Prepared by
KSENIA TRETIAKOVA
Structural Option
AE Consultant: Dr. Andres Lepage

04.04.2012

Architectural Engineering
Pennsylvania State University 2012

Southwest Housing, Arizona State University

Final Summary Report

Southwest Student Housing Building

1000 Apache Boulevard East, Tempe, Arizona

Project Team:

- **Owner** - Arizona State University
- **Architect** - BOKA Powell
- **Structural Engineer** - Thornton-Tomasetti
- **MEP Engineer** - WSP Flack+Kurtz
- **Agency CM** - Romani Group, Inc.

Basics:

- **Purpose** - Dormitories
- **Size** - 268 units with 528 beds;
  Area per story - 13,000 ft^2
  Total area - 260,000 ft^2
- **Stories** - 20 stories
- **Estimated Total Cost** - $37,358,413
- **Distinguishing features** - modular building (3 or 4 modules per floor), prefabricated bathrooms, constructed as a modified lift slab

Construction:

- **Projected schedule** - 302 days total
  125 days Preconstruction
  177 days Construction
- 4 weeks for concrete cores
- 2 days for each half-floor
  (Each floor is constructed on the ground in (2) halves, which are separately lifted into place with (6) 75-ton strand jacks, placed at the corners of the finished concrete cores. Interior work starts immediately on each floor once it is constructed and lifted into place.)

Structural:

- **Foundation** - concrete piers (12 to 60" in diameter) penetrating 12.5 to 47.5' into the ground; piers and mats are located under each core to directly support gravity load
- **Superstructure** - composite floor (3-1/4" lightweight concrete on 3" metal deck) attached to structural steel frame made of wide flange beams (sizes from W14x22 to W24x176) using Hilti fasteners;
  Typical bay size: 12'-6"x13'
- **Lateral System** - gravity and lateral system are the same: (3) 8" thick concrete cores, 25'x25'on center with a single layer of rebar running through center

MEP Systems:

- **Mechanical** - 1st floor mechanical room contains chillers, pumps and water tanks 4-pipe system with single fan coil units on each pipe supply hot and chilled water;
  Bathroom exhaust fans located on roof, above stacked bathrooms
- **Fire Safety** - wet system in building, dry system in parking lot; jockey pumps in mechanical room;
  1 sprinkler in each sleeping room, foyer and bath-room; all corridors are sprinkled
- **Lighting/Electrical** - 1 main panel at each floor with subs in each unit; Electrical design is currently incomplete and pending.

Ksenia Tretiakova
Structural Option

CPEP Website:
http://www.engr.psu.edu/ae/thesis/portfolios/2012/KKT5018/

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Ksenia Tretiakova, Structural Option
AE Consultant: Dr. Andres Lepage

Executive Summary

The Southwest Student Housing building is a new building to be constructed in Tempe, AZ. It will be built using slip-forms for the concrete core structure that will function both as the gravity and lateral system. The floors will be assembled using lift-slab construction for ease of assembly and speed of erection. The building will cost an estimated $37 million, and 177 days of construction to complete.

In order to test the versatility of this type of building construction, this report focuses on redesigning the structural system to withstand increased seismic design loads. The new design loads for the building are about 325% greater than the original seismic design loads, which resulted in a doubling of the overall concrete volume (an increase in wall thickness from 8" to 16"), and quintupling of reinforcement volume.

To truly investigate the impact of transitioning the building design to SDC D, the building must be evaluated from a cost and scheduling standpoint as well. This report investigates the bare material cost difference between the original building design and the redesign geared toward SDC D. The overall cost difference totals to an increase of about 8% of the total building cost. The resulting impact on the schedule is minimal, with approximately 10 to 20 additional days needed to slip-form the larger cores. The construction method is the primary reason that the impact on the schedule is so small--the fluid pre-assembly of the majority of the components needed for construction allows for minimal time delays throughout the actual construction process.

In addition to cost and scheduling, this report includes investigations on the impact of the structural redesign on the typical building floor plan. To have a stiffer building, the cores were made to be as continuous as possible, which removed the majority of the openings that were previously present. These openings gave the residents access to the interior of the cores for usable apartment unit space. Making the walls continuous closes off that usable space, unless the floor plan is rearranged. The *Effect on Architecture* section provides several options for how to rearrange the apartment units to take advantage of some corridor space to provide access to the cores without having openings. The maximum decrease in unit area for the new floor plan options was found to be about 5% of the original apartment unit area, while some apartments received up to a 33% increase in area.

This report also discusses the potential for the Southwest Student Housing building to become LEED Certified. Ultimately, it is concluded that the building could become LEED Certified with relative ease and minimal cost investment if the owner and contractor take the time to plan ahead for certain things during the preconstruction phase of this project.

Ksenia Tretiakova, Structural Option
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Introduction

The Southwest Student Housing building is a 20-story project commissioned by Arizona State University (ASU). An artistic rendering of how the building will potentially appear can be found in Figure 1. This building will contain apartments that can be rented by students who attend ASU. There are 268 apartment units in the building plan, consisting of studio apartments and one to four bedroom units. In total, there will be 528 beds in the Southwest Student Housing building.


Figure 1 - Rendering of potential building appearance

This project began in November of 2010 and is still currently in the works, due to several modifications to the overall building design. The Thornton-Termohlen Group is responsible for the structural design and the ideas for the construction methods that will be employed, which is a unique feature of this particular building design. The construction method was chosen for its high speed, ease, and low cost.

This building will be erected using lift-slab construction-- a construction method that has long been frowned upon in the United States as a result of the catastrophic collapse of L'Ambiance Plaza in 1987. According to individuals involved with the company, this method of construction has been used elsewhere around the world for the last 40 years; the intent of this project, and others by the Thornton-Termohlen Group, is to reintroduce the lift-slab construction method to the United States because of its speed, utility and low cost. With this construction method, the estimated time in construction is 177 days from pouring the foundations to completing the final interior finishes.

The Southwest Student Housing building has three concrete cores as its primary structural system. These cores will be the first item constructed. Once they are fully erected, each floor will be assembled one half at a time as indicated in Figure 2, and then lifted into place with 75-ton strand jacks located at the corners of each core. The floors will be erected from the top-down. They will contain all prefabricated partitions, bathrooms, and the building envelope for that floor.


Figure 2 - Half a floor lifted into place

General Information

Site Information

The Southwest Student Housing building is located at 1000 Apache Boulevard East, in Tempe, Arizona. This location is on the Arizona State University's campus. From the satellite map pictured in Figure 3, it can be observed that the site is located in an urban area with an already-developed site. The dimensions of the site are about 150' x 300', with an additional piece of land sprouting out of the northwestern portion of the site (the irregular shape is highlighted in red in Figure 3). The site is located within 400 feet of 5 different bus stops.

The geotechnical report for this site indicates a 10 to 35 foot layer of Silty and Poorly Graded Sand followed by a layer of Sand Gravel Cobble down to a total of 100 feet into the ground.

Figure 3 - Site map, 1000 Apache Blvd East, Tempe, AZ (modified from http://maps.google.com)

Building Floor Plan

The building design has a long, thin footprint that is 52 feet wide and 250 feet long, which means the building will need to be oriented either with the long axis in the North-South direction, or diagonally on the site. This sort of orientation will provide considerable sun exposure to the windows of the building, allowing for natural daylighting to be an option in the design.

Figure 4 - Typical floor plan with bays marked

The floor plan is split into almost square bays, 13 ft (short direction) by 12.5 feet (long direction), as can be seen in Figure 4. The plan is very regular and modular to allow for speed and ease of construction. Each floor will capitalize on the use of prefabricated bathrooms, pre-plumbed and pre-wired partition walls, and mechanical modules that can be slid into the building through the corridor that runs across each floor in the long direction.

Building Envelope

The theme of "fast" and "modular" extends to the building envelope as well. The envelope consists of exterior insulation finishing system (EIFS) cladding and conventional glazing. To assemble the building, the EIFS and glazing are assembled on each floor before it is lifted into place. The envelope is erected at the edge of the floor, and then slid into place like a puzzle piece after the floor is lifted to its designated height/location. Figure 5 shows the location of the cladding while the floor is being lifted into place. Once each floor is lifted and affixed to its end location, long aluminum tabs will be slid into the gaps created by the panels of EIFS, and all interior cracks and openings will be caulked closed.

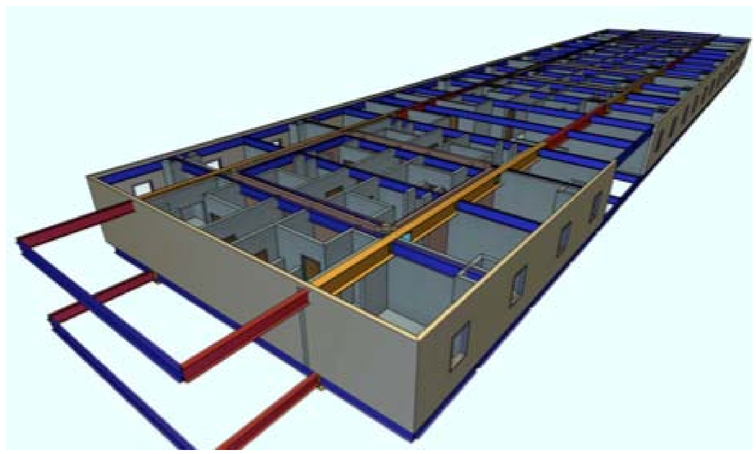

Figure 5 - How the cladding is lifted on the floor

Structural Systems

Foundation

According to the area geotechnical report, the Southwest Student Housing building will exert significant loads on the foundation elements. As a result, the report recommends a deep foundation system that penetrates through the second layer of soil on the site in order to limit settlement. Specifically, the report calls for drilled piers with no pier shaft sized with a diameter less than one foot. Each pier is expected to penetrate at least twice the shaft diameter into the second layer of soil. A potential foundation layout can be found in Appendix A, along with relevant calculations.

Officials working on this project have stated that, though the soils report requires deep foundations, the building designers are planning on having a mat foundation. The designers intend on proving that their design works for the soil conditions, and submitting the building design for peer review.

Floor System

The floor system is identical on every floor. It consists of 3-1/4" lightweight concrete topping on 3" metal deck, with minimum 20 gage. According to officials working on this building design, the concrete is not expected to work in composite with the steel. The deck runs in the long direction of the building footprint, and is supported by a structural steel frame, with clear spans of 12.5 feet. The structural steel wide flange sizes run from W14x22 infill beams to W24x176 interior girders, as indicated on the close-up of the framing plan in Figure 6. The girders span the length of the building while the beams span the entire short direction. An important thing to note is that each beam that runs through the girders is continuous at all points. The infill beams span either 13 feet (one bay in the short direction) or 24 feet (the inside distance of the concrete core walls). Each structural steel element in the floor system is cambered, with the interior girders cambered up to 4 inches at the ends of the building. Camber diagrams from the structural engineers can be found in Appendix A.

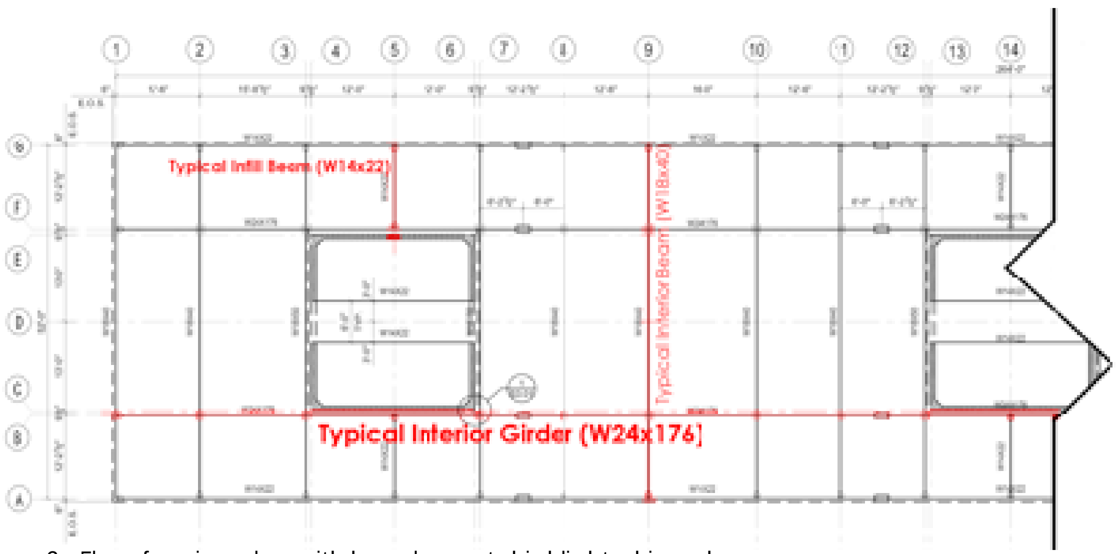

Figure 6 - Floor framing plan with key elements highlighted in red

Gravity and Lateral System

Unlike the majority of conventional construction, there are no columns in this building. The three concrete cores carry the entire gravity load of each floor. Each core is a hollow 25'x25' square tube punctuated by irregular openings to accommodate the doorways in the floor plan, as seen in Figure 7. The core walls are 8 inches thick and minimally reinforced according to ACI 318-05.

At each level where a floor is to be located, each corner of every core has an indentation. Once a floor is lifted to its target height, a wide-flange is inserted through a cutout in the girder to rest on the corner indentation, as demonstrated in Figure 8. This wide-flange detail takes all of the floor loads and transfers them into the cores.

Figure 7 - Observe the multitude of openings in the concrete cores

The concrete cores are also the building's sole lateral force resisting system. Each core functions as a set of shear walls that resist the lateral forces transferred by the floor diaphragm. On each floor, the individual shear walls are connected by 2 foot coupling beams above the openings for the corridor and doors. Seismic forces do not govern this building's design because of the location in Tempe, AZ and the soil content of the site.

The design gravity loads for this building are summarized in Table 1 below. The design lateral loads can be found in Technical Report 1 on the CPEP website listed on the Thesis Abstract.

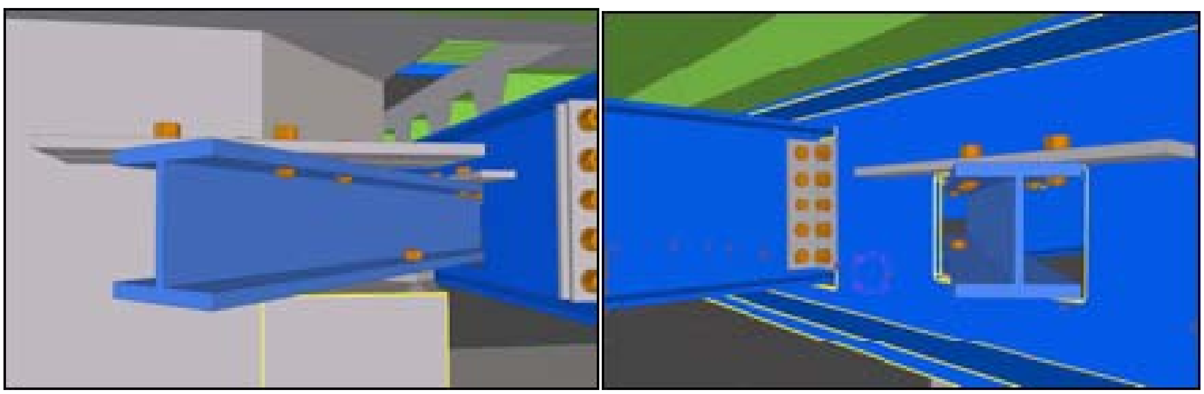

Figure 8 - Core corner detail (floor connection to concrete core)

Table 1 - Design gravity loads for original building

Load Type	Load Value (psf)
Construction Dead Load	59
Superimposed Dead Load	15
Live Load	80
Façade Load	15
Snow Load	0

Roof System

The roof system is a simple, long-lasting construction of the typical floor framing described in the Floor System section of this report, and an Ethylene Propylene Diene Terpolymer (EPDM) membrane on top. There is no mechanical equipment on the roof- the major elements of the mechanical system will be located on the ground floor, and will serve each unit in the building via a 2-pipe system.

Proposal Information and Thesis Scope of Work

Problem Statement

The design of the Southwest Student Housing building is very simple, but elegant. The balance of cost vs. speed of construction has been finely tuned, and the structural design is above adequate for the design loads in its location in Tempe, Arizona. Modularity is a key concept within the design. It is used to accelerate the construction process and have each floor equipped with façade walls and MEP systems within the 4 days it takes to pour and finish each floor. The floor system is a reasonable solution for the construction method when compared to other alternatives. Little can be altered in this design that could allow for faster construction or lower construction costs.

An important item to consider is the applicability of this design to other areas of the United States, such as areas with high seismic activity. This design is intended for construction in a wide variety of locations and would benefit from refinement to make it suited to high seismicity areas. Therefore, it is highly pertinent to investigate the functionality and alterations of this building design and construction method for an area such as St. Louis, Missouri. St. Louis was chosen to minimize the number of design parameters that influence the cost of construction. Appendix C shows a comparison of the costs of construction and the seismic design coefficients for several U.S. cities with high seismic activity. The cost of construction in St. Louis, MO is the closest to that of the existing location. In order to bring the building into SDC D, the site class will have to be altered from C to D. To accommodate these changes, the structural design would need to be reexamined (especially the floor-to-core connections), as would the cost for the new system design and any changes to the construction schedule. There is also a great potential need to alter the floor plans and modules to accommodate the structural design changes. The building envelope system might also need to be examined for ability to accommodate seismic drift, if time permits.

Additionally, the current building design is not LEED certified. Sustainability has been an important design aspect of many buildings in the twenty-first century, and should be considered with each new building design. As a result, it is crucial to consider what it would take for the building to achieve, at minimum, LEED certified status. More importantly, any changes or additions to the building design would need to be practical and appropriate for the occupancy, budget and location.

Proposed Solutions

If this building were relocated to and redesigned for St. Louis, MO with site class D, it would need to be designed as a building in Seismic Design Category D. To alter the design of this building for SDC D, the new seismic design loads would need to be calculated and compared to new wind design loads.

The concrete cores would have to increase in cross-sectional area and reinforcing. Potentially, a higher strength concrete might prove useful when changing building locations to SDC D. A careful review of the floor plans would be necessary, in order to change the floor plan to minimize openings in the core walls.

Additionally, the floor-to-core connections would need to be investigated and altered to satisfy special seismic provisions. If time permits, the cladding would need to be investigated and redesigned to accommodate seismic drifts and seismic design forces on nonstructural components.

The solutions to the problem statement would also require analysis and design in several breadths for thoroughness, and to ensure that these redesigns can truly be compared to the original design of the Southwest Student Housing building.

Breadth Studies

To truly be able to compare the original design to the design in an area of high seismicity, it is necessary to take an in-depth look at the construction costs and schedules. The impact of altering the design for high seismic lateral loads would be great: the cost for construction would increase significantly, due in part to increased material cost. It would be necessary to analyze the area prices for different strengths of concrete and compare the costs to the current building design. It would also be important to consider the schedule, which could potentially be prolonged, resulting in the owner (Arizona State University) losing potential profits from opening the building earlier. An analysis of the profit change due to schedule change would also be necessary.

Additionally, the floor plans and modules in the building would need to be redesigned to accommodate the alterations to the structure. Potential streamlining of the module design might accelerate the construction schedule and provide a greater profit that would need to be considered in cost and schedule evaluations. The module design might also have separate changes relating back to initial manufacturing costs, which should be examined if time permits. Additionally, it would also be beneficial to examine the potential for a module design that is applicable to this type of building design in both SDC B and SDC D.

As a result of the need for in-depth cost and schedule evaluation, one of the breadth studies can be classified as a Construction Management breadth. The other breadth study would be with regards to Architecture, and how the floor plan and module design would need to be modified as a result of the changes to the structural system. The Architecture breadth would involve module design and floor plan design, including an evaluation of the locations of openings, stairs and elevators.

A third breadth study to carry out will center on Sustainability. This breadth will require evaluation of LEED points throughout the building, as well as analysis of potential changes that can be made to bring the building to LEED certified status. Ultimately, if LEED certified status can be achieved, a cost and schedule evaluation will follow to gauge the impact of expanding the sustainability of the building design.

Structural Investigations (Depth Studies)

Design Codes, References and Standards

Model Code:

International Building Code, 2006 Edition

Design Codes:

American Institute of Steel Construction "Specifications for Structural Steel Buildings", AISC 360-05 (13^{th} ed.) and AISC 360-10 (14^{th} ed.)
American Concrete Institute "Building Code Requirements for Structural Concrete", ACI 318-05

Structural Standards:

American Society of Civil Engineers "Minimum Design Loads for Buildings and other Structures", ASCE7-05

Deflection Criteria:

Limit Unfactored Live Load deflections to L/360 or less

Limit Total (Service) Load deflections to L/240 or less

Limit building drift to h/400 or less

Materials

Structural Steel:

- All Rolled Shapes – ASTM A992 Grade 50
- All Plates and Connection Material – ASTM A36
- All Tubular Sections – ASTM A500 Grade B
- All Pipe Sections – ASTM A53 Grade B
- Anchor Rods – ASTM F1554

Cast-in-Place Concrete:

- Foundations – 4000 psi normal weight
- Slab on Grade – 4000 psi normal weight
- Structural Slab on Grade – 5000 psi normal weight
- Lightweight Concrete – 4000 psi
- Walls (core) – 4000 – 5000 psi

Reinforcement:

- Deformed Bars – ASTM A615 Grade 60 typ.
- Welded Wire Fabric – ASTM A195

Welding Electrodes:

- E70xx Low Hydrogen

Bolting Materials:

ASTM 325 or A490

St Louis Site Information

The choice of St Louis, MO as the new site for this building was very important. The goal of this location choice was to create a loading situation where the building would experience strong seismic loads (Seismic Design Category D) without having the building undergo loads that are considered extreme, such as those in Alaska or California. Putting the building site in St Louis brought the overall seismic design category of the design loads to Category C; changing the soil type to Site Class D brings the seismic design category to Category D.

Table 2 - Seismic design forces for different locations and wall thicknesses

Floor #	Seismic Design Forces					
	Tempe, AZ; 8" walls		St Louis, MO; 8" walls		St Louis, MO; 16" walls	
	fi (k)	Mz (k-ft)	fi (k)	Mz (k-ft)	fi (k)	Mz (k-ft)
20	29.5	368.4	68.5	856.8	81.0	1011.9
19	27.0	705.9	90.2	1984.5	111.9	2410.3
18	24.6	1013.6	83.6	3029.0	103.2	3699.8
17	22.3	1292.9	77.1	3992.4	94.7	4883.7
16	20.2	1544.9	70.8	4876.9	86.5	5965.2
15	18.1	1770.8	64.6	5684.6	78.6	6947.7
14	16.1	1972.0	58.7	6417.9	71.0	7834.7
13	14.2	2149.6	52.9	7079.0	63.6	8629.8
12	12.4	2304.9	47.3	7670.6	56.5	9336.6
11	10.8	2439.4	42.0	8195.1	49.8	9959.0
10	9.2	2554.2	36.8	8655.2	43.4	10500.9
9	7.7	2650.8	31.9	9053.8	37.2	10966.4
8	6.4	2730.6	27.2	9393.7	31.5	11359.8
7	5.2	2795.0	22.7	9678.0	26.1	11685.5
6	4.0	2845.5	18.6	9910.1	21.0	11948.4
5	3.0	2883.5	14.7	10093.6	16.4	12153.3
4	2.2	2910.7	11.1	10232.3	12.2	12305.8
3	1.4	2928.6	7.9	10330.4	8.5	12411.6
2	0.8	2939.0	5.0	10392.9	5.2	12477.2
1	0.4	2943.8	2.9	10428.8	3.2	12517.5

Design Loads:

The transition to a site in St. Louis, Missouri creates alternate design loads for the building. The floor gravity loads and wind loads do not change from the loads in Tempe, AZ, but the Snow and Earthquake loads change significantly. The new seismic lateral loads increase by about 400% overall. In Table 2, the seismic loads for the original site can be compared to the new seismic loads for walls the same thickness, as well as walls twice the thickness. Related calculations, design coefficients and design factors can be found in Appendix B. Table 3 shows the loads used to design and model the building under the site conditions in St Louis, MO.

Table 3 - Loads used to design and model the building in St Louis, MO

Gravity Loads		
Construction Dead Load	59 psf	
Superimposed Dead Load	15 psf	
Live Load	80 psf	
Façade Load	15 psf	
Snow Load	20 psf	
Base Shear	1001.4 psf	
Model Masses		
Roof	1.725 E-06	k-s2/in2
Typical Floor	2.574E-06	k-s2/in2
First Floor	3.158E-06	k-s2/in2

Core Design

The redesign of the concrete cores began with choosing the wall thickness for the new seismic base shear. The first portion of the core design calculations can be found on page 4 of the Core Design section of the Structural Investigations Appendix (Appendix C). The initial sizing for the walls was based off of the assumption that the openings from the original design are no longer present, and that the cores will only have openings for the 6-foot corridor running through the middle of the floor plan.

Initial hand calculations for a base shear of 1001 kips yielded a need for a wall thickness of at least 9.3 inches, if 4000 psi concrete is used in St Louis. For an initial trial size of 16-inch walls, the building period was found to be 2.17 seconds when the building was modeled in ETABS using rigid diaphragms and cracked sections (0.5 section multiplier for walls, 0.25 for coupling beams).

The cores are in compression even when the building is subjected to 120% (accounting for torsion) of the overturning moment created by the seismic design base shear. This compression is due to the overall building self-weight counteracting any tensile force the building experiences. As a result of the entire building cross-section experiencing only compressive stress, only the minimum moment reinforcement for SDC D is necessary in the walls, while adhering to Chapter 21 of ACI 318-05. The choice was made to also include boundary elements to maintain structural integrity under seismic lateral loads when also holding gravity loads. When running through hand calculations, the boundary elements were seen to function essentially as columns. Overall, the maximum compressive stress in the concrete under loading was found to be 0.253f'c, with 120% of the design overturning moment applied to

Table 4 - Modes and deflections of original building and new building under St. Louis seismic forces

Design	Original	New Design
Max Deflection	16.202	6.126
Min Deflection	-4.296	-0.888
Mode 1	3.943	2.167
Mode 2	3.521	2.025
Mode 3	3.319	1.797

account for torsion.

Ultimately, the cores were designed to have 16" walls (still 25 feet long on center), a concrete strength of 4000 psi, reinforced with #4 bars spaced at 6 inches on center. The boundary elements extend 118 feet up, and are discontinued when the axial stress of the concrete is under 0.15f'c. Figure 9 shows a drawing of the core layout while Figure 10 shows the boundary reinforcement details. Table 4 shows a comparison of periods and deflections of the original design and the new design.

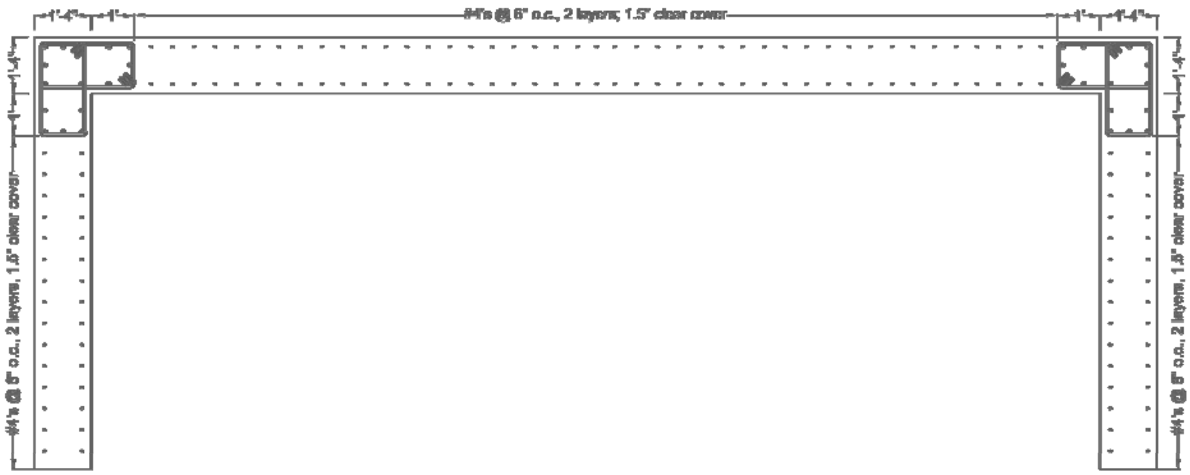

Figure 9 - Core wall reinforcement detailing

Once the core walls were designed and modeled, the coupling beam reinforcement was designed. The shear at the end of a coupling beam was found at each level for 120% of the seismic design load; the values can be found on page 9 of the core design calculations in Appendix C. The maximum shear was found to be about 131 kips. To design the reinforcement for the coupling beams, 80% of the maximum shear was taken to design the moment reinforcement, then divided by 0.9 to change the Φ factor to 1.0 (because of the equation used- see page 9 of the core design calculations), then multiplied by 1.25 to account for potential reinforcement yield over strength (see Figure R21.3.4, note 2 of ACI 318-05). This value was used to compute the necessary longitudinal reinforcement areas; shear reinforcement areas were computed using the assumption that the concrete will take no shear. Figure 11 shows the final coupling beam redesign. Diagonal reinforcement was deemed unnecessary because the aspect ratio of the coupling beam was under the ACI 318-05 limit of 4. Clear cover for all concrete was assumed to be 1.5 inches or more.

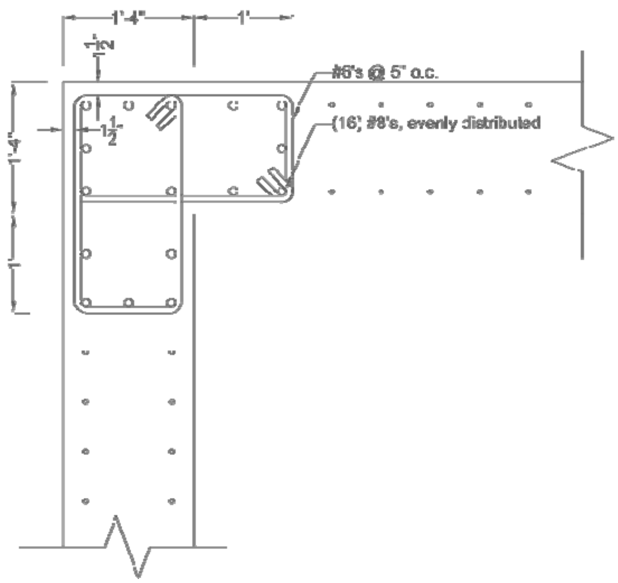

Figure 10 - Boundary element reinforcement corner detail

In addition to this design, the primary design (or, "New Design 1"), the *Effect on Architecture* section describes another core design that was briefly investigated as a secondary option to better accommodate a potential new and more modular floor plan. As such, the *Effect on Architecture* section also includes an additional table of periods and deflections to compare the original and both new designs.

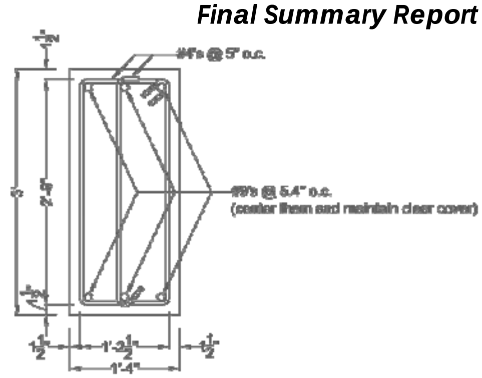

Figure 11 - Coupling beam reinforcement detail

Floor System Design

The floor system itself was not redesigned. The reason for engaging in a floor system design was the need to better transfer lateral forces through the floor diaphragm and into the concrete cores to satisfy special seismic design requirements. The simple corner supports designed by the Thornton-Termohlen Group would be insufficient for Seismic Design Category D. There were many iterations of design to create a reliable solution for the attachment of the floor system to the core- these can be found in Appendix D. Ultimately, two solutions were chosen as most pragmatic for maintaining the current construction method and minimizing any interference with the construction schedule. Figures 12 and 13 on the next two pages show these two designs.

Steel Collar Design

Figure 12 shows the *Steel Collar* design, which consists of a 3 foot deep steel plate embedded in the concrete core at the level of each coupling beam. The steel plate is attached to the core via a multitude of shear connector studs (designed to withstand the gravity loads from the floors, as well as the tension produced by the moment applied by the cantilevered portions of each floor).

Once a floor is lifted into place along the steel plate, corbels will be welded close to the corners of the core walls, under the main girders running lengthwise through the building. The floor would then be rested on these corbels (designed only for gravity loads) while the more permanent connection of the floor slab to the core would be made through the concrete topping. In order to make this connection, the concrete would need to be stopped about a foot from the core initially, before the floor is lifted into place. Once the floor is lifted, shear studs can be welded to the steel plate, in the middle of the concrete topping. Finally, additional concrete will be hand-poured to fill in the foot-wide gap that was initially left free of concrete.

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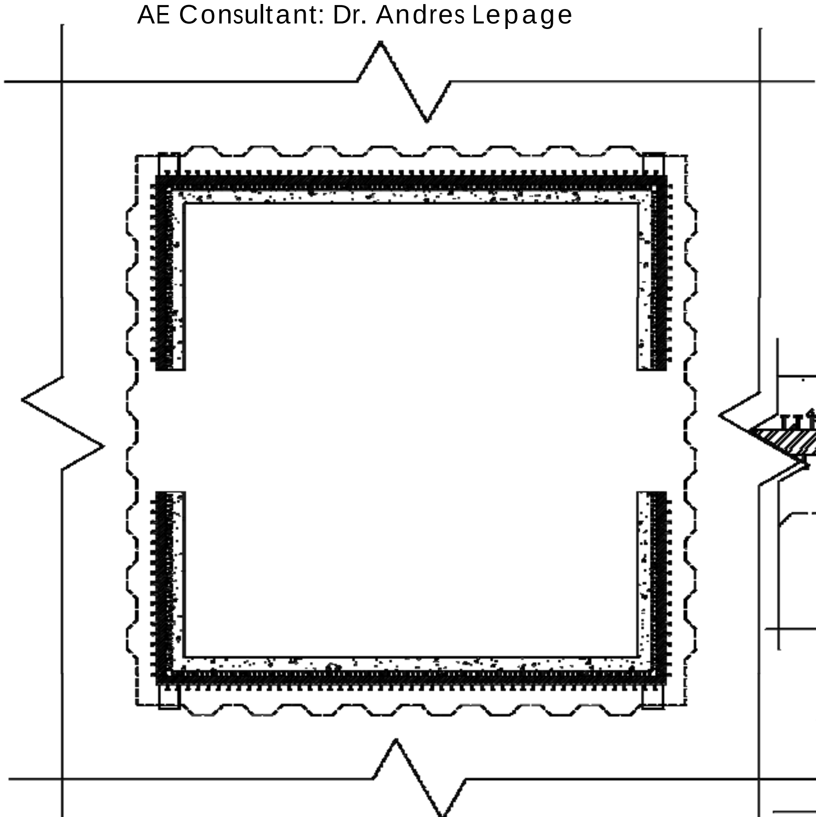
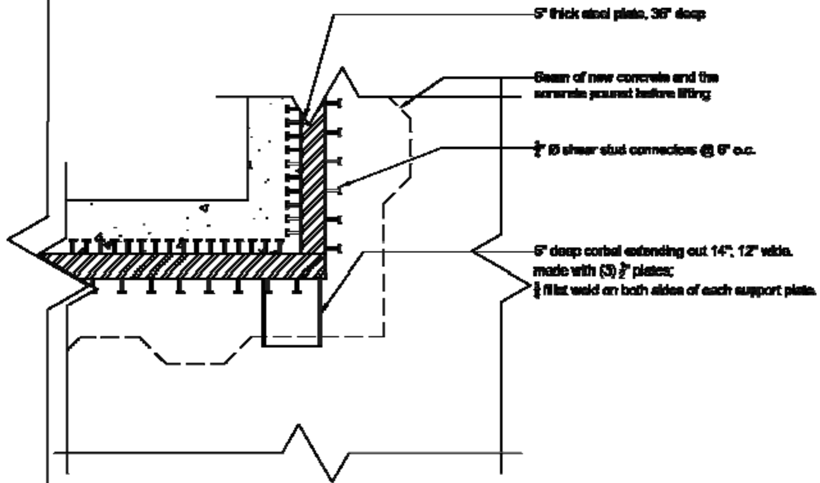
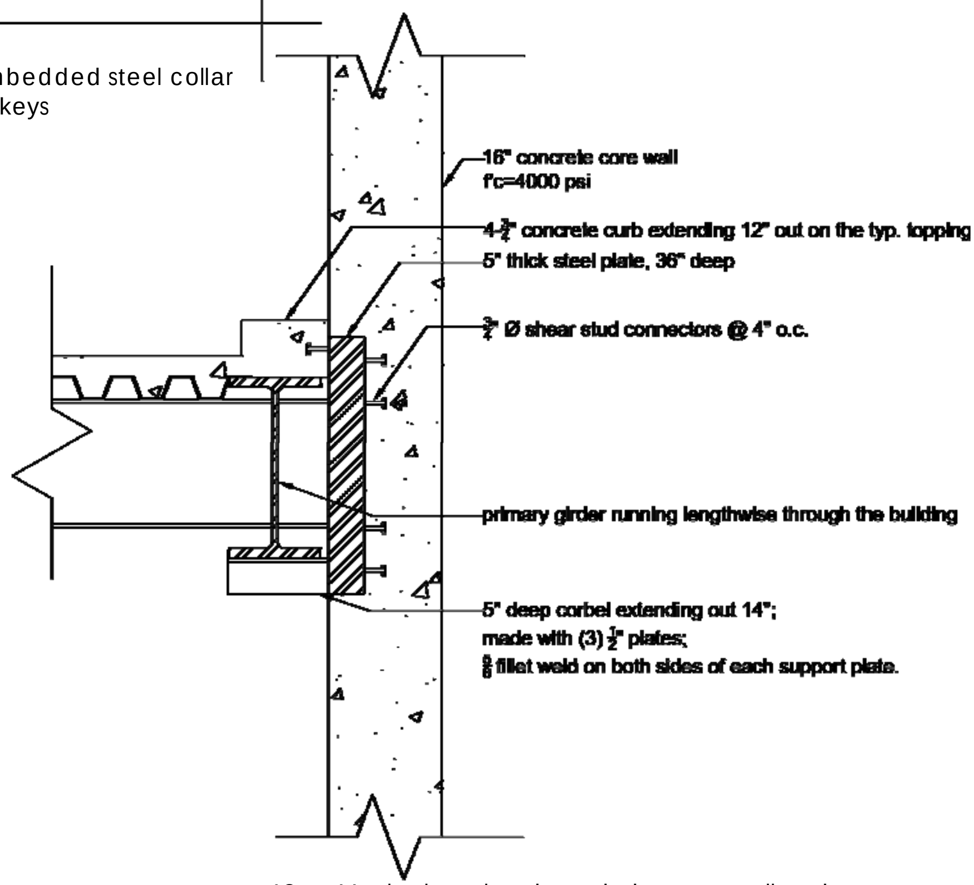


12.a - Plan view of one core with embedded steel collar at a floor level, and concrete shear keys

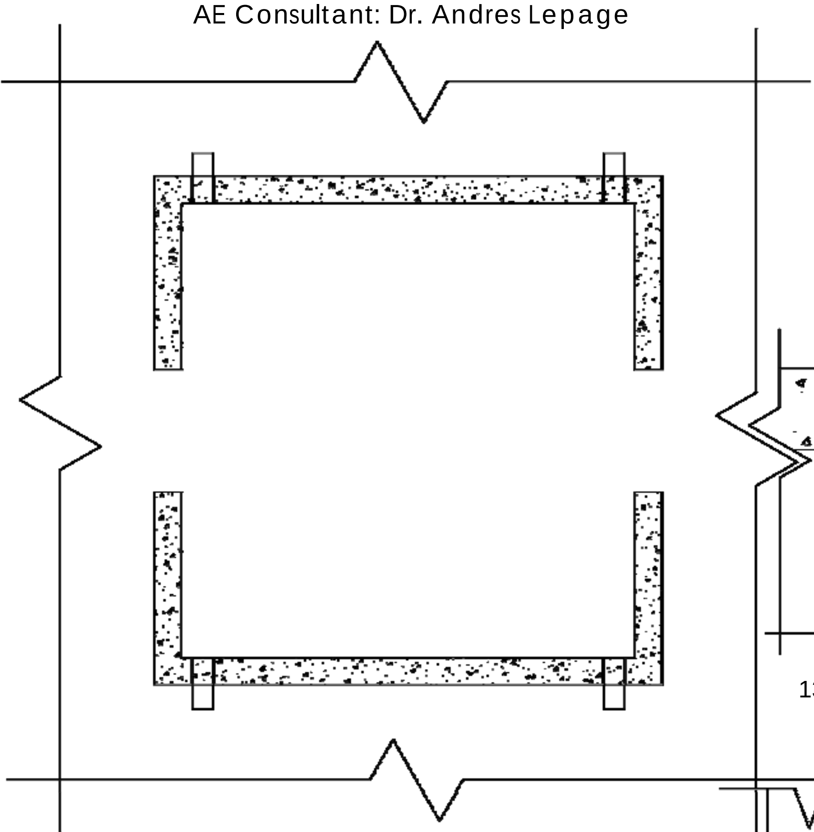


12.b - Labeled close-up of core corner from 12.a

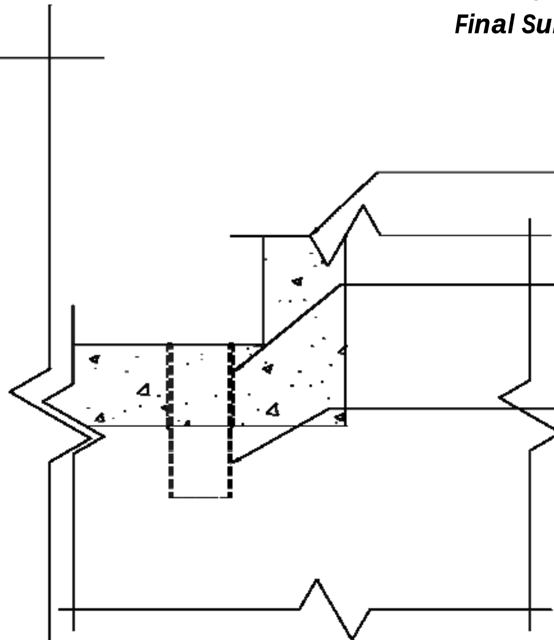


12.c - Vertical section through the core wall to show detail of steel collar and concrete floor curb

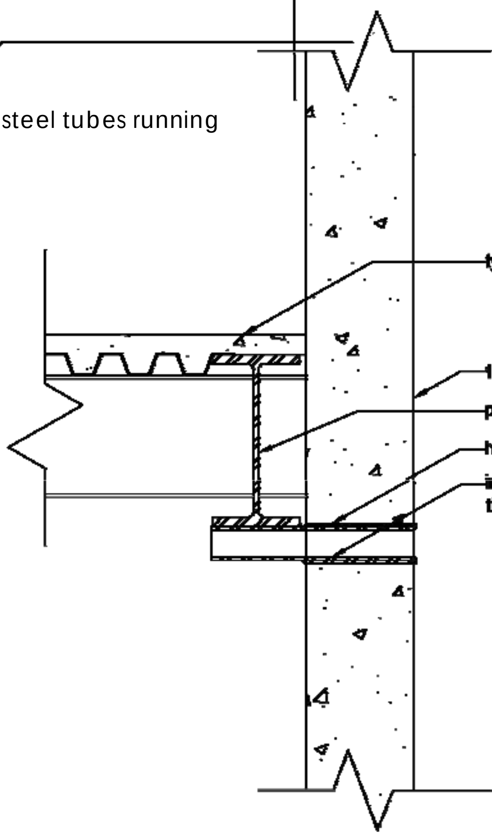
Figure 12 - Steel Collar Design



13.a - Plan view of one core with steel tubes running through core walls



13.b - Labeled close-up of core corner from 13.a



13.c - Vertical section through the core wall to show detail of the tube support inside the embedded tube

Figure 13 - Drag Strut Design

The shear studs and concrete topping were checked using IBC 2006 and PCI handbook, with spot checks from Appendix D of ACI 318-05 for concrete breakout strength in tension and shear, as well as concrete pryout strength. These calculations can be found on pages 14 to 17 of the floor system design section of the calculations in Appendix D. It was found that the original design's 3-1/4" concrete topping would be insufficient for withstanding the maximum floor diaphragm shear (found at the 17th floor to be 179 kips) multiplied by the overstrength factor for special reinforced concrete shear walls (2.5) found in Table 12.2-1 of ASCE 7-05. The Steel Collar design would require the presence of a curb around the core where the concrete topping was 8 inches thick for a foot past the core walls on all sides, as shown in Figure 12.

Drag Strut Design

Figure 13 shows an alternate design that was explored toward the end of the work and research for this report. This design would take advantage of the presence of continuous beams running through the main girders and running along the core walls by using them as collector elements for the diaphragm forces through the use of shear studs and composite action, as well as (potentially) additional reinforcement in the slab. This design could be constructed by installing hollow tubes running through the concrete cores. Once a floor is lifted into place, another tube could be inserted under the primary girders to act as corbels (similar to the Steel Collar design), and then welded into place at both faces of the core walls. To transfer the diaphragm forces, the deck would need about a shear stud per foot of beam length-- each collector element would have to take about 75 kips of shear.

Additional investigation should be taken into this design. The collector elements would need to be designed as beam-column elements because of the axial load they would experience as a result of acting as a collector element. The welds for the tubes would also need to be carefully designed, especially since they would experience a unique and unusual loading condition due to the seismic forces acting in torsion, horizontally and also vertically when the building is in motion.

Structural Investigations Summary

In order to accommodate the loads for Seismic Design Category D, the concrete volume for this building would need to be doubled from its original design. The original design contains about 8 cubic yards of concrete per foot of height while the new design contains almost 17. The steel detailing is considerably greater as a result of the use of boundary elements and heavily reinforced coupling beams to withstand the design seismic shear forces. The material takeoffs and comparison of these construction materials can be found in the *Effect on Cost and Scheduling* section of this report. Additionally, the key detail of the attachment of the floor diaphragm to the core is very elaborate, instead of a simple connection like the original Thornton-Termohlen Group design. This building design and construction method can still potentially be used in areas that require special seismic designs, but would require additional insight through peer review. There was a key assumption made initially that ultimately was not met by the design: that there would be no extreme torsional irregularity (to meet height limit exception 12.2.5.4 of ASCE 7-05). Unfortunately, due to the long, thin shape of this building's footprint, it experiences considerable torsional irregularity. With the current design, the torsional amplification factor is about 2.1 when using the deflections computed by ETABS with 120% of the design base shear. Even if the wall thickness is increased to 24 inches, and a high strength concrete (8000 psi) is used, the torsional amplification factor is about 1.7. The geometry of the core walls would need to be greatly altered to meet the height limit exception in section 12.2.5.4 of ASCE 7-05 (which allows special reinforced concrete shear wall structures greater than 100 feet tall), thus sparking the need for additional peer review of the design.

Effect on Architecture (Breadth Study)

The structural investigations carried out on this building yielded architectural repercussions. The main impact of the alterations to the core wall design was the need to eliminate all openings in the cores, excluding the corridor. This led to the typical floor plan for the building to be rearranged. Options 1 and 2 offer different floor plans that accommodate the new design requirements. Appendix E contains the notes taken while working through the Architectural breadth study of this report.

Option 1

Option 1 was the first floor plan layout that manifested as a result of the new seismic design. The need for the cores to be closed off completely on two sides brought out the necessity to cut the central corridor short in order to still provide tenants access to the inside of the two outer cores. Figure 14 shows the Option 1 floor plan, including the layout of the bedrooms and prefabricated bathrooms. Table 5 in the *Summary* subsection of this section shows the area comparisons between the original floor plan and both new floor plans that accommodate the seismic design.

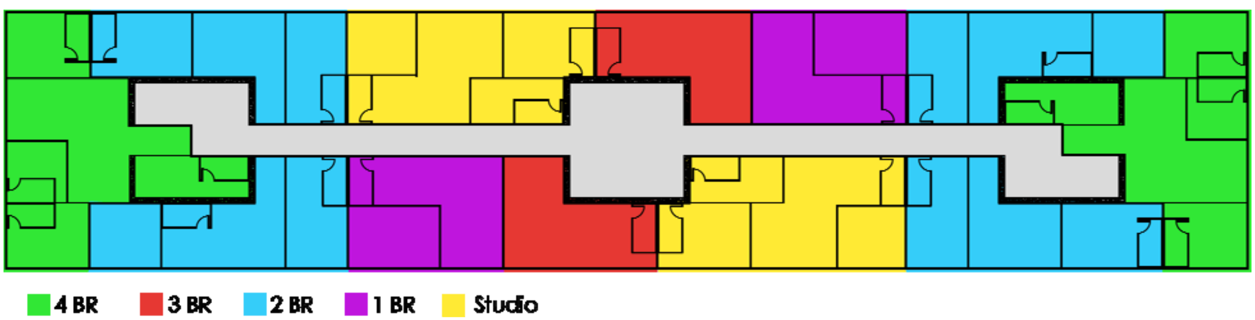


Figure 14 - Option 1 floor plan

Option 2

The second option was brought about after considering the theme of "modularity" that echoes throughout this entire project. Option 1 presents some difficulty with retaining modularity as a result of the shape of some of the apartments. The position of the bathrooms also deviates from the original design, which focused on keeping the bathrooms against the wall of the central corridor, or against the core walls as much as possible. Presumably, this placement pattern was to ensure ease of plumbing the building. Thus, the second option tries to emulate more of the patterns observed in the original floor plan design by maintaining more modular apartment boundaries and placing the bathrooms against the corridor as much as possible. This option also takes an idea from Option 1 of cutting off the ends of the central corridor in order to create better access to the cores.

Another very important factor of Option 2 (see Figure 15) is the clearly different core wall shape: instead of having continuous walls in the long direction and walls cut into two by the corridor in the short direction, each core is symmetric, so the building would be supported by cores that have mainly corner support. Making symmetric cores allows for better prediction of shear wall performance, as well as more stable stress distribution throughout each wall. Having the openings all in the central portion of the core walls also allows for the boundary elements in the design, which were not possible if the layout of the openings from the original design was used.

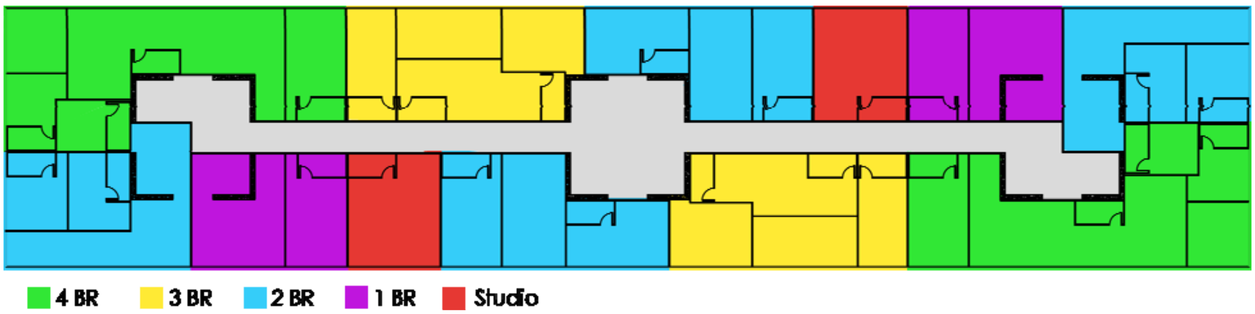


Figure 15 - Option 2 floor plan

Architectural Summary

Table 5 - Area comparisons for all options; % change is the % of the original unit size

Room Type	Original Design	Option 1	% Change	Option 2	% Change
Studio	431	541	26	431	0
1 Bedroom	541	719	33	719	33
2 Bedroom A	913	877	-1	938	3
2 Bedroom B	863			858	-1
3 Bedroom	1150	1091	-5	1060	-8
4 Bedroom	1438	1396	-3	1488	3

Table 6 - Modes and deflections for the original design and both redesign options

Design	Original	Option 1	Option 2
Max Deflection	16.20	6.13	9.74
Min Deflection	-4.30	-0.89	-2.55
Mode 1	3.94	2.17	2.78
Mode 2	3.52	2.03	2.49
Mode 3	3.32	1.80	2.33

Two alternate floor plan options were presented in this section of the Final Summary Report on the Southwest Student Housing building. These floor plans both accommodate the new seismic design described in the *Structural Investigations* section of this report. Option 1 allows for the use of continuous shear walls in the long direction of the building, ensuring the structural stability of the building in that direction against lateral forces. The wall continuity in Option 1 is also useful for limiting the already extreme torsional irregularity that this building experiences, while Option 2 propagates the aforementioned irregularity and increases the building's period further. Table 6 shows a comparison of the building modes and drifts for both options, as well as for the original design.

In order to attach the floor system to the walls in Option 2, the current Steel Collar design would need to be revisited to re-portion the steel plates to only the corners, which has the potential to cause some problems with the shear stud layout for the embedment of the plate in the core.

On the other hand, Option 2 allows for easier separation of each floor into modules that can be shipped in separately and slid into place before each floor is lifted, allowing for slightly greater ease of construction. Figure 16 shows the basic blocking of potential modules on the floor plans for both new designs as well as the original design. The areas of every unit in both options are never reduced by more than 8% of each original unit's area. In some cases, the apartment units even experience a great increase in area, up to 33% of the original area for that unit type! This increase in area is made possible by the removal of a portion of the corridor that is a little over 70 feet long, total (around 35 feet off per side).

Overall, the floor plan option should be chosen after a peer evaluation is conducted on the structural design. The peer evaluation can shed light on what direction to go in terms of the structural design. Additionally, Figure 17 shows a core layout that would be more versatile for floor plans, making it worthwhile to investigate further.

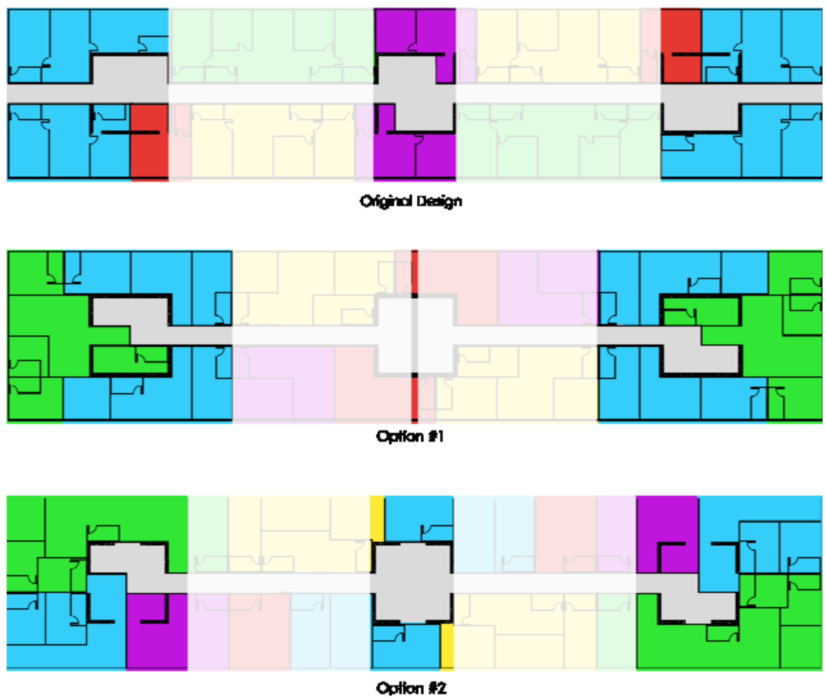


Figure 16 - Potential module breakup for each design: each change of gradient (from vivid to light to vivid) indicates a potential module

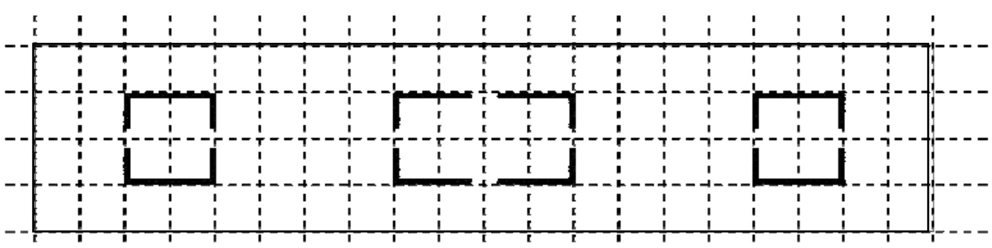


Figure 17 - Potential core layout worth investigating: central core is extended out

Effect on Cost and Scheduling (Breadth Study)

Construction Costs

The transition from Seismic Design Category B to D is generally an expensive one for any construction project. The Southwest Student Housing building is no different. As mentioned in the *Structural Investigations* section of this report, the concrete volume more than doubled as a result of this transition. The quantity of reinforcement greatly increased due to increased minimum reinforcement ratio requirements by ACI 318-05, as well as the addition of boundary elements and beefed up coupling beam reinforcement. In addition to these volume increases, the material cost for added features such as the steel collar plates, shear stud connectors, welds and corbels must be taken into account. The overall building cost was not re-evaluated for each design because the only changes were made to the structural system, which allowed for a narrow scope of investigation.

Table 7 shows the general bare material costs for the main changes to the structural system-- the concrete, the steel reinforcement, the steel plates, the shear stud connectors, and the welds. The two designs in Table 7 refer to Options 1 and 2 of the core layout that were mentioned in the *Effect on Architecture* section of this report.

More detailed tables of cost analysis, including base prices per unit and the material takeoff calculations, can be found in Appendix F, along with additional calculations and notes related to this section. All of these costs were based on Tempe, AZ prices in order to allow for direct comparisons. The costs displayed are bare material costs only, and do not take into account labor. Labor costs and additional assumptions are noted in Appendix F, but not considered in this analysis because of the great deviation in labor costs from area to area.

The steel plates used for the Steel Collar design were estimated using the weight of steel, with the material cost being taken from the Steel Projects section of RS Means. The line numbers for each item are available in the overall material costs table in Appendix F. All costs took into account 10% added waste for each material.

Ultimately, the adjustments to the building design to accommodate a change from Seismic Design Category B to D would incur a material cost increase of approximately $3 million, which is about 8% of the total building cost, not taking into account any additional labor costs or schedule increases.

Table 7 - General bare material costs for primary changes to structural system

Bare Material Costs			
Item	**Original Design**	**Option 1**	**Option 2**
Concrete	113372.92	247340.18	216552.68
Reinforcement	74384.57	381027.09	432257.53
Welds	0.00	1080.00	1080.00
Shear Studs	0.00	70553.60	6364.80
Other Steel	0.00	2069809.20	2069809.20
Total	187757.49	2769810.07	2726064.21
Difference from Original	0.00	2582052.59	2538306.72

Construction Schedule

Several key assumptions were made before evaluating this project's schedule: the first was that everything would be assembled at the same rate for both projects. The second was that all of the added steel parts for the floor system connections would not take additional time (justification for this is provided below). The final assumption was that the welders could work easily at a similar productivity level as what was listed in RS Means while suspended in the air under a lifted floor slab.

The assumption that all the added steel parts for the floor system connections would take no additional time to assemble comes from the construction methodology. Slip-formed concrete walls have to have the reinforcement pre-assembled above the slip-form as it rises, so that the concrete pour rate does not depend on how much of the steel is assembled. The steel plates and corbels for the collar design would have to come prefabricated. As a result of these items coming prefabricated, the main labor for them would be the effort it takes to use a crane to lift each plate into place. While this job is not easy, it is certainly doable; especially when the concrete walls would be rising at half the speed of the original design.

The third assumption, that welders can work easily at a similar productivity level to what is listed in RS Means while suspended under the lifted floor slab, is necessary to be able to quantify the length of time it would take for a single team to complete any of the welds necessary for the floor system-to-core connections.

Overall, the schedule shouldn't be altered greatly as a result of the switch to SDC D. Since the concrete volume is about doubled, it would take double the time to slipform the cores: initially, it takes 10 days to slipform all of the cores up the full building height. Consequently, it would take 20 days to slipform the newer, thicker cores up to the full building height.

Beyond that, a single welding team would have two days to weld the corbels for half a floor. Each floor contains about 20 feet of 5/8" continuous fillet weld, so half a floor would contain 10 feet of weld. A single welding team can complete 12 feet of ¾" welds per day, and it takes 2 days to prepare a half-floor to be lifted. Taking all of this into account results in the conclusion that a single welding team would have 2 days to complete a welding task that should take no longer than 1 day according to RS Means-- a reasonable amount of time, even when taking into account the potential for any sort of delays due to the unusual circumstances of where the welding would take place.

Apart from the doubled concrete volume, the only other item that would have a true effect on the construction schedule would be the installation of shear studs and the final pour of the concrete curb around the core in order to create a strong connection from the floor diaphragm to the core. There is also a potential that the schedule would not be altered at all, because a team could start pouring the concrete as all the other floors are lifted into place. This would result in the completion of all of the connections at most a day or two after all of the floors are lifted into place, which is when the upper floors are being finished (this process takes 12 days per floor according to the Thornton-Termohlen Group). A conclusive answer to this would need to be investigated further with more information from the original design team about how the current construction schedule is split up.

Evaluation of Sustainability (Breadth Study)

The goal of the sustainability study of this building was to evaluate the current status of the building in terms of LEED ratings. Additionally, this study was meant to find a cost effective way to bring the building up to LEED Certified status, with minimal effort on the part of the owner and contractor. This study demonstrates that LEED Certified can be attainable by almost any project, as long as the owner and contractors dedicate more time to planning before starting the construction portion of the project.

This section discusses the LEED point breakdown by the groups defined in the New Construction rating system found on the United States Green Building Council (USGBC) website. The credits are listed and tallied by grouping under each subsection.

Ultimately, the current design has 20 LEED points and the potential to get up to 41 points total, yielding a LEED Certification for the building.

Sustainable Sites

Original Design

The original design possesses 12 of the Sustainable Sites credits, as seen in Table 8 below. These credits are primarily in relation to the urbanized area, proximity to bus stops, and previously developed site.

New Design

An additional 7 credits can be obtained with some planning:

1 credit for having covered storage facilities for 15% of the residents

A cost analysis for this credit can be found on page 2 of the Sustainability notes in Appendix G; estimated at approximately $70/sf, with an assumption that it would require about 400 sf to complete this requirement, which totals to a cost of about $28,000.

2 credits for providing no new parking

Currently, the presence of resident parking on the first level of the building is still up in the air. Planning on no parking costs nothing and achieves 2 credits.

1 credit for restoring or protecting a certain portion of the site

The site will require landscaping anyway. The cost was estimated by making an assumption about the cost/sf via estimating the shaded area provided by one full-grown tree; Calculations can be found in Appendix G. Overall estimated cost for this credit is $170,000.

1 credit for shading the same portion of the site

See above credit for restoring or protecting the site, these two credits go hand in hand and would share the cost overall.

1 credit for changing the roof EPDM color to white-on-black instead of conventional black (no cost)

	Currently has	Can plan to attain
SS Prerequisite 1 (Points - 0): Erosion and Sedimentation Control	0	
SS Credit 1 (Points - 5): Site Selection	1	
SS Credit 2 (Points - 5): Development Density and Community Connecitvity	5	
SS Credit 3 (Points - 1): Brownfield Redevelopment		
SS Credit 4 (Points - 12): Alternative Transportation	6	3
SS Credit 5 (Points - 2): Site Development-- Protect or Restore Habitat		1
SS Credit 6 (Points - 2): Stormwater Management		2
SS Credit 7 (Points - 2): Heat Island Effect		2
SS Credit 8 (Points - 1): Light Pollution Reduction		

Water Efficiency

The original design should be able to meet the prerequisites because of the vast availability of water-efficient fixtures. Other than that, the other credits in this section would cost a significant amount of money to obtain because the efficiency of the most readily available fixtures is never more than about 20% efficient, according to various major plumbing manufacturing sites.

	Currently has	Can plan to attain
WE Prerequisite (Points - 0): Water Use Reduction		0
WE Credit 1 (Points - 2 to 4): Water Efficient Landscaping		
WE Credit 2 (Points - 2): Innovative Wastewater Technologies		
WE Credit 3 (Points - 2 to 4): Water Use Reduction		

Energy and Atmosphere

This section was not evaluated because the designers provided no information on whether or not the building project met the prerequisites for the Energy and Atmosphere section. If the prerequisites are not met, the cost of the credits for this section rise rapidly, which is against the goal of the Sustainability study carried out in this report.

Materials and Resources

Original Design

The original design possesses only 2 of the Materials and Resources credits. These credits relate to the use of materials from within 500 miles of the site. The concrete for the project would be local, from very close to the Tempe, AZ city premises, if not from inside the city itself. As a result, with the large volume of concrete on this project, the Regional Materials credit is met very easily.

New Design

An additional 7 credits can be obtained with some planning:

1 credit for having a waste management plan before starting construction

ASU already advocates for waste management and recycling on construction projects, and would provide bins to make it easier. Should not cost anything.

2 credits for using 10% by cost salvaged, refurbished or reused materials

Can plan to use salvaged finishing items, including doors, frames, casework, maybe even flooring; Should not incur additional cost.

2 credits for using 20% recycled materials, by cost

Use of recycled steel and concrete aggregate, as well as salvaged goods for furnishings, casework, finishes and flooring, even partition walls, would easily achieve these credits. Should not incur additional cost.

1 credit for use of rapidly renewable materials for 2.5% of total cost

Whatever flooring, finishes or casework present can be both salvaged and rapidly renewable resources (such as bamboo or linoleum); formwork can also be counted, if necessary. There might be costs incurred due to the specificity, but it is a cost that would be difficult to estimate.

1 credit for the use of certified wood

Can be achieved by simply following the previous credit- using certified and recycled/salvaged wood for flooring, casework, doors, frames and so on. Should cost nothing.

	Currently has	Can plan to attain
MR Prerequisite 1 (Points - 0): Storage and Collection of Recyclables	0	
MR Credit 1 (Points - 1 to 4): Building Reuse--Maintain Existing Walls, Floors and Roof		
MR Credit 2 (Points - 2): Construction Waste Management		1
MR Credit 3 (Points - 1 to 2): Materials Reuse		2
MR Credit 4 (Points - 1 to 2): Recycled Content		2
MR Credit 5 (Points - 2): Regional Materials	2	
MR Credit 6 (Points - 1): Rapidly Renewable Materials		1
MR Credit 7 (Points - 1): Certified Wood		1

Indoor Environment Quality

Original Design

The original design can easily meet the prerequisites for this group of credits simply by following the ASHRAE design standards. The original design has 6 of the credits in this group. These credits come mostly from the fact that every apartment unit will have thermostats and a large quantity of daylighting due to the building's position on site. The IAQ management plan is a simple credit to obtain (mainly paperwork), and the thermal comfort credit involves simply meeting an ASHRAE standard for thermal comfort in the building.

New Design

An additional 5 credits can be obtained with some planning:

4 credits can be obtained by using low-emitting materials

These credits simply take some research: in the preconstruction phase, a member of the construction team can look up materials such as adhesives and paints that meet the requirements of both the owner and the LEED credits. Money will already be spent to obtain these materials, so taking the time to plan ahead and be careful with the choices will cost nothing but time.

1 credit can be obtained by sending out a survey to the residents to evaluate whether or not they are thermally comfortable after the first 6 to 18 months of occupancy. Will come with a printing cost if paper surveys are sent out, or zero cost if the residents are sent emails.

	Currently has	Can plan to attain
IEQ Prerequisite 1 (Points - 0): Minimum IAQ Performance	0	
IEQ Prerequisite 2 (Points - 0): Environmental Tobacco Smoke (ETS) Control	0	
IEQ Credit 1 (Points - 1): Outdoor Air Delivery Monitoring		
IEQ Credit 2 (Points - 1): Increased Ventilation		
IEQ Credit 3 (Points - 2): Construction IAQ Management Plan	2	
IEQ Credit 4 (Points - 4): Low-Emitting Materials		4
IEQ Credit 5 (Points - 1): Indoor Chemical and Pollutant Source Control		
IEQ Credit 6 (Points - 2): Controllability of Systems	2	
IEQ Credit 7 (Points - 2): Thermal Comfort	1	1
IEQ Credit 8 (Points - 2): Daylighting and Views	1	

Innovation in Design

Original Design

The original design has no credits in this group

New Design

An additional 1 credit can be obtained with some planning:

1 credits can be obtained by having a LEED Accredited Professional on staff for this project; Chances are that there is already a LEED AP on this project, but there are cost-free options in the case that a LEED AP is not present: the many consulting companies for this project include Limbach, WSP Flack & Kurtz and Thornton-Tomasetti; Among the many staff in these companies, there are many LEED APs available that could be brought in as part of the consulting group.

	Currently has	Can plan to attain
ID Credit 1 (Points - 1 to 5): Innovations in Design		
IAPP Credit 2 (Points - 1): LEED Accredited Professional		1

Summary and Conclusions

The transition from Seismic Design Category B to D increased the overall seismic design loads from about 235 kips to about 1000 kips-- an increase of approximately 325% of the original base shear. In order to resist this force, the concrete volume in the building had to be increased by 100%, while the reinforcement redesign yielded an overall volume increase of about 420%. The overall building cost (bare material only) increased by about 8% of the total cost. The schedule would increase minimally-- perhaps by 10 to 20 days more than the original 177-day construction schedule. As a result of the minimal schedule changes, the building revenue would be minimally affected.

Ultimately, designing for higher seismic loads always requires bulking up an existing system, which means an increase in material and cost. There is no way to avoid additional expenses and time delays when a project simply ends up having a more complex design. The Southwest Student Housing building has a relatively simple original design, with a much more complicated seismic design as a result of the floor system-to-core connections; this feature makes the SW Student Housing building a great example of the changes and complications involved with altering a building design to withstand higher seismic forces. A key point mentioned in the *Structural Investigations* portion of this report was the reoccurring issue with extreme torsional irregularity in the building. This issue would need to be addressed before this building design could be considered even remotely viable for SDC D design. Thus, the need for additional peer review is great.

Apart from looking at this design from a structural and construction management perspective, it is also important to examine it from an architectural perspective. The *Effect on Architecture* section covers the necessity to change the floor plan to accommodate the newly reshaped concrete cores of the structure. With the current typical building floor plan, there are about 70ft of corridor space that could be used as apartment space. If these 70ft of corridor space (approximately 420 sf) were to be used for apartment space, the building would be able to easily accommodate the need to have continuous shear walls running in the long direction. Additionally, the extra corridor space allows for an apartment unit to have up to a 33% increase of area compared to the original unit dimensions. The *Effect on Architecture* section also shows several potential floor plan layouts that incorporate the extra corridor space, yielding at most a decrease of 5% of the original unit area in any given apartment under the new arrangement.

As to the subject of sustainability, the *Evaluation of Sustainability* section demonstrates that, with some simple planning ahead in the preconstruction phase, the building design could be turned into a LEED Certified design at close to no additional cost.

Credits and Acknowledgements

This project was a long, tough ride that was made many times easier by the following individuals, who never ceased to provide support and assistance throughout the entire process:

A very huge thank you to Charlie Thornton for being so receptive and providing me with a building for this thesis project. This gratitude extends to the Thornton-Termohlen Group for providing the project, as well as to Anthony Kelly for his help with the architectural side of things.

Brian Howells, who took the time to speak to me about the parking technology that TTG will be incorporating into their buildings.

Thornton-Tomasetti, for hosting TTG in the Philadelphia office, where I had the opportunity to meet many important and great people in my industry. The meeting was a phenomenal and eye-opening experience that cemented my decisions about my future.

Dr. Andres Lepage, who would, without fail, always see me or talk to me on the phone in order to sort out my countless issues and mistakes. I'm sorry for using up 2 hours for every 1-hour meeting slot you gave me!

Dr, Thomas Boothby, who went out of his way to talk to me about my troubles and gave me some fantastic ideas.

Prof. Kevin Parfitt, who always cracked the whip to make sure I was still on time when I was working on my graduate research.

Dr. Memari, who is awesome.

I would also like to extend a very big thanks to Stephen Pfund for providing endless support and a sounding board for every crazy idea. Thank you, Jonathan Minnick, for helping to keep me sane during the final stretches of this project and always encouraging me to keep going. The hours you two have spent on the phone with me mean more than you'll ever know!

Additionally, I would also like to thank my mom for never doubting me, and always being proud to have me as a daughter.