2009-2010 AE Senior Thesis

Technical Report II

Structural Study of Alternate Floor Systems for University Medical Center at Princeton

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Executive Summary

This report investigates alternate floor systems and compares those designs with the existing steel composite beam floor system for the New Hospital at the University Medical Center at Princeton. The three other floor systems considered are:

a. Precast hollow core plank
b. Two-way flat slab
c. One-way slab with beams

The typical bay size in the New Hospital is 30'x30'. These bays are strung along the north and south facades with a row of 18'x30' bays in the middle. For this report, a typical three-bay section of the floor plan was taken in both the N-S and E-W direction and used to analyze each system.

The criterion established to effectively evaluate these floor systems is as follows: lateral system impact, foundation impact, overall weight, fire protection, depth, floor layout impact, constructability, cost, vibration, and deflection.

Floor vibration was determined to be the governing factor for the design of the slabs. This is due to the fact that the building is a hospital with patients, doctors, and machinery sensitive to slight oscillating of the floor system. Using AISC Design Guide 11, thicknesses for each system were determined according to vibration requirements. From there, the flexural and shear capacities were checked using hand calculations, RAM Structural System, ACI 318-08, and Nitterhouse specifications. RS Means was used to determine approximate costs for each system.

Upon completion of the analysis, the existing steel composite beam floor system was determined to be the best option of the four systems considered. The main advantage of this system is that it is much lighter than the other three options. Any of the other choices would have caused substantial changes to the foundation and lateral force resisting system. The composite system also performed the best under vibration, a critical requirement for a hospital.

The two-way flat slab remains a viable option simply because it is 10" shallower than the composite system and also performs well with floor vibrations. The remaining two systems are eliminated from further consideration because they require too much foundation and floor layout adjustment.

Introduction

The University Medical Center at Princeton is a new state-of-the-art medical facility currently under construction in Plainsboro, NJ. The project consists of a Central Utility Plant, a Diagnostic and Treatment Center (D&T) and a New Hospital. The site already has an existing building (Building #2) and it will be connected to the north side of the New Hospital as part of the project. The Medical Office Building (MOB) is only proposed at this time. The 800,000 square foot complex is set to be complete by the summer of 2010.

The scope of this thesis project will be limited to structural analysis and re-design of the New Hospital (Figure 1). This is the tallest portion of the complex at 92'-0" from grade to roof with a 14'-0" metal panel system above for a total height of 106'-0" above grade.

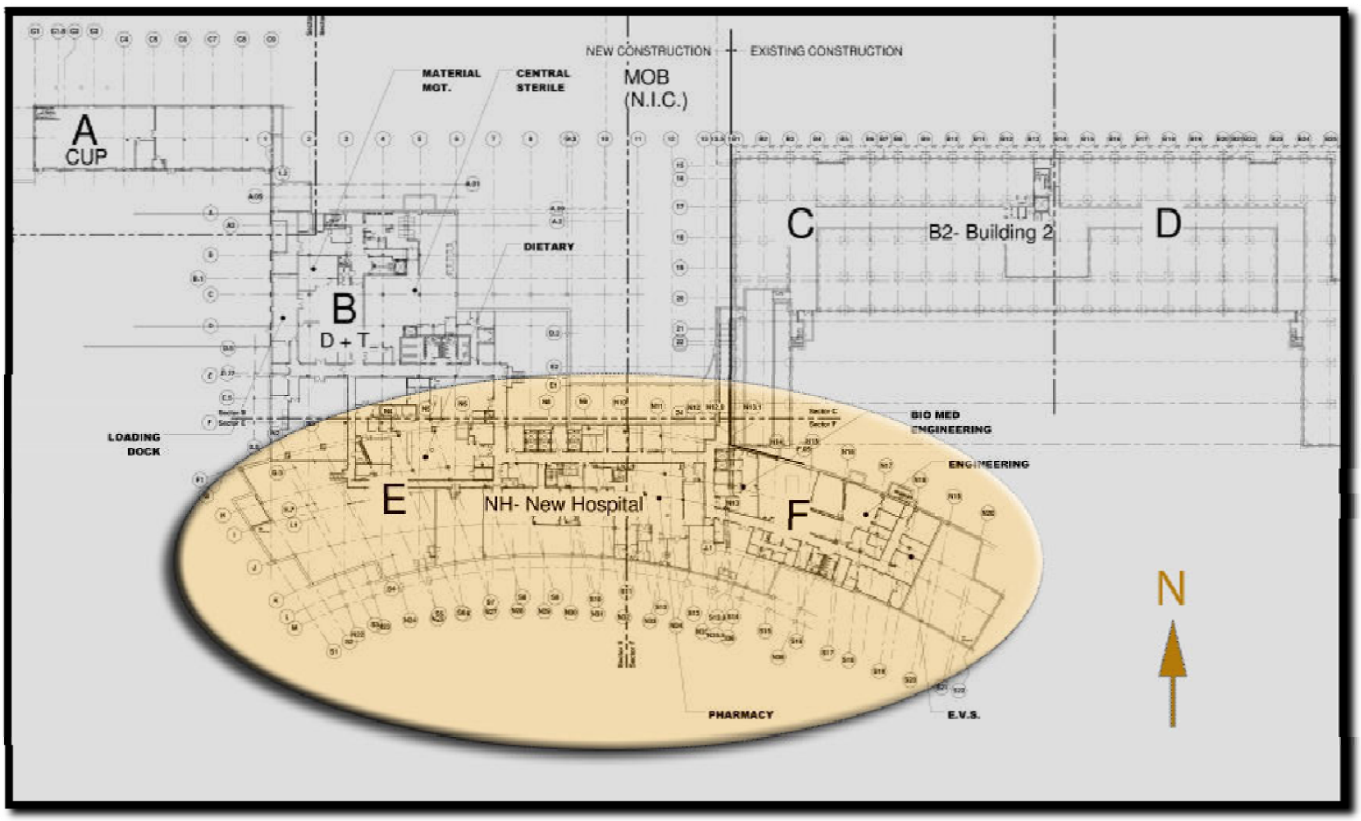


Figure 1: Overall Plan University Medical Center at Princeton

The designed floor system for the New Hospital is a composite beam with lightweight concrete slab on top of composite deck. The purpose of this report is to analyze three alternate floor systems and compare the results with the current floor system. The floor systems selected are as follows:

1. Precast Hollow Core Plank
2. Two Way Flat Slab
3. One Way Slab with Beams

The precast hollow core plank was chosen because it is a viable structural steel framing alternative to the composite beam. It also fits into the typical bay size for this building. A two way flat slab and one way slab with beams are practical systems which provide a comparison between the existing steel framing and concrete framing.

In order to effectively compare the four systems, a typical three-bay span in both directions was selected (see Figure 2 below). Since the moments in a two-way slab vary along the length of the frame, it was necessary to consider this large of an area (Figure 3 on next page). The final comparison however only considers a single 30' x 30' bay (Figure 4 next page).

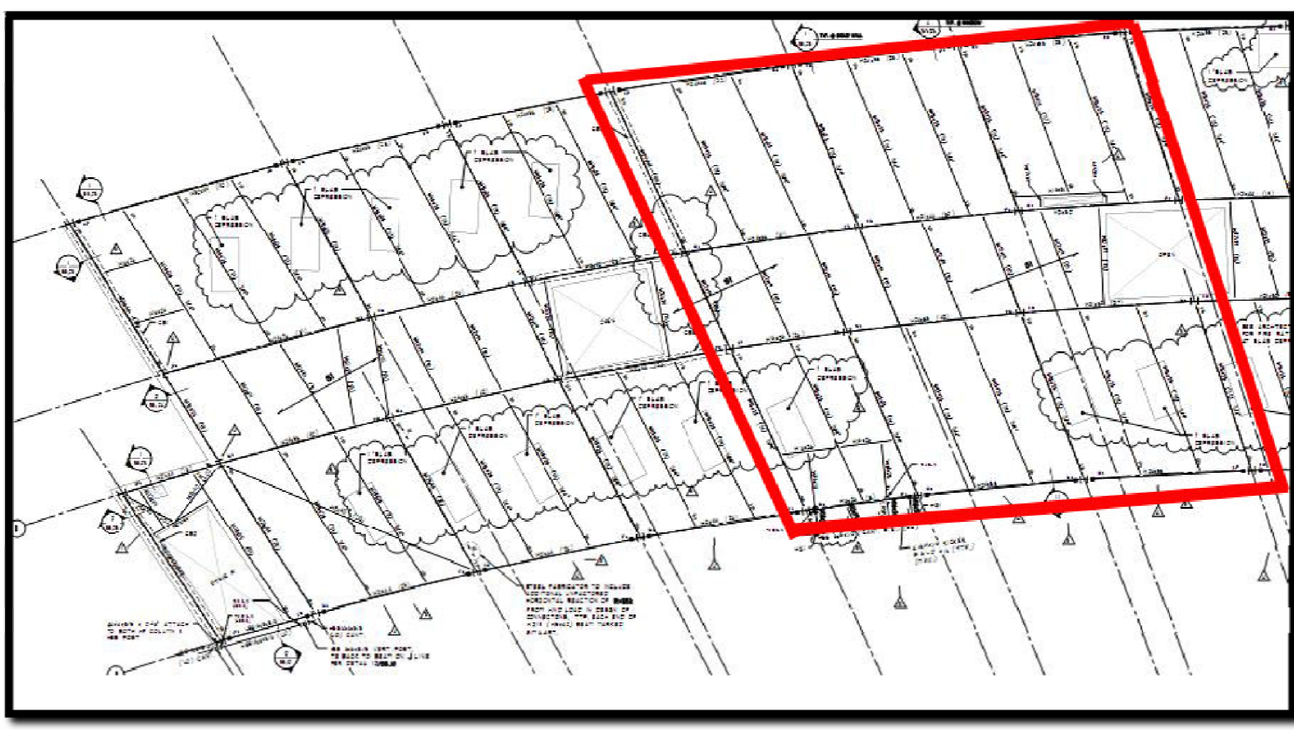


Figure 2: Three-bay span in both directions

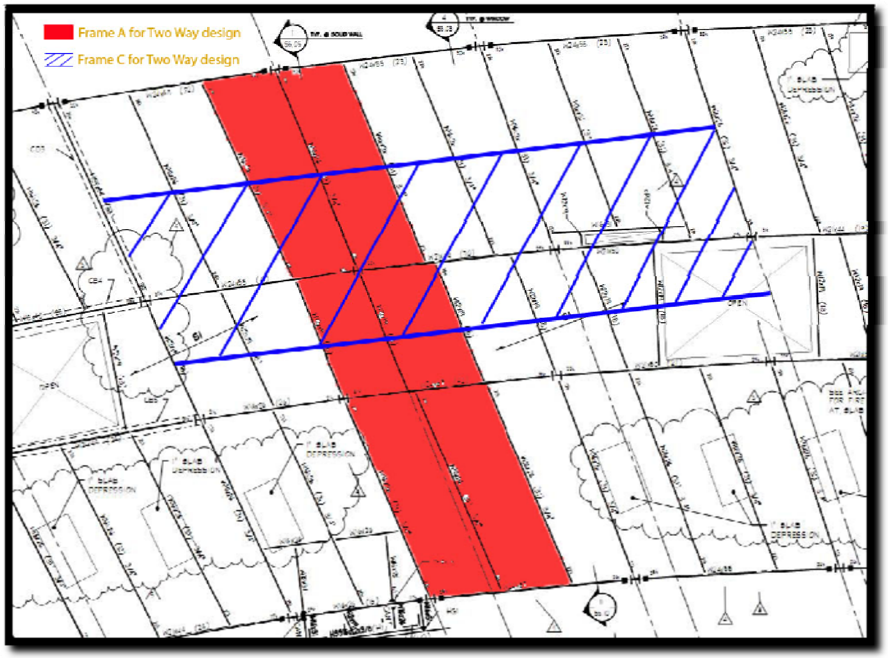


Figure 3: Designated frames for two-way flat slab design

It should be noted that other options were considered for this report but some were determined to not be feasible. A castellated beam system was considered in an attempt to better coordinate the MEP systems with the structural system. However the typical span length (30') is not long enough to gain full efficiency from a castellated beam. To avoid a drastic adjustment to the column layout, this system was discarded.

Another floor system under early consideration was a post-tensioned slab. It was discovered that this floor system is not ideal for a hospital since heavy medical equipment could not easily be attached and/or removed from the floor without damaging the tendons near the top of the slab.

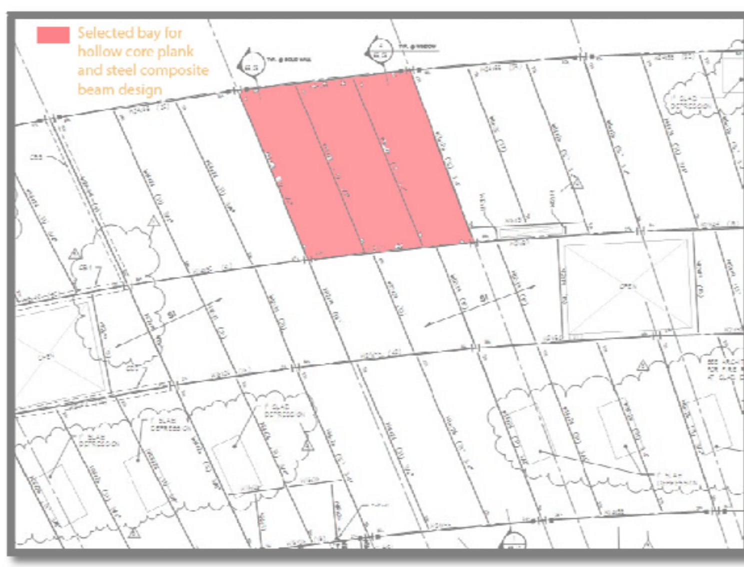


Figure 4: 30'x30' bay used for final comparison of all floor systems

Structural System Overview

The structural system of the New Hospital at the University Medical Center was designed by O'Donnell & Naccarato Structural Engineers using a Load Resistance Factor Design approach. It is a structural steel building with a composite floor diaphragm. Braced frames run in both directions and there are two long moment frames spanning the entire length of the building on both the south and north facades. Both the braced and moment frames are the building's main resistance to lateral load. Due to the great length of the building in the west-east direction, an expansion joint was placed at a distance from the western façade roughly equal to 2/3 of the total building length. This effectively splits the building into two different structures which behave on their own.

Foundation

Concrete piers with sizes anywhere from 18" x 18" to 48" x 78" are attached to the base of the steel columns and transmit vertical load from the superstructure to the concrete spread footings. The size of these footings varies from as small as 3'-0" x 3'-0" x 14" to as large as 21' x 21' x 50".

All footings supporting braced frame columns have mini-piles attached at their base in order to help with the high tension forces resulting from lateral loading. These piles extend to decomposed bedrock (8'-30' deep) and provide a tensile capacity of up to 150 kips. The top of all exterior footings are at a minimum depth of 42" below grade.

The floor at the base level is concrete slab-on-grade with thicknesses from 4"-12".

Huge concrete retaining walls with footings up to 17'-0" wide trace the perimeter of the foundation system.

Superstructure

The structural steel provides both gravity and lateral load resistance for the building. Columns are typically W14 while beams and girders range from W12-W27 shapes. Rectangular HSS shapes are used for the diagonal members in the braced frames and round HSS columns support the massive glass façade on the south face of the hospital. The HSS columns are intentionally exposed for architectural purposes. The floor layout is uniform and has a typical bay size of 30' x 30'.

The floor system spanning over the main area of the building is composite construction. Typically, the concrete slab is 3-1/4" lightweight concrete poured over a 3" composite metal deck. In certain mechanical and roof areas, the floor system switches to a 6-1/2" normal weight concrete due to higher loads in those areas.

The composite floor is considered to act as a rigid diaphragm and therefore able to transmit lateral forces from the façade to the braced frames. There are six braced frames in the N-S direction for each wing of the hospital. In the W-E direction, there are four braced frames and two long moment frames on the north and south sides of the building. All of these frames contribute to the lateral force resisting system.

Lateral System

The primary components of the lateral force resisting system in the New Hospital are braced and moment frames. Expansion joints are located between the D&T building and the New Hospital and within the New Hospital itself at about 2/3 the length of the building from the west façade.

On the western wing of the facility, there are six braced frames running in the N-S direction. In the W-E direction, there are four braced frames and two long moment frames. The eastern wing has a similar layout with six braced frames in the N-S and four in the W-E as well as two moment frames in the W-E.

Materials

All of the major structural materials incorporated into the design of the New Hospital at the University Medical Center are listed in Figure 5 below. The corresponding material strengths are to the right of each item.

Concrete	
Footings	f'c = 3000 psi
Retaining walls	f'c = 3000 psi
Foundation walls	f'c = 3000 psi
Piers	Min. of f'c = 3000 psi
Slab on grade	f'c = 3500 psi
Slab on metal deck	f'c = 4000 psi
Lightweight concrete	f'c = 3500 psi
Structural Steel	
Wide Flange Shapes	ASTM A992
Rectangular/Square HSS Shapes	ASTM A500 Grade B
Steel Pipe Sections	ASTM A501 or ASTM A53, Type E or S, Grade B
Angles	ASTM A36
Plates	ASTM A36
¾" Bolts	A325 or A490
Anchor Rods	ASTM F1554 Grade 55
Welding Electrode	E70XX
Reinforcement	
Reinforcing bars	ASTM A615 Grade 60
Welded Wire Fabric	ASTM A185
Decking	
Roof deck	1-1/2" Galvanized Type B Metal Deck, 22 Ga.
Floor deck	3" LOK-Floor Composite Metal Deck, 20 or 18 Ga.
¾" Shear Studs	ASTM A108
Masonry	
Solid Units	ASTM C90, f'c = 1900 psi
Hollow Units	ASTM C90, f'c = 1900 psi
Ivany Units	f'c = 3000 psi
Grout	f'c = 3000 psi
Brick	ASTM C216 Grade SW, f'c = 3000 psi

Figure 5: Structural materials used and design strengths

Design Loads

Live loads were obtained from ASCE7-05 and are considered to be the absolute minimum design loads allowed for a hospital (Figure 6). Most of the dead loads are assumed based upon standard industry practice (Figure 7). For a preliminary analysis such as this, these assumptions are practical. The weight of lightweight and normal weight concrete was calculated and is considered to be accurate. This calculation can be found in Appendix C.

Live Loads	
First Floor Corridors	100 psf
Lobbies	100 psf
Corridors above First Floor	80 psf
Patient Rooms	40 psf
Operating Rooms	60 psf
Roof	20 psf
Penthouse Floor	100 psf
Offices	50 psf
Stairs	100 psf
Partitions	20 psf

Figure 6: Live loads per ASCE7-05

Dead Loads	
Superimposed	
MEP	8 psf
Ceiling	5 psf
Total	13 psf
Typical Floor	
3" metal deck	3 psf
3-1/4" LW concrete	48 psf
Allowance for steel framing	5 psf
Total	56 psf
Mechanical Roof	
3" metal deck	3 psf
6-1/2" NW concrete	100 psf
Allowance for steel framing	7 psf
Total	110 psf
Hospital Roof	
3" metal deck	3 psf
6-1/2" NW concrete	100 psf
Allowance for steel framing	6 psf
MEP	20 psf
Total	129 psf
Walls	
Curtain wall	25 psf

Figure 7: Assumed dead loads

Some of the design loads used by the designers at O'Donnell and Naccarato differed from those loads listed in the tables above. For a typical floor, the design dead load was 65 psf and the design live load was 85 psf. The design dead load for the hospital roof was 140 psf. Because this facility is a hospital it is not unusual for the designer to use higher load values in order to guarantee a safer design.

Design Considerations

In order to have a complete investigation of the floor systems considered in this report, a set of criterion was established and grouped into appropriate categories.

Structural	Architectural	Construction	Serviceability
Weight	Depth	Constructability	Deflection
Lateral system impacts	Floor plan adjustments	Cost	Vibration
Foundation impacts			
Fire protection			

The layout chosen for the floor system design is a three-bay span located on the north end of the New Hospital. This area of the floor plan is mainly patient rooms so a live load of 40 psf was used along with the universal superimposed dead load of 33 psf*.

Due to the sensitivity of patients, surgeons, and medical equipment, vibration is a significant factor in the design of floor systems for hospitals. Floor vibration affects human beings occupying the space as well as machinery. Therefore, AISC Design Guide 11 has two separate requirements for an operating room. The first requirement states that acceptable vibration for human comfort in an operating room is to be no greater than 0.25% of gravity. The second requirement originally set the maximum vibrational velocity for operating rooms at 8,000 μin/s. This standard was recently changed to 4,000 μin/s.

The design of every floor system considered in this report is governed by these vibration requirements. It is important to note that while the bays being designed are patient rooms and not operating rooms, this design standard was used in order to provide versatility within the floor plan. If the owner ever wanted to re-order the floor layout or add more operating rooms, this design standard would make that possible.

*Note: It is now acknowledged that partition weight should be included with the live load. The slab designs were already completed before this discovery and therefore the slab loading is slightly unconservative. (1.2*33+1.6*40=103.6k as opposed to 1.2*13+1.6*53=100.4k)

Floor System Designs

Composite Steel Beam

The current floor system was analyzed so there could be a proper reference for the other three systems. The composite steel beams and girders were designed under gravity loading using RAM Structural System. The member sizes determined through this analysis were very similar to the original design with some variations in beam weight and amount of shear studs needed.

The designed composite steel beam was also checked for vibration requirements. This analysis was completed by using procedures laid out in AISC Design Guide 11 and can be found in Appendix A. It was determined that the existing floor system met the requirements for human comfort and sensitive equipment (assuming a walking pace of 50 steps/min).

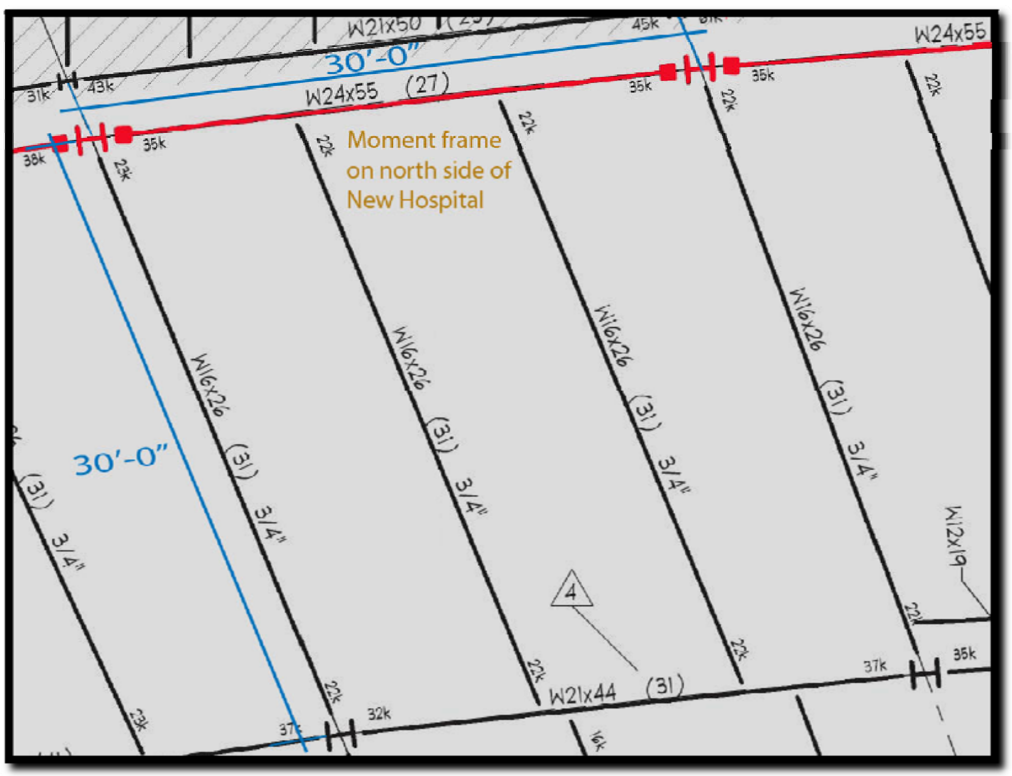


Figure 8: Current framing plan for composite beam floor system

Floor Map

RAM Steel v12.1
DataBase: Composite Beam
Building Code: IBC

Floor Type: Level 4

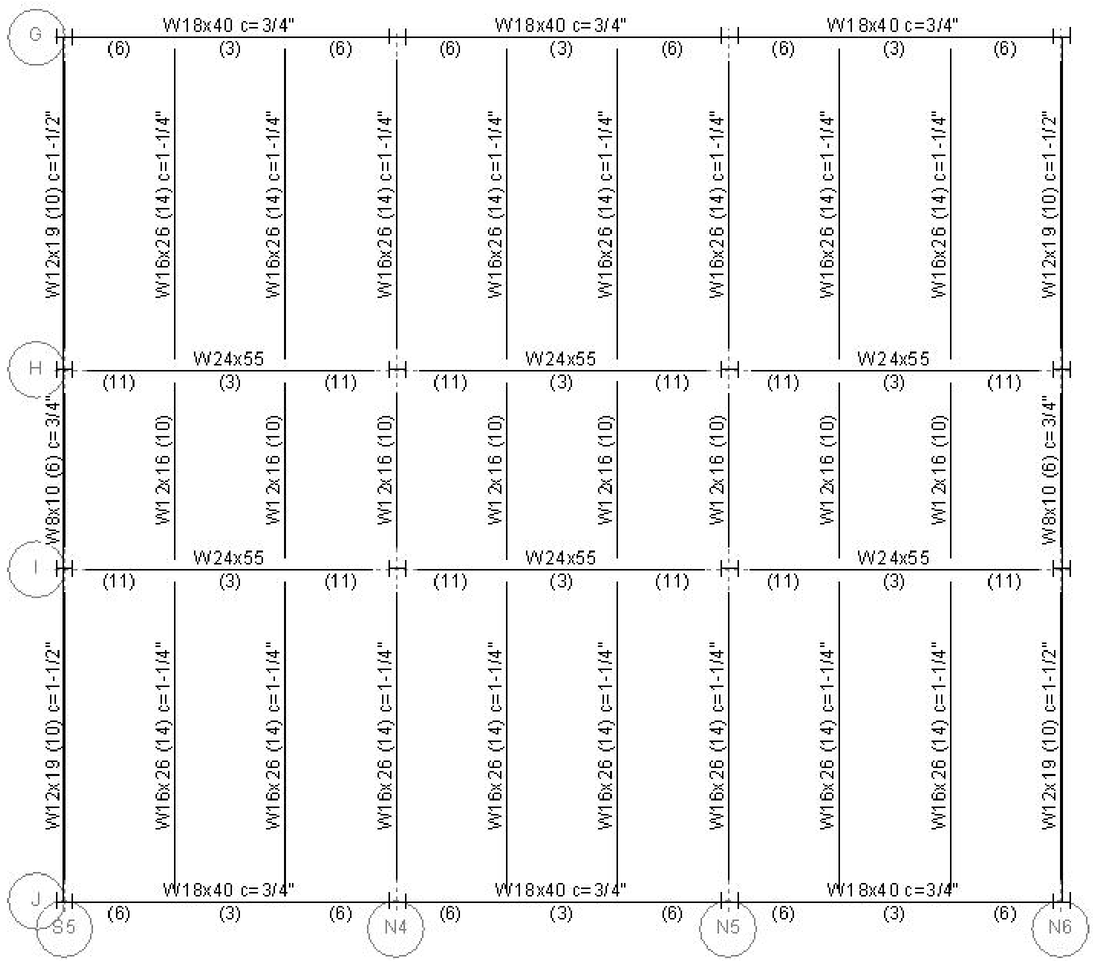


Figure 9: Composite beam and composite girder designs from RAM Structural System

Precast Hollow Core Plank

The first alternative considered is a precast hollow core plank floor system. This system was selected because it is capable of effectively spanning 30'-0" which is the typical span length for this floor layout and it can be placed on a steel frame which provides an alternative to the composite steel beam without having to change the entire structural system of the building.

Design of the hollow core plank for bending was determined to be 12" x 4'-0" with a 2" topping using product specifications from Nitterhouse Concrete Products Inc., a well-known precast concrete producer. For the vibration check, the planks were assumed to have pinned connections at the girder supports. While this plank design met the criteria for sensitive equipment, it fell short of meeting the vibration requirement for human comfort. The 12" plank will still be considered but it will not be a good system for vibration control. The vibration calculation can be found in Appendix B.

The steel girders supporting the planks were designed using RAM Structural System. The results of the design are listed in Figure 10 below.

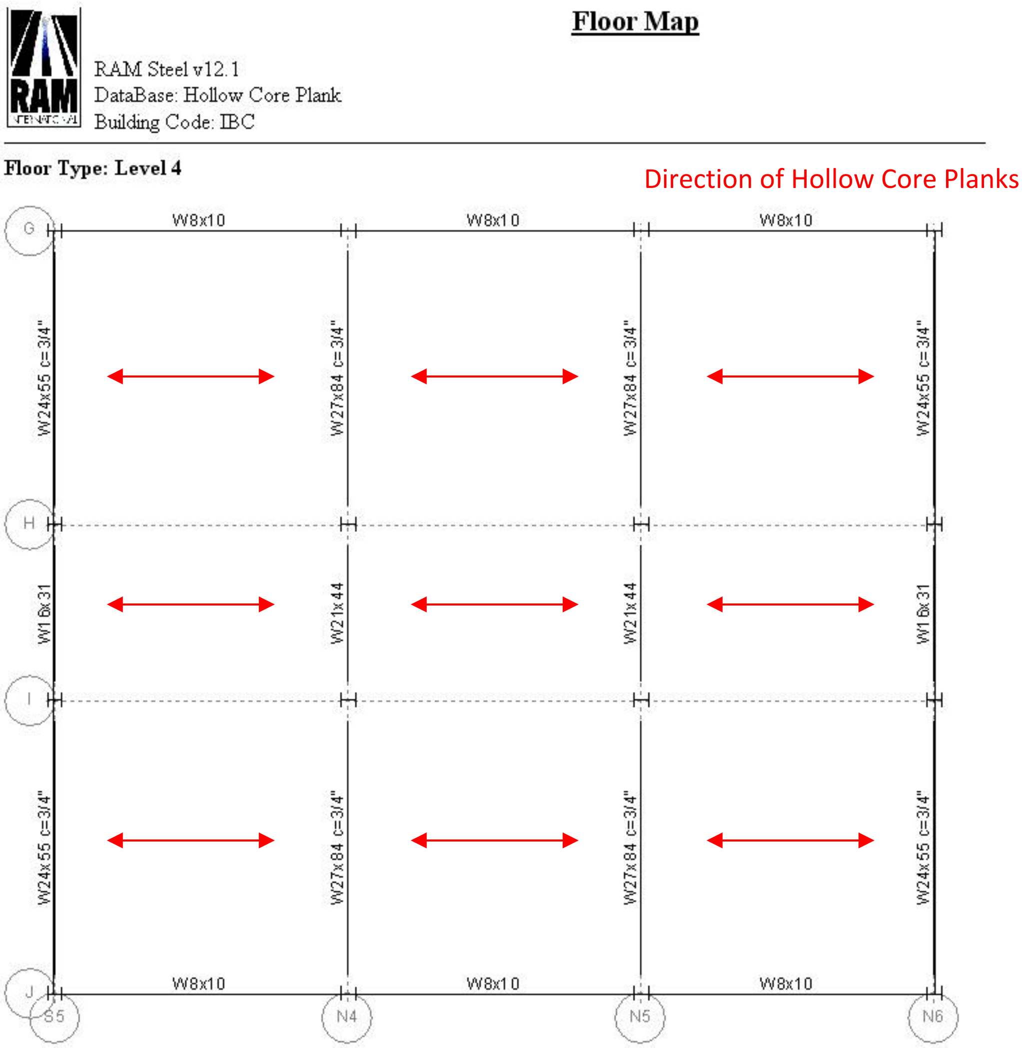


Figure 11: Design of steel girders for hollow core plank system

The steel girders are 27" and 21" deep in their respective 30' and 18' spans. This already will be a problem for the hollow core plank system considering the plank thickness is already 12". In order for this system to be effective, the column layout will have to be squeezed tighter.

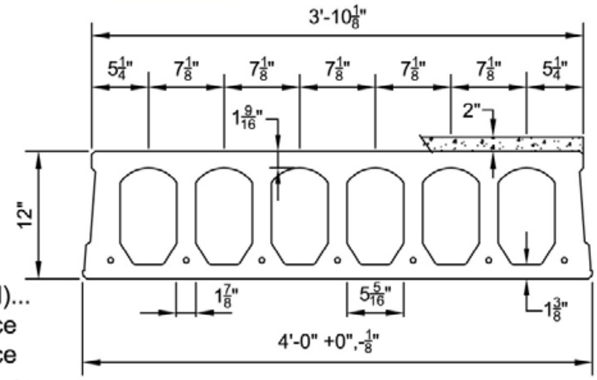
On the next page is the design chart from Nitterhouse. Highlighted in yellow is the weight of the precast member and the maximum allowable load for a 32' span. Since these hollow core planks are 4'-0" wide, all of the floor systems will be evaluated as 4'-0" strips instead of the standard unit strip.

Prestressed Concrete
12"x4'-0" Hollow Core Plank

2 Hour Fire Resistance Rating With 2" Topping

PHYSICAL PROPERTIES
Composite Section

A_c = 361 in.^{2}	Precast b_w = 14.25 in.
I_c = 7840 in.^{4}	Precast S_{bcp} = 1081 in.^{3}
Y_{bcp} = 7.26 in.	Topping S_{tct} = 1644 in.^{3}
Y_{tcp} = 4.74 in.	Precast S_{tcp} = 1653 in.^{3}
Y_{tct} = 6.74 in.	Precast Wt. = 308 PLF
	Precast Wt. = 77.00 PSF



DESIGN DATA

1. Precast Strength @ 28 days = 6000 PSI
2. Precast Strength @ release = 3500 PSI
3. Precast Density = 150 PCF
4. Strand = 1/2"Ø and 0.6"Ø 270K Lo-Relaxation.
5. Strand Height = 1.75 in.
6. Ultimate moment capacity (when fully developed)...
   6-1/2"Ø, 270K = 205.4 k-ft at 60% jacking force
   7-1/2"Ø, 270K = 235.4 k-ft at 60% jacking force
7. Maximum bottom tensile stress is $10\sqrt{f'c}$ = 775 PSI
8. All superimposed load is treated as live load in the strength analysis of flexure and shear.
9. Flexural strength capacity is based on stress/strain strand relationships.
10. Deflection limits were not considered when determining allowable loads in this table.
11. Topping Strength @ 28 days = 3000 PSI. Topping Weight = 25 PSF.
12. These tables are based upon the topping having a uniform 2" thickness over the entire span. A lesser thickness might occur if camber is not taken into account during design, thus reducing the load capacity.
13. All load values are controlled by ultimate flexural strength or fire endurance limits.
14. Load values may be different for IBC 2000 & ACI 318-99. Load tables are available upon request.
15. Camber is inherent in all prestressed hollow core slabs and is a function of the amount of eccentric prestressing force needed to carry the superimposed design loads along with a number of other variables. Because prediction of camber is based on empirical formulas it is at best an estimate, with the actual camber usually higher than calculated values.

SAFE SUPERIMPOSED SERVICE LOADS — IBC 2006 & ACI 318-05 (1.2 D + 1.6 L)

Strand Pattern		SPAN (FEET)																		
		32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	48	50
6 - 1/2"ø	LOAD (PSF)	133	119	107	95	84	74	65	56	49	41	34								
7 - 1/2"ø	LOAD (PSF)	170	154	139	125	113	101	91	81	72	63	56	48	42						

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Chambersburg, PA 17202-9203
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This table is for simple spans and uniform loads. Design data for any of these span-load conditions is available on request. Individual designs may be furnished to satisfy unusual conditions of heavy loads, concentrated loads, cantilevers, flange or stem openings and narrow widths. The allowable loads shown in this table reflect a 2 Hour & 0 Minute fire resistance rating.

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12F2.0T

Two Way Flat Slab

The thickness of the two way flat slab was determined by vibration requirements. In order to determine the natural frequency of the slab, the deflection of the slab under load needs to be approximated.

To begin, an assumption is made stating that the slab is pinned on all four sides (which it is not but that will be adjusted later). The total deflection is equal to $\Delta cx + \Delta my$ where Δcx is the deflection of the slab along the column strip and Δmy is the deflection of the slab in the middle of the bay. Typical transverse distribution of moments in a slab will send 90% of the moment to the column strip and 10% to the middle strip.

The next step will be to assume that Δcx deflects 90% of what it would deflect as a simply supported beam and Δmy deflects 10% of what it would normally deflect as a simply supported beam. Since Δmy sees moment from both sides of the slab, that value increases to 20%. Once the "artificial" deflections are calculated, they are summed together and then multiplied by 0.40. This assumes that the slab is actually 80% rigid. This of course depends on the size of the columns but for now the assumption is made.

The final Δt is used to determine the natural frequency and eventually the necessary thickness needed to meet the vibration guidelines. It is certainly a rough approximation so the values cannot be considered exact. However, it gives a general idea of where the slab thickness needs to be and allows for comparison to other floor systems.

The rest of the slab is designed by hand. These calculations can be viewed in Appendix C.

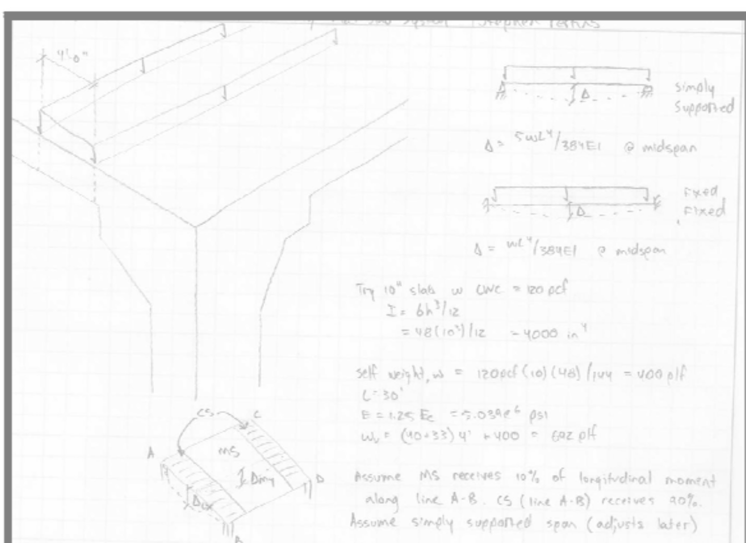


Figure 12: Graphic for deflection of two way flat slab

One Way Slab with Beams

The deflection value for a one-way slab is assumed to be 60% of the deflection for a simply supported beam. This estimation was arrived at by evaluating the mid-span moments of a simply supported beam and a one-way slab with integral beams. The moment in the middle of a simply supported span (wL^2/8) is roughly 40% higher than the moment in the middle of a one-way slab with integral beams (wL^2/14). If the moment decreases by this amount, it is assumed that the deflection will also decrease by roughly the same amount in order to get a “ballpark” figure. Working under this assumption, the natural frequency of the slab can be determined which will lead to a minimum thickness required to meet vibration criterion. This thickness was determined to be 16”. This complete calculation can be found in Appendix D.

The beams were sized using the CRSI Handbook. Even though there are no exterior beams in the bays selected to be designed, the exterior beams were designed anyway. Also note that f’c=4000 psi for these charts. The assumption made in the hand calculations is that f’c=5000 psi. Therefore designing off of this chart is conservative.

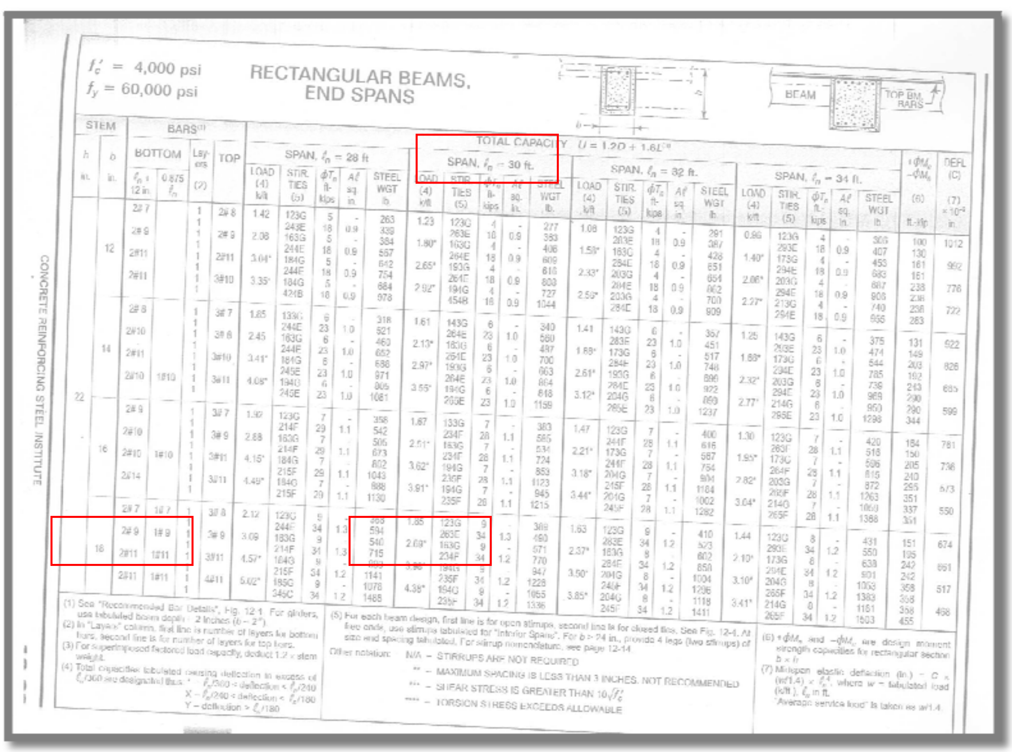


Figure 13: Design table for beams at exterior spans from CRSI manual

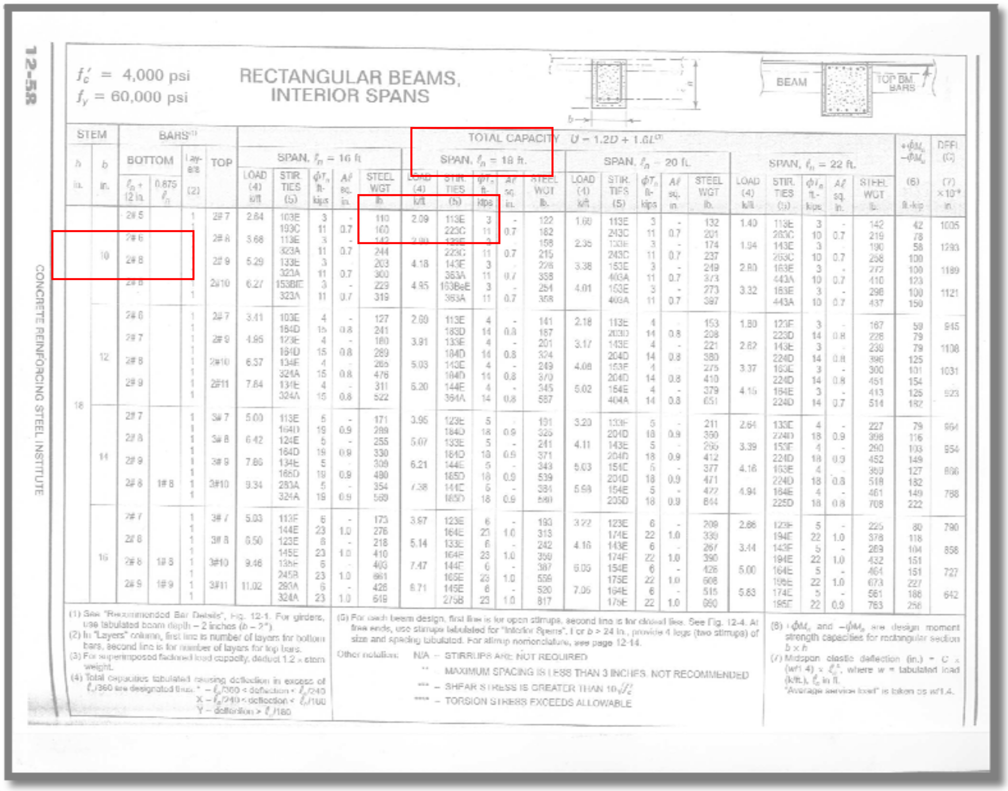


Figure 14: Design table for beams at interior spans from CRSI Manual.

Floor System Comparisons

Structural Criterion

The floor system significantly impacts the lateral force resisting system (LFRS) of a building. Since the hollow core plank system can work with a structural steel frame, the LFRS does not have to be re-configured for this system. The planks will be effective in transmitting lateral forces from the façade to the braced frames and the 2" topping will provide extra stiffness to the diaphragm. Longitudinal joints between planks can be utilized to transfer shear forces from one plank to the other.

The two-way and one-way systems will require a significant change to the LFRS of the hospital. Since the framing material is changing from steel to concrete, the steel braced frames will have to be removed. The one-way floor system has beams running in the N-S direction so there is still an option to have moment frames in that direction of the building, especially with the inherent moment connection at the beam-column intersections. It is likely that concrete shear walls will have to be designed for the two-way flat slab system since there are no beams. Shear walls will also be needed for the one-way system in the W-E direction.

Even though the concrete floor systems have a major impact on the current lateral design, they are heavier systems which make the building stiffer and able to resist wind forces more easily.

On the other hand, a heavier system will require a larger foundation. The existing spread footings are already rather large so switching to a concrete floor system might require a mat foundation in order to handle the extra building weight.

Seismic considerations must also be considered. From Tech Report I, it was determined that wind load controls the lateral design. However if the steel frame is switched out for a concrete frame, the seismic loading will increase significantly and might even lead to seismic forces controlling over wind forces.

One distinct advantage the concrete systems have over the steel systems is fire protection. Composite beam and hollow core plank floor systems will require applied fireproofing in order to obtain the necessary two hour rating where the concrete systems naturally meet that requirement.

Architectural Criterion

The width of the designed hollow core plank is 4'-0" which does not match with the typical 30' span of the current floor layout. For ease of construction and pre-fabrication of the precast planks the current bays will likely need to be reduced to 28' x 28' or increased to 32' x 32' so that the 4' plank fits evenly. This could shuffle the floor plan of the hospital a little but shouldn't have a tremendous impact.

The assumed column size for the concrete floor systems is 18" x 18" which is slightly larger than the 14" steel columns currently designed. These columns might protrude out of the interior walls forcing slight modifications to particular areas of the floor plan.

Another significant architectural consideration is the depth of each floor system. The depth of the existing composite beam system is typically just over 22". The one-way slab will require the same depth so that will have no impact on the overall height of the building. The hollow core plank actually increases the floor system depth by nearly 20". This alone practically eliminates it as a viable floor system for this building. The only way to significantly reduce the depth would be to tighten the column spacing which would create numerous architectural problems. The two-way flat slab is the only option which reduces the overall depth. It is 12" deep in the middle of the slab and 15" deep around the columns. The additional 10" per floor would result in a total decrease in building height of 5'.

Construction Criterion

The easiest floor systems to build are the composite beam and hollow core plank. With composite beam, the metal decking acts as the formwork for the concrete and there is no shoring required once the steel is erected. The hollow core plank is cast off-site and is ready to be installed when it arrives. Both concrete systems will require formwork and concrete placement which is labor intensive and much slower. The advantage for concrete is the shorter lead time as compared to steel.

Constructability doesn't necessarily equate to lower costs. The least expensive floor system of the four is the two-way flat slab at nearly $12/SF. The composite beam is not much more at $12.40/SF. The one-way slab and hollow core plank are the most expensive at around $15/SF. These calculations can be viewed in Appendix G.

Serviceability Criterion

As mentioned earlier, floor vibrations controlled the design of every system considered in this report. While all systems met the requirement for sensitive equipment at 50 steps/min, only the composite beam system met the requirement for human comfort. Since vibration is not a strength issue, it is up to the designer and owner to determine how much vibration is acceptable. The bays designed were not supporting operating rooms so these requirements are not exactly applicable. However if the owner did want to rearrange the floor layout of the hospital it is a good idea to design a significant portion of the floor system to handle vibration to the same standard as an operating room.

Due to the focus on handling the vibration issue, all of the floor systems should have no issues with deflection.

Below is a matrix which lists the evaluation for each system under every criterion.

The weight determination for each system can be found in Appendix E.

Design Comparison				
Floor System:	Composite Beam	Hollow Core Plank	Two-way flat slab	One-way slab with beams
Lateral Impacts	n/a	Keep braced frames. Extra stiffness due to 2" topping.	Shear walls needed. Overall building stiffness. Increased seismic loads.	Shear walls with possible moment frames. Overall building stiffness. Increased seismic loads.
Weight	42.2 psf	80.13 psf	120 psf	171 psf
Foundation Impacts	n/a	Increase spread footing size. Possible mat foundation.	Increase spread footing size. Possible mat foundation.	Increase spread footing size. Possible mat foundation.
Fire Protection	Fireproof to achieve 2 hour rating.	Fireproof to achieve 2 hour rating.	No fireproofing.	No fireproofing.
Depth	6.25"	12" + 2" topping	12"	16"
Total Depth	22.25"	41"	12-15"	22"
Floor Plan Impact	n/a	Would require significant column adjustment to reduce depth.	Slightly larger columns might affect floor plan.	Slightly larger columns might affect floor plan.
Constructability	Easiest	Easier	Longer, more labor intensive	Longer, more labor intensive
Cost	$12.40/SF	$15.18/SF	$11.96/SF	$14.59/SF
Vibration	Meets all requirements.	Meets sensitive equip. @ 50 steps/min.	Meets sensitive equip. @ 75 steps/min	Meets sensitive equip. @ 50 steps/min
Deflection	No issue	No issue	No issue	No issue
Viable Alternative?	Existing	No Too much floor plan adjustment. More expensive and heavier than composite beam.	Yes Decreased floor thickness without much floor plan impact. Inexpensive and good for vibration.	No Loses to two-way slab in nearly every category. Much heavier than composite but with same depth.

Figure 15: Design comparison matrix

Summary

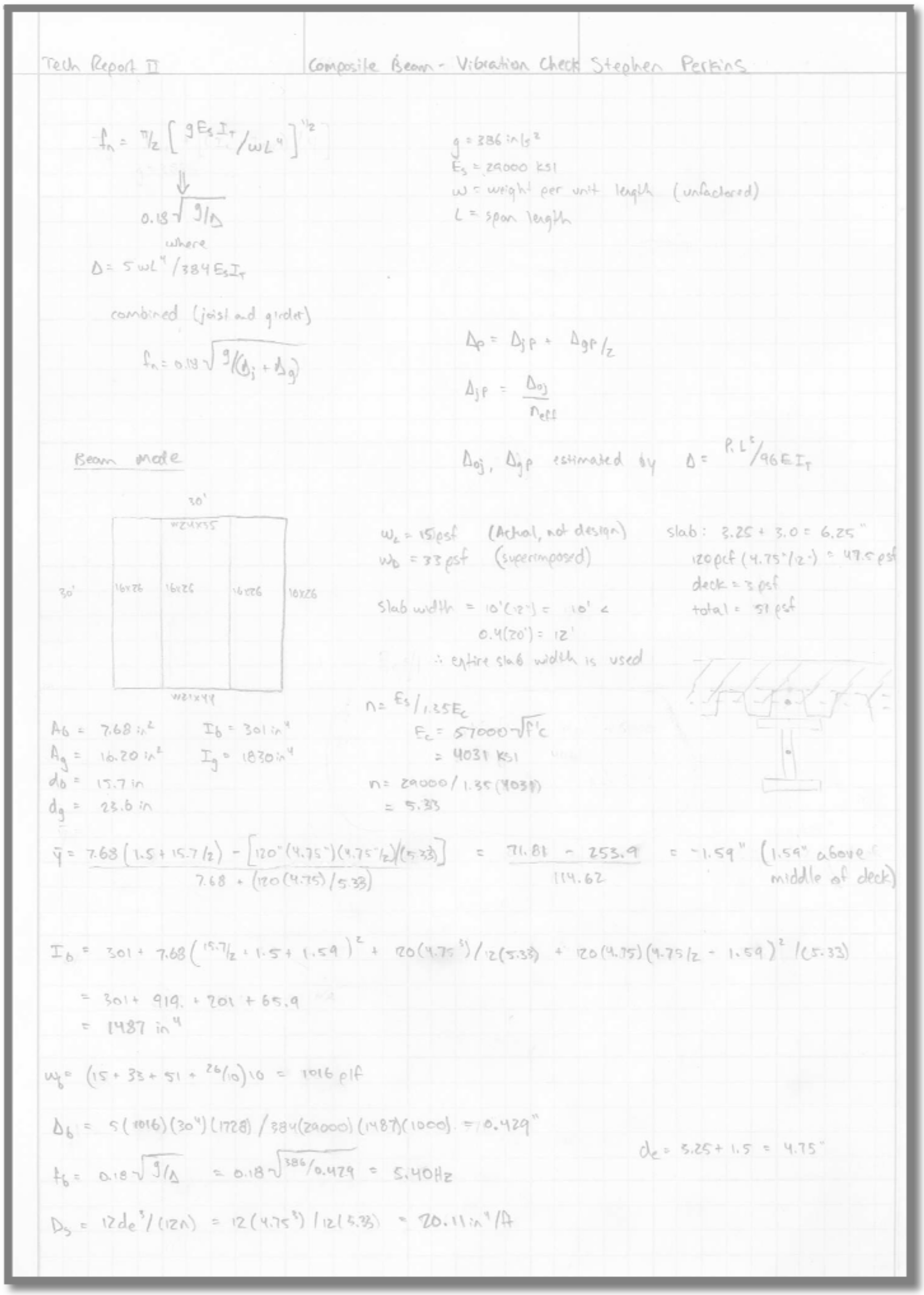
Upon completion of the alternate floor system study, it appears that the existing composite beam system is the best floor system for the New Hospital at the University Medical Center at Princeton. While it is 22" deep at typical locations, it is clearly the lightest system of the four considered. This has a significant impact when it comes to foundation size and seismic loading. There is extra importance placed upon weight in this case simply because the spread footings are rather large already. Moving to a heavier floor system will likely cause an entire re-design of the building's foundation.

The two-way flat slab still remains a viable option to replace the composite beam. It is 10" shallower than the composite beam and less expensive, but by only a small amount. Due to deflections being lesser in two-way slabs than one-way, it can handle floor vibrations much better than the other alternatives. While it is substantially heavier than the composite system, that weight can provide more stiffness to the building as a whole which will improve its lateral resistance. Of course, the foundation issue still exists with this system as well as a complete overhaul of the lateral force resisting system. After these adjustments have been made, it is likely to cost far much more than it does right now. For now, it still remains as a possible choice.

The precast hollow core plank system will not work for this building mainly due to initial layout of the columns and bays. Planks are better in rectangular bays where they do not have to span as long a distance. While it is easy to construct and wouldn't change the lateral system, the architectural ramifications of smaller bays or taller floor-to-floor spans is too much when there are better options already considered.

The one-way slab with beams was chosen for this study because it was thought to be better for point loading and might have an advantage with inherent moment connections at the beam-column intersections. These benefits do not outweigh the costs of a much heavier system that is more expensive and is beaten out by its concrete counterpart, the two-way flat slab, in nearly every category.

Appendix A



Tech Report II | Composite Beam - Vibration Check | Stephen Perkins

$f_n = \pi/2 \left[g E_s I_T / w L^4 \right]^{1/2}$

$\Downarrow$

$0.18 \sqrt{g/\Delta}$

where

$\Delta = 5 w L^4 / 384 E_s I_T$

$g = 386 \text{ in/s}^2$
$E_s = 29000$ ksi
w = weight per unit length (unfactored)
L = span length

combined (joist and girder)

$f_n = 0.18 \sqrt{g/(\Delta_j + \Delta_g)}$

$\Delta_p = \Delta_{jp} + \Delta_{gp}/2$

$\Delta_{jp} = \dfrac{\Delta_{oj}}{n_{eff}}$

Δ_{oj}, Δ_{gp} estimated by $\Delta = P_1 L^3 / 96 E I_T$

Beam mode

30'
W24x35
30' 16x26 16x26 16x26 16x26
W21x44

$w_L = 15$ psf (Actual, not design)
$w_D = 33$ psf (superimposed)

slab: $3.25 + 3.0 = 6.25''$
120 pcf $(4.75''/12'') = 47.5$ psf
deck = 3 psf
total = 51 psf

Slab width = $10'(12'') = 10' <$
$0.4(30') = 12'$
$\therefore$ entire slab width is used

$A_b = 7.68 \text{ in}^2$ $I_b = 301 \text{ in}^4$
$A_g = 16.20 \text{ in}^2$ $I_g = 1830 \text{ in}^4$
$d_b = 15.7$ in
$d_g = 23.6$ in

$n = E_s / 1.35 E_c$
$E_c = 57000 \sqrt{f'c}$
$= 4031$ ksi
$n = 29000 / 1.35(4031)$
$= 5.33$

$$\bar{y} = \frac{7.68(1.5 + 15.7/2) - [120''(4.75'')(4.75''/2)/(5.33)]}{7.68 + (120(4.75)/5.33)} = \frac{71.81 - 253.9}{114.62} = -1.59''$$ (1.59" above middle of deck)

$$I_b = 301 + 7.68(15.7/2 + 1.5 + 1.59)^2 + 120(4.75^3)/12(5.33) + 120(4.75)(4.75/2 - 1.59)^2/(5.33)$$

$= 301 + 919. + 201 + 65.9$
$= 1487 \text{ in}^4$

$w_b = (15 + 33 + 51 + 26/10)10 = 1016$ plf

$\Delta_b = 5(1016)(30^4)(1728)/384(29000)(1487)(1000) = 0.429''$

$f_b = 0.18\sqrt{g/\Delta} = 0.18\sqrt{386/0.429} = 5.40 \text{ Hz}$

$d_e = 3.25 + 1.5 = 4.75''$

$D_s = 12 d_e^3/(12n) = 12(4.75^3)/12(5.33) = 20.11 \text{ in}^4/\text{ft}$

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$D_b = I_b / s = 1487\ in^4 / (10') = 148.7\ in^4/ft$ $\quad s = 10.0'$

Effective Beam Panel width $\quad C_b = 2.0$

$B_b = C_b (D_s / D_g)^{1/4} L_b$ $\quad L_b$ = span length = 30'

$= 2.0 (20.11 / 148.7)^{1/4} (30')$
$= 36.39'$

Weight of beam panel

$W_b = (w / s) B_b L_b = (1016\ \#/ft) / (10\ ft)\ (36.4')(30') / 1000$
$= 111^k$

Girder Mode

Effective slab width

$0.4 L_g = 0.4 (24)(12)$
$\approx 115''$ * controls

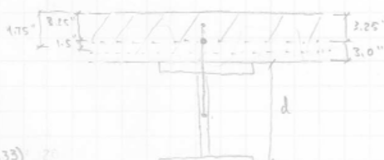
$30'(12) = 360''$

Depth concrete $= 3.25 + (3.0/2)$
$= 4.75''$

$$\bar{y} = \frac{16.20 (23.6/2 + 3.0) - [115(3.25)(3.25/2)/5.33]}{16.20 + [115(3.25)/(5.33)]}$$

$$= \frac{239.8 - 114}{86.32}$$

$= 1.46''$ below T/deck



$I_g = 1830 + 16.2 (23.6/2 + 3 - 1.46)^2 + 115 (3.25)^3 / 12 (5.33)$
$\quad + 115 (3.25) (3.25/2 + 1.46)^2 / 5.33$

$= 1830 + 2882.9 + 62 + 667$
$= 5442\ in^4$

$w_g = (1016/10)\ 30 + 55 = 3103$ plf

$\Delta_g = 5 (3103)(30^4)(1728) / 384 (29000)(5442)(1000) = 0.358''$

$f_g = 0.18 \sqrt{g/\Delta} = 0.18 \sqrt{386 / 0.358} = 5.91\ Hz$

$B_g = C_g (D_b / D_g)^{1/4} L_b$ $\quad D_b = 148.7$
$= 1.8 (149 / 227)^{1/4} (30')$ $\quad D_g = 5442 / 24 = 227$
$= 48.6'$

$W_g = (w/s) B_b L_b = (3103/24)\ 48.6\ (30) / 1000 = 189^k$

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$\Delta_g' = L_g/B_b\,(\Delta_g)$

$= (30/36.39)(0.358'')$ → effectively stiffened (can reduce)

* girder span (30') is less than beam panel width (3

$= 0.295''$

Total:

$f_n = 0.18\sqrt{g/(\Delta_b + \Delta_g')} = 0.18\sqrt{386/(0.429+0.295)} \approx 4.16 \text{ Hz}$

↳ within range of human perception
∴ must check for walking excitation

$W = \Delta_b/(\Delta_b + \Delta_g') * W_b + \Delta_g'/(\Delta_b + \Delta_g') * W_g$

$= 0.429/(0.429+0.295) * 111^k + 0.295/(0.429+0.295) * 189^k$

$= 65.8^k + 77.0^k$

$= 143^k$

$\beta W = 0.05(143^k)$

$= 7.14^k$

$\frac{a_p}{g} = \frac{P_o e^{-0.35 f_n}}{\beta W} = \frac{65(e^{-0.35(4.16)})}{7140} = 0.0023 = 0.23\%g < 0.25\%g$ for operating room

* Concluded that existing floor system is satisfactory for walking excitation. Standard for comparison is an operating room. If floors meet this criteria, then they will meet all criteria for other hospital spaces.

→ Now must consider sensitive equipment (quasi static vibration)

$V = U_v \Delta_p / f_n$ where $U_v = \pi F_m f_o^2$

Design Assumption: Weight of person walking = 185 lb
walking rate = 75 steps/min

$F_m/W = 1.5$ (Fig 6.4 AISC Design Guide 11)

$F_m = 1.5(185 \text{ lb})$

$= 278 \text{ lb}$

$f_o = 1/t_o = 2.5$ (Fig 6.4 AISC Design Guide 11)

$U_v = \pi(278)(2.5^2) = 5459 \text{ lb/s}^2$

$\Delta_{ob} = L^3/96EI = 30^3(1728)/96(29000)(1487)(1000) = 1.13e^{-5} \text{ in/lb}$

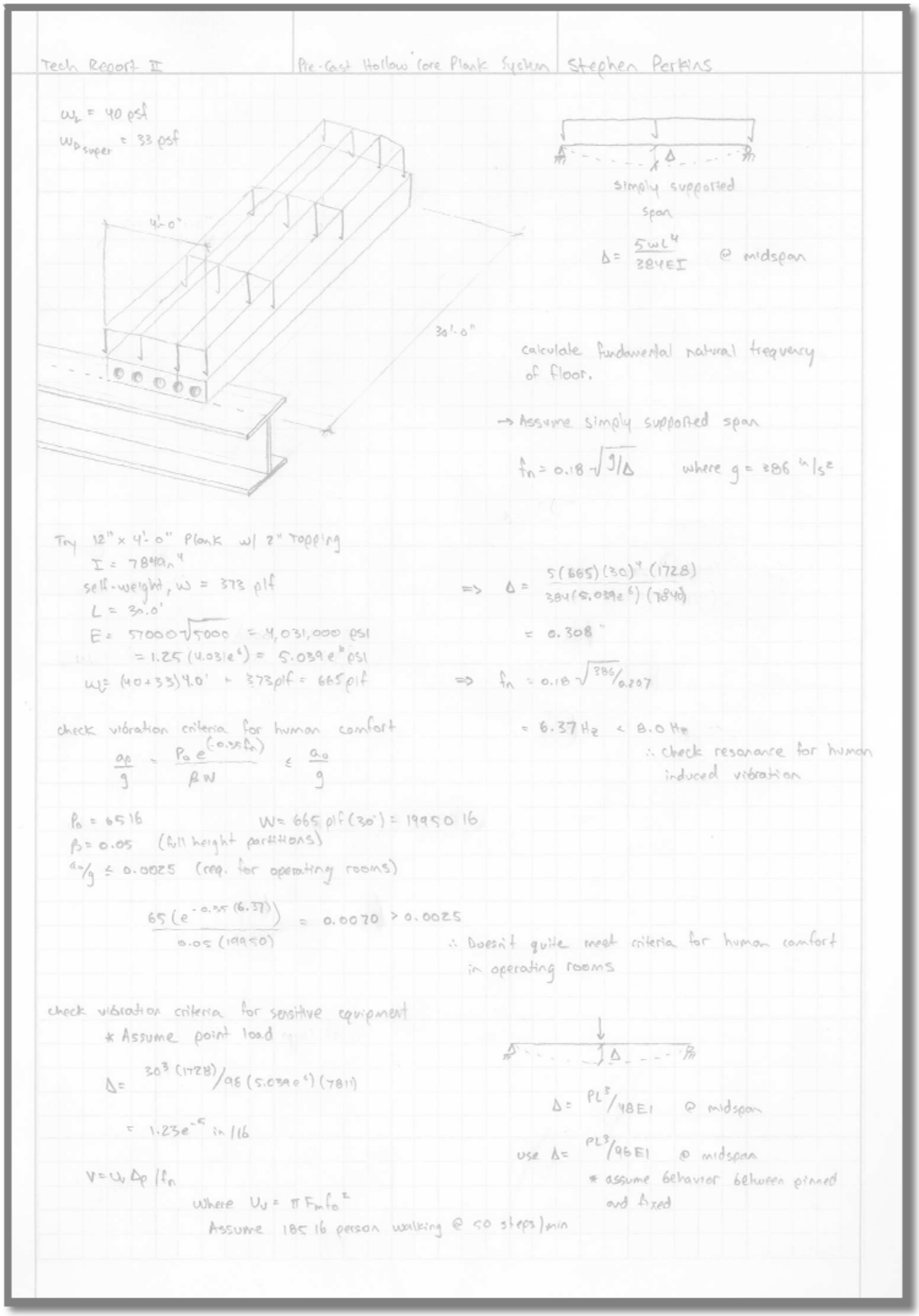
$\Delta_{gp} = 30^3(1728)/96(29000)(5442)(1000) = 3.08e^{-6} \text{ in/lb}$

$\Delta_p = \frac{\Delta_{ob}}{N_{eff}} + \frac{\Delta_{gp}}{2} = \frac{1.13e^{-5}}{2} + \frac{3.08e^{-6}}{2} = 7.19e^{-6} \text{ in/lb}$

$V = U_v \Delta_p / f_n = (5459)(7.19e^{-6})/4.16 = 0.00944 = 9440 \ \mu\text{in/s}$

* Standard for operating room = 4000 μin/s

Appendix B



Tech Report II | Pre-Cast Hollow Core Plank System | Stephen Perkins

$w_L = 40$ psf

$w_{D_{super}} = 33$ psf

4'-0"

30'-0"

simply supported span

$\Delta = \frac{5wL^4}{384EI}$ @ midspan

calculate fundamental natural frequency of floor.

→ Assume simply supported span

$f_n = 0.18\sqrt{g/\Delta}$ where $g = 386$ in/s²

Try 12" x 4'-0" Plank w/ 2" Topping

$I = 7840$ in⁴

self-weight, $w = 373$ plf

$L = 30.0'$

$E = 57000\sqrt{5000} = 4{,}031{,}000$ psi

$= 1.25(4.031e^6) = 5.039e^6$ psi

$w_T = (40+33)4.0' + 373$ plf $= 665$ plf

$\Rightarrow \Delta = \frac{5(665)(30)^4(1728)}{384(5.039e^6)(7840)}$

$= 0.308"$

$\Rightarrow f_n = 0.18\sqrt{386/0.207}$

$= 6.37$ Hz < 8.0 Hz

∴ check resonance for human induced vibration

check vibration criteria for human comfort

$\frac{a_p}{g} = \frac{P_o e^{(-0.35 f_n)}}{\beta W} \leq \frac{a_o}{g}$

$P_o = 65$ lb $\qquad W = 665$ plf$(30') = 19950$ lb

$\beta = 0.05$ (full height partitions)

$a_o/g \leq 0.0025$ (req. for operating rooms)

$\frac{65(e^{-0.35(6.37)})}{0.05(19950)} = 0.0070 > 0.0025$

∴ Doesn't quite meet criteria for human comfort in operating rooms

check vibration criteria for sensitive equipment

* Assume point load

$\Delta = 30^3(1728)/96(5.039e^6)(7811)$

$= 1.23e^{-5}$ in/lb

$\Delta = PL^3/48EI$ @ midspan

use $\Delta = PL^3/96EI$ @ midspan

* assume behavior between pinned and fixed

$V = U_v \Delta_p / f_n$

where $U_v = \pi F_m f_o^2$

Assume 185 lb person walking @ 50 steps/min

Tech Report II | Precast Hollow Core Plank System | Stephen Perkins

Fig 6.4 AISC Design Guide 11

$F_m/W = 1.30$

$F_m = 1.30(185) = 241$ lb

$f_o = 1/t_o = 1.25$

$U_v = \pi(241)(1.25^2) = 1183$ lb/s²

$V = (1183)(1.23e^{-5})/6.37$

$= 0.00227$ in/s $\Rightarrow$ 2270 μin/s < 4000 μin/s

Assume 185 lb person walking @ 75 steps/min

$F_m/W = 1.5$

$f_o = 2.5$

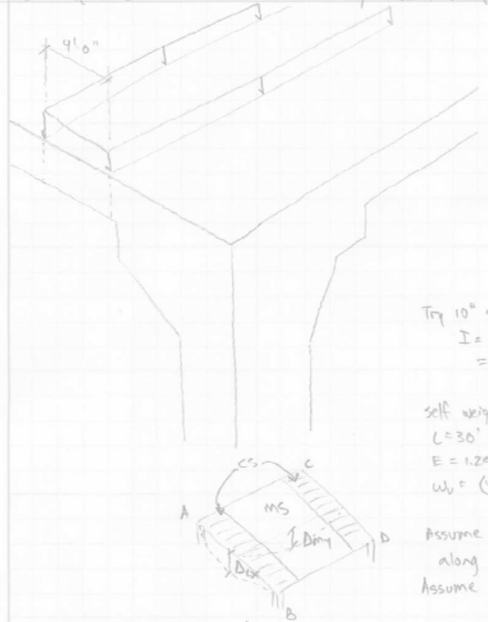
$U_v = \pi(1.5(185))(2.5^2) = 5449$ lb/s²

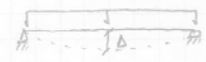
$V = (5449)(1.23e^{-5})/7.78$

$= 0.0086$ in/s $\Rightarrow$ 8600 μin/s > 4000 μin/s

Appendix C

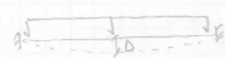
Tech Report II | Two-Way Flat Slab System | Stephen Perkins





simply supported

$\Delta = 5wL^4/384EI$ @ midspan



Fixed Fixed

$\Delta = wL^4/384EI$ @ midspan

Try 10" slab w LWC = 120 pcf

$I = bh^3/12$

$= 48(10^3)/12 \quad - 4000\ in^4$

self weight, w = 120pcf (10)(48)/144 = 400 plf

$L = 30'$

$E = 1.25\ E_c = 5.039e^6$ psi

$w_L = (40+33)4' + 400 = 692$ plf

Assume MS receives 10% of longitudinal moment along line A-B. CS (line A-B) receives 90%.
Assume simply supported span (adjusts later)

$\Delta_{cx} = 0.9(5)(692)(30^4)(1728)/384(5.039e^6)(4000)$

$= 0.563"$

$\Delta_{my} = 0.2(5)(692)(30^4)(1728)/384(5.039e^6)(4000)$

$= 0.125"$

$\Delta = \Delta_{cx} + \Delta_{my} = 0.563 + 0.125 = 0.688"$

Now, adjust for condition b/t simple + fixed.
Assume it reduces by 75%

$\Delta_{Total} = 0.40(0.688) = 0.275"$

$f_n = 0.18\sqrt{386/0.275} = 6.74\ Hz$

check for human comfort

$$\frac{a_p}{g} = \frac{P_o e(-0.35 f_n)}{\beta W} \le \frac{a_o}{g}$$

$P_o = 65\ lb$

$\beta = 0.05$

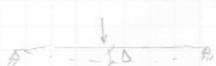
$W = 692(30) = 20760\ lb$

$$\frac{a_p}{g} = \frac{65(e^{-0.35(6.74)})}{0.05(20760)} = 0.0059$$

$0.0059 > 0.0025$ ∴ Does not meet requirement

check for sensitive equipment

*Assume point load



$\Delta = PL^3/48EI$

$$= \frac{30^3(1728)}{48(5.039e^{-6})(4000)}$$

$= 4.82e^{-5}$ in/lb

$\Delta_{cx} = 0.9(4.82e^{-5}) = 4.34e^{-5}$ in/lb

$\Delta_{my} = 0.2(4.82e^{-5}) = 9.64e^{-6}$ in/lb

$\Delta = 4.34e^{-5} + 9.64e^{-6} = 5.30e^{-5}$ in/lb

$\Delta_T = 0.4(5.30e^{-5}$ in/lb$) = 2.120e^{-5}$ in/lb

$F_m/W = 1.3$

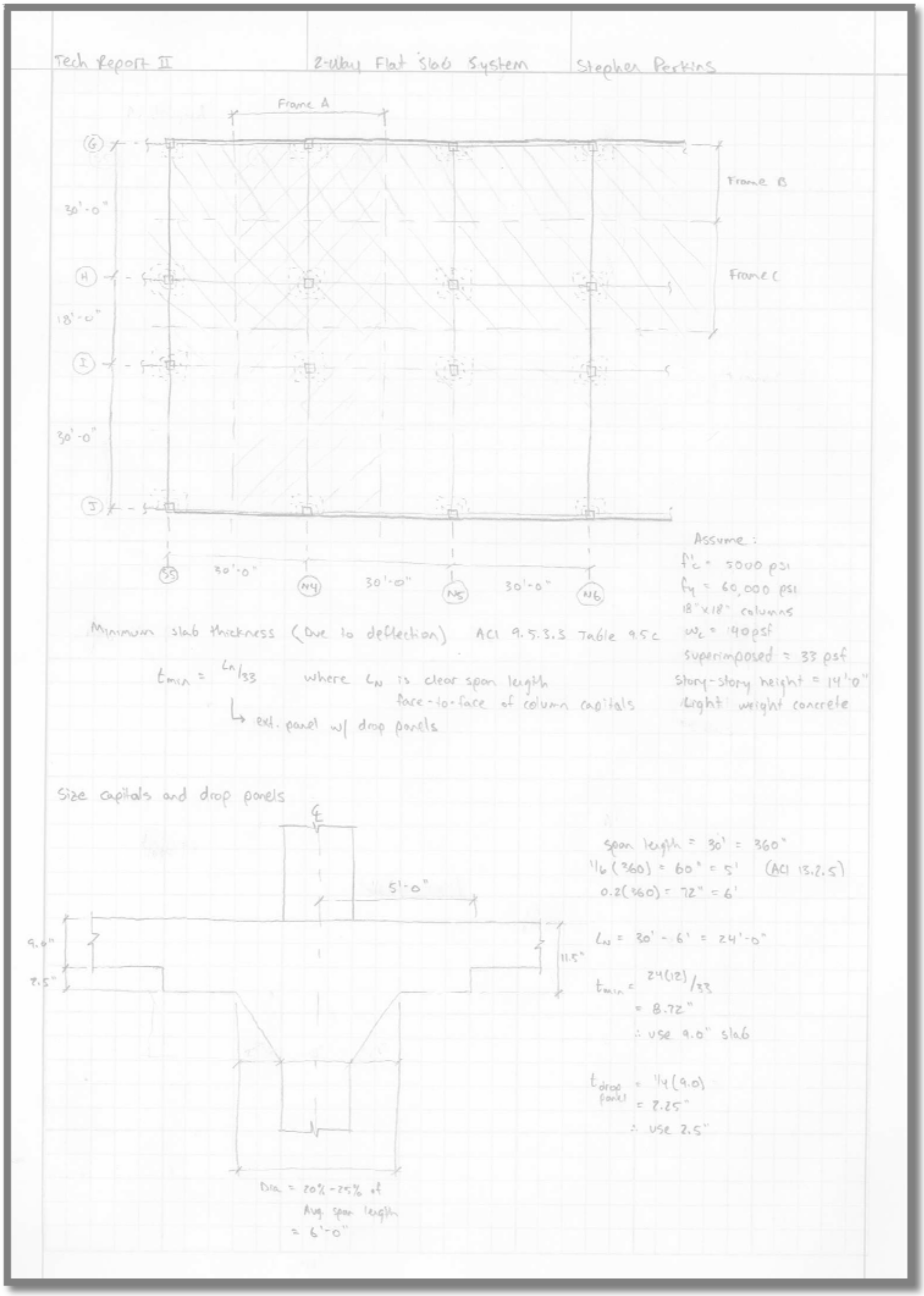
$f_o = 1.25$

$F_m = 1.3(185\ lb) = 241\ lb$

$U_v = \pi(241)(1.25^2) = 1183$ lb/s

$V = 1183(2.12e^{-5}$ in/lb$)/6.74 = 0.0037$ in/s $= 3700\ \mu$in/s $< 4000\ \mu$in/s

∴ Meets criteria!



Tech Report II 2-Way Flat Slab System Stephen Perkins

Assume:
f'_c = 5000 psi
f_y = 60,000 psi
18"x18" columns
w_c = 140psf
superimposed = 33 psf
Story-story height = 14'-0"
Light weight concrete

Minimum slab thickness (Due to deflection) ACI 9.5.3.3 Table 9.5c

$t_{min} = l_n/33$ where l_n is clear span length face-to-face of column capitals

↳ ext. panel w/ drop panels

Size capitals and drop panels

span length = 30' = 360"
1/6 (360) = 60" = 5' (ACI 13.2.5)
0.2(360) = 72" = 6'

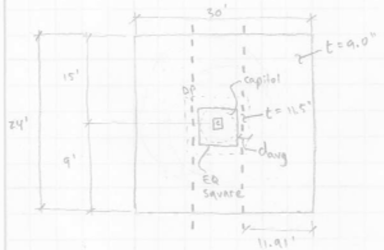
l_n = 30' - 6' = 24'-0"

$t_{min} = 24(12)/33$
= 8.72"
∴ use 9.0" slab

$t_{drop\ panel}$ = 1/4 (9.0)
= 2.25"
∴ use 2.5"

Tech Report II | Two Way Flat Slab System | Stephen Perkins

Check Shear - Wide Beam Action



Equivalent square dia. = a^2

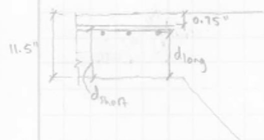
$a^2 = \frac{\pi(6.0')^2}{4} = 28.27'$

$a = 5.32'$

$d_{short} = 11.5 - 0.75 - 0.625/2 = 10.44"$

$d_{long} = 10.44 - 0.625/2 = 10.13"$

$d_{avg} = (10.44 + 10.13)/2$
$= 10.28"$



bar dia = 0.625"
(#5)

Critical Section:
$15.0' - 5.32/2 - (10.28/12)0.5 = 11.91'$

$w_{slab} = (9.0/12)\,120\ pcf = 90.0\ psf$
$w_{super} = 33\ psf$
$w_D = 1.2(90 + 33) = 148\ psf$
$w_L = 1.6(40) = 64\ psf$
$w_u = 212\ psf = 0.212\ ksf$

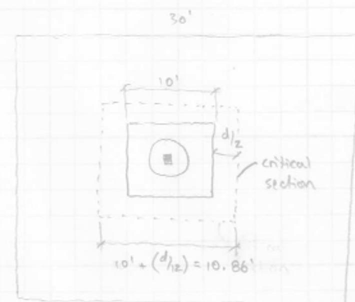
$V_u = w_u A$
$= 0.212(24')(11.91')$
$\approx 61^k$

$V_c = 2\sqrt{f'_c}\,bd$
$= 2\sqrt{5000}\,(24 \times 12)(10.28 - 2.5)/1000$
$= 316.9^k$

$\phi V_c = 0.75(316.9)$
$\approx 238^k > 61^k$ ✓ ok

Check Shear - Punching Shear around Drop Panel

$d_{avg} = 10.28"$
$b_o = 4(10' + 10.28"/12) = 4(10.86')$
$= 43.43' = 521.1"$
$\beta = 1.0$ for sq. columns
$\alpha = 40$ for int. columns



$V_u = (0.212\ ksf)[(30' \times 24') - 10.86'^2]$
$= 128^k$

$$V_c = \min \begin{cases} 4\sqrt{f'_c}\,b_o d = 4\sqrt{5000}\,(521)(10.28) = 1515^k \\ (2 + 4/\beta_c)\sqrt{f'_c}\,b_o d = (2 + 4/1.0)\sqrt{5000}\,(521)(10.28) = 2272^k \\ \left(\frac{\alpha d}{b_o} + 2\right)\sqrt{f'_c}\,b_o d = \left(\frac{40(10.28)}{521} + 2\right)\sqrt{5000}\,(521)(10.28) = 1056^k \end{cases}$$

* controls

$\phi V_c = 0.75(1056) = 792^k > 128^k$ ✓ ok!

Tech Report II | Two Way Flat Slab System | Stephen Perkins

Check Shear - Punching around column capitol

$d_{avg} = 10.28''$

$b_o = \pi(6' + {}^{10.28}/_{12}) = \pi(6.86)$

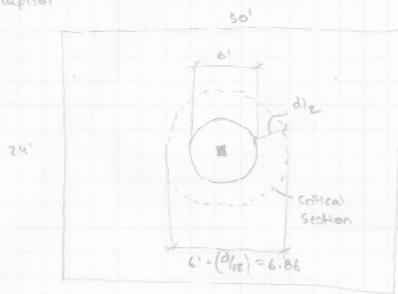
$= 21.54' = 258.5''$

$\beta = 1.0$

$\alpha = 40$

$V_u = 0.212\left[(30 \times 24) - \pi\frac{(6.86^2)}{4}\right]$

$= 145^k$



$$V_c = \min \begin{cases} 4\sqrt{f'_c}\, b_o d = 4\sqrt{5000}\,(258.5)(10.28) = 752^k \\ (2 + {}^{4}/_{\beta_c})\sqrt{f'_c}\, b_o d = (2 + {}^{4}/_{1.0})\sqrt{5000}\,(258.5)(10.28) = 1127^k \\ ({}^{\alpha d}/_{b_o} + 2)\sqrt{f'_c}\, b_o d = ({}^{40(10.28)}/_{258.5} + 2)\sqrt{5000}\,(258.5)(10.28) = 675^k \end{cases}$$

$\phi V_c = 0.75(675) = 506^k > 145^k$ ✓ ok!

* Shear checks were performed prior to vibration analysis. Actual slab thickness due to vibration requirements is greater than slab thickness used for shear checks. Therefore, it is assumed that thicker slab will satisfy punching shear requirements.

Tech Report II | Two Way Flat Slab System | Stephen Perkins

Min. slab thickness

$t_{min} = l_n/33$ where $l_n = 30.0' - 2(3.0) = 24.0'$

$= 24(12)/33$

$= 8.73"$

$12.0" > 8.73"$ ✓ ok ∴ Do not need to check deflection

Total static moment

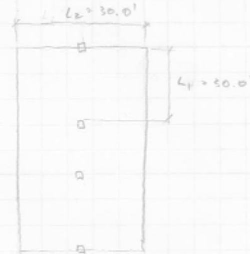
Frame A: $M_o = w_u l_2 l_n^2/8$

where $l_n = l_1 - 2/3 c$ c = dia of capital = 6.0'

$l_n = 30 - 2/3(6) = 26.0'$

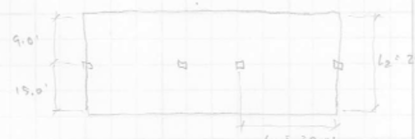
$w_u = 1.2(120+33) + 1.6(40) = 248$ plf $= 0.248$ ksf

$M_o = 0.248(30)(26^2)/8 = 629$ ft·k



Frame C: $l_n = 26.0'$

$M_o = 0.248(24)(26^2)/8 = 503$ ft·k



Longitudinal Distribution of Static Moment

for interior span

for end span w/o beams

Frame A

$M^-_{ext_L} = 0.26(629) = 164$ ft·k

$M^+_{ext} = 0.52(629) = 327$ ft·k

$M^-_{ext_R} = 0.70(629) = 440$ ft·k

$M^-_{int} = 0.65(629) = 409$ ft·k

$M^+_{int} = 0.35(629) = 220$ ft·k

Frame C

$M^-_{ext_L} = 0.26(503) = 131$ ft·k

$M^+_{ext} = 0.52(503) = 262$ ft·k

$M^-_{ext_R} = 0.70(503) = 352$ ft·k

$M^-_{int} = 0.65(503) = 327$ ft·k

$M^+_{int} = 0.35(503) = 176$ ft·k

Frame A Longitudinal Moments

+	327		220		327	
−	164	440	409	409	440	157

Frame C Longitudinal Moments

+	262		176		262	
−	131	352	327	327	352	126

$\alpha l_2/l_1 = 0$ → No edge beams

A: $l_2/l_1 = 30/30 = 1.0$

C: $l_2/l_1 = 24/30 = 0.8$

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ACI 13.6.4 Transverse Distribution

Frame A + C

Negative @ exterior span
- 100% to CS
- 0% to MS

Positive
- 60% to CS
- 40% to MS

Negative @ interior span
- 75% to CS
- 25% to MS

Summary of moments

Frame A Total width = 30.0' CS = 15.0' MS = 15.0'

Total M	-164	+327	-440	-409	+270	-409	-440	+327	-157
M_{cs}	-164	+196.2	330	-307	+132	-307	-330	+196	-157
M_{ms}	0	+130.8	-110	-102	+88	-102	-110	+131	0

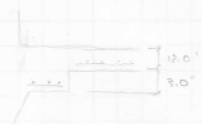
Frame C Total width = 24.0' CS = 12.0' MS = 12.0'

Total M	-131	+262	-352	-327	+176	-327	-352	+262	-131
M_{cs}	-131	+157	-264	-245	+106	-245	-264	+157	-131
M_{ms}	0	+105	-88	-82	+70	-82	-88	+105	0

Reinforcement Design for column strip

	Frame A					Frame C				
	−Ext	+Ext	−Ext	−Int	+Int	−Ext	+Ext	−Ext	−Int	+Int
M_u	-164	+19.6	-330	-307	+132	-131	+157	-264	-245	+106
slab width, b	120"	180"	120"	120"	180"	120"	144"	120"	120"	144"
eff. depth, d	13.88"	10.88"	13.88"	13.88"	10.88"	13.13"	10.13"	13.13"	13.13"	10.13"
$M_u * 12/b$	-16.4	+13.1	-33	-30.7	+8.8	-13.1	+13.1	-26.4	-24.5	+8.83
$M_n = M_u/0.9$	-182.2	+218	-367	-341.1	+146.7	-145.6	+174.4	-293.3	-272.2	+117.8
$R = M_n/bd^2$ (psi)	94.6	122.8	190.5	177	82.6	84.5	141.6	170.1	157.9	95.7
ρ	0.0016	0.0021	0.0032	0.0030	0.0014	0.0014	0.0024	0.0029	0.0027	0.0016
$A_{s req}$ (in^2)	2.66	4.11	5.33	4.99	2.74	2.21	3.50	4.57	4.25	2.33
$A_{s min}$ (in^2) = 0.002bt	3.60	4.32	3.60	3.60	4.32	3.60	5.46	3.60	3.60	5.46
$N = A_s/0.44$	8.2	9.82	12.1	11.3	9.82	8.2	7.9	10.4	9.66	7.9
N_{min} = width/2t	4	7.5	4	4	7.5	4	6	4	4	6
# bars	9	10	13	12	10	9	8	11	10	8

$A_{\#6} = 0.44in^2$



*Moments in A are greater than in C ∴ place reinf at bottom for frame A

$d_1 = 15.0 - 0.750/2 - 0.75 = 13.88"$
$d_2 = 12.0 - (0.750/2) - 0.75 = 10.88"$
$d_3 = 13.88 - 0.750 = 13.13"$
$d_4 = 10.88 - 0.750 = 10.13"$

Tech Report II | Two Way Flat Slab System | Stephen Perkins

Calculate ρ for Frame A CS

$\bar{Ext}$

$$R = \rho f_y \left(1 - 0.59\rho \, f_y / f'_c\right)$$

$$0.0946 = 60\rho\left(1 - 0.59\rho\,(60/5)\right)$$

$$= 60\rho - 424.8\rho^2$$

$$424.8\rho^2 - 60\rho + 0.0946 = 0$$

$$\frac{60 \pm \sqrt{60^2 - 4(424.8)(0.0946)}}{2(424.8)}$$

$\rho = 0.0016$

$\overset{+}{Ext}$ $424.8\rho^2 - 60\rho + 0.1228 = 0$
$\rho = 0.0021$

$\bar{Ext}$ $424.8\rho^2 - 60\rho + 0.1905 = 0$
$\rho = 0.0032$

$\bar{Int}$ $424.8\rho^2 - 60\rho + 0.177 = 0$
$\rho = 0.0030$

$\overset{+}{Int}$ $424.8\rho^2 - 60\rho + 0.0826 = 0$
$\rho = 0.0014$

Calculate ρ for Frame C CS

$\bar{Ext}$ $424.8\rho^2 - 60\rho + 0.0845 = 0$
$\rho = 0.0014$

$\overset{+}{Ext}$ $424.8\rho^2 - 60\rho + 0.1416 = 0$
$\rho = 0.0024$

$\bar{Ext}$ $424.8\rho^2 - 60\rho + 0.1701 = 0$
$\rho = 0.0029$

$\bar{Int}$ $424.8\rho^2 - 60\rho + .1579 = 0$
$\rho = 0.0027$

$\overset{+}{Int}$ $424.8\rho^2 - 60\rho + 0.0957 = 0$
$\rho = 0.0016$

Calculate ρ for Frame A MS

$\overset{+}{Ext}$ $424.8\rho^2 - 60\rho + 0.0818$
$\rho = 0.0014$

$\bar{Ext}$ $424.8\rho^2 - 60\rho + 0.0688$
$\rho = 0.0012$

$\bar{Int}$ $424.8\rho^2 - 60\rho + 0.0638$
$\rho = 0.0011$

$\overset{+}{Int}$ $424.8\rho^2 - 60\rho + 0.0551$
$\rho = 0.0009$

Calculate ρ for Frame C MS

$\overset{+}{Ext}$ $424.8\rho^2 - 60\rho + 0.0948$
$\rho = 0.0016$

$\bar{Ext}$ $424.8\rho^2 - 60\rho + 0.0794$
$\rho = 0.0013$

$\bar{Int}$ $424.8\rho^2 - 60\rho + 0.0748$
$\rho = 0.0013$

$\overset{+}{Int}$ $424.8\rho^2 - 60\rho + 0.0632$
$\rho = 0.0011$

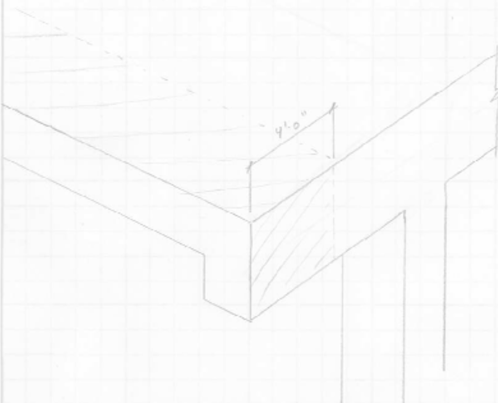
Tech Report II | Two Way Flat Slab System | Stephen Perkins

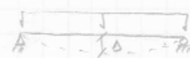
Reinforcement Design for middle strip

	Frame A					Frame C				
	$\bar{Ext}$	$\overset{+}{Ext}$	$\bar{Ext}$	$\bar{Int}$	$\overset{+}{Int}$	$\bar{Ext}$	$\overset{+}{Ext}$	$\bar{Ext}$	$\bar{Int}$	$\overset{+}{Int}$
M_u	0	+130.8	-110	-102	+88	0	+105	-88	-82	+70
slab width, b	180"	180"	180"	180"	180"	144"	144"	144"	144"	144"
eff. depth, d	10.88"	10.88"	10.88"	10.88"	10.88"	10.13"	10.13"	10.13"	10.13"	10.13"
$M_u \times 12/b$	0	+8.72	-7.33	-6.8	+5.87	0	+8.75	-7.33	-6.83	+5.83
$M_n = M_u/0.9$	0	+145.3	-122.2	-113.3	+97.8	0	+116.7	-97.8	-92.1	+77.8
$R = M_n/bd^2$ (psi)	0	81.8	68.8	63.8	55.1	0	94.8	79.4	74.8	63.2
ρ	0	0.0014	0.0012	0.0011	0.0009	0	0.0016	0.0013	0.0013	0.0011
$A_{s\,req}$ (in²)	0	2.74	2.35	2.15	1.76	0	2.33	1.90	1.90	1.60
$A_{s\,min}$ (in²)	4.32	4.32	4.32	4.32	4.32	3.46	3.46	3.46	3.46	3.46
N	9.82	9.82	9.82	9.82	9.82	7.86	7.86	7.86	7.86	7.86
N_{min}	7.5	7.5	7.5	7.5	7.5	6	6	6	6	6
# bars	10	10	10	10	10	8	8	8	8	8

Appendix D

Tech Report II | One-Way Slab w/ Beams System | Stephen Perkins

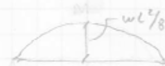




simply supported

$\Delta = 5wL^4/384EI$ @ midspan

* Beams add rigidity to end supports so deflection will be less



moment diagram for simply supported

moment diagram for one-way slab w/ integral beams

→ reduction in moment by 40%

∴ will assume a reduction in Δ by 40%

Try 10" slab w/ w_c = 120 pcf

$I = 48''(10^3)/12 = 4000\ in^4$

→ take 70% = 2800 in^4

$L = 30.0'$

$E = 1.25 E_c = 5.039e^6$ psi

self-weight = 400 plf

$W_u = (40+33)4' + 400 = 692$ plf

$$\Delta = \frac{0.60(5)(692)(30^4)(1728)}{384(5.039e^6)(2800)} = 0.54''$$

$$f_n = 0.18\sqrt{386/0.54} = 4.82\ Hz$$

check vibration for human comfort

$$\frac{a_p}{g} = \frac{P_o e^{(-0.35 f_n)}}{\beta W} \le \frac{a_o}{g}$$

P_o = 65 lb

β = 0.05

$W = 692(30') = 20760$ lb

$$\frac{65e^{-0.35(4.82)}}{0.05(20760)} = 0.0115 > 0.0025$$

∴ Does not meet criteria for human comfort in operating room

check vibration criteria for sensitive equipment

$$\Delta = 50^3(1728)(0.6)/48(5.039e^6)(2800) = 4.13e^{-5}\ in/lb$$

$\Delta = PL^3/48EI$ @ midspan

* Added rigidity at ends with beams. Therefore, reduce by 40%

Assume 185 lb person walking @ 50 steps/min

$F_m/W = 1.3$

$f_o = 1.25$

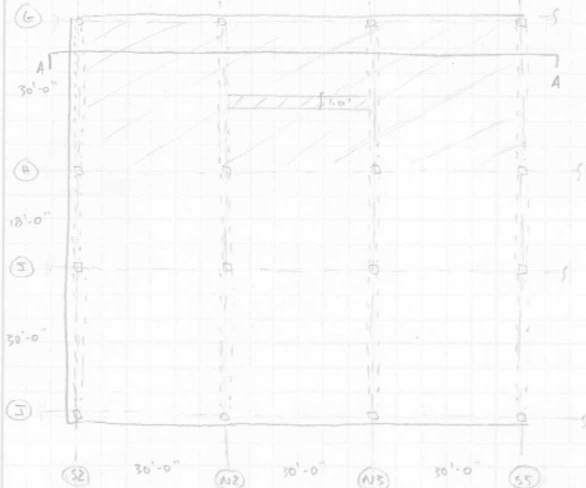
$F_m = 1.3(185) = 241$ lb

$U_v = \pi(241)(1.25^2) = 1181$ lb/s

$V = 1181(4.13e^{-5})/4.82 = 0.01011$ in/s $= 10116\ \mu in/s > 4000\ \mu in/s$

∴ Does not meet criteria for sensitive equipment

Tech Report II | One Way Slab w/ Beams System | Stephen Perkins



$f'_c = 5000$ psi
$f_y = 60{,}000$ psi

$w_u = 1.2D + 1.6L$

self-weight
$120(^{16}/_{12})(1.0) = 160$ plf

Superimposed
$33\text{psf} * (1.0) = 33$ plf

live
$40\text{psf} * (1.0) = 40$ plf

$w_u = 1.2(160+33) + 1.6(40)$
$= 296$ plf

Min. thickness (Due to deflection)

$t_{min} = {}^{l_n}/_{28}$ → both ends continuous
$= 30(12)/28$
$= 12.9"$ ∴ use 16" due to vibration requirements

Factored moments using ACI coefficients ch. 8.3.3

sec A-A

Int. span End span Ext edge

Moment @ 1 ⇒ $-w_u L_n^2/24 = -246(30^2)/24 = -9225$ ft·lb $= -9.23$ ft·k
@ 2 ⇒ $+w_u L_n^2/14 = +246(30^2)/14 = +15814$ ft·lb $= +15.81$ ft·k
@ 3 ⇒ $-w_u L_n^2/9 = -246(30^2)/9 = -24600$ ft·lb $= -24.60$ ft·k
@ 4 ⇒ $-w_u L_n^2/11 = -246(30^2)/11 = -20127$ ft·lb $= -20.13$ ft·k
@ 5 ⇒ $+w_u L_n^2/16 = +246(30^2)/16 = +13838$ ft·lb $= +13.84$ ft·k

$$\rho_{max} = 0.85\,\beta_1 \, {}^{f'_c}/_{f_y} \left(^{\varepsilon_u}/_{\varepsilon_u + 0.004}\right)$$
$$= 0.85(0.80)\,^{5}/_{60}\left(^{0.003}/_{0.003+0.004}\right)$$
$$= 0.024$$

Tech Report II	One Way Slab w/ Beams System	Stephen Perkins

$d = 16.0 - (0.75 + 0.50) = 14.75''$

clr cover $= 0.75''$

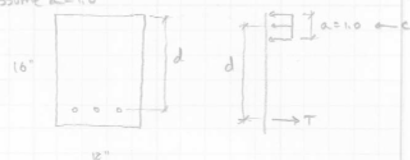
Assume bar dia of $1.0''$ (conservative)

$A_s = M_u / \phi f_y (d - a/2)$

$= 24.60(12) / 0.9(60)(14.75 - 1.0/2)$

$= 0.38 \text{ in}^2$

Assume $a = 1.0''$



check assumption

$C = T$

$0.85 f'_c a b = A_s f_y$

$a = 0.38(60) / 0.85(5)(12)$

$= 0.45''$

3 $A_s = 24.6(12) / 0.9(60)(14.75 - 0.45/2)$

$= 0.376 \text{ in}^2$ @ 3

1 $A_s = 9.23(12) / 0.9(60)(14.75 - 0.45/2)$

$= 0.14 \text{ in}^2$ @ 1

2 $A_s = 15.81(12) / 0.9(60)(14.525)$

$= 0.24 \text{ in}^2$ @ 2

4 $A_s = 20.13(12) / 0.9(60)(14.525)$

$= 0.31 \text{ in}^2$ @ 4

5 $A_s = 13.84(12) / 0.9(60)(14.525)$

$= 0.21 \text{ in}^2$ @ 5

Min steel required for shrinkage and temperature cracking

$A_s = 0.0018 * A_c$

$= 0.0018 * 12(16)$

$= 0.346 \text{ in}^2/\text{ft}$

↳ need increase for all critical sections except 3

Shear check

$V_u = 0.296(30)/2 = 4.44^k$

@ critical section a distance d from face $\Rightarrow 4.44 - 0.296(14.75/12) = 4.08^k$

$V_u = 2\sqrt{f'_c}\, bd = 2\sqrt{5000}(12)(14.75) = 25.0^k > 4.08^k$ ✓ ok

Preliminary design of reinforcement:

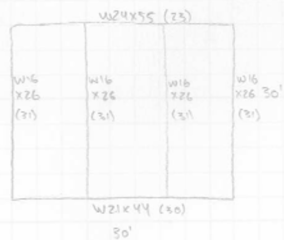
Place #6 bars @ 14" o.c. in all sections of slab $\quad A_{\#6} = 0.44 \text{ in}^2$

$(12/14)(0.44) = 0.377 \text{ in}^2/\text{ft} > 0.346 \text{ in}^2/\text{ft}$ shrinkage + temp

$> 0.376 \text{ in}^2/\text{ft}$ req. for 3

Appendix E

Tech Report II | Floor System Weight | Stephen Perkins



Only considering weight for one typ 30' x 30' bay.

Composite Beam

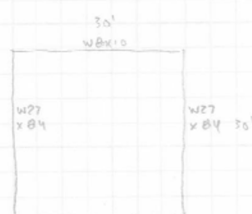
Steel Framing : 55plf (30') = 1650 lb
44plf (30') /2 = 660 lb
26plf (30') x 3 = 2340 lb
Total = 4650 lb = 4.65^k

Concrete Slab : 120pcf (3.25"/12)(30')(30') = 29250 lb = 29.25^k

Composite Deck : 3psf (30')(30') = 2700 lb = 2.7^k

Shear Studs : (10 lbs/stud)(131 studs) = 1310 lb = 1.31^k

Total Weight (k) = 38^k
(psf) = 42.2



Hollow Core Plank

Steel Framing : 10plf (30') = 300 lb
84plf (30') = 2520 lb
Total = 2820 lb = 2.82^k

Hollow Core Plank : 77psf (30')(30') = 69300 lb = 69.3^k
Total Weight = 72.12^k = 80.13 psf

Two Way Flat Slab

Concrete Slab : 120pcf (12"/12)(30')(30') = 108000 lb = 108^k

Total Weight = 108^k = 120 psf

One Way Slab w/ Beams

Concrete Framing : 120pcf (22"/12)(18"/12)(30') = 9900 lb = 9.9^k

Concrete slab : 120pcf (16"/12)(30')(30') = 144000 lb = 144^k

Total Weight = 154^k = 171 psf

Appendix F

One Way Slab w/ Beams
Vibration Analysis

											fo	1.25
	wlive	40	psf	width	4	ft	f'c	5000	psi		β	0.05
	wdead	33	psf	span	30	ft	Po	65	lb		Fm/W	1.3
	Design-for 185 lb person walking at 50 steps/min											
	16			14			12				10	
I	11468.8	in^4		7683.2	in^4		4838.4	in^4			2800	in^4
w	640	plf		560	plf		480	plf			400	plf
wu	932	plf		852	plf		772	plf			692	plf
E	5038136	psi		5038136	psi		5038136	psi			5038136	psi
Δ	0.18	in		0.24	in		0.35	in			0.54	in
fn	8.42	Hz		7.21	Hz		6.01	Hz			4.83	Hz
ap/g	0.0024			0.0041			0.0069				0.0116	
Δ(point)	1.01E-05	in/lb		1.51E-05	in/lb		2.39E-05	in/lb			4.13E-05	in/lb
Uv	1180.6	lb/s^2		1180.6	lb/s^2		1180.6	lb/s^2			1180.6	lb/s^2
V	0.001415	in/s		0.002467	in/s		0.004700	in/s			0.010108	in/s
	1415	μin/s		2467	μin/s		4700	μin/s			10108	μin/s

											fo	2.5
	wlive	40	psf	width	4	ft	f'c	5000	psi		β	0.05
	wdead	33	psf	span	28	ft	Po	65	lb		Fm/W	1.5
	Design-for 185 lb person walking at 75 steps/min											
	16			14			12				10	
I	11468.8	in^4		7683.2	in^4		4838.4	in^4			2800	in^4
w	640	plf		560	plf		480	plf			400	plf
wu	932	plf		852	plf		772	plf			692	plf
E	5038136	psi		5038136	psi		5038136	psi			5038136	psi
Δ	0.13	in		0.18	in		0.26	in			0.41	in
fn	9.67	Hz		8.28	Hz		6.90	Hz			5.54	Hz
ap/g	0.0017			0.0030			0.0054				0.0096	
Δ(point)	8.21E-06	in/lb		1.22E-05	in/lb		1.95E-05	in/lb			3.36E-05	in/lb
Uv	5448.7	lb/s^2		5448.7	lb/s^2		5448.7	lb/s^2			5448.7	lb/s^2
	0.004626	in/s		0.008066	in/s		0.015363	in/s			0.033041	in/s
V	4626	μin/s		8066	μin/s		15363	μin/s			33041	μin/s

Two Way
Flat Slab
Vibration
Analysis

										fo	1.25
	wlive	40	psf	width	4	ft	f'c	5000	psi	β	0.05
	wdead	33	psf	span	30	ft	Po	65	lb	Fm/W	1.3
	Design- for 185 lb person walking at 50 steps/min										
	12			11			10			9	
I	6912	in^4		5324	in^4		4000	in^4		2916	in^4
w	480	plf		440	plf		400	plf		360	plf
wu	772	plf		732	plf		692	plf		652	plf
E	5038136	psi		5038136	psi		5038136	psi		5038136	psi
Δ(cx)	0.36	in		0.45	in		0.56	in		0.73	in
Δ(mx)	0.08	in		0.10	in		0.13	in		0.16	in
Δ(total)	0.18	in		0.22	in		0.28	in		0.36	in
fn	8.39	Hz		7.56	Hz		6.74	Hz		5.93	Hz
ap/g	0.0030			0.0042			0.0059			0.0083	
Δ(point,cx)	2.51E-05	in/lb		3.26E-05	in/lb		4.34E-05	in/lb		5.95E-05	in/lb
Δ(point,mx)	5.58E-06	in/lb		7.25E-06	in/lb		9.65E-06	in/lb		1.32E-05	in/lb
Δ(point,total)	1.23E-05	in/lb		1.59E-05	in/lb		2.12E-05	in/lb		2.91E-05	in/lb
Uv	1180.6	lb/s^2		1180.6	lb/s^2		1180.6	lb/s^2		1180.6	lb/s^2
V	0.001729	in/s		0.002490	in/s		0.003718	in/s		0.005797	in/s
	1729	µin/s		2490	µin/s		3718	µin/s		5797	µin/s

Two Way Flat Slab Vibration Analysis

										fo	2.5
	wlive	40	psf	width	4	ft	f'c	5000	psi	β	0.05
	wdead	33	psf	span	28	ft	Po	65	lb	Fm/W	1.5
	Design- for 185 lb person walking at 75 steps/min										
	12			11			10			9	
I	6912	in^4		5324	in^4		4000	in^4		2916	in^4
w	480	plf		440	plf		400	plf		360	plf
wu	772	plf		732	plf		692	plf		652	plf
E	5038136	psi		5038136	psi		5038136	psi		5038136	psi
Δ(cx)	0.28	in		0.34	in		0.43	in		0.55	in
Δ(mx)	0.06	in		0.08	in		0.09	in		0.12	in
Δ(total)	0.13	in		0.17	in		0.21	in		0.27	in
fn	9.63	Hz		8.68	Hz		7.74	Hz		6.81	Hz
ap/g	0.0021			0.0030			0.0045			0.0066	
Δ(point,cx)	2.04E-05	in/lb		2.65E-05	in/lb		3.53E-05	in/lb		4.84E-05	in/lb
Δ(point,mx)	4.54E-06	in/lb		5.89E-06	in/lb		7.84E-06	in/lb		1.08E-05	in/lb
Δ(point,total)	9.99E-06	in/lb		1.30E-05	in/lb		1.73E-05	in/lb		2.37E-05	in/lb
Uv	5448.7	lb/s^2		5448.7	lb/s^2		5448.7	lb/s^2		5448.7	lb/s^2
V	0.005651	in/s		0.008139	in/s		0.012152	in/s		0.018951	in/s
	5651	µin/s		8139	µin/s		12152	µin/s		18951	µin/s

Appendix G

Cost Analysis

Composite Beam Concrete and Placement

Description	Quantity	Units	Material	Labor	Equipment	Total	Cost
LWC 4000 psi	9.04	CY	106	15.5	5.65	127.15	$ 1,149.44

Steel Framing

Description	Quantity	Units	Material	Labor	Equipment	Total	Cost
W16 x 26	30	LF	43	2.44	1.74	47.18	$ 1,415.40
W24 x 55	30	LF	91	3.18	1.69	95.87	$ 2,876.10
W21x 44	30	LF	72.5	3.32	1.76	77.58	$ 2,327.40

Steel Decking

Description	Quantity	Units	Material	Labor	Equipment	Total	Cost
3", 20 Ga.	900	SF	2.98	0.48	0.04	3.5	$ 3,150.00

Shear Studs

Description	Quantity	Units	Material	Labor	Equipment	Total	Cost
3/4" dia 4.75" long	131	LF	0.66	0.79	0.41	1.86	$ 243.66
					Grant Total		$ 11,162.00
					Cost per SF		**$ 12.40**

Hollow Core Plank

12" Plank

Description	Quantity	Units	Material	Labor	Equipment	Total	Cost
12" thick	900	SF	8.35	0.79	0.47	9.61	$ 8,649.00

Steel Framing

Description	Quantity	Units	Material	Labor	Equipment	Total	Cost
W27 x 84	30	LF	139	2.96	1.58	143.54	$ 4,306.20
W8 x 10	30	LF	16.5	4.06	2.9	23.46	$ 703.80
					Grand Total		$ 13,659.00
					Cost per SF		**$ 15.18**

Two Way Flat Slab

Concrete and Placement

Description	Quantity	Units	Material	Labor	Equipment	Total	Cost
LWC 5000 psi	33.33	CY	111	12.05	4.39	127.44	$ 4,247.58

Slab Formwork

Description	Quantity	Units	Material	Labor	Equipment	Total	Cost
2 use	900	SF	2.62	3.67	0	6.29	$ 5,661.00

Reinforcing Steel

Description	Quantity	Units	Material	Labor	Equipment	Total	Cost
#6	62	Each	6.4	7.45	0	13.85	$ 858.70
					Grand Total		$ 10,767.28
					Cost per SF		**$ 11.96**

One Way Slab w/ Beams

Concrete and Placement

Description	Quantity	Units	Material	Labor	Equipment	Total	Cost
LWC 5000 psi	44.44	CY	111	12.05	4.39	127.44	$ 5,663.43

Beam Formwork

Description	Quantity	Units	Material	Labor	Equipment	Total	Cost
12" wide, 2 use	150	SF	2.62	3.67	0	6.29	$ 943.50

Slab Formwork

Description	Quantity	Units	Material	Labor	Equipment	Total	Cost
2 use	900	SF	2.62	3.67	0	6.29	$ 5,661.00

Reinforcing Steel

Description	Quantity	Units	Material	Labor	Equipment	Total	Cost
#6	62	Each	6.4	7.45		13.85	$ 858.70
					Grand Total		$ 13,126.63
					Cost per SF		**$ 14.59**