Review of Existing Precast Concrete Gravity Load Floor Framing Systems

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This paper reviews 19 precast structural floor systems from North America and overseas that are suitable for office building construction. This review includes a discussion of the impact of the structural system on the non-structural systems. This review was conducted as part of a research project directed towards the development of new precast concrete floor systems for gravity loads for application in occupied office buildings having a regular spacing of columns. A companion paper presents the assessment of these floor systems. The research addresses the need for innovation in the design and construction of precast concrete buildings.

Structural floor systems represent a major portion of both the cost and weight of precast concrete building frames. Structural floor systems in multistory buildings also have a significant impact on overall building height and on the design and installation of service systems, including plumbing (i.e., supply, drain-waste-vent, and fire protection), HVAC (i.e., heating, ventilation, and air conditioning), and electrical (i.e., power, security, and communication) systems. Significant improvements in overall building system efficiency can be gained by improving precast structural floor systems to reduce weight, depth, and cost, and to better accommodate service systems.

Traditional approaches to improving floor system efficiency have sought to minimize the weight, depth, and cost of structural floor systems through the use of new or higher strength materials and improved construction techniques. Automated fabrication and erection technologies offer additional potential for reduced fabrication and erection cost and time. In addition, a third opportunity exists in improved accommodation of service systems. In order to address these opportunities, new and innovative concepts for precast concrete floor systems are needed.

SCOPE OF PAPER

This paper and a companion paper[1] summarize progress made on research conducted at the Center for Advanced Technology for Large Structural Systems (ATLSS) on gravity load floor systems for precast concrete buildings. The main objective of the research is to develop new precast concrete floor systems for gravity loads for application in occupied office buildings with a regular spacing of columns. This research evolved from a Precast/Prestressed Concrete Institute (PCI) research project statement titled "Economical Framing Systems for Floors and Roofs."

This paper summarizes the essential elements of 19 precast structural systems that are suitable for office building construction. The companion paper presents the assessment of these systems. Together, these two papers indicate the current state-of-the-art in precast concrete structural systems and identify opportunities for the development of new systems and the improvement of existing systems. A more detailed presentation of the findings is given in a report by Prior et al. (1993).[2] A second report by van Zyverden et al. (1994)[3] describes the concepts that have been developed for new systems.

TERMINOLOGY

The following terminology is used throughout this paper and the companion paper:

Building System — The structural, service, and architectural systems of the building.

Structural System — All structural components of the building, including precast members, cast-in-place members, cast-in-place connections, welded connections, and bolted connections.

Services — Plumbing, HVAC, and electrical systems.

Architectural System — Architectural elements including interior spaces, building function, materials, partitions, exterior enclosures, noise control, thermal storage, and safety system.

Floor System — The structural floor system and the space below the floor (and above the finished ceiling of the level below) that is required for service systems and architectural systems.

SURVEY OF EXISTING PRECAST SYSTEMS

Numerous proprietary and nonproprietary precast structural systems have been developed in the United States and abroad in the last 30 years. For clarity, office buildings are defined as multistory, occupied structures, requiring square or rectangular bay sizes of 7.5 m (25 ft) or greater. The 19 systems (see Table 1) originated in the United States, Great Britain, Canada, Sweden, Hungary, Italy, Japan, and Australia.

A distinction is made between current systems and emerging systems. Current systems are those precast systems that have been used in the construction industry. Emerging systems are those systems that are still under development or awaiting patent approval. Information was not collected on loadbearing wall structures.

Table 1. Precast systems included in the survey of systems.

Current Systems
1a. U.S. Conventional with hollow-core slabs
1b. U.S. Conventional with double tees
2. Duotek (Canada)
3. Dycore (United States)
4. Dyna-Frame (United States)
5. Filigree Wideslab (United States, United Kingdom, and Japan)
6. PG Connection
7. RC Layered Construction
8. RPC-K (Japan)
9. IMS (Yugoslavia)
10. PD2 Frame (United Kingdom)
11. Prestressed Joist (United States)
12. Quickfloor (Australia)
13. Structurapid (Italy)
14. Swedish (Sweden)
15. Thomas (United States)
16. Tri/posite (United States)
Emerging Systems
17. Contiframe (United Kingdom)
18. Spanlight (United Kingdom)
19a. University of Nebraska A (United States)
19b. University of Nebraska B (United States)

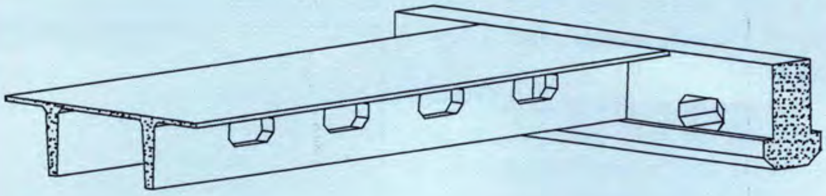
Current Building Systems

U.S. Conventional System — The conventional precast concrete system for office structures in the United States consists of precast inverted T-beams, L-shaped spandrel beams, multistory columns, and hollow-core slabs or double tees as floor members. The system generally uses cast-in-place concrete only for a floor topping. In general, simple span members are employed, with connections resisting shear and not moment.

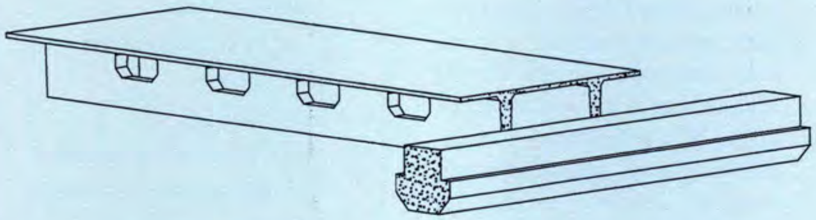
Gravity loads are transferred from floor members to inverted T-beams and then to column corbels. Horizontal loads are usually transmitted to shear walls through the roof and floors acting as horizontal diaphragms. In floors without composite topping, the shear transfer between floor members is usually accomplished by weld plates or grout keys. In floors with composite topping, the topping acts as the diaphragm, if it is adequately reinforced.

HVAC, plumbing, and electrical services are typically suspended beneath the structural floor system using standard hardware. When hollow-core slabs are used, holes can be drilled for toggle or expansion type bolts or anchors. If double tees are used as precast floor members, the duct system can run longitudinally between tee stems without contributing to the total depth of the floor system.

In the transverse direction, the ducts pass under the tee stems and may add to the total depth of the floor system. These transverse crossings are often at the exterior perimeter of the building, thus requiring a lower ceiling in this location only. Other designs use a deeper total floor depth (and a lower ceiling) in central corridors. Another alternative is to design the HVAC duct system to pass under the primary beams in just one location, where a utility closet is placed to hide the duct system and to allow the total floor depth to remain shallow in other areas of the building.



(a) Inverted T-beam (Type A) with 711 x 356 mm (28 x 14 in.) openings on a 1.52 m (5 ft) module



(b) Partial inverted T-beams (Type C) with 1270 x 356 mm (50 x 14 in.) openings on a 1.52 m (5 ft) module

Fig. 1. Duotek system.

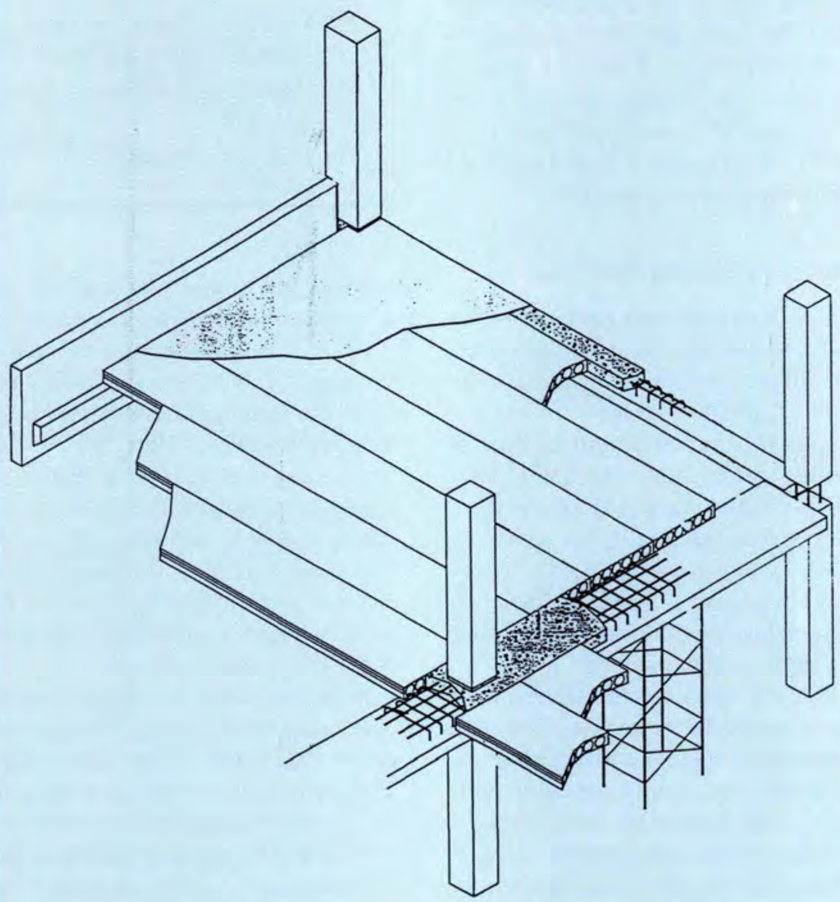


Fig. 2. Composite Dycore structural system (adapted from Ref. 5).

Duotek System — The Duotek system was developed in the late 1960s by the Ontario Precast Concrete Manufacturers Association and the Ontario Division of the Portland Cement Association.[4] The system was designed specifically for office or institutional structures, although it is unclear to what extent the system has been used by the precast concrete industry.

Duotek is a modular structural system that accommodates building services and components. The system consists of three precast concrete elements: columns, prestressed beams, and double tees, with cast-in-place connections between primary beams and columns. A 63 mm (2.5 in.) thick cast-in-place concrete topping completes the floor system. Beams and double tees are a constant depth, and the floor system has a constant 1.22 m (4 ft) total floor depth from underside of ceiling to top of floor finish.

Openings through primary beams and tee stems are provided at 1.52 m (5 ft) modular centers to accommodate the HVAC, plumbing, and electrical services. The system can be used for structures up to five stories in height. Structural bay sizes vary in 1.52 m (5 ft) modular increments up to 9.15 x 19.81 m (30 x 65 ft). Roof spans can be up to 24.4 m (80 ft).

Three types of beams are used with this system. Type A is an inverted T-beam with horizontal openings of 711 x 356 mm (28 x 14 in.) on a 1.52 m (5 ft) module [see Fig. 1(a)]. Spandrel beams, Type B, support tee slabs on one side and also include openings of 711 x 356 mm (28 x 14 in.) on a 1.52 m (5 ft) module. Type C primary beams allow services to run over the beam and under the double tee floor slab. The result is an opening provided for the services of 1270 x 356 mm (50 x 14 in.) on a 1.52 m (5 ft) module [see Fig. 1(b)].

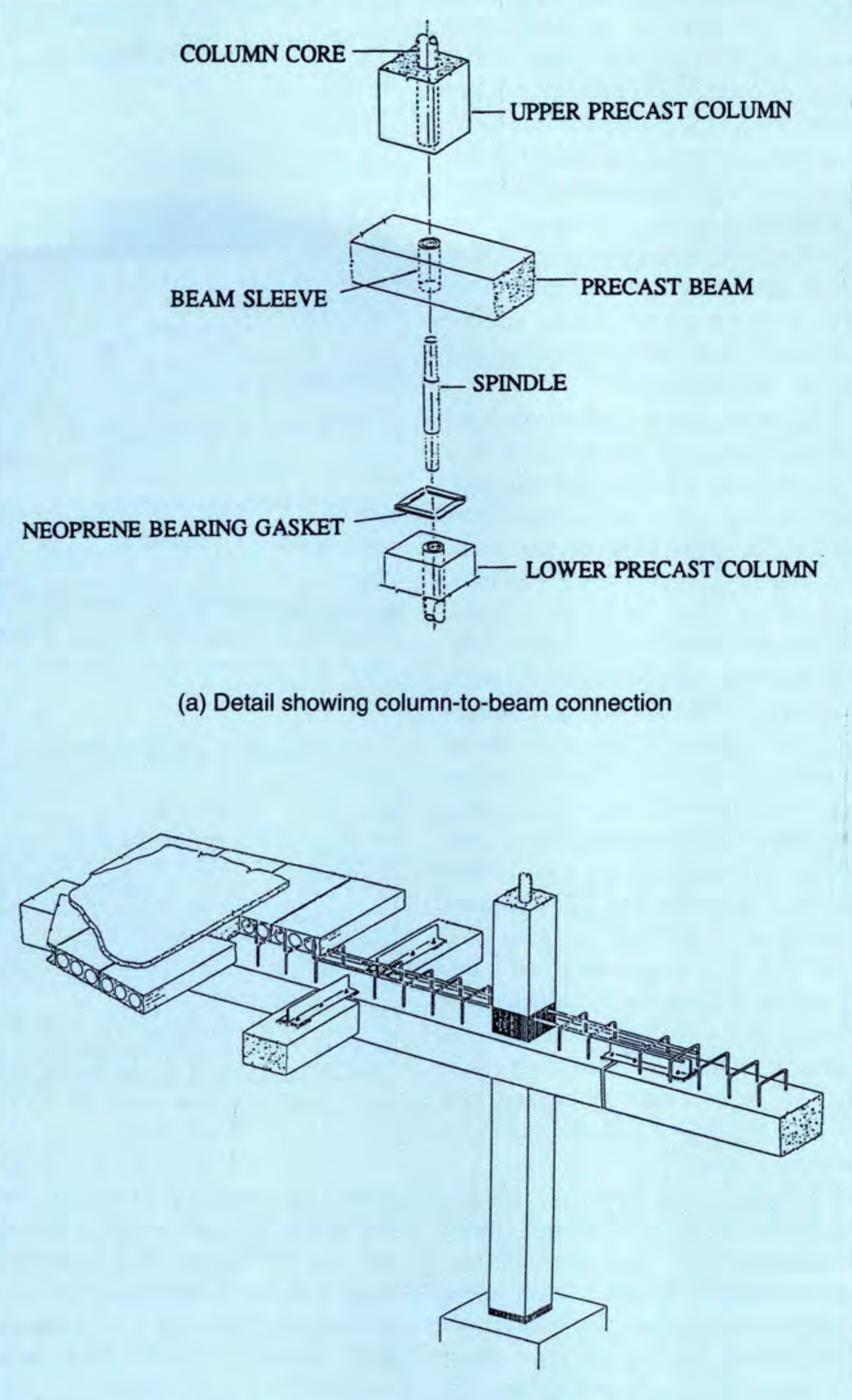
As shown in Fig. 1, double tee floor members are cast with blockouts to allow for horizontal passage of services. Double tees, 3.05 m (10 ft) wide x 813 mm (32 in.) deep with a maximum span of 19.81 m (65 ft), incorporate 711 x 356 mm (28 x 14 in.) openings on a 1.52 m (5 ft) module. Dapped ends on the tee members also allow for the passage of horizontal service systems. To accommodate the vertical service systems, openings up to 1.22 m (4 ft) wide can be made through the deck of the double tees.

The Duotek system is intended to fully accommodate building services for both initial requirements and future modifications. The 1.22 m (4 ft) total floor depth is intended to accommodate the precast structural members, HVAC, plumbing, and electrical services, and ceiling and lighting systems.

Dycore System — The Dycore system[5] has been used for many years throughout the United States for office buildings, schools, healthcare facilities, and parking garages. The key precast concrete elements include shallow soffit beams, high strength Dycore floor slabs, and multistory columns cast with blockouts at the beam level (see Fig. 2). The precast beam and floor members serve as stay-in-place forms for composite cast-in-place concrete. Connections are also composed of cast-in-place concrete. For spans over 7.62 m (25 ft), a 508 mm (20 in.) structural floor depth is required for office loading.[5] This depth comprises a 305 mm (12 in.) precast soffit beam and a 203 mm (8 in.) Dycore floor slab. This depth does not include the additional depth required for service systems.

Columns may be cast-in-place or precast with multistory precast columns containing blockout cavities at the beam level to facilitate beam-to-column connections. Interior soffit beams with protruding shear reinforcement are cast as shallow members to act as stay-in-place forms and tension elements for cast-in-place concrete. Interior soffit beams are 1.2 m (4 ft) wide and similar in configuration to Dycore hollow-core floor slabs, but the soffit beams are solid without voids.

Prior to placement of the cast-in-place concrete, negative moment beam reinforcement is tied to the precast soffit beam and to the column reinforcement. Dycore hollow-core slabs with a typical width of 1.2 m (4 ft), are used as floor members. Floor members are tied together with grout that is applied in shear keys of adjacent floor members.



(a) Detail showing column-to-beam connection

(b) Structural components (adapted from Ref. 6)

Fig. 3. Dyna-Frame system.

HVAC ducts, plumbing components, and electrical system conduits can be placed on the precast soffit and embedded in the composite cast-in-place concrete. Similarly, voids in Dycore slabs can be used to house electrical conduits and plumbing components. HVAC and plumbing services are typically suspended beneath the precast floor system with standard hardware. Blockouts can be cast in the floor members to allow for vertical passage of HVAC and plumbing systems and holes can be drilled in the floor members after they are erected.

Dyna-Frame System — The Dyna-Frame system[6,7] is typically used in multistory residential structures, office buildings, parking garages, and schools. The key to this system is the column-to-column splice and the column-to-beam splice. The standardized connections do not change as the design loads for the structure increase. For an office loading, a span of 7.3 m (24 ft) would require a 711 mm (28 in.) deep structural system.[8] This depth is comprised of a 508 mm (20 in.) rectangular beam and a 203 mm (8 in.) precast hollow-core slab.

The single-story precast columns are pretensioned and reinforced with a structural steel tube running longitudinally in the center of the column that is used in the splice made at each floor. The tube or column core does not protrude from either end of the column. The inside diameter of the column core is held constant at 100 mm (4 in.).

Beams can be single span, multispan, or cantilevered with beam splices at points of inflection. The beams are supported directly by the single-story columns. Beam sleeves, 152 mm (6 in.) in diameter, are cast in the beam to be concentric with the steel core of the supporting column [see Fig. 3(a)]. The beams are usually designed as composite members. The precast portion of the beam is designed to withstand the erection loads of the floor slab, concrete topping, and its own weight for both negative and positive moments.

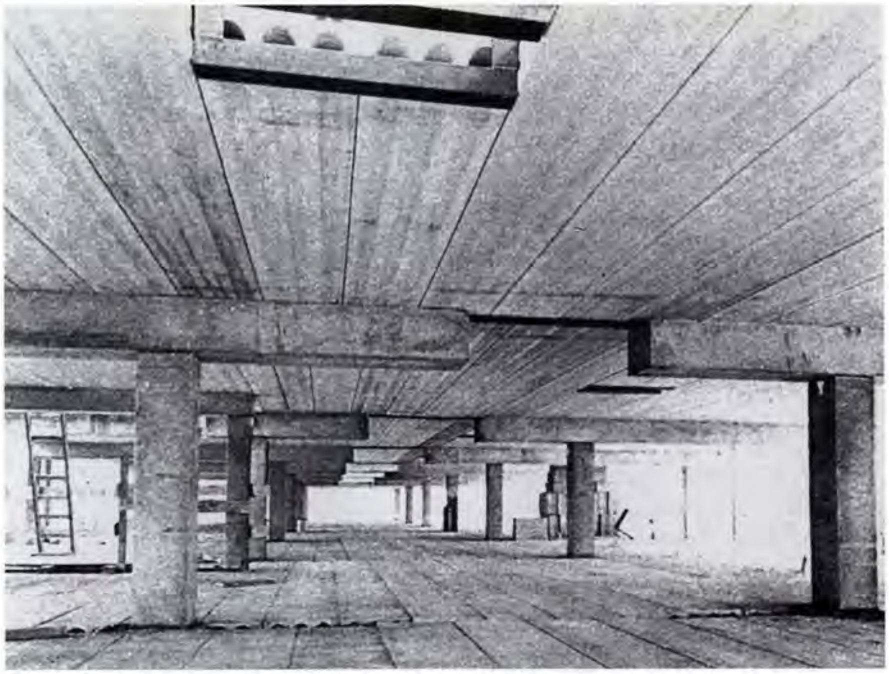


Fig. 4. Dyna-Frame system (adapted from Ref. 9).

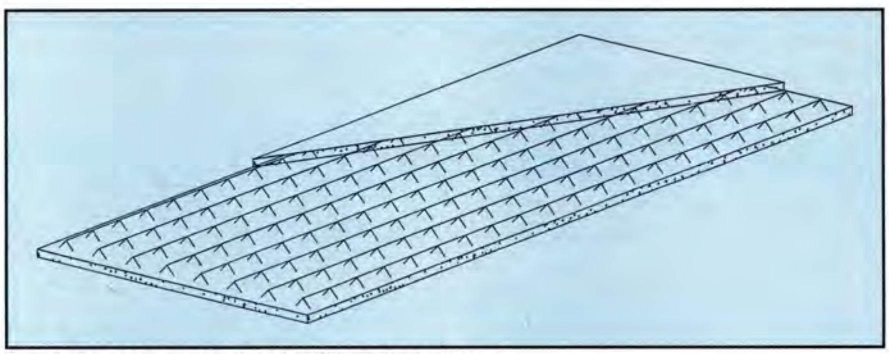


Fig. 5. Filigree precast slab with light steel truss.

The composite beam, including cast-in-place concrete and field-placed reinforcement, carries the superimposed loads. Mild steel reinforcement is field-placed over the column to carry the negative moment imposed on the beam by superimposed loads. If cantilevered beams are used, then a beam-to-beam splice is required. Steel connection angles and mild steel reinforcement, located in the cast-in-place top portion of the beam, provide the connection [see Fig. 3(b)]. The steel ties the beams together and transfers shear, but no attempt is made to transfer moment through this connection.[9] Hollow-core slabs are used as floor members with this system.

Accommodation of the horizontal service systems within the depth of the structural system is possible with the Dyna-Frame system if cantilevered beams are employed so that the interior beams do not extend across the full span (see Fig. 4). This provides an open space in which components of the service systems may be suspended with standard hardware without increasing floor system depth.

Filigree Wideslab System — The Filigree wideslab system was originally developed in Great Britain and is presently used there under the name of OMNIDEC.[10,11] This method of construction is used throughout the United States and is also used widely in Japan. Three systems from Japan that are included in this paper[12] (PG Connection System, RC Layered Construction System, and RPC-K System) all use Filigree-type precast floor members. Though often used for parking garages, the system has been used in residential construction, office buildings, and other multistory commercial structures.

Filigree construction employs reinforced precast floor panels that serve as permanent formwork. The panels are composite with cast-in-place concrete and contain the reinforcement required in the bottom portion of the slab. They also contain a steel lattice truss, which projects from the top of the precast unit (see Fig. 5). The steel truss ensures composite behavior between precast and cast-in-place concrete and provides the unit with stiffness during erection.

The typical thickness of the prefabricated unit is 57 mm (2.25 in.). The units are made in lengths up to 21 m (70 ft), and typical widths of 2.44 m (8 ft) or less. Slab units can be pretensioned; when reinforcing steel and concrete are field-placed, the resulting

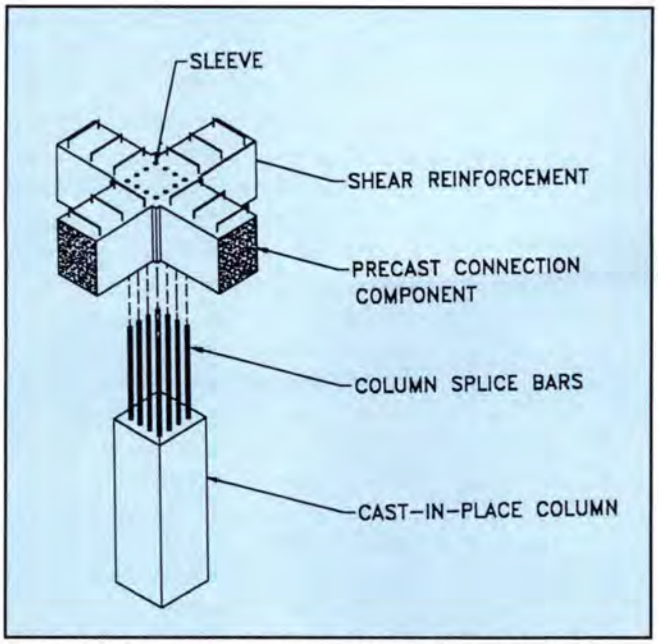


Fig. 6. PG Connection system — cross-shaped beam-to-column component.

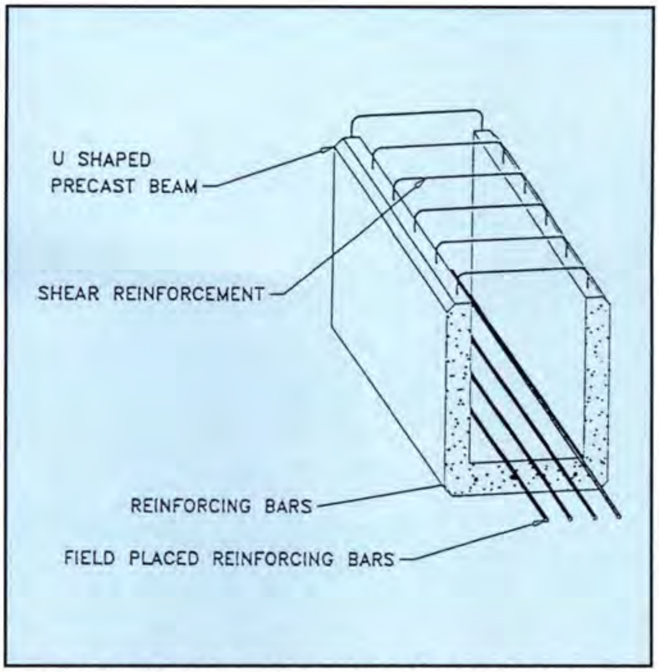


Fig. 7. RPC-K system — U-shaped precast shell beam.

floor is free of camber. To create a voided wideslab unit, lightweight void formers are pressed into the top surface of the precast unit during manufacture.

Both cast-in-place and precast beams are used with this system. Mid-State Filigree Systems manufactures a wide, shallow, interior soffit beam that is 63.5 mm (2.5 in.) deep. These beams are typically designed for medium range spans 4.57 to 7.62 m (15 to 25 ft). Beams can also be cast with voids to increase structural efficiency. The prefabricated wideslab unit is designed as a simply supported member.

Field-placed reinforcement provides continuity between floor members, soffit beams, and cast-in-place columns, and combines with cast-in-place connections to create a frame that acts monolithically under gravity forces. For spans of less than 7.3 m (24 ft), flat plate construction is employed, eliminating the extra depth that is required for beams. For a span of 11 m (36 ft) and a load of 2.39 kN/m^2 (50 psf), a structural depth of 330 mm (13 in.) is required.[10]

Electrical services can be placed within the cast-in-place portion of the floor system. Preformed holes, prepositioned junction boxes and attachment hardware are all available from the manufacturer. HVAC system components are suspended beneath the precast floor components and passed vertically through preformed blockouts in the floor members.

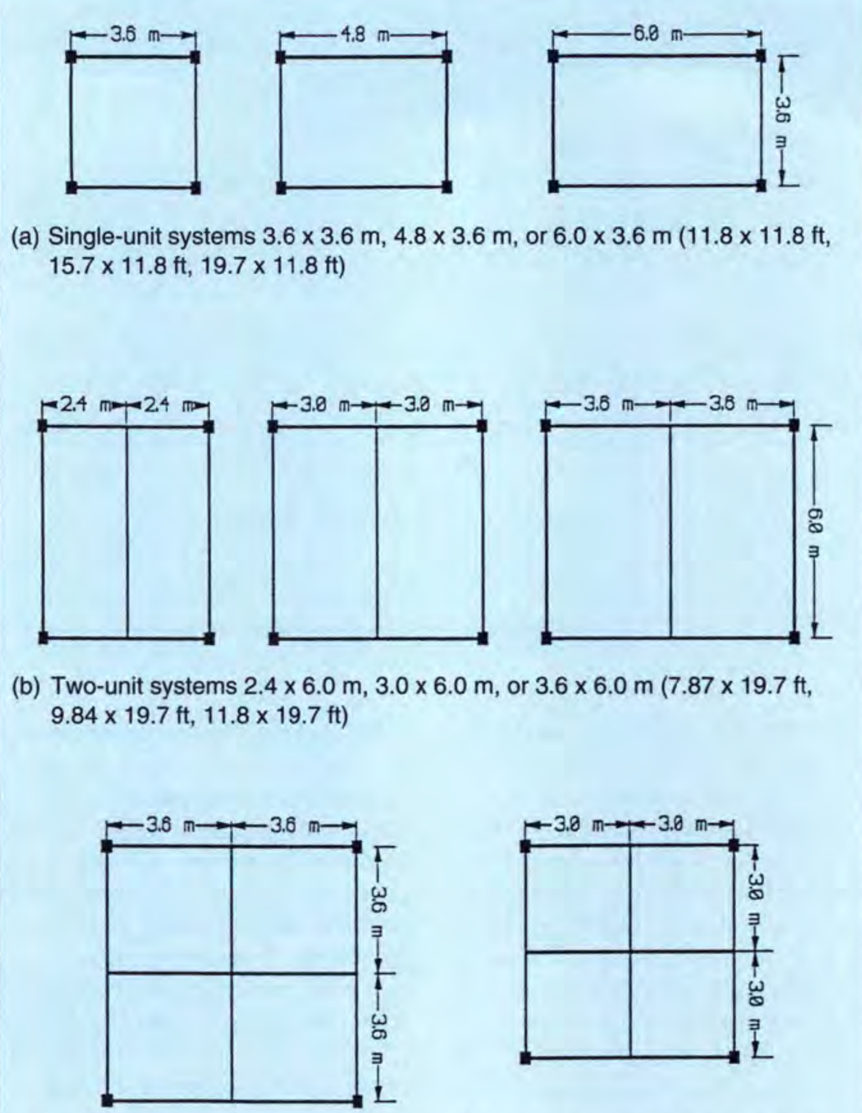
PG Connection System — This system and the next two systems are examples of precast concrete construction in Japan today. Information on precast structural systems developed in Japan can be found in a report titled "Existing Precast Frame Systems in Japan." This report, produced by the Joint Technical Coordinating Committee on Precast Seismic Structural Systems,[12] describes the state-of-practice of precast seismic structural systems in Japan and surveys existing precast frame buildings with respect to their use, scale, structural system, and structural connections.

The PG Connection system, developed by the Obayashi Corporation Technical Research Institute, employs precast cruciform beam components that are placed at column locations. The precast cruciform component is placed over the column, and beam-to-beam connections are made by welding or mechanical splices (see Fig. 6). Formwork is then built-up around the connection and the beam is completed with cast-in-place concrete. The column is cast-in-place and the floor slab is made of Filigree type slabs. The system has been used in the construction of multistory office and apartment buildings.

RC Layered Construction System — This structural system, developed by the Taisei Corporation, consists of single-span members connected with cast-in-place concrete. Components of the system include precast single-story columns, precast beams, and Filigree type slabs. Single-story columns are cast with reinforcing bars protruding from their upper face for the column-to-column connections. Single-span beams rest on the precast columns.

Once the precast slabs are positioned, negative moment reinforcing steel is placed longitudinally along the top of the beam and through the beam-to-column connection zone. Two-way reinforcement is placed on the precast floor slab. The concrete structural topping is placed over the entire floor system, resulting in monolithic connections. Construction of subsequent stories begins with precast columns being slipped over the protruding reinforcing bars from the lower column. The connection is then grouted.

RPC-K System — The RPC-K system, developed by Kabuki Construction Company, utilizes U-shaped precast beams that serve as stay-in-place forms for cast-in-place concrete (see Fig. 7). Other components of the system include cast-in-place columns and Filigree type floor members. Cast-in-place concrete is used for all connections between components. Longitudi-



(a) Single-unit systems 3.6 x 3.6 m, 4.8 x 3.6 m, or 6.0 x 3.6 m (11.8 x 11.8 ft, 15.7 x 11.8 ft, 19.7 x 11.8 ft)

(b) Two-unit systems 2.4 x 6.0 m, 3.0 x 6.0 m, or 3.6 x 6.0 m (7.87 x 19.7 ft, 9.84 x 19.7 ft, 11.8 x 19.7 ft)

(c) Four-unit systems 3.6 x 3.6 m or 3.0 x 3.0 m (11.8 x 11.8 ft, 9.84 x 9.84 ft)

Fig. 8. Modular composition possibilities for the IMS system.

nal and shear reinforcement are embedded in the precast portion of the beam. The longitudinal reinforcement protruding from the precast portion is bent upward into the column to provide anchorage. Additional longitudinal reinforcement is placed in the trough of the beam once the beam is in place.

To facilitate the column-to-column connection, the main reinforcement from cast-in-place lower columns protrudes upward to tie in the cast-in-place upper column. Filigree type slabs rest on the precast beams and reinforcement is placed across the trough of the beam to tie the components together. Negative moment reinforcing steel is placed both longitudinally and transversely on the precast slab, and then embedded with cast-in-place concrete.

IMS System — The IMS system, also known as the IMS-ZEZELJ system, originated in Serbia, Yugoslavia, at the Institute for Testing of Materials.[13] This system, originally developed in the 1950s, is intended to provide a prefabricated framework suitable for both commercial and residential buildings. Because the system can be designed for seismic forces, it has gained acceptance in regions of frequent seismic activity. The State Building Co. of Baranya County, Hungary, further developed the system for longer spans and for greater flexibility in accommodating utilities. The system has been used in Cuba, Hungary, and Yugoslavia for schools, hospitals, administrative buildings, offices, and hotels.[14]

The key precast element of this modular system is the pretensioned floor member, which is manufactured in two phases. In Phase 1, the unit is cast as a ribbed unit with a top flange. The reinforced ribbed slab is externally prestressed to produce compression in the top flange and tension in the bottom portion of the ribs. In Phase 2, the bottom of the floor is equipped with a wire mesh and immersed in fresh concrete.

Once the concrete has gained adequate strength, external stress is released from the ribbed unit, producing compression in both the top and bottom flanges and tension in the ribs. The floor unit is flat on both the top and bottom faces. Floor units are manufactured in either single-unit, two-unit, or four-unit systems (see Fig. 8). With post-tensioning, the precast edge beams become the main girders of the structural floor system.

The IMS system relies on friction and clamping action produced by post-tensioning to transfer vertical loads and bending moments from floor units and edge beams to the columns. The post-tensioning runs in the floor system and through the columns in both principal directions. In single-unit systems [see Fig. 8(a)], the prestressing tendons are placed between floor units but in multi-unit systems [see Figs. 8(b) and 8(c)], the tendons are also passed through ducts within the floor units. To erect this system, floor units are placed between columns on temporary steel hardware (see Fig. 9). Tendons are placed across several floor units and stressed. After prestressing, the groove between floor units is filled with concrete, and in multi-unit systems, ducts within the units are grouted.

HVAC, plumbing, and electrical systems are suspended beneath the precast floor system and fastened with standard hardware. Passage of vertical ducts and plumbing is accommodated using blockouts during the casting of floor units.

PD2 Frame System — The PD Frame was implemented in 1960. The PD2 Frame[15] was developed in 1972 based on the practical knowledge gained from the original system. The PD2 Frame is based on a planning module of 0.3 m (1 ft) and a maximum bay size of 10.8 x 7.2 m (36 x 24 ft). It is intended primarily for structures of one to four stories, but can be extended to greater heights. The vertical module is also 0.3 m (1 ft). This structural system has been used in Great Britain for schools, offices, hospitals, shops, and factories.

The precast components of the system include multistory columns, loadbearing exterior panels, inverted T-beams, L-shaped spandrel beams, and hollow-core floor slabs. Columns are typically up to four stories in height and prestressed or reinforced with mild steel reinforcement depending on loading conditions. Short steel tees are cast into the columns at the beam level for the beam-to-column connection (see Fig. 10).

Prestressed inverted T-beams serve as primary beams and L-shaped precast members act as spandrel beams. Both types of beams are cast with steel plates protruding from the end faces of the member. These plates are bolted to the steel tees in the columns. Floor members are commonly hollow prestressed units with widths that coincide with the 0.3 m (1 ft) planning module. Loadbearing panels can replace both columns and edge beams on the perimeter of the frame.

The structural depth of the floor system for a 7.2 m (24 ft) span and typical office loading is 645 mm (25.5 in.). An inverted T-beam 645 mm (25.5 in.) deep is required for a 5 kN/m^2 (100 psf) load and a span of 7.2 m (24 ft). For a similar span and loading, a spandrel beam with a depth of 320 mm (12.5 in.) is required.[15]

The PD2 Frame system utilizes notched beams to accommodate the horizontal services and reduce the total depth of the floor system. Notches 350 mm (14 in.) long and 100 mm (4 in.) deep are formed in the beams at the column-to-beam connection (see Fig. 11). Services may be assembled in large sections on the floor below and lifted into position on hangers attached to the beam above. Holes in the floor members allow the passage of vertical services.

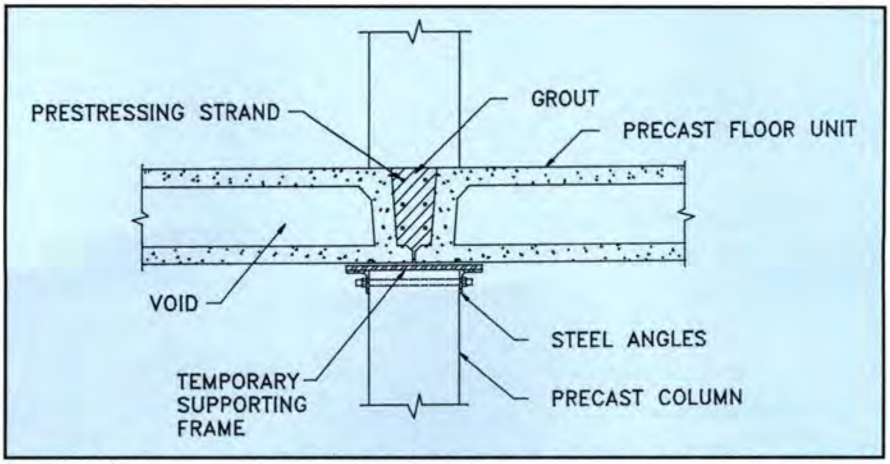


Fig. 9. IMS system — joint between floor units and column during construction.

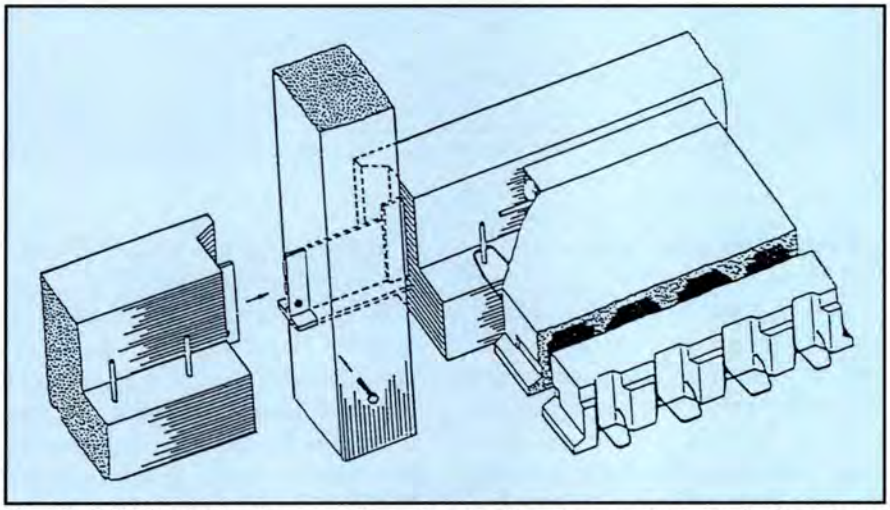


Fig. 10. PD2 Frame system — column-to-edge beam connection detail. The steel plate from the column is bolted to the steel beam plate for stability during erection (adapted from Ref. 15).

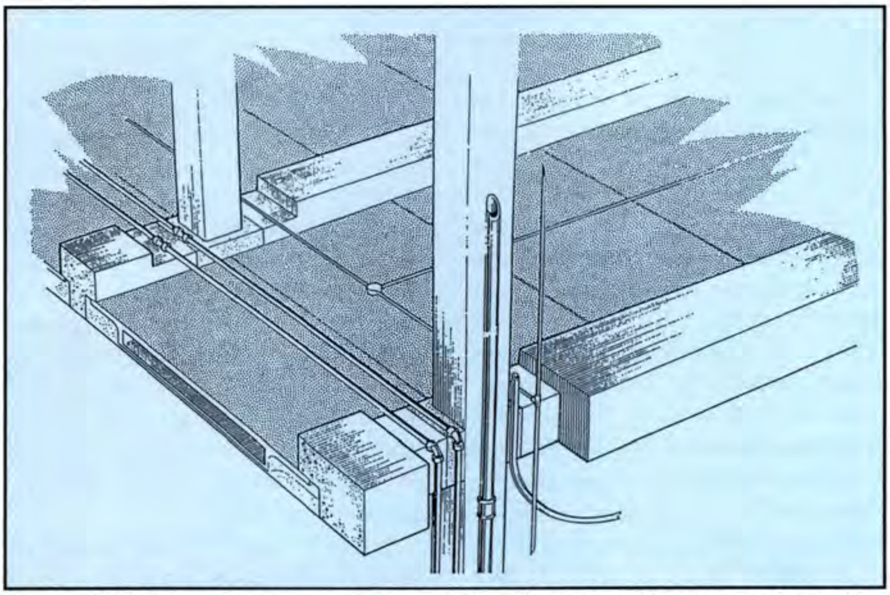


Fig. 11. PD2 Frame system — accommodation of services. Notches are formed in primary beams at the beam-to-column connection to allow services to pass without increasing total floor depth (adapted from Ref. 15).

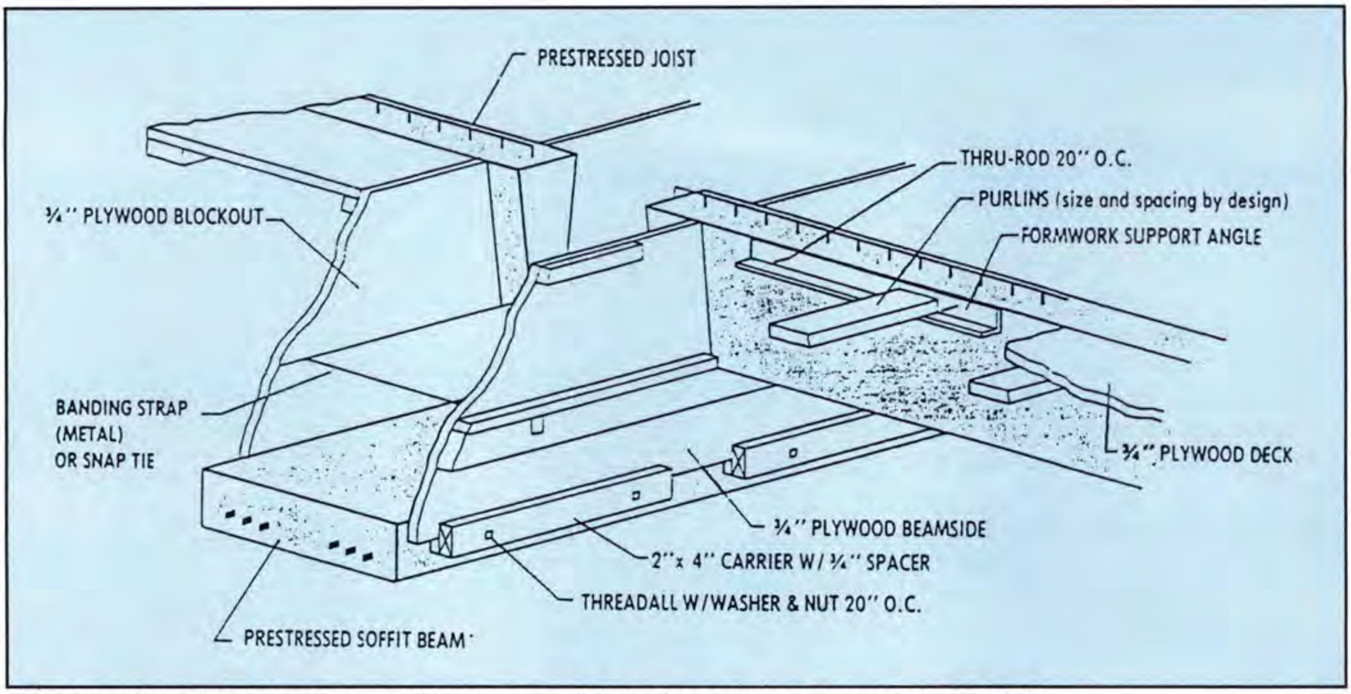


Fig. 12. Prestressed joist system — soffit beam assembly for deep beams (adapted from Ref. 17).

Prestressed Joist System — This system has been used for several years in hospitals, parking garages, department stores, and high rise office buildings.[16,17] The structural floor system can be thought of as a two-component system. Precast, prestressed floor joists serve as tensile components and the cast-in-place floor slab serves as the compressive component. The joists are supported by a soffit beam that is designed as a shored composite member. Longitudinal reinforcement is tied to shear reinforcement, which protrudes from the joists and soffit beams to provide continuity.

The precast portion of the soffit beam is cast in two standard cross sections: 610 mm wide x 165 mm deep (24 x 6.5 in.) or 406 mm wide x 241 mm deep (16 x 9.5 in.). Fig. 12 shows the soffit beam assembly. Keystone shaped joists are manufactured in four standard depths: 200, 300, 400, and 610 mm (8, 12, 16, and 24 in.). Spans range from 5 to 25.5 m (16.4 to 83 ft). Joists are cast with small holes through which steel pins are inserted to support formwork for the cast-in-place slab. For a typical office loading, a span of 9.1 m (30 ft) requires a 400 mm (16 in.) joist with a 76 mm (3 in.) cast-in-place topping. The joists are spaced 2 m (6.5 ft) on center. This floor system has the capacity to carry a superimposed live load of approximately 6 kN/m^2 (125 psf).[16]

HVAC, plumbing, and electrical systems are suspended beneath the concrete floor system with standard hardware. Electrical conduit and junction boxes can be placed in the cast-in-place floor slab, with cables pulled through the conduit after the concrete is placed. Blockouts in the floor slab allow the passage of vertical plumbing and ducts.

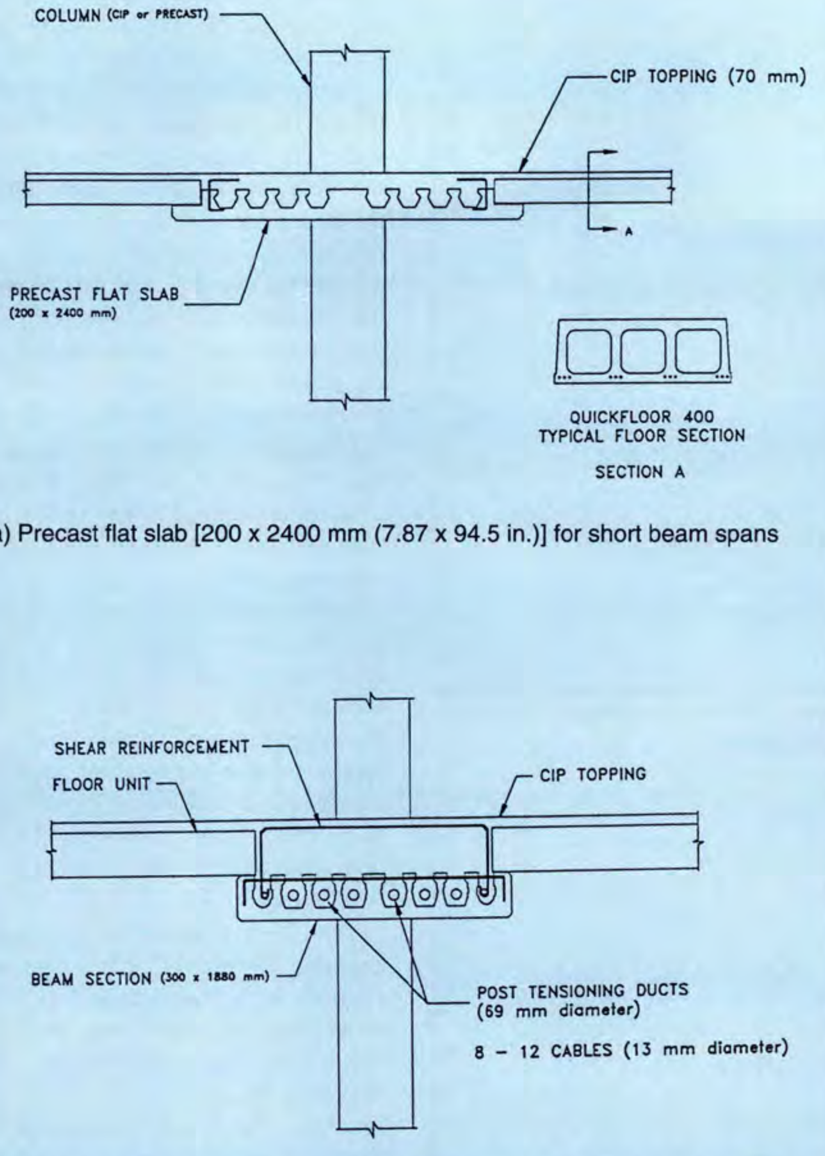
Quickfloor System — The Quickfloor system[18] was developed in Australia where it has been used for several years for various types of buildings. Precast beams, which serve as stay-in-place forms, are combined with cast-in-place concrete to produce a rigid monolithic frame. As shown in Fig. 13, the beams are similar in section to a hollow-core slab, except the top flange is not cast with the rest of the component. Precast floor units rest on the outer ledge of the beam, as shown in Fig. 13(a). A variation of this design is shown in Fig. 13(b), where the 300 x 1880 mm (11.8 x 74 in.) beam section supports the floor unit on its top surface.

Negative moment steel is tied to shear reinforcement protruding from the soffit beam and the whole area receives a steel mesh mat for continuity. Cast-in-place concrete ties the whole floor system together. For additional strength, post-tensioning ducts can be placed within the cavities of the precast beam. Beam components bear on column corbels that transfer loads to the single-story columns. The columns are either precast or cast-in-place.

The system can span up to 10 m (33 ft) in the beam as well as in the floor slab direction under a superimposed live load of 3.5 kPa (70 psf). The depth of the floor system is 585 mm (23 in.). If the beam span is reduced to 8.8 m (29 ft), the live load can be increased to 7.0 kPa (140 psf) with the same floor depth. The above span/depth figures are for an end bay, while internal bays can accommodate longer spans.

Electrical systems can be placed in the cast-in-place portion of the floor system and/or within the cores of the hollow-core floor slabs. Typically, plumbing and ducts are suspended beneath the precast floor system and anchored with standard hardware.

Structurapid System — The Structurapid system was first used in Italy in the early 1960s and since then has been used for residential and commercial buildings.[19] The system is comprised of precast column tubes and T-beams. The columns and beams are connected by means of a tongue and groove system of joining (see Fig. 14).



(a) Precast flat slab [200 x 2400 mm (7.87 x 94.5 in.)] for short beam spans

(b) Post-tensioned beam section [300 x 1880 mm (11.8 x 74.0 in.)] for medium to long spans

Fig. 13. Quickfloor system — typical beam cross sections.

Reinforcing steel is placed on the precast T-beam and bent down into the hollow column core. With the placement of cast-in-place concrete in the column cavity, a monolithic beam-to-column and column-to-column joint is developed. Hollow-core floor members rest on the beam flange. Shear reinforcement protrudes from the top of the beam to achieve continuity with the floor members. Cast-in-place concrete is used as a floor topping to provide a rigid floor diaphragm.

The structural system is intended for low rise (one to five stories) structures subjected to medium or light loading. A typical bay size is 4.57 x 4.57 m (15 x 15 ft). Larger bay sizes and heavier loadings can be accommodated if prestressed T-beams are used instead of conventionally reinforced concrete beams.

Swedish System — The conventional system used in Sweden for multistory commercial construction consists of precast multistory columns, precast inverted T-beams or rectangular beams, and untopped precast hollow-core slabs or double tees. While the components of the system are similar to the United States conventional system, the Swedish system takes advantage of modular coordination and integration of the piping and duct systems. The system is typically used in structures of less than 20 stories. Offices, schools, hospitals, department stores, and multistory residential buildings are frequently constructed using this system.[20]

This system uses a high degree of integration of plumbing and ducts into the structural floor system. For example, each core in the hollow-core floor slabs is given a specific service function. In this way, a systematic placement of services is achieved through the entire building. This method can only be utilized if floor slabs bear on the top surface of the precast rectangular beam members. Similar to the Duotek system, the beam components are cast with rectangular openings to allow mechanical and electrical services to pass.

Heating and ventilation systems are integrated into the precast frame and make use of the heat mass of the concrete floors through which the supply ventilation air is circulated before entering the room. The effects of using heat mass of the floors in this way are different during summer and winter conditions. If the climate is hot, a partial air conditioning system is achieved by cooling the floors with the cooler night air. If the climate is cold, possible surplus energy produced from activity in the building is stored more effectively in the floors.

Thomas System — The Thomas system[21] is comprised of multistory precast columns, composite shell beams, and precast double tee floor members. This system has been used in the midwestern United States for multistory office building construction. The key structural component of the system is the shell beam. As shown in Fig. 15, the beam flanges support the stems of the double tees and the beam is supported by precast column corbels. The pretensioned single span shell beams also serve as forms for cast-in-place concrete.

Columns are cast with four couplers at the beam level and Dywidag bars from the beam are threaded into the couplers during erection. Lightweight [1924 kg/m^3 (120 pcf)] precast double tees serve as floor members. For

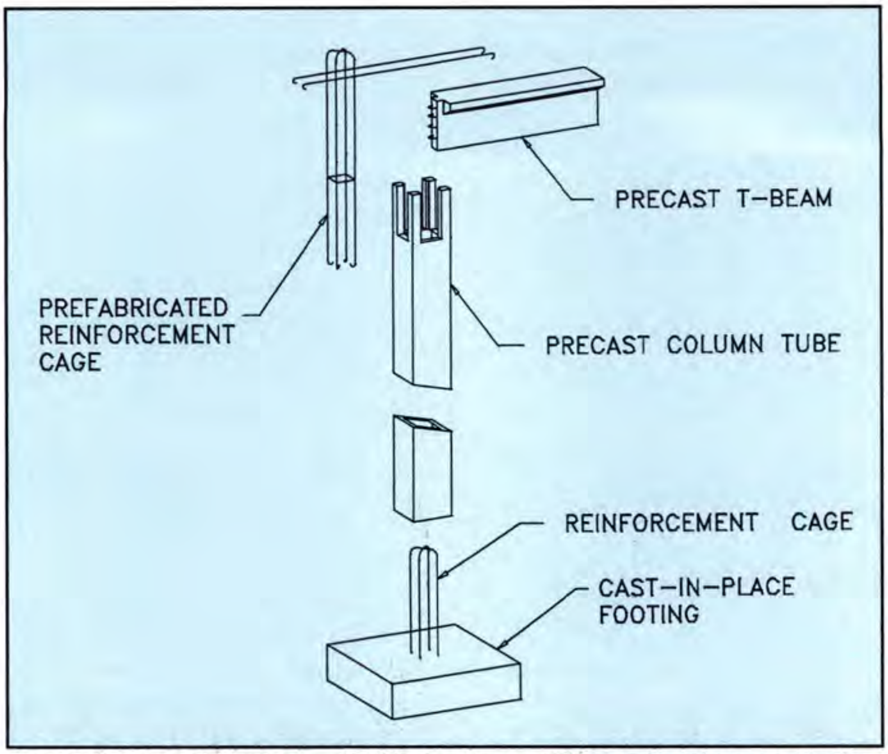


Fig. 14. Structurapid system — footing-to-column and beam-to-column connection. Tongue of T-beam is dropped into slot of precast column.

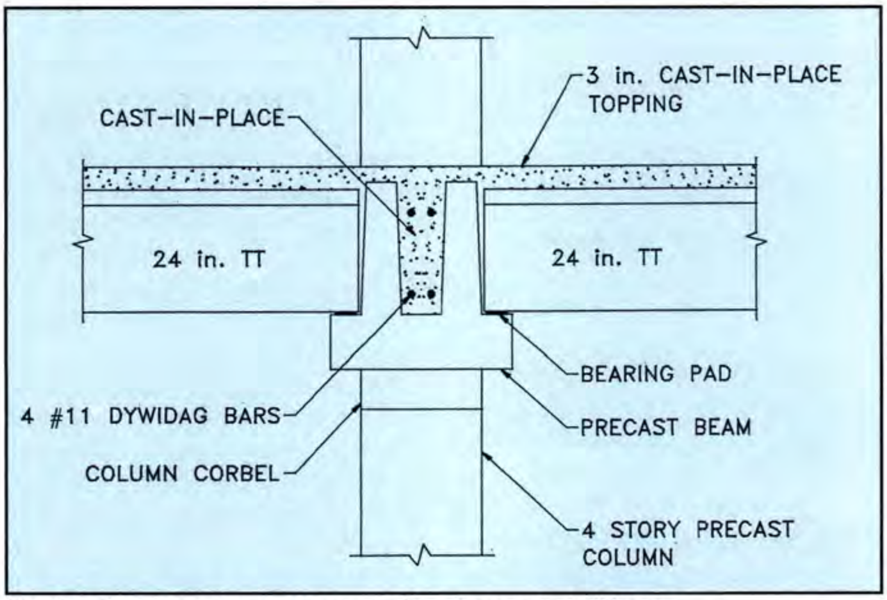


Fig. 15. Thomas system — cross section of precast shell beam.

5 kN/m² (100 psf) of live load and spans of 9.1 m (30 ft), a shell beam approximately 915 mm (36 in.) deep is required. With a 76 mm (3 in.) topping, the structural depth of the floor system is approximately 990 mm (39 in.) deep. Services are positioned beneath the precast floor and suspended with standard hardware.

Tri/posite System — Tri/posite[22] is a precast building system composed of three major components: structure, HVAC, and partitions. The Portland Cement Association (PCA), in cooperation with the architectural firm of Hellmuth, Obata and Kassabaum, developed the Tri/posite system for dormitory and academic buildings. The Tri/posite system was selected in 1969 by the University of California as the structural system for its University Residential Building System program.

The system uses precast columns, shear walls, and floor members in conjunction with cast-in-place beams and floor slabs. Floor members are similar in configuration to inverted double tees, with tee stems protruding upward. The flange of the precast double tee serves as the tensile component of the floor system. A plenum for plumbing, HVAC, and electrical services is provided within the structural depth of the precast system (see Fig. 16). The precast floor members provide a working platform for the service trades so overhead work is eliminated.

Multistory columns are cast up to four stories in length. These conventionally reinforced columns are cast with notches at the beam level for the cast-in-place beam-to-column connection. Horizontal holes are also cast into the column at the beam level to allow reinforcing bars to be threaded through and provide continuity between beams. Interior and exterior beams are cast-in-place and are made continuous by threading longitudinal beam reinforcement through the column and joining it with adjacent beam reinforcement.

The inverted double tee floor members are 394 mm (15.4 in.) deep and range in span from 4 to 10.7 m (13.3 to 35 ft) in 508 mm (20 in.) modules. Beam spans range from 2.54 to 6.10 m (8.3 to 20 ft), also in 508 mm (20 in.) modules. The structural depth of the floor system is 457 mm (18 in.). Included in this depth is the 63.5 mm (2.5 in.) deep cast-in-place concrete floor topping.

The system provides a plenum cross section of 356 x 914 mm (14 x 36 in.). The plenum works as a return air space with the HVAC duct positioned within it. The stems of the tees are cast with 200 x 250 mm (8 x 10 in.) oval perforations that allow services to run transversely. Similar holes are field-cast in the cast-in-place beams. According to PCA,[22] 203 x 406 mm (8 x 16 in.) rectangular ducts can also be accommodated. Electrical services are run through the plenum using conduit and junction boxes. Access to the HVAC, plumbing, and electrical services is provided by precast access panels that range in size from 305 x 915 mm (12 x 36 in.) to 915 mm (36 in.) square.

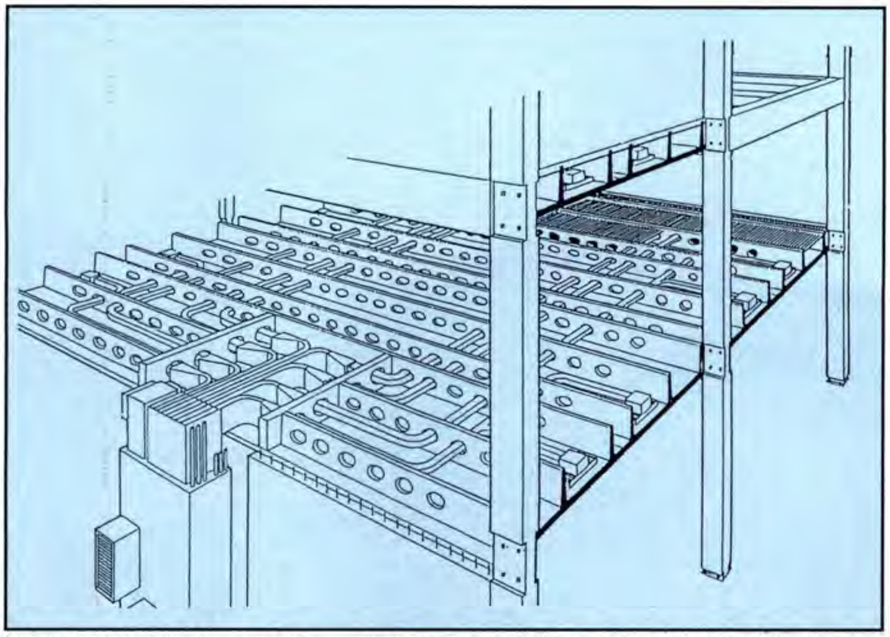


Fig. 16. Tri/posite floor system — provided within the structural depth of the floor system is a 356 x 914 mm (14 x 36 in.) plenum for services. Inverted double tees and cast-in-place beams are cast with 203 x 406 mm (8 x 10 in.) holes for services (adapted from Ref. 22).

Emerging Systems

Contiframe System — The Contiframe[23] system consists of single-story precast columns, precast multispan beams, precast infill beams, and precast, prestressed floor members (see Fig. 17). The Contiframe system attempts to avoid connections in highly stressed areas and to avoid costly fittings associated with the column-to-beam connections. The precast frame is analyzed as a cast-in-place frame and the results are used to position beam-to-beam connections at areas of low stress. The system was originally developed for office or similar type structures with spans of 6.0 to 7.2 m (19.7 to 23.6 ft).

Single-story precast columns are cast with four threaded rods protruding from the upper face. These rods pass through ducts in the beams and are coupled to rods protruding from the upper column. Columns are notched at both top and bottom to facilitate the connection. Details of the connection region are shown in Fig. 18. Internal beams can be single span or continuous over two spans. An infill beam, as shown in Fig. 17, is used to link multispan beams. Beams are tapered at each end and steel angles are embedded in each beam to allow the beams to be bolted together. Hollow-core floor members are used with the system and services are suspended beneath the floor members and anchored with standard hardware.

Spanlight System — The Spanlight system[24] has been under development at the Polytechnic of Central London. The system consists of precast reinforced columns, pretensioned spine beams, reinforced edge beams, and pretensioned hollow-core floor members (see Fig. 19). For typical office loading, a span of 8.5 m (28 ft) requires an 800 mm (31.5 in.) deep precast structural floor system. The depth of the beam is approximately 500 mm (20 in.) and the depth of the precast floor slab is 300 mm (12 in.).

The pretensioned spine beam is a shallow inverted double tee and is the key precast element of the system. The beam acts as a stay-in-place form for cast-in-place concrete and is subjected to two separate stages of prestressing. The precast portion of the beam is pretensioned upon casting in the plant. Once erected, cables are placed in the trough of the beam and tensioned. The trough portion of the beam is filled with cast-in-place concrete. The post-tensioning increases the beam capacity and provides continuity. The post-tensioning also produces a friction connection between the spine or edge beam and the column, enabling column corbels to be eliminated.

Cross tie bars are placed over the beam and incorporated into the cast-in-place concrete to provide continuity between hollow-core floor members. Spine beams are manufactured in three standard depths: 325, 410, and 500 mm (13, 16, and 20 in.). The maximum beam length is 9.1 m (30 ft) and the standard width is 915 mm (36 in.). Multistory precast columns are cast with four preformed holes at the floor level to allow spine beam prestressing cables to pass through. The rectangular column is notched at floor level to facilitate the attachment of a steel collar, which temporarily supports the spine or edge beam. The beams are erected without shoring.

In 1991, a full scale test on a spine beam was terminated after the beam had sustained a load of 23.2 kPa (484 psf).[25] Research is underway to improve the behavior of the beam-to-column connection and to reduce the midspan deflection of the beam.

University of Nebraska Systems — Recent work on precast floor systems has been conducted at the Center for Infrastructure Research at the University of Nebraska-Lincoln. Two systems, referred to as Nebraska A and Nebraska B, are included in this paper. The Nebraska A system involves the use of cast-in-place concrete, while the Nebraska B system does not. The objective of both systems is to reduce structural floor depth in an effort to reduce the total cost of the structure.

The Nebraska A system[26] (see Fig. 20) is a one-way composite beam and column structural system. The system utilizes precast beams, columns, and floor members with cast-in-place concrete. The key precast element in the system is a pretensioned shallow beam that is combined with cast-in-place concrete to form the finished beam. Voids are created within the beam to reduce self weight and improve structural performance. Near the columns, the top flange of the beam is not precast; it is constructed of cast-in-place concrete and field-placed reinforcement to provide continuity.

Diaphragm action is achieved through a cast-in-place topping placed

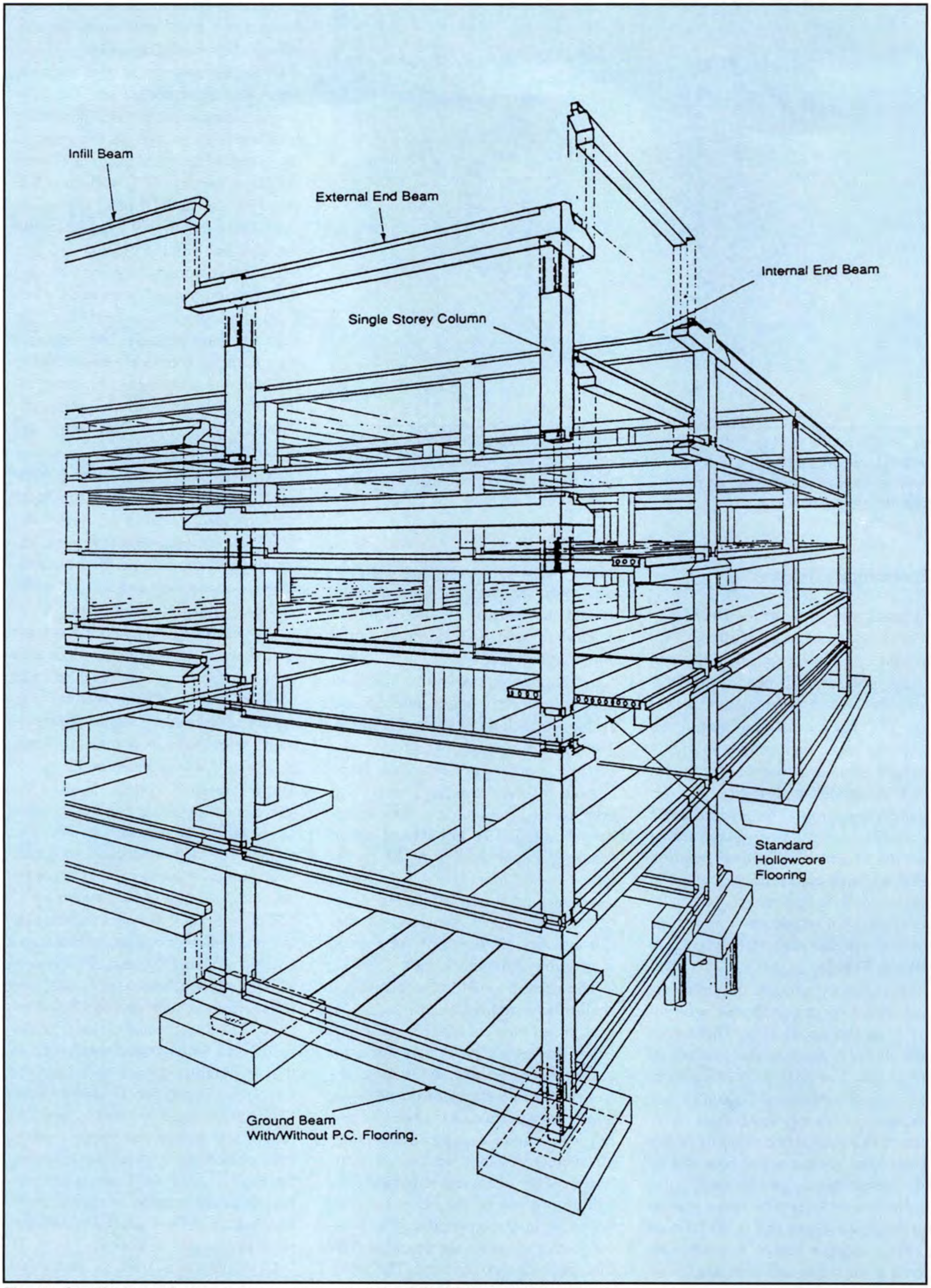


Fig. 17. Contiframe system — precast structural components (adapted from Ref. 23).

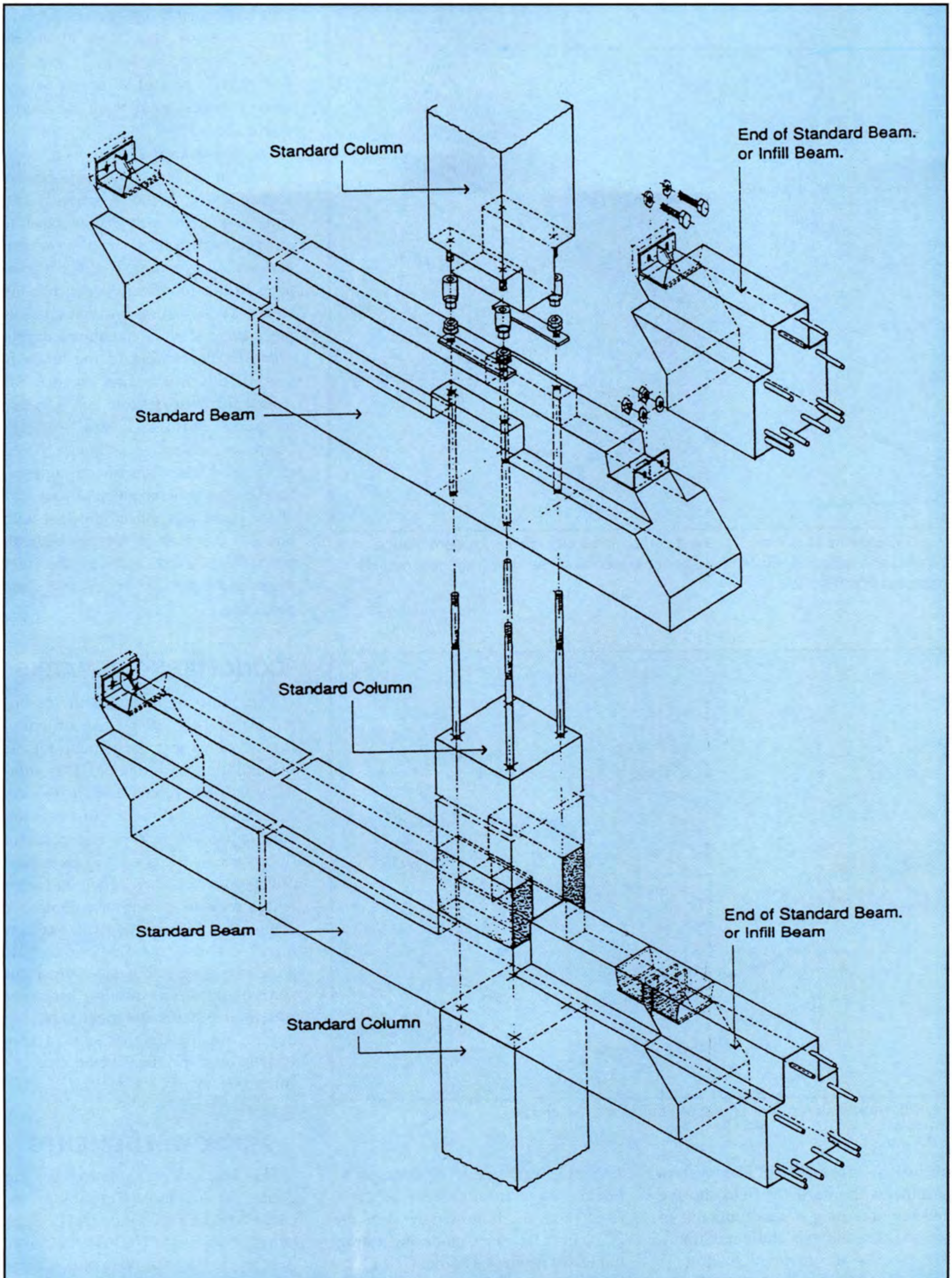


Fig. 18. Contiframe system — beam-to-column connection and bolted beam-to-beam mechanical connection (adapted from Ref. 23).

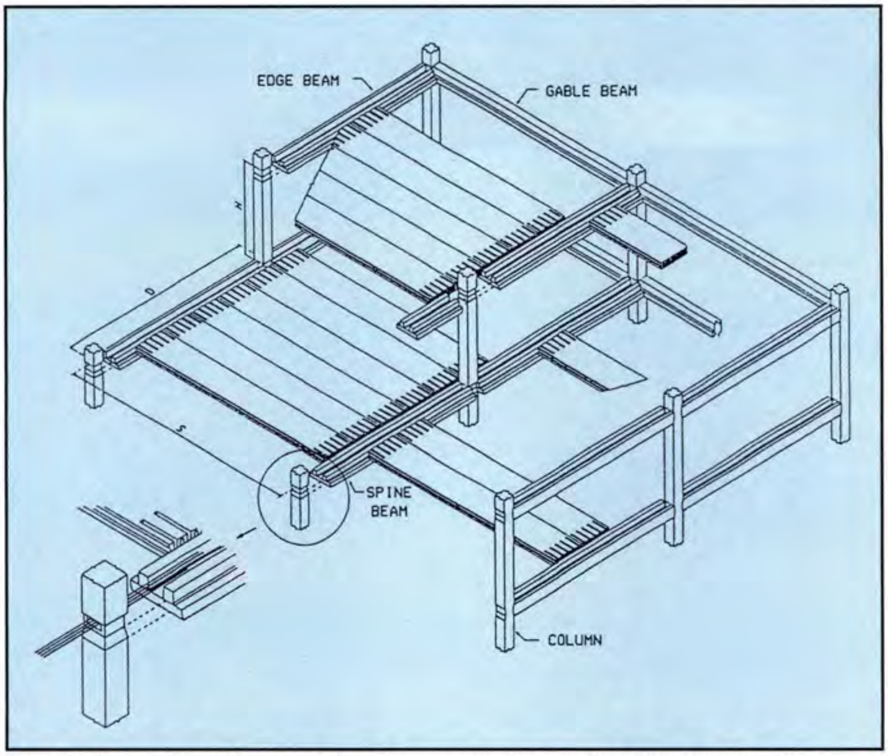


Fig. 19. Spanlight system — precast components include spine beams, edge beams, and columns. System is post-tensioned from the center of the structure (adapted from Ref. 24).

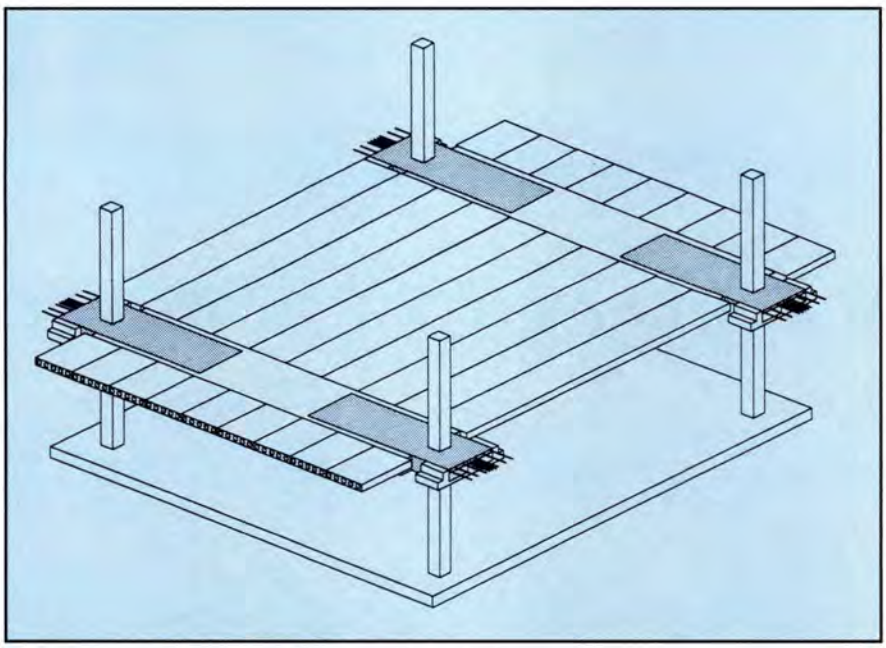


Fig. 20. Nebraska A system (adapted from Refs. 26 and 27).

on hollow-core slabs. The system eliminates the need for field shoring and requires only a small amount of formwork. Analysis indicates that a 410 mm (16 in.) inverted shallow T-beam is sufficient under a superimposed dead load of 1.7 kPa (35 psf) and live load of 2.4 kPa (50 psf), for a 10.8 m (36 ft) span. The inverted T-beam flange thickness is 203 mm (8 in.) and the hollow-core slabs are 203 mm (8 in.) deep, producing a structural floor depth of 410 mm (16 in.).

This structural system allows utilities to be contained within the precast beam component. The proposed concept recommends that the voids be divided into two spaces for electrical and air supply, as shown in Fig. 21. The beam is precast so access can be made to equipment from the floors above and below.

The Nebraska B system[27] is a modification of the Nebraska A system described above. In the Nebraska B system, the pretensioned shallow beam is entirely precast. Its cross section varies as shown in Fig. 22. The advantages of this modified system over the Nebraska A system are that cast-in-place concrete is not required during erection, precasting of the beam is simplified, and beams are pretensioned for both positive and negative moments. With this "dry" system, beams are spliced at a distance 1.5 m (5 ft) from the face of the support. Steel plates are embedded in each end of the beam and spliced together with bolts. A 0.305 m (1 ft) strip of fresh concrete is used to cover the steel plates and bolts for fire and corrosion protection.

CONCLUDING REMARKS

This paper summarizes the essential elements of 19 precast structural floor systems that are suitable for office building construction. This summary was assembled as part of a research project directed towards the development of new precast concrete floor systems for gravity loads for application in occupied office buildings with a regular spacing of columns. A companion paper presents the assessment of these systems. Together, these two papers indicate the current state-of-the-art in precast concrete structural systems and identify opportunities for the development of new systems and the improvement of existing systems.

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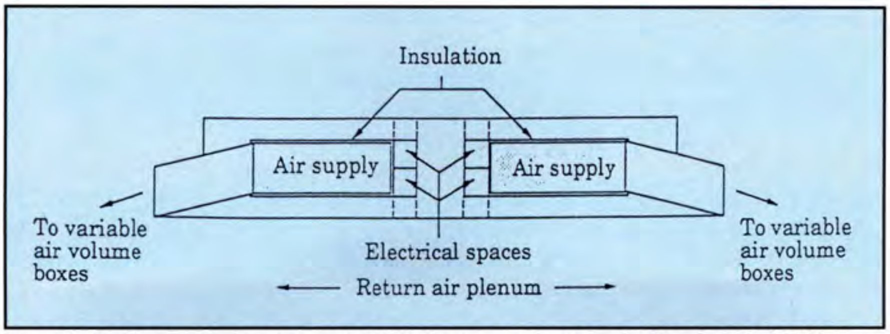

Fig. 21. Nebraska A system — voids in beam can house electrical and HVAC services (adapted from Refs. 26 and 27).

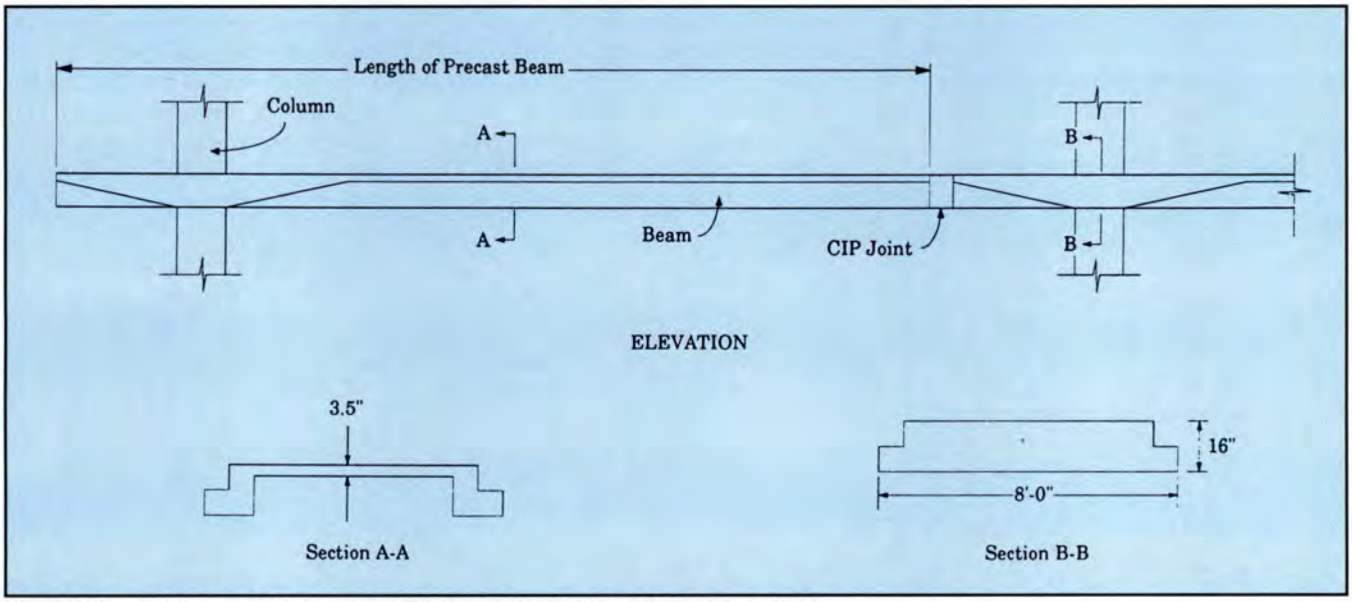

Fig. 22. Precast beam of Nebraska B system (adapted from Refs. 26 and 27).

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