PLASTIC VOIDED SLAB SYSTEMS: APPLICATIONS AND DESIGN

by

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Abstract

Reinforced concrete slabs are one of the most common components in modern building construction. Reinforced concrete slabs with plastic voids slabs are a new and innovative type of structural, concrete slab system developed to allow for lighter self-weight of the structure while maintaining similar load carrying capacity of a solid slab. Plastic voided slabs are capable of reducing the amount of concrete necessary to construct a building by 30 percent or more. This reduction can be beneficial in terms of financial savings as well as building performance.

This report examines a two-way, reinforced concrete slab with plastic voids construction in comparison to traditional flat plate reinforced concrete slab construction. The design process for plastic voided slabs is directly compared with traditional two-way flat plate reinforced concrete slabs through a design comparison of typical bays of 20' by 20' (6m by 6m), 25' by 25' (7.6m by 7.6m), 30' by 30' (9m by 9m) and 35' by 35' (10.7m by 10.7m). The traditional slab design process follows the ACI 318-11 *Building Code Requirements for Structural Concrete* chapter 13 Direct Design Method, while the plastic voided slab design process is modified from the *BubbleDeck Design Guide for compliance with BCA using AS3600 and EC2*. Sizes of traditional slab bays are compared to sizes of plastic voided slab bays. Results of the comparison study are presented.

Table of Contents

List of Figures

List of Tables

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Dedication

This report is dedicated to my family. I would like to specifically thank my parents, Kent and Lois Midkiff, for supporting me and encouraging me to push myself to be the best that I could be. Also I would like to thank my fiancée, Dana Ballou, for following me as I follow my dreams, no matter where they might take us.

Chapter 1 - Introduction

When designing a reinforced concrete structure, a primary design limitation is the span of the slab between columns. Designing large spans between columns often requires the use of support beams and/or very thick slabs, thereby increasing the weight of the structure by requiring the use of large amounts of concrete. Heavier structures are less desirable than lighter structures in seismically active regions because a larger dead load for a building increases the magnitude of inertia forces the structure must resist as large dead load contributes to higher seismic weight. Incorporating support beams can also contribute to larger floor-to-floor heights which consequently increases costs for finish materials and cladding.

A new solution to reduce the weight of concrete structures and increase the spans of two-way reinforced concrete slab systems was developed in the 1990s in Europe and is gaining popularity and acceptance worldwide. Plastic voided slabs provide similar load carrying capacity to traditional flat plate concrete slabs but weigh significantly less. This weight reduction creates many benefits that should be considered by engineers determining the structural system of the building.

Plastic voided slabs remove concrete from non-critical areas and replace the removed concrete with hollow plastic void formers while achieving similar load capacity as solid slabs. Voided slab principles have been applied in different applications dating back to the early 1900s.

This report examines the design process of plastic voided slabs. The principles behind plastic voided slab systems are presented. A parametric study of two-way flat plate reinforced concrete slabs and plastic voided slabs with the same design constraints is discussed.

Before plastic voided slabs can be fully understood, a thorough knowledge of flat plate reinforced concrete slabs- behavior, failure mechanisms, design, and limitations- is critical. Chapter 2 discusses traditional flat plate reinforced concrete slabs by describing how the slabs are constructed and resulting advantages and disadvantages of this construction. The design procedure and failure mechanisms for solid slabs are also described.

The principles of using voids in slabs have been applied in various applications for many years. Chapter 3 discusses the principles of voided slabs that led to the eventual invention of plastic voided slabs including previous applications of voided slab principles.

The development of plastic voided slabs is presented in Chapter 4, while applications of plastic voided slabs are presented in Chapter 5. The design process for plastic voided slabs is discussed in detail in Chapter 6. Chapter 7 contains the results and conclusions of a comparison study that compares two-way flat plate reinforced concrete slabs to plastic voided slabs. The parametric study consists of four different designs for each slab type. The four slab designs are square bays with dimensions of 20 feet by 20 feet (6m by 6m), 25 feet by 25 feet (7.6m by 7.6m), 30 feet by 30 feet (9m by 9m), and 35 feet by 35 feet (10.7m by 10.7m). The purpose of the study is to compare the design of a plastic voided slab to the design of a traditional two-way flat plate slab.

Chapter 2 - One-way and Two-Way Reinforced Concrete Slabs

Concrete was first used by the Romans for construction as early as 300 BC because it allowed for more flexibility in design than masonry construction, which was standard for large buildings at the time. Concrete has remained a popular building material, although the composition and construction method of concrete has changed minimally. However, over 2500 years, the most significant change to concrete has been the addition of steel reinforcement to increase concrete strength in tension. In common design practice, the concrete is designed to resist compressive force induced into a member, while reinforcing steel is designed to resist tensile forces. If needed, steel can be added to the compression region of a reinforced concrete member to help resist compressive forces, but concrete is not relied upon to resist tensile forces in the tension region (Gromiko and Shepard, 2013).

The addition of reinforcing steel in the tension regions of concrete led to modern concrete construction. Reinforced concrete members have smaller dimensions than non-reinforced concrete members. Concrete slabs benefit greatly from the addition of reinforcing steel, as slabs can now be measured in inches rather than feet. This section reviews modern two-way flat plate, reinforced concrete slab construction, including advantages and disadvantages, as well as describing the design process for flat plate slabs.

Solid Slab Types

Concrete slabs vary by type of frame construction. In steel frame buildings, concrete slabs often consist of a few inches of concrete placed over the top of steel deck. In precast concrete frame buildings, the slab is a topping slab, a few inches of concrete placed over a precast floor member such as a hollowcore plank. These slabs are supported by the hollowcore plank unless they are composite slabs. In cast-in-place concrete frame buildings, slabs are a few to several inches thick, depending on span, and can be cast with or without floor beams. Slabs in concrete frame buildings are the focus of this report.

Concrete slabs are typically classified as one-way or two-way systems based on the span lengths ratio in the two principal horizontal directions. Depending on the span length ratio, the flexural stiffness of the slab, solid reinforced concrete slabs are typically designed as either one-way or two-way slabs. A one-way slab typically has a span ratio greater than 2. One-way slabs are designed as if they span in only one direction. The slab spans to beams and depending on reinforcement placement spans continuously over multiple bays. These slabs are designed as one-foot wide sections that transfer loading in only one direction. Reinforcement is designed to resist flexure in the short direction, perpendicular to the beams. Typically, the long direction, parallel to the beams, is lightly reinforced, meeting temperature and shrinkage resistance requirements. One-way slabs are the simplest type of reinforced concrete slab to design because it requires less calculation and details than two-way slabs. Since the load applied to the slab is transferred in one direction to the beams and then to supporting girders and columns, one-way slab construction can lead to deeper structural members and larger floor-to-floor heights (Wight and MacGregor, 2009).

Two-way reinforced concrete slabs typically have span ratios less than 2 and are designed to span in two directions. Two-way slab systems come in many forms: flat plates, flat slabs, waffle slab, and two-way slab with beams. Flat plates, slabs with uniform thickness throughout, are typically used for lighter loads and shorter spans, 15 feet to 25 feet (4.6m to 7.6m). Flat slabs are used for higher load conditions, typically superimposed loads greater than 100 psf (4.8kPa) and longer spans, 25 feet to 35 feet (7.6m to 10.7m). The slabs of a flat slab system are not a constant thickness throughout- drop panels, thickening of the slab, at column locations are provided to transfer shear. These are less common today since more labor is required and the formwork costs are higher than the flat plate system. Waffle slabs are used for longer spans, 30 to 45 feet (9m to 13.7m). The slab thickness of the waffle slab is controlled by the required depth to transfer shear. The middle third of the span does not require this flexural stiffness; therefore to lighten the self-weight of the system, portions of the slab are reduced. The waffle slab is also known as a two-way pan-joist system. The two-way slab with beams incorporates the use of beams and girders, although two-way slabs can be supported only by columns and walls. Reinforcement for two-way slabs must be designed to resist flexure in both directions. Two-way slab design is more time intensive than one-way slab design as additional steps and checks are required in order to ensure proper design for the behavior of the system. Two-way slabs that do not use beams are shallower than two-way slabs with beams. With lighter loads and shorter spas, flat slabs lead to smaller floor-to-floor heights, thus reducing finish materials as well as mechanical and electrical loads. A flat plate slab is used in the parametric study in Chapter 7 (Wight and MacGregor, 2009).

Solid Flat Slab Advantages

Solid flat slabs have many advantages related to load carrying capacity as well as the affect using flat slabs can have on the design of the whole building. Solid flat slabs are typically used to transfer up to hundreds of pounds per square foot of load depending on slab thickness and span. For general commercial, retail, or residential buildings, a slab thickness of 10 inches (25cm) or less can be used for spans of 20 feet (6m) or less. In this type of design, no support beams or girders would be needed as the slab would be capable of spanning between columns with proper reinforcement detailing.

One of the biggest advantages for a two-way flat slab compared to one-way slabs or two-way slabs that transfer load to beams and girders is that floor-to-floor heights are generally smaller for flat slabs. When no beams and girders are present, the structure occupies far less space, as much as a foot less at each floor. In a multi-story building, this can lead to several feet being reduced from the height of the overall building. Reduced building height allows for many different types of savings including less finish material such as building cladding and paint as well as reducing HVAC load requirements.

Solid Slab Disadvantages

Solid reinforced concrete slabs are well understood and accepted in structural engineering, but they are not without disadvantages. These disadvantages must be considered alongside the advantages when choosing a slab system for a building. Some disadvantages of solid concrete slab construction are presented in this section include the use of formwork and the large mass associated with solid slabs.

Whether a slab is designed as a one-way slab or a two-way slab, large amounts of formwork are needed to frame the slab until the concrete can harden. One-way slabs also require formwork for the beams used to support the slab. Placement and removal of formwork is labor intensive. The cost of labor is one of the driving factors in construction costs and time spent installing and removing formwork increases project costs. In addition to cost concerns, formwork can have sustainability concerns. Many types of formwork can be used for slab construction, such as metal, plastic, or wood. Metal and plastic forms typically are reusable, but wooden formwork is often not reusable after two to three uses unless they are specialty forms for unique shapes and conditions, thus leading to the use of large amounts of lumber and plywood for a project. Additional wood for forms creates a large carbon footprint and lowers the sustainability level achieved by the building design.

Concrete is a strong material, but it is heavy when compared to the amount of strength it can provide. Solid concrete slabs have a large mass that partially offsets the strength benefits of the concrete. As a superimposed load on a slab increases, the slab thickness must increase, adding to the self-weight. The added weight is generally high in comparison to the superimposed load, and the weight accumulates as larger areas are considered. The slab weight must ultimately be carried by columns or walls. Normal weight reinforced concrete is generally assumed to weigh 150 pounds per cubic foot (23.6 kN/m^3) which includes reinforcement. For an example column, assume a tributary area of 400 square feet ($37m^2$). Adding one inch (2.5cm) of slab thickness over the entire slab area adds 5000 pounds (22.2 kN) of unfactored dead load for the column to support. If the same column supports multiple floors all experiencing similar thickness increases, the additional weight increases quickly. Solid slabs can have substantial mass, leading to larger and heavier supporting members such as beams, girders, and columns, and eventually increasing material costs as well as the need for stronger foundations.

Solid Slab Design

In order to understand and fully appreciate the benefits of plastic voided slabs, the design process for traditional solid slabs must be understood. Solid slab design can range from fairly simple to complex. This section discusses the various decisions, considerations, and design checks made during the design of a solid flat plate reinforced concrete slab. The *Building Code Requirements for Structural Concrete and Commentary* (2011), also known as the ACI 318-11, is used to design reinforced concrete slabs in the United States. The ACI 318-11 uses ultimate strength design.

Slab Type

As mentioned, two types of solid slabs are in existence: one-way and two-way. One-way slab design is far simpler than two-way slab design, but one-way slabs have shorter span limits which can limit their utility. One-way slabs depend on the use of intermediate beams for support. Since two-way slabs can be designed without intermediate beams, building design can necessitate the use of two-way slabs in order to minimize floor-to-floor height by avoiding beam usage. Determining the type of slab to design is one of the early decisions to be made in the solid slab design process.

The decision to use a flat plate or flat slab is based on a number of considerations. First, in order to use a two-way slab of any type the bays (the area between columns) must be relatively square as the ratio of the length of the long side to the length of the short side must be less than 2. In addition to considering the span ratio, the length of the span must be considered. Flat plates and flat slabs are most economical for spans between 15 feet and 35 feet (4.6m and 10.7m). For spans over 35 feet (10.7m), the slab must be several inches thick and it is often more economical for the design to incorporate beams and girders and use a thinner slab. If the span ratio and span length fall within the acceptable limits, the next design decision is whether to use a flat plate system or a flat slab system. As mentioned, flat plate slabs have uniform thickness but flat slabs do not. A flat slab usually has a thickness across most of the slab that is adequate to resist deflection and beam shear, which is discussed later in this chapter, while a drop panel is used near the column that adds thickness to the slab at that location to resist punching shear, which is also discussed later in this chapter. Columns with smaller bays have lower punching shear loads than columns with larger bays under the same superimposed load. Therefore, smaller bays are less likely to need additional thickness to resist punching shear, allowing flat plate systems to be used. Flat plates can be used for larger bays, but it may be more economical to incorporate a drop panel rather than increasing the slab thickness across the entire bay.

Slab Thickness

Once a slab type has been chosen, preliminary slab thickness must be calculated. The ACI 318-11 provides minimum thickness requirements (see table 9.5c and section 9.5 in the ACI 318-11) based on slab span, the location considered (end spans or interior spans), and the type of intermediate support, if any. Engineering judgment can be used to select a larger thickness, but these minimum values from the ACI 318-11 provide a starting point for design. The minimum thicknesses from table 9.5c in the ACI 318-11 have been developed over time and slabs conforming to these thickness limits have not resulted in systematic problems related to stiffness (ACI 318-11). Slab thickness is generally kept uniform across an entire floor for a flat plate system, so the largest minimum thickness is usually used for each condition. However, thicknesses can be changed if needed or desired. The thickness of flat slab systems can be initially designed by table 9.5c in the ACI 318-11, while the thickness at the drop panel will be selected to resist punching shear, which is discussed in the following section. The minimum thicknesses from section 9.5 of the ACI 318-11 also represent the minimum thicknesses needed to meet deflection criteria.

Shear

Two possible shear mechanisms can occur in flat plats, one-way or beam shear, and two-way or punching shear. Beam shear, one-way shear, is the result of load applied to the slab between supports. This type of shear is present in both one-way and two-way slabs. Punching shear, two-way shear, occurs around columns as a result of the large reaction force at the column and it involves a truncated cone surface around the column. Punching shear tends to govern the design for two-way slabs since those types of slabs are supported directly at the column (Wight & MacGregor, 2009).

Beam shear strength of a slab is calculated according to ACI 318-11 equation 11-3:

$$V_c = 2\lambda\sqrt{f'_c}b_w d. \text{ (Equation 2-1)}$$

The variable b_w represents the width of the shear section being considered and is generally taken as being equal to one foot since this strength is usually calculated on a per foot basis. The variable λ is the lightweight concrete factor from section 8.6 of the ACI 318-11 and accounts for the lower shear strength of lightweight concrete, while f'_c is the 28-day specified concrete compressive strength. These two values can be changed if needed, but they are generally chosen at the beginning of the design process and are constant throughout the design. The last variable to determine is *d*, the depth from the extreme fiber in compression to the centroid of tension reinforcement. The value of *d* is directly related to overall slab depth. As a result, changes in the slab depth change the value of *d*. In general, it is desirable to avoid adding reinforcement for beam shear resistance, so if the shear strength is too low using the value of *d* achieved from the assumed slab depth in the previous design step, the slab depth will be increased until an adequate value of *d* is reached.

Two-way slabs must consider punching shear when the slab is not supported by beams but instead is directly supported by the column. This shear force does not act on the entire slab, but on an area surrounding the column called the critical section. This critical section extends a length equal to *d*/2 to all sides of the column. The shear acts on a 45 degree line from the portion of column at the bottom of the slab to the top of the slab, leading to the *d*/2 influence area. In cases where no shear reinforcement is provided, three equations are available for the shear strength of the slab are noted in the ACI 318-11. ACI 318-11 equations 11-31 through 11-33 are the following:

$$V_c = (2 + \frac{4}{\beta})\lambda\sqrt{f'_c}b_0 d \text{ (Equation 2-2)}$$

$$V_c = (\frac{\alpha_s d}{b_0} + 2)\lambda\sqrt{f'_c}b_0 d \text{ (Equation 2-3)}$$

$$V_c = 4\lambda\sqrt{f'_c}b_0 d \text{ (Equation 2-4)}$$

The smallest value from the three equations is the value used for the shear strength of the concrete. The values for λ, d, and f'_c are the same as those for beam shear. The factor β is the ratio of the long side of the column to the short side of the column so that square columns have the highest shear strength. The factor b_o is the perimeter of the critical shear section that extends *d*/2 past the column face in all directions. The factor α_s is varies depending on the location of the column in the building. Interior columns have an α_s value of 40 while edge columns have a value of 30 and corner columns have a value of 20. This indicates that interior columns have higher shear strength than edge columns or corner columns. Larger critical section perimeters will have higher shear strength. The shear strength of the slab must be greater than the punching shear force at the column. Essentially, the shear strength is largely dependent on overall slab depth. If the section is not strong enough, the decision must be made to either increase the slab depth, add shear reinforcement, or a combination of those two options. In some cases, a drop panel is used, which increases slab depth near the critical section but keeps the slab depth smaller throughout the rest of the building. Shear reinforcement is another option to increase shear strength. Reinforcement for punching shear involves extending reinforcement bars from the slab across the critical section into the column.

Moment

Flexural reinforcement for two-way slab systems can be determined by following one of two different methods presented in Chapter 13 of the ACI 318-11. The Direct Design Method was used to perform the parametric study in Chapter 7 of this report and is discussed in this section. The Equivalent Frame Method can also be used to design flexural reinforcement.

The first step for designing flexural reinforcement is to find the total static moment for the span by following equation 13-4 in the ACI 318-11 which is as follows:

$$M_0 = q_u l_2 l_n^2 / 8 \text{ (Equation 2-5)}$$

The variable q_u is the load on the slab. The variable l_2 is the transverse span while l_n is the clear span in the direction the moment is being determined. After determining the total static moment, negative and positive factored moments are determined according to section 13.6.3 of the ACI 318-11. The magnitude of the negative and positive factored moments will vary depending on if the span being considered is an end span or an interior span as well as whether any support beams are used.

After determining positive and negative moments, column and middle strips must be located. Column strips are portions of the slab within a distance of half the slab span of the column, and middle strips are areas between the column strips. The moments are then factored based on the location (column or middle strip) as well as the ratio of the long-to-short span of slab and the beam-to-slab stiffness ratio if beams are used. Sections 13.6.4 and 13.6.6 of the ACI 318-11 provide the moment adjustments for column and middle strips respectively. After the moments are factored based on location, the reinforcement can be calculated.

Flexural reinforcement for positive moment regions is placed in the bottom portion of the slab and, for negative moment regions, is placed in the top portion of the slab. The amount of reinforcement needed to resist flexure is dependent on the amount of moment that will occur in the slab, the depth at which the reinforcement is placed, and the strength of the concrete and reinforcing steel. The ACI 318-11 specifies minimum amounts of reinforcement and maximum spacing that can be used for flexural reinforcement. In some cases, the amount of reinforcement needed for achieving the required flexural strength is less than the minimum specified in ACI 318-11, so the code minimums must be used instead.

Chapter 3 - Voided Slabs and Historical Applications

Voided slabs attempt to utilize the positive aspects of concrete slab construction while minimizing the negative attributes of solid slabs by lightening the self-weight of the structure. This section discusses the concept of voided slab construction and reviews a number of historical applications of voided slabs.

Voided Slab Construction

Voided slab construction removes concrete in locations of the slab that are less critical to resist the applied loads. Removing concrete from the slab interior while maintaining overall depth of the section allows for comparable utility in most applications as the section modulus and stiffness are roughly equivalent to a solid slab, but the self-weight of the section is greatly reduced. This reduction has many benefits.

Historical Applications of Voided Slabs

Voided slabs are not a new construction method. Variations of voided slabs have been utilized for centuries. Though voided slabs principles were used centuries ago, many different types of voided slab systems were developed in the 1900s. This section briefly introduces and reviews various voided slab systems that were commonly used prior to modern construction.

The Pantheon

One of the oldest and most well-known uses of voided slabs occurred in ancient Rome when the Pantheon utilized voided slab concepts in its spectacular dome. The dome consists of numerous coffers which are voids on one side of the slab, often referred to as a waffle slab. The coffers remove material, thus reducing the overall weight of the slab. This concept is a key factor in the longevity of the Pantheon dome. The dome has a diameter of 142 feet (43.3m) but was constructed of concrete without reinforcement, making it highly susceptible to cracking (Gibson, 2012). Since the dome is inherently weak, it must be as light as possible to ensure it can support its own weight. Voids on the interior side of the dome allow for the reduced weight necessary for proper functioning of the dome. Since construction of the Pantheon, waffle slabs have been used on countless buildings for decorative purposes and structural considerations.

Miller Precast System

An early type of precast hollow floor system was developed in 1929 by the Precast Floors Corporation of New York. The system was called the Miller Precast System. The Miller System consisted of 6-, 8-, or 10-inch (15cm, 20cm, or 25cm) deep by 12-inch (30.5cm) wide sections of concrete that were hollow in the middle (Stuart, 2008). The precast units were shipped in three segments that were aligned and supported on temporary shoring on site. The center segment came in standard lengths, while the end segments were constructed in custom lengths to allow for each specific location. Reinforcement was contained in the top and bottom portion of each segment and protruded out each end to be cast together after placement was finalized. A field-cast topping was applied to the units to contain additional reinforcement and provide continuity across beams. The Miller System was able to span larger distances than conventional one-way slabs because of its lower self-weight. Figure 3-1 shows a section through a Miller system unit, while Figure 3-2 shows an isometric of Miller system units prior to being joined.

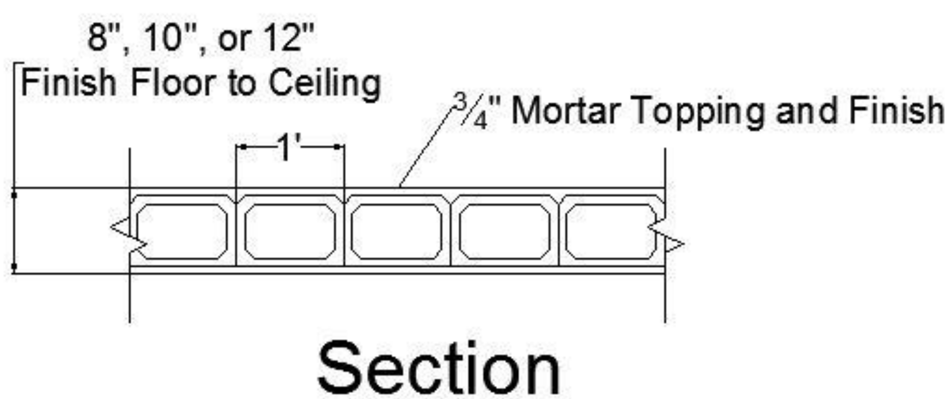

Figure 3-1: Miller System Section

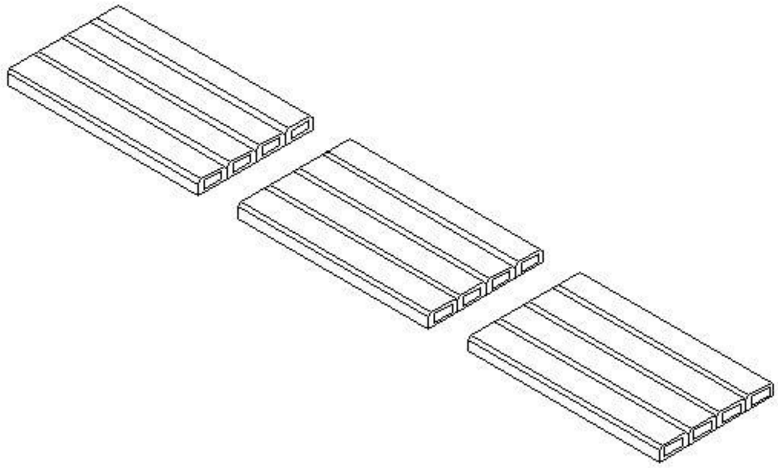

Figure 3-2: Miller System

Porete Floor System

The Porete Floor System was similar to the Miller System, consisting of hollow formed precast sections ranging from 4 to 6 feet (1.2m to 1.8m) in length (Stuart, 2008). Multiple sections could be combined into one long section by adding reinforcement in the topping slab. The Porete System could span 10 to 25 feet (3m to 7.6m) after temporary formwork was removed.

Pyrobar Precast Roof System

A third system, called the Pyrobar Precast Roof System, offered 4- to 6-inch (10cm to 15cm) deep hollow-core sections with widths of 12- to 18-inches (30cm to 45cm) and lengths of up to 6.5 feet (2m) that could be combined to form longer members (Stuart, 2008). The leading component all three systems was voids in the slab. The lighter self-weight allowed for long spans, while overall depth of the units allowed for necessary strength.

F&A System

Another type of voided slab system, referred to as the F&A System, was utilized in the 1950s. The F&A System combined precast concrete T-joists, hollow concrete blocks, and concrete topping to form a slab with high strength but low weight (Stuart, 2008). Hollow concrete blocks spanned between the T-joists were inverted so that the blocks could rest on the joists. Concrete was then poured on top of the assembly and acted compositely with the joists. This system could achieve high enough strength to resist floor loads of up to 900 pounds per square foot (43kPa) for short spans. The hollow blocks kept the system much lighter weight than solid concrete slabs for the same type of loading. Figure 3-3 shows a section through an F & A system.

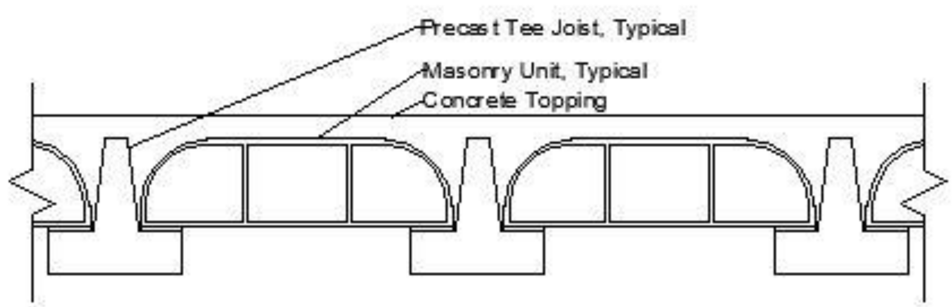

Figure 3-3: F&A System

Chapter 4 - Voided Slabs Using Plastic Voids

Plastic voided slab systems are an alternative to traditional concrete slab construction. Plastic voided slab systems are significantly lighter than solid concrete slabs while maintaining the ability to have large spans. Slabs are lighter because less concrete is used in voided slab construction than traditional slab construction. This section discusses how plastic voided slabs are constructed and how lighter weight and larger spans affect building design.

Construction

Depending on the manufacturer, plastic voided slab systems are constructed by two primary methods: a filigree method in which part of the system is precast off site, and a method in which the entire system is constructed on site. Both methods use the same three basic components. In both methods, the main component is the plastic void. These voids are often spherical, hollow, and made of recycled plastic. The voids allow the slabs to be lighter than traditional concrete slabs since the voids are nearly weightless and replace concrete in the center of the slab. The next main component is the steel cage. Steel reinforcement is added to resist flexure for the slab, but a cage of thin steel is also used to hold the voids in place, keeping them in the center of the slab. The third main component is the concrete, which surrounds the voids and forms the slab. The concrete ultimately determines slab strength. Though both methods use each of these components, the two methods use different approaches. Various companies have patented plastic voided slab systems using similar but slightly different methods, as will be discussed in this section.

Plastic Voided Slab Systems

Plastic voided slab systems were first introduced in Europe in the 1990s. Since that time, many European companies have patented their own systems. As a result, most uses of plastic voided slabs have occurred in Europe. Two plastic voided slab brands, BubbleDeck and Cobiax, have also been utilized in the United States. These two brands are the primary focus of this report, but this section briefly reviews all major brands and the slight differences that exist between them.

BubbleDeck

BubbleDeck is one brand of plastic void system which uses a precast filigree method to form voided slabs. In this method, the voids are assembled in steel cages and then concrete is poured to a height part way up the voids (Nasvik, 2011). The slab panels (filigree) are typically eight feet (2.5m) wide and thirty feet (9m) long. The filigree are then transported to the construction site and lifted in place by crane. Once in place, the top layer of concrete is placed, covering the voids and completing the slab. Wire trusses run between the precast and cast-in-place layers of concrete to ensure that the two layers bond properly.

Cobiax

Cobiax is another major brand of plastic void system. As compared to the BubbleDeck filigree system, Cobiax systems are an on-site application. When using Cobiax, workers first must use deck forms to form the bottom of the slab (Nasvik, 2011), and the bottom layer of reinforcing steel must also be placed. The voids arrive at the site bundled in steel wire cages which can be altered to fit the particular application, but the void bundles are secured to the reinforcement steel. After the bundles are in place, the top layer of reinforcement can be placed. Concrete is then placed in two lifts. Similar to the filigree method, the first lift covers the bottom reinforcement and a portion of the voids and holds the voids in place as the concrete becomes stiff. The second lift is poured after the first lift is stiff but still fresh, finishing the slab. This method requires more formwork and on-site labor than the BubbleDeck filigree method, but requires less transportation of materials.

U-Boot Beton

U-Boot Beton, or U-boot, is a voided slab system from the Italian company Daliform. U-boot does not use spherical void formers like previous systems, but uses truncated-pyramid shaped void formers instead. These void formers create many “I” shaped beams making up the slab (U-boot Beton, 2011). The U-boot system is similar to the Cobiax system in terms of construction because it is meant to be cast entirely on-site using formwork. After forms are erected, the steel and void formers are placed before the concrete is poured in two lifts. In addition to the many design benefits that all voided slab systems provide, the U-boot system has one benefit over systems that use spherical void formers the shape of the U-boot void formers allows them to be stacked efficiently during transportation to the site, saving space and potentially leading to reduced shipping costs compared to spherical former systems.

Effect on Design

As mentioned, plastic voided slabs are lightweight when compared to traditional slab construction. Plastic voided slab systems can reduce the dead load of slabs by as much as 35% when compared to solid slab construction with the same capacity (Mota, 2009). Lighter slabs affect many aspects of structural design, such as floor span, floor-to-floor height, column reinforcement and size, seismic effects, and sustainability.

By eliminating unnecessary concrete and reducing floor weight, voided slabs are able to achieve longer spans than traditional slabs. The ability to achieve longer spans allows for more design flexibility as fewer columns are required, leading to more beneficial open space. For example, more open space in retail construction means more display space. Plastic voided slabs have been used in Europe to achieve floor spans of over 50 feet (15.2m) in office buildings (Nasvik, 2011).

Typically, voided slab systems are thicker than solid slabs with the same capacity, but voided slab systems usually do not require beam supports. The cumulative height of beams and solid slabs is generally more than the height of voided slabs, meaning that the utilization of a voided slab can allow for reduced floor-to-floor heights. Smaller floor-to-floor heights impact many parts of a building, including exterior cladding and HVAC equipment (Nasvik, 2011). As a result, reduced floor-to-floor heights can lead to significant savings in some applications.

Lighter floor slabs also have a large effect on column size and reinforcement. Lighter floors mean smaller columns are able to be used as well as less reinforcing steel. Smaller columns can also lead to a large reduction in the overall amount of concrete and steel used in the entire building, consequently allowing for large savings in structural costs. In some cases, column dimensions have been reduced as much as 40% through the use of plastic voided slabs.

One of the biggest advantages of voided slabs is seismic performance. Weight is a leading factor in determining how much seismic force acts on a building during an earthquake. Reducing the weight of the slabs can lead to a large reduction in the overall seismic force induced in the building (Mota, 2009). Less seismic force leads to smaller components in the lateral force resisting system, allowing for greater savings in structural costs.

Sustainability is a significant issue in modern construction. The ability to save materials allows a building to have a smaller impact on the environment. Not only does the use of voided slabs contribute to sustainability by saving material, but voided slabs also use many recyclable materials, also contributing to smaller environmental impact. In plastic void construction, the voids are made using recycled plastic and the steel is made using recycled steel. If desired, the concrete can even be made using recycled aggregate. All these different aspects lead to a high degree of sustainability and an environmentally friendly design (Mota, 2009).

Chapter 5 - Examples of Plastic Voided Slabs

Plastic voided slabs were first introduced in Europe in the 1990s (Nasvik, 2011). Since their introduction, plastic voided slab systems have had success in European applications but have seen very little use in the United States. This section reviews projects that have used plastic voided slabs and discusses the reasons plastic voided slabs are used rather than a more traditional slab system.

La Bahn Hockey Arena

La Bahn Arena is a hockey arena for the women's hockey team of the University of Wisconsin at Madison. The arena was completed in 2012. An underground walkway connects the arena to the Kohl Center arena adjacent to La Bahn Arena. The roof of the walkway is essentially at ground level (Nasvik, 2011). The walkway runs underneath the street which creates an unusual load requirement for a roof slab. In addition to being able to support landscaping materials, the roof must also be able to support fire trucks driving on the street. In addition to unique loading, the project must be completed in a short time period per owner requirements.

Originally, the project was designed using a cast-in-place roof deck for the walkway. After consulting with BubbleDeck, the design team decided to use a BubbleDeck plastic voided slab system for the walkway roof to better accommodate the project challenges. La Bahn Arena was the first project to utilize BubbleDeck in the United States.

Precast deck panels were placed in less than two days after delivery to site. The panels included the plastic voids, most of the reinforcing, and the bottom layer of concrete. The top layer of concrete was completed a week later. Using BubbleDeck for the walkway allowed for a significantly shorter construction period for the roof deck than a solid concrete slab. It is also estimated that approximately $25,000 was saved on construction costs of the roof deck when compared to original project specifications (BubbleDeck North America, 2012).

Miami Art Museum

Slated for completion in late 2013, the new Miami Art Museum in Miami, Florida will be a 200,000 square foot (18,580m^2) facility featuring hanging gardens and a variety of other spaces. One goal for the architect was to provide an open-air structure with panoramic views, thus limiting the number of required columns. The project required a minimum of 2½ inches (6.5cm) of concrete cover over the slab reinforcement to protect against corrosion from salt spray from buildings in close proximity to Miami harbor. This cover requirement added a significant amount of dead load to the structure compared to slabs with normal cover.

In order to meet the project goals, the design team decided to utilize a Cobiax plastic voided slab system. The voided slab is utilized in 105,000 of the 200,000 square feet (9,754m^2 of 18,580m^2) in the building (Nasvik, 2011). This design eliminates nearly 1,000 cubic yards (765m^3) of concrete from the project and reduces the dead load of the building by nearly 4 million pounds (18,000kN). Voided slab construction was able to offset the effects of the additional weight of 2½ inches (6.5cm) of cover and allow for a minimal amount of columns compared to traditional slab construction. Figure 5-1 shows an aerial image of the museum during construction.

Figure 5-1: Miami Art Museum (Cobiax USA, 2013)

York University Life Science Building

York University in York, Ontario completed a new Life Science building in June 2012. The building is a 160,000 square foot (14,865m^2), four-story building that includes lecture halls, classrooms, offices, and secure laboratories for biology research. The building structure is comprised of reinforced concrete columns, flat plate slabs, and shear walls. Lecture hall bays include spans over 30 feet (9m) (Blackwell Bowick, 2012).

The use of solid flat slabs for the floor plates in the building necessitated the use of drop beams, creating unwanted increases in floor-to-floor heights. The decision was made to utilize a BubbleDeck plastic voided slab system, meaning that the beams would no longer be needed and the floor-to-floor heights could remain at a desired level. Replacing solid slabs with the voided slab system also allowed for smaller columns and foundations, as well as significantly reducing seismic forces for the building (BubbleDeck North America, 2012). BubbleDeck voided slabs also allowed the construction schedule to move at a faster pace for this project by reducing the time for slab construction.

Abuja, Nigeria Tower Hotel

In 2006, construction began on the Abuja Tower Hotel in Abuja, Nigeria. The tower consists of 22 floors that include a hotel, shopping areas, and restaurants. The plan consists of staggered rings spiraling up with an open center (Tower hotel, 2013). The architect and owner desired to have an open plan to allow for maximum use of the space. The U-Boot Beton system was used for the tower to lighten the slab, allow for minimal column use, and open the floor plan dramatically by allowing longer spans as compared to a solid slab system (U-boot Beton, 2011).

UEFA Headquarters

In early 2009, construction began on the new headquarters building for the Union of European Football Association (UEFA) in Nyon, Switzerland. A two-story parking garage was constructed adjacent to the office building. The building is circular in shape, with an opening in the middle consisting of a central courtyard, making the building’s overall shape similar to a doughnut. Glass curtain walls make up the exterior walls and courtyard walls. The architect wished to use no interior columns to allow for an open work space while also wanting to minimize columns along the exterior walls to maximize visibility through the curtain walls.

The span from curtain wall to curtain wall is 50 feet (15.2m), a difficult span for traditional concrete slabs. The structural engineer chose instead to use a plastic voided slab system to achieve the needed span. The Cobiax system was selected for use on the project, with a variety of overall slab depths. Overall depths range from 16 inches (40.6cm) to 24 inches (61cm). While these are considerable depths, no intermediate support beams were needed to support the slab, meaning the structure actually occupies less overall room than most comparable structures using more traditional construction. Building images with the slab still exposed are stunning because the only structural members present are two distant columns along the outer and inner walls with a long, flat span of slab running in between. Figure 5-2 shows an interior view with the slabs still exposed. Cobiax was also used in construction of the parking garage. The goal in the parking garage was to minimize the number of columns needed to support the deck to allow for the maximum number of parking spaces (*Cobiax Insight*, 2010). Figure 5-3 shows an aerial view of the headquarters building during construction while Figure 5-4 shows a rendering of the headquarters building.

Figure 5-2: UEFA Headquarters Interior (*Cobiax Insight*, 2010)

Figure 5-3: UEFA Headquarters Aerial (*Cobiax Insight*, 2010)

Figure 5-4: UEFA Headquarters Rendering (*Cobiax Insight*, 2010)

Palazzo Lombardia Headquarters

Began in 2008 and completed in 2010, the new administration building for the region of Lombardy, Italy is a 39-story, 530-foot (162m) skyscraper in Milan, Italy. Milan is located in northern Italy, which is an earthquake prone region. As such, buildings in this region require careful consideration of seismic effects. One of the most significant aspects of seismic effects is the building weight. In order to reduce the weight of the building, engineers for the Palazzo Lombardia considered the use of plastic voided slabs.

The switch from traditional slab construction to the Cobiax plastic voided slab system selected for construction contributed to a variety of savings in the building. The primary concern of weight reduction was achieved. Over 100,000 cubic feet (2830m^3) of concrete were saved, translating to a weight savings of over 15,000,000 pounds (66,700kN). Many beams were eliminated from the design as well, allowing for shorter floor-to-floor heights and reduction of the height of the building by nearly 22 feet (6.7m). This significant reduction in height created large savings for the overall project since large amounts of material were removed from the design, such as cladding and interior finishes. As a result of the design change, the amount of concrete used in the building was reduced by approximately 30 percent and the amount of steel used was reduced by approximately 10 percent (*Cobiax Insight*, 2010). Figure 5-5 shows an image of the building during construction where several floors are still exposed.

Figure 5-5: Palazzo Lombardia During Construction (*Cobiax Insight*, 2010)

Chapter 6 - Plastic Voided Slab Design

This section examines the design process for plastic voided slabs.

Development of Plastic Voided Slab Design

Though voided slab concepts have been common since the mid-1900s and have existed for well over a thousand years, plastic voided slab design is still very much in its infancy. The process used for designing plastic voided slabs can vary greatly on a case-by-case basis as well as variations based on what brand and type of voided slab system are used.

Plastic voided slabs have not yet been accommodated into the International Building Code, IBC, or any design standards in the United States. Without any code guidelines, engineers must exhaustively prove to building officials and building owners that the plastic voided slab can satisfy necessary strength and serviceability limits. As a primarily concrete system, plastic voided slabs must meet the requirements of the IBC 2012 and ACI 318-11 as well as further requirements for local building authorities. Having only completed a small number of projects in the United States, companies such as BubbleDeck and Cobiax are still developing design guidelines that follow United States codes and standards, listing out the process and steps to take in the design as well as which formulas to use and any necessary modifications. The design process described in the following sections is adapted primarily from the *BubbleDeck Design Guide for compliance with BCA using AS3600 and EC2 (2008)*. This document is the design guide for using BubbleDeck plastic voided slab systems in Australia and references AS3600 (the Australian concrete code) as well as the Eurocode. Formulas shown in this report have been modified as necessary to incorporate English units rather than metric units provided in the design guide.

The BubbleDeck Design Guide (2008) follows Eurocode 2 which uses ultimate limit state design which is the same as the ultimate strength design referred to by the ACI 318-11. This means that the final results for a plastic voided slab can be compared to a solid slab as well as being able to compare intermediate steps, including the design forces.

The design process for plastic voided slab systems involves determining the necessary slab thickness as well as providing adequate shear and bending strength. Adjustments must be made to allow for the use of solid slab structural analysis methods.

Fire rating for plastic voided slabs is very similar to solid slabs. Typical minimum coverage of 1” (2.5cm) can achieve a 2-hour fire rating for the slab. Actual values for deflection are also calculated similarly to solid slab, using the modified moment of inertia which is discussed in this chapter.

Structural Analysis

Plastic voided slabs using spherical void formers behave isotropically, meaning their properties are the same in all directions, allowing for the same methods of structural analysis used for traditional, solid two-way slabs. Slight adjustments must be made to a few variables from solid slab design, but the overall concept is the same for both solid slab and plastic voided slab design.

Moment of Inertia

The second moment of area, or moment of inertia, is a key variable when performing structural analysis of a slab. The uncracked moment of inertia, often represented by the symbol I, is dependent upon the width and thickness of a slab and ignores the contribution made by reinforcing steel since the steel is not engaged prior to cracking. For solid slabs, the moment of inertia prior to section cracking can be calculated using the following formula:

$$I_{solid} = bt^3/12 \text{ (Equation 6-1)}$$

$$b = width\ of\ section\ being\ analyzed$$

$$t = thickness\ of\ section\ being\ analyzed$$

Plastic voided slabs perform similarly to solid slabs. In order to calculate capacity, the equivalent solid slab properties must be calculated. The uncracked moment of inertia for plastic voided slabs:

$$I_{PVS,conc} = \frac{D^3}{12} - 0.124a^3 \text{ (Equation 6-2)}$$

The overall thickness of the slab is represented by the variable *D*, while the distance from the center of one void to the center of a solid section is represented by the variable a. Figure 6-1 provides a visual for the two variables used in the equation. After determining the moment of inertia for the concrete, the uncracked moment of inertia of the section can be determined. The uncracked moment of inertia can be attained through the following formula:

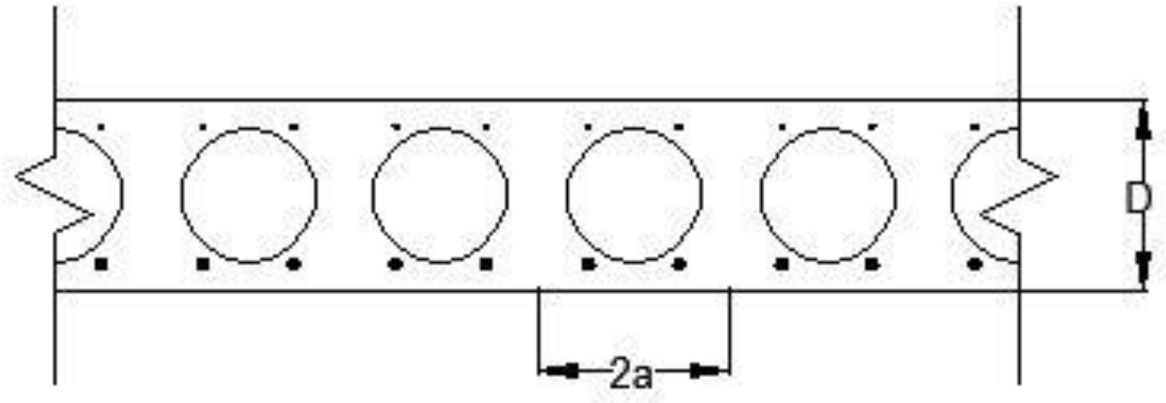

Figure 6-1: Basic Voided Slab Geometry

$$I_{PVS,uncracked} = I_{PVS,conc} + I_{eq,steel} + A_{eq,steel}(\frac{D}{2} - d_{eq,steel})^2 \text{ (Equation 6-3)}$$

The moment of inertia of the steel is dependent on the size and number of reinforcing bars used in the section. The variable $d_{eq,steel}$ is the depth of the reinforcing bars. When the distance between the reinforcement and the centroid of the section is larger, the contribution from the steel to the moment of inertia of the section will be larger.

The moment of inertia represents the stiffness of a section. Results of the previous equations show that the stiffness of a plastic voided slab is roughly 90 percent the stiffness of a solid slab with the same overall thickness, despite the utilization of far less concrete.

Manufacturer's testing has shown that voids play a lesser role in cracked sections than in uncracked sections. For cracked sections, the moment of inertia for a plastic voided slab can be conservatively taken as 90 percent of the moment of inertia of a solid slab of equal thickness, represented by the following formula:

$$I_{PVS,cracked} = 0.9\ I_{solid,cracked} \text{ (Equation 6-4)}$$

Moment Analysis

After attaining the uncracked and cracked moments of inertia for the plastic voided slab, further analysis can be performed. One of the first steps in determining moment capacity is to find the cracking moment of the section. The cracking moment is the flexural limit at which cracks first develop in the section. Prior to cracking, the moment capacity of the section is dependent primarily on the concrete. After cracking, the steel reinforcement resists internal tension and contributes to the moment capacity of the section.

The cracking moment for solid concrete sections is determined by equation 9-9 from the ACI 318-11:

$$M_{cr} = f_r I_g / y_t \text{ (Equation 6-5)}$$

The variable f_r represents the modulus of rupture of the section. The variable I_g is the gross moment of inertia of the section. The distance from the centroid of the section to the extreme fiber in tension is represented by the variable y_t. The modulus of rupture can be calculated by equation 9-10 from the ACI 318-11:

$$f_r = 7.5\lambda\sqrt{f'_c} \text{ (Equation 6-6)}$$

Where λ is the factor used for lightweight concrete and f'_c is the compressive strength of the concrete, as mentioned.

The cracking moment for plastic voided slabs is calculated in a similar fashion to the method for solid slabs, but with a few modifications. The formula used is shown below:

$$M_{PVS,cr} = 0.8\left[\frac{I_{BD,uncracked}}{y_t}\right] f_r \text{ (Equation 6-7)}$$

The formula shows that the modified moment of inertia is utilized rather than the gross moment of inertia used for solid sections. In addition to the modified moment of inertia, the cracking moment is also reduced by twenty percent, as shown by the coefficient 0.8.

After the cracking moment and the cracked and uncracked moments of inertia have been determined, the effective moment of inertia can be calculated. The effective moment of inertia is used to determine the stiffness of the slab. The formula for calculating the effective moment of inertia is shown below:

$$I_{PVS,ef} = I_{PVS,cracked} + (I_{PVS,uncracked} - I_{PVS,cracked})\left(\frac{M_{PVS,cr}}{M_a}\right)^3 \text{ (Equation 6-8)}$$

The effective moment of inertia cannot be greater than the uncracked moment of inertia. The variable M_a represents the moment applied to the section. This formula is the same formula seen in Equation 9-8 in the ACI 318-11, with the exception that modified cracked and uncracked moments of inertia are used for the plastic voided slab.

Once the effective moment of inertia has been calculated, structural analysis can be performed in the same manner as traditional slabs. Hand calculations or computer analysis can be used with the simple substitution of the modified effective moment of inertia.

Strength Calculations

After performing the structural analysis, determining the shears and moments, the actual strength of the section must be calculated and compared to structural analysis results. Ultimate strength in bending must be calculated along with shear ultimate strength and serviceability checks. If any of these calculations indicate that the section is not adequate due to the depth of the slab, the section will need to be changed and the structural analysis must be redone with the new section properties and compared to updated strength calculations. Figure 6-2 shows the location of the neutral axis and the compression and tension zones of the slab system for a typical load pattern.

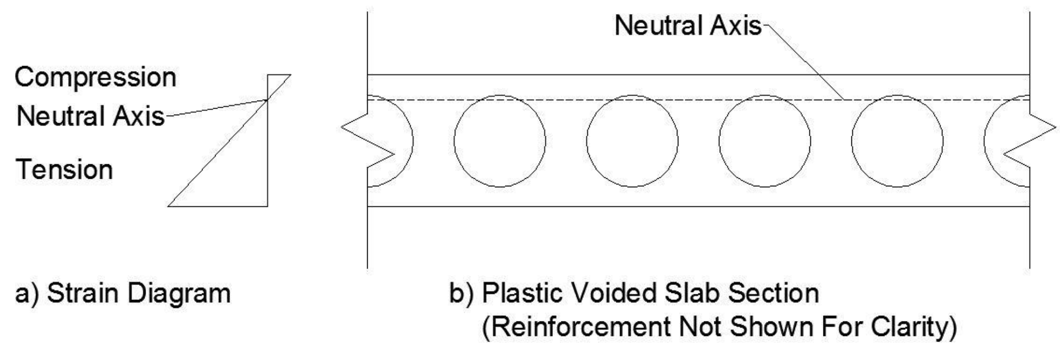

Figure 6-2: Compression and Tension Zones in a Plastic Voided Slab

Bending Strength

Manufacturer's testing on plastic voided slab sections has shown that, in most cases, the compression block for slab sections in bending is confined to the solid slab portion at the top of the section. In high loading conditions, the stress block has been shown to partially enter the void zone, but tests indicate that the effect of this is insignificant in all but the most extreme circumstances. The ratio of total amount of moment resisted by the void region to the total amount of moment resisted by the whole section is represented by the variable μ_{ms}. When this ratio is less than 0.2, moment stresses are able to redistribute within the section and conventional design principles can be used to determine bending strength of the slab. The ratio μ_{ms} is calculated as follows:

$$\mu_{ms} = M_u 1.96D/(f'_c h^3) \text{ (Equation 6-9)}$$

D is the void diameter and h is the overall depth of the slab. M_u is the design moment on the slab which can be attained from structural analysis. After determining the moment ratio, the maximum depth of the neutral axis, which is also the maximum depth of the compression stress block, can be calculated using the following equation:

$$\mu_{ms} = [(d_n - c_{void})z_{void}]/(d_n z) \text{ (Equation 6-10)}$$

The variable c_{void} is the cover on top of the plastic void. The distance from the center of the bottom layer of flexural steel to the center of the top solid section of concrete is represented by the variable z. The variable z_{void} represents the distance from the bottom layer of flexural steel to the top of the plastic void. The depth of the neutral axis is represented by the variable d_n. These variables are shown in Figure 6-3. Provided the moment ratio is less than 0.2, strength calculations for traditional slabs can be used with the substitution of the modified moment of inertia and depth to the neutral axis.

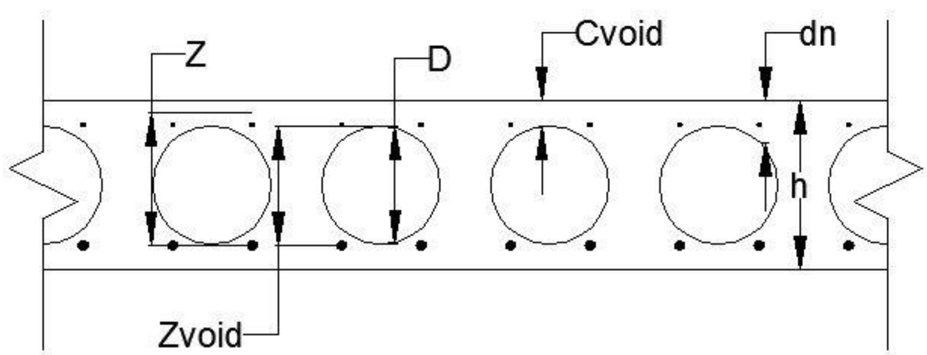

Figure 6-3: Dimensions for a Plastic Voided Slab

Shear Strength

Though ultimate limit state design is used in the Eurocode 2 and for flexural design in the BubbleDeck Design Guide (2008), allowable stress design is used to check shear requirements for plastic voided slabs in the BubbleDeck Design Guide (2008). This means that shear forces must be calculated from structural analysis using service loads. If factored loads are used, the forces used for shear design will be incorrect.

As mentioned, plastic voided slabs are not recommended for areas of high punching shear, such as areas around columns or areas with high concentrated loads. The recommendation is often made to remove voids around columns to make the slab solid. Punching shear for slabs with plastic voids should be limited by the following equations:

$$v_{Ed} < v_{Rd,max} \text{ (Equation 6-11)}$$

$$v_{Ed} = \frac{V_{max}}{u_{col} d_{om}} = shear\ stress\ along\ column\ perimeter \text{ (Equation 6-12)}$$

Where:

$$u_{col} = column\ perimeter$$

$$d_{om} = \frac{d_x + d_y}{2} = mean\ effective\ depth\ of\ the\ slab \text{ (Equation 6-13)}$$

$$d_x, d_y = slab\ depth\ in\ the\ x\ and\ y\ direction\ from\ the\ column$$

And:

$$v_{Rd,max} = .5 v f_{cd} = maximum\ allowable\ shear\ stress\ in\ the\ section \text{ (Equation 6-14)}$$

$$v = 0.6/[1 - \left(\frac{f'_c}{36260}\right)] \text{ (Equation 6-15)}$$

$$f_{cd} = f'_c/1.5 \text{ (Equation 6-16)}$$

Areas around columns where the above limitations cannot be met should be made solid and checked for punching shear by the ACI 318-11 equations for solid slabs. Per the BubbleDeck design guide (2008), maximum allowable stress in solid slabs is determined by the following equations:

$$v_{Rd,c} = 0.63k(100\rho_l f'_c)^{1/3} \geq v_{min} \text{ (Equation 6-17)}$$

$$k = 1 + (\frac{200}{d_{om}})^{1/2} \leq 2.0 \text{ (Equation 6-18)}$$

$$\rho_l = (\rho_{lx}\rho_{ly})^{1/2} \leq 0.02 \text{ (Equation 6-19)}$$

$$\rho_{lx},\ \rho_{ly} = tension\ steel\ reinforcement\ ratio\ of\ the\ column\ in\ the\ x\ and\ y\ directions$$

$$v_{min} = 0.426k^{3/2} {f'_c}^{1/2} \text{ (Equation 6-20)}$$

The maximum allowable shear stress in the voided regions of the slab is determined by the following equation:

$$v_{PVS\ Rd,c} = 0.6 v_{Rd,c} \text{ (Equation 6-21)}$$

Using the above equations, the perimeter of the solid region of the slab can be determined using the following equation:

$$u_{solid} = V_{max}/(v_{PVS\ Rd,c} d_{om}) \text{ (Equation 6-22)}$$

To find the distance from the face of the column to the minimum extent of solid slab, u_{solid} from the above equation should be equated to the following equation:

$$u = 2\pi a + 2(bx + by) \text{ (Equation 6-23)}$$

$$bx, by = column\ dimensions\ in\ the\ x\ and\ y\ direction$$

Setting equation 6-22 and equation 6-23 equal will yield the value for a, the distance between the column face and the solid slab perimeter.

After the extent of the solid slab area has been determined, the perimeter over which the column tension steel must extend must be determined. The steel must extend partially into the voided region of the slab to allow for proper action across the solid-voided interface. The first step to determine this perimeter is to evaluate the shear capacity of the voided slab including only the capacity added by the top reinforcement. The following equations are used to determine this capacity.

$$v_{PVStypRd,c} = 0.6v_{typRd,c} \text{ (Equation 6-24)}$$

$$v_{typRd,c} = v_{Rd,c}\ using\ \rho_{lx}\ and\ \rho_{ly}\ for\ top\ mat\ steel\ only$$

After determining the shear capacity of the voided slab, the tension steel perimeter can be determined using the following equation:

$$u_{steel} = V_{max}/(v_{PVStypRd,c}d) \text{ (Equation 6-25)}$$

The perimeter u_{steel} is the minimum distance the column tension steel must extend to ensure proper action across the solid-voided slab interface.

Chapter 7 - Parametric Study

This chapter discusses parameters of the parametric study by first giving an overview of the slabs included in the study, results from the study, and general conclusions.

Parametric Study Overview

Though plastic voided slabs can be compared to conventional one-way slabs, plastic voided slabs are most efficient when designed similar to two-way slabs without support beams. For this reason, the parametric study compares interior bays of a flat plate system to interior bays of a plastic voided slab system. The primary goal of the study was to compare the relative weight of a plastic voided slab to the relative weight of a flat plate.

Many parameters must be considered when designing a concrete slab. For a comprehensive comparison between two-way slabs and plastic voided slabs, a study must consider not only different bay sizes, but also span conditions and different weights and strengths of concrete. However, the purpose of this study was to provide a quick, illustrative comparison between flat plate slabs and plastic voided slabs. As a result, the two slab systems were compared by designing each for four different bay sizes. The four bay sizes are 20 feet by 20 feet (6m by 6m), 25 feet by 25 feet (7.6m by 7.6m), 30 feet by 30 feet (9m by 9m), and 35 feet by 35 feet (10.7m by 10.7m).

Each bay was designed as an interior span with no support beams which is typical for flat plates. An interior span was chosen since the majority of the structure is an interior span condition for buildings. In addition, each side of the bay will behave similarly. The specified 28-day compressive strength of the concrete used for the study is 4000 pounds per square inch (27,580kPa) and the yield strength of the reinforcing steel is 60,000 pounds per square inch (413,685kPa). Square columns with 16-inch (40.6cm) dimensions are used for all bays. Superimposed loads were also constant across each design. The self-weight for each design varied based on the type and thickness of the slab. A superimposed dead load of 20 pounds per square foot (.96kPa) and a live load of 80 pounds per square foot (3.83kPa) were used to represent loads similar to a generic commercial building.

The flat plates were designed following the method described in Chapter 2. Slab thickness was selected to be the smallest constructible thickness that did not require shear reinforcement and met 2-hour fire ratings. Flexural reinforcement varied across column and middle strips per the ACI 318-11 code.

Plastic voided slabs are designed following the method described in Chapter 6. An attempt was made to match slab thicknesses of the two systems. Sizes of the plastic voids were chosen to be the largest size available that still met strength requirements. Values for plastic voids were selected according to the BubbleDeck Design Guide (2010). The solid slab around the columns is also included in the design.

Parametric Study Results

This section discusses results of the comparison study, including slab thicknesses, flexural reinforcement, bay weight, and solid perimeters.

Slab Thickness

As shown in Table 7-1, the overall thickness of the plastic voided slab matched the thickness of the traditional flat plate. The lone exception is the 20 feet by 20 feet (6m by 6m) bays. The manufacturer information on plastic void formers listed the smallest available void size as a seven-inch (18cm) diameter void. The recommended minimum slab thickness for a seven-inch (18cm) void is 10 inches (25cm), thus requiring the minimum thickness for a plastic voided slab bay for this study to be 10 inches (25cm).

The reason the plastic voided slab bays are designed to the same thickness as the flat plate bays relates to the required moment capacity of the sections. Both types of bays have a similar relative required moment capacity for the same span. The plastic voided slab bays are slightly lighter, requiring less strength, but they also have a slightly lower capacity than solid slabs. Thinner voided slabs could be used, but they require more reinforcement which would eliminate the financial benefit of using the thinner slab.

Span	Slab Type	Overall Depth (inches)	Void Diameter (inches)
20 ft x 20 ft	Traditional Slab	8	-
20 ft x 20 ft	Plastic Voided Slab	10	7
25 ft x 25 ft	Traditional Slab	10	-
25 ft x 25 ft	Plastic Voided Slab	10	7
30 ft x 30 ft	Traditional Slab	12	-
30 ft x 30 ft	Plastic Voided Slab	12	9
35 ft x 35 ft	Traditional Slab	14	-
35 ft x 35 ft	Plastic Voided Slab	14	10.5

Table 7-1: Parametric Study Slab Thicknesses

Reinforcement

Although the primary financial benefit of using a plastic voided slab system rather than using a traditional two-way flat plate slab is the reduced amount of concrete, the amount of steel used for reinforcement is an item that must be considered. A design may reduce the amount of concrete, but if it greatly adds to the amount of reinforcement needed, the cost savings will not be as significant since material and labor costs for the steel will be greater. Therefore, the most important design consideration after slab thickness is the size and amount of reinforcement used in the section. Selections were made by choosing the smallest bar not requiring spacing that was judged to be too close. If a close spacing was required, a larger bar was examined. For a given section, a larger size of reinforcing bar requires the use of fewer bars and allows for wider spacing of the bars. Table 7-2 shows the type and amount of reinforcement that was used for each slab as well as the weight of the reinforcement. The percentage of reinforcement by weight for each plastic voided slab compared to the corresponding flat plate is also shown. Table 7-3 also shows the maximum moment and the moment capacity for each bay, as well as the percent utilization.

For the 20 feet by 20 feet (6m by 6m) bays, number four bars were used for both construction types. The solid slab used 65 bars in each direction with a 12-inch (30.5cm) on center spacing across most of the section (a six-inch (15cm) on center spacing was used across a portion of the column strip). The plastic voided slab design used a 10-inch (25cm) thick slab, compared to eight inches for the solid slab design. The thicker slab had a higher capacity from the concrete, meaning that only approximately half as much steel was required. Only 33 bars were needed for the 10-inch (25cm) plastic voided slab to achieve the required moment capacity.

For the 25 feet by 25 feet (7.6m by 7.6m) bays, both designs had an overall thickness of 10 inches (25cm) and a similar number of bars were used for each design, but the solid slab required the use of larger bars. The solid slab required 70 number 5 bars to reach the needed capacity. The plastic voided slab used 64 bars but was still able to use a number 4 bar size, demonstrating that the lighter slab requires less reinforcement.

The 30 feet by 30 feet (9m by 9m) bays, both 12 inches (30.5cm) thick, used number 6 bars for reinforcement. In this case, the plastic voided slab used only approximately 60 percent as many bars as the solid slab (45 bars compared to 77), again demonstrating that the lighter slab requires less reinforcement.

For the 35 feet by 35 feet (10.7m by 10.7m) bays (each 14 inches or 36cm thick), the plastic voided slab used both a smaller bar (number 6 compared to number 7) as well as a significantly lower number of bars (67 compared to 97). The reason behind the major difference in size and amount of reinforcement is related to the span. Thirty-five feet is a significantly large span for a flat plate, requiring a thick slab that includes a significantly large self-weight. The larger load means that a higher capacity is needed, leading to more reinforcement. On the other hand, a plastic voided slab of the same thickness is much lighter, so the amount of reinforcement is not as substantial.

Span	Slab Type	Number of Bars (each direction)	Weight of Each Bar (plf)	Total Weight (lbs)	% Weight
20 ft x 20 ft	Traditional Slab	65	0.668	1736.8	-
20 ft x 20 ft	Plastic Voided Slab	33	0.668	881.76	51
25 ft x 25 ft	Traditional Slab	70	1.043	3650.5	-
25 ft x 25 ft	Plastic Voided Slab	64	0.668	2137.6	59
30 ft x 30 ft	Traditional Slab	77	1.502	6939.24	-
30 ft x 30 ft	Plastic Voided Slab	45	1.502	4055.4	58
35 ft x 35 ft	Traditional Slab	97	2.044	13878.76	-
35 ft x 35 ft	Plastic Voided Slab	67	1.502	7044.38	51

Table 7-2: Parametric Study Reinforcement

Span	Slab Type	Maximum Moment (kft)	Moment Capacity (kft)	Percent Utilization (%)
20 ft x 20 ft	Traditional Slab	115	125	92
20 ft x 20 ft	Plastic Voided Slab	110	120	92
25 ft x 25 ft	Traditional Slab	263	290	91
25 ft x 25 ft	Plastic Voided Slab	225	240	94
30 ft x 30 ft	Traditional Slab	500	600	83
30 ft x 30 ft	Plastic Voided Slab	420	450	93
35 ft x 35 ft	Traditional Slab	890	972	92
35 ft x 35 ft	Plastic Voided Slab	720	760	95

Table 7-3: Parametric Study Moment Capacity and Percent Utilization

Bay Weight

As shown in Table 7-4, significant weight savings were achieved by the plastic voided slab bays compared to the corresponding flat plate. The weight savings are expected since the majority of each plastic voided slab bay is composed of hollow voids, with solid slab portions surrounding the columns at each bay to resist punching shear that develops at the column. The weight of steel reinforcement is also included for both bay types; therefore, the amount of weight saved is not a simple proportion of weight of the plastic voided slab section to weight of the solid slab section. For spans of 20 feet (6m) and larger, it can be expected that plastic voided slabs have weight savings of greater than 30 percent, as demonstrated in this study.

In addition to being lighter than solid slab bays of the same size, plastic voided slab bays can be lighter than solid slab bays that are smaller than the plastic voided slab bays. Table 7-4 demonstrates this result as the 8-inch (20cm) thick, 20 feet by 20 feet (6m by 6m) solid slab bay has the same weight per area (100 pounds per square foot or 4.8kPa) as the 14-inch (36cm) thick, 35 feet by 35 feet (10.7m by 10.7m) plastic voided slab bay. This is a significant result since fewer columns would be needed to support a slab of similar weight. Using a plastic voided slab bay of the same size and thickness as the solid slab design saves a significant amount of concrete in the slab and a slightly smaller amount of concrete in the columns, while using a larger bay with a slightly larger thickness may not save a significant amount of concrete in the slab but can greatly reduce the overall use of concrete by completely eliminating several columns from the design. This type of solution is more feasible when a large number of bays are used at each story of the building. If only a few bays are used, it may be more feasible to use a similar size lighter bay.

Span	Slab Type	Slab Weight (psf)	Total Bay Weight (lbs)	% Weight
20 ft x 20 ft	Traditional Slab	100	41737	-
20 ft x 20 ft	Plastic Voided Slab	65	28201	68
25 ft x 25 ft	Traditional Slab	125	81776	-
25 ft x 25 ft	Plastic Voided Slab	65	47124	58
30 ft x 30 ft	Traditional Slab	150	141939	-
30 ft x 30 ft	Plastic Voided Slab	85	91558	65
35 ft x 35 ft	Traditional Slab	175	228254	-
35 ft x 35 ft	Plastic Voided Slab	100	151009	66

Table 7-4: Parametric Study Bay Weights

Solid Perimeter

As described, in most applications for plastic voided slabs, the slab must be made solid around columns. Punching shear develops at the column and shear strength of the plastic voided slab is generally not high enough to meet needed capacity. The simple solution is to avoid placing the plastic void formers in a certain perimeter around each column. As part of the parametric study, solid perimeters around columns were examined. Larger bay sizes led to larger tributary areas for columns, thus leading to larger loads on the columns. Larger column loads result in higher punching shear load and, therefore, require higher shear capacity in the slab. Table 7-5 shows that as the span and column load increase, the solid perimeter for plastic voided slabs increases.

Span	Slab Type	Solid Perimeter Around Column (inches)	Distance From Column Face to Solid Boundary (inches)
20 ft x 20 ft	Traditional Slab	-	-
20 ft x 20 ft	Plastic Voided Slab	201	22
25 ft x 25 ft	Traditional Slab	-	-
25 ft x 25 ft	Plastic Voided Slab	313	40
30 ft x 30 ft	Traditional Slab	-	-
30 ft x 30 ft	Plastic Voided Slab	428	58
35 ft x 35 ft	Traditional Slab	-	-
35 ft x 35 ft	Plastic Voided Slab	531	75

Table 7-5: Parametric Study Solid Perimeters

Conclusions

Reinforced concrete slabs are used in many modern buildings. As architects attempt to use more open layouts by utilizing larger column-to-column spans, concrete slabs can become thick and heavy when designing a traditional flat plate. As illustrated in the parametric study, plastic voided slab systems can be used to reduce the structure weight with minimal impact to the overall building design.

The benefits of using plastic voided slabs rather than solid slabs are greater for larger spans. Smaller spans do not require substantially thick slabs, therefore only small voids can be utilized and minimal savings are achieved. Larger spans are capable of using larger voids that greatly reduce the overall weight of the slab while meeting load capacity requirements.

Construction of plastic voided slabs requires more steps than solid slabs, but the construction process is not significantly more complicated. For bays of the same size, plastic voided slabs typically require less reinforcement. The only major change is placement of the plastic void formers. The void formers are placed above the bottom layer of reinforcement and are usually contained in a cage of very thin steel bars. The cage of void formers is typically constructed at the manufacturer's facility and shipped to the construction site, allowing for quick placement of the void formers and minimal changes to the construction schedule compared to solid slab systems.

Architectural freedom can also be achieved by utilizing plastic voided slabs. Plastic voided slabs make it possible to achieve longer spans with the same amount of concrete in the slab, allowing for less columns and a more open interior space.

Overall, plastic voided slab systems provide an excellent alternative to solid concrete slabs for many applications. Weight and cost savings as well as architectural flexibility can be achieved with plastic voided slabs.

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Appendix A - Solid Slab Calculations

This appendix includes the calculations for flat plate bays used in the parametric study.

Project: **20 x 20**
Engineer: **CJM**
Date: **9/27/2013**
Sheet No.: **1** of **3**

CONCRETE TWO-WAY SLAB DESIGN-DIRECT DESIGN METHOD

20' x 20'

Requirements for ACI 318, Section 13.6:

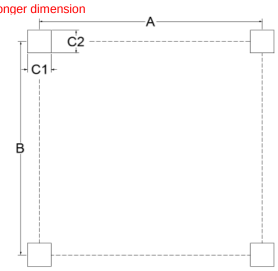
Requirement	
1) Three or more spans in both directions:	**True**
2) Rectangular panels, with a ratio of longer to shorter span center to center of supports not greater than 2	**True**
3) Successive span lengths center-to-center of supports in each direction shall not differ by more than one-third of longer span	**True**
4) Offset of columns by a maximum of 10% of span (in direction of offset) permitted	**True**
5) Gravity only loads and uniform. Unfactored LL shall not exceed two times unfactored DL.	**True**

Direct Design Method Allowed

f'_c = 4000 psi f_y= 60 ksi
Concrete= NW λ= 1
E= 3604996.533 psi
Slab: Without drop panels; Interior Panel; Interior Panel

Span Width (A), L_1= 20 ft
Span Length (B), L_2 = 20 ft
Column Width (C1)= 16 in
Column Length (C2)= 16 in
Clear Span A, Ln_A= 18.66666667 ft
Clear Span B, Ln_B= 18.66666667 ft
βspan= 1
βcolumn= 1

A is the longer dimension



Initial Thickness:

Thickness: $t_{Req'd}$= Ln/ 33
$t_{Req'd}$= **6.79** in.

For slabs with beams spanning between supports: use this section only if supports beams span between all supports

Assumed thickness, t= 7 in

Long Direction:
I_s= **6860** in^4 b_w= 0 in h_w= 0 in w_{top}= 0 in y_{bar}= 0 in
I_b= **0** in^4
α_L= EI_b/EI_S= 3604996.5 * 0 / (3604996.533 * 6860)
α_L= **0**

Short Direction:
I_s= **6860** in^4 b_w= 0 in h_w= 0 in w_{top}= 0 in y_{bar}= 0 in
I_b= **0** in^4
α_S= EI_b/EI_S= 3604996.5 * 0 / (3604996.533 * 6860)
α_S= **0**

α_M= **0** change slab drop menu from Support beams $Ln_{largest}$= 18.667 ft
h= **do not use** in

Use: t= 7 in.

Uniform Service Loads

Loads (k/ft^2)	
DL	LL
0.12	**0.08**

20 psf + slab

Uniform Ultimate Load

w_u = 1.2 * 0.12 + 1.6 * 0.08 = **0.272** k/ft^2

Shear Check

t= 8 in
cover= 0.75 in
$d_{assumed}$= **6.75** in

Beam Shear:
V_{u1}= w_u(.5Ln-d)= 0.272 *(0.5* 18.667 - 6.75 /12)
V_{u1}= **2.385666667** k
ϕVc= ϕ2(f'c$^{.5}$)bd= 0.75*2*(4000)$^{1/2}$*12* 6.75 /1000
ϕVc= **7.684334714** k **ok**

Punching Shear: Not an issue with slabs supported on all sides with beams
b_0= 2[(C_1+$d_{assumed}$)+(C_2+$d_{assumed}$)]= 2[(16 + 6.75)+(16.00 + 6.75)]
b_0= **91** in
α_S= **40** Interior Column
Equation 11-31: (2+4/β_{column})= **(2+4/** 1)= **6.0**
Equation 11-32: (α_sd/b_o+2)= **(** 40 * 6.75 / 91 + 2)= **5.0**
Equation 11-33: **4.0**
Coefficient: **4.0**
ϕVc= ϕ*Coefficient*λ*($f'_c$$^{1/2}$)$b_o$d= .75* 4.0 * 1 * (4000.00 $^{1/2}$)* 91 * 6.75
ϕVc= **116.5457432** k
Column Tributary Area= **400** ft^2= 20 ft * 20 ft
V_{u2}= [A-(C_1+$d_{assumed}$)*(C_2+$d_{assumed}$)]*w_u= [400 - (16 + 6.75)*(16 + 6.75)/144]* 0.272
V_{u2}= **107.8223819** k **ok**

Project: **20 x 20**
Engineer: **CJM**
Date: **9/27/2013**
Sheet No.: **2** of **3**

Flexure Check

Long Direction

Static Moment, M_{0L}= $(w_uL_2)(Ln_a)^2/8$

M_{0L}= 236.9422222 kft

Moment Distribution

Interior Span:

M(-)= 154.0124444 kft

M(+)= 82.92977778 kft

End Span: **Slab w/o Interior beams w/o edge beam**

$M(-_{interior})$= 166 kft

M(+)= 123 kft

$M(-_{exterior})$= 62 kft

Column Strip: Smaller of $.25L_1$ and $.25L_2$ either side of a column

Interior Column Strip= 10 ft

Edge Column Strip= 5 ft

Middle Strip: Bounded by column strips

Middle Strip= 10 ft

L_2/L_1= 1

$\alpha_{f1}=\alpha_L$= 0

$\alpha_{f1}L_2/L_1$= 0

Column Strip Moment Factors:

Interior (-)= **0.75** 13.6.4.1 ACI 318

Positive (+)= **0.6** 13.6.4.4 ACI 318

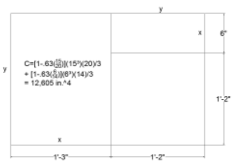
C= $\Sigma(1-.63x/y)x^3y/3$

C= **0** edge beams only,

βt= (EcbC)/(2EcsIs)

βt= 0

Exterior (-)= **1** 13.6.4.2 ACI 318



Moment: **Interior Span** **Both end spans if corner section**

Column Stip Interior (-)= 115.5093333 kft

Middle Strip Interior (-)= 38.5 kft

Column Stip Positive (+)= 49.75786667 kft

Middle Strip Positive (+)= 33.2 kft

Column Stip Exterior (-)= Does Not Apply

Middle Strip Exterior (-)= Does Not Apply

Beam/Slab Distribution: Applies only for support beams and/or edge beams

Column Strip Interior (-)

Beam Coefficient= 0 13.6.5 ACI 318

Beam Moment= 0 kft

Slab Coefficient= 1

Slab Moment= 115.5093333 kft

Column Strip Positive (+)

Beam Coefficient= 0 13.6.5 ACI 318

Beam Moment= 0 kft

Slab Coefficient= 1

Slab Moment= 49.75786667 kft

Column Strip Exterior (-)

Beam Coefficient= 0 13.6.5 ACI 318

Beam Moment= 0 kft

Slab Coefficient= 1

Slab Moment= 0 kft

Short Direction

Static Moment, M_{0S}= $(w_uL_1)(Ln_b)^2/8$

M_{0S}= 236.9422222 kft

Moment Distribution

Interior Span:

M(-)= 154.0124444 kft

M(+)= 82.92977778 kft

End Span: **Slab w/o Interior beams w/o edge beam**

$M(-_{interior})$= 166 kft

M(+)= 123 kft

$M(-_{exterior})$= 62 kft

Column Strip: Smaller of $.25L_1$ and $.25L_2$ either side of a column

Interior Column Strip= 10 ft

Edge Column Strip= 5 ft

Middle Strip: Bounded by column strips

Middle Strip= 10 ft

L_1/L_2= 1

$\alpha_{f2}=\alpha_S$= 0

$\alpha_{f1}L_2/L_1$= 0

Column Strip Moment Factors:

Interior (-)= **0.75** 13.6.4.4 ACI 318

Positive (+)= **0.6** 13.6.4.1 ACI 318

C= $\Sigma(1-.63x/y)x^3y/3$

C= **0** edge beams only

βt= (EcbC)/(2EcsIs)

βt= 0

Exterior (-)= **1** 13.6.4.2 ACI 318

Moment: **Interior Span**

Column Stip Interior (-)= 115.5093333 kft

Middle Strip Interior (-)= 38.5 kft

Column Stip Positive (+)= 49.75786667 kft

Middle Strip Positive (+)= 33.2 kft

Column Stip Exterior (-)= Does Not Apply

Middle Strip Exterior (-)= Does Not Apply

Beam/Slab Distribution Applies only for support beams and/or edge beams

Column Strip Interior (-)

Beam Coefficient= 0 13.6.5 ACI 318

Beam Moment= 0 kft

Slab Coefficient= 1

Slab Moment= 115.5093333 kft

Column Strip Positive (+)

Beam Coefficient= 0 13.6.5 ACI 318

Beam Moment= 0 kft

Slab Coefficient= 1

Slab Moment= 49.75786667 kft

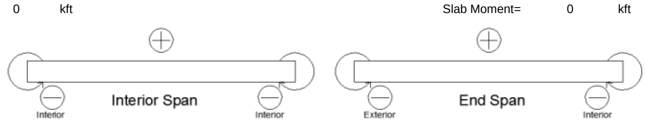
Column Strip Exterior (-)

Beam Coefficient= 0 13.6.5 ACI 318

Beam Moment= 0 kft

Slab Coefficient= 1

Slab Moment= 0 kft



Summary	Positive (kft)	Interior Negative (kft)	Exterior Negative (kft)
Beam	0.0	0.0	0.0
Column Strip Slab	49.8	115.5	0.0
Middle Strip Slab	33.2	38.5	0.0

Summary	Positive (kft)	Interior Negative (kft)	Exterior Negative (kft)
Beam	0.0	0.0	0.0
Column Strip Slab	49.8	115.5	0.0
Middle Strip Slab	33.2	38.5	0.0

Project: **20 x 20**
Engineer: **CJM**
Date: **9/27/2013**

Flexural Reinforcement

m= fy/(.85f'c)

m= 17.64705882

R_u= Mu/(ϕbd^2)

ρ= (1-(1-(2R_um/fy))$^{.5}$)/m

$A_{s(min)}$= .0018bh

$Spacing_{maximum}$= 2h= 16 in

Long Direction

	Column Strip			Middle Strip		
	+	Int. (-)	Ext. (-)	+	Int. (-)	Ext. (-)
Moment (kft)	49.8	115.5	0.0	33.2	38.5	0.0
b (in)	120	120	60	120	120	120
d (in)	6.75	6.75	6.75	6.75	6.75	6.75
h (in)	8	8	8	8	8	8
fy (ksi)	60	60	60	60	60	60
f'c (ksi)	4	4	4	4	4	4
R_u (ksi)	0.121	0.282	0.000	0.081	0.094	0.000
ρ	0.002	0.005	0.000	0.001	0.002	0.000
A_s (in^2)	1.668	3.975	0.000	1.105	1.286	0.000
$A_{s(min)}$ (in^2)	1.728	1.728	0.864	1.728	1.728	1.728
Bars Used	**4**	**4**	**4**	**4**	**4**	**4**
$A_{s(used)}$, each (in^2)	0.2	0.2	0.2	0.2	0.2	0.2
# bars required	8.6	19.9	4.3	8.6	8.6	8.6
spacing (in)	13.3	6.0	12.0	13.3	13.3	13.3
Use						
# bars	**10**	**20**	**5**	**10**	**10**	**10**
spacing (in)	12	6	12	12	12	12
$A_{s(provided)}$ (in^2)	2	4	1	2	2	2

Short Direction

	Column Strip			Middle Strip		
	+	Int. (-)	Ext. (-)	+	Int. (-)	Ext. (-)
Moment (kft)	49.8	115.5	0.0	33.2	38.5	0.0
b (in)	120	120	60	120	120	120
d (in)	6.75	6.75	6.75	6.75	6.75	6.75
h (in)	8	8	8	8	8	8
fy (ksi)	60	60	60	60	60	60
f'c (ksi)	4	4	4	4	4	4
R_u (ksi)	0.121	0.282	0.000	0.081	0.094	0.000
ρ	0.002	0.005	0.000	0.001	0.002	0.000
A_s (in2)	1.668	3.975	0.000	1.105	1.286	0.000
$A_{s(min)}$ (in2)	1.728	1.728	0.864	1.728	1.728	1.728
Bars Used	**4**	**4**	**4**	**4**	**4**	**4**
$A_{s(used)}$, each (in2)	0.2	0.2	0.2	0.2	0.2	0.2
# bars required	8.6	19.9	4.3	8.6	8.6	8.6
spacing (in)	13.3	6.0	12.0	13.3	13.3	13.3
Use						
# bars	**10**	**20**	**5**	**10**	**10**	**10**
spacing (in)	12	6	12	12	12	12
$A_{s(provided)}$ (in^2)	2	4	1	2	2	2

Moment and Shear Transfer from Slab to Column

applies to end spans without edge beams

Long Direction

Include? **No**

b, Column Diameter + (2)(1.5h)= 40 in

γ_f= 1/(1+(2/3)(b_1/b_2)$^{.5}$)

γ_f= 0.580584754

M_u= 0.0 kft

$\gamma_f M_u$= 0 kft

Add **3** # | **4**

for a total of **6** # | **4** across b

As= 1.2 in^2

a= $A_s$fy/(.85f'cb)

a= 0.529411765 in

ϕMn=Mu= ϕA_sfy(d-a/2)

ϕMn=Mu= 35.02058824 kft ok

Across full column strip at end: **10** # | **4**

As= 2 in^2

a= 0.588235294 in

Mn= 64.55882353 kft

γ_v= 0.419415246

$\gamma_v M_n$= 27.07695484 kft

A_c= (2a+b)d= 415.125 in^2

c_{AB}= 6.103912602 in

Jc= d[2a^3/3-(2a+b)(c_{AB})2]+ad^3/6

J_c= 18255.86716 in^4

V_u= 53.91119097 k

v_u= (V_u/A_c)+($\gamma_v M_n c_{AB}$/J_c)

v_u= 238.5066545 psi

4(f'c$^{.5}$)= 252.9822128 psi

ok

Short Direction

Include? **No**

b, Column Diameter + (2)(1.5h)= 40 in

γ_f= 1/(1+(2/3)(b_1/b_2)$^{.5}$)

γ_f= 0.580584754

M_u= 0.0 kft

$\gamma_f M_u$= 0 kft

Add **3** # | **4**

for a total of **6** # | **4** across b

As= 1.2 in^2

a= $A_s$fy/(.85f'cb)

a= 0.529411765 in

ϕMn=Mu= ϕA_sfy(d-a/2)

ϕMn=Mu= 35.02058824 kft ok

Across full column strip at end: **10** # | **4**

As= 2 in^2

a= 0.588235294 in

Mn= 64.55882353 kft

γ_v= 0.419415246

$\gamma_v M_n$= 27.07695484 kft

A_c= (2a+b)d= 415.13 in^2

c_{AB}= 6.103912602 in

Jc= d[2a^3/3-(2a+b)(c_{AB})2]+ad^3/6

J_c= 18255.86716 in^4

V_u= 53.91119097 k

v_u= (V_u/A_c)+($\gamma_v M_n c_{AB}$/J_c)

v_u= 238.5066545 psi

4(f'c$^{.5}$)= 252.9822128 psi

ok

Project: **25 x 25**
Engineer: **CJM**
Date: **9/27/2013**
Sheet No.: **1** of 3

CONCRETE TWO-WAY SLAB DESIGN-DIRECT DESIGN METHOD
25' x 25'

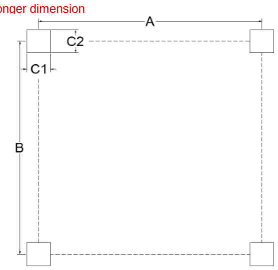
Requirements for ACI 318, Section 13.6:

1) Three or more spans in both directions:	**True**
2) Rectangular panels, with a ratio of longer to shorter span center to center of supports not greater than 2	**True**
3) Successive span lengths center-to-center of supports in each direction shall not differ by more than one-third of longer span	**True**
4) Offset of columns by a maximum of 10% of span (in direction of offset) permitted	**True**
5) Gravity only loads and uniform. Unfactored LL shall not exceed two times unfactored DL.	**True**

Direct Design Method Allowed

f'_c =	4000	psi f_y=	60	ksi	Span Width (A), L_1=	25	ft
Concrete=	NW	λ=	1		Span Length (B), L_2 =	25	ft
E=	3604996.533	psi			Column Width (C1)=	16	in
					Column Length (C2)=	16	in
Slab	Without drop panels				Clear Span A, Ln_A=	23.66666667	ft
	Interior Panel				Clear Span B, Ln_B=	23.66666667	ft
	Interior Panel				βspan=	1	
					βcolumn=	1	

A is the longer dimension



Initial Thickness:

Thickness: $t_{Req'd}$= Ln/ 33

$t_{Req'd}$= **8.61** in.

For slabs with beams spanning between supports: use this section only if supports beams span between all supports

Assumed thickness, t= 7 in

Long Direction:

I_s= **8575** in^4 b_w= 0 in h_w= 0 in w_{top}= 0 in y_{bar}= 0 in

I_b= **0** in^4

α_L= EI_b/EI_S= 3604996.5 * 0 / (3604996.533 * 8575)

α_L= **0**

Short Direction:

I_s= **8575** in^4 b_w= 0 in h_w= 0 in w_{top}= 0 in y_{bar}= 0 in

I_b= **0** in^4

α_S= EI_b/EI_S= 3604996.5 * 0 / (3604996.533 * 8575)

α_S= **0**

α_M= **0** change slab drop menu from Support beams $Ln_{largest}$= 23.667 ft

h= **do not use** in

Use: **t= 9 in.**

Uniform Service Loads

Loads (k/ft^2)	
DL	LL
0.15	0.08

20 psf + slab

Uniform Ultimate Load

w_u = 1.2 * 0.15 + 1.6 * 0.08 = **0.308** k/ft^2

Shear Check

t= **10** in
cover= **0.75** in
$d_{assumed}$= **8.75** in

Beam Shear:

V_{u1}= w_u(.5Ln-d)= 0.308 *(0.5* 23.667 - 8.75 /12)

V_{u1}= **3.420083333** k

ϕVc= ϕ2(f'c$^{.5}$)bd= 0.75*2*(4000)$^{1/2}$*12* 8.75 /1000

ϕVc= **9.96117463** k **ok**

Punching Shear: Not an issue with slabs supported on all sides with beams

b_0= $2[(C_1+d_{assumed})+(C_2+d_{assumed})]$= 2[(16 + 8.75)+(16.00 + 8.75)]

b_0= **99** in

α_S= **40** Interior Column

Equation 11-31: $(2+4/\beta_{column})$= **(2+4/** 1)= **6.0**

Equation 11-32: $(\alpha_s d/b_o+2)$= **(** 40 * 8.75 / 99 + 2)= **5.5**

Equation 11-33: **4.0**

Coefficient: **4.0**

ϕVc= ϕ*Coefficient*λ*$(f'_c{}^{1/2})b_od$= .75* 4.0 * 1 * (4000.00 $^{1/2}$)* 99 * 8.75

ϕVc= **164.3593814** k

Column Tributary Area= **400** ft^2= 20 ft * 20 ft

V_{u2}= $[A-(C_1+d_{assumed})*(C_2+d_{assumed})]*w_u$= [400 - (16 + 8.75)*(16 + 8.75)/144]* 0.308

V_{u2}= **121.8897969** k **ok**

Project: **25 x 25**
Engineer: **CJM**
Date: **9/27/2013**
Sheet No.: **2** **of 3**

Flexure Check

Long Direction

Static Moment, M_{0L}= $(w_uL_2)(Ln_a)^2/8$

M_{0L}= 539.1069444 kft

Moment Distribution

Interior Span:

M(-)=	350.4195139	kft
M(+)=	188.6874306	kft

End Span: **Slab w/o Interior beams w/o edge beam**

$M(-_{interior})$=	377	kft
M(+)=	280	kft
$M(-_{exterior})$=	140	kft

Column Strip: Smaller of $.25L_1$ and $.25L_2$ either side of a column

Interior Column Strip=	12.5	ft
Edge Column Strip=	6.25	ft

Middle Strip: Bounded by column strips

Middle Strip= 12.5 ft

L_2/L_1= 1

$\alpha_{f1}=\alpha_L$= 0

$\alpha_{f1}L_2/L_1$= 0

Column Strip Moment Factors:

Interior (-)=	**0.75**	13.6.4.1 ACI 318
Positive (+)=	**0.6**	13.6.4.4 ACI 318

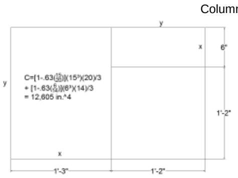
C= $\Sigma(1-.63x/y)x^3y/3$

C= **0** edge beams only,

βt= (EcbC)/(2EcsIs)

βt= 0

Exterior (-)= **1** 13.6.4.2 ACI 318



Moment: **Interior Span** **Both end spans if corner section**

Column Stip Interior (-)=	262.8146354	kft
Middle Strip Interior (-)=	87.6	kft
Column Stip Positive (+)=	113.2124583	kft
Middle Strip Positive (+)=	75.5	kft
Column Stip Exterior (-)=	Does Not Apply	
Middle Strip Exterior (-)=	Does Not Apply	

Beam/Slab Distribution: Applies only for support beams and/or edge beams

Column Strip Interior (-)

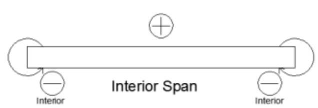
Beam Coefficient=	0	13.6.5 ACI 318
Beam Moment=	0	kft
Slab Coefficient=	1	
Slab Moment=	262.8146354	kft

Column Strip Positive (+)

Beam Coefficient=	0	13.6.5 ACI 318
Beam Moment=	0	kft
Slab Coefficient=	1	
Slab Moment=	113.2124583	kft

Column Strip Exterior (-)

Beam Coefficient=	0	13.6.5 ACI 318
Beam Moment=	0	kft
Slab Coefficient=	1	
Slab Moment=	0	kft



Summary	Positive (kft)	Interior Negative (kft)	Exterior Negative (kft)
Beam	0.0	0.0	0.0
Column Strip Slab	113.2	262.8	0.0
Middle Strip Slab	75.5	87.6	0.0

Short Direction

Static Moment, M_{0S}= $(w_uL_1)(Ln_b)^2/8$

M_{0S}= 539.1069444 kft

Moment Distribution

Interior Span:

M(-)=	350.4195139	kft
M(+)=	188.6874306	kft

End Span: **Slab w/o Interior beams w/o edge beam**

$M(-_{interior})$=	377	kft
M(+)=	280	kft
$M(-_{exterior})$=	140	kft

Column Strip: Smaller of $.25L_1$ and $.25L_2$ either side of a column

Interior Column Strip=	12.5	ft
Edge Column Strip=	6.25	ft

Middle Strip: Bounded by column strips

Middle Strip= 12.5 ft

L_1/L_2= 1

$\alpha_{f2}=\alpha_S$= 0

$\alpha_{f1}L_2/L_1$= 0

Column Strip Moment Factors:

Interior (-)=	**0.75**	13.6.4.4 ACI 318
Positive (+)=	**0.6**	13.6.4.1 ACI 318

C= $\Sigma(1-.63x/y)x^3y/3$

C= **0** edge beams only

βt= (EcbC)/(2EcsIs)

βt= 0

Exterior (-)= **1** 13.6.4.2 ACI 318

Moment: **Interior Span**

Column Stip Interior (-)=	262.8146354	kft
Middle Strip Interior (-)=	87.6	kft
Column Stip Positive (+)=	113.2124583	kft
Middle Strip Positive (+)=	75.5	kft
Column Stip Exterior (-)=	Does Not Apply	
Middle Strip Exterior (-)=	Does Not Apply	

Beam/Slab Distribution Applies only for support beams and/or edge beams

Column Strip Interior (-)

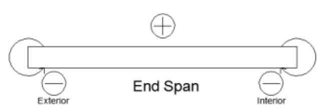
Beam Coefficient=	0	13.6.5 ACI 318
Beam Moment=	0	kft
Slab Coefficient=	1	
Slab Moment=	262.8146354	kft

Column Strip Positive (+)

Beam Coefficient=	0	13.6.5 ACI 318
Beam Moment=	0	kft
Slab Coefficient=	1	
Slab Moment=	113.2124583	kft

Column Strip Exterior (-)

Beam Coefficient=	0	13.6.5 ACI 318
Beam Moment=	0	kft
Slab Coefficient=	1	
Slab Moment=	0	kft



Summary	Positive (kft)	Interior Negative (kft)	Exterior Negative (kft)
Beam	0.0	0.0	0.0
Column Strip Slab	113.2	262.8	0.0
Middle Strip Slab	75.5	87.6	0.0

Project: **25 x 25**
Engineer: **CJM**
Date: **9/27/2013**
Sheet No.: **3** **of 3**

Flexural Reinforcement

m= fy/(.85f'c)

m= 17.64705882

R_u= Mu/(ϕbd^2)

ρ= (1-(1-(2R_um/fy))$^{.5}$)/m

$A_{s(min)}$= .0018bh

$Spacing_{maximum}$= 2h= 20 in

Long Direction

	Column Strip			Middle Strip		
	+	Int. (-)	Ext. (-)	+	Int. (-)	Ext. (-)
Moment (kft)	113.2	262.8	0.0	75.5	87.6	0.0
b (in)	150	150	75	150	150	150
d (in)	8.75	8.75	8.75	8.75	8.75	8.75
h (in)	10	10	10	10	10	10
fy (ksi)	60	60	60	60	60	60
f'c (ksi)	4	4	4	4	4	4
R_u (ksi)	0.131	0.305	0.000	0.088	0.102	0.000
ρ	0.002	0.005	0.000	0.001	0.002	0.000
A_s (in^2)	2.933	7.004	0.000	1.942	2.259	0.000
$A_{s(min)}$ (in^2)	2.700	2.700	1.350	2.700	2.700	2.700
Bars Used	**5**	**5**	**5**	**5**	**5**	**5**
$A_{s(used)}$, each (in^2)	0.31	0.31	0.31	0.31	0.31	0.31
# bars required	9.5	22.6	4.4	8.7	8.7	8.7
spacing (in)	15.0	6.5	15.0	16.7	16.7	16.7
Use						
# bars	**10**	**25**	**5**	**10**	**10**	**10**
spacing (in)	15	6	15	15	15	15
$A_{s(provided)}$ (in^2)	3.1	7.75	1.55	3.1	3.1	3.1

Short Direction

	Column Strip			Middle Strip		
	+	Int. (-)	Ext. (-)	+	Int. (-)	Ext. (-)
Moment (kft)	113.2	262.8	0.0	75.5	87.6	0.0
b (in)	150	150	75	150	150	150
d (in)	8.75	8.75	8.75	8.75	8.75	8.75
h (in)	10	10	10	10	10	10
fy (ksi)	60	60	60	60	60	60
f'c (ksi)	4	4	4	4	4	4
R_u (ksi)	0.131	0.305	0.000	0.088	0.102	0.000
ρ	0.002	0.005	0.000	0.001	0.002	0.000
A_s (in2)	2.933	7.004	0.000	1.942	2.259	0.000
$A_{s(min)}$ (in2)	2.700	2.700	1.350	2.700	2.700	2.700
Bars Used	**5**	**5**	**5**	**5**	**5**	**5**
$A_{s(used)}$, each (in2)	0.31	0.31	0.31	0.31	0.31	0.31
# bars required	9.5	22.6	4.4	8.7	8.7	8.7
spacing (in)	15.0	6.5	15.0	16.7	16.7	16.7
Use						
# bars	**10**	**25**	**5**	**10**	**10**	**10**
spacing (in)	15	6	15	15	15	15
$A_{s(provided)}$ (in^2)	3.1	7.75	1.55	3.1	3.1	3.1

Moment and Shear Transfer from Slab to Column

applies to end spans without edge beams

Long Direction

Include? **No**

b, Column Diameter + (2)(1.5h)= 46 in

γ_f= 1/(1+(2/3)(b_1/b_2)$^{.5}$)

γ_f= 0.576447475

M_u= 0.0 kft

$\gamma_f M_u$= 0 kft

Add **3** # | **4**

for a total of **6** # | **4** across b

As= 1.2 in^2

a= $A_s$fy/(.85f'cb)

a= 0.460358056 in

ϕMn=Mu= ϕ$A_s$fy(d-a/2)

ϕMn=Mu= 46.00703325 kft ok

Across full column strip at end: **10** # | **4**

As= 2 in^2

a= 0.470588235 in

Mn= 85.14705882 kft

γ_v= 0.423552525

$\gamma_v M_n$= 36.06425176 kft

A_c= (2a+b)d= 573.125 in^2

c_{AB}= 6.338024809 in

Jc= d[2a^3/3-(2a+b)(c_{AB})2]+ad^3/6

J_c= 28593.38474 in^4

V_u= 60.94489844 k

v_u= (V_u/A_c)+($\gamma_v M_n c_{AB}$/J_c)

v_u= 202.2661355 psi

4(f'c$^{.5}$)= 252.9822128 psi

ok

Short Direction

Include? **No**

b, Column Diameter + (2)(1.5h)= 46 in

γ_f= 1/(1+(2/3)(b_1/b_2)$^{.5}$)

γ_f= 0.576447475

M_u= 0.0 kft

$\gamma_f M_u$= 0 kft

Add **3** # | **4**

for a total of **6** # | **4** across b

As= 1.2 in^2

a= $A_s$fy/(.85f'cb)

a= 0.460358056 in

ϕMn=Mu= ϕ$A_s$fy(d-a/2)

ϕMn=Mu= 46.00703325 kft ok

Across full column strip at end: **10** # | **4**

As= 2 in^2

a= 0.470588235 in

Mn= 85.14705882 kft

γ_v= 0.423552525

$\gamma_v M_n$= 36.06425176 kft

A_c= (2a+b)d= 573.13 in^2

c_{AB}= 6.338024809 in

Jc= d[2a^3/3-(2a+b)(c_{AB})2]+ad^3/6

J_c= 28593.38474 in^4

V_u= 60.94489844 k

v_u= (V_u/A_c)+($\gamma_v M_n c_{AB}$/J_c)

v_u= 202.2661355 psi

4(f'c$^{.5}$)= 252.9822128 psi

ok

Project: **30 x 30**
Engineer: **CJM**
Date: **9/27/2013**
Sheet No.: **1** of **3**

CONCRETE TWO-WAY SLAB DESIGN-DIRECT DESIGN METHOD

30' x 30'

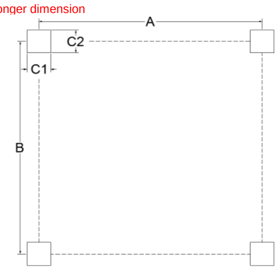
Requirements for ACI 318, Section 13.6:

Requirement	
1) Three or more spans in both directions:	True
2) Rectangular panels, with a ratio of longer to shorter span center to center of supports not greater than 2	True
3) Successive span lengths center-to-center of supports in each direction shall not differ by more than one-third of longer span	True
4) Offset of columns by a maximum of 10% of span (in direction of offset) permitted	True
5) Gravity only loads and uniform. Unfactored LL shall not exceed two times unfactored DL.	True

Direct Design Method Allowed

f'_c =	4000	psi f_y=	60	ksi	Span Width (A), L_1=	30 ft
Concrete=	NW	λ=	1		Span Length (B), L_2 =	30 ft
E=	3604996.533	psi			Column Width (C1)=	16 in
					Column Length (C2)=	16 in
Slab	Without drop panels				Clear Span A, Ln_A=	28.66666667 ft
	Interior Panel				Clear Span B, Ln_B=	28.66666667 ft
	Interior Panel				βspan=	1
					βcolumn=	1

A is the longer dimension



Initial Thickness:

Thickness: $t_{Req'd}$= Ln/ 33
$t_{Req'd}$= **10.42** in.

For slabs with beams spanning between supports: use this section only if supports beams span between all supports

Assumed thickness, t= 7 in

Long Direction:	I_s=	10290	in^4	b_w=	0 in		h_w=	0	in	w_{top}= 0 in	y_{bar}=	0 in
	I_b=	0	in^4									
	α_L=	EI_b/EI_S=	3604996.5 *	0 / (	3604996.533	*	10290	)				
	α_L=	0										
Short Direction:	I_s=	10290	in^4	b_w=	0 in		h_w=	0	in	w_{top}= 0 in	y_{bar}=	0 in
	I_b=	0	in^4									
	α_S=	EI_b/EI_S=	3604996.5 *	0 / (	3604996.533	*	10290	)				
	α_S=	0										
	α_M=	0	change slab drop menu from Support beams				$Ln_{largest}$=	28.667 ft				
	h=	do not use	in									

Use: **t= 10.5 in.**

Uniform Service Loads

Loads (k/ft²)	
DL	LL
0.17	0.08

20 psf + slab

Uniform Ultimate Load

w_u = 1.2 * 0.17 + 1.6 * 0.08 = **0.332** k/ft²

Shear Check

t= 12 in
cover= 0.75 in
$d_{assumed}$= **10.75** in

Beam Shear:

V_{u1}= w_u(.5Ln-d)= 0.332 *(0.5* 28.667 - 10.75 /12)
V_{u1}= **4.46125** k
ϕVc= ϕ2(f'c^.5)bd= 0.75*2*(4000)^1/2*12* 10.75 /1000
ϕVc= **12.23801454** k **ok**

Punching Shear: Not an issue with slabs supported on all sides with beams

b_0= $2[(C_1+d_{assumed})+(C_2+d_{assumed})]$= 2[(16 + 10.75)+(16.00 + 10.75)]
b_0= **107** in
α_S= **40** Interior Column

Equation 11-31: $(2+4/\beta_{column})$= **(2+4/** 1)= **6.0**
Equation 11-32: $(\alpha_s d/b_o+2)$= **(** 40 * 10.75 / 107 + 2)= **6.0**
Equation 11-33: **4.0**
Coefficient: **4.0**

ϕVc= ϕ*Coefficient*λ*$(f'_c{}^{1/2})b_o d$= .75* 4.0 * 1 * (4000.00 ^1/2)* 107 * 10.75
ϕVc= **218.2445927** k

Column Tributary Area= **400** ft²= 20 ft * 20 ft

V_{u2}= $[A-(C_1+d_{assumed})*(C_2+d_{assumed})]*w_u$= [400 - (16 + 10.75)*(16 + 10.75)/144]* 0.332
V_{u2}= **131.1502309** k **ok**

Project: **30 x 30**
Engineer: **CJM**
Date: **9/27/2013**
Sheet No.: **2** **of 3**

Flexure Check

<u>Long Direction</u>

Static Moment, M_{0L}= $(w_uL_2)(Ln_a)^2/8$

M_{0L}= 1023.113333 kft

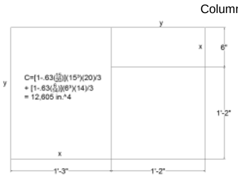
Moment Distribution

Interior Span:
M(-)= 665.0236667 kft
M(+)= 358.0896667 kft

End Span: **Slab w/o Interior beams w/o edge beam**
$M(-_{interior})$= 716 kft
M(+)= 532 kft
$M(-_{exterior})$= 266 kft

Column Strip: Smaller of $.25L_1$ and $.25L_2$ either side of a column
Interior Column Strip= 15 ft
Edge Column Strip= 7.5 ft
Middle Strip: Bounded by column strips
Middle Strip= 15 ft
L_2/L_1= 1
$\alpha_{f1}=\alpha_L$= 0
$\alpha_{f1}L_2/L_1$= 0

Column Strip Moment Factors:
Interior (-)= **0.75** 13.6.4.1 ACI 318
Positive (+)= **0.6** 13.6.4.4 ACI 318
C= $\Sigma(1-.63x/y)x^3y/3$
C= 0 edge beams only,
βt= (EcbC)/(2EcsIs)
βt= 0
Exterior (-)= **1** 13.6.4.2 ACI 318



Moment: **Interior Span** **Both end spans if corner section**
Column Stip Interior (-)= 498.76775 kft
Middle Strip Interior (-)= 166.3 kft
Column Stip Positive (+)= 214.8538 kft
Middle Strip Positive (+)= 143.2 kft
Column Stip Exterior (-)= Does Not Apply
Middle Strip Exterior (-)= Does Not Apply

Beam/Slab Distribution: Applies only for support beams and/or edge beams

Column Strip Interior (-)
Beam Coefficient= 0 13.6.5 ACI 318
Beam Moment= 0 kft
Slab Coefficient= 1
Slab Moment= 498.76775 kft

Column Strip Positive (+)
Beam Coefficient= 0 13.6.5 ACI 318
Beam Moment= 0 kft
Slab Coefficient= 1
Slab Moment= 214.8538 kft

Column Strip Exterior (-)
Beam Coefficient= 0 13.6.5 ACI 318
Beam Moment= 0 kft
Slab Coefficient= 1
Slab Moment= 0 kft

<u>Short Direction</u>

Static Moment, M_{0S}= $(w_uL_1)(Ln_b)^2/8$

M_{0S}= 1023.113333 kft

Moment Distribution

Interior Span:
M(-)= 665.0236667 kft
M(+)= 358.0896667 kft

End Span: **Slab w/o Interior beams w/o edge beam**
$M(-_{interior})$= 716 kft
M(+)= 532 kft
$M(-_{exterior})$= 266 kft

Column Strip: Smaller of $.25L_1$ and $.25L_2$ either side of a column
Interior Column Strip= 15 ft
Edge Column Strip= 7.5 ft
Middle Strip: Bounded by column strips
Middle Strip= 15 ft
L_1/L_2= 1
$\alpha_{f2}=\alpha_S$= 0
$\alpha_{f1}L_2/L_1$= 0

Column Strip Moment Factors:
Interior (-)= **0.75** 13.6.4.4 ACI 318
Positive (+)= **0.6** 13.6.4.1 ACI 318
C= $\Sigma(1-.63x/y)x^3y/3$
C= 0 edge beams only
βt= (EcbC)/(2EcsIs)
βt= 0
Exterior (-)= **1** 13.6.4.2 ACI 318

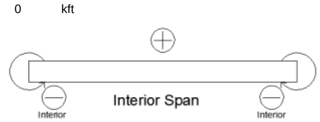
Moment: **Interior Span**
Column Stip Interior (-)= 498.76775 kft
Middle Strip Interior (-)= 166.3 kft
Column Stip Positive (+)= 214.8538 kft
Middle Strip Positive (+)= 143.2 kft
Column Stip Exterior (-)= Does Not Apply
Middle Strip Exterior (-)= Does Not Apply

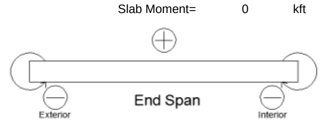
Beam/Slab Distribution Applies only for support beams and/or edge beams

Column Strip Interior (-)
Beam Coefficient= 0 13.6.5 ACI 318
Beam Moment= 0 kft
Slab Coefficient= 1
Slab Moment= 498.76775 kft

Column Strip Positive (+)
Beam Coefficient= 0 13.6.5 ACI 318
Beam Moment= 0 kft
Slab Coefficient= 1
Slab Moment= 214.8538 kft

Column Strip Exterior (-)
Beam Coefficient= 0 13.6.5 ACI 318
Beam Moment= 0 kft
Slab Coefficient= 1
Slab Moment= 0 kft





Summary	Positive (kft)	Interior Negative (kft)	Exterior Negative (kft)
Beam	0.0	0.0	0.0
Column Strip Slab	214.9	498.8	0.0
Middle Strip Slab	143.2	166.3	0.0

Summary	Positive (kft)	Interior Negative (kft)	Exterior Negative (kft)
Beam	0.0	0.0	0.0
Column Strip Slab	214.9	498.8	0.0
Middle Strip Slab	143.2	166.3	0.0

Project: **30 x 30**
Engineer: **CJM**
Date: **9/27/2013**
Sheet No.: **3** **of 3**

Flexural Reinforcement

m= fy/(.85f'c)

m= 17.64705882

R_u= Mu/(ϕbd^2)

ρ= (1-(1-(2R_um/fy))$^{.5}$)/m

$A_{s(min)}$= .0018bh

$Spacing_{maximum}$= 2h= 24 in

Long Direction

	Column Strip			Middle Strip		
	+	Int. (-)	Ext. (-)	+	Int. (-)	Ext. (-)
Moment (kft)	214.9	498.8	0.0	143.2	166.3	0.0
b (in)	180	180	90	180	180	180
d (in)	10.75	10.75	10.75	10.75	10.75	10.75
h (in)	12	12	12	12	12	12
fy (ksi)	60	60	60	60	60	60
f'c (ksi)	4	4	4	4	4	4
R_u (ksi)	0.138	0.320	0.000	0.092	0.107	0.000
ρ	0.002	0.006	0.000	0.002	0.002	0.000
A_s (in^2)	4.535	10.847	0.000	3.002	3.492	0.000
$A_{s(min)}$ (in^2)	3.888	3.888	1.944	3.888	3.888	3.888
Bars Used	**6**	**6**	**6**	**6**	**6**	**6**
$A_{s(used)}$, each (in^2)	0.44	0.44	0.44	0.44	0.44	0.44
# bars required	10.3	24.7	4.4	8.8	8.8	8.8
spacing (in)	16.4	7.2	18.0	20.0	20.0	20.0
Use						
# bars	**12**	**30**	**5**	**10**	**10**	**10**
spacing (in)	15	6	18	18	18	18
$A_{s(provided)}$ (in^2)	5.28	13.2	2.2	4.4	4.4	4.4

Short Direction

	Column Strip			Middle Strip		
	+	Int. (-)	Ext. (-)	+	Int. (-)	Ext. (-)
Moment (kft)	214.9	498.8	0.0	143.2	166.3	0.0
b (in)	180	180	90	180	180	180
d (in)	10.75	10.75	10.75	10.8	10.75	10.75
h (in)	12	12	12	12	12	12
fy (ksi)	60	60	60	60	60	60
f'c (ksi)	4	4	4	4	4	4
R_u (ksi)	0.138	0.320	0.000	0.092	0.107	0.000
ρ	0.002	0.006	0.000	0.002	0.002	0.000
A_s (in2)	4.535	10.847	0.000	3.002	3.492	0.000
$A_{s(min)}$ (in2)	3.888	3.888	1.944	3.888	3.888	3.888
Bars Used	**6**	**6**	**6**	**6**	**6**	**6**
$A_{s(used)}$, each (in2)	0.44	0.44	0.44	0.44	0.44	0.44
# bars required	10.3	24.7	4.4	8.8	8.8	8.8
spacing (in)	16.4	7.2	18.0	20.0	20.0	20.0
Use						
# bars	**12**	**30**	**5**	**10**	**10**	**10**
spacing (in)	15	6	18	18	18	18
$A_{s(provided)}$ (in^2)	5.28	13.2	2.2	4.4	4.4	4.4

Moment and Shear Transfer from Slab to Column

applies to end spans without edge beams

Long Direction

Include? **No**

b, Column Diameter + (2)(1.5h)= 52 in

γ_f= 1/(1+(2/3)(b_1/b_2)$^{.5}$)

γ_f= 0.572806008

M_u= 0.0 kft

$\gamma_f M_u$= 0 kft

Add **3** # **4**

for a total of **6** # **4** across b

As= 1.2 in^2

a= $A_s$fy/(.85f'cb)

a= 0.407239819 in

ϕMn=Mu= ϕ$A_s$fy(d-a/2)

ϕMn=Mu= 56.95045249 kft ok

Across full column strip at end: **10** # **4**

As= 2 in^2

a= 0.392156863 in

Mn= 105.5392157 kft

γ_v= 0.427193992

$\gamma_v M_n$= 45.08571891 kft

A_c= (2a+b)d= 747.125 in^2

c_{AB}= 6.573965827 in

Jc= d[2a^3/3-(2a+b)(c_{AB})2]+ad^3/6

J_c= 42127.09416 in^4

V_u= 65.57511545 k

v_u= (V_u/A_c)+($\gamma_v M_n c_{AB}$/J_c)

v_u= 172.197877 psi

4(f'c$^{.5}$)= 252.9822128 psi

ok

Short Direction

Include? **No**

b, Column Diameter + (2)(1.5h)= 52 in

γ_f= 1/(1+(2/3)(b_1/b_2)$^{.5}$)

γ_f= 0.572806008

M_u= 0.0 kft

$\gamma_f M_u$= 0 kft

Add **3** # **4**

for a total of **6** # **4** across b

As= 1.2 in^2

a= $A_s$fy/(.85f'cb)

a= 0.407239819 in

ϕMn=Mu= ϕ$A_s$fy(d-a/2)

ϕMn=Mu= 56.95045249 kft ok

Across full column strip at end: **10** # **4**

As= 2 in^2

a= 0.392156863 in

Mn= 105.5392157 kft

γ_v= 0.427193992

$\gamma_v M_n$= 45.08571891 kft

A_c= (2a+b)d= 747.13 in^2

c_{AB}= 6.573965827 in

Jc= d[2a^3/3-(2a+b)(c_{AB})2]+ad^3/6

J_c= 42127.09416 in^4

V_u= 65.57511545 k

v_u= (V_u/A_c)+($\gamma_v M_n c_{AB}$/J_c)

v_u= 172.197877 psi

4(f'c$^{.5}$)= 252.9822128 psi

ok

Project: **35 x 35**
Engineer: **CJM**
Date: **9/27/2013**
Sheet No.: **1** **of 3**

CONCRETE TWO-WAY SLAB DESIGN-DIRECT DESIGN METHOD

35' x 35'

Requirements for ACI 318, Section 13.6:

1) Three or more spans in both directions:	True
2) Rectangular panels, with a ratio of longer to shorter span center to center of supports not greater than 2	True
3) Successive span lengths center-to-center of supports in each direction shall not differ by more than one-third of longer span	True
4) Offset of columns by a maximum of 10% of span (in direction of offset) permitted	True
5) Gravity only loads and uniform. Unfactored LL shall not exceed two times unfactored DL.	True

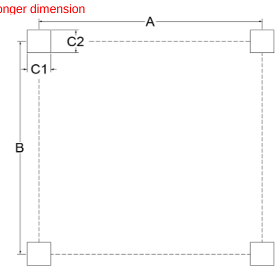
Direct Design Method Allowed

f'_c = 4000 psi f_y= 60 ksi
Concrete= NW λ= 1
E= 3604996.533 psi

Slab: Without drop panels
Interior Panel
Interior Panel

Span Width (A), L_1= 35 ft
Span Length (B), L_2 = 35 ft
Column Width (C1)= 16 in
Column Length (C2)= 16 in
Clear Span A, Ln_A= 33.66666667 ft
Clear Span B, Ln_B= 33.66666667 ft
βspan= 1
βcolumn= 1

A is the longer dimension



Initial Thickness:

Thickness: $t_{Req'd}$= Ln/ 33
$t_{Req'd}$= 12.24 in.

For slabs with beams spanning between supports: use this section only if supports beams span between all supports

Assumed thickness, t= 7 in

Long Direction:
I_s= 12005 in^4 b_w= 0 in h_w= 0 in w_{top}= 0 in y_{bar}= 0 in
I_b= 0 in^4
α_L= EI_b/EI_S= 3604996.5 * 0 / (3604996.533 * 12005)
α_L= 0

Short Direction:
I_s= 12005 in^4 b_w= 0 in h_w= 0 in w_{top}= 0 in y_{bar}= 0 in
I_b= 0 in^4
α_S= EI_b/EI_S= 3604996.5 * 0 / (3604996.533 * 12005)
α_S= 0
α_M= 0 change slab drop menu from Support beams $Ln_{largest}$= 33.667 ft
h= do not use in

Use: t= 12.5 in.

Uniform Service Loads

Loads (k/ft^2)	
DL	LL
0.20	0.08

20 psf + slab

Uniform Ultimate Load

w_u = 1.2 * 0.20 + 1.6 * 0.08 = 0.368 k/ft^2

Shear Check

t= 14 in
cover= 0.75 in
$d_{assumed}$= 12.75 in

Beam Shear:
V_{u1}= w_u(.5Ln-d)= 0.368 *(0.5* 33.667 - 12.75 /12)
V_{u1}= 5.803666667 k
ϕVc= ϕ2(f'c$^{.5}$)bd= 0.75*2*(4000)$^{1/2}$*12* 12.75 /1000
ϕVc= 14.51485446 k ok

Punching Shear: Not an issue with slabs supported on all sides with beams
b_0= 2[(C_1+$d_{assumed}$)+(C_2+$d_{assumed}$)]= 2[(16 + 12.75)+(16.00 + 12.75)]
b_0= 115 in
α_S= 40 Interior Column
Equation 11-31: (2+4/β_{column})= (2+4/ 1)= 6.0
Equation 11-32: (α_sd/b_o+2)= (40 * 12.75 / 115 + 2)= 6.4
Equation 11-33: 4.0
Coefficient: 4.0
ϕVc= ϕ*Coefficient*λ*($f'_c$$^{1/2}$)$b_o$d= .75* 4.0 * 1 * (4000.00 $^{1/2}$)* 115 * 12.75
ϕVc= 278.2013772 k
Column Tributary Area= 400 ft^2= 20 ft * 20 ft
V_{u2}= [A-(C_1+$d_{assumed}$)*(C_2+$d_{assumed}$)]*w_u= [400 - (16 + 12.75)*(16 + 12.75)/144]* 0.368
V_{u2}= 145.0876736 k ok

Project: 35 x 35
Engineer: CJM
Date: 9/27/2013
Sheet No.: 2 of 3

Flexure Check

Long Direction

Static Moment, M_{0L}= $(w_uL_2)(Ln_a)^2/8$

M_{0L}= 1824.845556 kft

Moment Distribution

Interior Span:

M(-)= 1186.149611 kft

M(+)= 638.6959444 kft

End Span: Slab w/o Interior beams w/o edge beam

$M(-_{interior})$= 1277 kft

M(+)= 949 kft

$M(-_{exterior})$= 474 kft

Column Strip: Smaller of $.25L_1$ and $.25L_2$ either side of a column

Interior Column Strip= 17.5 ft

Edge Column Strip= 8.75 ft

Middle Strip: Bounded by column strips

Middle Strip= 17.5 ft

L_2/L_1= 1

$\alpha_{f1}=\alpha_L$= 0

$\alpha_{f1}L_2/L_1$= 0

Column Strip Moment Factors:

Interior (-)= 0.75 13.6.4.1 ACI 318

Positive (+)= 0.6 13.6.4.4 ACI 318

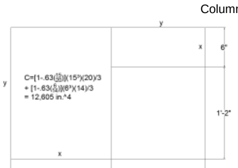
C= $\Sigma(1-.63x/y)x^3y/3$

C= 0 edge beams only,

βt= (EcbC)/(2EcsIs)

βt= 0

Exterior (-)= 1 13.6.4.2 ACI 318



Moment: Interior Span **Both end spans if corner section**

Column Stip Interior (-)= 889.6122083 kft

Middle Strip Interior (-)= 296.5 kft

Column Stip Positive (+)= 383.2175667 kft

Middle Strip Positive (+)= 255.5 kft

Column Stip Exterior (-)= Does Not Apply

Middle Strip Exterior (-)= Does Not Apply

Beam/Slab Distribution: Applies only for support beams and/or edge beams

Column Strip Interior (-)

Beam Coefficient= 0 13.6.5 ACI 318

Beam Moment= 0 kft

Slab Coefficient= 1

Slab Moment= 889.6122083 kft

Column Strip Positive (+)

Beam Coefficient= 0 13.6.5 ACI 318

Beam Moment= 0 kft

Slab Coefficient= 1

Slab Moment= 383.2175667 kft

Column Strip Exterior (-)

Beam Coefficient= 0 13.6.5 ACI 318

Beam Moment= 0 kft

Slab Coefficient= 1

Slab Moment= 0 kft

Short Direction

Static Moment, M_{0S}= $(w_uL_1)(Ln_b)^2/8$

M_{0S}= 1824.845556 kft

Moment Distribution

Interior Span:

M(-)= 1186.149611 kft

M(+)= 638.6959444 kft

End Span: Slab w/o Interior beams w/o edge beam

$M(-_{interior})$= 1277 kft

M(+)= 949 kft

$M(-_{exterior})$= 474 kft

Column Strip: Smaller of $.25L_1$ and $.25L_2$ either side of a column

Interior Column Strip= 17.5 ft

Edge Column Strip= 8.75 ft

Middle Strip: Bounded by column strips

Middle Strip= 17.5 ft

L_1/L_2= 1

$\alpha_{f2}=\alpha_S$= 0

$\alpha_{f1}L_2/L_1$= 0

Column Strip Moment Factors:

Interior (-)= 0.75 13.6.4.4 ACI 318

Positive (+)= 0.6 13.6.4.1 ACI 318

C= $\Sigma(1-.63x/y)x^3y/3$

C= 0 edge beams only

βt= (EcbC)/(2EcsIs)

βt= 0

Exterior (-)= 1 13.6.4.2 ACI 318

Moment: Interior Span

Column Stip Interior (-)= 889.6122083 kft

Middle Strip Interior (-)= 296.5 kft

Column Stip Positive (+)= 383.2175667 kft

Middle Strip Positive (+)= 255.5 kft

Column Stip Exterior (-)= Does Not Apply

Middle Strip Exterior (-)= Does Not Apply

Beam/Slab Distribution Applies only for support beams and/or edge beams

Column Strip Interior (-)

Beam Coefficient= 0 13.6.5 ACI 318

Beam Moment= 0 kft

Slab Coefficient= 1

Slab Moment= 889.6122083 kft

Column Strip Positive (+)

Beam Coefficient= 0 13.6.5 ACI 318

Beam Moment= 0 kft

Slab Coefficient= 1

Slab Moment= 383.2175667 kft

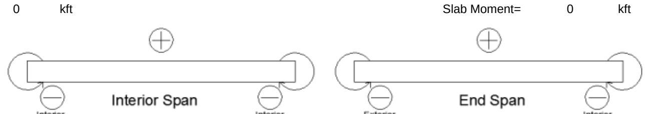
Column Strip Exterior (-)

Beam Coefficient= 0 13.6.5 ACI 318

Beam Moment= 0 kft

Slab Coefficient= 1

Slab Moment= 0 kft



Summary	Positive (kft)	Interior Negative (kft)	Exterior Negative (kft)
Beam	0.0	0.0	0.0
Column Strip Slab	383.2	889.6	0.0
Middle Strip Slab	255.5	296.5	0.0

Summary	Positive (kft)	Interior Negative (kft)	Exterior Negative (kft)
Beam	0.0	0.0	0.0
Column Strip Slab	383.2	889.6	0.0
Middle Strip Slab	255.5	296.5	0.0

Flexural Reinforcement

m= fy/(.85f'c)
m= 17.64705882
R_u= Mu/(φbd^2)
ρ= (1-(1-(2R_um/fy))$^{.5}$)/m
$A_{s(min)}$= .0018bh
$Spacing_{maximum}$= 2h= 28 in

Long Direction

	Column Strip			Middle Strip		
	+	Int. (-)	Ext. (-)	+	Int. (-)	Ext. (-)
Moment (kft)	383.2	889.6	0.0	255.5	296.5	0.0
b (in)	210	210	105	210	210	210
d (in)	12.75	12.75	12.75	12.75	12.75	12.75
h (in)	14	14	14	14	14	14
fy (ksi)	60	60	60	60	60	60
f'c (ksi)	4	4	4	4	4	4
R_u (ksi)	0.150	0.347	0.000	0.100	0.116	0.000
ρ	0.003	0.006	0.000	0.002	0.002	0.000
A_s (in^2)	6.833	16.391	0.000	4.520	5.260	0.000
$A_{s(min)}$ (in^2)	5.292	5.292	2.646	5.292	5.292	5.292
Bars Used	**7**	**7**	**7**	**7**	**7**	**7**
$A_{s(used)}$, each (in^2)	0.6	0.6	0.6	0.6	0.6	0.6
# bars required	11.4	27.3	4.4	8.8	8.8	8.8
spacing (in)	17.5	7.5	21.0	23.3	23.3	23.3
Use						
# bars	**15**	**30**	**7**	**15**	**15**	**15**
spacing (in)	14	7	15	14	14	14
$A_{s(provided)}$ (in^2)	9	18	4.2	9	9	9

Short Direction

	Column Strip			Middle Strip		
	+	Int. (-)	Ext. (-)	+	Int. (-)	Ext. (-)
Moment (kft)	383.2	889.6	0.0	255.5	296.5	0.0
b (in)	210	210	105	210	210	210
d (in)	12.75	12.75	12.75	12.8	12.75	12.75
h (in)	14	14	14	14	14	14
fy (ksi)	60	60	60	60	60	60
f'c (ksi)	4	4	4	4	4	4
R_u (ksi)	0.150	0.347	0.000	0.100	0.116	0.000
ρ	0.003	0.006	0.000	0.002	0.002	0.000
A_s (in2)	6.833	16.391	0.000	4.520	5.260	0.000
$A_{s(min)}$ (in2)	5.292	5.292	2.646	5.292	5.292	5.292
Bars Used	**7**	**7**	**7**	**7**	**7**	**7**
$A_{s(used)}$, each (in2)	0.6	0.6	0.6	0.6	0.6	0.6
# bars required	11.4	27.3	4.4	8.8	8.8	8.8
spacing (in)	17.5	7.5	21.0	23.3	23.3	23.3
Use						
# bars	**15**	**30**	**7**	**15**	**15**	**15**
spacing (in)	14	7	15	14	14	14
$A_{s(provided)}$ (in^2)	9	18	4.2	9	9	9

Moment and Shear Transfer from Slab to Column

applies to end spans without edge beams

Long Direction

Include? **No**
b, Column Diameter + (2)(1.5h)= 58 in
γ_f= 1/(1+(2/3)(b_1/b_2)$^{.5}$)
γ_f= 0.56957524
M_u= 0.0 kft
$\gamma_f M_u$= 0 kft
Add **3** # **4**
for a total of **6** # **4** across b
As= 1.2 in^2
a= $A_s$fy/(.85f'cb)
a= 0.365111562 in
φMn=Mu= φ$A_s$fy(d-a/2)
φMn=Mu= 67.86419878 kft ok
Across full column strip at end: **10** # **4**
As= 2 in^2
a= 0.336134454 in
Mn= 125.8193277 kft
γ_v= 0.43042476
$\gamma_v M_n$= 54.15575389 kft
A_c= (2a+b)d= 937.125 in^2
c_{AB}= 6.811437075 in
Jc= d[2a^3/3-(2a+b)(c_{AB})2]+ad^3/6
J_c= 59466.38078 in^4
V_u= 72.54383681 k
v_u= (V_u/A_c)+($\gamma_v M_n c_{AB}$/J_c)
v_u= 151.8487823 psi
4(f'c$^{.5}$)= 252.9822128 psi
ok

Short Direction

Include? **No**
b, Column Diameter + (2)(1.5h)= 58 in
γ_f= 1/(1+(2/3)(b_1/b_2)$^{.5}$)
γ_f= 0.56957524
M_u= 0.0 kft
$\gamma_f M_u$= 0 kft
Add **3** # **4**
for a total of **6** # **4** across b
As= 1.2 in^2
a= $A_s$fy/(.85f'cb)
a= 0.365111562 in
φMn=Mu= φ$A_s$fy(d-a/2)
φMn=Mu= 67.86419878 kft ok
Across full column strip at end: **10** # **4**
As= 2 in^2
a= 0.336134454 in
Mn= 125.8193277 kft
γ_v= 0.43042476
$\gamma_v M_n$= 54.15575389 kft
A_c= (2a+b)d= 937.13 in^2
c_{AB}= 6.811437075 in
Jc= d[2a^3/3-(2a+b)(c_{AB})2]+ad^3/6
J_c= 59466.38078 in^4
V_u= 72.54383681 k
v_u= (V_u/A_c)+($\gamma_v M_n c_{AB}$/J_c)
v_u= 151.8487823 psi
4(f'c$^{.5}$)= 252.9822128 psi
ok

Appendix B - Plastic Voided Slab Design

This appendix includes the calculations for plastic voided slab bays used in the parametric study.

Plastic Voided Slab Design
Project: 20 x 20 PVS
Engineer: CJM
Date: 9/27/2013
Sheet No: 1 of 2

Assumed thickness, h=	10	in	Void Diameter, D=	7	in
1/2 axis spacing, a=	4	in	Slab Weight=	64.89844	psf
f'c=	4000	psi			
fy=	60000	psi			

Moment Design

$\mu_{ms} \leq 0.2$, use solid slab design practice to evaluate voided slab

μ_{ms}=	$M_u 1.96D/(f'ch^3)$		
w_u=	0.23	k/ft^2	20psf superimposed dead + 80psf live
L_n=	20	ft	
M_u=	$w_u L_n^2/8$		
M_u=	11.5	kft/ft	
μ_{ms}=	0.039445		
$\mu_{ms} \leq 0.2$?	YES, USE MODIFIED SOLID SLAB DESIGN		

Determine modified neutral axis

μ_{ms}=	$[(d_n - c_{void})z_{void}]/(d_n z)$	
c_{void}=	h-D-d'assumed	
$d'_{assumed}$=	1.25	in
c_{void}=	1.75	in
z_{void}=	D	
z_{void}=	7	in
z=	$(h-D-d'_{assumed})/2+D$	
z=	7.875	in
dn=	1.83	

ΦMn≥Mu

ΦMn=	$\Phi A_s fy(d-d_n/2)$				
d=		8.75	in		
Mu=	20 ft *			11.5	kft/ft
Mu=		230	kft		
Φ=		0.9			
$A_{s,req}$=	$Mu/(\Phi fy(d-d_n/2))$				
$A_{s,req}$=		6.52343473	in^2		
Assume #	4 bars				
		0.2	in^2/each		
Need		33	bars		
Spacing=		7.272727273	in		

	Project:	20 x 20 PVS		
	Engineer:	CJM		
	Date:	9/27/2013		
	Sheet No:	2	of	2

Shear Design

v_{ed}=	$V_{max}/(u_{col}d_{om})$		
V_{max}=	92	k	
u_{col}=	64	in, column perimeter	
d_{om}=	$.5(d_x+d_y)$	mean effective depth of slab	
d_x=	10	in, slab depth in x direction from column	
d_y=	10	in, slab depth in y direction from column	
d_{om}=	10	in	
v_{ed}=	143.75	psi	
$v_{rd,max}$=	$.5vf_{cd}$		
v=	.6/[1-(f'c/36260)]		
v=	0.674395536		
f_{cd}=	f'c/1.5		
f_{cd}=	2666.666667	psi	
$v_{rd,max}$=	1798.388097	psi	
If $v_{ed} \geq v_{rd,max}$ eliminate voids around column			
$v_{ed} \geq v_{rd,max}$?	no		
If above is yes, check the following			
$v_{Rd,c}$=	$.63k(100\rho_l f'c)^{1/3} \geq v_{min}$		
k=	$1+(200/d_{om})^{1/2} \leq 2$		
k=	2		
ρ_l=	0.02		
v_{min}=	$.426k^{3/2}f'c^{1/2}$		
v_{min}=	76.20519667	psi	
$v_{Rd,c}$=	76.20519667	psi	
$v_{BD\ Rd,c}$=	$.6v_{Rd,c}$		
$v_{BD\ Rd,c}$=	45.723118	psi	
u_{solid}=	$V_{max}/(v_{BD\ Rd,c}d_{om})$		
u_{solid}=	201.2111247	in	solid perimeter
u=	$2\pi a+2(bx+by)$		
bx=	16	in	
by=	16	in	
a=	21.83784719	in	distance from column face to void region

Plastic Voided Slab Design
Project: 25 x 25 PVS
Engineer: CJM
Date: 9/27/2013
Sheet No: 1 of 2

Assumed thickness, h=	10	in	Void Diameter, D=	7	in
1/2 axis spacing, a=	4	in	Slab Weight=	64.89844	psf
f'c=	4000	psi			
fy=	60000	psi			

Moment Design

$\mu_{ms} \leq 0.2$, use solid slab design practice to evaluate voided slab

μ_{ms}=	$M_u 1.96D/(f'ch^3)$		
w_u=	0.23	k/ft^2	20psf superimposed dead + 80psf live
L_n=	25	ft	
M_u=	$w_u L_n^2/8$		
M_u=	17.96875	kft/ft	
μ_{ms}=	0.061632813		
$\mu_{ms} \leq 0.2$?	YES, USE MODIFIED SOLID SLAB DESIGN		

Determine modified neutral axis

μ_{ms}=	$[(d_n - c_{void})z_{void}]/(d_n z)$	
c_{void}=	h-D-d'assumed	
$d'_{assumed}$=	1.25	in
c_{void}=	1.75	in
z_{void}=	D	
z_{void}=	7	in
z=	$(h-D-d'_{assumed})/2+D$	
z=	7.875	in
dn=	1.88	

ΦMn≥Mu

ΦMn=		$\Phi A_s fy(d-d_n/2)$			
d=		8.75	in		
Mu=	25	ft	*	17.96875	kft/ft
Mu=		449.21875	kft		
Φ=		0.9			
$A_{s,req}$=		$Mu/(\Phi fy(d-d_n/2))$			
$A_{s,req}$=		12.78186798	in^2		
Assume #	4	bars			
		0.2	in^2/each		
Need		64	bars		
Spacing=		4.6875	in		

	Project:	25 x 25 PVS		
	Engineer:	CJM		
	Date:	9/27/2013		
	Sheet No:	2	of	2
	Shear Design			
v_{ed}=		$V_{max}/(u_{col}d_{om})$		
V_{max}=		143	k	
u_{col}=		64	in, column perimeter	
d_{om}=		$.5(d_x+d_y)$	mean effective depth of slab	
d_x=		10	in, slab depth in x direction from column	
d_y=		10	in, slab depth in y direction from column	
d_{om}=		10	in	
v_{ed}=		223.4375	psi	
$v_{rd,max}$=		$.5vf_{cd}$		
v=		.6/[1-(f'c/36260)]		
v=		0.674395536		
f_{cd}=		f'c/1.5		
f_{cd}=		2666.666667	psi	
$v_{rd,max}$=		1798.388097	psi	
If $v_{ed} \geq v_{rd,max}$ eliminate voids around column				
$v_{ed} \geq v_{rd,max}$?		no		
If above is yes, check the following				
$v_{Rd,c}$=		$.63k(100\rho_l f'c)^{1/3} \geq v_{min}$		
k=		$1+(200/d_{om})^{1/2} \leq 2$		
k=		2		
ρ_l=		0.02		
v_{min}=		$.426k^{3/2}f'c^{1/2}$		
v_{min}=		76.20519667	psi	
$v_{Rd,c}$=		76.20519667	psi	
$v_{BD\ Rd,c}$=		$.6v_{Rd,c}$		
$v_{BD\ Rd,c}$=		45.723118	psi	
u_{solid}=		$V_{max}/(v_{BD\ Rd,c}d_{om})$		
u_{solid}=		312.7520743	in	solid perimeter
u=		$2\pi a+2(bx+by)$		
bx=		16	in	
by=		16	in	
a=		39.59015567	in	distance from column face to void region

Plastic Voided Slab Design
Project: 30 x 30 PVS
Engineer: CJM
Date: 9/27/2013
Sheet No: 1 of 2

Assumed thickness, h=	12	in	Void Diameter, D=	9	in
1/2 axis spacing, a=	4	in	Slab Weight=	85	psf
f'c=	4000	psi			
fy=	60000	psi			

Moment Design

$\mu_{ms} \leq 0.2$, use solid slab design practice to evaluate voided slab

μ_{ms}= $M_u 1.96D/(f'ch^3)$

w_u= 0.26 k/ft^2 20psf superimposed dead + 80psf live

L_n= 30 ft

M_u= $w_u L_n^2/8$

M_u= 29.25 kft/ft

μ_{ms}= 0.074648438

$\mu_{ms} \leq 0.2$? YES, USE MODIFIED SOLID SLAB DESIGN

Determine modified neutral axis

μ_{ms}= $[(d_n - c_{void}) z_{void}]/(d_n z)$

c_{void}= h-D-d'assumed

$d'_{assumed}$= 1.5 in

c_{void}= 1.5 in

z_{void}= D

z_{void}= 9 in

z= $(h-D-d'_{assumed})/2+D$

z= 9.75 in

dn= 1.63

ΦMn≥Mu

ΦMn= $\Phi A_s fy(d-d_n/2)$

d= 10.75 in

Mu= 30 ft * 29.25 kft/ft

Mu= 877.5 kft

Φ= 0.9

$A_{s,req}$= $Mu/(\Phi fy(d-d_n/2))$

$A_{s,req}$= 19.62757927 in^2

Assume # 6 bars

0.44 in^2/each

Need 45 bars

Spacing= 8 in

	Project:	30 x 30 PVS		
	Engineer:	CJM		
	Date:	9/27/2013		
	Sheet No:	2	of	2

Shear Design

v_{ed}=	$V_{max}/(u_{col}d_{om})$		
V_{max}=	235	k	
u_{col}=	64	in, column perimeter	
d_{om}=	$.5(d_x+d_y)$	mean effective depth of slab	
d_x=	12	in, slab depth in x direction from column	
d_y=	12	in, slab depth in y direction from column	
d_{om}=	12	in	
v_{ed}=	305.9895833	psi	
$v_{rd,max}$=	$.5vf_{cd}$		
v=	.6/[1-(f'c/36260)]		
v=	0.674395536		
f_{cd}=	f'c/1.5		
f_{cd}=	2666.666667	psi	
$v_{rd,max}$=	1798.388097	psi	
If $v_{ed} \geq v_{rd,max}$ eliminate voids around column			
$v_{ed} \geq v_{rd,max}$?	no		
If above is yes, check the following			
$v_{Rd,c}$=	$.63k(100\rho_l f'c)^{1/3} \geq v_{min}$		
k=	$1+(200/d_{om})^{1/2} \leq 2$		
k=	2		
ρ_l=	0.02		
v_{min}=	$.426k^{3/2}f'c^{1/2}$		
v_{min}=	76.20519667	psi	
$v_{Rd,c}$=	76.20519667	psi	
$v_{BD\ Rd,c}$=	$.6v_{Rd,c}$		
$v_{BD\ Rd,c}$=	45.723118	psi	
u_{solid}=	$V_{max}/(v_{BD\ Rd,c}d_{om})$		
u_{solid}=	428.3026659	in	solid perimeter
u=	$2\pi a+2(bx+by)$		
bx=	16	in	
by=	16	in	
a=	57.98061903	in	distance from column face to void region

Plastic Voided Slab Design
Project: 35 x 35 PVS
Engineer: CJM
Date: 9/27/2013
Sheet No: 1 of 2

Assumed thickness, h=	14	in	Void Diameter, D=	10.5	in
1/2 axis spacing, a=	4	in	Slab Weight=	100	psf
f'c=	4000	psi			
fy=	60000	psi			

Moment Design

$\mu_{ms} \leq 0.2$, use solid slab design practice to evaluate voided slab

μ_{ms}=	$M_u 1.96D/(f'ch^3)$		
w_u=	0.28	k/ft^2	20psf superimposed dead + 80psf live
L_n=	35	ft	
M_u=	$w_u L_n^2/8$		
M_u=	42.875	kft/ft	
μ_{ms}=	0.080390625		
$\mu_{ms} \leq 0.2$?	YES, USE MODIFIED SOLID SLAB DESIGN		

Determine modified neutral axis

μ_{ms}=	$[(d_n - c_{void}) z_{void}]/(d_n z)$	
c_{void}=	h-D-d'assumed	
$d'_{assumed}$=	1.5	in
c_{void}=	2	in
z_{void}=	D	
z_{void}=	10.5	in
z=	$(h-D-d'_{assumed})/2+D$	
z=	11.5	in
dn=	2.2	

ΦMn≥Mu

ΦMn=		$\Phi A_s fy(d-d_n/2)$			
d=		12.5	in		
Mu=	35	ft	*	42.875	kft/ft
Mu=		1500.625	kft		
Φ=		0.9			
$A_{s,req}$=		$Mu/(\Phi fy(d-d_n/2))$			
$A_{s,req}$=		29.25194932	in^2		
Assume #	6	bars			
		0.44	in^2/each		
Need		67	bars		
Spacing=		6.268656716	in		

	Project:	35 x 35 PVS	
	Engineer:	CJM	
	Date:	9/27/2013	
	Sheet No:	2 of 2	

	Shear Design			
v_{ed}=		$V_{max}/(u_{col}d_{om})$		
V_{max}=		340	k	
u_{col}=		64	in, column perimeter	
d_{om}=		$.5(d_x+d_y)$	mean effective depth of slab	
d_x=		14	in, slab depth in x direction from column	
d_y=		14	in, slab depth in y direction from column	
d_{om}=		14	in	
v_{ed}=		379.4642857	psi	
$v_{rd,max}$=		$.5vf_{cd}$		
v=		.6/[1-(f'c/36260)]		
v=		0.674395536		
f_{cd}=		f'c/1.5		
f_{cd}=		2666.666667	psi	
$v_{rd,max}$=		1798.388097	psi	
If $v_{ed} \geq v_{rd,max}$ eliminate voids around column				
$v_{ed} \geq v_{rd,max}$?		no		
If above is yes, check the following				
$v_{Rd,c}$=		$.63k(100\rho_l f'c)^{1/3} \geq v_{min}$		
k=		$1+(200/d_{om})^{1/2} \leq 2$		
k=		2		
ρ_l=		0.02		
v_{min}=		$.426k^{3/2}f'c^{1/2}$		
v_{min}=		76.20519667	psi	
$v_{Rd,c}$=		76.20519667	psi	
$v_{BD\ Rd,c}$=		$.6v_{Rd,c}$		
$v_{BD\ Rd,c}$=		45.723118	psi	
u_{solid}=		$V_{max}/(v_{BD\ Rd,c}d_{om})$		
u_{solid}=		531.147379	in	solid perimeter
u=		$2\pi a+2(bx+by)$		
bx=		16	in	
by=		16	in	
a=		74.34887731	in	distance from column face to void region

Appendix C - Image Copyrights

This section lists the copyright permissions for images not created by the author.

Re: Image Copyrights

DELETE REPLY REPLY ALL FORWARD ...

Stefan Sommer <stefan.sommer@cobiax.com>
Mon 11/18/2013 5:25 AM

mark as unread

To: Corey Midkiff;

Corey,

Permission is granted for the use as described below.

Good luck with your Master's report.

Best regards
Stefan

Am 15.11.2013 um 16:39 schrieb Corey Midkiff <midkiff@ksu.edu>:

> The paper I am writing is called my Master's Report. It is essentially the summary of my research for my Master's Degree.
>
> Corey Midkiff
> Graduate Student-Architectural Engineering
> midkiff@k-state.edu

From: Stefan Sommer <stefan.sommer@cobiax.com>
Sent: Friday, November 15, 2013 1:16 AM
To: Corey Midkiff
Cc: Charlie Caruso
Subject: Fwd: Image Copyrights

Dear Corey

Apologies for the late reply, I have been on a business trip this week.

For what kind of publication would you need these pictures? I need this information for the owners of the pictures (it's not us).

Best regards
Stefan

Stefan Sommer
Marketing Manager

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www.cobiax.com

Winner of Swiss Environmental Award
& German Material Efficiency Award

Anfang der weitergeleiteten Nachricht:

Von: Charlie Caruso <ccaruso@cobiaxusa.com>
Betreff: FW: Image Copyrights
Datum: 12. November 2013 17:57:54 MEZ
An: Christian Roggenbuck <christian.roggenbuck@cobiax.com>, Stefan Sommer <stefan.sommer@cobiax.com>
Kopie: "mrussillo@cobiaxusa.com" <mrussillo@cobiaxusa.com>, "midkiff@k-state.edu" <midkiff@k-state.edu>

Christian/ Stefan
Corey is asking permission to use these photo, could you please answer him for us.
Thanks
Charlie

From: Corey Midkiff [mailto:midkiff@ksu.edu]
Sent: Monday, November 11, 2013 4:07 PM
To: ccaruso@cobiaxusa.com
Subject: Image Copyrights

Mr. Caruso,

A few months back, you shared some information with me about Cobiax to assist with a paper I am writing on plastic voided slab systems. The information was really helpful and I am very grateful for it. I was hoping you might be able to grant me permission for images from the documents you sent me. I have attached the images to this email. They are from the following buildings:
Miami Art Museum
UEFA Headquarters
Altra Sede

The images from the last two were taken from the 2010 customer magazine which I have also attached as reference. If I could have your companies permission to use these images, I would greatly appreciate it.

Corey Midkiff
Graduate Student-Architectural Engineering
midkiff@k-state.edu
