# Assessment of Existing Precast Concrete Gravity Load Floor Framing Systems


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*This paper and a companion paper provide a review and assessment of existing precast concrete gravity load floor framing systems suitable for office buildings. The companion paper reviews 19 precast structural systems. The assessment presented in this paper treats interactions between the structural, service, and architectural systems that comprise the building system. The assessment indicates the current state-of-the-art in precast concrete structural systems for office buildings and leads to conclusions regarding opportunities for the development of new systems and the improvement of existing systems. Work in progress is focusing on the most promising concepts evolving from this study with a view towards developing a modern, economical, and efficient precast concrete floor system.*

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 research project evolved from a Precast/Prestressed Concrete Institute (PCI) research project statement titled "Economical Framing Systems for Floors and Roofs."

A total of 19 precast structural systems that are suitable for office building construction are reviewed by Pessiki et al. in Ref. 1. The efficiency and performance of 16 of these systems were assessed using criteria that were developed with input from industry professionals. This assessment led to the identification of opportunities for the development of new or improved systems. This paper discusses the criteria used in the assessment of the systems, presents the results of the assessment, and outlines the opportunities that were identified for the development of new systems. A report by Prior et al.[2] presents more complete information on the review and assessment of systems.

## DEVELOPMENT OF ASSESSMENT CRITERIA

The first stage of the assessment required the identification of key assessment criteria to provide a consistent basis for evaluating the precast structural systems in the survey. A criterion can be defined as a characteristic of the structural system, or of its interaction with other systems in the building, that allows a judgment to be made about the effectiveness of the structural system. To develop the criteria, interviews were conducted with precast concrete designers, precast concrete fabricators, mechanical (i.e., HVAC and plumbing) designers, and a mechanical fabricator to assess their views on the various factors that affect the suitability of a precast concrete structural system for office building construction.

The set of criteria is shown in Fig. 1. The criteria are divided into three primary categories: Structural, Service, and Architectural. Criteria in the Structural category identify how effectively the precast system meets the structural needs of the building. Criteria in the Service category identify the impact of a precast structural system on the HVAC, plumbing, and electrical service systems. Criteria in the Architectural category identify the impact of the structural system on the architectural system of the building.

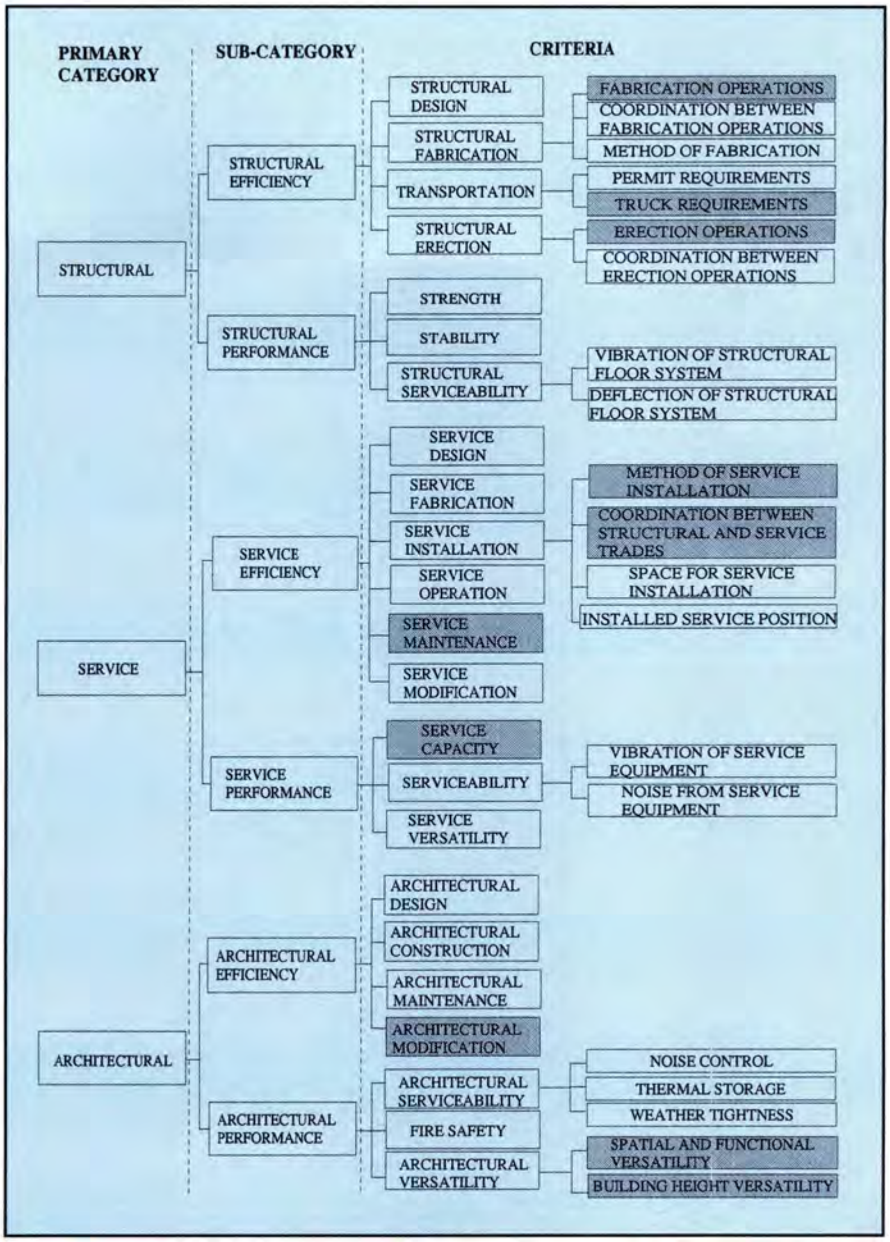



Fig. 1. Structural, Service, and Architectural assessment criteria.

As shown in Fig. 1, each of the three primary categories is divided into two subcategories. The first subcategory, Efficiency, pertains to the design, construction, and operation phases of the building. These criteria are generally measured in terms of time and cost. The second subcategory, Performance, pertains to the ability of the system to meet its designed function and/or to adapt to a different function. These criteria are measured in qualitative terms.

### Criteria Used for Assessment

All criteria shown in Fig. 1 have an impact on the efficiency and performance of the overall building system. However, a participant in the construction process may emphasize different criteria depending on the role and objectives of the participant. For example, if an owner's primary objective is to construct an office building that can easily accommodate different tenants,

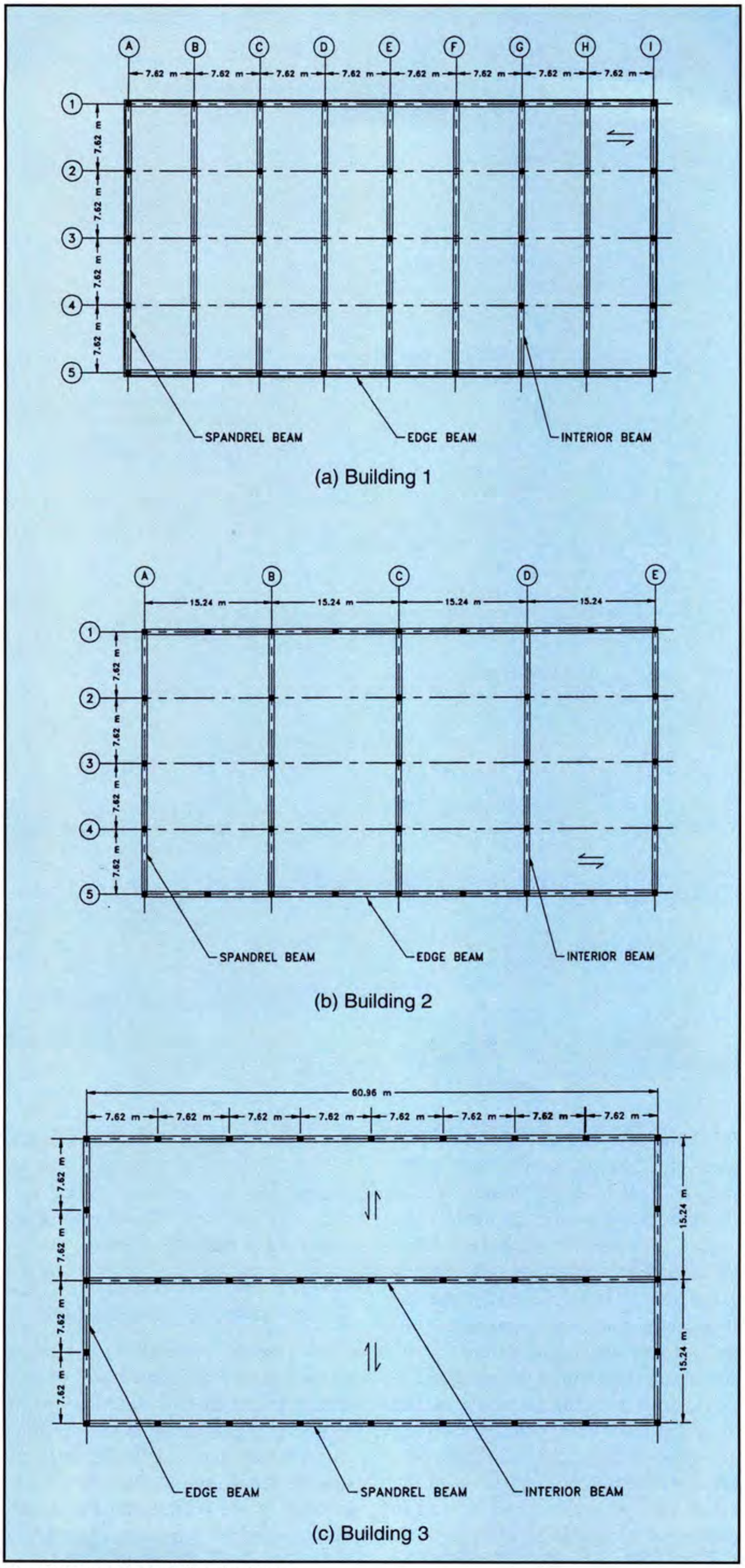



Fig. 2. Example building layouts.

then the owner may consider service modification and architectural modification criteria to be very important.

The assessment of existing systems was made using those criteria that were considered to have a major impact on the efficiency and performance of the building system and those criteria that help identify significant differences among precast structural systems. These criteria are highlighted with shading in Fig. 1. The assessment presented in this paper is considered preliminary because additional industry input may provide other criteria of major importance that should be included in an assessment.

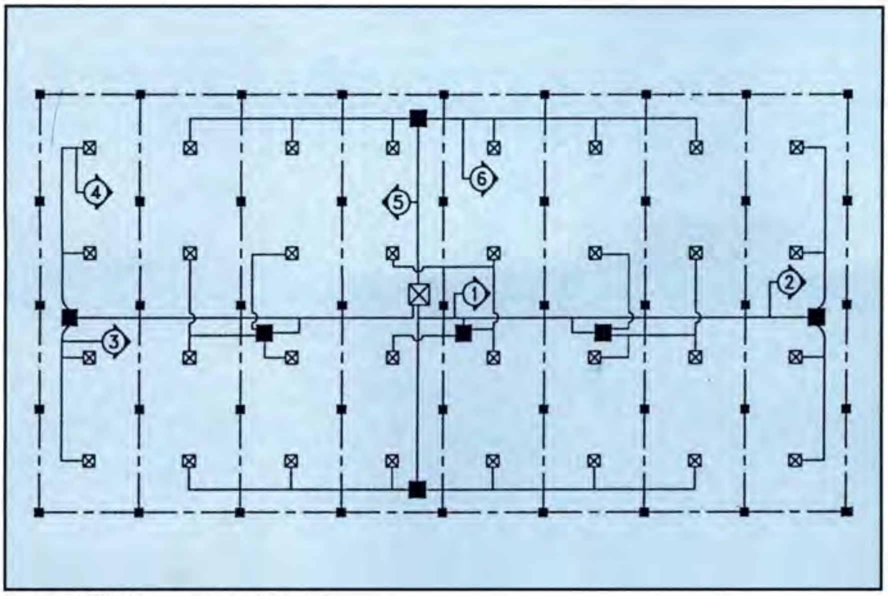
It is important to note that structural design, service design, and architectural design are not included in the assessment. Structural design is not included because the efficiency of the design effort will not differ significantly among the precast structural systems in the survey. Both service design and architectural design efforts will change between systems, but it was not possible to quantify these changes in the assessment. It is also important to note that strength and stability are not considered in the assessment, because if strength and stability requirements cannot be met, then it is useless to assess the precast structural system with additional criteria. Therefore, it is assumed that each system has sufficient strength and stability to meet the requirements of a multistory office building.

## EXAMPLE BUILDINGS

An example office building and two modifications of this building were selected to serve as bases for comparisons of the systems. The example buildings were developed in sufficient detail to allow quantities to be calculated to serve as measures for many of the assessment criteria. However, the example buildings were simplified by removing stairs and elevator and service shafts to reduce the complexity of the assessment.

### Structural Layout

Buildings 1, 2, and 3 are four stories in height and 30.5 x 61 m (100 x 200 ft) in plan. The length and/or direction of floor spans differs for each build-



| HVAC section number | Duct dimensions mm x mm (in. x in.) |
|---|---|
| 1 | 1120 x 458 (44 x 18) |
| 2 | 460 x 255 (18 x 10) |
| 3 | 400 x 200 (16 x 8) |
| 4 | 250 x 150 (10 x 6) |
| 5 | 760 x 300 (30 x 12) |
| 6 | 550 x 200 (22 x 8) |

Fig. 3. HVAC layout, Building 1.

ing. As shown in Fig. 2(a), Building 1 has 7.6 m (25 ft) beam and floor spans, with floor members spanning in the longitudinal direction of the building. Spandrel beams and interior beams support floor loads and edge beams are included to develop frame action under lateral force. In Building 2 [Fig. 2(b)], floor spans are increased to 15.2 m (50 ft). Building 3 [Fig. 2(c)] also consists of 15.2 m (50 ft) floor spans, but the direction of the floor spans is in the transverse direction of the building.

## Selection and Layout of HVAC System

The three major service systems within a building are electrical, plumbing, and HVAC. While electrical and plumbing services are important systems, in an office building they are often secondary to the HVAC system in terms of space requirements and operation costs. To assess the impact of the structural system on the HVAC system, a typical office building HVAC system was chosen and approximate duct sizes were calculated for use in assessing the impact of the structural floor system on the typical HVAC system.

A variable-air-volume (VAV) system was chosen because this system is applicable where a cooling load exists throughout the year, such as the interior zone of office buildings. The system consists of a central air-handling unit with heating and cooling coils, a single duct supply system, VAV boxes, supply ducts with air diffusers, a return air duct or plenum, and a return air fan.

The size of the horizontal supply ducts depends on the size of the zone that must be supplied and also the distance to the zone. A typical layout of horizontal ducts was chosen so approximate duct sizes could be calculated (see Fig. 3). The vertical service shaft is located in the center of the building with two primary supply ducts, one to each side of the building. It was assumed that a central corridor can be located beneath these ducts and that the ceiling can be dropped in these areas. Rather than using return ducts, the area above the suspended ceiling is used as the return air plenum. Required duct sizes for selected sections of the HVAC network are shown in Fig. 3.

# ASSESSMENT OF EXISTING PRECAST SYSTEMS

Of the 19 systems included in Ref. 1, 16 are included in the assessment and are listed in Table 1. Available information was not sufficient for the remaining three systems in the survey to include them in the assessment. The following sections discuss the assessment criteria and present the assessment of the 16 systems. Because of space limitations, only those criteria shown shaded in Fig. 1 are treated here. A discussion of all of the criteria can be found in Ref. 2.

## Structural Criteria

The structural criteria selected for the assessment are fabrication operations, truck requirements, and erection operations.

**Fabrication Operations —** The total cost of fabrication is affected by the cost of labor, materials, and the number of components that need to be fabricated. The cost of both materials and labor may vary significantly by geographic location and this cost variation requires consideration in evaluating fabrication efficiency. The tasks/operations required in fabrication are broken down as follows:

**1.** Construction of forms — From the interviews, it was found that the number of different forms and the complexity of the forms have a major impact on fabrication costs. While the cost of a form is small in comparison to total construction costs, cost of forms becomes a factor if a number of new forms are required for a precast structural system. Advantages exist for systems with fewer different pieces because the number of forms is reduced and the material and labor cost associated with additional forms is eliminated.

Table 1. Summary of various fabrication and construction requirements.

| System | Number of components | Number of forms | Number of truck trips | Shoring requirements | Reinforcement/ post-tensioning | Quantity of cast-in-place concrete (m³) | Number of crane picks |
|---|---|---|---|---|---|---|---|
| U.S. Conventional with hollow-core slabs | 1053 | 4 | 219 | 0 | 0 | 0 | 520 |
| U.S. Conventional with double tees | 573 (337; 319) | 4 | 211 (209; 202) | 0 | 0 | 377 | 573 (337; 319) |
| Duotek | 565 (343; 323) | 4 | † | 0 | 0 | 377 | 565 (343; 323) |
| Dycore | 1053 | 3 | 270 | Beam | Beam | 265 | 520 |
| Dyna-Frame | 1952 | 3 | 249 | Beam | Beam | 76 | 885 |
| Filigree Wideslab | 788 | 3 | † | Beam, Floor | Beam, Floor | † | 788 |
| IMS | 698 | 3 | † | Beam, Floor | Beam, Floor | 0 | 698 |
| PD2 Frame | 1053 | 4 | † | 0 | Beam | 0 | 520 |
| Prestressed Joist | 1050 (596; 572) | 3 | 90 (123; 120) | Beam | Beam, Floor | 717* | 609 (383; 359) |
| Quickfloor | 1188 | 3 | 280 | Beam | Beam | 906 | 655 |
| Structurapid | 1188 | 3 | † | Beam | Beam | † | 655 |
| Swedish | 1053 | 4 | † | 0 | 0 | 0 | 520 |
| Thomas | 653 (377; 359) | 4 | 253 (305; 295) | Beam | Beam | 220 | 653 (377; 359) |
| Tri/posite | 578 | 2 | † | Beam, Floor | Beam, Floor | 803* | 578 |
| Contiframe | 1216 | 5 | † | 0 | 0 | 0 | 683 |
| Spanlight | 1053 | 4 | 217 | Beam, Floor | Beam-Tensioning | 147 | 520 |
| University of Nebraska A | 1053 | 4 | 257 | Beam | Beam | 159 | 520 |
| University of Nebraska B | 1188 | 4 | 257 | 0 | 0 | 0 | 655 |

**Note:** 1 m³ = 1.309 cu yd.
Number required for Example Buildings 2 and 3 is shown in parenthesis.
* Formwork required.
† Not enough information available.
Beam – This field operation is required for the beam component.
Floor – This field operation is required for the floor component.

The complexity of the form also affects the form construction costs. Complex end geometries result in higher form costs. However, a form that can be used repeatedly can spread the form cost over many units. The complexity of the form is also a function of the number of minor variations between different precast concrete components. These minor variations may not require the construction of new forms but instead may use blockouts that are inserted in the form. If the number of blockouts are limited or the blockouts are modular, then the impact of these variations on the cost may be insignificant.

**2.** Placement of steel plates, bars, and strands — Form congestion is a major concern in fabrication. The area of a precast concrete member that connects to an adjoining member requires additional reinforcing steel, embedded plates, and inserts. With access only from the top of the form, much of this hardware must be threaded in and around other items, increasing fabrication costs. Martin[3] indicates that in some cases it may be economical to increase the size of the precast member just to accommodate the steel hardware. Interference with shear and longitudinal reinforcement may also limit the use of draped prestressing tendons.

According to industry interviews, standard dimensional tolerances on the placement of steel plates, bars, and strands are not difficult to achieve in the precasting plant and alignment of steel plates for the welded connections between precast components is not a problem. Precasters also indicated that the required tolerances associated with mechanical splices can be easily achieved in the prefabrication plant.

**3.** Concrete placement — The participants in the interviews indicated that, in their opinion, concrete placement and finishing of precast concrete members is an efficient operation in the precasting plant.

**4.** Stripping and handling — A number of items must be considered in stripping the form from the precast concrete member. The orientation of the member (horizontal, vertical, or some angle in between) will affect the efficiency of stripping the form. For example, the inverted double tee members of the Tri/posite system are cast as double tees and then rotated. This operation is difficult in precasting plants that do not have a rotating table.

Member geometry will affect form suction and will impose stresses on the precast component during stripping. The member weight and the weight of any additional items that must be lifted (such as forms that remain with the item during stripping) must also be considered.[4] The available crane capacity is a consideration in both the plant and the construction site, but most fabrication plants can accommodate the production of very large members without difficulty. The size of members is usually limited by transportation requirements.

For this assessment, the effort required in fabrication is measured by the number of precast components required for Buildings 1, 2, and 3, and the number of different forms required for each precast structural system. It is assumed that all systems use precast columns, but other structural components are cast-in-place or precast depending on the individual system. As shown in Table 1, the number of precast components required for each system varies significantly. Many systems are not completely precast and some, such as the Tri/posite, Filigree, and Prestressed Joist systems, are largely cast-in-place. The number of precast components is lower for these systems. A large percentage of the components required are floor members. Thus, systems with larger floor members require fewer components.

A second fabrication consideration is the number of forms that are required for each system. As shown in Table 1, the majority of the structural systems require either three or four forms. The exceptions to this are the Tri/posite (two forms) and Contiframe (five forms) systems.

**Truck Requirements** — The size and weight of precast components is often controlled by transportation requirements. The common payload for standard trailers without special permits is 178 kN (20 tons) with width and height restricted to 3.05 m (10 ft) and length to 12.19 m (40 ft). Low-boy trailers allow the height to be increased. However, low-boys cost more to operate and have a shorter bed length. If the precast components exceed the weight capacity of standard transport equipment, then higher capacity or special trailers are required. Information from interviews indicates that it may be economical to use higher capacity trailers in particular circumstances because the number of truck trips is reduced and large precast members can reduce erection costs.

The erection schedule will dictate the order or sequence of components transported to the site. An efficient precast system will optimize the truck capacity while meeting sequence requirements. Precast components that "fit together" allow more components to be transported with each truck trip. For example, a 98 kN (11 ton) unit may not be economical because only one unit can be shipped per load (assuming other smaller components cannot be shipped with it), while two 89 kN (10 ton) units could be shipped on one load.[4]

For this assessment, truck requirements were evaluated in terms of the number of truck trips needed to transport the precast elements for the example buildings. A standard truck with the limitations described above was assumed. Results are listed in Table 1. In all cases, the factor that limits the number of components on the truck is the weight of the components, not their height or width. For 15.2 m (50 ft) floor members and multistory columns, the standard trailer length is disregarded with the understanding that a larger truck could be used if proper permits are obtained. For many of the systems, insufficient detailed information was available to accurately calculate the dimensions and weights of the individual members; therefore, a total number of truck trips is not given. Systems such as the Prestressed Joist system that use extensive cast-in-place concrete require fewer truck trips.

**Erection Operations** — As in fabrication, the total cost of erection is affected by the cost of both labor and materials. While the quantity of labor is a factor, the type of labor required is also important because different labor specialties may receive different pay rates. Geographic location has a significant impact on the cost of materials and labor, and the availability of a particular labor specialty also varies with location. Environmental conditions also affect the efficiency of field work. The erection operations required are broken down as follows:

**1.** Handling — The number of precast concrete components to be handled is a major consideration. Erection is facilitated when the orientation of members during transport is the same as their final orientation in the structure. Connections should be designed so that the unit can be lifted, set, and unhooked in the shortest possible time. Before the hoist can be unhooked, the precast component must be stable and in its final position. Some precast units, such as double tees and hollow-core slabs, are inherently stable and require no additional connections before releasing the crane. Others, such as columns, wall panels, and single tees, often require supplemental shoring, guying, or fastening. Planning for the fewest, quickest, and safest operations to be performed before releasing the hoist will improve the efficiency of handling.[3]

Crane size must also be considered. The position of the crane depends on the site and the method of erection, and will determine the crane size required because crane capacity is a function of weight and reach. Large cranes with a 1780 kN (200 ton) capacity are readily available.

**2.** Placement of reinforcement — Several factors must be considered in calculating the cost of field-placed reinforcing steel. The quantity of field-placed reinforcing steel is a major consideration, especially in areas where the labor rate for iron workers is high. Many systems, such as Dycore, require only negative moment reinforcing steel over precast soffit beams.

**3.** Concrete placement — The requirements associated with cast-in-place concrete vary from system to system but a major consideration is the need for formwork. Many precast systems use precast concrete elements as stay-in-place forms for cast-in-place concrete. Filigree construction uses a large quantity of cast-in-place concrete but eliminates the need for formwork. Many other systems use concrete for a floor finish or topping. Systems that do not use the precast elements as stay-in-place forms have material and labor costs associated with temporary formwork. An additional consideration with cast-in-place concrete is climate. Cold weather requires special provisions for placing and cur-

Table 2. Summary of required field operations.

| System | Field operations required | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | I |
| U.S. Conventional with hollow-core slabs | | | ✓ | ✓ | ✓ | | | | |
| U.S. Conventional with double tees | | | ✓ | ✓ | ✓ | | | | ✓ |
| Duotek | | | ✓ | ✓ | ✓ | | | | ✓ |
| Dycore | ✓ | ✓ | | | ✓ | ✓ | | | ✓ |
| Dyna-Frame | | | | ✓ | ✓ | ✓ | | | ✓ |
| Filigree Wideslab | ✓ | | | | | ✓ | | ✓ | ✓ |
| IMS | ✓* | | | | ✓ | | ✓ | | |
| PD2 Frame | | | ✓ | ✓ | | ✓ | | | ✓ |
| Prestressed Joist | ✓ | ✓ | | | | ✓ | | ✓ | ✓ |
| Quickfloor | ✓ | | ✓ | | ✓ | ✓ | | | ✓ |
| Structurapid | | | | | ✓ | ✓ | | | ✓ |
| Swedish | | | ✓ | ✓ | ✓ | | | | |
| Thomas | | | ✓ | ✓ | | | | | ✓ |
| Tri/posite | ✓ | ✓ | | | ✓ | ✓ | | ✓ | ✓ |
| Contiframe | | | ✓ | | ✓ | | | | |
| Spanlight | ✓ | | | | ✓ | ✓ | ✓ | | ✓ |
| University of Nebraska A | ✓* | ✓ | | | | ✓ | | | ✓ |
| University of Nebraska B | | | ✓ | | ✓ | | | | |

All systems require column bracing. All systems require precast member to be aligned and leveled.
✓ This field operation is required.
* Requires temporary brackets at columns.

**Key to Field Operations**

A. Erect shoring, remove shoring.
B. Construct formwork, remove formwork.
C. Bolt connections.
D. Weld connections.
E. Grout connections.
F. Place reinforcement.
G. Place prestressing cables, tension cables.
H. Place blockouts.
I. Place concrete, finish concrete.

ing concrete; these provisions increase the erection time.

**4.** Post-tensioning — Post-tensioning of precast building structures is not widely used in the United States so the lack of labor and equipment needed to efficiently use post-tensioning may be a problem in some areas. Systems that make use of post-tensioning may also require temporary supports during erection for stability. The cost of post-tensioning labor and equipment often determines whether post-tensioning is an economical alternative.

**5.** Shoring and bracing — Temporary shoring and bracing is sometimes required for erection stability. Initial costs associated with shoring and bracing can be very expensive. A significant additional cost is the labor cost associated with setting up and breaking down the shoring. According to precast erectors who regularly use shoring, initial costs are not as much of a factor as the field labor required.

**6.** Welding — Welded connections are common in precast concrete structures. A major consideration is the minimization of concrete cracking around welded connections. A reduction in the amount of heat used in welding results in less cracking. Welding in cold temperatures requires preheating of the precast concrete member and increases the cost of the welding process. The cost of welders across the United States requires consideration when evaluating whether a system is cost effective to erect.

**7.** Grouting — The use of grout for connections is common practice. As with cast-in-place concrete, climate is the major issue. For example, in cold temperatures, a grouted column-to-column dowel type connection needs to be heated before and after grouting.

**8.** Bolting — Connecting precast concrete members with bolted connections is a fast procedure. This type of connection provides immediate erection stability.

For the assessment, erection efficiency is measured by the number of erection operations required, the need for shoring and field placed reinforcement, the quantity of cast-in-place concrete required, and the number of crane picks required for each system. Table 2 indicates the field operations required with each system. As Table 1 shows, many systems require shoring for the beams. Four systems surveyed also require shoring of floor members. Several systems eliminate shoring requirements completely and require very little field work.

Several systems require extensive field-placed reinforcement and cast-in-place concrete. However, the need for formwork is a more important consideration than the quantity of cast-in-place concrete. Filigree construction and the Quickfloor system eliminate the need for formwork by using precast concrete members as stay-in-place forms. The Prestressed Joist system uses an efficient method to construct formwork for the floor system, but significant effort is required to construct formwork for the beams. The Tri/posite system uses cast-in-place beams and requires that openings be provided in the beams, making beam formwork difficult to construct.

The average number of crane picks for Building 1 is approximately 625 (see Table 1). The Dyna-Frame system requires significantly more crane picks (885) than the other systems because of the narrow floor slabs [0.6 m (2 ft)] and single-story columns that are used with the system. However, this number of picks can be reduced if wider slabs are employed. Crane requirements are reduced for systems that utilize hollow-core slabs because it is assumed that three slabs are lifted with each crane pick. While lifting three pieces at once reduces the number of crane picks, the floor slabs are positioned with the aid of the crane and this slows erection.

It can be seen from Table 1 that an increase in floor span from 7.62 to 15.24 m (25 to 50 ft) results in fewer precast concrete components and a reduction in the number of crane picks by approximately 40 percent. Thus, significant erection savings are achieved with the four systems that can span 15.2 m (50 ft).

## Service Criteria

The service criteria used for the assessment are method of service installation, coordination between structural and service trades, service maintenance, and service capacity.

**Method of Service Installation —** This criterion refers to the method employed to install ducts, plumbing, and other equipment. The structural system affects how the service systems are installed. Many precast concrete systems allow the HVAC system to be assembled on the floor and raised into position. This is a very efficient method of installation. Precast systems with openings for horizontal service systems to pass through cannot employ this method. These structural systems often require portions of the HVAC and plumbing systems to be assembled from shorter than normal segments in order to accommodate the tight spaces that are provided. This increases the number of connections and slows the installation process.

For the assessment, methods of installation are divided into three general categories rated from A to C. Method A is considered the most efficient while Method C is considered the least efficient. Each category is described below.

**A.** The most efficient installation method is considered to be placing ducts, pipe, or conduit on a precast structural surface and connecting the service components. This method is efficient because the service component is placed in its installed position immediately and does not require additional movement. Thus, HVAC equipment, ducts, plumbing, and electrical conduit are quick to install and overhead work is eliminated.

**B.** Another efficient method allows sections of the HVAC system (e.g., ducts) or pipe to be assembled on the floor, and then raised into position. This allows many of the connections to be made in a position that is easy to work in. Some overhead work is necessary once the services are raised into position. This method of installation is possible with systems that provide openings in beams, but is not possible if openings are located in closely spaced ribs.

**C.** The least efficient method of installation requires services to be assembled in a position that is not easy to work in. Systems with horizontal openings in closely spaced ribs require that short sections of pipe and duct be used. Installation is slow for these systems because of the increase in connections and the amount of overhead work.

As indicated in Table 3, the majority of systems suspend the horizontal service systems beneath the precast structural floor system and, thus, receive a B rating. The Nebraska A system receives an A rating because the services are installed in an efficient manner in position on the precast concrete floor. The Tri/posite system receives a dual rating of A and C. While it is efficient to place the services on the precast floor system and then connect components, it is much more difficult if services must be threaded through closely spaced openings, as is the case with the Tri/posite system.

Table 3. Evaluation of service efficiency and performance.

| System | Method of service installation A to C | Coordination between structural and service trades A to C | Service maintenance A to F |
|---|---|---|---|
| U.S. Conventional with hollow-core slabs | B | A | A |
| U.S. Conventional with double tees | B | A | C |
| Duotek | C | A | D |
| Dycore | B | B | A |
| Dyna-Frame | B | A | B |
| Filigree Wideslab | B | B | A |
| IMS | B | A | A |
| PD2 Frame | B | A | A |
| Prestressed Joist | B | B | A |
| Quickfloor | B | B | A |
| Structurapid | B | A | A |
| Swedish | B | B | B |
| Thomas | B | A | C |
| Tri/posite* | A,C | C | E |
| Contiframe | B | A | A |
| Spanlight | B | A | A |
| University of Nebraska A† | A | C | F |
| University of Nebraska B | B | A | A |

**Note:** For method of service and service maintenance, electrical services are not considered.

* The Tri/posite system received an A and a C for installation because, while the floor system provides a platform for installation, services still need to be threaded through openings, hindering the installation process.

† This precast system as described may accommodate services within the beam component. The system is evaluated assuming services will be housed in the beam component.

**Coordination Between Structural and Service Trades —** Coordination between the structural erection trades and the HVAC, plumbing, and electrical trades affects the efficiency of work in the field. Additional requirements for coordination between structural and non-structural trades typically lead to schedule delays and inefficient use of labor. An example of this is electrical conduit placed in the cast-in-place portion of the floor slab. Conduit is placed by the electrician after the precast slab is placed and before the iron worker begins to place reinforcing steel. For most projects, an efficient system is one that limits this type of coordination.

The levels of coordination have been divided into three categories described below. Category A is considered the most efficient and Category C is considered the least efficient.

**A.** Systems in this category require no coordination between structural and service trades. At a given location, service trade activities are scheduled to occur after the structural trade activities are completed.

**B.** Systems in this category require only coordination between structural and service trades if electrical conduit is placed in the cast-in-place portion of the floor system or within hollow-core slabs.

**C.** Systems in this category require coordination between structural and service trades for placement of HVAC, plumbing, or electrical systems.

Table 3 shows that the majority of systems require little or no coordination between structural and service trades and receive an A rating. Several systems typically accommodate electrical conduit in the cast-in-place floor and receive a B rating. The Swedish system also receives a B rating for coordination because the cores of hollow-core slabs are often used for electrical conduit, requiring coordination between the precast erector and the electrical contractor.

Two systems received a C rating, indicating that extensive coordination is required. The Tri/posite system requires coordination because the horizontal service systems are placed within the structural floor system. The Nebraska A system also requires coordination if the beam void is used to house electrical or HVAC components. Both structural systems require coordination between service system installers, iron workers, and laborers positioning precast members and placing concrete.

**Service Maintenance** — The service maintenance criterion addresses the impact of the structural system on efficient maintenance of the service systems. The key issue in maintenance is the accessibility of services that was emphasized by the mechanical design professionals. The degree of accessibility is directly affected by the structural system. A second issue in maintenance is the efficiency of routine service on equipment. For example, a piece of equipment may be installed between the stems of a double tee without a problem; however, the clearances provided to service the equipment may be too small, making the maintenance operation more costly.

In most situations, the access of the service systems is ultimately a function of the degree of integration with the structural system. In general, the greater the level of integration, the more difficult the services are to maintain or replace. For evaluation purposes, accessibility is defined by six categories. Category A identifies a precast system that allows for easy access to services while Category F indicates a precast system that provides no access to services.

**A.** Services are suspended beneath the structural floor system, making unrestricted access to the services possible.

**B.** Services are free to run parallel to the beams with no restrictions, but when running perpendicular to them, must pass through openings provided in the beams at a limited number of locations. This arrangement, though similar to the Category A arrangement, does not merit the same rating due to the congestion of services that may arise at the openings in the beams.

**C.** Services are positioned between floor units. This arrangement applies to ribbed floor systems (e.g., double tee floor systems or joists) and confines lateral access.

**D.** Services pass through openings that are provided in both the floor units and the beams. The degree to which access is restricted at these openings is a function of the size of the openings provided and the size of the services that are being passed through the openings.

**E.** Services are encased within the structural floor system with access in only a limited number of places (e.g., access panels).

**F.** Services are encased in the floor system with essentially no access.

Table 3 shows that the majority of precast systems incorporate services in a manner that allows for easy access. Exceptions are the Tri/posite and Nebraska A systems, which provide limited access to services that are encased in the floor system.

**Service Capacity** — The service capacity criterion addresses the impact of the structural system on the capacity of the HVAC system. The capacity of the system refers specifically to the supply and return ducts of the HVAC system, rather than the capacity of the equipment that drives the system. There are several aspects of this portion of the system that are affected by the structural system.

One aspect is the capacity of the supply and return ducts. The structural system may limit the size of the horizontal and/or vertical ducts. This limitation will inhibit the performance of the HVAC system because, to achieve the desired rate of air exchange in the enclosed space, it may be necessary to exceed the maximum desirable air velocity in the ducts. An alternative is to reduce the air velocity and, therefore, reduce the rate of air exchange in the space. Either option has drawbacks.

Another aspect is the capacity of the supply and return devices provided in each room. The structural system, in conjunction with the building layout desired by the owner/architect, may limit the size and number of diffusers and returns that can be placed in a room. For example, a structural system that employs double tees cannot have openings cut in the top flange where the stem is located. These constraints can limit the size and number of distribution and return devices in the room. This would limit the capacity of the HVAC system in much the same way that undersized ducts would.

Limits on the capacity of the HVAC system are possible with systems that use floor unit and beam openings to accommodate secondary ducts. The Duotek, Tri/posite, and Swedish systems limit duct size and, thus, may limit the HVAC capacity. The Duotek system uses 712 x 356 mm (28 x 14 in.) beam openings. As Fig. 3 indicates, it is not practical to pass primary ducts (HVAC Section 1) through these openings. However, the openings provided by the Duotek system accommodate the secondary HVAC ducts of Building 1.

It should be noted that Building 1 is small in plan and the duct requirements for this building are minimal. More serious problems arise for a building that is larger in plan. The

Tri/posite system uses 200 x 250 mm (8 x 10 in.) tee stem openings that would not accommodate the secondary HVAC duct requirements of Building 1. With openings of this size, supply ducts need to be divided into smaller ducts to achieve the desired capacity. This will reduce installation efficiency and increase material costs. Information was not available on the size of the beam openings in the Swedish system.

## Architectural Criteria

Architectural criteria address the impact of the structural system on the efficiency or performance of the architectural system of the building. The architectural criteria used for the assessment are architectural modification, spatial and functional versatility, and building height versatility.

**Architectural Modification** — The architectural modification criterion addresses the efficiency of modifying an existing building to serve a different functional or spatial arrangement. For example, changing a school into office space may require the relocation of interior walls or partitions. A structural system that uses interior loadbearing walls is more difficult to modify than an open frame system. Changing the functional or spatial arrangement may also require moving, adding, or filling in large vertical openings for shafts and stairways. If the structural system does not allow new openings to be framed in, or old openings to be filled in, this type of modification may be very difficult.

This criterion was evaluated by investigating the ability of each system to accommodate a 3.66 x 2.41 m (14 x 8 ft) vertical shaft for a stairway. It was found that the Prestressed Joist system best accommodates an opening of this size. Framing can be constructed around the opening and gravity loads can be transferred to adjacent joists. With this system, stringers can be framed between joists.

Filigree construction can also accommodate large vertical openings. The systems that use hollow-core slabs or double tees do not easily accommodate an opening of this size. Two hollow-core slabs and one double tee need to be removed or cut. This is easier with hollow-core floor systems. The problem arises in framing around the opening. The hollow-core slabs and double tees surrounding the opening may not accommodate the additional load. Therefore, vertical support from additional columns or loadbearing walls may be required.

Some systems, such as the IMS system, would be very difficult to modify for an opening of this size. The post-tensioned floor units would limit the possible location of this opening and, due to the small floor units, it may not be possible to fit the opening within one unit. In the preceding discussion, the additional load imposed on a given system by the added stair framing was ignored. These loads may also pose a significant problem for some of the systems.

**Spatial and Functional Versatility** — This criterion addresses the ability of the structural system to accommodate varying dimensions and shapes of the interior spaces. This depends on the capacity of the structural system to cover a range of spans, to accommodate large vertical openings (for shafts and stairs), and to accommodate nonrectilinear spaces. For example, an architectural layout may require a span of 11 m (36 ft). This span requirement eliminates many precast structural floor systems that are unable to effectively span this length.

In addition, the structural system must accommodate large vertical openings required for service shafts, stairways, and other spaces. These openings can occur in a variety of locations with respect to the column lines and a versatile structural system will easily frame around these openings. Finally, some structural systems adapt better to nonrectilinear spaces than others.

The spatial and functional versatility criterion is measured by the range of beam and floor unit spans that can be achieved. For office loads, it is assumed that conventional hollow-core slabs have a practical span range of 4.6 to 10.7 m (15 to 35 ft) and that conventional double tees have a practical span range of 6.1 to 18.3 m (20 to 60 ft).

A typical office building requirement is 9.1 m (30 ft) square bays. Table 4 shows that all but four of the systems can achieve this requirement. While Filigree construction can be used for long spans, it is predominantly used for shorter spans, except for parking garage construction where it has been used for spans longer than 9.1 m (30 ft). The IMS, Structurapid, and Tri/posite systems have all been developed for spans of less than 9.1 m (30 ft) and need to be modified for larger spans.

**Building Height Versatility** — This criterion addresses the impact of the structural system on the building height. This impact occurs in two different ways. First, the height of the building is affected by the total depth of the floor system including both the structural depth and the depth allocated to services. That is, a deep floor system results in a taller building. This is a special concern when restrictions on building height are imposed by local building codes. When the building services are placed within the structural floor depth, only the structural floor depth affects the building height. When the services are placed below the structural floor system, the building height is controlled by the structural floor depth plus the depth allocated to services.

The second impact of the structural system on building height is a limitation on the number of stories that can be constructed with the system because of limits on dead and live load carrying capacity of the columns or foundation or because of concerns about stability.

Total floor depth for each system for Building 1 is shown in Table 4. Total floor depth is based on the structural depth, the depth required for HVAC ducts, and an additional 200 mm (8 in.) depth assumed to be required for electrical and plumbing service systems. The total floor depth is calculated for three regions in the building. The deepest floor system is in the central corridor region and is governed by the structural depth plus the depth required for primary HVAC ducts (Section 1 in Fig. 3). It is assumed that the ceiling can be dropped in this region.

The ducts for the perimeter zones are positioned at the perimeter of the

Table 4. Summary of practical span ranges and total floor depths.

| System | Practical member span ranges for office loading | | Structural floor depth (mm) | Total floor depth (mm) | | |
|---|---|---|---|---|---|---|
| | Beams (m) | Floor units (m)* | | Corridor | Perimeter | Interior |
| U.S. Conventional with hollow-core slabs | 6.1 – 12.2 | 4.6 – 10.7 | 660 | 1321 | 1067 | 864 |
| U.S. Conventional with double tees | 6.1 – 12.2 | 6.1 – 18.3 | 711 | 1372 | 1118 | 965 |
| Duotek | 6.1 – 9.14 | 6.1 – 18.3 | 1016 | 1473 | 1219 | 1219 |
| Dycore | 4.6 – 10.7 | 4.6 – 10.7 | 508 | 1168 | 914 | 711 |
| Dyna-Frame | 4.6 – 12.2 | 4.6 – 10.7 | 711 | 914 | 1118 | 914 |
| Filigree Wideslab | 4.6 –7.6 | 4.6 – 9.1 | † | † | † | † |
| IMS | † | 2.4 – 7.2 | † | † | † | † |
| PD2 Frame | 6.1 – 12.2 | 4.6 – 10.7 | 650 | 1321 | 1067 | 853 |
| Prestressed Joist | 4.6 – 12.2 | 4.6 – 15.2 | 572 | 1232 | 978 | 914 |
| Quickfloor | 4.5 – 10.0 | 4.5 – 10.0 | 560 | 1220 | 966 | 768 |
| Structurapid | 3.1 – 7.6 | 4.6 – 7.6 | † | † | † | † |
| Swedish | 6.1 – 12.2 | 6.1 – 12.2 | 711 | 1372 | 1118 | 914 |
| Thomas | † | 6.1 – 18.3 | † | † | † | † |
| Tri/posite† | 2.5 – 6.1 | 4.0 – 10.7 | † | † | † | † |
| Contiframe | 4.6 – 9.1 | 4.6 – 9.1 | 660 | 1321 | 1067 | 864 |
| Spanlight | 4.6 – 9.1 | 4.6 – 9.1 | 584 | 1245 | 991 | 813 |
| University of Nebraska A | 5.0 – 11.0 | 5.0 – 10.7 | 406 | 1067 | 813 | 609 |
| University of Nebraska B | 5.0 – 11.0 | 5.0 – 10.7 | 406 | 1067 | 813 | 609 |

**Note:** 1 m = 3.28 ft; 100 mm = 3.94 in.

* Span lengths given are for member only. Bay dimensions in the floor unit direction are increased by the width of the soffit beams or girders.

† Information not available.

building and it is assumed that the ceiling can be dropped in this region. Total floor depth for the perimeter region is a function of structural depth plus the depth required for HVAC Section 6. It is assumed that the floor system in the interior region of the building has a constant depth and the floor depth for this region is a function of structural depth plus the depth required for HVAC Section 5.

For the 7.62 m (25 ft) square bays of Building 1, Table 4 shows that the University of Nebraska and Dycore systems have a significantly shallower structural depth than the other systems. The Duotek system is deeper than the other systems, with a structural depth of 1016 mm (40 in.). However, the Duotek system can span more than 7.62 m (25 ft) with this structural depth.

The deepest portion of most floor systems is the central corridor where primary ducts are located and where it is often feasible to drop the ceiling. The Dyna-Frame system enables primary ducts to pass between girders rather than beneath them, thus reducing total floor depth. As Table 4 indicates, the total floor depth of the Dyna-Frame system is the same in the corridor and interior region of the building. For most other systems, the floor system in the corridor is approximately 380 mm (15 in.) deeper than the interior region of the building.

## DISCUSSION OF OPPORTUNITIES FOR NEW PRECAST SYSTEMS

The objective of the assessment was to identify opportunities for the development of new precast structural systems. The opportunities are presented here in terms of desired physical attributes of the structural system that lead to improved efficiency and performance. In some cases, the desired physical attributes of the structural system are directly linked to improved structural, service, and architectural efficiency and performance. In other cases, the desired physical attributes of the structural system are linked to desired physical attributes of the service or architectural systems and these service or architectural system attributes lead to improved efficiency and performance.

The impact of a particular physical attribute is presented in terms of selected criteria presented earlier. Many of the physical attributes affect more than one efficiency and/or performance criterion. In some cases, contradictions arise whereby a given change in a particular physical attribute may cause improved efficiency and/or performance in terms of some criteria, but reduced efficiency and/or performance in terms of other criteria.

## Structural Efficiency and Performance

A number of physical attributes of the precast structural system are linked directly to improved structural efficiency and performance. The desired changes in these physical attributes are listed in Table 5, along with the efficiency and performance criteria affected by these attributes.

Table 5. Approach to improve structural efficiency and performance.

| Criteria considered | Approach (structural system) |
|---|---|
| **Efficiency**<br>Fabrication operations | Reduce number of precast components<br>Reduce number of different precast components<br>Use components that can be mass produced<br>Increase modularity |
| Truck requirements | Use components which group together efficiently to utilize truck capacity |
| Erection operations | Reduce number of precast components<br>Reduce quantity of field-placed reinforcement<br>Reduce formwork for cast-in-place concrete<br>Simplify and reduce the number of connections |
| **Performance**<br>Strength | Increase member strength<br>Increase connection strength |
| Deflection of structural floor system | Increase member stiffness |

As indicated in Table 5, reducing the number of precast concrete components and reducing the number of different precast components can improve the efficiency of fabrication operations. Fabrication operations can also be improved by using structural members that can be mass produced and by increasing modularity. The use of precast components that group together efficiently on a truck can be used to improve transportation efficiency.

Reducing the number of precast components to reduce handling requirements, reducing the quantity of field-placed reinforcement, and reducing the required amount of formwork for cast-in-place concrete can improve erection efficiency. Erection efficiency can also be improved by reducing the number of connections and by simplifying connections to allow for quick erection. An opportunity exists in developing self-aligning connections that reduce labor and increase construction safety.

Increasing member strength and connection strength can improve structural performance. Performance can be further improved by developing shallow floor and beam members with high stiffness so that deflections are not the design limitation.

## Service Efficiency and Performance

Physical attributes of the precast structural system that affect service efficiency and performance are presented in Table 6. Reducing structural depth can increase the space available for services, thereby improving service design, installation, capacity, and versatility. Reducing structural depth can also contribute to a reduction in total floor depth. This reduces the heating, ventilating, and air conditioning volume of the building and, thus, improves efficiency. However, if a reduction in structural depth is used solely to reduce total floor depth and not to increase space for services, then the improvements in service design, installation, capacity, and versatility are not obtained.

The use of large horizontal openings in members may improve service efficiency and performance. Specifically, large horizontal openings can contribute to increased space for services, which may improve service design, installation, maintenance, modification, capacity, and versatility. For this improvement to be realized, the openings must be sufficiently large to easily accommodate the main components of the service systems (e.g., main HVAC

Table 6. Approach to improve service efficiency and performance.

| Criteria considered | Approach | |
|---|---|---|
| | Service system | Structural system |
| **Efficiency**<br>Service design and service installation | Increase space for services | Reduce structural depth<br>Avoid integration of services<br>Use large horizontal openings |
| Service maintenance and service modification | Increase space for services | Increase space between tee stems |
| | Avoid encased or restricted access | Use large horizontal openings<br>Avoid integration of services |
| Service operation | Reduce building volume by reducing total floor depth | Reduce structural depth<br>Integrate services |
| **Performance**<br>Service capacity | Increase space for services | Reduce structural depth<br>Use large horizontal openings |
| Service versatility | Increase space for services | Reduce structural depth<br>Use large horizontal openings |

Table 7. Approach to improve architectural efficiency and performance.

| Criteria considered (Group A) | Approach (structural system) |
|---|---|
| **Efficiency**<br>Architectural design | Increase modularity |
| Architectural modification | Accommodate large vertical openings |
| **Performance**<br>Spatial and functional versatility | Accommodate a range of span lengths<br>Accommodate nonrectilinear spaces<br>Accommodate large vertical openings |

| Criteria considered (Group B) | Approach | |
|---|---|---|
| | Architectural system | Structural system |
| **Efficiency**<br>Architectural construction — materials | Reduce total floor depth | Reduce structural depth<br>Integrate services |
| **Performance**<br>Building height versatility | Reduce total floor depth | Reduce structural depth<br>Integrate services |

ducts). Otherwise such openings may prove inefficient except, perhaps, for smaller services such as secondary ducts, plumbing, and electrical conduit. If large openings cannot be provided, integration of services through the openings should be avoided.

Integration of services within the structural floor depth is another approach to reducing total floor depth and, thus, reducing building volume, again leading to an improvement in the efficiency of service operation. However, as noted above, if services are integrated using horizontal openings that are too small, inefficiencies in service design, installation, and maintenance and modification may result. Services should not be integrated by encasement within the structural system, unless the services require little or no maintenance. Examples of this include electrical conduit and a return air plenum.

In ribbed floor systems, increasing the space between ribs will increase the space for services and may, therefore, improve the efficiency of service maintenance and service modification.

### Architectural Efficiency and Performance

A number of physical attributes of the structural system can affect architectural efficiency and performance, as shown in Table 7. The relationships shown in Group A involve only the precast structural system. For the relationships shown in Group B, the desired physical attributes of the structural system are linked to desired physical attributes of the architectural system and these architectural system attributes lead to improved architectural efficiency and performance.

Table 7 shows that an increase in the modularity of the precast structural system can improve the efficiency of architectural design. Further, the ability to accommodate large vertical openings leads to efficient architectural modification. Precast structural systems need to achieve a range of span lengths, accommodate nonrectilinear spaces, and accommodate large vertical openings in order to achieve spatial and functional versatility.

The relationships shown in Group B indicate that reducing structural depth and integrating services reduce the total floor depth and that a reduced total floor depth will result in more efficient use of architectural materials and improved performance with respect to versatility in building height.

## CONCLUSIONS

The major findings from the assessment of existing systems are as follows:

**1.** In the Structural category, the assessment focused on fabrication and erection efficiency. The assessment showed that there is a large variation among systems in the number of precast concrete components required for the example building. Systems with large units require fewer components and, thus, appear to be more efficient to fabricate and erect. However, systems with large units can make efficient transport of components by truck difficult.

There is also a large variation in the level of field effort required for each system. Some systems require shoring, extensive field-placed reinforcement, or extensive formwork for cast-in-place concrete. Thus, precast systems can be broadly classified as prefabrication-oriented systems or field-oriented systems. Opportunities to improve prefabrication-oriented systems include using fewer, larger components, within the constraints imposed by transportation requirements, and simplifying field connections. Opportunities to improve field-oriented systems include reducing the quantity of field-placed reinforcement and the quantity and complexity of field-placed formwork.

**2.** In the Service category, the assessment focused on service installation, maintenance, and capacity. A structural system that allows the services to be installed on a precast concrete surface provided by the structural system must also integrate the services within the structural system. As a result, structural systems of this type require additional coordination between structural and service trades and provide reduced access for service maintenance.

Structural systems that require the services to be threaded through openings in closely-spaced ribs of the structural components make service installation difficult and also provide reduced access for service maintenance. Structural systems with floor member and beam openings to accommodate services may indirectly limit the service system capacity.

The most common method of service installation is to connect the service components on the floor and raise them into position from below. Services placed between closely-spaced ribs of the structural system are less accessible for maintenance than services placed below the structural floor system. The placement of service systems below a structural system with a flat bottom appears to provide the best combination of easy installation, access for maintenance, and no limits on service system capacity.

Precast structural systems can be broadly classified as integrated systems or layered systems. In a layered system, the structural system and the service systems occupy separate layers. Reducing the structural depth and, thus, reducing the total floor depth will have a positive impact on the efficiency and performance of the overall building system. In an integrated system, the service systems are contained within the structural floor depth to reduce the total floor depth. Providing adequate space and sufficiently large horizontal openings in the structural system for the services will avoid negative effects on service efficiency and performance and result in a positive impact on the overall building system.

**3.** In the Architectural category, the assessment focused on architectural modification, spatial and functional versatility, and building height versatility. The assessment found that very few of the existing precast structural systems can easily accommodate modification to the architectural system (i.e., adding large vertical openings in the floor system). Most of the structural systems can achieve typical office spans of 9.1 m (30 ft), and a few can achieve significantly larger spans. There is a wide variation among the systems in the total floor depth required for the example building. The total floor depth also varied significantly between locations in the example building. The existing precast structural systems that were designed to minimize the total floor depth appear to have achieved this objective. Opportunities to improve precast concrete floor systems for spatial and functional versatility include increased adaptability to variations in span and accommodation of large vertical openings and nonrectilinear spans.

## RECOMMENDATIONS

The U.S. Conventional system and other precast concrete floor systems assessed in this paper are used in various types of buildings throughout the United States. However, improvements in existing systems and the development of new systems can increase the frequency of use of precast concrete in office building construction.

In the development of the precast floor systems, significant attention is often given to issues related to structural efficiency and performance. In seeking further improvements in existing precast systems or the development of new systems, design professionals, producers, and researchers should also focus on attributes of the structural system identified in this paper that will lead to improved efficiency and performance of service and architectural systems in office buildings.

## FUTURE WORK

A report by van Zyverden et al.[5] describes the concepts that have been developed for new systems. Work in progress involves the detailed development of the most promising new concepts. Additional work, with the benefit of additional industry input, is needed to review and verify the assessment criteria and to review and verify the assessment of existing precast structural systems presented in this paper.

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