An Engineers Guide to:
Economical Concrete Floor Systems

Numerous types of cast-in-place and precast concrete floor systems are available to satisfy virtually any span and loading condition. Reinforced concrete allows a wide range of structural options and provides cost-effective solutions for a multitude of situations—from residential buildings with moderate live loads and spans of about 25 ft, to commercial buildings with heavier live loads and spans ranging from 40 ft to 50 ft and beyond. Shorter floor-to-floor heights and inherent fire and vibration resistance are only a few of the many advantages that concrete floor systems offer, resulting in significant reductions in both structural and nonstructural costs.

Since the cost of the floor system can be a major part of the structural cost of a building, selecting the most effective system for a given set of constraints is vital in achieving overall economy. This is especially important for buildings of low-and medium heights and for buildings subjected to relatively low wind or seismic forces, since the cost of lateral load resistance in these cases is minimal. The information provided below will help in selecting an economical cast-in-place concrete floor system for a variety of span lengths and superimposed gravity loads. Also presented is basic information on the advantages of the systems, as well as general information on practical framing layouts and formwork. Long-span floor systems are also included in the discussion.

From concept to completion, the 21 story mixed-use Astor Place Tower, New York, New York is a show-case for the versatility of reinforced concrete in building construction.

General Considerations

The main components of cast-in-place concrete floor systems are concrete, reinforcement (mild and/or post-tensioned), and formwork. The cost of the concrete, including placing and finishing, usually accounts for about 30% to 35% of the overall cost of the floor system. Where mild reinforcement is utilized, a concrete mix with a compressive strength of 4,000 psi yields the least expensive system. Where post-tensioned reinforcement is used, a concrete compressive strength of at least 5,000 psi is usually specified to attain, among other things, more cost-effective anchorages and higher resistance in tension and shear.

Having the greatest influence on the overall cost of the floor system is the formwork, which is about 45% to 55% of the total cost.

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Three basic principles govern formwork economy for site-cast concrete structures:

- Specify readily available standard form sizes. This is essential to achieve economical formwork. Most projects do not have the budget to accommodate custom forms, unless they are required in a quantity that allows mass production.

- Repeat sizes and shapes of the concrete members wherever possible. Repetition allows forms to be reused from bay to bay and from floor to floor, resulting in maximum overall savings.

- Strive for simple formwork. There are countless variables that must be evaluated and then integrated into the design of a building. Economy has traditionally meant a time-consuming search for ways to reduce the quantities of materials. For example, it may seem appropriate to vary the depth of beams with the loading and span variations, providing shallower beams where the loads or spans are smaller. This approach would result in moderate savings in materials, but would create additional costs in formwork, resulting in a substantially more expensive structure—quite the opposite effect of that intended. Providing a constant beam depth while varying the amounts of reinforcement along the span length is the simplest and most cost-effective solution.

Further information on economical formwork is provided for each of the systems discussed below.

In the preliminary design stage, it is very important to consider fire resistance. State and municipal building codes throughout the U.S.

Waterfront Seattle Marriott uses optimized concrete floor systems.

regulate the fire resistance of the various elements and assemblies of a building structure. Structural frames, floor and roof systems, and load-bearing walls must be able to withstand the stresses and strains imposed by fully developed fires and must carry their own dead load and superimposed loads without collapse.

Concrete floor systems offer inherent fire resistance. No additional protective measures are required to achieve code-prescribed fire-resistance ratings when the floor system is completed.

Fire-resistance rating requirements usually vary from 1 to 4 hours, with 2 hours typically required for buildings. In general, the concrete member thickness required for structural purposes will usually be adequate to provide at least a 2-hour fire-resistance rating. If the thickness necessary to satisfy fire-resistance requirements exceeds that required for structural purposes, consideration should be given to using a different type of aggregate that provides higher fire resistance for the same thickness. The minimum cover requirements to the main reinforcement specified by ACI 318-05 (Ref. 1), which will be adopted by reference in the 2006 *International Building Code*, are adequate for at least a 2-hour fire-resistance rating as well. In all cases, the local building code governing the specific project should be consulted to ensure minimum fire-resistance requirements are satisfied.

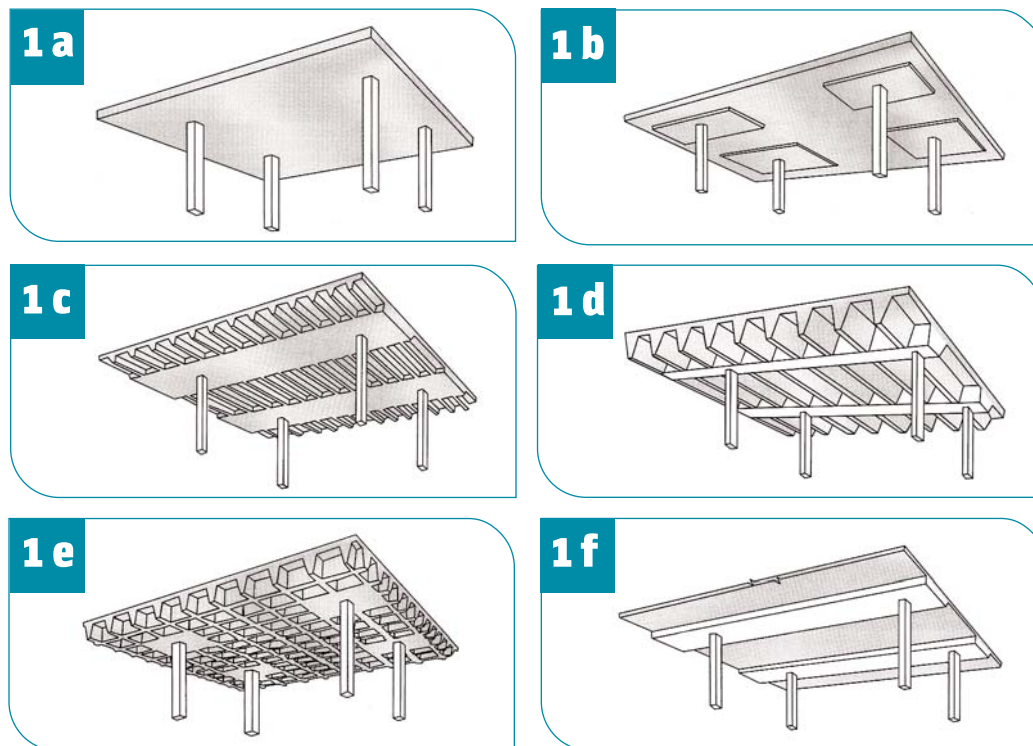**1 a**

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Figure 1: Cast-in-place reinforced concrete floor systems: (1a) Flat plate (1b) Flat slab (1c) One-way joist (1d) Wide-module joist (1e) Two-way joist (1f) Banded-beam.

Flat Plate System

A flat plate floor system is a two-way concrete slab supported direct-ly on columns with reinforcement in two orthogonal directions (Figure 1a). Primarily used in hotels, multi-family residential build-ings, and hospitals, this system has the advantages of simple con-struction and formwork and a flat ceiling, the latter of which reduces ceiling finishing costs, since the architectural finish can be applied directly to the underside of the slab. Even more significant are the cost savings associated with the low-story heights made possible by the shallow floor system. Smaller vertical runs of cladding, partition
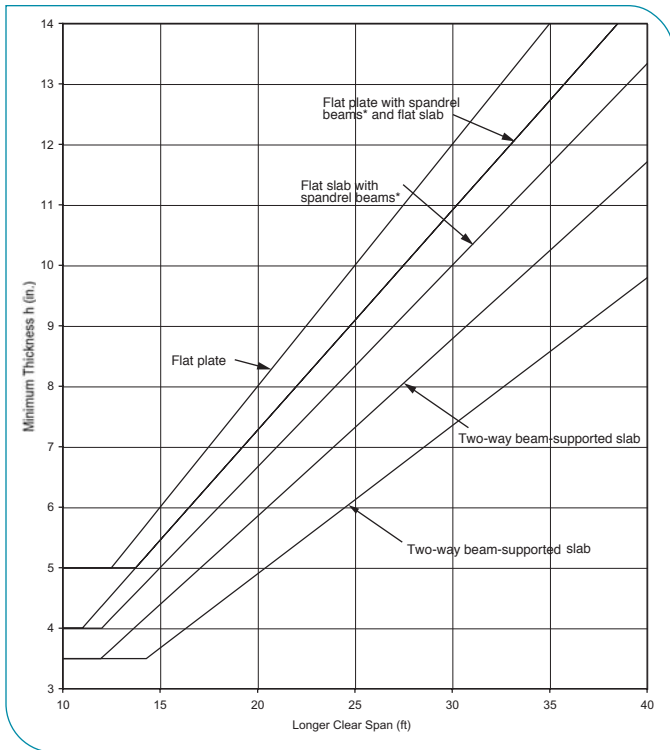

Figure 2: Minimum thickness of slabs without interior beams per ACI Sect. 9.5.3

walls, mechanical systems, plumbing, and a large number of other items of construction translate to large cost savings, especially for medium and high-rise buildings. Moreover, where the total height of a building is restricted, using a flat plate will result in more stories accommodated within the set height.

The thickness of a flat plate is controlled by the deflection require-ments given in Sect. 9.5.3 of ACI 318-05. Minimum slab thicknesses for flat plates with Grade 60 reinforcing bars, based on ACI 9.5.3, are summarized in Figure 2 as a function of the longest clear span between supports.

Flat plate systems are economically viable for short to medium spans and for moderate live loads. Up to live loads of about 50 psf, the deflection criteria usually govern, and the economical span length range is 15 ft to 25 ft. For live loads of 100 psf or more, punching shear stresses at the columns and bending moments in the slab con-trol the design. For these cases, the flat plate is economical for spans between 15 ft and 20 ft. A flat plate floor with a live load of 100 psf is only about 8% more expensive than one with a live load of 50 psf, primarily due to the minimum thick-ness requirements for deflection. Floor pan-els with an aspect ratio of 2 would be about 30% more expensive than panels with an aspect ratio of 1; the thickness of the rectangular panel is governed by the greater span length, resulting in a loss of economy.

An architect's rendering of the Trump International Hotel and Tower, Chicago, Illinois. It will be the tallest concrete building in the U.S.

On average, the formwork costs for flat plates represent approxi-mately 46% of the total floor cost. Concrete material, placing, and finishing account for about 36% of the cost. The remaining 18% is the material and placing cost of the mild reinforcement.

Flat Slab System

The flat slab is similar to the flat plate, but has thickened portions around the columns called drop panels, which are used primarily to resist punching shear stresses associated with longer spans and/or heavier loads (Figure 1b). Although drop panels result in somewhat higher formwork costs, a relatively shallow slab system is achieved in situations where punching shear would otherwise preclude the use of a flat plate.

The minimum slab thickness prescribed in ACI 318-05 for flat slabs is 10% less than that required for flat plates with similar span lengths
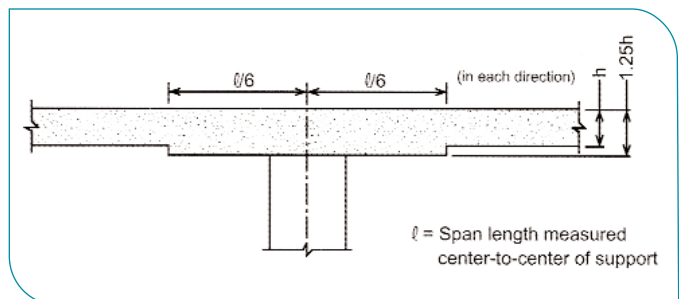

Figure 3: Drop panel dimensions per ACI Sect. 13.3.7

(Figure 2). In order to take advantage of this allowable reduction in slab thickness, the drop panels must have the minimum dimensions given in ACI 13.2.5, which are illustrated in Figure 3. Drop dimensions are also controlled by formwork considerations. Figure 4 shows the standard lumber dimensions that are used when forming drop panels. Using other depths will unnecessarily increase formwork costs.

For a live load of 50 psf or less, flat slabs are economically viable for span lengths between 25 ft and 30 ft. The economical range is 20 ft to 25 ft for a 100 psf live load. An increase in live load from 50 psf
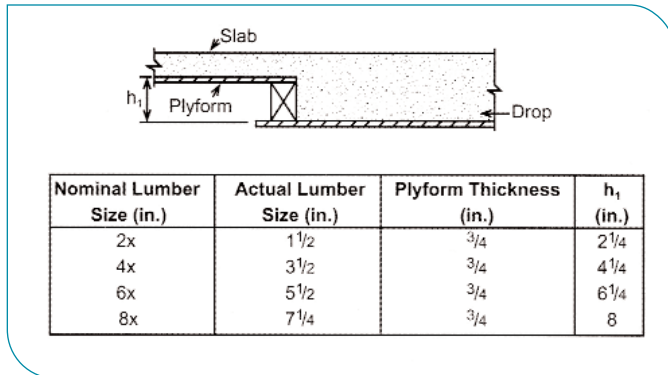

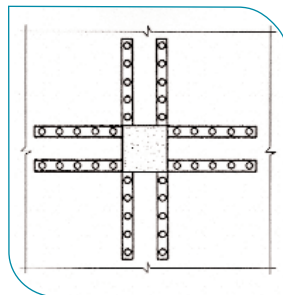| Nominal Lumber Size (in.)	Actual Lumber Size (in.)	Plyform Thickness (in.)	h_1 (in.)
2x	$1^{1}/2$	$^{3}/4$	$2^{1}/4$
4x	$3^{1}/2$	$^{3}/4$	$4^{1}/4$
6x	$5^{1}/2$	$^{3}/4$	$6^{1}/4$
8x	$7^{1}/4$	$^{3}/4$	8

Figure 4: Drop panel formwork details

Figure 5: Shear stud reinforcement for slabs

to 100 psf results in only a 4% increase in overall cost, since the material quantities are usually controlled by deflections. The formwork costs account for approximately 47% of the total floor system cost. The concrete material, placing, and finishing costs are about 36%, while the material an placing costs of the mild reinforcement are 17%.

In lieu of drop panels, shear studs also provide a simple and economical way of providing shear resistance around the columns, while preserving the benefits of a flat ceiling (Figure 5). In addition, they generally do not interfere with the other reinforcement at the column-slab joint.

One-Way Joist System

A standard one-way joist floor system consists of evenly spaced concrete joists (ribs) spanning in one direction, a reinforced concrete slab cast integrally with the joists, and beams that span between the columns, perpendicular to the joists (Figure 1c). The joists are formed by using pan forms that are 30 in. wide and range in depth from 8 in. to 24 in. (Figure 6). The varying depths provide flexibility to satisfy a wide range of span and loading conditions.

The main advantages of this system are: (1) they are economical for long spans with heavy loads, (2) the pan voids reduce the dead load, and (3) electrical and mechanical equipment can be placed between joists, which means the overall floor depth need not be increased to

accommodate this equipment. The longer spans and inherent vibration resistance make this an attractive floor system for office buildings, hospitals, and schools.

Wide-module joists, or "skip" joists, are similar to the standard one-way joists except the pans are 53 in. or 66 in. wide (Figure 1d). For the 53-in. pans, the pan depth varies from 16 in. to 24 in., and for the 66-in. pans, the range is 14 in. to 24 in. (Figure 6). The advantages of the wide-module system are the same as those listed above for the standard joist system. However, the wide-module joists are more economical for very long span lengths, and provide large, column-free spaces for maximum flexibility in space planning—all without concerns for vibration.

The overall depth of the joists is governed by the deflection requirements in ACI 9.5.2. For 30-in. pan form systems, the thickness of the slab spanning between the joists is usually controlled by fire resistance requirements, since the structural requirements for the slab are minimal.
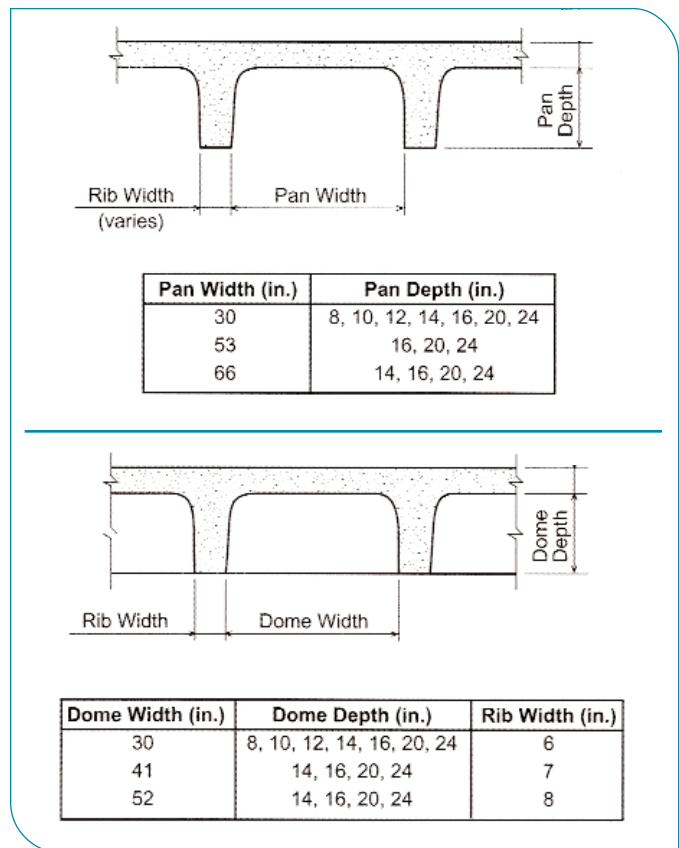

Pan Width (in.)	Pan Depth (in.)
30	8, 10, 12, 14, 16, 20, 24
53	16, 20, 24
66	14, 16, 20, 24

Dome Width (in.)	Dome Depth (in.)	Rib Width (in.)
30	8, 10, 12, 14, 16, 20, 24	6
41	14, 16, 20, 24	7
52	14, 16, 20, 24	8

Figure 6: Standard form dimensions for one-way joist construction
Figure 7: Standard form dimensions for two-way joist construction

To achieve overall formwork economy, the depth of the supporting beams should be the same as the overall depth of the joists. If additional capacity is required, the beams should be made wider, not deeper. Also, the beams should be as wide as, or wider than, the columns into which they frame. In addition to assuring formwork economy, this also alleviates some of the reinforcement congestion that can occur at the joints.

Systems formed with the 30-in. pans are usually economical for spans between 30 ft and 35 ft, while systems utilizing the 53-in. and 66-in. pans are viable for span lengths between 35 ft and 50 ft and beyond. The difference in cost of systems formed with 30-in., 53-in., and 66-in. pans is less than 6% for live loads up to 100 psf and span lengths between 35 ft and 40 ft. Also, an increase in live load from 50 psf to 100 psf results in only a 5% increase in the overall cost of the floor system. Depending on the loads, post-tensioning the joists may result in the most economical solution for spans greater than about 40 ft to 45 ft. On average, the formwork costs account for approximately 51% of the total floor system cost. The concrete material, placing, and finishing costs are about 31%, and the material and placing costs of the mild reinforcement are 18%.

Two-Way Joist System

A two-way joist system, or waffle slab, is comprised of evenly spaced concrete joists spanning in both directions and a reinforced concrete slab cast integrally with the joists (Figure 1e). The floor system is formed with domes that are 30 in., 41 in., and 52 in. wide, resulting in 3-ft, 4-ft, and 5-ft modules, respectively (Figure 7).

A solid slab section around the columns is usually provided for shear resistance. Waffle slabs are economically viable for long spans with heavy loads, and are commonly used in office buildings, warehouses, and industrial plants.

For design purposes, waffle slabs are considered as flat slabs with the solid heads acting as drop panels. Thus, the minimum thickness requirements of ACI 9.5.3 must be satisfied. To determine the deflection requirements, the cross-section of the floor system is transformed into an equivalent section of uniform thickness. This is accomplished by determining a slab thickness that provides the same moment of inertia as the two-way joist section.

Two-way joists are economical for spans between 40 ft and 50 ft. Similar to the other floor systems, increasing the live load from 50 psf to 100 psf results in an overall cost increase of about 4%.

Approximately 52% of the total floor system cost can be attributed to the formwork. The concrete material, placing, and finishing costs are about 33%, and the material and placing costs of the mild reinforcement are 15%.

Banded-Beam System

A banded-beam system typically consists of a uniform slab with thickened portions below the slab along the column lines parallel to the longer spans (Figure 1f). As a rule, the thickened portions of the slab, commonly referred to as band-beams, are post-tensioned. The primary purpose of thickening the slab is to provide an increased drape for the tendons that are banded in this region. Increasing the drape allows larger upward prestressing forces to counteract the load effects in the long direction. Depending on the span lengths and/or the magnitude of the loads, either non-prestressed or post-tensioned reinforcement is used in the slab in the direction perpendicular to the bands.
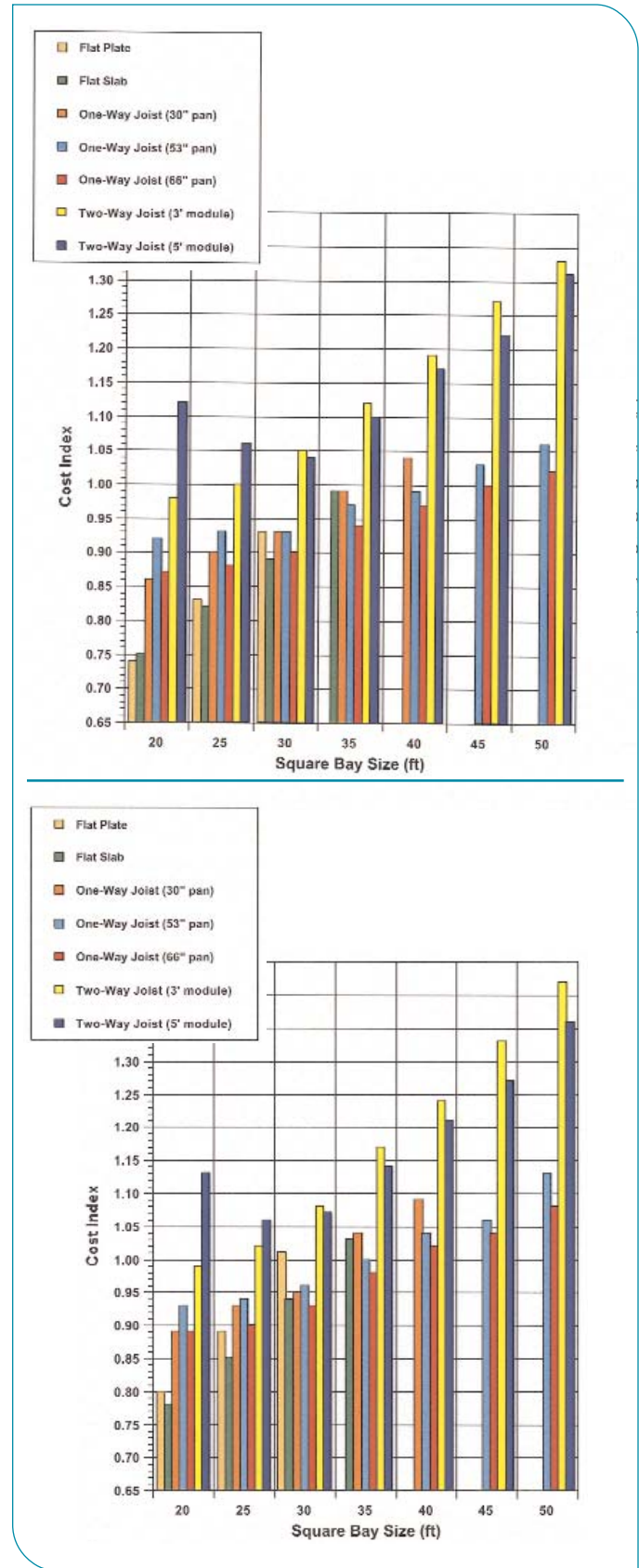

Figure 8: Relative costs of reinforced concrete floor systems, live load = 50 psf
Figure 9: Relative costs of reinforced concrete floor systems, live load = 100 psf

The overall thickness of the band-beam is typically 12 in. to 18 in., and the width can vary from 4 ft to 10 ft. Depending on the spans and loads, the slab is usually 7 in. to 9 in. thick. One of the main advantages of this system is that long, unobstructed spans can be achieved with a minimum structural floor depth. This results in lower floor-to-floor heights and significant cost savings. Also, vibration is not an issue due to the inherent damping properties of the concrete. Tenant modifications can be easily accommodated when non-prestressed reinforcement is used in the slab perpendicular to the band-beams.

Banded-beam systems are economically viable for span lengths from 35 ft to 50 ft and beyond. An increase in the live load from 50 psf to 100 psf results in about a 6% increase in overall cost. Also, post-tensioning the slab perpendicular to the band-beams typically becomes cost-effective for spans greater than about 30 ft. The formwork accounts for approximately 45% of the total cost, with the concrete and reinforcement accounting for 30% and 25%, respectively.

Overview

Figures 8 and 9 show the relative costs of the flat plate, flat slab, one-way joist, and two-way joist systems for various square bay sizes and for live loads equal to 50 psf and 100 psf, respectively. Normal weight concrete with a compressive strength of 4,000 psi, Grade 60 reinforcing bars, and a superimposed dead load of 20 psf is assumed in all cases. The cost index is the ratio of the total cost—which is comprised of the in-place costs of concrete, reinforcement, and formwork for that particular case—to the average total cost for all cases, including both live load cases. The figures clearly show the most cost-effective solutions for the various span and loading conditions, and, thus, can be used as a guide in selecting an economical concrete floor system in the preliminary design stages.

The in-place costs used in this analysis are based on average costs for the U.S. as provided in Ref. 2. The size and geographic location of the project, the availability of skilled labor, and local building code requirements are only a few of the many factors that can significantly affect costs. Therefore, results obtained at the local level may vary from those presented in the figures.

A comprehensive discussion on concrete floor systems can be found in Refs. 3, 4, 5, and 6. Included are quantities of concrete, reinforcement, and formwork for various span and loading conditions. Cost indices are also provided, including values for the banded-beam system.

For a detailed overview of design examples, guides, and software please visit the PCA buildings page at www.cement.org/buildings.

References

1. *Building Code Requirements for Structural Concrete (318-05) and Commentary* (318R-05), American Concrete Institute, Farmington Hills, MI, 2005.

2. *Concrete and Masonry Cost Data*, 23rd edition, R.S. Means Co., Inc., Kingston, MA, 2005.

3. *Concrete Floor Systems—Guide to Estimating and Economizing*, (SP041) 2nd edition, Portland Cement Association, Skokie, IL, 2000.

4. *Long-Span Concrete Floor Systems* (SP339), Portland Cement Association, Skokie, IL, 2000

5. *Simplified Design Reinforced Concrete Buildings of Moderate Size and Height* (EB104), Portland Cement Association, Skokie, IL 2004.

6. *PCA Notes on ACI 318-05* (EB705), Portland Cement Association, Skokie, IL 2005.

Concrete floor systems under construction in a mixed-use San Diego, California, building.