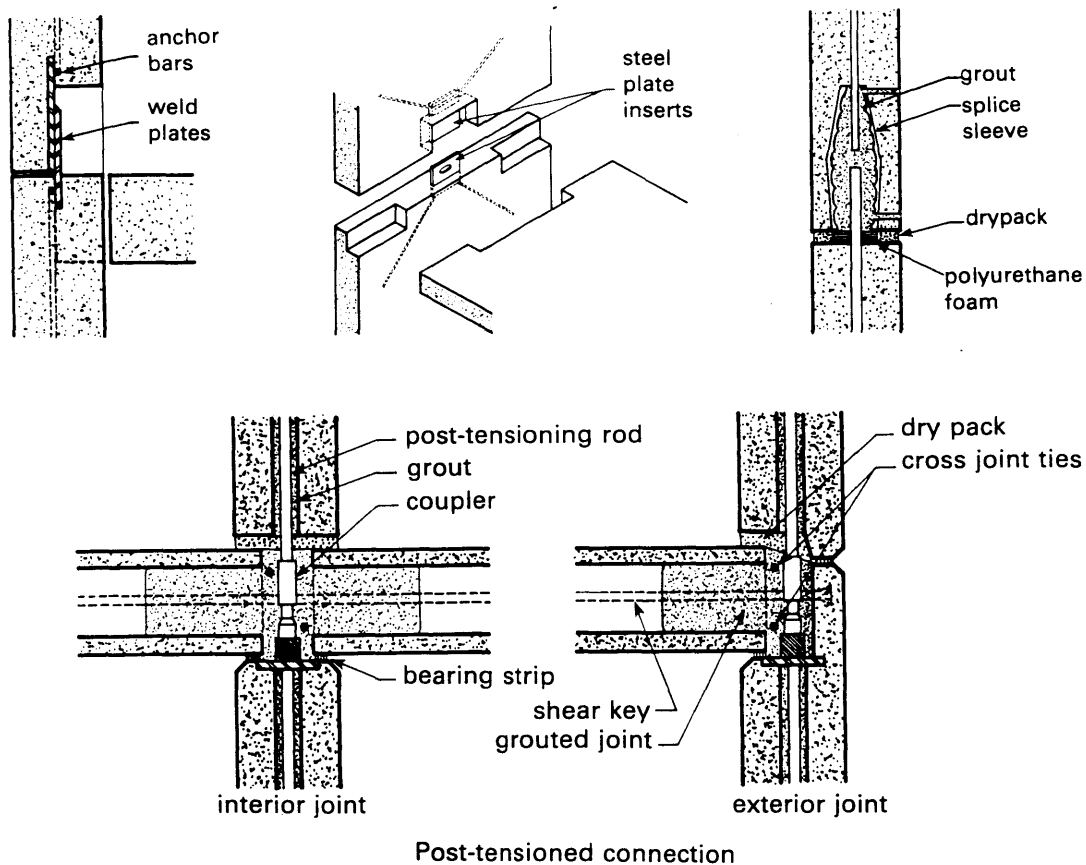
Post-tensioned connection

(Figure 7-18) Source: PCI Design Handbook
Connections through horizontal connections

The ends of slabs are usually embedded into the connections to transfer the shear load without interrupting the vertical continuity of a load path. The Design and Construction of Large-Panel Concrete Structures: Report 2 describes the connection of hollow core slabs and load-bearing wall panels: "Various details are currently in use for this connection. Most widely used among these is the 'platform' connection (also known as the 'closed' or 'American type connection). . . In the typical 'American' connection, prestressed hollow core slabs extending over wall panels are continuously supported on bearing pads. Cast-in-place grout fills the vertical space between floor plank and usually a portion of the hollow cores of the plank itself."[13] (Figure 7-19) Precast solid slabs can be connected in the same way as "American" connections (Figure 7-20).

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[13]Design and Construction of Large-Panel Concrete Structures: Report 2. p. 75.
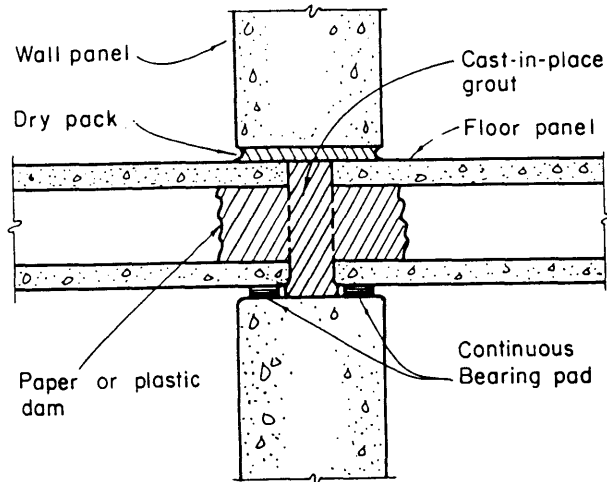
(Figure 7-19) Source: Design and Construction of Large-Panel Concrete Structures: Report 2.
A detail of an "American" connection
Grout fills a vertical space to make a vertical load path as well as to ensure the shear load transfer.
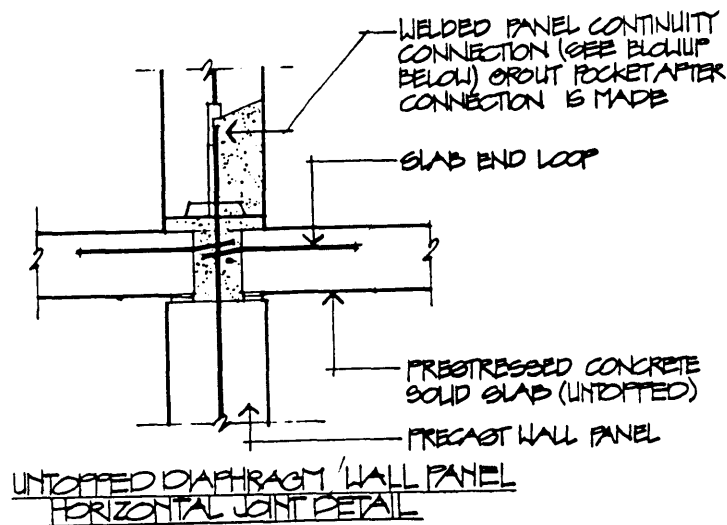
(Figure 7-20) Source: Plant Cast Precast concrete and Prestressed concrete: a Design Guide
A detail of a horizontal connection of precast solid slabs

(c) Vertical connections

As discussed in Subsection 6.2.2, the primary consideration concerning the vertical connections between load-bearing wall panels is the shear induced by lateral loads. The PCI Design Handbook notes that "In addition to the transfer of vertical shear forces due to lateral loads, vertical joints may also be subject to shear forces induced by

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differential loads on adjacent panels."[14] Cast-in-place connections are commonly used to attain shear friction between panels (Figures 7-21 and 7-22).
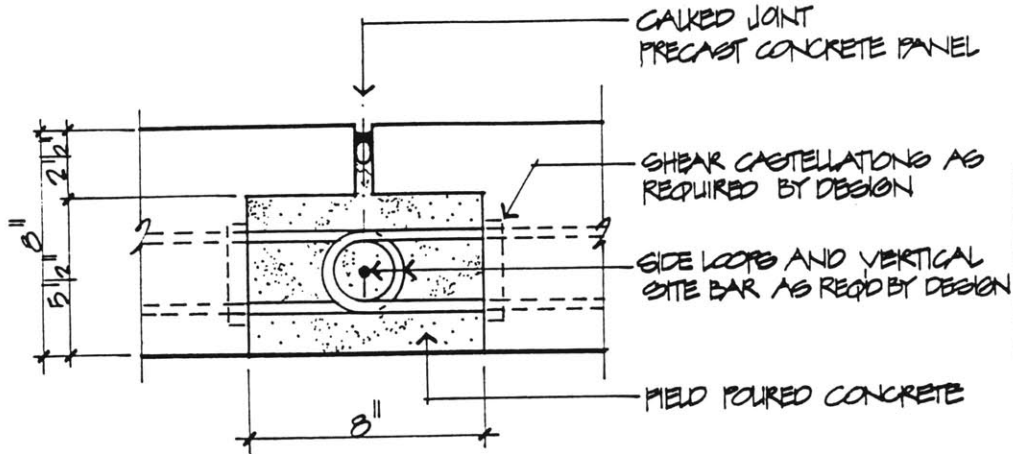

(Figure 7-21) Source: <u>Plant Cast Precast concrete and Prestressed concrete: a Design Guide</u>
A detail of typical vertical connection
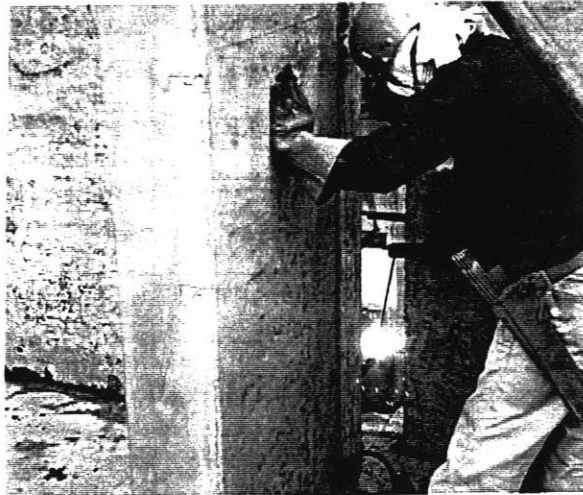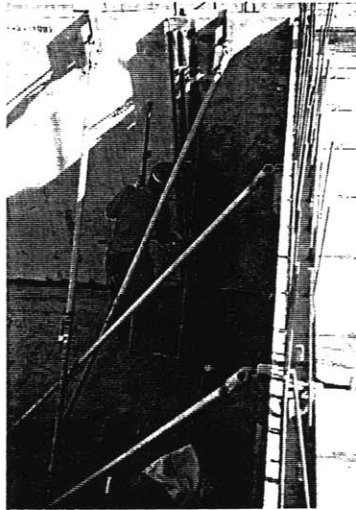
(Figure 7-22) Source: Personal file
cast-in-place connections, Japan.
left: welding of re-bars projected from pieces, right: a shuttering for cast-in-connection

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[14]<u>PCI Design Handbook</u>. p. 6-39.

Chapter 8
Conclusion

In conclusion, generic characteristics of each precast concrete structural system are suggested with regard to their advantages, articulations and connections, and dimensions.

1. Advantages in terms of planning

a. **Unbraced frame system**

The absence of any kinds of braces or load bearing walls makes this structural system suitable for open systems allowing freedom for interior layouts.

b. **Braced frame system**

High lateral load rigidity and/or long spans can be accomplished. When simple pin frame and braces are combined, economical structures can be built.

c. **Large panel structural system**

Load bearing wall panels provide lateral rigidity to the structural system and sufficient fire resistance and sound protection as well.

2. Articulations and connections of structural members

The variations in the articulations and connections of structural members show the outlines of each structural system, where structural requirements have to be coherent with various technological aspects, such as casting, transportation, and erection. Following are typical articulations of structural members and the typical required types of connections.

a. **Unbraced frame system**

Column base structural system

• Multi-story columns are essential for the column base structure; requires beam to column pin connections.

Moment-resisting frame structural system

• Multi-story columns or tree columns are advantageous to reduce the costly moment-resisting connections, but tight tolerances are required when connections are mechanical. The alternative of connections depends on the required ductility; requires beam to beam mechanical connections or cast-in-place connections.

• Single-span beams and single-story columns attached by cast-in-place connections constitute ductile frame structures; requires beam to column cast-in-place connections.

b. Braced frame system

<u>Long span braced frame structural system</u>

• Beam and column units, which are moment-resisting frame units in a single vertical plane, is advantageous at precasting and transportation process; requires mechanical beam to beam connections or cast-in place connections.

<u>High-rise braced frame structural system</u>

• Beam and column units are applicable for the frame at the perimeter of the hull-core structural system; requires mechanical beam to beam connections or cast-in-place connections.

• Single-span beams and single-story columns are employed by the equal span grid system; requires beam to column cast-in-place connections.

c. Large panel system

<u>Cross wall system and mixed system</u>

• Multi-story wall panels are not applicable for cross walls. Single-story wall panels or L-shaped units are used; requires slab to wall connections by re-bar and grouting or by cast-in-place.

<u>Spine wall system</u>

• Multi-story wall panels are feasible for exterior walls, but increased structural rigidity cannot be expected; requires slab to wall connections by corbels on multi-story wall panels.

3. The dimensions of structural systems

The maximum building height and span length of a structural system affects the types of housing that employ the structural system. Although approximate numbers could be suggested, these numbers vary according to the location of constructions because they are dictated not only by the load capacities inherent to each structural system but also by regional factors, such as seismic design requirements, soil conditions and construction codes. In this thesis, low-rise, medium-rise, and high-rise represent 1 - 4 , 4 - 15, and over 15 stories, respectively. Additionally, low rise specification excludes interior structural walls, and medium and high rise specifications include these elements.

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a. **Unbraced frame system**

Column base structural system

• The pin connections between column and beam accommodate precast prestressed beams and/or slabs which provide long spans. The maximum height of this structural system is limited to low-rise designs because the lateral load capacity depends on the rotational characteristics of footings.

Moment-resisting frame structural system

• The maximum building height corresponds to medium-rise housing.

b. **Braced frame system**

Long span braced frame structural system

• Generally, the braced frame structural system has longer maximum spans than unbraced frame and large panel structural systems. Maximum building height depends on the configurations of braces and types of frames, which are either moment-resisting frames or pin frames. When pin frames are braced, the maximum height is about twenty stories. However, moment-resisting frame structures with braces, such as the spine wall system, has greater maximum height, which is up to thirty stories.

c. **Large panel system**

• Although the information about the maximum height of this structural system is limited, most of the precedents show that it has been successfully employed in high-rise multifamily houses up to twenty-five stories. The dimensions of inner spaces are usually dictated by architectural requirements rather than structural economy.

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References

Ehrenkrantz, Ezra D. Architectural Systems. New York: McGraw-Hill, Inc., 1989.

Architectural Precast Concrete, Second Edition. Chicago: Precast / Prestressed Concrete Institute. 1989.

PCI Design Handbook. Chicago: Precast / Prestressed Concrete Institute. 1985.

Roger-Bruno, Richard. répertoire des systémes de construction industrialisés en habitation. Montreal, Canada: Société Canadienne d' Hypothéques et de Logement, 1990

Ching, Francis D.K. Architecture: Form, Space, and Order. New York: Van Nostrand Reinhold Company, Inc. 1979

Allen, Edward. Fundamentals of Building Construction. N.Y.: John Wiley & Sons. 1985.

Mainstone, Rowland. Developments in Structural Form. M.A.: The MIT Press. 1975.

Means Open Shop Building Construction Cost Data 1992. Massachusetts: R.S. Means Company, Inc.. 1991.

Phillips, W, R. , & Sheppard, D. A. Plant Cast Precast concrete and Prestressed concrete: a Design Guide. Illinois: PCI. 1980.

Herrey, A, and Litle, W. A. Industrialized Housing Feasibility Study. M.A.: Massachusetts Institute of Technology. October 1972.

Eliott, K. S. (1992). The Design of Modern Precast Concrete Multistory Framed Structures in the United Kingdom. PCI Journal, May-June 1992, pp. 32-47.

Englekirk, R. E. (1987). U.S.-Japan Seminar on Precast Concrete Construction in Seismic Zones. PCI Journal, March-April 1987, pp. 80.

Foster, J. S. Structure and Fabric Part 2. Great Britain: B T Batsford Limited. (1977).

Guise, David. Design and Technology in Architecture: Revised Edition. New York: Van Nostrand Reinhold. (1991).

Diamant, R, M, E. Industrialized Building 3. Great Britain: Iliffe Books Ltd. 1968.

U.S. Department of Housing and Urban Development, Office of Policy Development and Research. Design and Construction of Large-Panel Concrete Structures: Report 2. (1976) .

Sebestyén, Gyula. Large-Panel Buildings. (A. Frankovszky, Trans.) Budapest: Publishing House of the Hungarian Academy of Science. 1965.

Habraken, N. J., Variations: The systematic Design of support. Massachusetts: The MIT Press. 1976.

The Architectural Forum. July-August 1972.

U.S. Department of Housing and Urban Development. Feed back: Operation Breakthrough. 1973.

Barch, M. B. Precast Exposed Concrete Finishes: The Architects' Journal Information Library, 26 March 1969.

The International Symposium on Box-unit Construction: III-1. Hungarian Institute for Building Science. May 23-25, 1973.

Ghosh, S. K. and Rabbat, B. G. (Eds.). Notes on ACI 318-89: Building Code Requirements for Reinforced Concrete. 1990. Portland Cement Association.

Moghadam, H. R. A Cost Study of an American Precast Panel System. Thesis Civil Engineering. 1977. Massachusett Institute of Technology.

Source of Graphics

Werk, March, 1971. Germany

Nikkei architecture. January, 1994. Japan

Herrey, A, and Litle, W. A. Industrialized Housing Feasibility Study. M.A.: Massachusetts Institute of Technology. October 1972.

Foster, J. S. Structure and Fabric Part 2. Great Britain: B T Batsford Limited. 1977.

PCI Design Handbook. Chicago: Precast / Prestressed Concrete Institute. 1985.

Englekirk, R. E. (1987). U.S.-Japan Seminar on Precast Concrete Construction in Seismic Zones. PCI Journal, March-April 1987, pp. 80.

Toda Technics: Toda-Rahmen Precast Concrete Method (a pamphlet). Toda Corporation. Japan. May, 1992.

Architectural Plus. July - August. 1974.

Allen, Edward. Fundamentals of Building Construction. N.Y.: John Wiley & Sons. 1985.

10. Diamant, R, M, E. Industrialized Building 1. Great Britain: Iliffe Books Ltd. 1965.

The Architects' Journal. 19. March 1969. London, Great Britain.

Architectural Precast Concrete, Second Edition. Chicago: Precast / Prestressed
       Concrete Institute.

Catalogue. Homes of many Forms. International form corporation, Jacksonville,
       Florida.

Diamant, R, M, E. Industrialized Building 3. Great Britain: Iliffe Books Ltd. 1968.

Nikkei architecture. January 31, 1994. Japan

Roger-Bruno, Richard. répertoire des systémes de construction industrialisés en
       habitation. Montreal, Canada: Société Canadienne d' Hypothéques et de
       Logement, 1990

Phillips, W, R. , & Sheppard, D. A. Plant Cast Precast concrete and Prestressed
       concrete: a Design Guide. Illinois: PCI. 1980.

U.S. Department of Housing and Urban Development, Office of Policy Development
       and Research. Design and Construction of Large-Panel Concrete Structures:
       Report 2. (1976) .

U.S. Department of Housing and Urban Development, Office of Policy Development
       and Research. Design and Construction of Large-Panel Concrete Structures:
       Report 4. (1977) .

Mainstone, Rowland. Developments in Structural Form. M.A.: The MIT Press.
       1975.

Habraken, N. J., Variations: The systematic Design of support. Massachusetts: The
       MIT Press. 1976.

Diamant, R, M, E. Industrialized Building 1. Great Britain: Iliffe Books Ltd. 1965.

Barch, M. B. Precast Exposed Concrete Finishes: The Architects' Journal
       Information Library, 26 March 1969.

Monthly Building Engineering Magazine. Japan. January 1994.

Kenchiku Gijyutu. Japan. December 1992.