CONTINUOUS PRECAST/PRESTRESSED CONCRETE SHALLOW FLOOR SYSTEM

Faten Fawzy, George Morcous, Mark Lafferty and Maher K. Tadros

ABSTRACT

This paper presents the development of a new precast prestressed concrete floor system that eliminates the need for shear walls and reduces floor height. The main criteria for the design of the proposed system include: shallow structural depth, resistance to lateral loads, use of hollow core planks, consistency with prevailing erection techniques, fire protection, and elimination of corbels. The proposed system consists of continuous precast columns, partially continuous 13 in. deep inverted tee beams, partially continuous 8 in. hollow-core planks, and minimum of 2 in. thick composite topping. The shallowness of the new system and its ability to resist lateral loads are the key advantages, which result in rapid, economic, and green construction. This paper presents the main concepts adopted in the system development as well as the proposed construction sequence. A design summary of the new system and brief discussion on the testing plan are also presented.

KEYWORDS: shallow floor, inverted-tee beam, hollow-core, shear wall, corbels.

INTRODUCTION

The hollow core (HC) floor system utilizes HC planks supported by inverted tee (IT) precast/prestressed concrete beams, which are in turn supported on column corbels or wall ledges. This floor system is an economical and fire-resistant solution for rapid construction with excellent deflection and vibration characteristics. The top surface can be prepared for installation of a floor covering by placing a thin non-structural cementitious topping, or a 2-3 in. concrete composite topping. A typical floor system would require approximately 28 in. deep IT plus a 2 in. thick composite topping for a 30 ft bay size and 100 psf live load. In addition, this system requires the use of shear walls to resist lateral loads.

On the other hand, post-tensioned concrete flat slab floor systems can be built with a span-to-depth ratio of 45, which results in a total depth of 8 in. for a 30 ft span floor. This system also offers the owners and developers the flexibility during remodelling due to the elimination of structural walls.

Precast concrete floor systems could gain significant advantages over post-tensioned concrete flat slab floor systems if they became shallower and detailed to resist lateral loads without shear walls. This is because precast concrete floor systems are advantageous in terms of rapid construction, economy, and high quality of plant production.

This paper presents the development of a new precast prestressed concrete floor system for multi-story office, commercial, hotel/motel and condominium buildings. This development focuses on minimizing the depth of IT beams and developing continuity in HC and IT directions to resist lateral loads without the need for shear walls. Minimizing floor height results in savings in architectural, mechanical and electrical systems and may allow for additional floors for the same building height. As an example, in a 12-story building, saving 12 in. in each story allows for one extra story. Although a shallow beam cost may be higher than that of a deeper beam, the cost of the structural frame may still be lower, and the cost of the total building would most likely be lower. The potential lower cost occurs because of reduced HC plank spans, as a relatively wide beam would be necessary, and the lateral loads would be reduced for the same number of floors. Furthermore, the AME is about 75 to 80% of the total building cost, and any small savings in these systems would have a significant impact on the overall project economics.

BACKGROUND AND CURRENT PRACTICES

The various flooring systems that are currently available can be categorised into:

- **Cast-in-place slab systems -** The cast-in-place concrete slab floor system is the most flexible floor system as it provides the designer with freedom in floor plan designs. The main advantage of this system is that it is the shallowest system available, especially if post-tensioning is applied. With a span to depth ratio as high as 45 for post-tensioned two-way slab systems the result is a 9 in. thick slab for a typical bay of 32 ft x 32 ft compared to a 13 in. thick slab for the same bay when no post-tensioning is used. There is no need for beams to support the slab. The drawbacks are the slow cast-in-place construction and the cost of forming and post-tensioning. This system is often employed in residential applications due to the clean, flat soffit produced. For more information on the different types of post-tensioned floor systems and their span ranges, please refer to the Post-tensioning Manual 6th Edition[1]. Other drawbacks of the cast-in-place construction, in general, are the cost and duration required for shoring, forming, pouring, and stripping operations. In addition, post-tensioning operations increase the construction cost, duration and complexity as shown in Fig. 1.

Fig. 1 Construction of post-tensioned cast-in-place concrete slab (PTI 2006)

- **Open web steel joist systems -** The open web steel joist system is an economical solution for commercial applications as shown in Fig. 2. A 28-32 in. deep open web steel joist is typically used for 32 ft span with 4-6 ft spacing. Metal decking is generally used to form a 2.5 in. - 4.5 in. thick composite slab. The utilities can pass through the joist openings, saving the height needed for the utilities. However, as steel prices continue to climb, these systems become less attractive. Also, a false ceiling is required to cover the unattractive framing system, resulting in a large total floor height. Several commercial products are currently available in the US market. For more information, visit the web site of the Steel Joist Institute[2].

Fig. 2 Construction of open-web steel joist floor system (SJI 2009)

- **Precast concrete floor systems –** The Precast concrete floor system can be made of a wide range of precast concrete products, such as HC slabs, solid slabs, double trees, and IT/rectangular/L-shaped beams. These products can be also used in conjunction with steel beam and cast-in-place concrete topping in some applications to satisfy design requirements.

A common precast concrete system utilizes HC slabs supported by precast prestressed IT beams which are in turn supported on column corbels or wall ledges. It provides an economical and fire-resistant floor system with excellent deflection and vibration characteristics for both residential and commercial applications. The top surface can be prepared for installation of a floor covering by placing a thin non-structural cementitious levelling topping, or a 2-3 in. concrete composite topping[2]. For a 32 ft span, a 28 in. deep beam that is 40 in. wide can be used in addition to a 2 in. cast-in-place topping, which results in a total of 30 in. thick floor. Some effort has been made in the past to minimize the depth of the precast concrete floor systems, including the use of steel beams instead of precast IT beams. Fig. 3 shows some of the steel-beam shapes used in Europe to support HC planks. The first two shapes are plate girder (built up) sections, and the third is a rolled steel section.

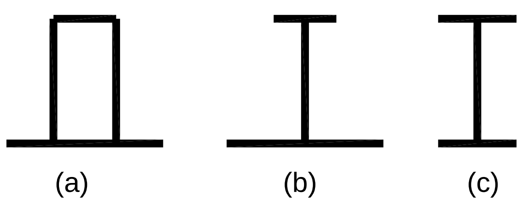


Fig. 3 European practices in designing HC supporting beams

These steel beam systems satisfy the minimum depth criterion as the planks are supported on the bottom plate, however the *fib* bulletin[3] indicates through examples that these beams are limited to about 6 m (20 ft) spans. This span is considerably less that the 30 ft spans generally required for office building applications. It is slightly shorter than the approximately 24 ft required in hotel applications, and is reasonable for apartment/condo applications. They may merit further investigation if the fire protection issues of the underside of the beam can be satisfactorily resolved and if the cost of fabrication is lower than an equivalent prestressed concrete beam.

New steel products have been introduced recently to the US market that can span up to 40 ft. with a depth as shallow as 20 in. Example of these products is a hollow steel beam made from welded steel plates with holes in the sides to be completely filled with concrete after installation to work as a composite beam for superimposed dead loads and live load. Despite the structural efficiency of these products and its ease of installation, the cost and fire resistance are the main disadvantages when compared to precast concrete products.

Low, et al. developed a shallow beam system, however, this system required a single story column which is inconsistent with multi-story column construction practices[4,5]. Also, the beam weight and the complex design were discouraging to users. Thompson and Pessiki developed a system of double tees and ITs, however, this system did not address the use of HC planks, which is most dominant in non-parking applications[6].

A successful system must take into account the prevailing erection practices in the US, and must be within the production capabilities of precasters specializing in building products. It is desirable to completely erect the precast frame and HC planks before cast-in-place operations commence. It is also desirable to use multi-story columns. Thus, the beam pieces should be shorter than the clear space between columns. Precasters generally require that beam width not exceed 4 ftt, prestressing not exceed 30-0.5 in. strands and concrete strength not exceeding 4,500 psi at release and 6,500 psi at final conditions. These constraints were considered by the research team in developing the new system. The main criteria for the design of the proposed floor system include:

1. Shallow structural depth.
2. Satisfactory structural resistance under 100 psf live load
3. Able to resist lateral loads without shear walls for up to six-story building
4. Utilizing HC planks
5. Consistency with prevailing erection techniques
6. Minimal topping thickness
7. Acceptable live load deflection
8. Fire protection
9. Corrosion protection

PROPOSED DESIGN AND DATAILS

The three main challenges faced in this proposed system were:

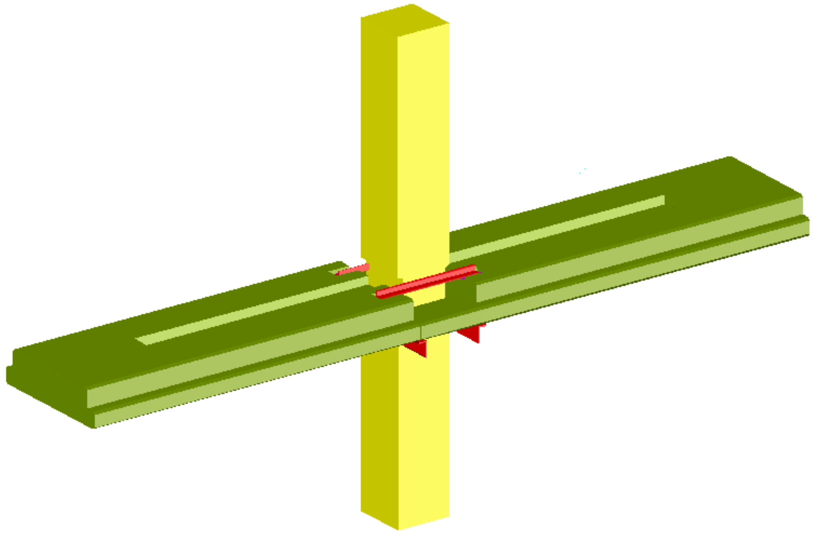
Minimizing the depth of the IT beams: This was achieved by making the beam wider (48 in.) to have the most amount of strands in a fewer number of rows, which lower the centroid of prestressing force for higher flexural capacity. Also, reducing the beam depth was achieved by making it continuous for topping weight and live loads which resulted in an ultimate negative moment at beam section at column face of 512 k.ft.

Eliminating the need for shear walls: This was achieved by detailing and designing the 2 in. composite topping to make both IT beams and HC planks continuous for live load. This continuity created adequate negative moment capacity in the IT and HC directions to suppress the positive moments generated by lateral loads, such as wind loads.

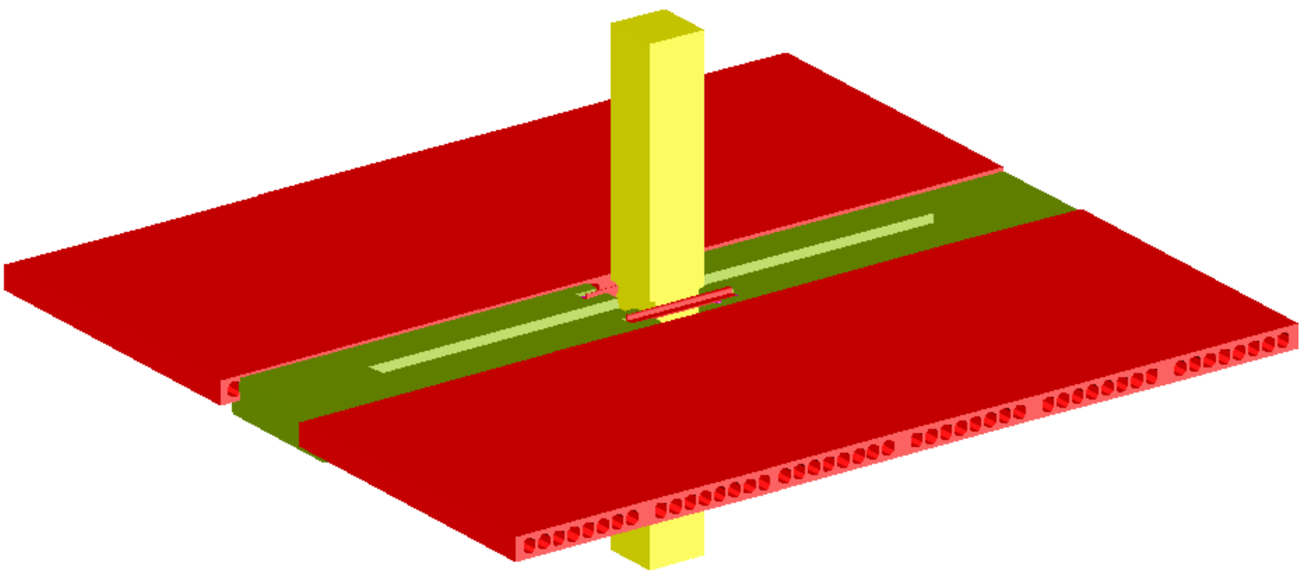
Eliminating corbels: This was achieved by using temporary supports in place of column corbels during construction. The beam-column connection was designed to transfer the vertical shear from the beam to column under ultimate loads after the removal of the temporary support. Two theories were used in designing the beam-column connection: shear friction and punching shear. Full scale testing was carried out to evaluate the adequacy of the above-mentioned connections. Testing results will be published in the PCI Journal shortly.

The proposed floor system consists of continuous precast columns and partially continuous 13 in. deep IT beams, partially continuous 8 in. HC planks, and minimum of 2 in. composite concrete topping. This system benefits the precast/prestressed industry by utilizing typical components that are easy to produce, handle, and erect. The 8 in. thick and 48 in. wide HC planks are the most affordable precast product due to their light weight and use in several applications. Also, the 48 in. wide and 13 in. thick IT beams are simple in fabrication, handling and shipping. All the connections in the new system are greatly simplified for the precaster and contractor to speed up fabrication and erection operations, which will result in the quick and wide use of this system. Two key methods can be used to achieve the structural capacity of the proposed shallow floor system under gravity and lateral loads: a) increasing the beam width up to 48 in., and b) making it continuous for topping weight and live loads. This continuity necessitates having openings through the continuous column in the beam direction to allow the negative reinforcement of the beam to go through the column. This will also provide adequate support for the beam, so that the temporary corbels below the beams can be removed. HC planks are also designed with partial continuity to provide adequate resistance to lateral load in their direction without the need for bottom reinforcement.

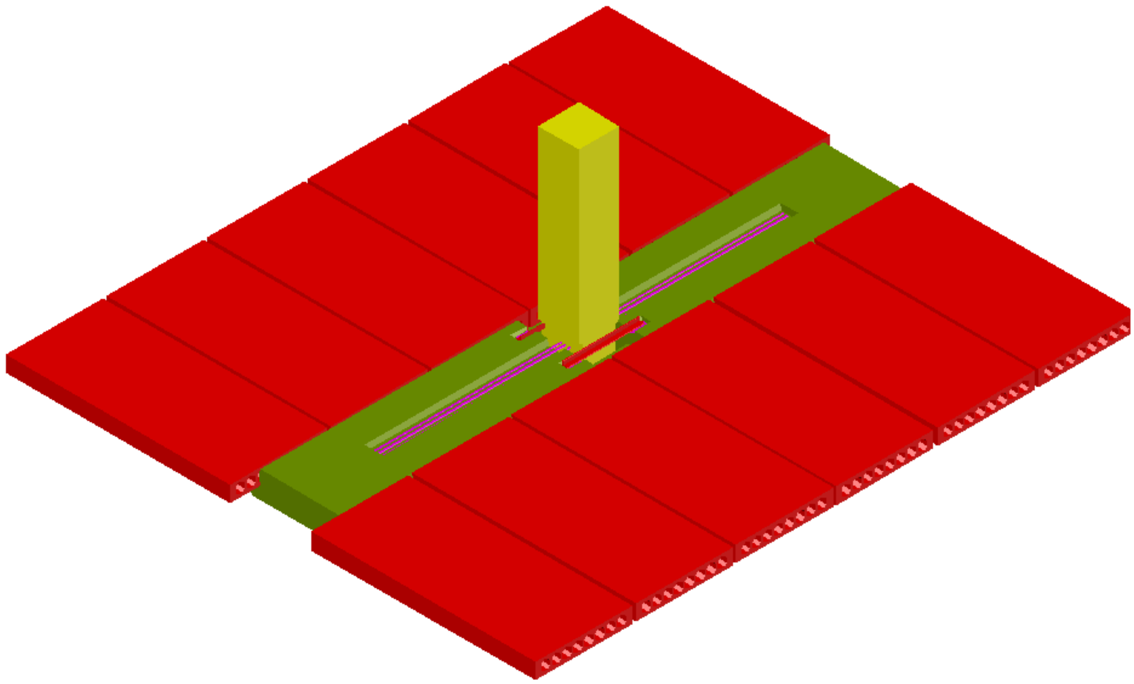
Fig. 4 (a,b,c,d,e,f and g) shows the 3D representation of the construction sequence of the proposed system. First, beams are supported by steel angles that act as temporary corbels to carry loads during construction as shown in Fig. 4(a). In addition, two steel angles are welded at the steel plates on the top of the beam and sides of the column to stabilize the beam when loaded from one side by HC planks. Fig. 4 (b) shows the floor after installing HC planks on beam ledges. The beam is working as a simply supported beam for all loads up to this point. The first continuity reinforcement is placed at beam pockets and through the column opening as shown in Fig 4 (c) and grouted with HC keys as shown in Fig. 4(d). This reinforcement makes the beam continuous for topping weight and creates a stronger connection with the column. Topping reinforcement that provides continuity for live load in both IT and HC direction is placed as shown in Fig. 4 (e and f). After topping is poured, topping reinforcement provides adequate continuity in both IT and HC directions as sown in Fig. 4(g). Finally temporary corbels are removed after topping concrete reaches the required compressive strength.



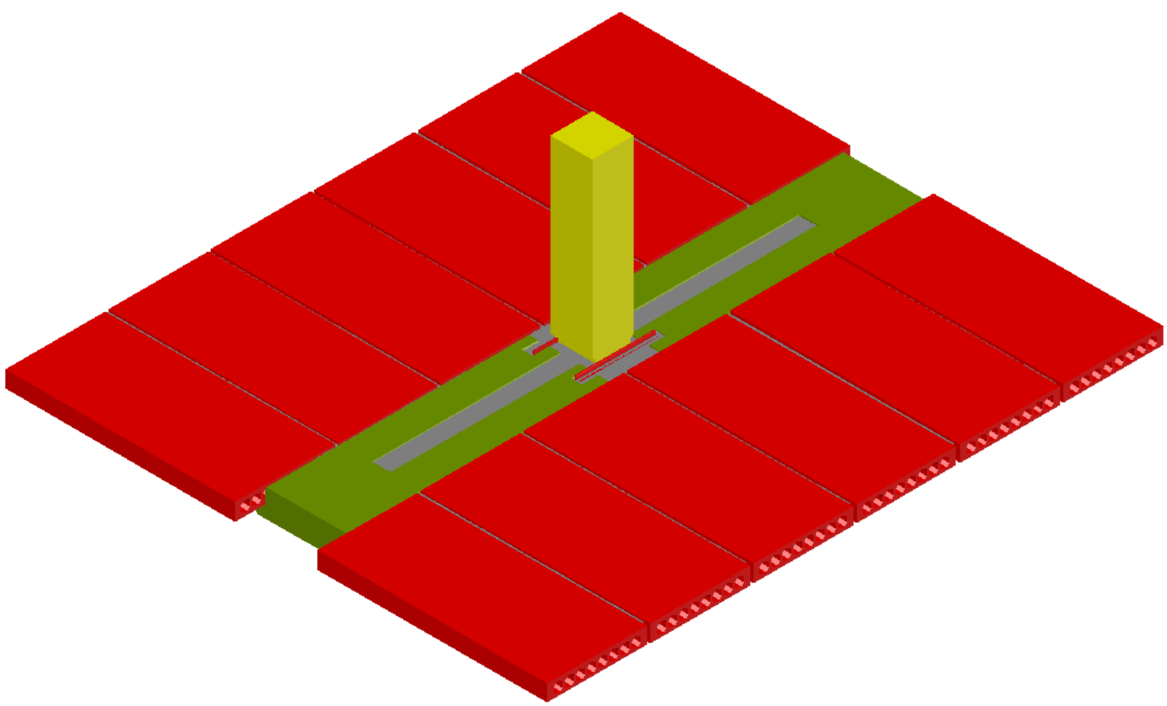
(a) Erection of the precast column and beams using temporary corbels



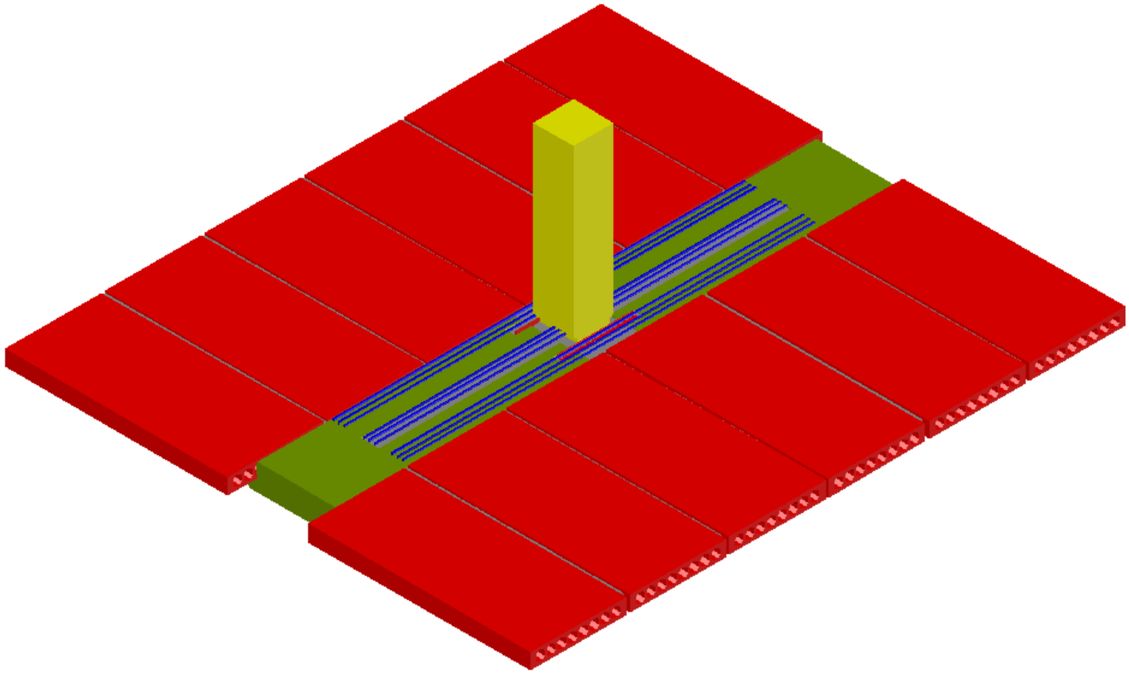
(b) Erection of Hollow-core planks



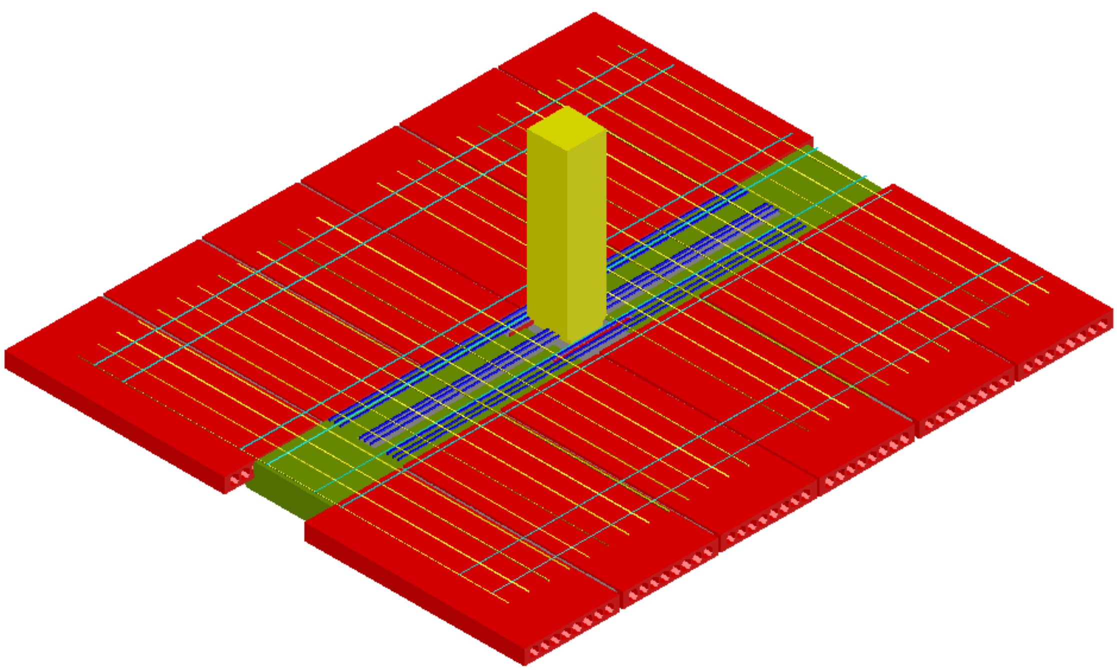
(c) Installation of continuity reinforcement in the beam pocket



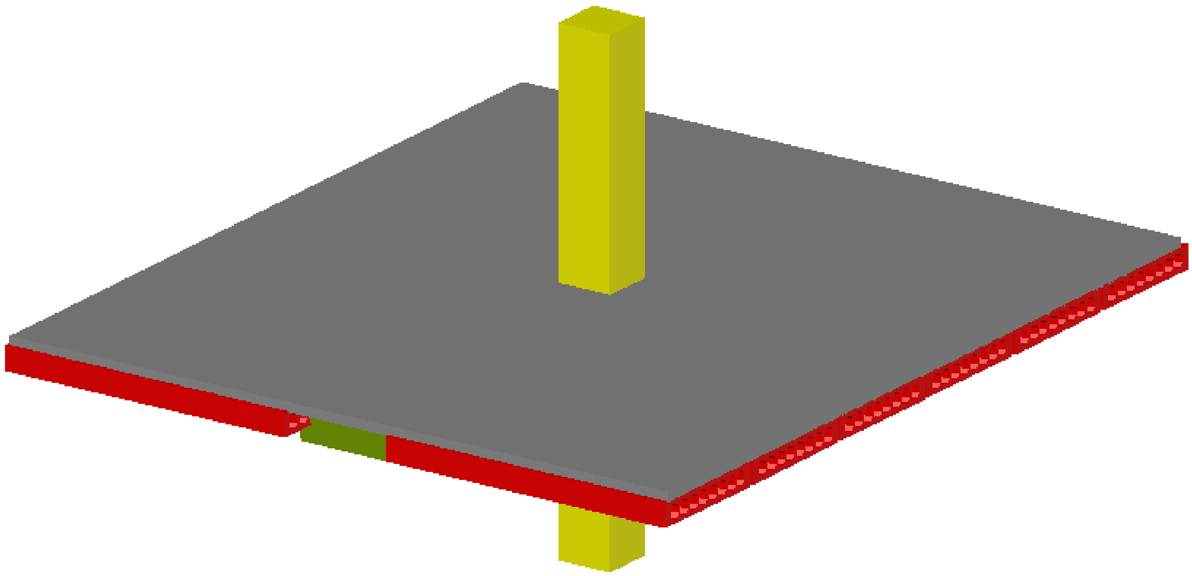
(d) Grouting Hollow-core keys and beam pocket



(e) Installation of continuity reinforcement in the topping



(f) Installation of welded wire reinforcement in the topping



(g) Pouring the topping
Fig. 4 Construction Sequence of the Proposed System

The new system is targeting multi-story buildings with 6 to 8 stories and bay size of 32 ft x 32 ft, which is typical for most hotels and office buildings. Fig. 5 shows the plan of an example building that will be used in the analysis and design of the proposed system. The building has 4 bays in the HC direction and 3 bays in the IT beam direction and consists of 8 stories. Gravity and lateral loads were calculated in accordance to ASCE 7-05, while the design of each component was performed in accordance to the ACI-318-08 code and PCI Design Handbook 6th edition.

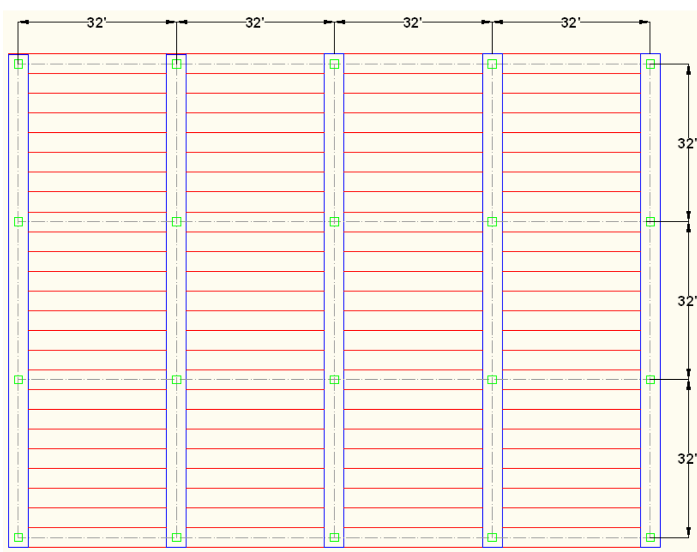
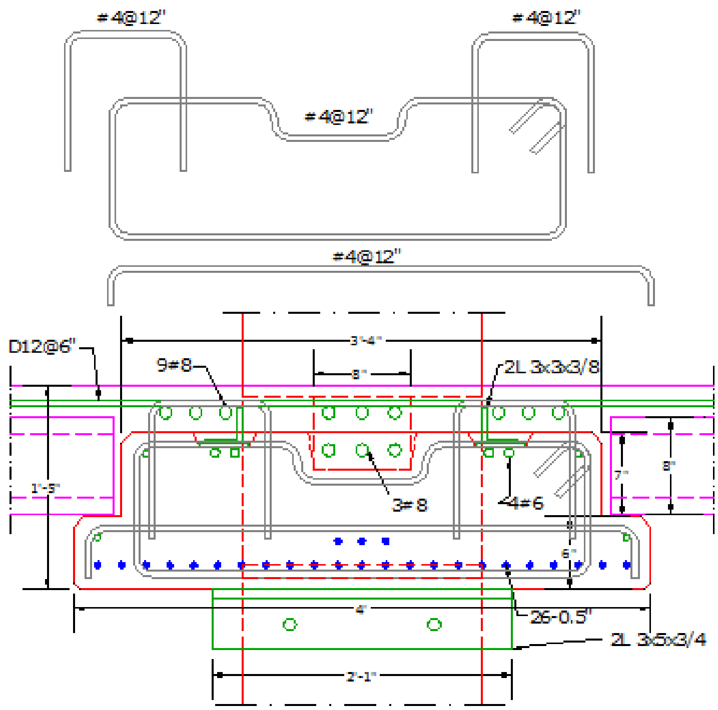


Fig. 5 Plan view of 8-story building used as an example

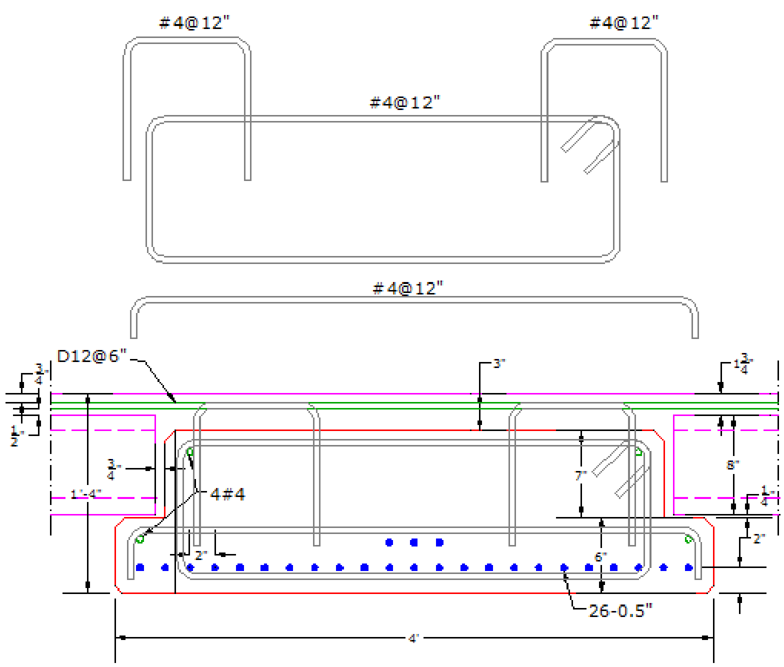
Below are the data used in the analysis and design of the example building:

- Bay Size = 32 ft x 32 ft
- 8-story building
- Wind Load = 25 psf
- Live Load = 100 psf
- 8” x 4 ft H.C. with 2” composite topping
- Concrete strength of beam = 4,500 psi at release and 6,000 psi at final
- Concrete strength of topping = 3,500 psi
- Prestressing strands are 0.5 in. diameter Grade 270 low-relaxation
- 20” x 20” full-height continuous columns 6,000 psi
- No shear walls

Fig. 6 shows the dimensions and reinforcement details of the proposed inverted tee beam as well as its connection with the hollow core and column.



End Section



Mid-Span Section

Fig. 6 Dimensions and reinforcement details of the designed beam

WORK IN PROGRESS

To experimentally investigate the constructability and structural capacity of the proposed system, a full-scale specimen of 20 ft x 20 ft area around an interior column was fabricated at Concrete Industries (CI) Inc. This specimen includes a 14 ft long column, two IT beam segments 11 ft long each, and 8 hollow core segments 8 ft long each. The design and detailing were reviewed by the CI engineering staff and slightly revised to .facilitate production and erection. The specimens were shipped to the structural laboratory at Peter Kiewit Institute (PKI) for erection and testing. Erection was done by a crew of professional erectors from CI with the help of the lab technician and graduate students and under the supervision of the project investigators. Three primary tests were performed on the specimen: a) IT beam continuity test, b) hollow-core continuity test, and c) beam-to-column connection test. Tests were performed under the supervision of the research team. Some of these tests were performed in several stages to maximize the benefit from the specimen. Test results are being analyzed and will be presented in the PCI Journal.

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