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Courtesy of Bernard Tschumi Architects

Pro-Con Structural Study of Alternate Floor Systems
October 29, 2003

Executive Summary

This report studied the various benefits and drawbacks to several alternate floor systems for the University of Cincinnati Athletic Center. The alternate systems were selected, assumptions and design decisions were made, and each system was evaluated in a weighted pro-con format to determine which ones are viable alternatives to the existing floor system.

The original system and alternatives #1, #2, and #4 are viable options. Alternative #3 is not a viable option.

Original System: Composite steel beams with composite slab on metal deck
- Lower steel member weight
- Reduced beam depths (good for architectural criteria)
- Increased construction time due to shear stud installation

Alternative #1: Non-composite steel beams with composite slab on metal deck
- Heavier members
- Better vibration control
- Good durability and fire resistance

Alternative #2: Non-composite steel beams w/ non-composite slab on form deck
- Highly constructible and flexible for unique floor plan
- Increased beam depth will reduce flr-to-flr height, plenum space
- Increased construction time due to shear stud installation

Alternative #3: Steel joists with composite slab on metal deck
- Lower individual member weight
- Inefficient and costly due to custom span lengths
- Building services equipment can be run through open webs, saving plenum space

Alternative #4: Concrete one-way pan joists
- Lower material cost
- Heavier dead load can impact foundation, lateral system
- Potential for huge material and labor savings if diagrid is concrete

Introduction

The purpose of this report is to study the various benefits and drawbacks to several alternate floor systems for the University of Cincinnati Athletic Center. The alternate systems will be selected, assumptions and design decisions will be made, and each system will be evaluated in a weighted pro-con format to determine which ones are viable alternatives to the existing floor system.

Existing Floor System

The floor framing system consists of typical steel composite wide flange beams with composite metal decking supporting one-way slab diaphragms. Most connections are shear only, however, some elements framing into full height columns near the atrium are designed with moment connections to support atrium walkways. The layout irregular due to the highly curved shape of the building, however, the N-S direction spacing is typically 9' o.c. within 27' bays. In general, three main framing areas can be identified on the above-grade floors as shown in Figure 1. These are:

Orange – North bays (longer, more regular spans)
Green – Elevator and stair cores (highly varied, shorter spans)
Pink – Atrium bays (regular spacing with moment connections)

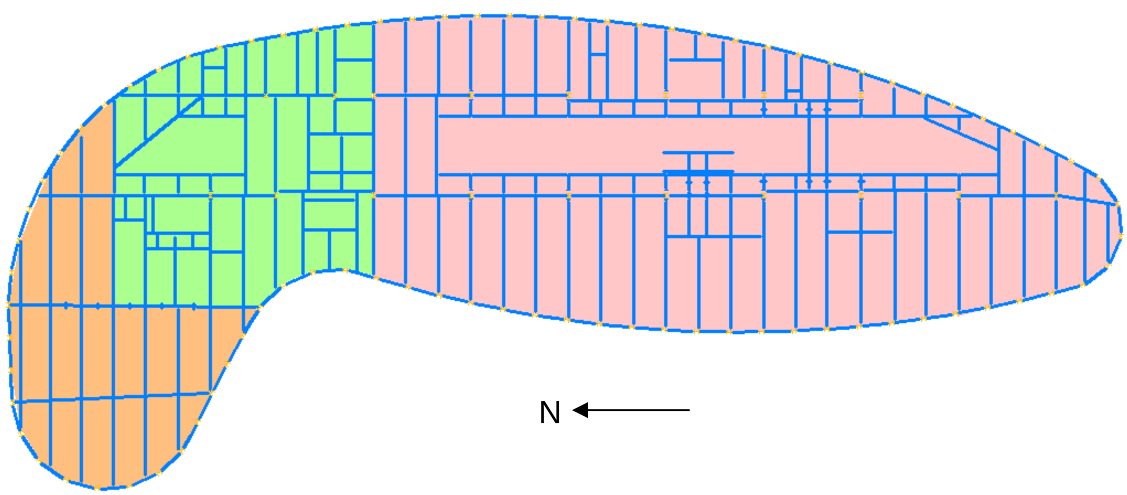

Figure 1: Main framing areas

Alternative Floor Systems

Four alternative floor systems were chosen from the wide variety of available systems in the building industry. They are:

1) Non-composite steel beams with composite slab on metal deck
2) Non-composite steel beams w/ non-composite slab on form deck
3) Steel joists with composite slab on metal deck
4) Concrete one-way pan joists

These systems were chosen primarily because of their initially assumed feasibility for the University of Cincinnati Athletic Center. Because of the unique floor layout of the building, many systems, such as precast hollow-core planks, pre-tensioned floors, and two way slabs, were ruled out as viable options. Although is it possible to alter the plan of the building, it is assumed that the layout of the building is rigidly set, and significant repositioning of columns or squaring off any exterior curves is architecturally unacceptable. The four systems chosen all share a reasonable degree of flexibility to the building's unusual layout. They are also all quite common systems in the building industry and, with the exception of the concrete pan joists, similar to the existing floor system. This will aid in performing a more valid comparison later on.

Design Process

The alternative systems were designed to be as consistent as possible with the original system. Therefore, a typical bay (Figure 2) was chosen to represent the entire building system. Of course, this presents a fairly inaccurate perspective of the many different spans and loading conditions found in a mixed-use facility such as the UC Athletic Center, but it was necessary in order to keep the scope of this report manageable.

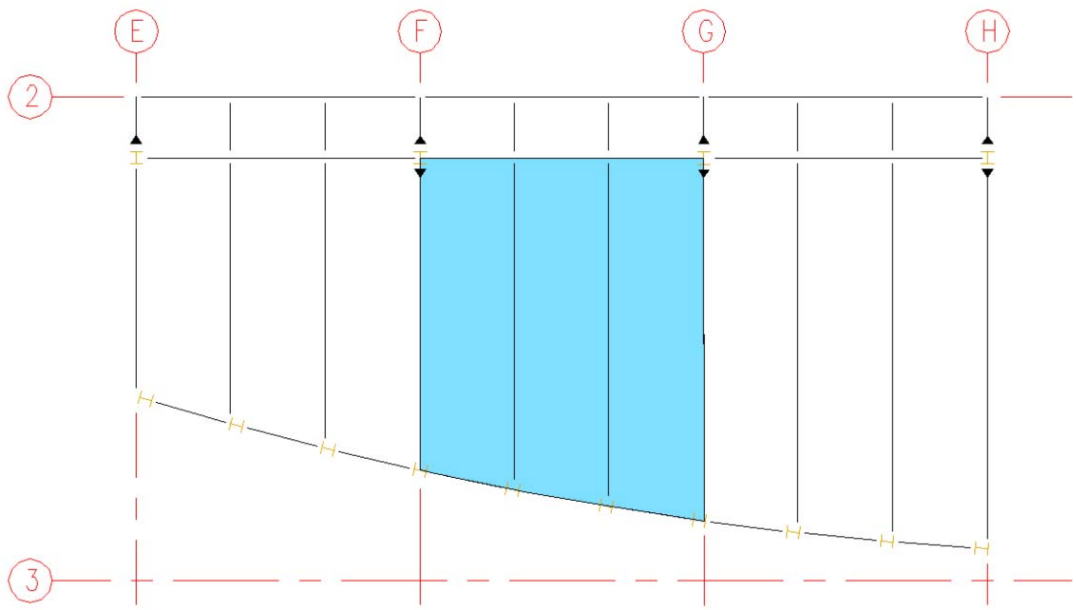

Figure 2: Representative bay

The representative bay is found on levels 500-800 (floors 2-5) between gridlines F & G and 2 & 3. It is a 27' by approximately 30' office bay on the west side of the atrium. Just outside the bay is the atrium walkway, which is cantilevered from the corner columns of the bay. The walkway framing was included in the analysis for member sizing because it has a significant effect on the beams framing into the columns.

Two design methods were used to obtain final member sizes. For the three steel-framed alternatives, once loading was determined (see Appendix A) RAM Steel computer models automatically sized the members after relevant layout and loading data was inputted. The two wide flange alternatives were run at least twice, once without depth restrictions, and once with. The restrictions were chosen to reflect a reasonable member depth and to promote repetitive members, as one would do in hand design. Graphic summary outputs (maps) for each RAM analysis are found in Appendix B. For the concrete one-way pan joist system, hand calculations were performed along with referencing the CRSI manual to find suitable member sizes and reinforcing steel. Calculations are found in Appendix C.

The applicable codes and standards as dictated by the 1998 Ohio Basic Building Code were used for analysis, including AISC LRFD specification and ACI 318. However, particular design considerations such as reinforcement detailing, shear stud spacing, and welded wire mesh sizes are not necessary for the purpose of this report and therefore were not considered.

Finally, once representative member sizes were found the advantages and disadvantages of each system were evaluated. Discussion is provided only for the most significant or unique characteristics of the systems. Several other considerations were taken into account, collated, weighted and summarized in an overall System Comparison Chart. With so many variables affecting a floor's possibility as an alternate system, it is convenient to effectively quantify each one's performance.

System Evaluation

Original System: Composite steel beams with composite slab on metal deck

System properties
- Slab: 6.5" thick (4.5" cover), $f'_c = 3.0$ ksi, Normal weight
- Deck: 2" USD Lok-Floor, 18 gage
- Framing: Composite A992 steel wide flange girders and beams @ 9' o.c., ¾" shear studs

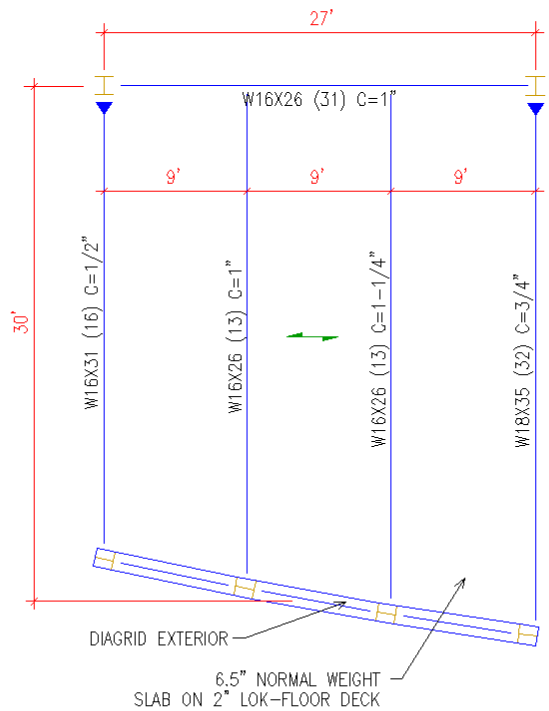

Figure 3: Existing framing plan

Design Results
- Loads: 101psf (DL), 50psf (LL)
- Member sizes (shear studs):
  - Interior Beams – W16X26 (13)
  - Cantilevered Beams – W16X31 (16), W18X35 (32)
  - Girder – W16X26 (31)

Advantages/Disadvantages
- One of the main advantages to this system is that the composite action of the steel beam working with the concrete slab allows for smaller beam weights. Even with the addition of shear studs (approximately 10 pounds each every 2 feet = 5 lb/ft additional), the result is a reduction of steel in the building. This system is very efficient in carrying the required loads. Very little of the superstructure is wasted weight. The exception is that composite beams are no more effective than non-composite beams for cantilevers such as those framing into the columns.
- The system also minimizes floor depth, since the moment arm of the steel acting with the concrete is higher. The increased stiffness reduces live load deflection, but more importantly allows more plenum space for equipment. The ability to keep floor to floor height at a minimum is highly valued for a building such as this. An increased story height will have major architectural implications on the façade, such as undesirable aesthetic changes in the diagrid proportionality.
- Though steel erection is a relatively quick process, the addition of shear studs increases the erection time, since shear studs must be installed manually in the field by tack welding. Labor is a major cost in the overall building budget, so labor-intensive shear studs are a disadvantage.

Alternative #1: Non-composite steel beams with composite slab on metal deck

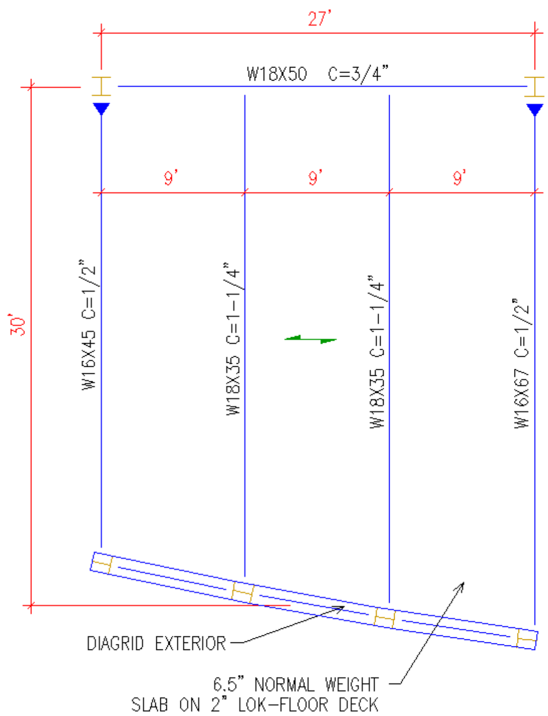

Figure 4: Alternative #1 framing plan

System properties

Slab: 6.5" thick (4.5" cover), f'_c = 3.0 ksi, Normal weight

Deck: 2" USD Lok-Floor, 18 gage

Framing: Non-composite A992 steel wide flange girders and beams @ 9' o.c.

Design Results

Loads: 101psf (DL), 50psf (LL)

Member sizes:

Interior Beams – W18X35

Cantilevered Beams – W16X45, W16X67

Girder – W18X50

Advantages/Disadvantages

- Steel erection time, as mentioned in the previous section, is relatively quick. However, the lead time required for a steel building is much greater than that of concrete. Procurement of the steel may be an issue in a fast track project.
- Since there is no composite action, members are heavier. This adds to building weight and cost. On the other hand, heavier floors tend not to be as susceptible to unwanted vibrations.
- As with the other steel wide flange systems, this alternative is fairly durable. Unlike concrete, there are no major concerns of cracking or spalling. The beams can also be fire-proofed with cementitious spray to meet the 2-hr fire rating. When this happens rust and corrosion are kept to a minimum.

Alternative #2: Non-composite steel beams w/ non-composite slab on form deck

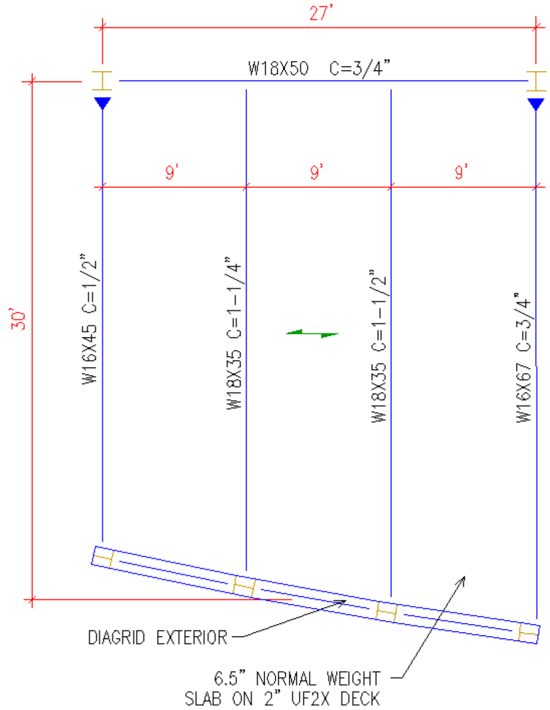

Figure 5: Alternative #2 framing plan

System properties

Slab: 6.5" thick (4.5" cover), $f'_c = 3.0$ ksi, Normal weight

Deck: USD UF2X deck, 20 gage

Framing: Non-composite A992 steel wide flange girders and beams @ 9' o.c.

Design Results

Loads: 102psf (DL), 50psf (LL)

Member sizes:

- Interior Beams – W18X35
- Cantilevered Beams – W16X45, W16X67
- Girder – W18X50

Advantages/Disadvantages

- A non-composite system is one of the most constructible floors in the industry. The connections are shear bearing and relatively easy to install. The floor deck is quickly attached to the supporting beam and concrete can be poured right away. Because non-composite systems are highly flexible, they can accommodate the unusual framing pattern and atypical bays of the UC Athletic Center.
- Depth is an issue in non-composite design. The members are larger than in composite design. Only by inefficiently increasing their weight can depth criteria be met. Floor-to-floor height and reduced plenum space become an issue.

Alternative #3: Steel joists with composite slab on metal deck

System properties

Slab: 6" thick (4.5" cover), $f'_c = 3.0$ ksi, Normal weight

Deck: 1.5" USD Lok-Floor, 20 gage

Framing: A992 Steel wide flange girders w/ steel joists @ 4.5' o.c.

Design Results

Loads: 98psf (DL), 50psf (LL)

Member sizes:

Interior Joists – 24LH06*, 24LH07*

Cantilevered Beams – W18X40

Girder – W21X50

*Note: RAM found that LH series joists were more efficient for this particular span than K series joists

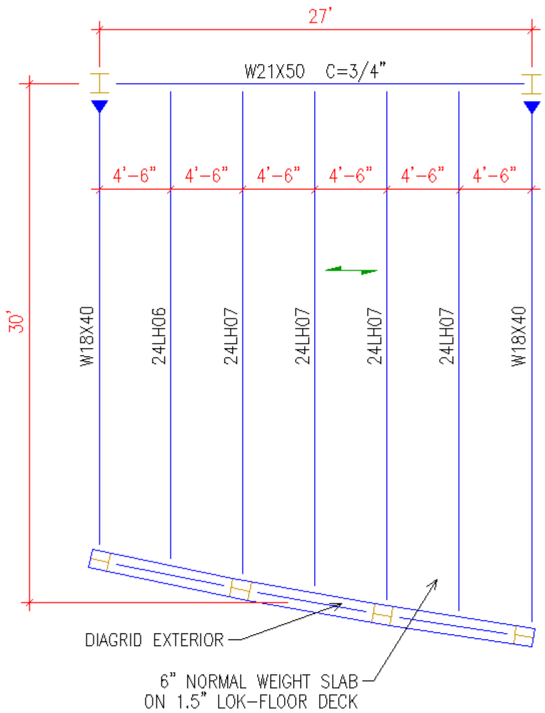

Figure 6: Alternative #3 framing plan

Advantages/Disadvantages

- One main advantage to a joist system is its weight. Although comparable to the wide flange systems in steel density per square foot, each individual joist weighs about half as much as a regular I-beam. This could have positive effects on the required crane size for the project. Additionally, the joists could be rotated 90 degrees to span in the N-S direction, which would reduce joist weight, but increase the size of the cantilevered beams
- The major drawback to a steel joist system is its impracticality for custom applications. The curved shape of the UC Athletic Center presents a new span length for each and every joist. Their fabrication would become extremely inefficient, driving up costs. Installation also becomes more complex and susceptible to error in the field, increasing labor costs.
- Although the depth of the joists is large, many building services can run through the open webs without impacting floor-to-floor height.

Alternative #4: Concrete one-way pan joists

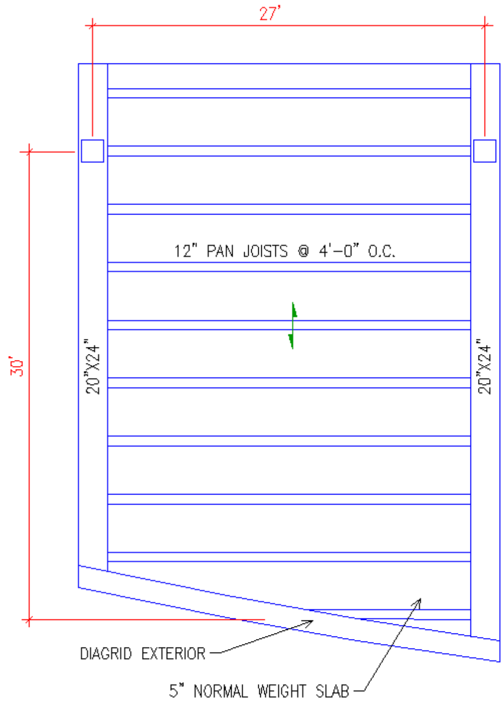

Figure 7: Alternative #4 framing plan

System properties

Concrete: $f'_c = 3.0$ ksi, Normal weight

Slab: 5" thick, minimum temperature and shrinkage reinforcement

Joists: 40" pan (48" o.c.), 8" rib, 12" deep,

Design Results

Loads: 130psf (DL), 50psf (LL)

Member sizes:

Pan Joists – 2 #5 bottom reinf., $f_y = 60$ksi

Joist girders – 20" deep, 24" wide, 3 #9 bottom reinf., 11 #8 top reinf., $f_y = 60$ksi

Advantages/Disadvantages

- Concrete systems are, in general, less costly than comparable steel systems. Converting to a concrete system could have a major impact on the building cost because of its effect on the exterior diagrid. The diagrid is perhaps the most labor-intensive component of the UC Athletic Center, as it requires an enormous amount of steel detailing and field welding. The possibility of creating an efficient system of formwork to cast the diagrid in place could drastically reduce the cost of not only the floor system but the entire building.
- The lateral and foundation systems could be negatively affected by the monolithic construction and increased building self weight. The building would likely require complete redesign to account for the increased soil bearing loads and seismic effects.
- Vibration would be limited due to concrete's stiffness characteristics and increased weight.
- Concrete is much better in fire resistance than steel. No additional fire proofing would be necessary with a 5" slab.

System Comparison Chart

The System Comparison Chart was developed to provide a quantitative summary and evaluation of the different floor system alternatives. It is not an exhaustive study of every design consideration applicable to floors, but it does highlight many of the criteria that were addressed in the System Evaluation section.

		System				
Consideration	**Weight**	**Comp. / Comp.**	**Non-comp. / Comp.**	**Non-comp. / Non-comp.**	**Steel joists**	**Concrete pan joist**
Depth (flr-to-flr height, plenum space)	8	10	7	7	5	7
Weight (foundation/seismic design)	5	8	7	7	10	3
Construction Time (lead time, erection)	5	8	9	9	6	10
Constructability (feasibility)	7	9	10	10	2	6
Material Cost	5	7	8	8	4	10
Labor Cost	6	8	7	7	4	10
Efficiency (use of material)	3	10	9	8	6	5
Fire resistance (2 hr. minimum)	4	7	7	7	3	10
Floor vibration (weight, stiffness)	3	8	7	7	6	10
Durability	5	10	10	10	8	8
Applicability to rest of building	9	10	10	10	5	10
Score out of 10		**8.8**	**8.4**	**8.4**	**5.2**	**8.1**

Conclusion

Based on the advantages and disadvantages discussed in the System Evaluation section and combined with the System Comparison Chart, each alternative floor system was evaluated according to its viability for the University of Cincinnati Athletic Center. The evaluations are summarized below.

System	**Viable option?**	**Support for decision**
Existing comp./comp. system	Yes	Economical, good flr-to-flr heights
Non-comp./comp.	Yes	Practical, though not many advantages over existing system
Non-comp./non-comp.	Yes	Practical, though not many advantages over existing system
Steel joists	No	Customization requirements are too costly and inefficient
Concrete pan joists	Yes	Would require significant redesign, but benefits could be dramatic

Notes:

- Full calculations and design materials are available upon request.
- All images courtesy of Bernard Tschumi Architects or Arup Services, NY.

Appendices

Pages

ARUP

Job No.	Sheet No. 1 of 3	Rev.
Member-Location		
Job Title: GRAVITY LOAD CALCS	Drg. Ref.	
	Made by BJG	Date	Chd.

ORIGINAL SYSTEM

6.5" NW slab on 2" Lok-Floor deck
Composite steel beams

Self weight: slab + deck = 66 psf (From USD manual, pg. 28)
steel = 5 psf (assumed)

71 psf

Superimposed: From drawings, 20 psf (partitions)
10 psf (ceilings + services)

30 psf

Live: From drawings, **50 psf**

Total = 101 psf (DL) + 50 psf (LL)

ALT. # 1

Slab as above
Non-composite steel beams

All loads same as original system

Total = 101 psf (DL) + 50 psf (LL)

ALT. #2

6.5 slab on ??? form deck (must select)
Non-composite steel beams @ 9' o.c.

Deck selection

Try UF2X deck (max span = 9')
Slab weight from tables = 67 psf
LL = 50 psf
W = 67 psf (DL) + 30 psf (superimp.) + 50 psf (LL)
$W_u = 1.2(97) + 1.6(50) = 196$ psf

From tables, max load = 244 > 196 ∴ OK (20 gage)

Weight

Dead = 67 psf + 5 psf (steel) + 30 psf = 102 psf

TOTAL = 102 psf (DL) + 50 psf (LL)

ALT. #3

?? slab on ?? comp deck (must select)
Steel joists @ 4.5' o.c.

Deck Selection

Try 1.5" Lok-Floor, from tables in USD manual 22 gage will work, but due to specs 20 gage min.

ARUP

Job No.	Sheet No. 3 of 3	Rev.
Member-Location		
Drg. Ref.		
Made by	Date	Chd.

Job Title GRAVITY LOAD CALCS

Slab selection

Due to UL fire reqs., 4.5" min cover ⇒ 6" slab

Slab weight from tables = 63 psf

Steel = 5 psf

Superimposed = 30 psf

Total = 98 psf (DL) + 50 psf (LL)

ALT. #4

Self wt. = calculated from panjoist design = 100 psf

Superimposed = 30 psf

Live = 50 psf

Total = 130 psf (DL) + 50 psf (LL)

Appendix B - RAM Steel layout maps

Floor Map

RAM Steel v7.0
DataBase: Typical office bay - steel - noncomp-comp
Building Code: UBC2

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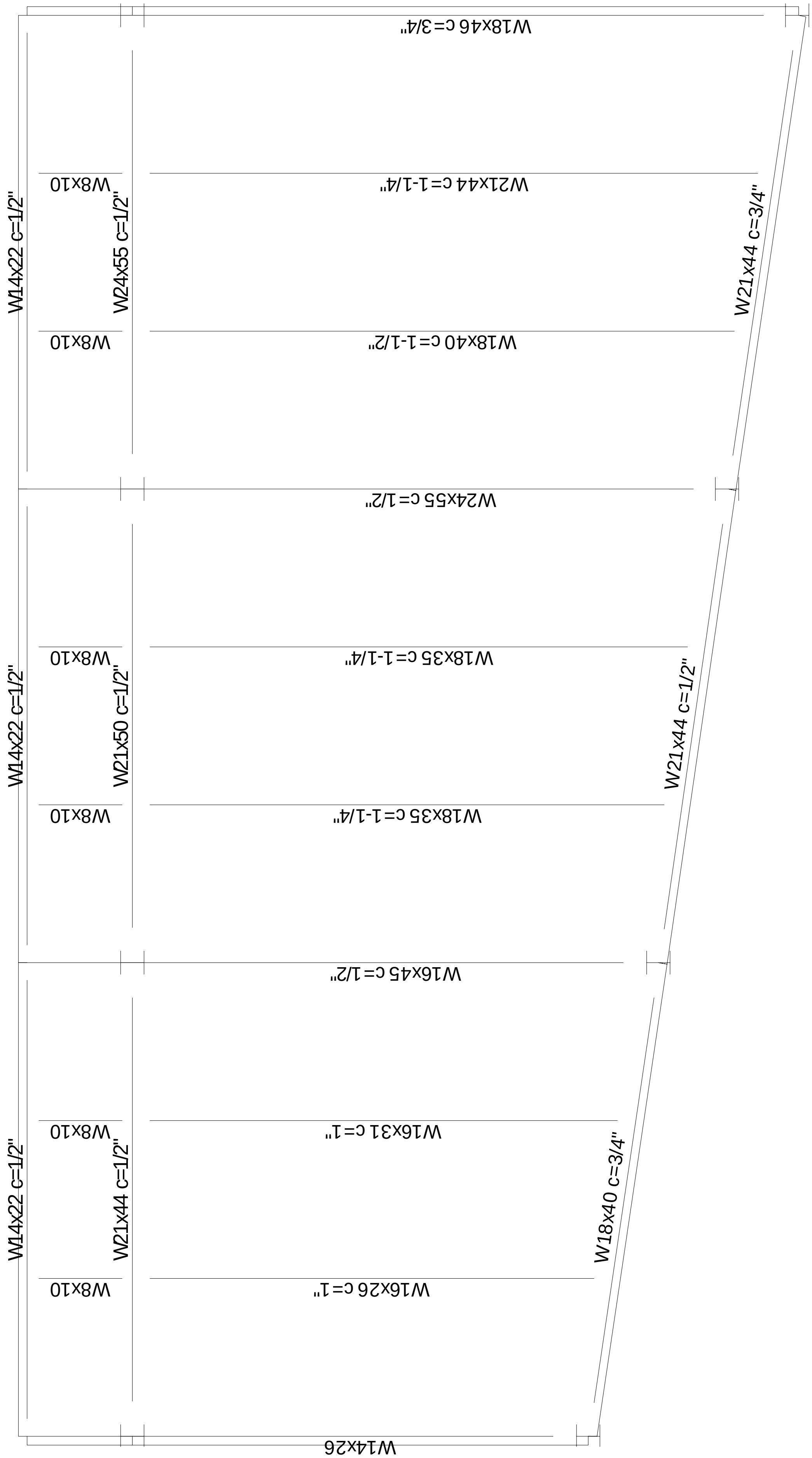
Floor Type: Composite

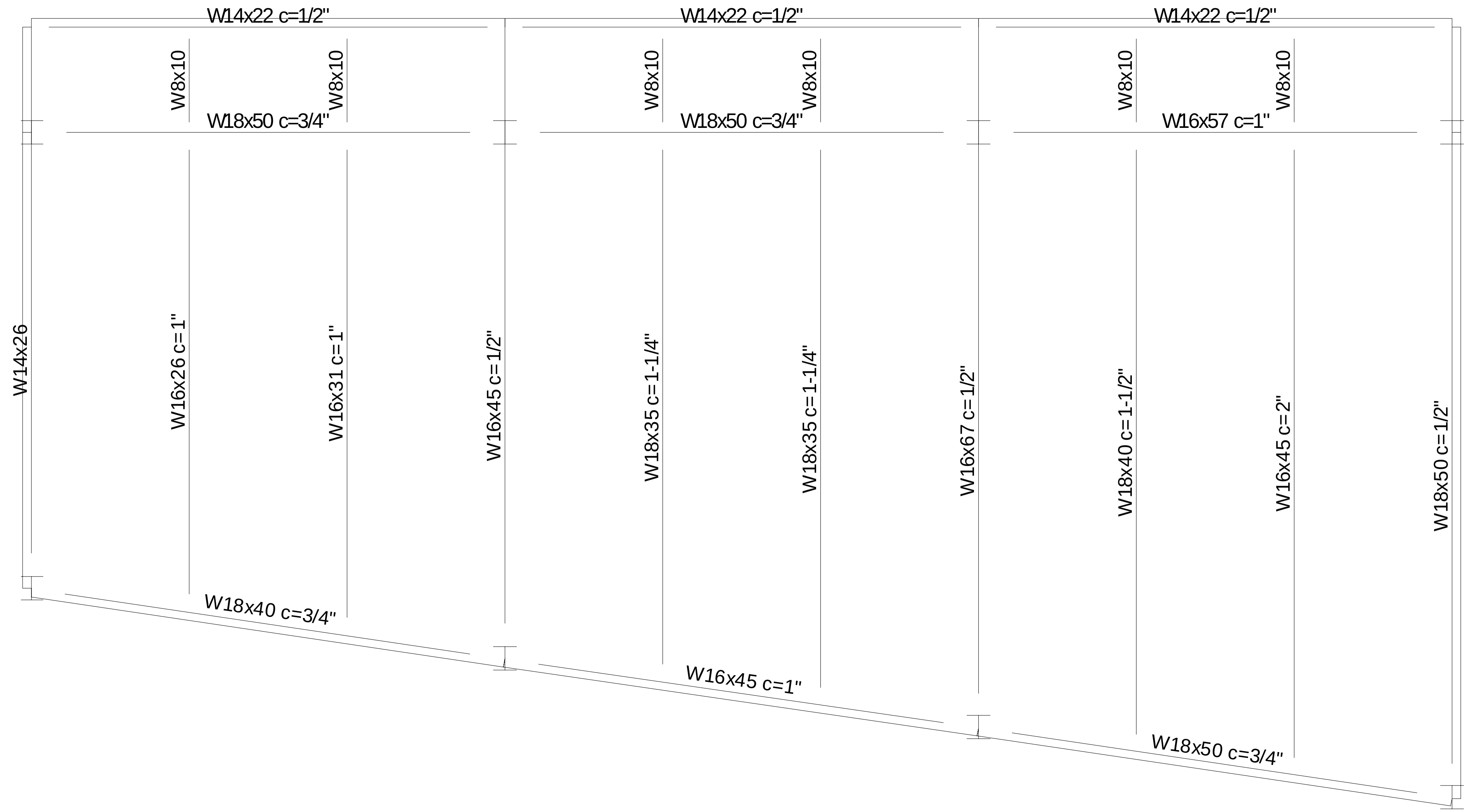


Floor Map

RAM Steel v7.0
DataBase: Typical office bay - steel - noncomp-comp - restricted
Building Code: UBC2

10/29/03 07:25:47

Floor Type: Composite



Floor Map

RAM Steel v7.0
DataBase: Typical office bay - steel - noncomp-noncomp
Building Code: UBC2

10/29/03 07:31:15

Floor Type: Composite

Floor Map

RAM Steel v7.0
DataBase: Typical office bay - steel - noncomp-noncomp - restricted
Building Code: UBC2

10/29/03 07:34:22

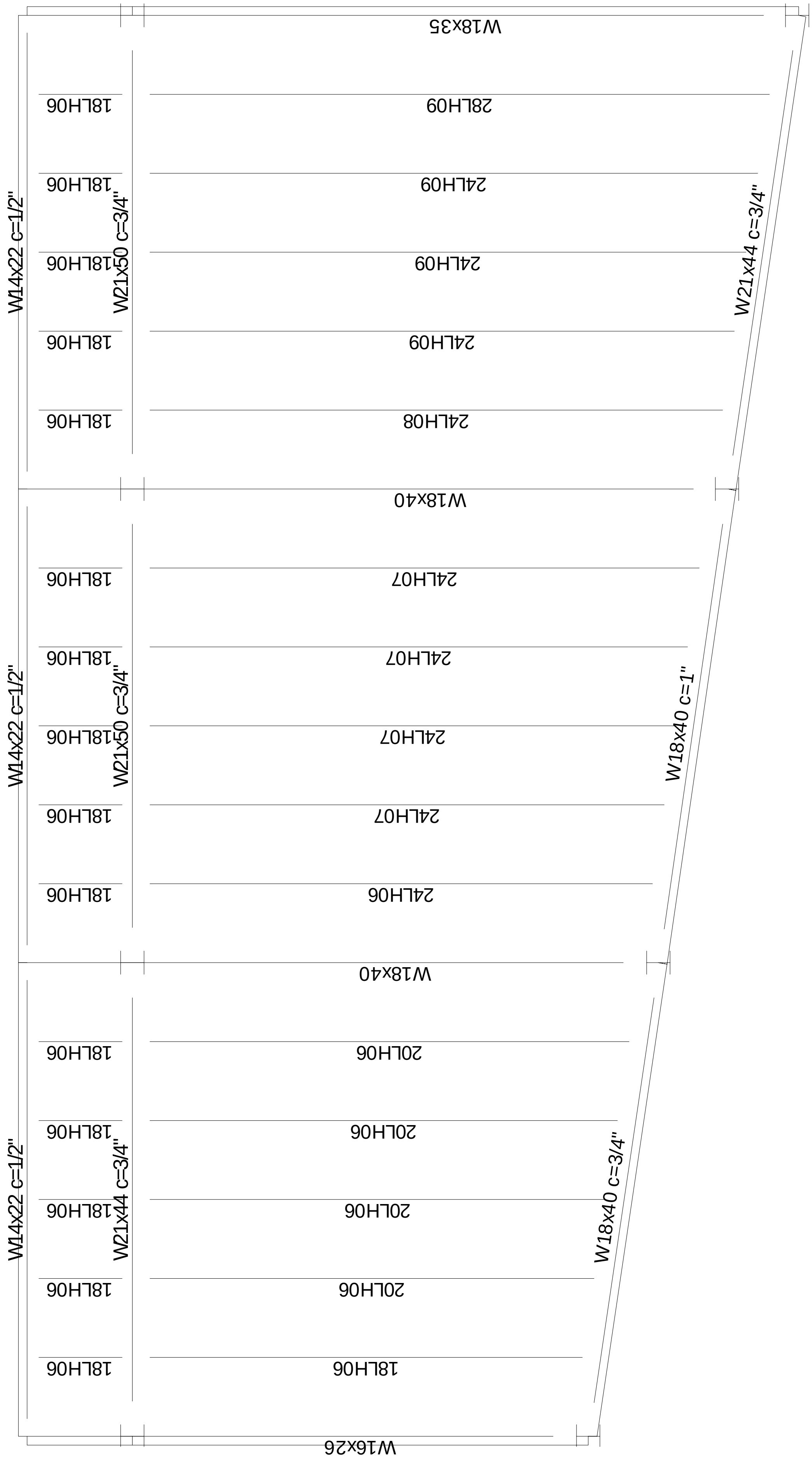
Floor Type: Composite

Floor Map

RAM Steel v7.0
DataBase: Typical office bay - joists - e-w
Building Code: UBC2

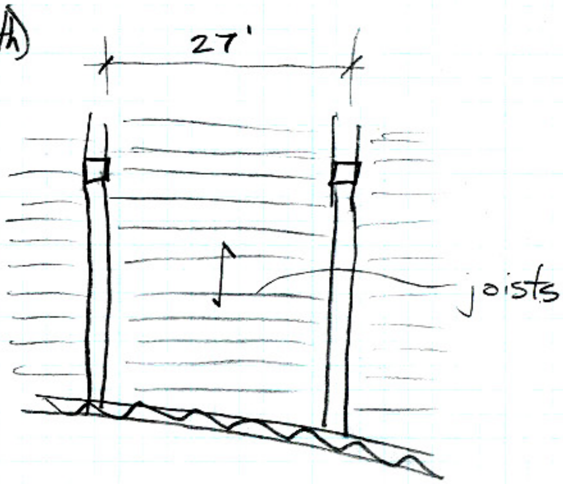
10/29/03 07:40:57

Floor Type: Composite



ASSUME: 5" NW slab (min for 2-hr fire rating)

Try 40" joist system (8" rib width)



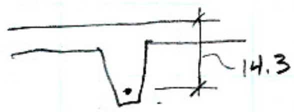
Design joist depth

Min. height $= \frac{\ell_u}{21} = h$

$\ell_u = 27' - 2'$ (assume beam width = 2')

$= 25' = 300"$

$\therefore h = \frac{300}{21} = 14.3"$



pan depth = 14.3" + 1.5" cover + .5" ϕ bar − 5" slab = 11.3" → 12"

Self weight

rib: 8 in rib × 12" depth × 145 $\frac{lb}{ft^3}$ / 144 $\frac{in^2}{ft^2}$ = 96.7 $\frac{lb}{ft}$

slab: 5" · $\frac{1 ft}{12 in}$ · 145 $\frac{lb}{ft^3}$ · 48" trib width · $\frac{1 ft}{12 in}$ = 242 $\frac{lb}{ft}$ along rib

Total = 96.7 + 242 = 339 $\frac{lb}{ft}$

Superimposed weight

30 psf · 48" · $\frac{1'}{12"}$ = 120 $\frac{lb}{ft}$

Live load

50 psf · 48" · $\frac{1'}{12"}$ = 200 $\frac{lb}{ft}$

$W_u = 1.2(339 + 120) + 1.6(200) = 871 \frac{lb}{ft} = .871 \frac{k}{ft}$

Reinf. from CRSI manual: 2 #5 bars

ARUP

Job No. | Sheet No. 2 of 2 | Rev.

Member-Location

Job Title CONCRETE PAN-JOIST DESIGN

Drg. Ref.

Made by BJG | Date | Chd.

Girders

Assume 12" + 5" = 17" → probably needs to be deeper

Loads: $.871\ \frac{k}{ft} \cdot 27' \cdot \frac{12}{48"} = 5.9\ \frac{k}{ft}$ (Approx. 30')

From CRSI manual, choose 20" × 24" w/ 3 #9 bottom reinf.
11 #8 top reinf.

$\therefore$ Self weight $= 20" \cdot \frac{1}{12} \cdot 24" \cdot \frac{1}{12} \cdot 145\ \frac{lb}{ft^3} = 483\ \frac{lb}{ft}$

Per area $= 483\#/27' + 339\#/4' \approx 100$ psf