LDA-0806

Residence Hall Construction:

A structural and environmental study of W.P.I.'s latest construction endeavor

A Major Qualifying Project submitted to the faculty of Worcester Polytechnic Institute
In partial fulfillment of the requirements for the Degree of Bachelor of Science.

Submitted

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To:

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On:

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ABSTRACT

This report focuses on the design of Worcester Polytechnic Institute's newest residence hall, located on Boynton St. in Worcester, MA. The study includes the analysis and design of four alternative floor systems for the residence hall, as well as an investigation into the possible building materials for the accompanying parking garage. In addition, an in-depth examination of the LEED certification process and green building alternatives was conducted to determine if it was possible to achieve a higher level of certification and construct a more environmentally friendly building. Cost and other feasibility factors were considered for each aspect of the research. The report closes with conclusions and recommendations based on the obtained results.

Authorship

Several chapters of this report were collaborations of all three group members. Variations from this shared authorship are summarized in the table below.

Chapter 1: Introduction	All group members
Chapter 2: Background	All group members
Chapter 3: Methodology	All group members
Chapter 4: Structural Analysis & Design	Michael Belsky & Matthew Desjardin
Chapter 5: Cost Estimate of Residence Hall Structure	Matthew Desjardin
Chapter 6: Environmental Analysis	Hallie Schiess
Chapter 7: Conclusions & Recommendations	All group members

Capstone Design

In order to achieve the Capstone Design necessary to fulfill our degree requirements, we completed a Major Qualifying Project that focused on the new WPI residence hall in terms of structural and environmental alternatives. The project addresses the following Capstone Design considerations: economic, environmental, sustainability, health and safety, and manufacturability.

Economic

We researched different structural system alternatives. A cost estimate of the structural elements was performed for each alternative, and weighed on the appropriateness of each. The feasibility of green building system options was judged considering construction, operating, maintenance, and life-cycle costs.

Environmental

An in-depth analysis of LEED construction was performed and different options were investigated to see if a higher level of LEED could be achieved (silver is the current target level). Alternative green structures and materials were researched and considered as possible options for use in the residence hall. These alternative green options were used to fulfill a LEED credit or to improve the overall environmental friendliness of the building.

Sustainability

Sustainability was a key consideration in the study of LEED practices and green building systems. One aspect of sustainability that was investigated was the materials of building construction. Using recycled materials and wood from sustainable tree farms is crucial to obtaining a high level of LEED certification. Also, green building systems such as rainwater harvesting and grey water systems can reduce the fresh water use requirements of the building thus increasing its sustainability.

MANUFACTURABILITY

Manufacturability, or in the case of buildings, constructability, was a significant factor in the final choice of the most appropriate floor system. For the residence hall building, it was very important to keep the overall elevation at or under 55 feet. The alternate methods of construction were investigated to determine whether or not they could meet this requirement.

HEALTH AND SAFETY

The most significant way that safety affected our design was through the use of the *International Building Code*. By following the guidelines it sets forth, the integrity of our designs was ensured, and the safety of potential residents guaranteed.

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Chapter 1: Introduction

Over the last few years, Worcester Polytechnic Institute has been involved in many construction projects as a part of their master plan. This plan calls for developing a vibrant lower campus linking WPI's main campus with the downtown Worcester area and Gateway Park, an 11-acre mixed-use life sciences-based campus. A new residence hall, arts walk, and parking garage are currently being constructed on a lot located between Dean St. and Boynton St., next to Founders Hall. Completion is schedule for the fall of 2008.

Figure 1: Aerial rendering (Cannon Design)

The new apartment-style residence hall will accommodate 232 upperclassmen with a variety of state-of-the-art facilities. Every student will live in a four-person apartment including a full kitchen, living room, compartmentalized bath-rooms, and either single or double bedrooms. The building will also include a recreation and fitness facility, technology suits on every floor, music rooms, and full wireless internet access. WPI alumni and friends will be the major source of funding for this project by a host of name giving opportunities for the main areas and rooms, as well as the building itself (Urbanski, 2007).

The new residence hall has many unique design options to suit the needs and desires of WPI. Some of the more unique materials used are abuse- and mold-resistant drywall for the typical partitions and core-board around the elevator shafts in lieu of the more typical concrete masonry units in order to provide adequate fire resistance. Also a spray-on insulation material replaces the more typical rigid foam boards for the exterior enclosures. The chillers that will sit atop the building are developed by Smardt, and they use ground-breaking electromagnet technology to reduce friction in place of typical lubricants. The decision to be one of the first buildings in the country to utilize this technology was made well after beginning construction due to the fast-track nature of the project.

FIGURE 2: RENDERED VIEW FROM BOYNTON ST. (CANNON DESIGN)

The new residence hall will also be the second building on the WPI campus to receive certification from the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED). It is expected to receive a silver level certification, but the final application for certification is not submitted until the project is closed out. A large number of the points required to attain LEED certification were designed into the project, such as building materials and site layout. The remaining points are obtained through environmentally friendly construction practices, a responsibility which falls upon the contracting company. One of the most significant of these practices is the recycling of demolition and construction waste. Ninety-five percent of the debris from demolition was recycled. During construction there are several recycling dumpsters for cardboard, wood, metals, and miscellaneous materials. A prominent green feature of the building is its green roof, atop the central part of the building.

The building's exterior finishes were designed to coincide with its neighboring buildings. The outside will consist of mainly glass, brick masonry, and architectural precast panels. The large portion of the enclosures consisting of glazing,

FIGURE 3: RENDERED VIEW FROM DEAN ST. (CANNON DESIGN)

atypical to residence halls, is made possible by the floor plan which places the living room area of each apartment where the large windows are. The masonry will blend in with the surrounding brick buildings, and the wide expanse of glass will compliment Founder's Hall, where the new Goat's Head restaurant is completely surrounded by windows.

The Gilbane Building Company, who has just recently completed the parking garage at WPI's Gateway Park, was hired as the construction manager of this project. Gilbane, Inc. is one of the largest privately held family-owned companies in the construction industry with 22 offices nationwide and revenues topping three billion dollars (Gilbane, Inc.). Cannon Design of Boston, an international architectural, engineering, and planning firm, was hired as the project design team. Cannon was founded over 60 years ago. They have more than 700 employees working out of 15 offices. Projects are being completed in 42 states, 8 provinces, and in Europe and Asia (Cannon Design).

This project involves three sub-sections of study all concerning the new WPI residence hall. The first consists of structural activities concerning both structures. The design of the residence hall starts with the research and design of alternative floor systems. The remaining structure, from girders to columns to foundation, is then designed for each of the floor systems. In the second activity, the structure of the parking garage is designed using precast concrete and metal framing individually.

The next section of our report is a cost estimate of our structural work. An estimate was performed for each of the alternative designs for the residence hall and parking garage. The construction cost estimates encompass the structural costs of the building, from the floor through the frame, and down to the foundations.

The final section of the project is an environmental study that involves two parts. The first part concerns the US Green Building Council's LEED certification system. This involves determining what is needed to obtain a higher level of certification, what it will mean for WPI and the residence hall in the future, and if achieving that higher level warrants the additional cost. The second part of the environmental study is the research of several green building options that were open to WPI. These include the green roof, and possible alternatives such as rainwater harvesting and a grey water system.

The report ends with our conclusions based on the information obtained in the three sections. There are a number of questions that this section will address and discuss, and they will touch on the most salient issues raised in this project. The following is a list of the questions answered in the Conclusions and Recommendations section:

- Which of the structural alternatives proposed is the most economically feasible?
- Does this structural alternative meet the elevation related requirements of the building?
- Is it possible to obtain a higher level of LEED Certification, and what are the implications?
- Of the green building systems researched, would any provide a net benefit for WPI?

Chapter 2: Background

Steel Frame Construction

Prior to the 19th century, metals had little role in construction. The first all metal structure, a cast iron bridge, was built in the late 18th century in England and still carries traffic more than two centuries after its construction. Cast iron and wrought iron were commonly used for the framing of industrial buildings in first half of the 19th century, but cost and brittleness severely prohibited their usefulness. At the time steel was a very uncommon material of construction and an expensive product to work with. Once inexpensive steel finally became available in the 1850s with the introduction of two very economical steel making processes, the Bessemer process and the open-hearth method, the demand for steel frame construction skyrocketed.

Steel frame construction has become a very common practice in modern building construction. Physical characteristics such as the ability to span long distances, slender shape, and light weight in proportion to strength all have made steel a viable material for construction. Although steel's major weakness is its tendency to corrode in certain environments and lose strength during severe building fires, if these events are accounted for, steel can offer endless design possibilities.

The composition of steel

Steel is any range of alloys of iron and carbon that contain less than 2 percent carbon. Ordinary structural steel, called mild steel, contains less than three-tenths of 1 percent carbon plus traces of detrimental impurities. Ordinary cast iron contains 3 to 4 percent carbon and larger quantities of impurities. The carbon content is the most crucial determinate property; too much makes a hard but brittle metal, while too little produces a soft, weak metal.

Most steel today that is converted from iron is manufactured by the basic oxygen process. A hollow, water-cooled lance is lowered into a container of molten iron and recycled steel scrap. Oxygen is then pressure blown from the lance into the metal in order to burn off excess carbon and impurities. Other metallic elements, such as nickel and chromium, can also be added to the container at the end of the process to alter the physical and aesthetic properties.

THE PRODUCTION OF STRUCTURAL STEEL SHAPES AND ENGINEERED PRODUCTS

Most structural steel for buildings is produced from scrap steel in mills that commonly use electric furnaces and can roll shapes up to 40 inches deep. The scrap which is used for structural steel most commonly comes from old junk automobiles, with each possible mill consuming up to 300,000 junk cars in a year (Allen & Iano, 2004, p. 374).

In order to form steel beams or girders, hot steel blanks are passed through a succession of rollers that squeeze the metal into the proper dimensions, specified by the American Institute of Steel Construction (AISC). The finished shape exits the last set of rollers as a continuous length which is then cut according to a desired length and then cooled on a cooling bed; a roller straightener can be used to correct any crookedness upon cooling. Each piece of steel is then labeled with its shape designation and batch number, to verify structural specifications, before it will be sent off for fabrication.

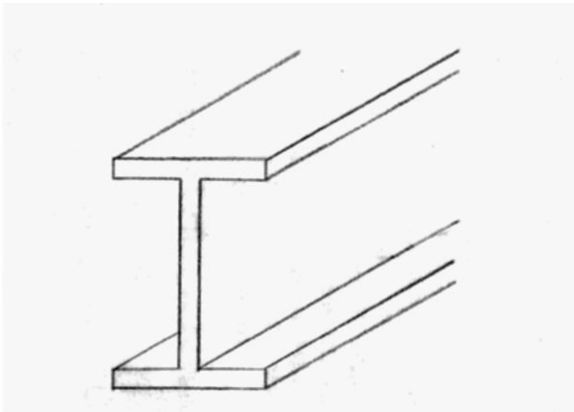

FIGURE 4: WIDE-FLANGE STEEL BEAM

Wide-flange shapes are most commonly used for beams and columns. Wide-flange shapes in comparison with I-shaped beams are more efficient structurally because they include a larger amount of steel in the flanges, resulting in increased load-carrying capacity for the member. Wide-flange shapes can vary in depth from 4 to 40 inches and in weight per linear foot, with members ranging from 9 to 730 pounds (Allen & Iano, 2004, p. 376). Common nomenclature for wide-flange shapes begins with the letter W, followed by the nominal depth of the shape in inches, a multiplication sign, and the weight of the shape in pounds per foot. Thus, A W18 x 28 would be a wide-flanged shape having a nominal depth of 18 inches and weight of 28 pounds per linear foot. Information about steel shapes can be found in the *Manual of Steel Construction* published by the American Institute of Steel Construction.

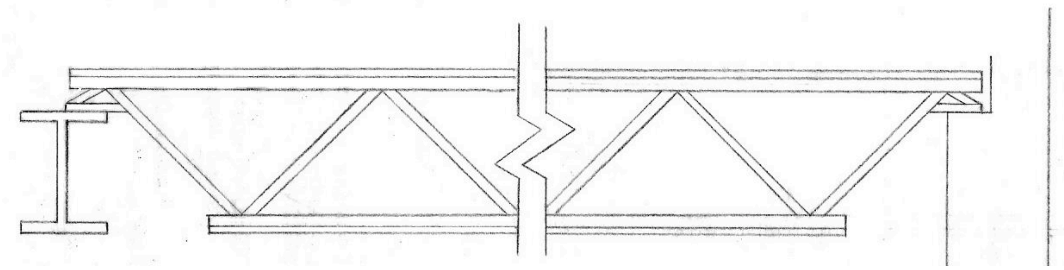

FIGURE 5: OPEN-WEB JOIST ON BEAM AND BEARING WALL

Among the many structural steel products that are engineered and fabricated, the most common is the open-web joist. An open-web steel joist is a mass produced truss that can be used to support floor and roof decks. Open-web joists are classified in three series: the K series joists for spans up to 60 feet and a depth ranging from 8 to 30 inches, the LH series for long spans ranging up to 96 feet and depths ranging from 18 to 48 inches, and finally the DLH series for deep long spans which span up to 144 feet and have depths ranging from 52 to 72 inches (Allen & Iano, 2004, pp. 377-379).

JOINING STEEL MEMBERS

There are three common fastening techniques for joining steel shapes into a building frame: rivets, bolts, welds, or any combination of the three. A rivet consists of a cylindrical body with a formed head that is forged to a white heat and inserted through a hole and hot-worked with a pneumatic hammer to produce a second head on the other side. As the rivet cools in between the two joining members, it shrinks, clamping the members tightly together. Riveting was originally a very common practice, but it has been replaced by the more reliable and predictable, less labor intensive techniques of bolting and welding.

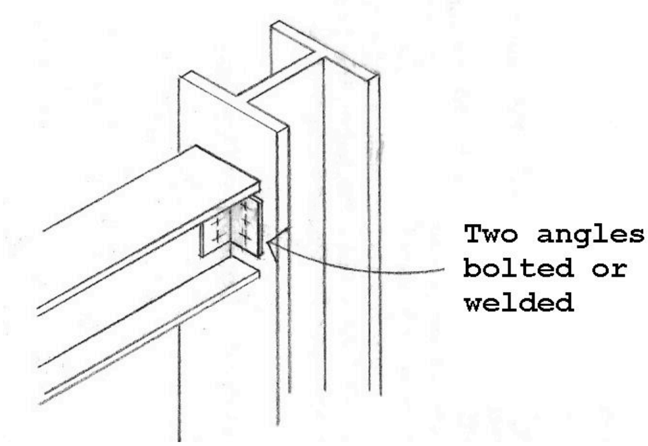

FIGURE 6: ONE TYPE OF SHEAR CONNECTION

The technique of bolting steel members together is a very efficient method of steel frame construction. Bolting is advantageous because it is quick and easy for field connections that need to only resist shearing forces and can be accomplished under adverse weather conditions or difficult physical accessibility. The use of an air-compressed impact wrench, along with a spud wrench, makes the application of bolting steel members together very cost efficient and time saving for project designers. Two types of bolts are commonly used in steel frame construction: carbon steel bolts and high-strength bolts. Carbon steel bolts are commonly bought in hardware stores and can be used in structural joints where their lower strength is sufficient, primarily for shear and bearing. High-strength bolts are heat treated during the manufacturing process to acquire their necessary strength. Depending upon the installation technique, high-strength bolts develop their connecting ability through their shear resistance or through tightening to the point in which the members they join are kept together by friction. Washers may or may not be required depending on the type of bolt and its specification; a washer will be required in certain cases to spread the load of the bolt over a larger area.

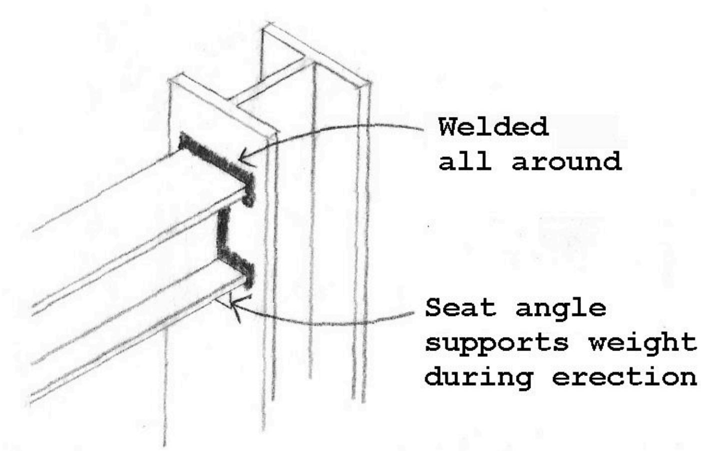

FIGURE 7: ONE TYPE OF RIGID (MOMENT) CONNECTION

Welding offers unique capabilities to structural designers. Welding can join members of a steel frame as if they were a massive whole, as well as provide a stronger connection for the members they join in resisting both shear and moment forces compared to bolting. Often, a combination of bolting and welding can be used to take advantage of each ones capabilities. Bolts can resist the shear forces associated with the dead load of the member while field welds are being performed. These field welds will then be the primary permanent structural connection.

RESISTING LATERAL FORCES

Typical connections for steel frame construction include angles, plates, or tees as transitional parts of the members being joined. A simple bolted connected from beam-to-column may involve one or two angles bolted to the beam's web during prefabrication and then bolted to the flange of the connecting column in the field. Because the beam flanges are not connected to the columns, there is limited transfer of bending moment. A moment-transmitting connection is made when the flanges of a beam are connected strongly by the means of full-penetration groove welds to the supporting column.

Three basic mechanisms are commonly used to stabilize buildings against lateral forces such as wind and earthquakes: diagonal bracing, shear panels and rigid frames. Diagonal bracing works by creating stable triangular configurations within the otherwise unstable rectangular geometry of a building frame. Connections within a diagonally braced frame don't need to transmit moment since they behave like shear connections. Shear panels are stiff walls that are made of concrete or steel and act like braced rectangles within the building frame. Rigid frames, constructed using moment connections, are capable of stabilizing a frame against lateral forces without using diagonal bracing or shear panels. A larger number of the connections in a frame stabilized in this manner must be moment connections, but many may also be shear connections.

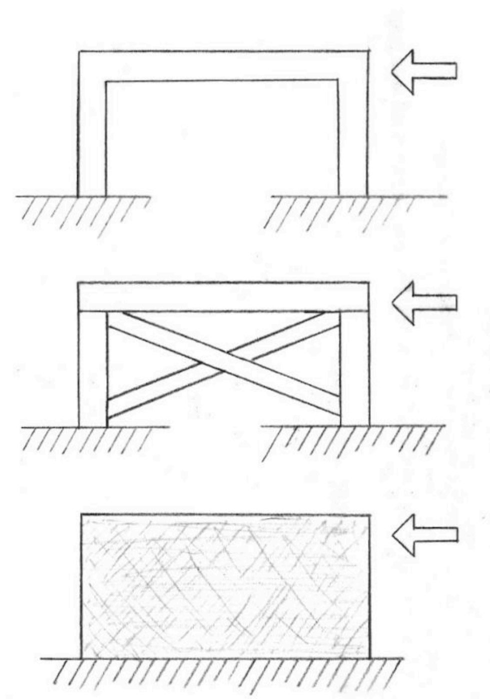

FIGURE 8: LATERAL LOAD RESISTANCE MECHANISMS; RIGID FRAME (TOP), DIAGONAL BRACING (MIDDLE), AND SHEAR PANELS (BOTTOM).

There are three types of steel frame construction defined by the American Institute of Steel Construction (AISC), each of which is classified according to the manner in which they achieve stability against lateral forces. AISC Type 1, rigid frame construction, assumes that beam-to-column connections are significantly rigid so that the geometric angles between members will remain virtually unchanged. AISC Type 2 construction, simple frame construction, assumes shear connections only and requires diagonal bracing or shear panels for lateral stability. AISC Type 3 construction is classified as semi-rigid, in which the connections are not as rigid for those required for AISC Type 1 construction, but possess a dependable and predictable moment-resisting capacity that can be used to stabilize the building (Allen & Iano, 2004, p. 391).

FLOOR AND ROOF SYSTEMS

The floor and roof decking of a building, along with the supporting structural members comprise a significant portion of the dead loads that act within a steel frame. Several floor systems such as metal decking with concrete topping, composite metal decking, cast-in-place concrete, and precast concrete slabs can all serve economical choices for construction. Each option has advantages and disadvantages that must be address pre-construction to format proper scheduling and to finalize design issues.

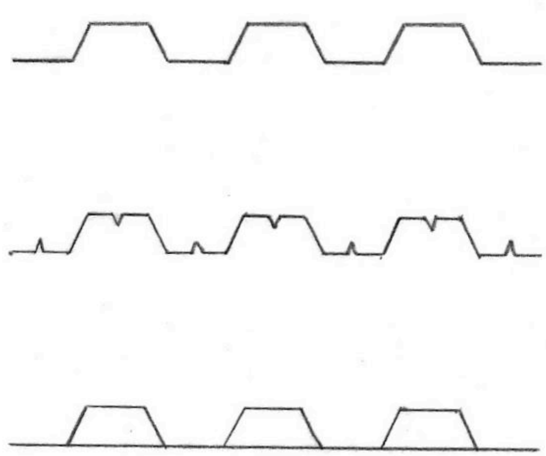

FIGURE 9: TYPES OF METAL DECKING; STANDARD FORM DECKING (TOP), COMPOSITE DECKING (MIDDLE), AND CELLULAR DECKING (BOTTOM).

Metal decking is a thin sheet of steel that has been corrugated to increase its stiffness. The spanning capability of a metal deck is determined by the thickness of the sheet from which it is made and the depth and spacing of the corrugations. The spacing also depends on whether the decking sheets are single or cellular. Single corrugated sheets are commonly used where concentrated loads are not expected and deflection criteria are not stringent. Single corrugated decks are used as permanent formwork for concrete floor decks, with a wire fabric reinforced concrete slab supported by the steel decking until the slab can support itself and its live loads. Cellular decking is manufactured by welding together two sheets, one corrugated and one flat. It can be made stiff enough to support normal floor loads without structural assistance from the concrete topping. Cellular decking can also add the benefit of providing extra space for electrical and communications wiring. Metal decking is usually puddle welded to the beams, joists, and girders by melting the deck together with the supporting members below.

Composite metal decking is designed to work together with the concrete floor topping to make a stiffer, lighter, and less expensive system. The metal decking serves as tensile reinforcement for the concrete, to which it bonds by means of special rib patterns in the sheet metal or by small steel rods or wire fabric welded to the tops of the corrugations. Composite construction is often carried beyond the decking to include the beams in the floor. In these applications, shear studs are welded to the top of each beam every few inches before the concrete topping is placed. The purpose of these shear studs is to create a strong shear connection between the concrete slab and the steel beam. Thus, the concrete acts as a part of the beam's top flange and helps resist bending forces. The load bearing capacity of the steel member has been greatly increased by taking advantage of the unused strength of the concrete topping.

Solid concrete floor and roof slabs can also be used in steel building frames instead of metal decking and concrete fill. Concrete can be cast-in-place over removable forms made of plywood, fiberglass, or steel plates. The cost of such a procedure varies greatly with the size and complexity of the project, as well as the ability to reuse forms within a project or reuse forms from a previous project. Concrete floors can also be erected in the form of precast concrete planks, described in more detail in the Precast Concrete Construction section.

LOAD-RESISTANCE FACTOR DESIGN IN STEEL STRUCTURES

The design of most structures is controlled by building codes and design specifications. Municipal and state governments concerned with the safety of the public have established building codes to control the construction of various structures within their jurisdiction. These codes in particular, are actually laws or ordinances that specify minimum design loads, design stresses, construction types and material quality.

Currently, the American Institute of Steel Construction (AISC) has published recommended practices for regional and national use in steel construction. Using the AISC specification, two main design techniques are accepted: the Load and Resistance Factor Design (LRFD) and the Allowable Strength Design (ASD). The *International Building Codes* (IBC) was also published because of the need for a modern building code that emphasizes performance. It is intended to provide a model set of regulations to safeguard the public. Nearly all municipal and state building codes have adopted the AISC specification and the IBC.

One of the most difficult tasks faced by any structural engineer is the estimation of the loads that may apply to a structure during its operation. Loads are classified according to their character and duration of application. The three main types of loads acting on any structure are dead loads, live loads and environmental loads.

Dead loads are loads of constant magnitude that remain in one position. They consist of the structural frame's own weight and the weights of other fixtures that are permanently attached to the frame. For a steel-frame building, the weights of the frame, walls, floors, plumbing and fixtures are all examples of dead loads. The weights of many materials are given in Part 17 of the LRFD Manual and even more detailed information on dead loads is provided in *ASCE 7-05*, *Minimum Design Loads for Buildings and Other Structures*.

Live loads are loads that may change in position and magnitude. They are caused when a structure is occupied, used, and maintained. Live loads are classified as but not limited to floor loads, traffic loads for bridges, impact loads and longitudinal loads. A great deal of information on the magnitude of these various loads, along with specified minimum values, is presented in *ASCE 7-05*.

Environmental loads are the external forces that are likely to occur based on geographic location and surroundings. For buildings, environmental loads are caused by rain, snow, wind, temperature change, and earthquakes. Sections 6 through 9 of *Minimum Design Loads for Buildings and Other Structures* provide a great deal of information concerning these loads, including charts and formulas for estimating their magnitudes.

The load and resistance factor design method (LRFD) has become a common steel design method taught to students in most colleges and universities in the United States. Load and resistance factor design is based on a limit states philosophy. The term limit state is used to describe a condition at which a structure or some part of the structure fails to perform its intended function. The two categories of limit states are strength and serviceability. Strength limit states are based on the safety or load-carrying capacity of structures and include plastic strengths, buckling, fracture, fatigue, and overturning. Serviceability limit states refer to the performance of structures under normal service loads and are concerned with the uses and/or occupancy of structures including excessive deflections, slipping, vibrations, cracking, and deterioration. Not only must a structure be capable of supporting the design or ultimate loads, it must also be able to support the service or working loads in such a manner as to meet the requirements of the users or occupants of the structure.

The LRFD Specification concentrates on very specific requirements relating to the strength limit state and allows the designer some freedom of judgment regarding the serviceability area. This method is a probabilistic approach, using safety factors to increase the ultimate loads and decrease the strengths so that the probability of failure is approximately one in 10,000. In the LRFD method, the working or service loads (Q_i) are multiplied by certain load or safety factors (λ_i) which are almost always larger than 1.0 and the resulting “factored loads” are then used for designing the structure. The purpose of these factors is to account for the uncertainties involved in estimating the magnitudes of dead or live loads. The magnitudes of load factors vary depending on the type and combination of the loads and are presented in the ASCE 7, section 2.

A structure is proportioned to have an ultimate strength sufficient to support the factored loads. This relationship is represented by the following equation:

$$\lambda_i \cdot Q_i \leq \varphi R_n$$

The left-hand side of the equation refers to the load effects on the structure, while the right-hand side refers to the resistance of the structure. The strength is considered to equal the nominal strength of the member or component (R_n) multiplied by a resistance reduction factor (ϕ), which is typically less than 1.0, to account for uncertainties in material strengths, dimensions, and workmanship. For any particular member, the sum of products of load effects and load factors must be less than or equal to the resistance factor multiplied by the nominal resistance.

PRECAST CONCRETE CONSTRUCTION

Precast concrete is a versatile building material that can be used to create nearly all components of the structure and shell. It can also be used in conjunction with any other material to create the most desirable building possible. Precast units are factory designed and made, and are typically available in a range of pre-selected sizes and styles for which structural information is available on an individual basis. Structural precast components are often pre-stressed as well. This process involves placing tensioned steel strands in the positive moment regions of the precast element. This accomplishes two things. First, the reinforcement causes the surrounding concrete to start off in compression, allowing greater loads to be added without cracking of the concrete. Also, the pre-tensioning creates a camber in the member that decreases the final deflection to allow greater spans than concrete elements without pre-stressed strands.

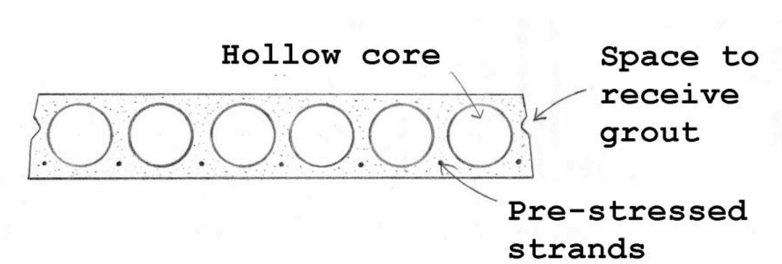

FIGURE 10: TYPICAL HOLLOW-CORE SLAB SECTION

The structural units most typical in precast concrete construction are floor and roof units, beams, girders, columns, and load-bearing walls. Floor and roof units are usually tee-shaped or slab-type members. Tee-shaped elements consist of a two to four inch slab cast together with one or two joists up to 32” deep, and they can span up to 100’. Single-tee shapes require temporary bracing to keep them from tipping over while they are installed, but they can achieve slightly longer spans. Precast slabs come in two general varieties, solid flat slabs, and hollow-core slabs. The most popular style of precast slab is hollow-core, delivering flexural strength in the critical top and bottom sections, and removing weight from the low-stress central areas. These slabs are light-weight and easy to erect in any weather conditions that would delay the pouring of concrete. Depending upon the use of the building, tee-shaped and slab-type floors may require the addition of a thin cast-in-place concrete topping to smooth out the floor and enhance the diaphragm performance of the floor system. For parking garage applications, this topping may be a layer of asphaltic concrete. At the very least, there may be shear keys along the edges of these members which when grouted, cause the individual members to move together.

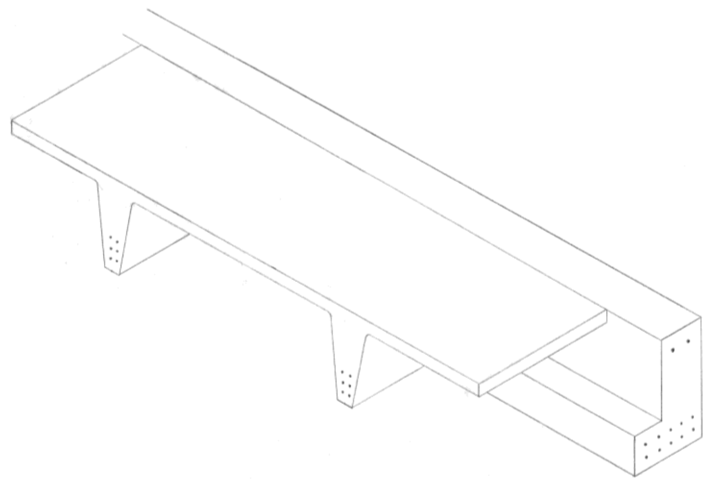

FIGURE 11: DOUBLE-TEE ATOP AN L-SHAPED BEAM

Precast beams are available in three major shapes. Rectangular beams are the most simple, and are useful if another member must be supported across the top. L and inverted-T shapes allow for floor and roof members to rest on one or two sides respectively. Another common shape is the AASHTO girder, an hourglass shaped beam originally designed for highway overpasses. It is a strong shape, capable of carrying heavy loads at spans over 50’, and its use has been extended to some buildings (Ching & Adams, 2001). Precast beams typically rest on protrusions, or corbels from precast columns. They come in a variety of sizes, but they are typically rectangular. These columns can be symmetrically loaded resulting in a concentric load condition, or unevenly loaded resulting in an eccentric load condition. This plays a role in the design of the member and its reinforcement.

Floor and roof units do not have to rest upon beams, however. Load-bearing precast walls often have corbels or slots on which precast slabs can rest. Not all precast wall panels are load-bearing, but all play important roles. These wall panels are often used as shear panels to resist lateral forces in steel framed construction. Besides ordering these precast panels from a manufacturer, they may also be cast-in-place on the ground and put in place once cured in a method known as tilt-up construction.

Nearly all of these precast elements are connected in similar ways. Most typically, plates and bolts are cast into the unit by the manufacturer, and connected on the site with plates, angles, nuts, and welds. When one element must rest upon another, plastic or rubber bearing plates are used to prevent the potential damage resulting from contact.

RESIDENCE HALL DESIGN

The design of a residence hall has few unique requisites distinguishing it from an average apartment building. Typically the considerations spanning all dormitories are not structural in nature, but rather deal with finishes and hardware. The constant use and abuse of the structure suggests that when life-cycle costs of door hardware, toilet accessories, drywall, *et cetera* are taken into account, the cost of higher grade (abuse resistant, institutional) items is actually less. The cost disparity is due to the high expense of labor and materials for renovation, but it is also important to consider scheduling issues, since the building is occupied throughout most of the year.

The structural implications of a residence hall are mainly confined to the determination of the proper live load. *ASCE 7-05* suggests a live load of 40 psf for private apartments. Due to the denser living conditions of a dormitory where there will be fairly small two-occupant rooms (presumably with double the furniture and belongings of a single), the value is taken to be higher in magnitude. Cannon Design used a value of 60 psf (from their construction documents) for the private areas of the building, which will be the value used in this study.

The biggest consideration in the design of a residence hall, which is typically determined at the beginning of the design process, is the number of beds. This end unit and its corresponding price are integral, because in effect, all economy of the building will be based on this parameter.

PARKING GARAGE DESIGN

Similar to the number of beds in the residence hall, the end unit of parking spaces and the corresponding price are integral to the design of a parking garage. These considerations carry the most weight during conceptual phases of the pre-construction process. More implicit in the structural design is the functionality of the building. Most parking garages, in one structural bay, will have parking on each side, and either a single- or double-lane roadway between. These long spans require tight spacing of large beams when dealing with a steel framed structure. The precast equivalent is the double-tee shaped element, which in effect is comprised of tightly spaced concrete joists cast integrally with a precast floor slab.

COST ESTIMATING IN BUILDING CONSTRUCTION

In practice, cost estimating is a very involved process in which many factors must be taken into consideration. Depending on the type of project, a cost estimate may be used to give the owner an idea of how much the project will cost, provide the owner with a guaranteed maximum price, or be used as a competitive bid. With each of these situations, the accuracy of the cost estimate becomes increasingly important for the welfare of the company providing it. If an estimate is too high, the contractor may not get the project or will not get repeat business from that owner. Alternatively, if the bid is too low, the firm providing it will likely lose money on the project.

The process of estimating cost typically starts with the quantification of building materials, known as a take-off. This involves reviewing construction documents and determining the amount of materials used in the proper units. These may be cubic yards as with concrete, square feet as with most floor, wall, and ceiling finishes, tons as with asphalt or structural steel, or any other suitable standard.

Applying an accurate cost to these materials is one of the challenges of cost estimating. The most common and most accurate methods are requesting quotes from vendors and subcontractors and using historical data from previous jobs. When these methods are unavailable, a cost estimating publication may be used to approximate the cost. Typical publications include *RSMeans*, *Sweets*, *ENR*, *Craftsman*, and *BNi*, among others. Simply multiplying the take-off quantity by the cost retrieved by any of these means will yield an approximate base price for the building materials and installation.

To improve the accuracy of a cost estimate, it is necessary to consider many additional factors. Labor and equipment are an area that often requires special attention. Often times productivity rates change due to regional or weather related reasons. A change in productivity can tend to change the unit price greatly, especially when the relative cost of labor to materials is high, as with many finishes. The productivity will also change the scheduling of the project. If the task is on the critical path of a construction project, this change is even more drastic. When the time value of money is considered, this change in productivity may cause large changes in cost. Labor and equipment costs are also very important when dealing with small amount of work. For example, whether a saw-cutting contractor is brought in to cut ten feet of a hundred, the cost of equipment and mobilization remains the same. The unit prices found in publications more accurately reflect the cost of cutting one hundred feet, and if they are used to calculate the cost of the ten foot cut, the actual price will be under-shot.

Another factor to consider, already mentioned briefly, is the time value of money and the increase in material costs. If an eighteen month job is to begin in the spring of 2008, using 2008 base prices will cause the estimate to be inaccurately low. For a rough estimate, it is common to project all costs to the midpoint of the project. For a more accurate cost, each trade should be projected individually using the construction schedule. Some material costs may tend to increase at greater rates than average. Steel, for example, has been increasing much faster than many other building materials due to growing foreign demand. *ENR* is renowned for maintaining and publishing accurate time-cost indices.

Another factor to consider, and the final one discussed in this section, is that of location. Material costs depend greatly on supply, demand, and location of origin. Depending on where the project is located, the actual cost of materials may be significantly higher or lower than the national average. Pricing labor is much the same, varying due to supply, demand, and the presence of union labor. *RSMeans* provides location indices for both materials and installation (includes labor and equipment), divided by division for greater accuracy.

LEED Certification

About LEED certification

Leadership in Energy and Environmental Design (LEED) is a non-profit organization created and developed by the U.S. Green Building Council (USGBC). It was established in hopes of defining a benchmark standard in the construction industry that would work to make the concept of green building a more commonplace and competitive part of the industry. The goal is that ultimately “green building” will become the common practice and incentives like LEED certification won’t be necessary to promote.[1]

The LEED standards work to promote a whole building approach that helps to provide sustainability to the building as well as contribute to human and environmental health. The standards of LEED address five main areas: water savings, sustainable site development, energy efficiency, materials selection, and indoor environmental quality. Within these five sections there are many sub-sections that specify the unique conditions that need to be met. These are

[1] U.S. Green Building Council, LEED Rating System:http://www.usgbc.org/DisplayPage.aspx?CMSPageID

the broad subjects that LEED is concerned with and they work as a jumping off point for which requirements can be created.

Keeping the whole building method in mind, the LEED system provides certification levels unique to different construction types. Currently there are nine types of applications:

- New Commercial Construction and Major Renovation projects
- Existing Building Operations and Maintenance
- Commercial Interiors projects
- Core and Shell Development projects
- Homes
- Neighborhood Development
- Guidelines for Multiple Buildings and On-Campus Building Projects
- LEED for Schools
- LEED for Retail

The USGBC is also working on creating a LEED standard for Healthcare and Laboratories. The classifications try to make certification for buildings a unique process where the industry can be assured that if a building is LEED certified it is positively a green building in a consistent view when compared to similar buildings.

The process to acquire a LEED certification requires the building to earn points based on fulfilling certain assignments. There are four levels of certification: certified, silver, gold, and platinum. The level achieved is determined by how many points are obtained.

Why should the industry want to build green? There are many reasons why building green is a positive experience. Not only does it work to improve the life of the building in terms of the life-cycle and repairs needed, but it cuts the yearly operating costs and provides an increased asset value for the building. It helps to create a more healthy and comfortable environment for the occupants as well as limits the environmental impacts. It reduces the amount of waste brought to landfills, and saves in energy, water conservation, and the amount of harmful greenhouse gases emitted. Once a building is certified it can also qualify for tax rebates, zoning allowances, and many other incentives that are unique to specific cities. Along with that it promotes an owner's commitment to environmental health and social compassion.[2] This can in turn help to attract building residents who may deeply care about helping the environment and may not have been interested in the beginning. Once a building is certified it is allowed to display the LEED plaque that is nationally recognized. The plaque for achieving a silver level is shown below in Figure 12. For the other three levels, the plaque looks the same, but the word silver is changed to certified, gold, or platinum and the color may change.

FIGURE 12: LEED SILVER PLAQUE

Specific to our project the group looked at the requirements for obtaining a silver level in the New Commercial Construction and Major Renovation projects. In this area six sections were reviewed: Sustainable Sites, Water Efficiency, Energy & Atmosphere, Materials and Resources, Indoor Environmental Quality, and Innovation & Design Process. Each area was reviewed to determine which requirements the new residence hall is achieving and the additional requirements that may be achieved with a little extra effort.

HOW POINTS ARE ACQUIRED

There are six major subsections under the LEED for New Construction where a building can obtain points. As previously stated, a building achieves one of four levels of LEED certification by accruing a certain number of points. These points are obtained by doing certain tasks, using certain materials, creating certain systems, etc. These six sections and the tasks assigned underneath were decided upon by the LEED organization taking into account the 5 main areas of environmental concern that green building is trying to solve.

The first subsection is Sustainable Sites. It has a total of 14 possible points. These points are achieved by what site is chosen for the newly constructed building, how the waste of that site is taken care of and disposed, and what type of site the building is constructed on. This section

[2] U.S. Green Building Council: http://www.usgbc.org/

was created because for every piece of undeveloped land that is taken away a habitat and ecosystem is disrupted. As new buildings are created their surfaces and pavements absorb heat and radiate it back out, increasing the surrounding temperatures. As rain gathers on the roof and flows off the surrounding soil is eroded and the local bodies of water receive that run-off which in turn affects the aquatic life. Nothing is untouched when a new building is constructed and this section works to make that disruption as small as possible.

Water Efficiency has a total of 5 possible points. This is concerned with whether the new building is designed to have efficient landscaping and water use, the option for using alternative water technologies, and options for water use reduction. Efficient landscaping is concerned with how much water is needed for irrigation, if that water is reused, and how that water is collected. Currently the United States water deficit is approximately 3,700 billion gallons.[3] This means that the US is using 3,700 billion more gallons of water than they are returning to the natural water system and recharging local aquifers and water sources. This section tries to reduce the amount of fresh water used by buildings as much as possible.

Energy and Atmosphere has a possible 17 total points. The typical forms of energy used these days, coal, fossil-based fuel, and natural gas, all have harmful effects on the environment and until the world stops using these materials to create energy they will continue being mined, etc and continue to harm the earth and surrounding habitats. This section encompasses strategies for energy reduction and points are given if a way to reuse energy on the property has been determined. The type of energy used can also obtain the owner points if it is a material that is less harmful to the environment and the process through which it creates energy does not emit any harmful gases or smoke.

Materials and Resources is the next section that has a maximum of 13 points. This area is concerned with how much of the already existing materials are reused, how waste is taken care of, and how recyclables are stored and then thrown out. Finally it has a part where if certified

[3] USGBC, New Construction and Major Renovation. Version 2.2 3rd Ed. 2006

wood is used points can be obtained. Material or building reuse is important because construction and demolition wastes create ~40% of the total waste in the US.[4] By reusing a building the process of having to design and construct a completely new building is gotten rid of. Along with that the manufacturing and transporting of all the raw materials needed to construct that building is gone. Instead it is possible to renovate an existing building and decrease the amount of new materials that will be sued.

The section Indoor Environmental Quality has 15 total possible points. It is expected that Americans these days spend close to 90% of their time indoors. Indoors is where it has been suggested by the Environmental Protection Agency that harmful levels of pollution reside, sometimes two to five times greater than outdoors.[5] In this section LEED is concerned with low-emitting materials, ventilation in the building, thermal conditions, the amount of natural sunlight, and the controllability of all these systems. All of these credits were created in hopes of maintaining a better indoor air quality for the occupants of the buildings.

The final section is Innovation & Design Process with a total of 5 points. Here the owner and builder can gather points by being creative in their design of the building as well as taking the advice of a LEED Accredited professional. As we all know, green building is a field that is constantly growing and LEED wants to be able to acknowledge those people who have ideas that may not coincide with the LEED checklists or that may be above and beyond anything that LEED asks for. In this way a building can be built as green as the owner wants it to be.

A complete list of all the possible ways to gather points for LEED certification can be seen in Appendix D.

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[4] USGBC, New Construction and Major Renovation. Version 2.2 3rd Ed. 2006

[5] USGBC, New Construction and Major Renovation. Version 2.2 3rd Ed. 2006

LEED LEVELS

There are four levels of LEED certification: Certified, Silver, Gold, and Platinum. The points that are needed to achieve each level are shown in Table 1.

TABLE 1: LEED LEVEL REQUIREMENTS

Certified	Silver	Gold	Platinum
26-32 pts	33-38 pts	39-51 pts	52-69 pts

The level of LEED certification that a building obtains truly depends upon what the owner wants. Each requirement that LEED asks for is easily done if prepared for and thought through from the beginning. This includes the design time so that a schedule and cost analysis can include all of the green options that are required.

HOW LEED CERTIFICATION CAN AFFECT WPI

LEED certification can be very useful for both the owner of the building and its occupants. Just by using green techniques the energy usage and operating costs of the building are reduced because the systems are improving its performance. By being green the asset value of the building is increased and the reputation of the owner is seen to be dedicated to sustainability and social responsibility.

Concerning the occupants of the building the greater amount of sunlight that is required by LEED help to improve the productivity of the people. Relating that to students it has been shown through studies that a better air quality and a larger amount of natural sunlight can contribute to students progressing 20% faster on math tests and 26% faster on reading (RS Means Green Building: Project Planning and Cost Estimating). The better working quality can also help in employee retention as the more pleasant working environment is a hard one to leave.

WHAT GREEN REQUIREMENTS WPI IS MEETING

The following is a bulleted list of the requirements for LEED certification and green building that WPI is meeting. This information was obtained through a presentation made by Neil Benner, project manager from Gilbane, to the civil course Construction Project Management.

- 95% of waste formed during the construction process is being recycled.
- One half of wood products are Forest Stewardship Council (FSC) certified. This means that the wood is Forest-Safe and is bought from mills that forest safely and follow the strict standards set by the FSC.

The FSC are global leaders in responsible and safe forestry. They practice sustainable forestry practices and are responsible for supporting other organizations in being environmentally friendly.

- The residence hall uses adhesives that don't have rogue volatile organic compounds (VOCs).

Volatile organic compounds have a high vapor pressure and low water solubility. They are most commonly human-made and are used and produced in the manufacturing of refrigerants, paints, and pharmaceuticals. They are common contaminants of ground-water.[6] Organic compounds can stay in the air long after they are emitted and are commonly at a higher concentration indoors than out. The danger of them is their effect on human health. It can vary from causing cancer to causing nothing, but what types cause what is basically unknown. Nothing is known either about the levels of organic compounds found in a home.[7]

- The residence hall will not use plywood that has added formaldehydes.

[6] U.S. Geological Survey: http://toxics.usgs.gov/definitions/vocs.html

[7] U.S. Environmental Protection Agency: http://www.epa.gov/iaq/voc.html

Formaldehyde is the most common VOC. It is a colorless, but very powerful smelling gas that can cause eye, nose, and throat irritation, allergic reactions, skin rash, and more. High concentrations of formaldehyde can also trigger allergic reactions to people with asthma.[8]

- The carpet installed in the residence hall will have low formaldehyde concentrations.
- Paint containing low VOC's will be used in the residence hall.
- All materials used in the construction of the residence hall are fabricated and harvested within 500 miles of the construction site.
- Mechanical systems installed in the residence hall will have optimized efficiency.
- Concrete used in the residence hall will contain fly ash.

Fly ash is one of the three byproducts of coal combustion. It is defined by the ACI Committee as "the finely divided residue resulting from the combustion of ground or powdered coal, which is transported from the firebox through the boiler by flue gases." [9] It is commonly formed in coal-fired electric plants. There are two types of fly ash: Class F and Class C. The classes were determined by the chemical composition. Class F is produced from bituminous and anthracite coal while Class C is created by burning subituminous or lignite coal, and is the preferable choice of distributors who create this ready-mix solution.

Fly ash is used in Portland Cement and decreases the amount of cement that is needed, reduces the energy needed to produce completely new materials, conserves already made new materials, and helps to reduce air pollution. Companies that use fly ash usually substitute about 20-35% of Portland cement with the ash. This in turn lessens the amount of Portland cement used and allows us to recycle already created materials. Not only does using fly ash help to support the environment it is actually a positive thing concerning cement. It improves the quality and performance of the concrete as well as the plastic properties. This means that the

[8] RS Means Green Building: Project Planning and Cost Estimating: 2002

[9] A Sourcebook for Green and Sustainable Building: http://www.greenbuilder.com/sourcebook/Flyash.html#Define

workability of the concrete is better, there is less water demand, lowers the heat of hydration of the concrete, reduces permeability and corrosion of reinforcing steel and segregation and bleeding, and increases sulphate resistance. (3) The use of fly ash in Portland cement needs to fulfill the requirements of *ASTM C 618 Standard Specification for Flyash and Raw or Calcined Natural Pozzolan Class C Flyash for use as a Mineral Admixture in Portland Cement* to be able to be used legally in construction.

In terms of points what follows is the current status of how WPI is doing in achieving the LEED credits. There are a total of 38 points that are planned on and are implicit to the current design, are currently in construction, or are already achieved. Considering the six sections of LEED for new construction, there is a total of 8 points in the Sustainable Sites section with 4 already closed and set, 1 currently in construction, and 3 are in the design and planned on. A total of 4 points is seen for the Water Efficiency section, all are in the design of the building, but as of yet are not achieved. 6 points total are planned for the section Energy & Atmosphere with 5 points in the design and 1 currently being constructed. Materials and Resources has a total of 5 points with all 5 being constructed right now. 11 points are chosen for the Indoor Environmental Quality section with 6 being constructed and the last 5 in the design. In the last section, Innovation & Design Process, there is a total of 3 points, 2 in design, and the last an ongoing process as it concerns a LEED accredited professional.

GREEN BUILDING OPTIONS

This section of the background researches different green building options that are open to WPI as ways to successfully achieve a LEED credit or just as an option to have a greener residence hall. There are four main options that were looked into:

- A green roof – One of which is already being installed on approximately 1/3 of the residences hall.
- Rainwater Harvesting
- Greywater System
- Dual-Flush toilets

A number of materials that are coined “green” were also researched to see if they could be useful in the construction of the new residence hall. These are:

- Cork Flooring
- Linoleum Flooring
- Recycled Glass Countertops

GREEN ROOF

The main objective of a green roof is to replace the environmental footprint that is to be lost when the building is constructed. They are helpful in limiting the amount of water loss by absorbing, filtering, and detaining any rainfall. This in turn keeps large amounts of water from pouring off the building and eroding soil that lies immediately below. The layers of a green roof are set in how they work and the only variance are the plants used. The layers can be seen in .

FIGURE 13: TYPICAL GREEN ROOF LAYERS (LOW IMPACT DEVELOPMENT CENTER, INC., 2007)

The type of green roof can vary from “intensive” which can have a large variety of plants and can even include trees and shrubs to “extensive” which is usually only grasses and mosses. The intensive roofs require a large amount of maintenance, but are usually open to the public and have the atmosphere of a park or large open space. The extensive roofs require low maintenance, can be constructed with as low as 1.5” depth of soil, and are usually not open to the public. These can be a good option if you don't want to put too much time or energy into the roof after it has been constructed.[10]

RAINWATER HARVESTING

Rainwater harvesting is an idea that is becoming increasingly well known to the public. It is a solution for reducing the amount of water a building may use. The basic concept is that when it rains the water from the roof is caught and directed to a holding and filtration system. From there it can be used for irrigation purposes or secondary water use, such as toilets.

There are four main components of rainwater harvesting to consider when first deciding if the building will work for this system: capture, conveyance, holding, & distribution. To capture it needs to be considered how big the roof is and how much water it will be able to catch with its specific surface area. This can be found by calculating the area of the roof and then multiplying that by the annual rainfall, which can be found for any geographic location online. Now it should be noted that the number calculated will be the ideal situation so there will be some inefficiencies that will need to be considered. These inefficiencies are the roofing material, which can slow down the water transport or soak up some of the water itself.

The next step is how to take the captured rainwater and transport it down from the roof to a holding tank. These conveyance systems are usually a more high-tech gutter system that leads to holding tanks. The only difference between these gutters and a normal system would be that there is a screen installed so that before the water hits the tanks the screen can filter out some of the larger debris that might be floating in the water. The screen should have holes larger than a normal screen, say one used for a door, so that

FIGURE 14: BARREL STORAGE TANK (CITY OF PORTLAND, OR)

[10] "The Green Roof Research Program at MSA" http://www.hrt.msu.edu/faculty/Rowe/Green_roof.htm

the water doesn't clog up and start to run over, but small enough that larger sticks or leaves can be blocked. There is a maintenance issue with these gutters though because it will need to be checked that there are no blockages anywhere along the line. This would probably require a weekly check or at least one before a big rainstorm is predicted.

The holding tank for the runoff water is the next concern. What the captured rainwater is going to be used for determines how many tanks will be needed. Without purification, the rainwater is useful for landscaping and irrigation purposes or toilet water. Depending on the demands the storage can be simple, as seen in Figure 14 or complicated as seen in Figure 15.

FIGURE 15: FLOWER POT PURIFICATION SYSTEM (CITY OF PORTLAND, OR, 2008)

The storage tanks will tend to be on the larger size as all of the water collected during each rainstorm won't be used at once the tanks will have to be big enough to contain a large enough amount of water to supply the required demands even when not raining. Considering the geographic locations and that available space can be limited there are both above and below ground tank options. A complete rainwater holding system can be underground if planned for at the beginning of the process. Unfortunately there are maintenance factors where the barrels must be checked regularly to make sure there are no leaves or debris in them as well as the barrels must be emptied within 10 days to ensure that no bugs or similar things are breeding in them. This would require that if the barrels were stored underground that there was a way to reach them.

GREY WATER SYSTEM

Grey water is any water that comes from your home excepting toilet and food wastewater. This leaves laundry, kitchen/sink water, bathroom & miscellaneous. The breakdown of a household's wastewater can be seen in Figure 16. All of this water is only slightly dirty when it is considered used and thrown out when in truth there are other things it could be used for rather than using a completely new batch of fresh water. Any toilet or food wastewater is called "black water" and must have a government directed cleaning process before it is usable again. The difference between grey water and black water is that there is less nitrogen and much fewer pathogens in greywater.

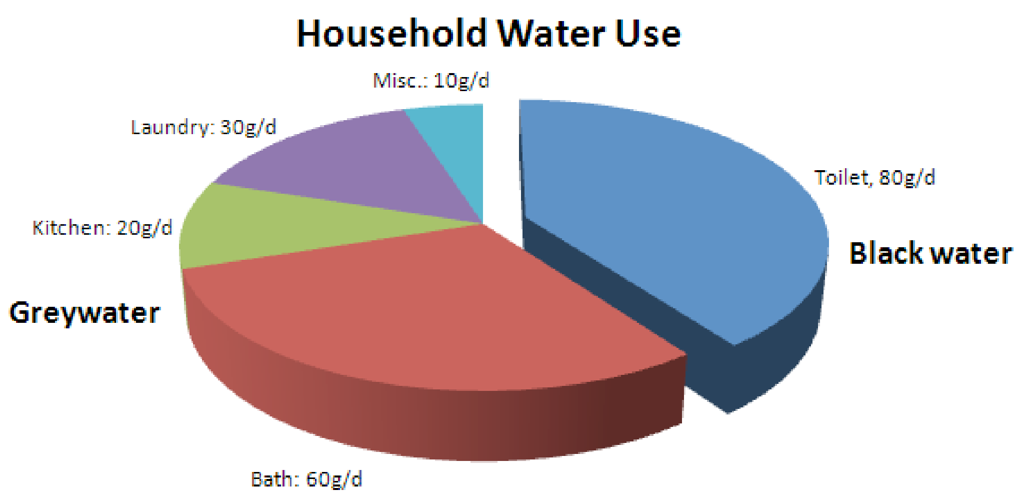

FIGURE 16: GREYWATER BREAKDOWN (CARL LINDSTROM, 2000)

The positive aspects of grey water other than just saving the small amounts of fresh water in this world are many. Looking at personal reasons there is less strain on the septic tank and treatment plant because there is less water being piped through. Along with this if the surrounding area does not have room for a septic system a grey water system can substitute for a higher upfront cost, but a greater outcome. This will help with the wear and tear that these systems usually experience. When the grey water is used for irrigation purposes it has far more nutrients that help the soil and plants to grow faster and become healthier. Even if your household cannot use the entire amount of grey water you have allowing it to go back into the ground after its treatment is a better choice because then the earth can reclaim the nutrients and reuse them.

The constricting factor with a grey water system is that though the grey water is fairly clean it does still have bacteria in it and can become anaerobic and decompose. This means that there does need to be a purifying system of some level. Once the grey water is piped out of your house it should enter a settling/filtration tank. This tank should be twice the size of your expected daily output and the grey water will want to move slowly through it so that any larger debris and sludge can settle to the bottom. A sand filter is a typical option because it allows gradual movement of the water, but the millions of tiny sand particles have a large amount of surface area where bacteria and sludge can stick. Finally you will need to disinfect the grey water, chlorine is commonly used, and then it can be used again. If used for irrigation purposes it is important to note that the water must be inserted underground, never on top of the soil. A portrayal of one type of system can be seen in Figure 17.

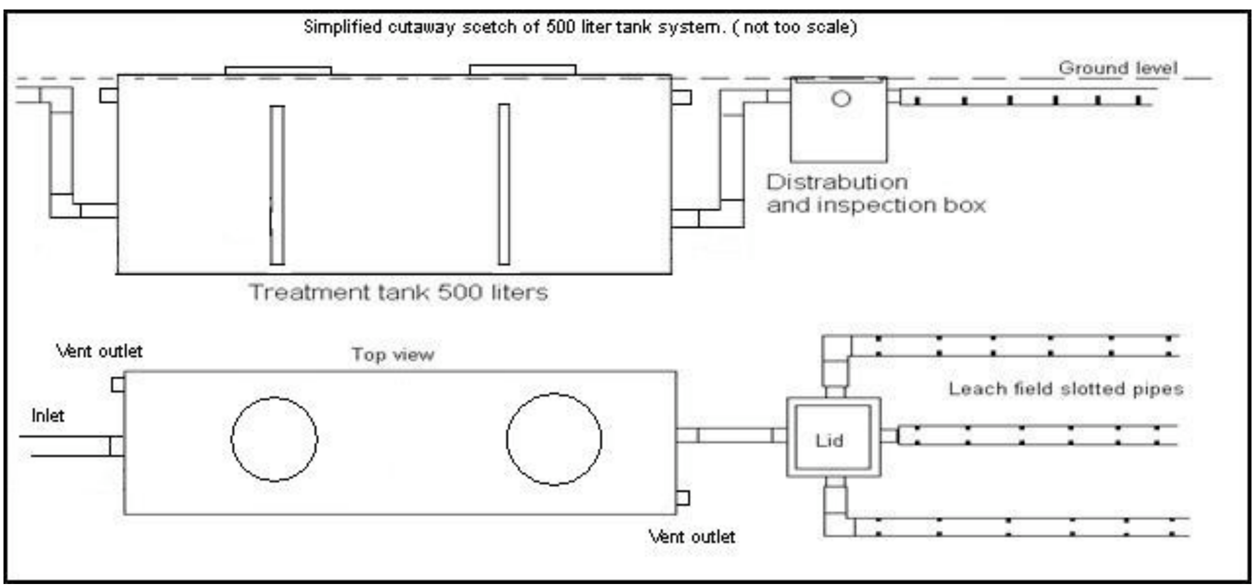

FIGURE 17: ONE TYPE OF GREYWATER TREATMENT SYSTEM[11]

[11] Bioloo Composting Toilets & Greywater Systems:www.bioloo.co.nz/GREY%20WATER%20cutaway.JPG 2005

DUAL-FLUSH TOILETS

It has long been a standard that there is one flush for a toilet no matter what was put in the bowl. In the past the average was 3.5 gallons per flush. This has since then been updated, and currently the standard is the equivalent of 1.6 gallons per flush. Right now North America is one of the only countries that still using only single flush toilets. Europe and Australia have been using dual flush toilets for a while now and have seen a significant decrease in overall water use.

Dual Flush toilets are exactly what they sound like. They have two flush options, one for a liquid and one for solids. The basin has two different holds and depending on which flush option is chosen the correct hold opens and flows into the bowl. Each option uses a different amount of water, with the large flush using ~1.6 gallons per flush and the lighter using about half that, ~0.8 gallons per flush.

Dual flush toilets are very flexible and can work by themselves or can be inserted into an entire water saving system such as rainwater harvesting or a grey water system. By doing this a household or building can effectively cut out the fresh water usage in terms of toilets and irrigation. This in turn doesn't only help the environment, but decreases the water payments needed to be made.

GEOTHERMAL HEATING

Geothermal heating uses the energy of the earth to either heat or cool a building. The practice has been in use since the 1940s (U.S. Department of Energy, 2005). The idea is that instead of using the outside air temperature as the medium through which we heat our houses we are using the constant temperature of the earth. This means that rather than the heat having to adjust with the seasons it is always related to one constant temperature. Depending upon the building's location in the world, the ground temperature ranges from ~45 degrees F to ~75 degrees F. Then as the weather gets hotter, the earth's temperature is cooler, and as the weather gets colder, the earth's temperature is warmer.

By inserting a pipe several feet below the ground surface, it is possible to tap into either a constant temperature water pocket or the earth's energy. With this heat, water is then run through a loop where the heat is deposited into the house. This is a low energy system because to increase the temperature of a house by five degrees, the water temperature flowing through the loop only has to be raised by one degree. These systems can be used for cooling as well. Rather than water gaining heat from the earth and transporting it into the house, heat is taken from the house and transported back down to the earth thus cooling the temperature of the building. During the months the system is being used for cooling there will usually be an excess amount of heat which could then be used to heat the bath and shower water rather than using a hot water heater, thus additionally cutting costs.

There are two different ways to set up the geothermal heat pipes, a closed or open loop system. An open loop takes water from a well and then once the water has completed its path through the earth and the house it is deposited into another well or a drainage field. A closed loop contains a mixture of water and antifreeze and the same quantity of liquid is circled through the pipes. It is possible for the pipes to be placed vertical or horizontal, but vertical tends to be more expensive.

Most of the energy used for the system goes toward the pump and compressor that moves the water through the loop. The rest of the energy is then used for fans and controls that will help to distribute the hot or cold air throughout the house. The upfront cost for a geothermal heating system is $2500 per ton of capacity.[12] So a typical residential size 3-ton unit would cost approximately $7500. A normal heating system usually costs around $4000 dollars.[13] Even though there is approximately an extra $3000 to purchase the geothermal system, over a lifetime of paying for fuel with a conventional system the upfront cost would be paid back in only a few years.

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[12] U.S. Department of Energy: http://www.eere.energy.gov/consumer/your_home/space_heating_cooling/index.cfm/

[13] U.S. Department of Energy: http://www.eere.energy.gov/consumer/your_home/space_heating_cooling/index.cfm/

The geothermal system sounds like a good idea and seems like it would be a reasonable system to have for a student residence hall even though it is a large building. Unfortunately it would need a much higher upfront cost and it would have to be the decision of the college if they wanted to put that much more money into their building right at the beginning. The system as well would require maintenance to make sure the appliances are all running smoothly and that there are no blockages or breaks anywhere.

CORK FLOORING

Cork flooring is the bark taken from the Cork Oak trees found in southwest Europe and northwest Africa. The bark is harvested approximately every 10 years where the harvesting requires having the bark taken from the tree.

It does not hurt the tree and a new layer of bark starts to grow as soon as the old layer is taken off. The cork oak trees can last for 150-250 years meaning that one tree can have at a minimum 15 harvesting times. This makes cork an extremely useful and environmentally friendly material. A picture of a cork oak tree can be seen in Figure 18.

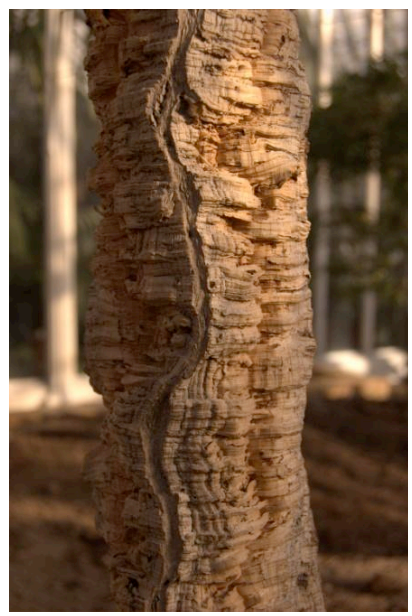


FIGURE 18: CORK OAK TREE (MARTIN OLSSON, 2006)

Cork flooring has many special qualities that stem from the fact that it is a bark. Because it is a bark that must protect the tree it is naturally anti-fungal, anti-microbial, and hypo-allergenic making it an excellent choice for people with allergies. The structure of the cork in terms of cellular level also makes it very resilient to blows, dents, and scratches. The cork also absorbs sound well, which would be a plus in a residence hall where you do not want sound to transfer far. The cork floor can also be coated with a polyurethane finish that will allow it to be able to resist lots of use, as in a commercial building. This finish can be repainted every year or so as seen fit by the owner to stay fresh and looking nice. Cork flooring can also be used in any room in your house though there are special considerations if you decide to use it in your bathroom. Cork is resistant to water and with a polyurethane finish is even more, but it does reach a point so owners should be careful to not leave any large puddles of water on the floor.

LINOLEUM FLOORING

Linoleum flooring was invented 150 years ago and was very popular until the invention of vinyl caused it to be forgotten about. Linoleum is made up of mainly renewable resources such as cork dust, linseed oil, rosin, limestone, wood flour, and pigments that determine the color. This is then pressed on to a jute backing and hung in drying rooms to cure. The flooring is available in tile or sheets and is then installed with an adhesive. After the linoleum is made all remnants of the process are then recycled back into the production process. The manufacturing and disposal of linoleum creates no toxins and is biodegradable. Linoleum is very durable and maintains a fresh clean look for years with a low amount of maintenance. It is also water resistant which makes it a good choice for bathroom, laundry rooms, mudrooms, or counter tops. If something spills on it the simplest clean up would require sweeping and an occasional mopping.

RECYCLED GLASS

Recycling has grown in popularity over the years and one of the newest fads is to create countertops, floors, objects, decorations, tiles, etc out of glass objects that would be put into a landfill. Any type of glass that can be considered trash can be taken and formed into something else useful. Different companies specialize in certain types of recycled glass. One may use a lot of airplane windshields while another may use only bottles of all colors. This glass can be mixed with ceramic tile if wanted and is then placed in concrete and sanded down to feel as smooth as a granite or stone counter top. An example of what a recycled glass countertop can look like is shown in Figure 19. These countertops can be created in any color or design.

FIGURE 19: RECYCLED GLASS COUNTERTOP

(VETRAZZO, 2007)

LEED BACKGROUND WRAP-UP

The environmental background section was written to enlighten the group members and readers about two main objectives. The first was to learn more about what LEED is so that it can be understood why WPI is putting such large amounts of time, energy, and money into obtaining a LEED certification. After understanding the goal of LEED it was important to research the process for a new construction building and what specific tasks would need to be done to successfully achieve it. Finally it needed to be known what WPI was already doing to achieve this certification since this MQP started during the middle of the construction process.

The second objective of this section was to increase knowledge of green building options that are designed and installed in a building in hopes of lessening the building's overall use of water or energy. Different materials that are known as being more environmentally friendly were also looked into. The options that were researched were considered to see if they could help to achieve a LEED credit which would help in turn to achieve certification or to see if they would be possible to run and maintain in a dormitory which will see lots of action and use.

Chapter 3: Methodology

Structural Analysis & Design

Residence hall

The design of the residence hall was initiated by introducing the reader to the layout of the building. An alphanumeric grid allowed for easy reference to columns, and all unique girders and structural bays were named with a logically based designation system. In addition, an elevation view was used to display the top of slab elevations.

The design of the cast-in-place floor systems began with the determination of the proper slab thickness for fire resistance. Using the corresponding weight of this slab, it was possible to choose spacing of the structural infill members based on two limiting factors: the allowable span of the deck and the allowable depth of the supports (brief calculations were performed to guess the probable depth of these members). The reinforcement in the slabs was then designed based on the forces likely to occur in the slab. The slabs were checked for shear resistance and bending moments.

The supporting members of the cast-in-place floor systems were then designed using LRFD methods. In the case of the open-web joist systems, design tables provided by the Steel Joist Institute provided reference for selecting member sizes. The rolled steel beams were chosen according to American Institute of Steel Construction guidelines in the *Manual of Steel Construction*. The beams of the cast-in-place systems were designed to work in partial composite action with the concrete floor, which required the selection of the proper number of shear studs.

In order to design the precast floor systems, the longest span was considered. Using the service loads, as specified by the Precast Concrete Institute, the minimum possible thickness of the cast-in-place floor was chosen from the *PCI Design Handbook*. Using this thickness, the appropriate pre-tensioned strand designation was selected for all of the spans.

With each of the floor systems designed, the area of focus shifted to the frame design for gravity loads. For each of the cast-in-place options, the dead and live loads acting through the infill members to the girders were used to determine the minimum possible size every unique girder, using partial composite action, according to the *AISC Manual.* A similar approach was taken for the precast system, except that the girders were not designed for composite action.

The weights of the selected girders for each system were then incorporated into the dead loads of the structure. Using these loads, and the tributary area of each column, the magnitude of axial compression was determined for each column on each floor. Using the *AISC Manual*, the appropriate column sizes were chosen. For constructability purposes, one set of columns was selected for the first two floors, another for the third and fourth, and a final set of column sizes was selected for the fifth floor.

The final element of the structure was the foundation. A simplified approach was used to determine the required bearing area of the foundations. The forces acting on the foundations through the columns and the net allowable pressure of the soil were used to determine the required are for all spread and strip footing. These areas were compared to similarly sized footings in order to estimate a footing depth, as well as pedestal sizes for the spread footings, and frost walls for the strip footings.

PARKING GARAGE

The design for the parking garage presents two different structural alternatives: a steel frame and a precast concrete design. The scope of design involved determining the primary structural supports such as floor systems, girders and columns. Suggestions for the lateral load resisting systems were also addressed.

In defining each alternative, both garages have the same structural design and layout. The main function of the garage is to support two way traffic and parking on both sides. Layouts of the garage are established along with labels for each member. A plan view given by Cannon design is used as the basis for defining the garage layout.

The selection of floor systems for each garage is based on precast design values given in the *PCI Design Handbook*. Since precast double tees are commonly used in parking garages, they will be used as the type of floor system in each design. Each floor system will be capable of supporting the superimposed load acting along their span. Images are used to illustrate the interface of these designs.

Design of the steel frame garage is based on the design strength values given for structural steel shapes in Table 3-2 of the *AISC Design Manuel* using the LRFD method. Each girder will be designed based on their flexural strength and deflection under loading. The column sizes will be selected by their axial compressive force in relation to unbraced length in Table 4-2. Other elements of the design that were considered are the effective flange widths of the girders for support of the floor systems; as well as, flange length and web depth for the connection of girders to columns. Examples of bracing for lateral loads within this structure were also explored.

The *PCI Design Handbook* is used for the design of the precast concrete garage. Using published values for L beams, inverted tees and rectangular beams; girder sizes are selected. Girder design is based on the calculated load acting per linear foot along the beams span. Columns are designed to handle the load acting in axial compression and their factored moment. Again, PCI design tables will be used to specify the column dimensions. Lateral force resisting systems such as shear walls are also specified and analyzed. All finalized designs will be based on keeping the garage as simplistic as possible while still being visually appealing.

COST ESTIMATE

A cost estimate of the structural elements of the parking garage was performed. This included the superstructure and the substructure of the building. In order to accomplish this, the first step was to take off the quantities of all the structural building materials. The materials associated with the floor slabs were typically taken off in square feet, or squares (100 SF). The exception to this is the sheet steel edge forms, taken off in linear feet. Joists, beams, girders, and columns were taken off in linear feet. The elements of the substructure were taken off individually by cubic yard, excepting the slab on grade, taken off in SF, and the associated reinforcement, taken off in squares.

The next step to creating the cost estimate was determining unit costs of all the structural elements taken off. In some cases the typical unit costs were available in *RSMeans Building Construction Cost Data 2008.* For most other materials, the unit costs had to interpolated or extrapolated from the costs of the same item of different sizes. In a few cases, it was necessary to make an educated guess based on a similar building material, as with foundations.

In all cases, the unit costs were adjusted to the projected Worcester cost using location indices from the reference section of *RSMeans Building Construction Cost Data 2008*. It was not necessary to adjust the cost for time, because the midpoint of the structural activities of the construction project was approximately the end of 2007, making the 2008 costs sufficiently accurate.

In order to obtain an estimated cost of the structure, the take-off quantities were simply multiplied by the unit costs. A final cost was determined for each element, the sub- and superstructures, and the entire system. Finally, these values were compared to typical square foot costs of similar structures in order to gauge the accuracy of the estimate.

ENVIRONMENTAL STUDY

The following sections detail the process that was completed to discover how much higher of a cost it would be for WPI to achieve a gold level LEED certification rather than the planned for silver. It will also show how certain options for green building would affect the residence hall if WPI chose to include them. This section shows the thoughts that went behind what options were chosen to be used in the cost analysis. What follows is how the LEED credits this MQP wanted to shoot for were chosen and what analysis went into them as well as how the green building alternatives were used to either achieve a LEED credit or to make the building more environmentally friendly.

U.S. GREEN BUILDING COUNCIL'S LEED CERTIFICATION

It was common knowledge at the beginning of this project that WPI was striving to obtain a Silver LEED certification for the new student residence hall. For each LEED project there is a checklist that specifies what the project owner needs to do to achieve each point. For this project we needed to know what tasks WPI was doing to accrue points. To do this, we downloaded the LEED checklist from the USGBC website, which is open and accessible to all, and it was reviewed to see which options WPI was likely to choose. These options were decided upon using common sense and the limited knowledge the group had at the beginning of the project. An example of this is credit 2.1 Construction Waste Management where 50% of the waste from the construction process has to be reused instead of disposed. This credit was known to be achieved by attending a presentation by Neil Benner, project manager from Gilbane, where he said that 95% of the waste was being recycled. Unfortunately this common sense review left many questions, as the list of probable tasks and practices seemed greater than what WPI was expecting to complete.

The next step was to talk to people who knew more about the LEED section of the construction project and would be able to supply the needed information. Alfred Dimoura, Assistant VP for Facilities at WPI, was able to supply us with the LEED checklist completed by members of the residence hall project. This allowed us to see exactly how WPI was planning on obtaining their silver certification. Once it was determined where WPI was obtaining its points, the next step was to see how many extra points were needed to increase the certification from a silver level to a gold. A list of possible additional tasks to accrue points was examined, and the corresponding number of points was tallied.

Using information from the background if WPI succeeds in obtaining all of their planned 38 points, then one extra point would bump them up to 39 points and a Gold level certification would be achieved. For the purpose of this report we will look into what it would take WPI to achieve an extra 5 points, thus ensuring that a gold certification would be obtained.

LEED for New Construction Checklist

The next step was to see what points that weren't planned on being achieved would be possible to include in the residence hall design or construction without creating a large amount of extra work for all parties involved in the design and construction of the residence hall. This work could be that it requires a day of installation, which would not only cause the schedule to change, but require money to pay the laborers for a day of work. A day may not seem like a huge set back to some, but in terms of this MQP a day is simply used as an example that would change the current schedule and might require changes in deliveries or disposals. It could also require time in the design phase if the credit required certain appliances to be incorporated into the building. These are a few examples of what credits might require from the design or construction process. The checklist was reviewed and each task that had a "no" beside it was further researched. The "no" signified that it was a credit that WPI was not planning on obtaining in the process of achieving a LEED certification. The tasks researched were:

- Brownfield Redevelopment
- Alternative Transportation, Bicycle Storage and Changing Rooms & Low-Emitting and Fuel-Efficient Vehicles
- Site Development, Protect or Restore Habitat & Maximize Open Space
- Heat Island Effect, Non-Roof
- Innovative Wastewater Technologies
- Optimize Energy Performance
- Building Reuse (3 credits equaling 3 points)
- Materials Reuse (2 credits equaling 2 points)
- Rapidly Renewing Materials
- Increase Ventilation
- Indoor Chemical and Pollutant Source Control
- Thermal Comfort, Design & Verification
- Innovation in Design (2 credits equaling 2 points)

Out of these 20 credits there are options that are not possible for this construction project. They were considered not possible because of things such as Brownfield Development credit where that point is achieved by the nature of the building site or the Building reuse credit where points are earned for reusing materials salvaged from buildings that previously existed on the construction site and were torn down to construct the new building. Consequently eleven credits were discarded because of the specific circumstances of the residence hall. This left nine credits to be researched.

Following are the nine credits that were considered to be the potential five credits that will help WPI achieve a gold LEED certification. The credit requirements are stated, and then the effects of achieving the credit were researched.

ALTERNATIVE TRANSPORTATION, BICYCLE STORAGE & CHANGING ROOMS

The cost, installation, and maintenance were researched. The total costs of bike racks were found by viewing numerous vendors and calculating an average cost for both movable and fixed bicycle racks. A discussion with graduate student Susan Peyser confirmed the fact that even though this credit seemed very easy, it is true that it is achieved by just supplying bike racks and changing rooms to the occupants of the building.

SITE DEVELOPMENT, MAXIMIZE OPEN SPACE

The site development credit required the group to approximate the area of the total construction site. Using that, the area of the open space that would be required was calculated to be 20% of the total area.

$$Total\ Site\ Area\ (sf)\ x\ 0.20 = Open\ Space\ Area\ \text{(sf)}$$

This square footage was too big of a size for just one single open space to be created so it was split into two sections. One was the green roof and the other was an open space between the parking garage and residence hall. To achieve this credit the green roof would need to be accessible to the occupants of the building. Thus the cost and maintenance of maintaining both the green roof and the open space were researched.

MATERIALS REUSE (2 CREDITS)

This credit required research into the materials that were disposed of after tearing down the two buildings that resided on the site. Unfortunately not much information was able to be found about what happened to these materials. Assumptions were made by the group that the materials that would potentially be reusable from the old buildings would be less than durable and not safe to use in the new residence hall. The materials that they would replace would also not save that much money for WPI so it would not be a great credit to achieve.

RAPIDLY RENEWABLE MATERIALS

This credit required intensive research into numerous renewable materials that would be a potential option for the residence hall. Factors such as durability, maintenance required, and installation of the products were considered in the decision to suggest that material for use. Vendors will also found and approximate costs were calculated for each specific material. To supply WPI with a total approximate cost a rough estimate of how much square footage would be required for the material to fill was calculated and used to calculate a total cost of outfitting the residence hall with renewable materials. For the cork flooring, which was assumed to be used for the flooring, an estimated square footage of two thirds of the building's total area was used. For the linoleum, assumed to be used in bathroom and kitchen flooring, the approximate square footage was one sixth of the total building area. And the recycled glass, used for kitchen counter tops, was approximated at one twelfth of the entire building's area.

INCREASED VENTILATION

This credit required research into how much an increased indoor air quality actually effects the occupants of the building and whether this increase of air quality is worth what the extra cost would be. Very little analysis was done in terms of cost because the group was unable to gain information about what type of HVAC systems are being installed in the residence hall since this is a fast track project and those decisions were not made when we began this project.

THERMAL COMFORT

This credit required thought into what it would take to supply an entire dormitory each with a specific thermostat that would be able to control that suite and that suite only. Logical thinking was used to decipher what kind of factors and characteristics a complicated system like that would require. Research was done into whether it was possible for WPI to save money by installing separate thermostats and if there would be any major or extraneous maintenance and installation issues that would be caused by having this complicated of a system.

OPTIMIZE ENERGY PERFORMANCE

This credit required information about the total energy usage of the residence hall. Extensive research into exactly what this credit required was needed to ensure that the group understood how to analyze and provide an intelligent suggestion for WPI. Information was received by the Cannon Design team to see what their potential thoughts were on how WPI was going to be able to achieve this credit. This information was then used to decipher if it was possible for extra points to be acquired through this credit by increasing the amount of energy saved in the building.

INNOVATIVE WASTEWATER TECHNOLOGIES

This credit allowed the group to utilize the green building alternatives that were researched in the background. Rainwater harvesting and dual flush toilets were chosen to successfully achieve this credit. This decision then required research into the cost of installing a rainwater harvesting system and the potential set ups that are possible. The decrease in water usage and the corresponding cost savings were noted as well. Lastly the processes needed to attach the rainwater harvesting system with the dual flush toilets were looked into.

Out of these nine options 5 were chosen to be considered the 5 extra points WPI should have made a part of their goal to successfully achieve a gold certification for the new student residence hall. The 5 credits chosen are:

- Alternative Transportation, Bicycle Storage & Changing Rooms
- Site Development, Maximize Open Space

- Optimize Energy Performance
- Innovative Wastewater Technologies
- Rapidly Renewable Materials

The effects of this research can be seen in the environmental results.

CHAPTER 4: STRUCTURAL ANALYSIS & DESIGN

RESIDENCE BUILDING

This section involves all structural activities concerning the residence hall building. It leads the reader from familiarization with the building to the design of the structural alternatives. The design of each floor system will lead to the design of its corresponding frame, from girders to columns, bracing, and foundation. The computer program AutoCAD was employed often to convey diagrammatic information to the reader.

DEFINITION OF FRAME LAYOUT

BUILDING FOOTPRINT

Figure 20 is a plan view of the new WPI residence hall depicting the footprint from which the frames were designed. It includes the enclosures, elevator shafts, and stairway shafts.

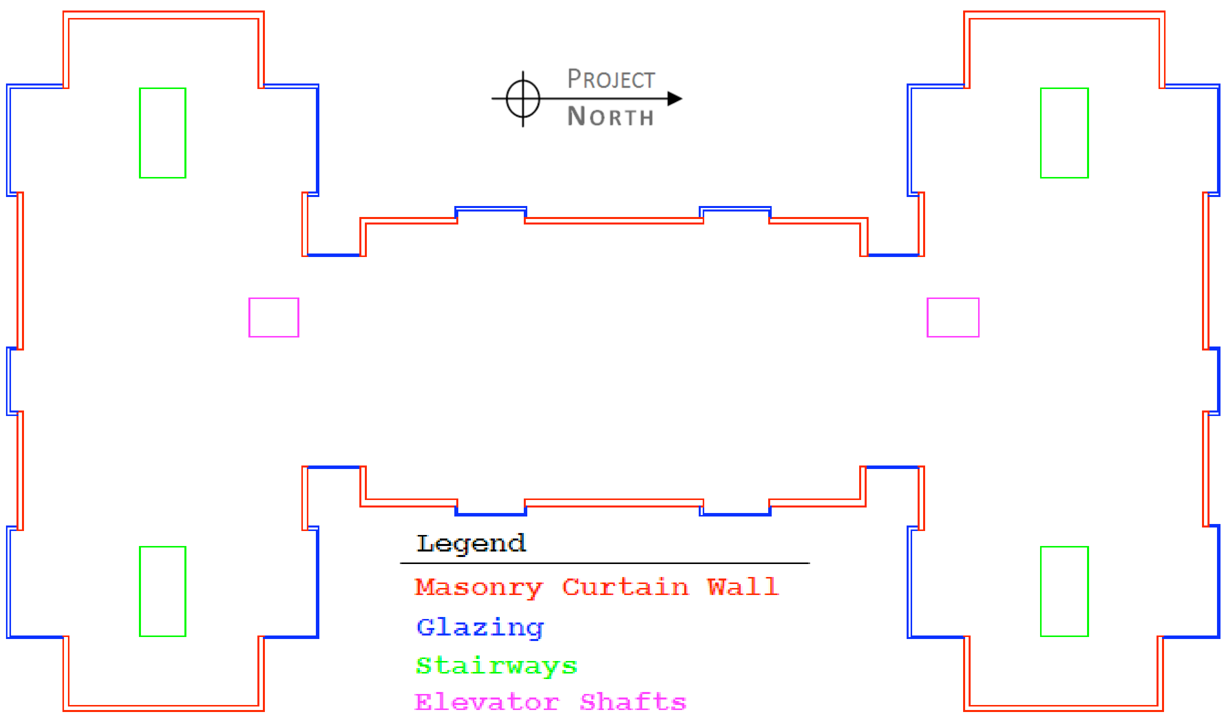


FIGURE 20: BUILDING ENCLOSURES & SHAFTS

COLUMN LOCATIONS & DESIGNATIONS

Figure 21 shows Cannon Design's on-center location of the columns in relation to the skin of the building. These are not the locations which were used for our design, but they are shown in order to display the changes we made. Dimensions and other information needed to complete Figure 20 and Figure 21 were taken from the construction documents prepared by Cannon Design.

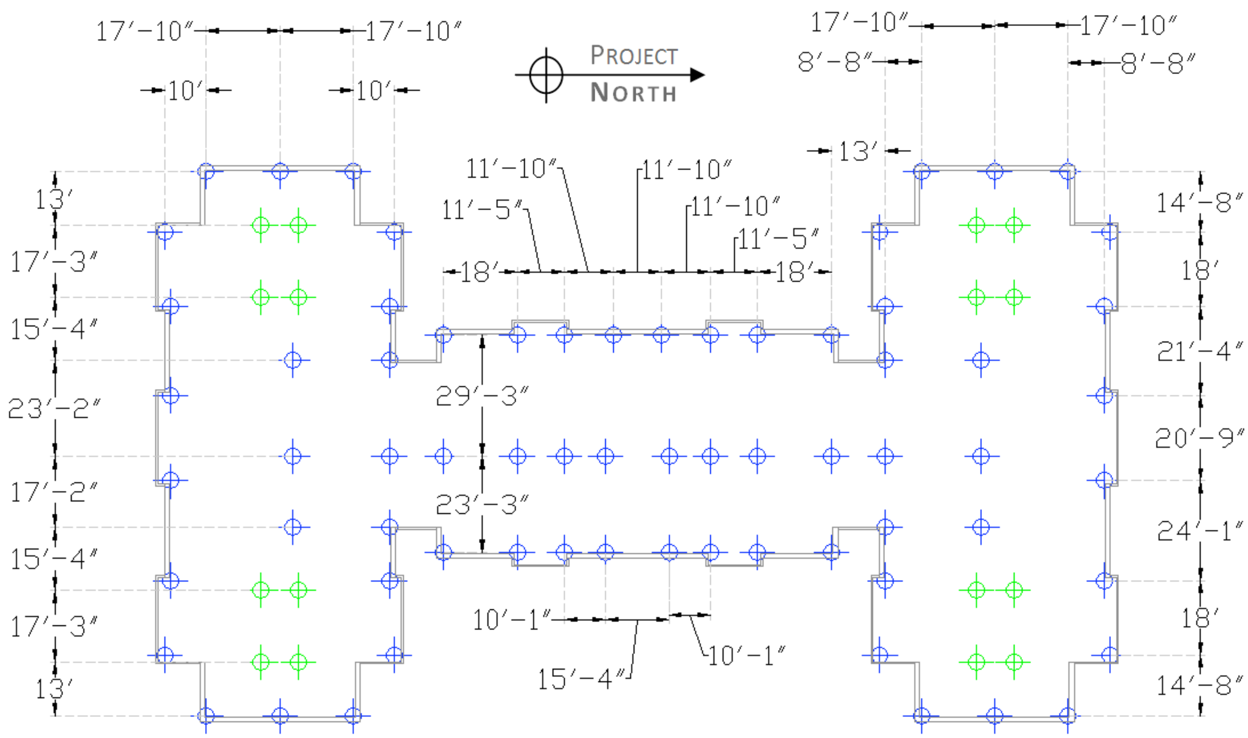


FIGURE 21: COLUMN LOCATIONS (CANNON DESIGN'S LAYOUT, DIMENSIONED)

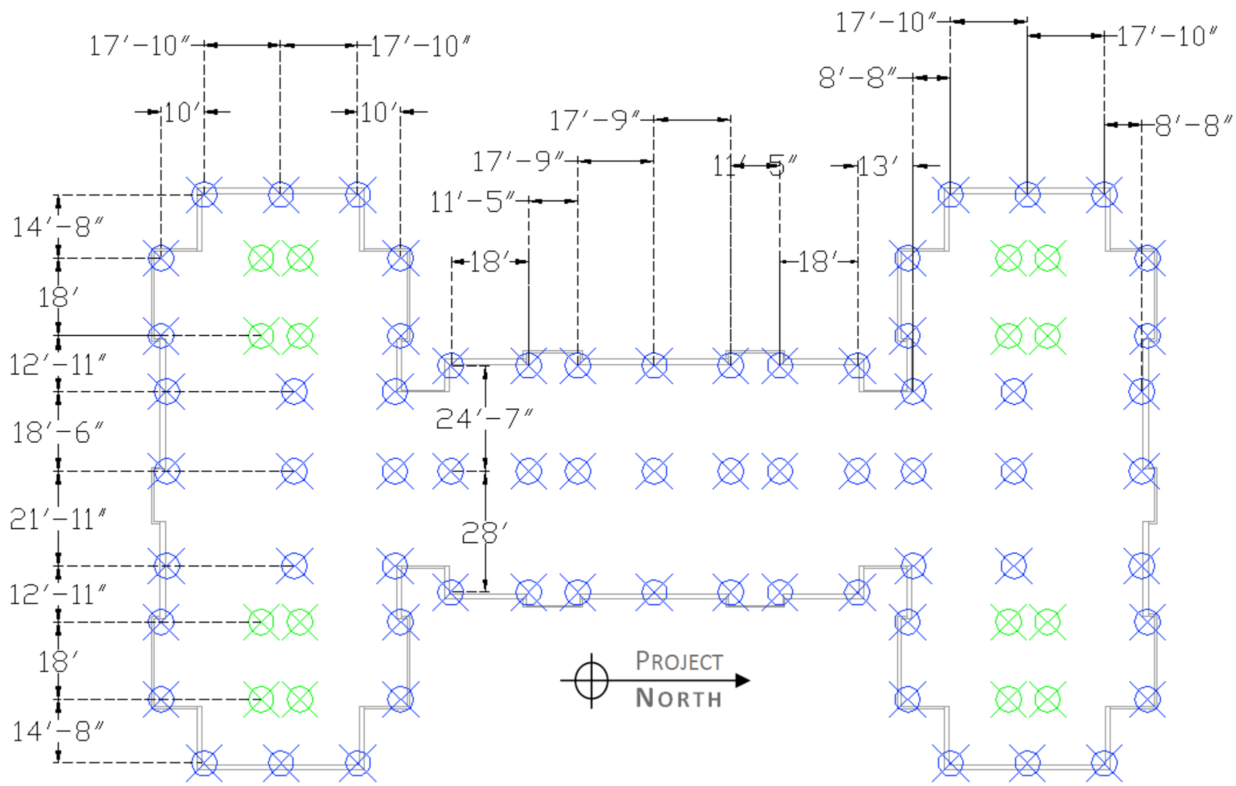


FIGURE 22: SIMPLIFIED COLUMN LOCATIONS (DIMENSIONED)

Figures 26 and 27 show the column locations that were used for structural design. Cannon Design's locations were simplified to create the scheme that was used, taking care not to make changes that would affect the functionality of the building or require major architectural changes. The principle differences are as follows:

- One column was added to each end, north and south, and the spacing of surrounding columns was adjusted in order to provide more consistently sized bays. SEE THE LIGHT BLUE BOX IN FIGURE 23.
- The corner columns of the stairways were adjusted to line up with the adjacent columns. The result was a 5” increase in the east-west length of the stairwell, which does not affect the means of egress or require major architectural changes. SEE THE GREEN BOX.
- The row of columns along the center on the north-south axis was moved approximately five feet to align with the new center column on the ends. These columns will were relocated from one side of the central corridor to the other without requiring changes to the layout of the rooms. SEE THE PINK BOX.

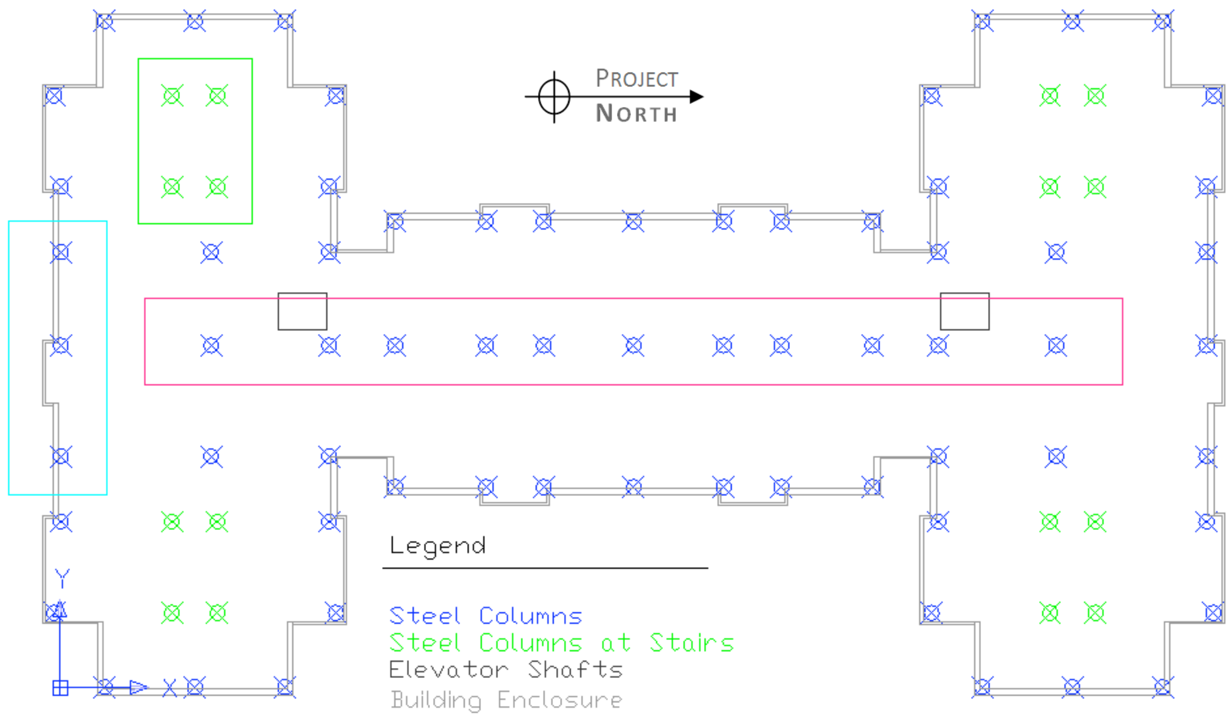


FIGURE 23: SIMPLIFIED COLUMN LOCATIONS (CHANGES HIGHLIGHTED)

Figure 24, following, presents the alphanumeric grid for column locations that was established for reference in the report.

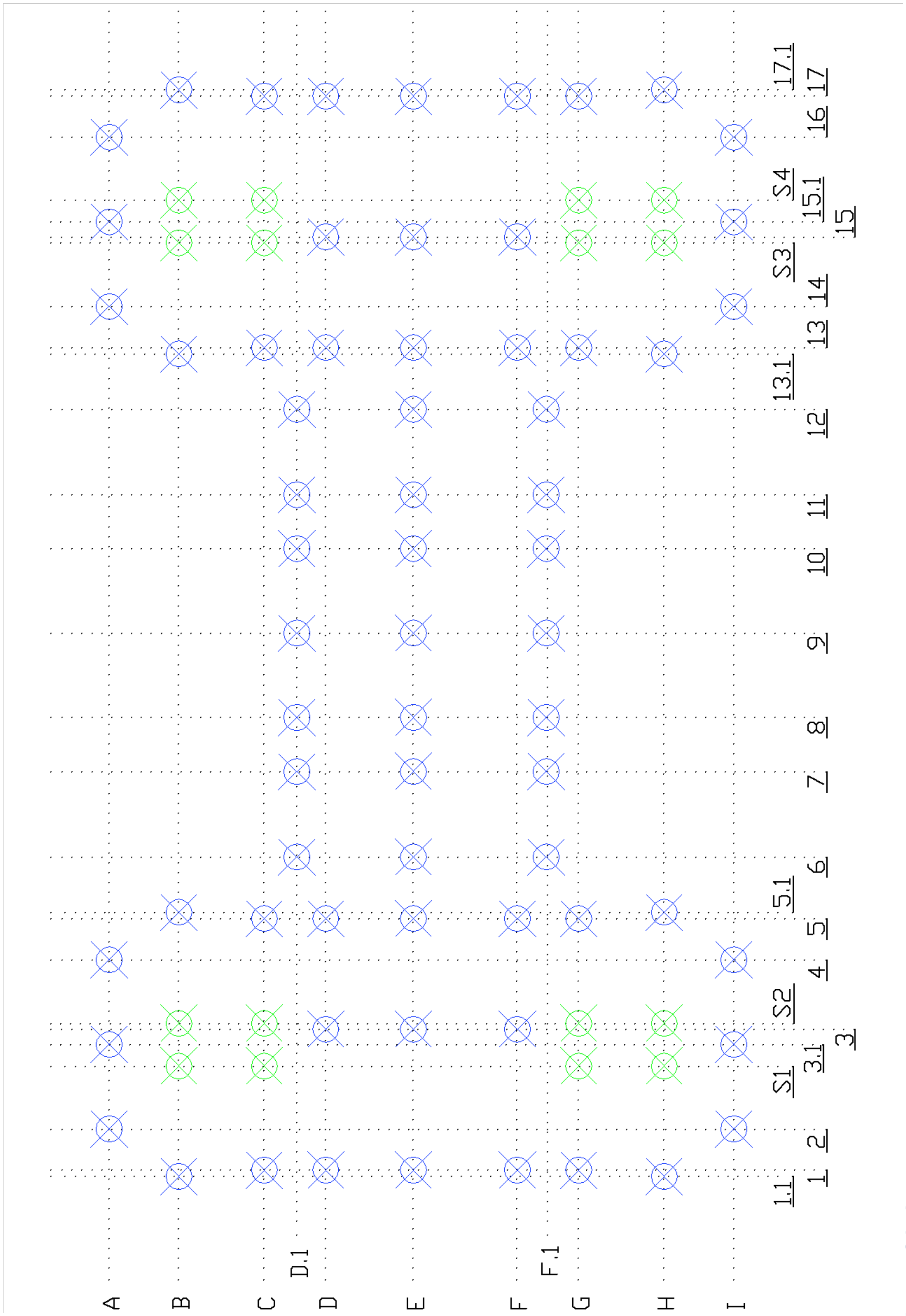


FIGURE 24: ALPHANUMERIC GRID FOR COLUMN LOCATIONS

RESIDENCE HALL UNITS

The residence hall is divided into four main types of units. Figure 25 outlines these units. Each is repeated often throughout the building. Their functions, floor plans, and finishes remain constant throughout the building. These units served as areas of focus for the design of the various flooring systems.

Each type of unit is repeated on floors two through five. Unit types 1 and 3 each contain two apartments and unit 2 contains one apartment. Unit type 4 is reserved for a common lounge, kitchen, and bathroom, and depending on the north or south layout, either a recycling room or a project room.

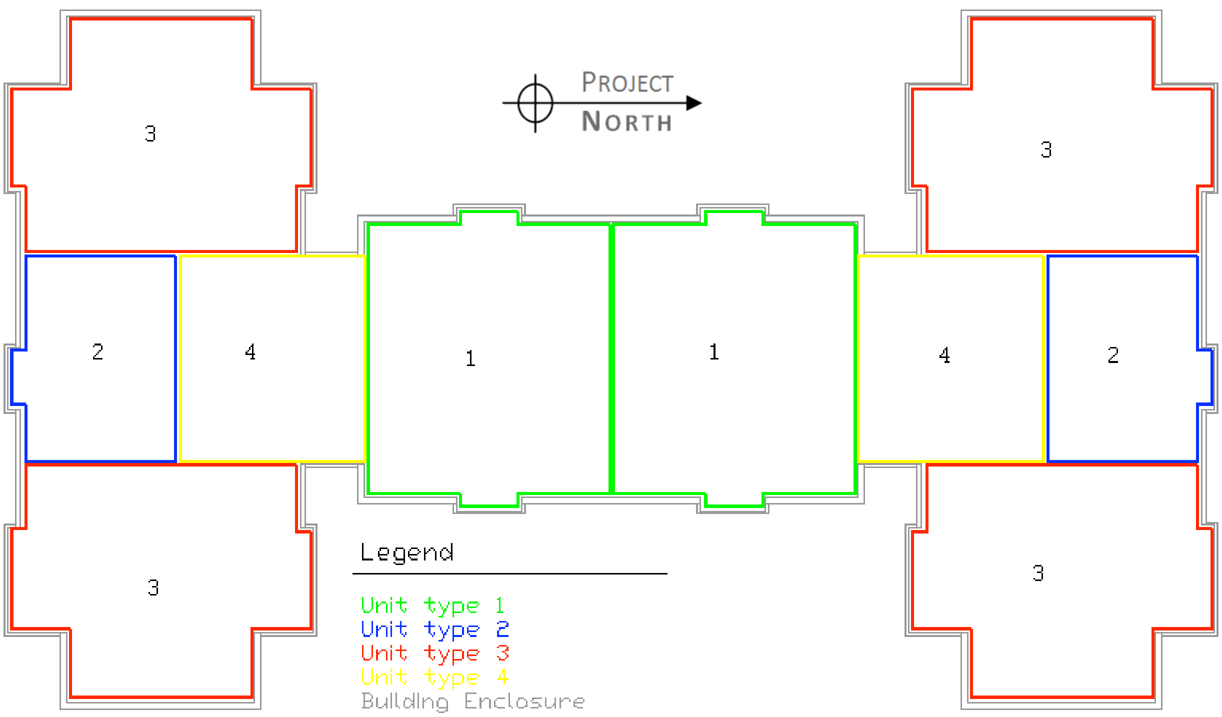


FIGURE 25: UNIT TYPES

As can be seen in Figure 25, units 1, 2, and 4 are symmetrical about the vertical centerline of the building. Units of type 3 are mirrored about both the vertical and horizontal centerlines of the building. This means that there are only four unique areas on which to focus, and the rest are simply repeated.

Figure 26 through Figure 28 provide further detail on each unit (2 and 4 are grouped together), including the distances between columns and girders.

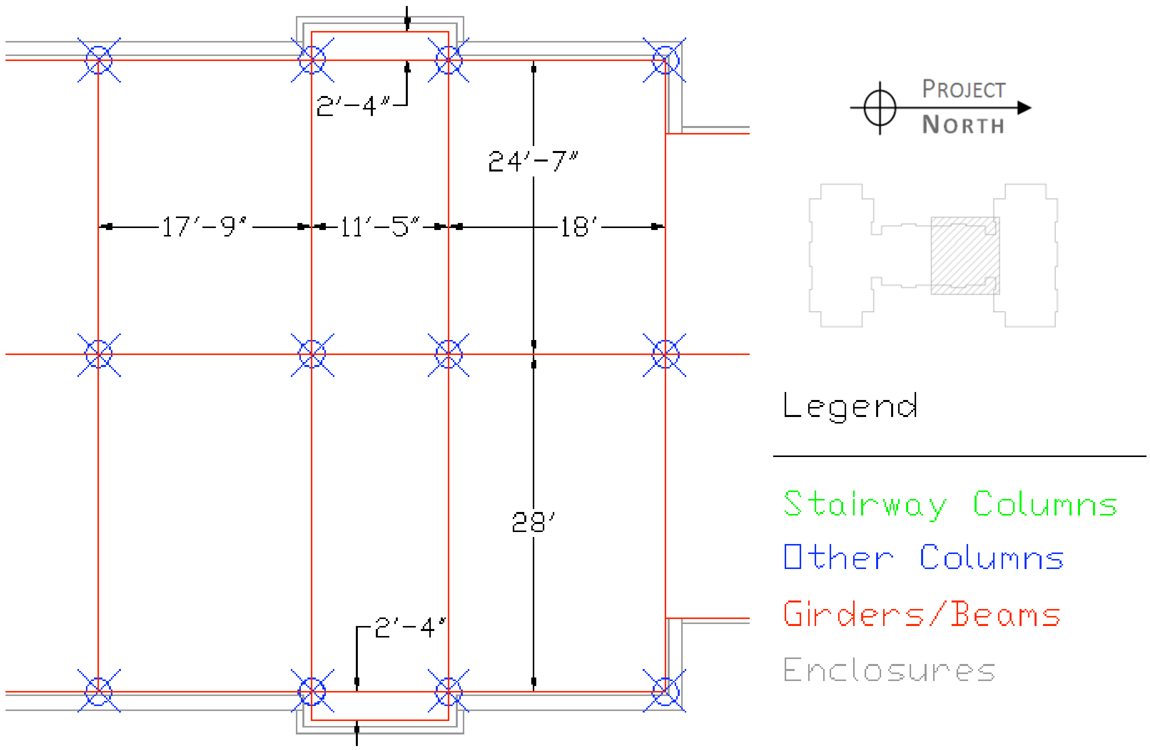


FIGURE 26: UNIT TYPE 1 FRAME DETAILS

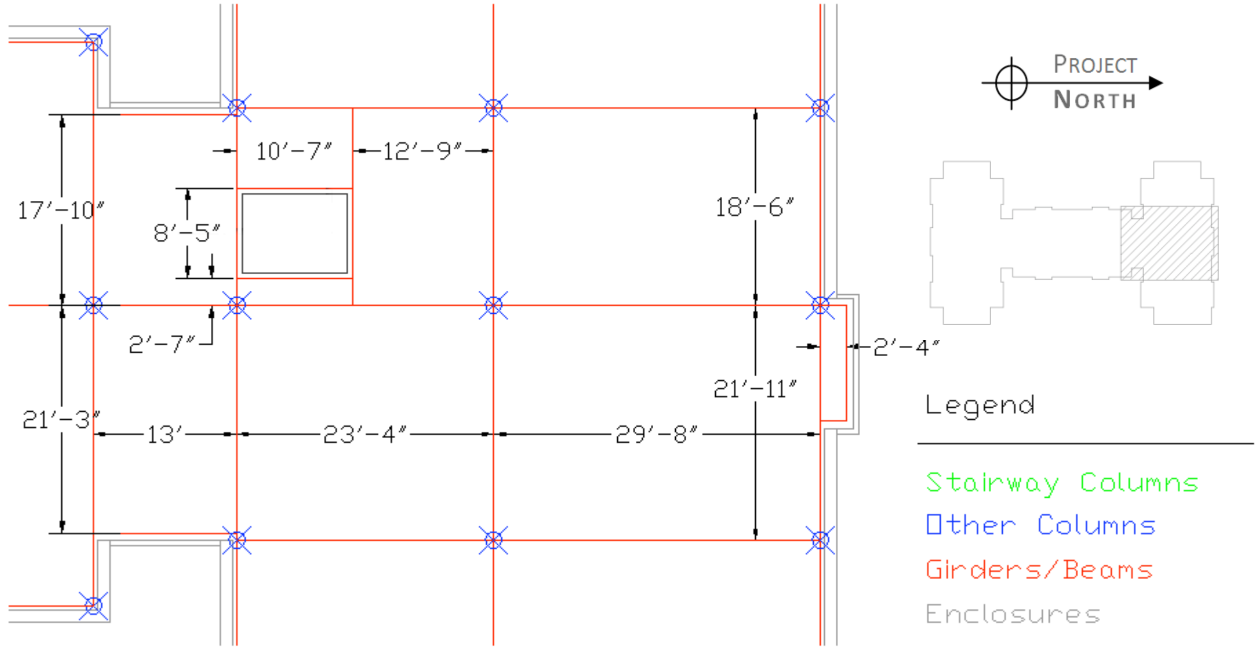


FIGURE 27: UNIT TYPE 2 & 4 FRAME DETAILS

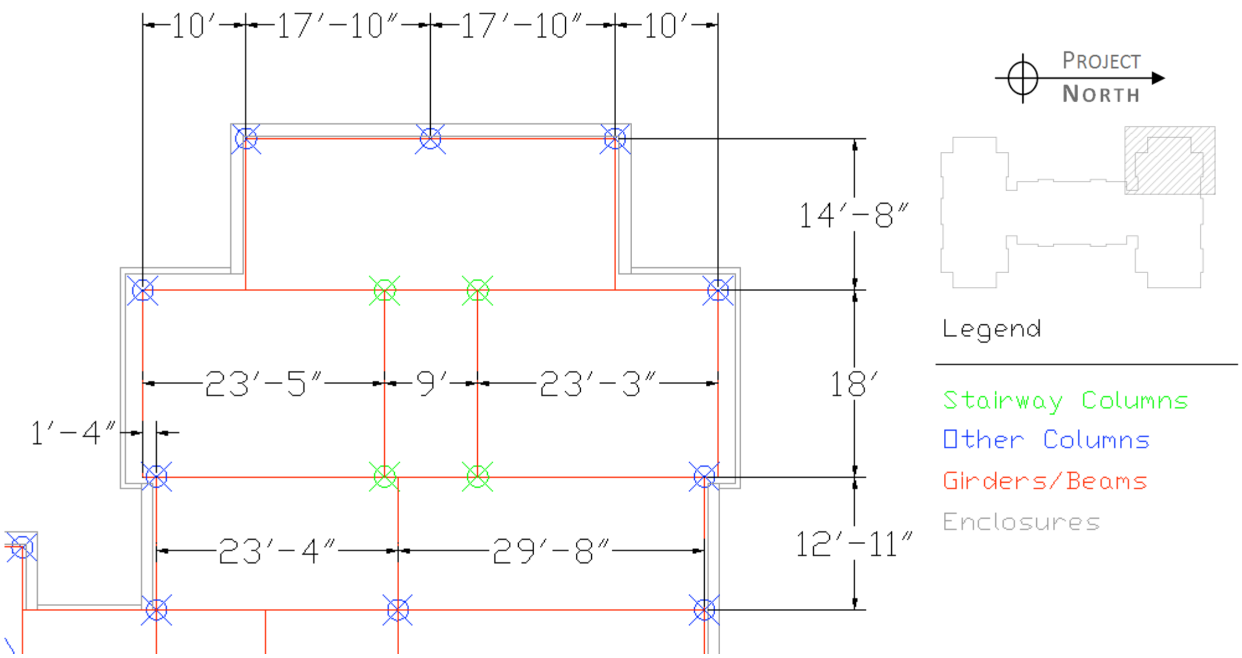


FIGURE 28: UNIT TYPE 3 FRAME DETAILS

Figure 29 shows the beam and girder layout for the entire building to put the individual units in perspective. This layout of the girders is the same for each of the alternate floor systems, though there are differences amongst the various systems. For instance, the precast slabs sit directly upon the girders, and the other concrete floors include secondary beams or joists.

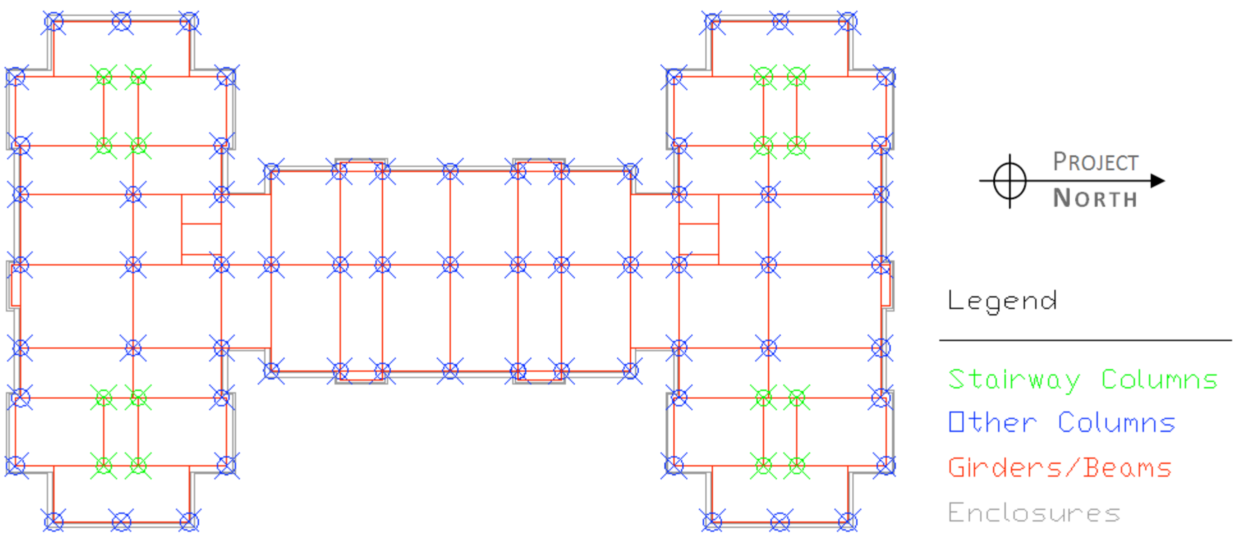


FIGURE 29: FRAME DETAILS (WHOLE BUILDING)

GIRDER DESIGNATIONS

Figure 30 designates a number for each girder in the frame of the new residence hall. They are referred to in the design of girders.

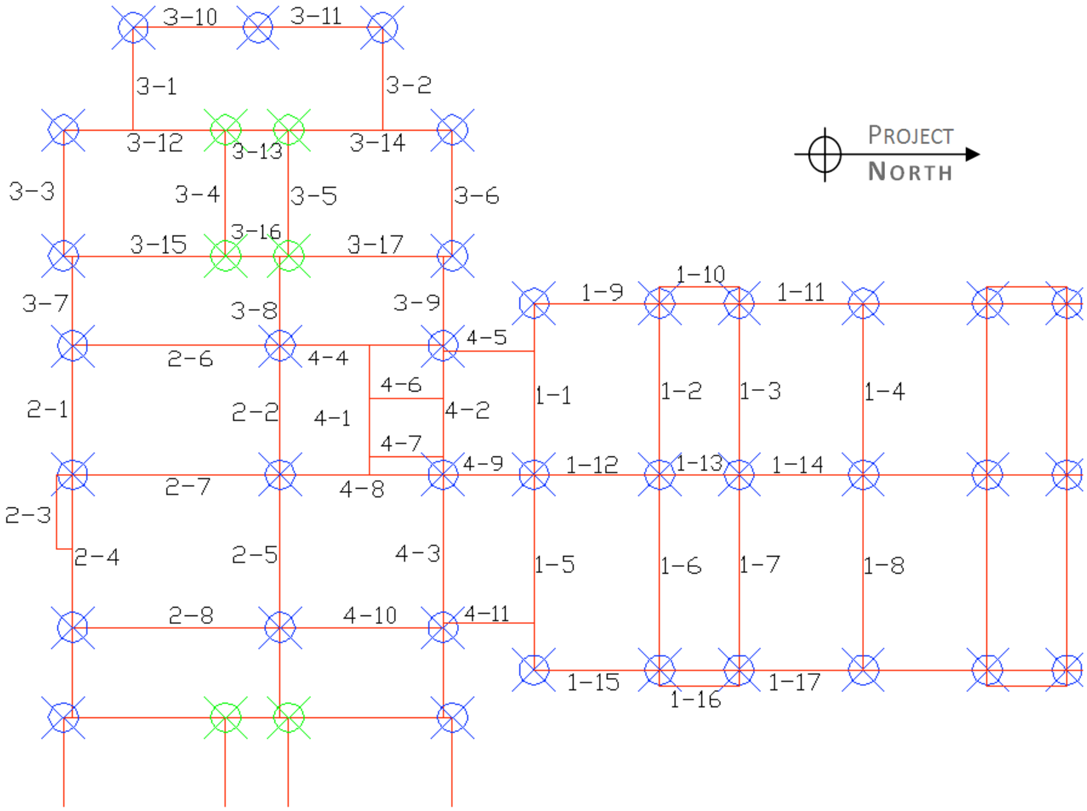


FIGURE 30: GIRDER DESIGNATIONS

BAY DESIGNATIONS

Figure 31 contains the bay designations that are referred to for the design of their infill members. Notice that all are repeated two or four times.

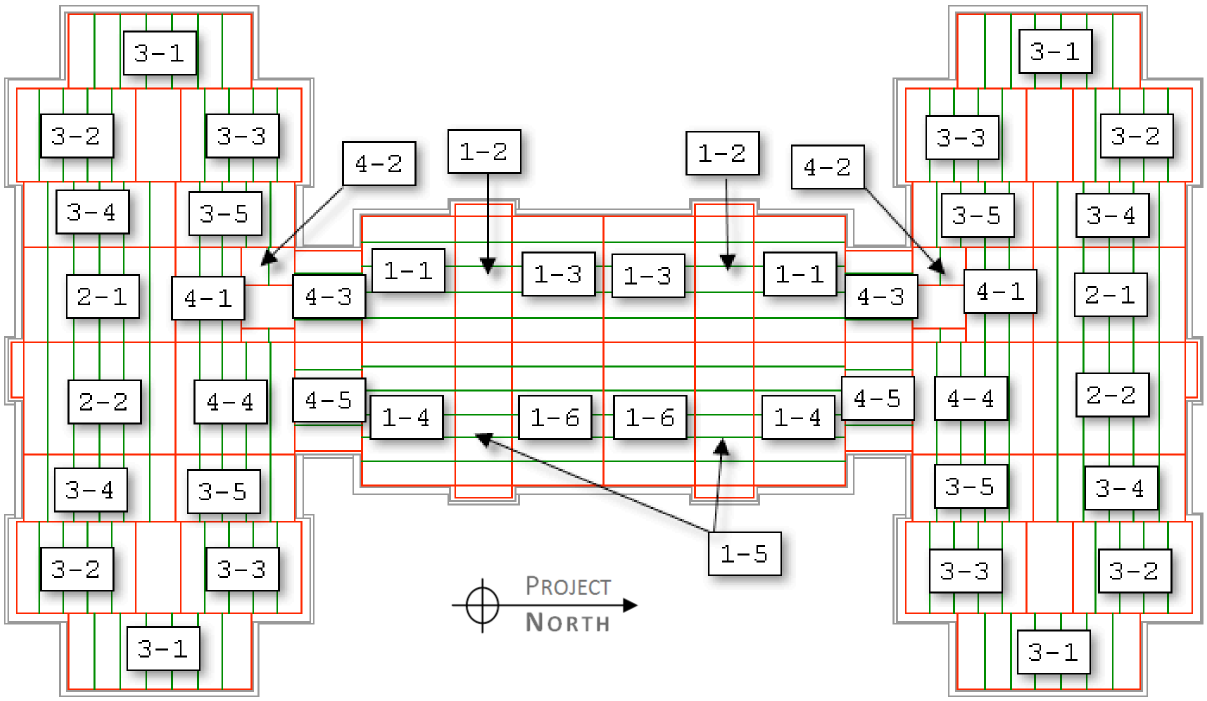


FIGURE 31: BAY DESIGNATIONS

ELEVATION VIEW LAYOUT

Figure 32 depicts a west elevation (from Boynton St.) view of the building. It shows the elevations of the top of the slabs in relation to sea level and in relation to each other, not the location of the girders. The top of steel elevations of the beams and girders will depend on the floor thickness, and will be specified in a later section. The elevation is shown in two parts that are the mirror images of each other. The foremost columns are shown in black, and columns that are set back are shown in gray.

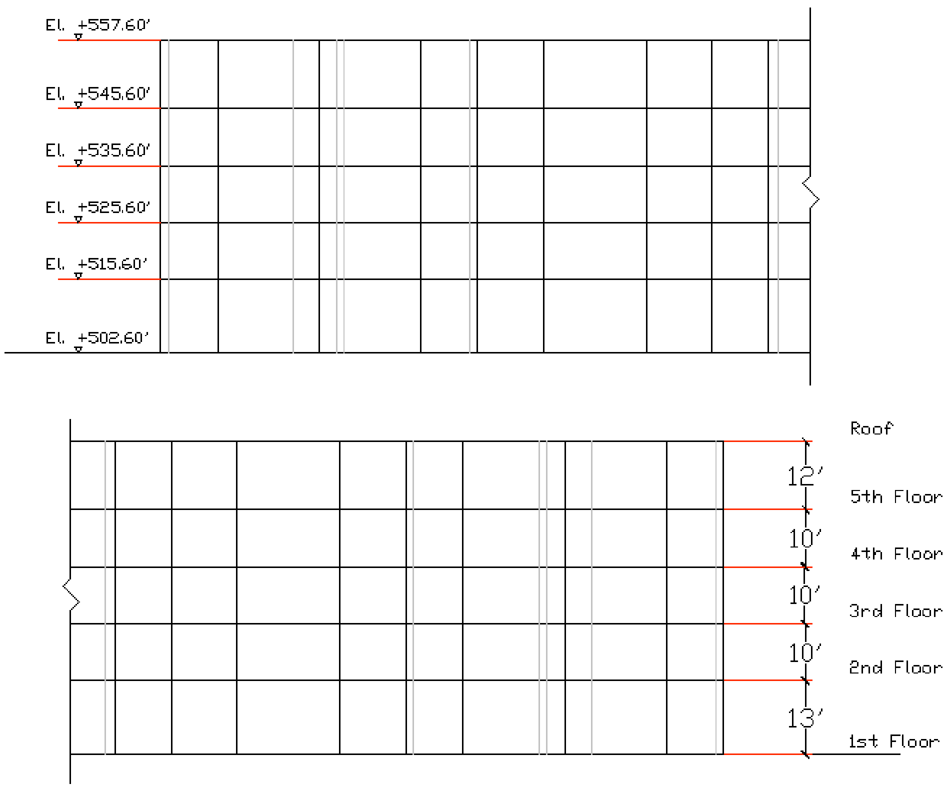


FIGURE 32: WEST ELEVATION WITH TOP OF SLAB ELEVATIONS (SOUTH END ABOVE, NORTH END BELOW)

In this section, the on-center locations of the columns and beams and the top-of-slab elevations were defined. The building was also divided into units which served as areas of focus. Columns, girders, and bays were all assigned designations based on location or unit number. With the location of the primary structural members defined, the next task was to design each of the four alternative floor systems.

FLOOR SYSTEMS

This section guides the reader through the steps involved in the design of each floor system. The four systems investigated were: (1) steel open-web joists with steel form deck and cast-in-place concrete, (2) rolled steel beams with steel form deck and cast-in-place concrete, (3) cast-in-place reinforced concrete slabs, and (4) precast concrete slabs. The design of the precast system was as simple as choosing standard slab sizes from a list based on their service loading, while the other systems required more complicated calculations. The concrete floors and their reinforcement were designed to span certain lengths between beams or joists. Those members were then chosen for adequate strength and deflection.

DESIGN LOADS

Table 2 shows the loads that were used in the design of the floor systems. This includes the live and dead loads which were superimposed on floors two through five. Table 3 contains the load information for each of the four load zones. Note that the mechanical enclosures and green roof loads only act on certain areas of the building. The load information in Tables 2 and 3 was gathered from the construction documents prepared by Cannon Design. Figures 38 and 39, on the next page, accompany these tables and display the areas on which each load type acts.

TABLE 2: SUMMARY OF SUPERIMPOSED FLOOR LOADS

LOAD TYPE	INTENSITY
LIVE LOADS	
Typical rooms	60 psf
Corridors above 1st floor	80 psf
All other public spaces, corridors, stairs and lobbies	100 psf
DEAD LOADS	
Ceilings	5 psf
Suspended mechanical	10 psf
Partitions	20 psf

TABLE 3: SUMMARY OF ROOF LOAD ZONES

LOAD ZONE	LOAD TYPES
ZONE 1	Mech. Enclosure: 50 psf
	Snow: 35 psf
ZONE 2	Snow drift: 35 to 60 psf (linear increase)
ZONE 3	Snow: 35 psf
ZONE 4	Green Roof: 40 psf
	Snow: 35 psf

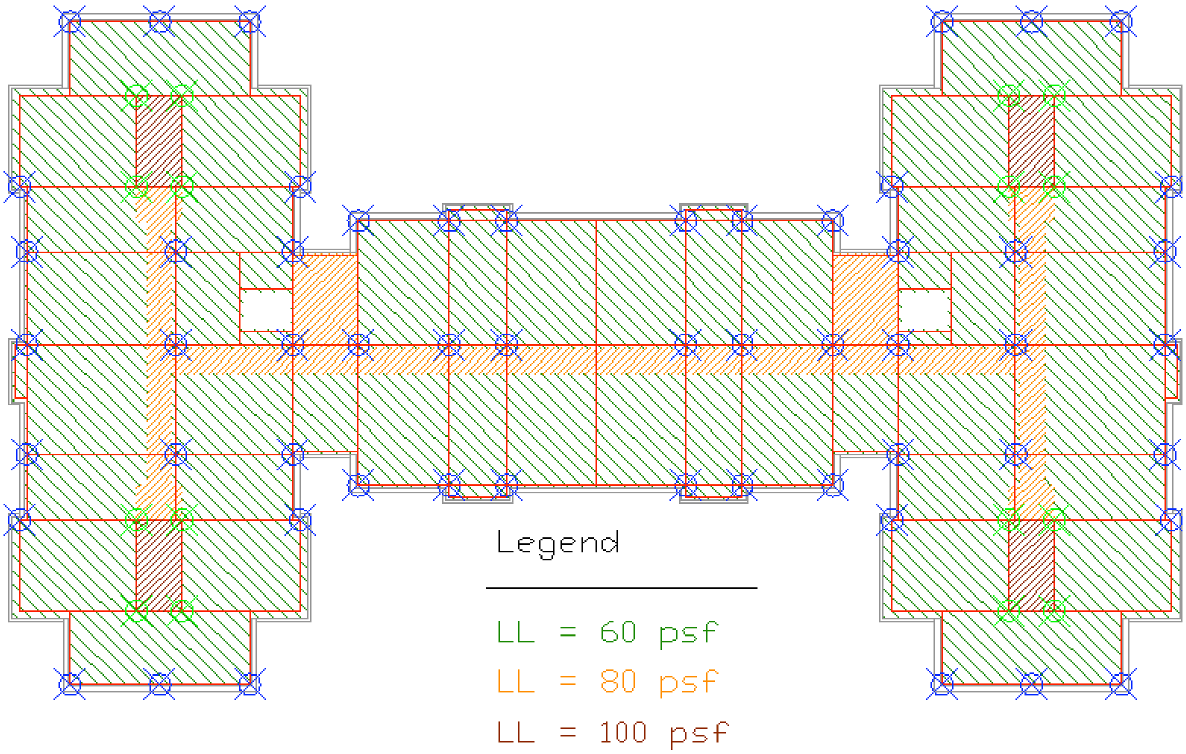


FIGURE 33: LIVE LOADS ACTING UPON THE FLOORS

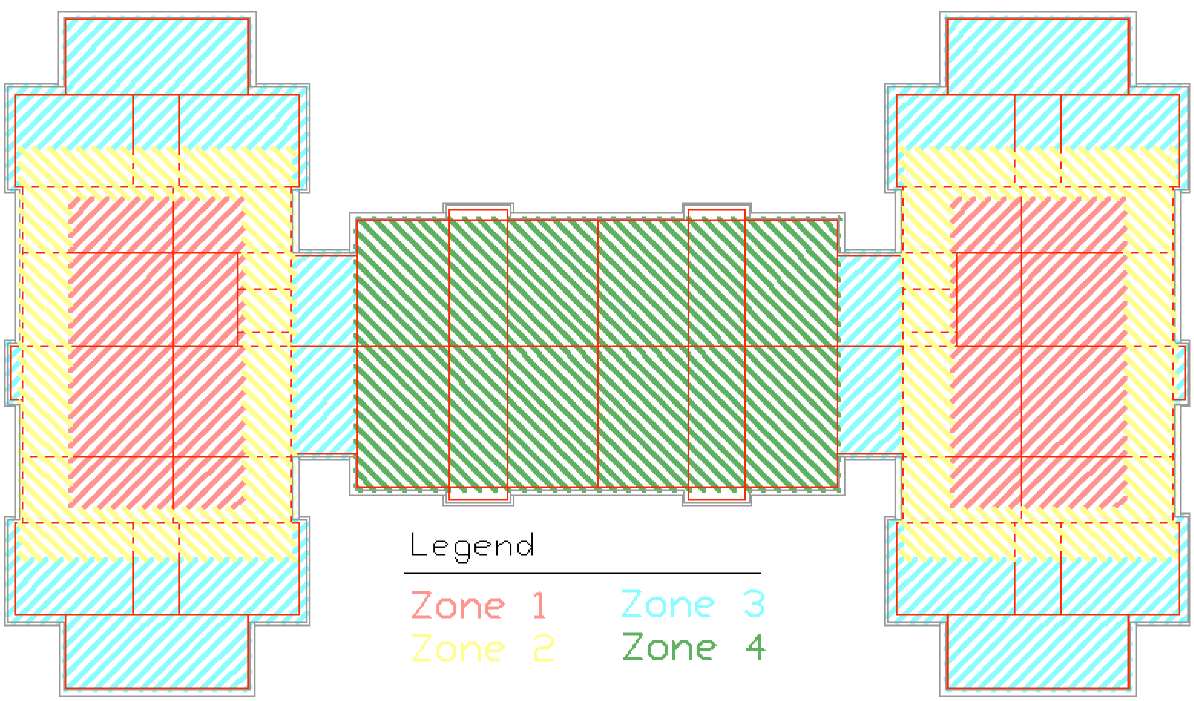


FIGURE 34: ROOF LOAD ZONES

ALLOWABLE SPANS IN STEEL FORM DECKING

Steel form decking is the style of metal decking chosen for this design. It is essentially a stay-in-place form for the casting of the concrete. It provides little to no permanent tension reinforcement because there is little bond between the steel and concrete.

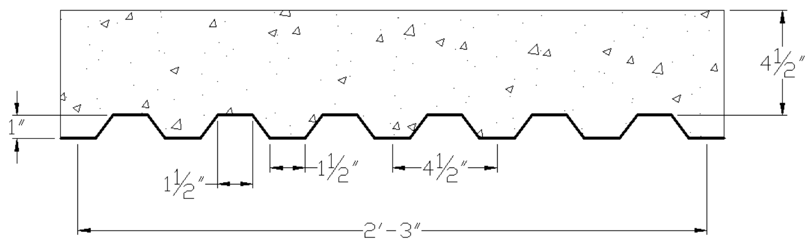
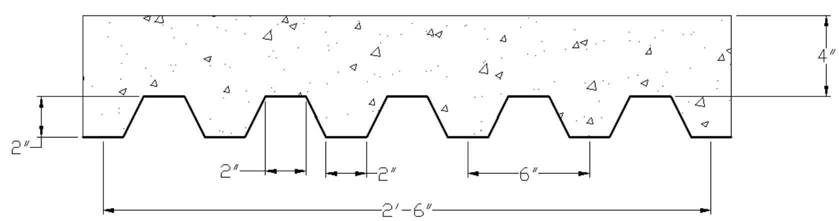
TABLE 4: MINIMUM EQUIVALENT THICKNESSES (STEEL DECK INSTITUTE, 2003)

Concrete Aggregate Type	Minimum eqivalent thickness (inches)* for fireresistance rating (hours)				
	1 hr.	1½ hrs.	2 hrs.	3 hrs.	4 hrs.
Siliceous	3.5	4.3	5.0	6.2	7.0
Carbonate	3.2	4.0	4.6	5.7	6.6
Sand-lightweight	2.7	3.3	3.8	4.6	5.4
Lightweight	2.5	3.1	3.6	4.4	5.1

Typically with steel form deck, the spans are restricted by the deflection of the ribbed sheet metal deck during the casting of the concrete. There are several things that must be considered before determining these allowable spans. To begin with, the required thickness of concrete for fire resistance rating must be determined. From the *International Building Code* (2006), the fire resistance rating for a residential occupancy building must be two hours. This refers to the required barrier between fire areas. These barriers include the floors and the walls surrounding elevators and stairs. Therefore, the effective slab thickness for siliceous concrete (from Table 4) must be at least five inches.

Two more considerations are the weight and style of the steel form deck. The forms used in this design were 20 gauge steel sheet, a common size for this application. The cross-sections of these deck styles are illustrated in their standard widths in Table 5, along with effective depth, moment of inertia, and cross-sectional areas of concrete and steel. Because the widths are unique for each style of deck, the moment of inertia and cross-sectional areas given are for a one foot section of the deck, so that the values for one style can be compared to those for another.

TABLE 5: TYPICAL FORM DECK STYLES.
DIMENSIONS FROM "DESIGNING WITH STEEL FORM DECK" (SDI, 2003).

TYPICAL 1" FORM DECK 	d_{eff} = 5.000"
	$A_{concrete}$ = 60.000 in.^{2}
	A_{steel} = 0.574 in.^{2}
	I = 0.0867 in.^{4}
TYPICAL 2" FORM DECK 	d_{eff} = 5.000"
	$A_{concrete}$ = 60.000 in.^{2}
	A_{steel} = 0.609 in.^{2}
	I = 0.03676 in.^{4}

The next step was to calculate the loads during construction, and from there, the allowable spans of the form decks during casting of the concrete. Table 6 shows the dead loads during construction. They are given as pounds per linear foot for a one foot slice along the span of the deck.

The allowable spans were calculated for each of two typical patterns, 1" standard deck and 2" standard deck. In order to calculate the allowable lengths, the moment of inertia of the deck along its neutral x-axis was first calculated. This moment of inertia, along with the loading during construction, and the modulus of elasticity of steel were used to determine the maximum permissible span which would keep the deflection under L/240. The allowable span during construction for a 1" deck was calculated to be 5'6". This is assuming the deck is continuous over at least three consecutive spans, which is satisfied in all areas of the building. For 2" deck the span was found to be 8'10".

TABLE 6: CONSTRUCTION LOADS FOR STEEL FORM DECK

Deck Type	Concrete Load[14] (plf)	Deck Load[15] (plf)	Rounded W_{total} (plf)
1"	62.5	2.0	65
2"	62.5	2.1	65

Using the allowable deck spans as a reference, the spacing of joists and in-fill beams was determined. Brief calculations showed that a relatively short deck span of about 3 feet was necessary for the joist system. This decision was made in order to keep the depth of the joists down to 18" or less. This was done to make sure that the overall floor depth was less than 2'6", which will allow the floor to ceiling height to remain above 7'6". Consequently, the typical 1" form was chosen. For the rolled steel beams, slightly longer deck spans were desired in order to reduce the number of beams. This is possible because they can carry a greater load than open-web joists of the same depth. For this application, the 2" deck form was chosen, allowing spans of 8.9 feet. The following sections take the reader through the remaining steps involved for the design of the joist and beam floor systems. This includes determining spacing, selection of reinforcement, and choice of member sizes.

METAL DECK AND CONCRETE ATOP OPEN-WEB JOISTS

The next step toward completion of the open-web joist design was spacing the joists so that the maximum spacing for form decking spans was not exceeded. Figure 35 shows a plan view of floors two through five with the specified joist locations used to design the floor system. Table 7 summarizes the number of joists and their spacing by bay.

[14] The concrete loads were determined using density of concrete = 150 pcf

[15] The deck loads were calculated using density of steel = 490. pcf

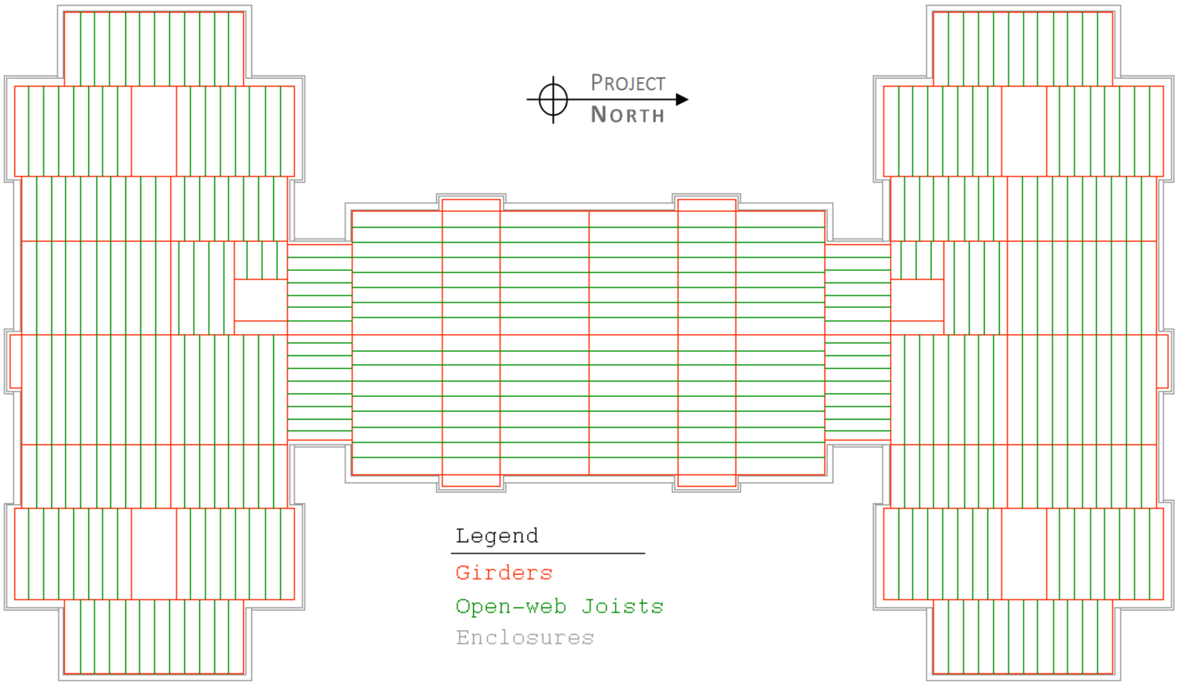


FIGURE 35: OPEN-WEB JOIST LAYOUT (ENTIRE BUILDING)

On the north and south ends of the building, the joists run in the east-west direction. This means the stiffness of the deck and slab runs along the north-south axis. The opposite is true in the central section.

TABLE 7: SPACING OF JOISTS

Bay #	# of Joists	Span	Spacing	Bay #	# of Joists	Span	Spacing
1-1	7	18’	3’	3-2	7	18’	3’
1-2	7	11’5”	3’	3-3	7	18’	3’
1-3	7	17’9”	3’	3-4	7	12’11”	3’
1-4	8	18’	3’1”	3-5	9	12’11”	3’
1-5	8	11’5”	3’1”	4-1	4	18’6”	3’
1-6	8	17’9”	3’1”	4-2	3	6’10”	3’
2-1	9	18’6”	3’	4-3	6	13’	2’6”
2-2	9	21’11”	3’	4-4	7	22’11”	3’
3-1	11	14’8”	3	4-5	8	13’	2’6”

The next step was to verify the adequacy of the thickness of the slab and to compute the required area of steel and determine proper reinforcement. For this procedure, the 1" deck with 4.5" concrete topping (total depth of 5.5") was modeled as a 4.5" thick balanced section of concrete. The concept of a balanced section means that the limit states of the concrete and reinforcing steel will reach their limit states at the same loading conditions. The design process of concrete slabs uses a system of load and resistance factors, employing moment and shear coefficients specified by the American Concrete Institute (ACI). All calculations can be seen in Appendix B.

The conclusion drawn from these calculations was that the required temperature and shrinkage steel for the joist system governed in both directions. This area is 0.108 in^2 per foot of slab.

With the required area of steel determined, the steel product was selected. For this application, with small areas of steel and the similar requirements in each direction, welded wire reinforcement (WWR) is the most suitable choice. From the Wire Reinforcement Institute's *Manual of Standard Practice*, it was found that two sheets of 6" x 6" - W2.9 x W2.9 WWR will yield an area of steel of 1.16 in^2. The weight for each wire is 0.170 plf, resulting in a total weight of 0.680 pounds per square foot of floor area. One sheet will be placed near the bottom of the slab, and one near the top, providing adequate cover of ¾" to resist surface cracking.

The following is a summary of the floor system's characteristics:

- Deck: 20 gauge A36 steel sheet, 1" typical form deck, 2.0 psf.
- Concrete: 5½" total depth, 3000 psi, normal weight concrete, 63.0 psf.
- Reinforcement: Grade 60 steel welded wire reinforcement, 2 sheets of 6" x 6" W2.9 x W2.9, less than one pound per square foot.

The design of the joist system was concluded with selection of member sizes based on the factored dead and live loads and the spacing and spans given in Table 7. The process of joist selection was as simple as computing the factored load per linear foot of the joist and choosing a suitable member based on this load and the span from the LRFD Design Tables provided by the Steel Joist Institute (SJI). Table 8 details the chosen joist sizes for each bay. The suffix "a" after a bay number means there is one member in that bay under a corridor which requires additional support. The corresponding joist shape is that unique member.

TABLE 8: JOIST SELECTION (FLOOR)

Bay Number	Joist Designation	Bay Number	Joist Designation
1-1	12K5	2-2a	16K7
1-2	10K1	3-1	12K3
1-3	12K5	3-2	12K5
1-4	12K5	3-3	12K5
1-4a	14K4	3-4	10K1
1-5	10K1	3-5	12K1
1-6	12K5	4-1	12K5
1-6a	14K4	4-2	8K1
2-1	12K5	4-3	10K1
2-1a	14K6	4-4	16K6
2-2	16K5	4-5	10K1

The roof presents a special case in the joist system design. To more adequately support the varying loads of the mechanical enclosures and snow drifts, joists were used only under the green roof section of the building, and rolled steel beams were chosen to span the bays of the north and south ends. Table 9 contains the chosen member sizes for all bays of the roof. For more information on how W-shape beams are chosen, refer to the next section.

TABLE 9: MEMBER SELECTION FOR JOIST SYSTEM (ROOF)

Bay Number	Member Shape	Bay Number	Member Shape
1-1	12K5	3-2	W10x15
1-2	8K1	3-3	W10x15
1-3	12K5	3-4	W10x12
1-4	12K5	3-5	W10x12
1-5	8K1	4-1	W10x17
1-6	12K5	4-2	W10x12

2-1	W10x22	4-3	8K1
2-2	W10x22	4-4	W10x22
3-1	W10x12	4-5	8K1

METAL DECK AND CONCRETE ATOP ROLLED STEEL BEAMS

The design process was much the same for steel beams as it was for open-web joists. Figure 36 illustrates the locations of beams on floors two through five.

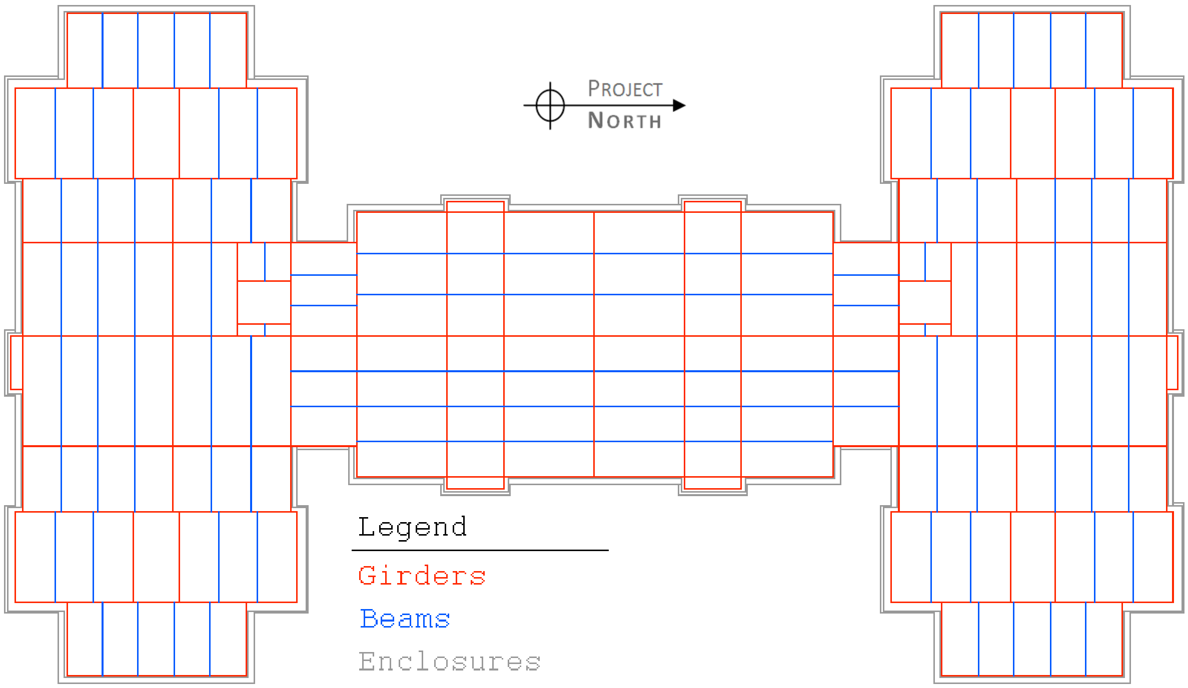


FIGURE 36: BEAM LAYOUT (ENTIRE BUILDING)

Table 10 documents the chosen spacing of the beams. The bays to which the table refers were designated in Figure 31.

TABLE 10: BEAM SPACING

Bay #	# of Beams	O.C. Spacing	Bay #	# of Beams	O.C. Spacing
1-1	2	98”	3-2	2	93”
1-2	2	98”	3-3	2	94”
1-3	2	98”	3-4	3	89”
1-4	3	84”	3-5	2	94”
1-5	3	84”	4-1	1	N/A*
1-6	3	84”	4-2	1	63”
2-1	3	89”	4-3	2	71”
2-2	3	89”	4-4	2	94”
3-1	4	86”	4-5	2	84”

*This beam is not centered, but is located 94” from one girder, and 61” from the other.

The process for determining requirements for reinforcement is the same as with the joist system. The requirement for temperature and shrinkage is dependent upon the cross sectional area of concrete. Therefore, since the area of concrete for the 1” deck and 2” deck are identical, so is the required steel, 0.108 in^2. Testing the thickness of the deck for deflection, moment, and shear, as was done for the joist system, the effective thickness of 5” was found to be adequate. Also, the cantilever area did not change at all from the joist system, so temperature requirements governed in those areas.

Due to the longer deck spans between steel beams, a more in-depth study of the required reinforcement was necessary. This allowed the specification of different types of WWR for the different major areas of the building. By specifying two different types of WWR, over-reinforcing of the slabs could be avoided, lowering the associated cost. A spreadsheet was utilized to determine the most critical areas.

In the top and bottom of the “I” (column locations 1 through 5 and 13 through 17 from Figure 24), where the spans run along the north-south axis, there are several areas whose required steel exceeds that for temperature and shrinkage. The most critical area was found to be in unit type 3 where the negative moment above a support adjacent to a discontinuous end (moment factor of -1/10) was found to be -1,522 ft-lbs. The corresponding area of steel required is 0.246 in^2. Similar numbers were found throughout the north and south ends, so the same gauge wire was used for those entire areas. Size W9.0 wire yielded an area of 0.270 in^2 per foot when laid at 4” intervals, which will suffice for this application. For the transverse direction, W4.0 size wires at 4” yielded an area of $0.120in^2$, enough to satisfy the criteria for temperature and shrinkage.

In the trunk of the “I” (columns 5 through 13 from Figure 24), where the spans run east-west, the governing requirement occurs above a support adjacent to a discontinuous end as well. This moment was calculated to be -1,470 ft-lbs, and required a steel area of 0.238 in^2. Wire size W8.0 laid at 4” yields 0.240 in^2, providing the necessary reinforcement, and once again wire size W4.0 wires should be laid at 4” intervals for shrinking of the concrete in the transverse direction.

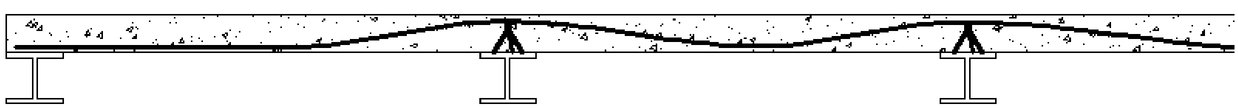


FIGURE 37: WELDED WIRE REINFORCEMENT DRAPING DIAGRAM (TYPICAL AREAS)

Because of the greater distance between the beams, the welded wire reinforcement can be draped instead of using two sheets. The *International Building Code* allows wire reinforcement to be placed at the top of slab above the supports and at the bottom of slab at mid-span, for spans under 10 feet. The draping of the WWR is illustrated in Figure 37. In the negative moment regions, a cover of ¾” must be maintained, but in all maximum moment areas the distance from steel to extreme compression fibers should be at least the design depth, 3.25”. This style of draping in Figure 37 was only used for the typical areas with no cantilever. In the cantilever areas, there is a negative moment above the end support, requiring the reinforcement to be raised, as in Figure 38.

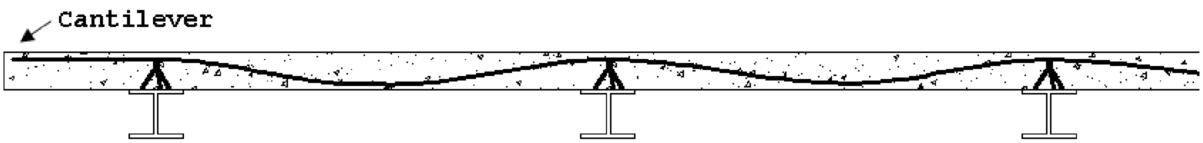


FIGURE 38: WELDED WIRE REINFORCEMENT DRAPING DIAGRAM (CANTILEVER AREAS)

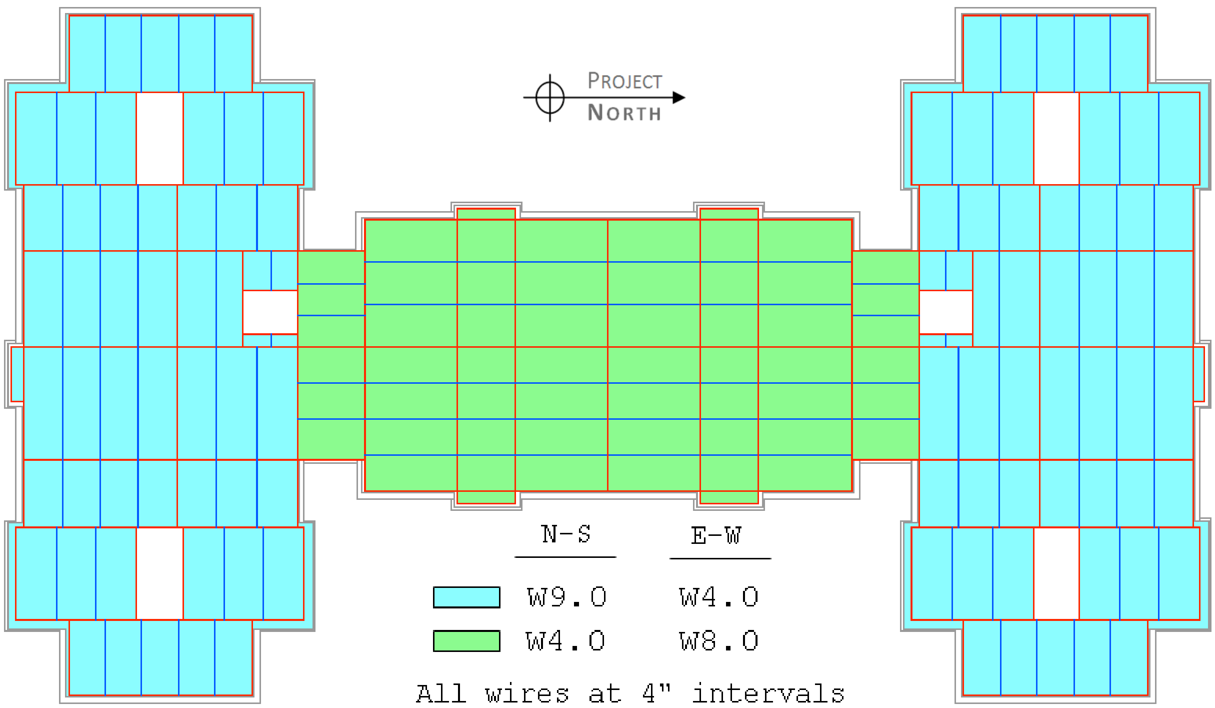


FIGURE 39: WELDED WIRE REINFORCEMENT SIZES FOR BEAM FLOOR SYSTEM

Here is a summary of the characteristics of the floor system on top of the beams:

- Deck: 20 gauge A36 steel sheet, 2" typical form deck, 2.0 psf.
- Concrete: 6" total depth, 3000 psi, normal weight concrete, 63.0 psf.
- Reinforcement: Grade 60 steel WWR, W9.0, W8.0, and W4.0 wires (see Figure 39 for location information) at 4" in both transverse and longitudinal directions.

The infill beams required for each bay were then designed. This process was more complicated than the selection of joists in several ways. The beams will be working in partial composite action with the concrete slab by means of shear studs welded to the beams, whose number will be kept down as low as possible for cost effectiveness. So for each beam the strength and serviceability during construction must be adequate, as well as the strength and serviceability of the composite system during service. Refer to Appendix B for a sample of the calculations used to determine beam size and number of studs. Table 11 contains the selected beam size and number of studs per beam for each structural bay of the floors, and Table 12 contains those chosen for the roof.

TABLE 11: BEAM SELECTIONS (FLOOR)

Unit	W shape	Studs per beam	Unit	W shape	Studs per beam
Unit 1-1	10 x 19	12	Unit 3-2	10 x 17	10
Unit 1-2	10 x 12	8	Unit 3-3	10 x 17	10
Unit 1-3	10 x 17	10	Unit 3-4	10 x 12	8
Unit 1-4	10 x 17	10	Unit 3-5	10 x 12	8
Unit 1-5	10 x 12	8	Unit 4-1	10 x 12	8
Unit 1-6	10 x 15	10	Unit 4-2	10 x 12	8
Unit 2-1	10 x 19	12	Unit 4-3	10 x 15	10
Unit 2-2	12 x 26	12	Unit 4-4	10 x 12	8
Unit 3-1	10 x 12	8	Unit 4-5	12 x 26	12

TABLE 12: BEAM SELECTION (ROOF)

Unit	W shape	Studs per beam	Unit	W shape	Studs per beam
Unit 1-1	10 x 19	12	Unit 3-2	10 x 15	10
Unit 1-2	10 x 12	8	Unit 3-3	10 x 15	10
Unit 1-3	10 x 19	12	Unit 3-4	10 x 12	8
Unit 1-4	10 x 17	10	Unit 3-5	10 x 12	8
Unit 1-5	10 x 12	8	Unit 4-1	10 x 17	10
Unit 1-6	10 x 17	10	Unit 4-2	10 x 12	8
Unit 2-1	10 x 22	10	Unit 4-3	10 x 12	8
Unit 2-2	10 x 22	10	Unit 4-4	10 x 22	10
Unit 3-1	10 x 12	8	Unit 4-5	10 x 12	8

CAST-IN-PLACE CONCRETE ATOP ROLLED STEEL BEAMS

Cast-in-place floors involve using plywood or a similar material as a temporary form for the concrete until it can support its own weight. In our design, the floor will rest upon steel beams in the same configuration as the previous section. This configuration makes the cast-in-place system nearly identical to the cast-in-place concrete and metal deck upon rolled steel beam design. The concrete must still have an effective depth of 5" thick for fire resistance, but because there is no corrugation, the total depth can be kept at 5". The weight of the concrete is the same (the average depth of the metal deck system is 5"), and the superimposed loads and span lengths are the same, meaning the amount of required reinforcement is also the same. The following is a summary of the characteristics of the system:

- Concrete: 5" total depth, 3000 psi, normal weight concrete, 63.0 psf.
- Reinforcement: Grade 60 steel WWR, W9.0, W8.0, and W4.0 size wires (see Figure 39 for location information) at 4" in both transverse and longitudinal directions.

PRECAST CONCRETE SLABS

The type of precast slab used for this design was hollow-core slabs. Hollow-core slabs have voids in various shapes in the low stress central regions. These voids decrease the weight and allow longer spans. Hollow-core slabs have pre-stressed strands about 1½" from the bottom of the slab. They are typically topped with cast-in-place concrete in order to increase strength, fire resistance, and diaphragm action, and to negate the camber of pre-stressed members.

The dilemma when designing a hypothetical system using precast elements is that the companies who manufacture precast elements often use proprietary designs and provide their allowable spans to architects and engineers who are designing a building with their products. Since access to these proprietary values was not available, tables for simple, non-proprietary hollow-core slabs from the *PCI Design Handbook* (1999) were used.

The maximum span between girders across which the precast elements are laid is under 22'. The maximum superimposed load is 115 psf in the corridors. From brief reference to the design tables in the *PCI Design Handbook* (1999), it was determined that a slab depth of 6" with 2" concrete topping would support the maximum load at the greatest span. Another consideration is fire safety. The fact that there is at least 4” of solid concrete and another 4” of concrete with circular voids suggests that there should be no problem achieving a two hour rating, considering the 5” solid concrete slab requirement from Table 4. To determine actual fire resistance, the providing manufacturer would have to be contacted. Even if the two hour rating is not achieved solely through the concrete, additional measures can be taken such as the addition of a fire-proofing material to the underside or the inside of the cores.

While the thickness remains constant throughout the building, the number and diameter of strands in the elements vary. The reason for this is not only economic, but if there are too many strands, the pre-stressing will be too great, causing an unacceptable camber. Conversely, if the strength is adequate, but the estimated camber is “too negative”, the strands may be increased to produce a more suitable deflection.

The precast slabs span from girder to girder in the same direction as the beams and joists in the previous sections. That is, they span N-S in the central part of the building, and E-W in the top and bottom of the “I”. For most of the spans of hollow-core and solid flat slabs, the strand designation 66-S (that is, six strands at six sixteenths of an inch in diameter, S for straight) was sufficient. For a few of the spans, additional strands of reinforcement were required. The full summary of the loads, strand designations, and estimated cambers for each span can be found in Appendix C: Table 30. The information needed for those tables was retrieved from the *PCI Design Handbook* (Precast Concrete Institute, 1999).

There is one area of the building in unit type 3 where the precast slabs will need to cantilever out beyond the girder, causing a negative moment in the slab. Typically, precast slabs contain reinforcement in the bottom area only, which can only resist the tension caused by positive moments. These negative moment regions require a couple of changes to be made. Grade 60 reinforcing steel is added to the top of the slab, and the voids for hollow-core slabs are filled in those areas only (Seraderian, 2007).

FRAME DESIGN FOR GRAVITY LOADS

For each of the four floor systems, a unique frame was designed. The frame for gravity loads encompasses all girders and columns supporting the building. For the three cast-in-place floor systems, the design of the girders was performed by the same process as the rolled steel infill beams. They must perform adequately during construction as well as in composite action with the cured concrete floor. For the precast floor slabs, the process was much the same, but no composite action was considered. The following four sections discuss the design methods used and detail the most critical areas for each of the four floor systems.

METAL DECK AND CONCRETE ATOP OPEN-WEB JOISTS

The girders that span through the building from the exterior walls act as the main supports for the design loads and are the most critical. The largest girders can be found in Unit 2 near the common areas and elevator shafts. These girders span about 30' and their deflection under service loading dictates their size. All girders which run perpendicular to the main supporting girders act like regular floor beams in this system, and therefore are significantly smaller. They provide support for the floor loads and the exterior walls

The critical area on the roof is under and around the mechanical enclosures. These girders must not only support a mechanical equipment load but a drift load due to snow. The green roof also adds a significant load in the middle of the building, so the girders in Unit 1 will be larger than those selected for the floor system. The girders running along the exterior of the building are relatively small since they support a small tributary area and don't experience large loads.

Table 37 in Appendix C summarizes the chosen column sizes for the frame supporting the joist system. The column designations refer to the alpha-numeric grid in Figure 24. Unique sizes were chosen for floors 1 & 2, 3 & 4, and 5. The column sizes specified are for half of the structure. All columns not in the alpha-numeric grid line number 9 are also mirrored about that line.

Designing the columns entailed determining the axial loading of the member and using the effective length to choose a properly sized member from chapter four of the *AISC Steel*

Construction Manual. Most columns are typical W shapes, but the columns surrounding the staircases were chosen to be hollow square columns, in accordance with the original design by Cannon Design. Their designations start with HSS. The first and second numbers are the nominal dimensions, and the final number is the nominal thickness of the section.

METAL DECK AND CONCRETE ATOP ROLLED STEEL BEAMS

The girder choices for this floor system are similar to those chosen above. The service load deflection acts as the main check to ensure safety and again, the largest W shapes can be found in Unit 2. The axial loading in the columns for this system were found to be almost identical for this system and the joist system, and no changes had to be made. Refer to Appendix C for a full summary of the chosen girder and column sizes.

CAST-IN-PLACE CONCRETE ATOP ROLLED STEEL BEAMS

The loads used in the frame design for the cast-in-place system are identical to those used in the same system with metal decking. Therefore, the chosen member sizes for this system are identical to those of the previous system.

PRECAST SLABS

The girders selected for the precast slab floor system were relatively larger than those of the other systems. This is due to the increased load and lack of composite action. During design, the deflection of these beams didn't become as important because the flexural strength of the W shape became the new critical check. Unit 2 again has the largest girders with a depth of 21 inches. See Appendix C for tables containing chosen member sizes.

DESIGN OF FOUNDATION

A simple method was used to determine dimensions of the building's footing sizes. The net allowable soil pressure, provided in the construction documents by Cannon Design, was given to be two tons per square foot. The unfactored load delivered down the columns to the foundations was divided by this net allowable pressure to determine the required bearing area of the footing. For strip footings, the columns were broken into groups, and their corresponding strip footing was designed using the load from all of the contributing columns. After these approximate dimensions were found, the weight of the foundation was factored in and adjustments were made when necessary.

The loads delivered down the columns were nearly identical for all cast-in-place floor systems. The only system which differed was the precast slab system.

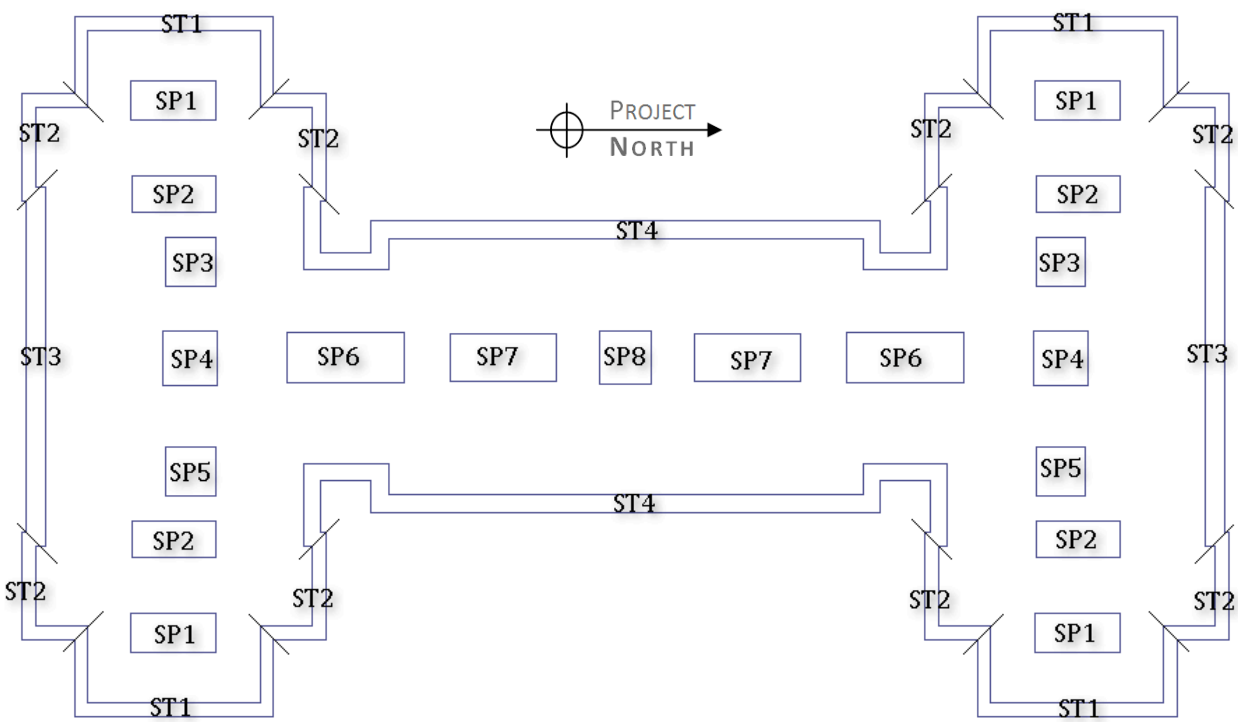


FIGURE 40: FOOTING LOCATIONS

The thickness of the strip footings was taken to be 12", typical for footings of this width. The thickness of the spread footings depended upon the plan dimensions of the footing. The construction documents from Cannon Design provided reference for the thickness of the footing based on the length and width. Footings which ended up being within close proximity to another footing were joined together for ease of construction and the corresponding cost benefit.

Table 13, below, contains the dimensions of the strip and spread footings for both the precast and cast-in-place systems. The footing designations refer to those shown in Figure 40.

TABLE 13: FOOTING DIMENSIONS

Footing	Cast-in-Place Systems		Precast Concrete System	
Spread	Plan Dimensions	Thickness	Plan Dimensions	Thickness
SP1	7'-6" x 16'-6"	20"	7'-6" x 16'-6"	20"
SP2	7'-0" x 16'-0"	20"	7'-0" x 16'-0"	20"
SP3	9'-6" x 9'-6"	24"	9'-6" x 9'-6"	24"
SP4	10'-6" x 10'-6"	28"	11'-0" x 11'-0"	28"
SP5	9'-6" x 9'-6"	24"	10'-0" x 10'-0"	26"
SP6	9'-6" x 22'-6"	24"	9'-6" x 22'-6"	24"
SP7	9'-0" x 20'-6"	24"	9'-0" x 20'-6"	24"
SP8	10'-0" x 10'-0"	26"	10'-0" x 10'-0"	26"
Strip	Width	Thickness	Width	Thickness
ST1	2'-6"	12"	2'-6"	12"
ST2	2'-9"	12"	2'-9"	12"
ST3	3'-9"	12"	4'-0"	12"
ST4	3'-3"	12"	3'-3"	12"

It was also necessary to choose a size for the concrete piers or pedestals which bear upon the spread footings, and a size for the frost wall which bears upon the strip footings. Dimensions for these foundation items were estimated based on Cannon Design's construction documents. The piers were chosen to be 24" x 24" and four feet tall (to penetrate below frost line). The frost wall was taken to be 12" wide and four feet high.

PARKING GARAGE

This section includes all structural activates in the design of a multi-level parking facility. It leads the reader from familiarization of the building to the complete structural design. Each structural alternative will lead to the design of its corresponding floor systems, girders, columns and bracing.

DEFINITION OF GARAGE LAYOUT

GARAGE FOOTPRINTS

Two main structural designs were used for the parking garage: a steel frame design and a precast concrete structure. Figures 41 and 42 display the plan view for each structural alternative. They include the parking levels, walkways, access routes and stairway shafts. The main difference between the two is that the precast design has a slightly larger interior span of 60 feet versus a span of 58.

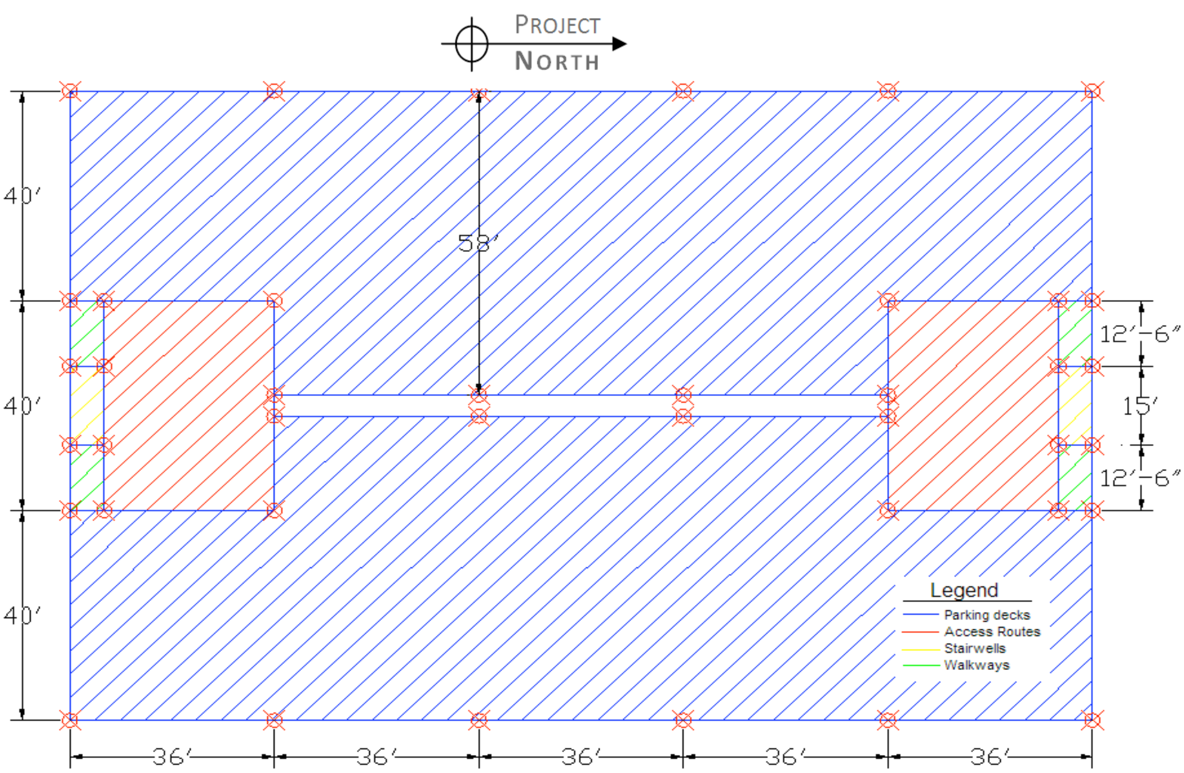


FIGURE 41: STEEL FRAME GARAGE FOOTPRINT

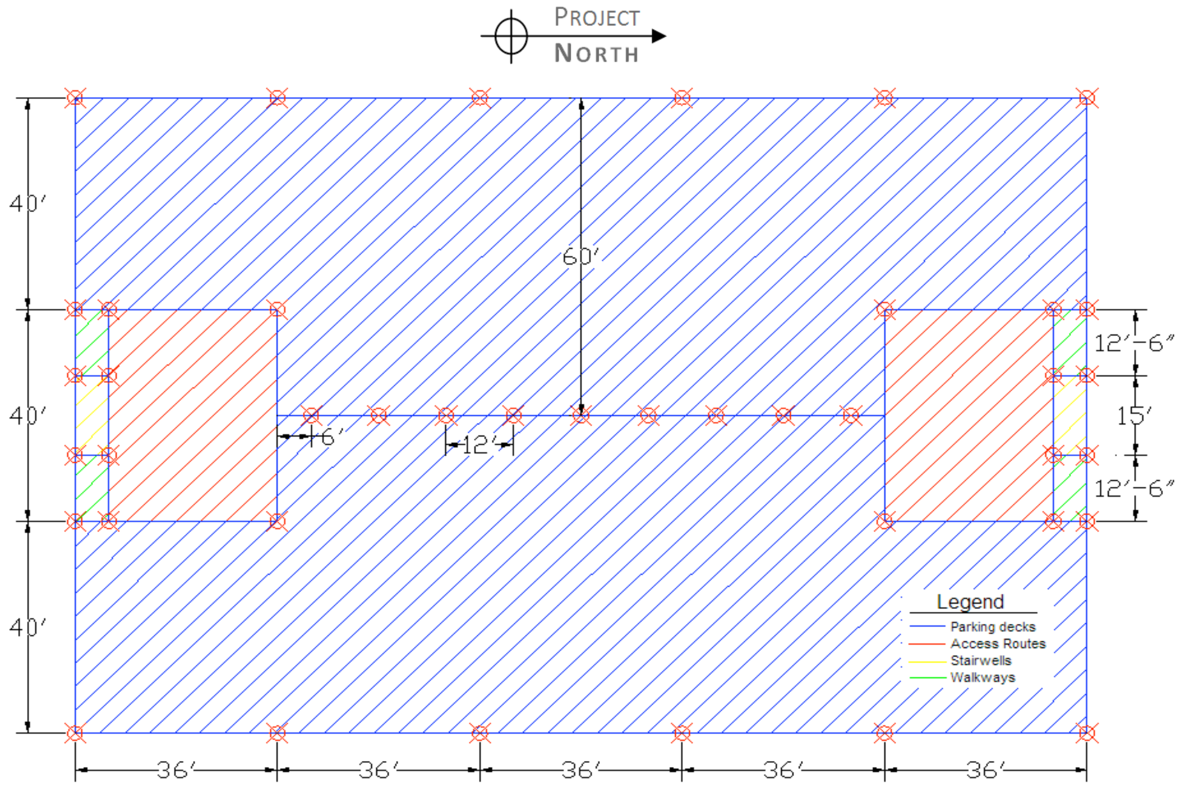


FIGURE 42: PRECAST CONCRETE GARAGE FOOTPRINT

ELEVATION VIEWS

For both garages, the levels located on the east side of the garage are all flat and start at an elevation of 501 feet above sea level. The floors located on the west side are all sloped upward running south to north with the first level starting at 6 feet below ground.

Figures 43, 44, 45, and 46 display the different elevation views for the steel framed parking garage. They show the elevation of each girder in relation to one another with an elevation of 501 feet noted as a datum in each figure. The second level is eight feet high and the third level is ten feet above. An estimated column height of 6.5 feet is used on the top levels of the garage to confine the area with a protective barrier or wall for safety. The column and girder locations are displayed in blue while the top of the concrete floor system is displayed in red.

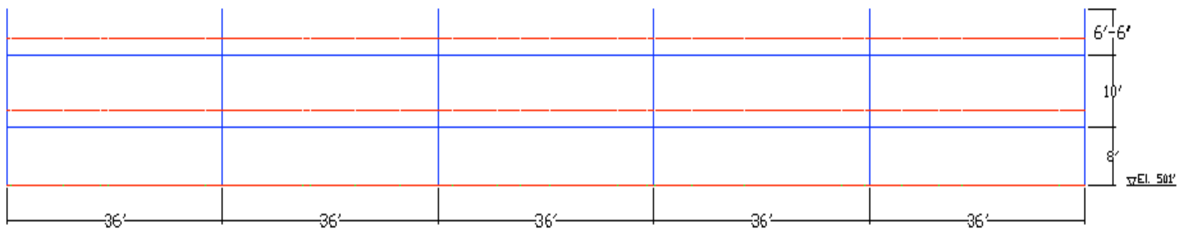


FIGURE 43: STEEL GARAGE, EAST ELEVATIONS AT TOP OF GIRDERS

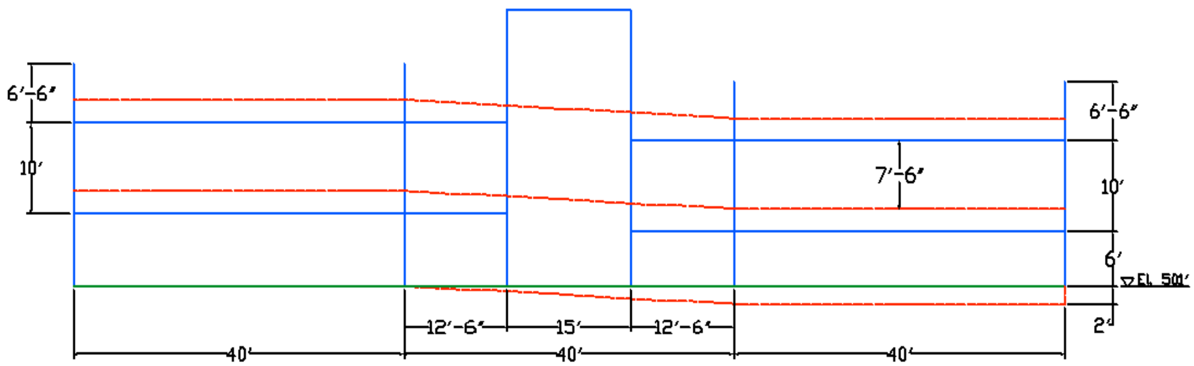


FIGURE 44: STEEL GARAGE, NORTH ELEVATIONS AT TOP OF GIRDER

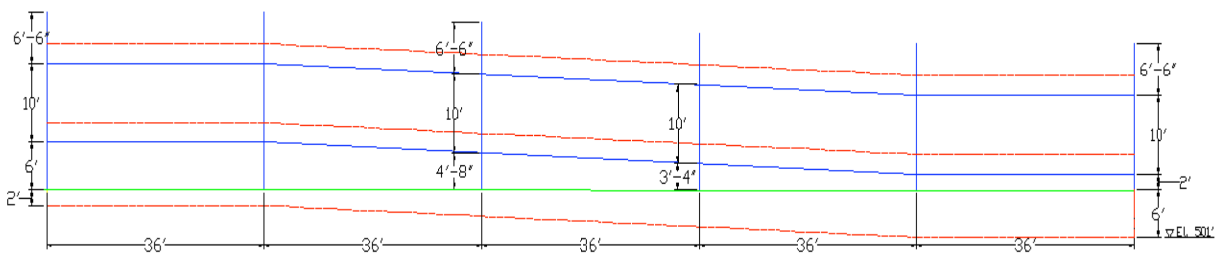


FIGURE 45: STEEL GARAGE, WEST ELEVATIONS AT TOP OF GIRDERS

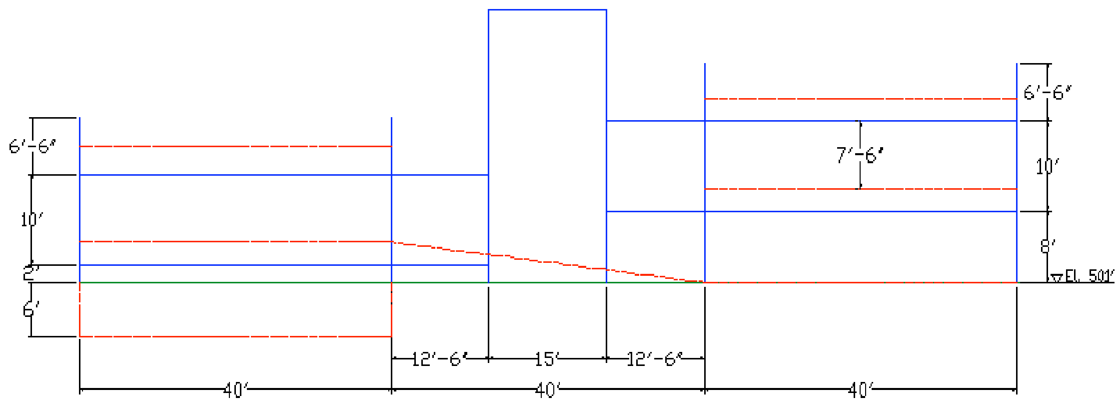


FIGURE 46: STEEL GARAGE, SOUTH ELEVATIONS AT TOP OF GIRDERS

Figures 47, 48, 49 and 50 display the four elevation views for the precast concrete parking garage. They show the elevations for the top support of each girder in relation to one another, as well as, the distance from the top of the concrete floor to the ceiling. The girders act as load bearing members and as walls. Their dimensions and elevations are specified in a later section. The overall column heights also depend on the depth of the girders.

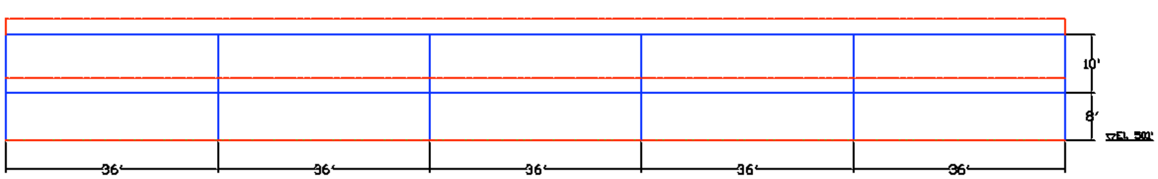


FIGURE 47: PRECAST GARAGE, EAST ELEVATIONS AT TOP OF GIRDERS

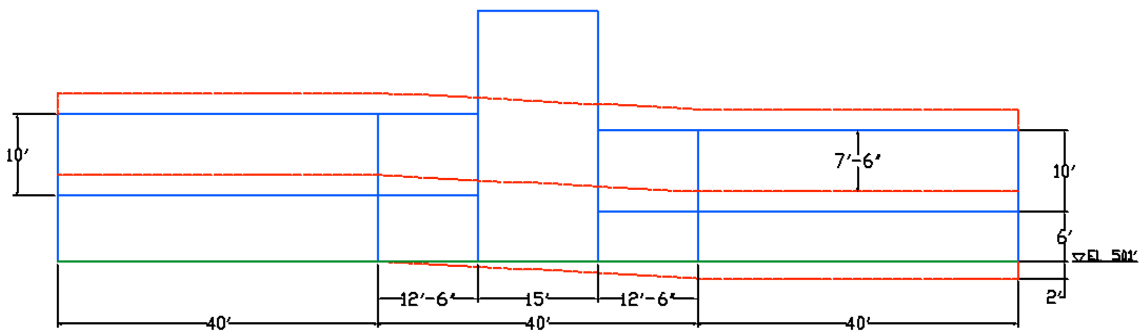


FIGURE 48: PRECAST GARAGE, NORTH ELEVATIONS AT TOP OF GIRDERS

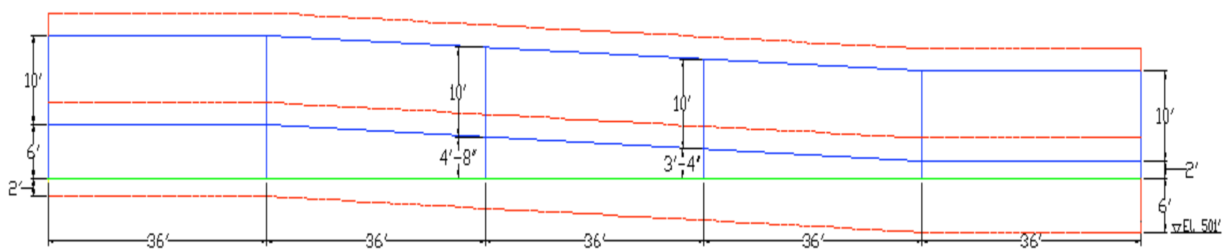


FIGURE 49: PRECAST GARAGE, WEST ELEVATIONS AT TOP OF GIRDERS

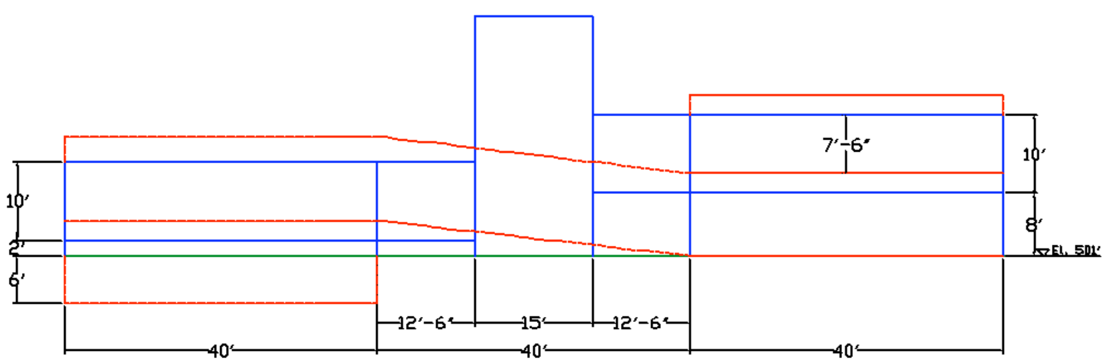


FIGURE 50: PRECAST GARAGE, SOUTH ELEVATIONS AT TOP OF GIRDERS

BAY DESIGNATIONS

Figures 51 and 52 show the different bay sizes that were used in designing the floor systems for each structural design. Both layouts have the same dimensions for Bays A, C and D but Bay B varies in length depending on the material used for the frame. For a steel framed garage, two sets of girders are necessary in the interior of the building while only one row of columns suffices for the precast design. Bay A has L shaped parking along the corner columns, Bay B has parking on both sides, Bay C is the car access routes and Bay D is a walkway into the stairwell. Every parking spot is 9 feet wide by 15 feet long and directed at a 90 degree angle to accommodate the flow of two way traffic.

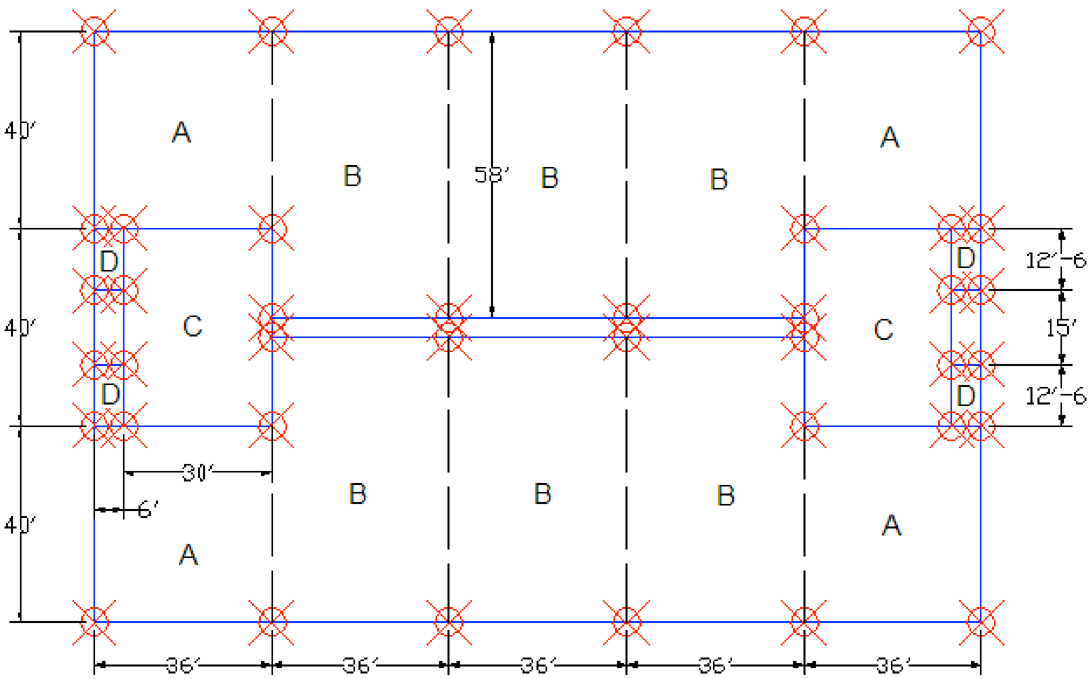


FIGURE 51: STEEL GARAGE BAY DESIGNATIONS

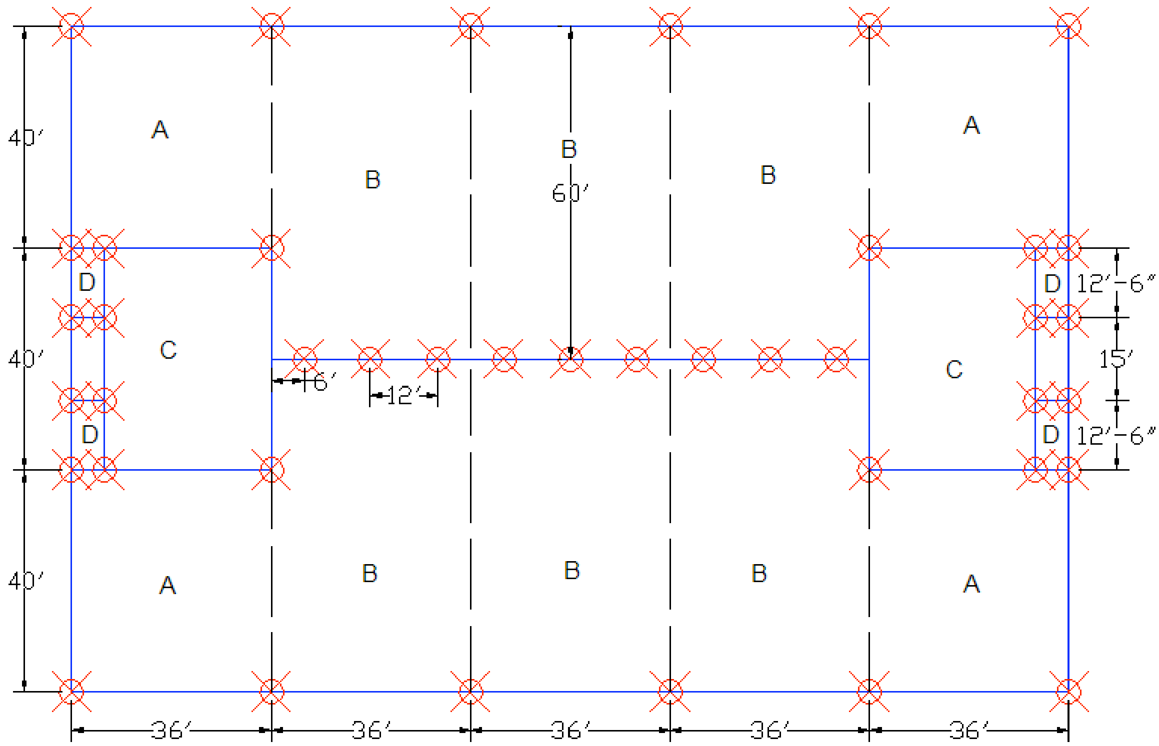


FIGURE 52: PRECAST GARAGE BAY DESIGNATIONS

GIRDER AND COLUMN DESIGNATIONS

Figures 53 and 54 display the girder and column designations for each structural alternative. The precast garage incorporates the use of axial load bearing shear walls through the center of the structure and along the access routes. They are noted by an “S” symbol on figure 54. Subsequent sections on member design refer to these figures.

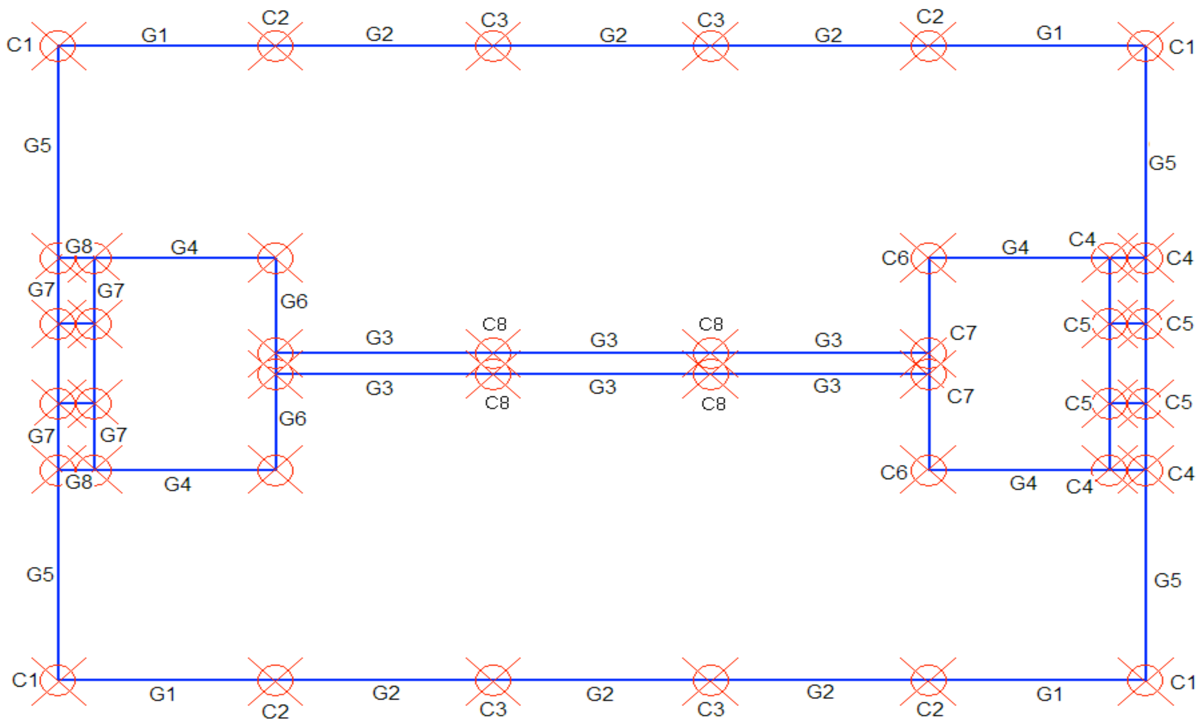


FIGURE 53: STEEL GARAGE GIRDER & COLUMN DESIGNATIONS

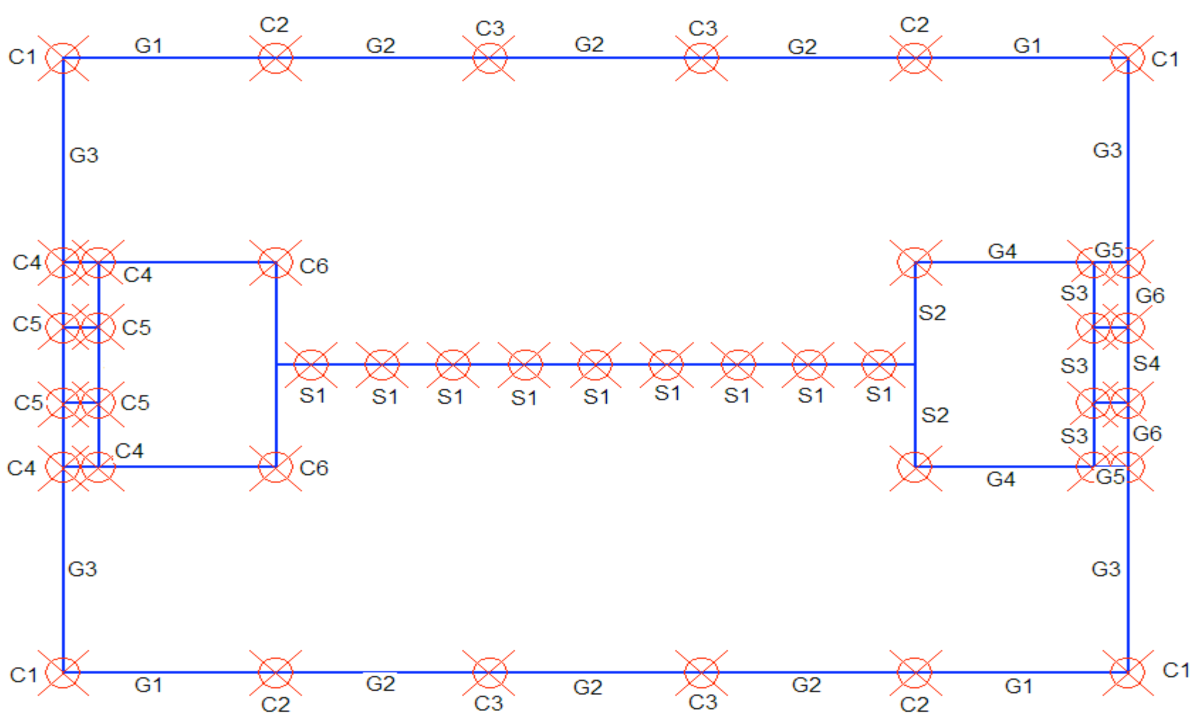


FIGURE 54: PRECAST GARAGE GIRDER & COLUMN DESIGNATIONS

GARAGE DESIGN

DESIGN LOADS

Table 14 shows the design loads that were used for both structural alternatives. These loads include live, snow, and wind. The weight of the dead load isn't listed due to the differences in weight between the alternative designs. It was calculated into our total factored load upon its designation. The tabulated load data was provided through construction documents prepared by Cannon Design.

TABLE 14: PARKING GARAGE DESIGN LOADS

Load Type	Intensity
Live	
Garages	40 psf
All other public spaces, corridors, stairs and lobbies	100 psf
Snow	
Flat roof snow load	35 psf
Wind	
End Zone	28 psf
Interior Zone	20 psf

FLOOR SYSTEMS

Using figures 51 and 52 as a reference, Tables 15 and 16 provide the selected types of precast floor systems for each parking garage. Using load factors, a total factored load of 81.5 psf was used on the garage floors and a 177.5 psf load for the walkways into the stairwell. Precast floor system types were selected using the *PCI Design Handbook* by comparing the safe superimposed service load versus span length to the actual factored load. Since typical widths for bays A, B, and C were either 36 or 30 feet, the precast double-tees were chosen to be 12 and 10 feet respectively, in order to allow the placement of three members per bay. Bay D contains two, four-foot wide solid precast concrete planks. Each precast plank in bay D must have 1 foot trimmed off its width in order to fit properly within this bay. Light weight concrete was selected to cut down on the overall dead load of the floor system for design of the structural frame. Figure 55 depicts how a precast floor section will sit atop the steel girders.

TABLE 15: STEEL FRAME FLOOR SYSTEM DESIGN

Steel Frame Parking Garage Floor System Selections					
Bay Type	Precast Member Selection	Strand Pattern	Span Length (ft)	Safe Super Imposed Load (psf)	Number of Members
A	12LDT30	128-D1	40	167	3
B	12LDT30	168-D1	58	92	3
C	10LDT26	88-S	40	83	3
D	LFS4	58-S	12.5	190	2

TABLE 16: PRECAST CONCRETE FLOOR SYSTEM DESIGN

Precast Concrete Parking Garage Floor System Selections					
Bay Type	Precast Member Selection	Strand Pattern	Span Length (ft)	Safe Super Imposed Load (psf)	Number of Members
A	12LDT30	128-D1	40	167	3
B	12LDT30	168-D1	60	82	3
C	10LDT26	88-S	40	83	3
D	LFS4	58-S	12.5	190	2

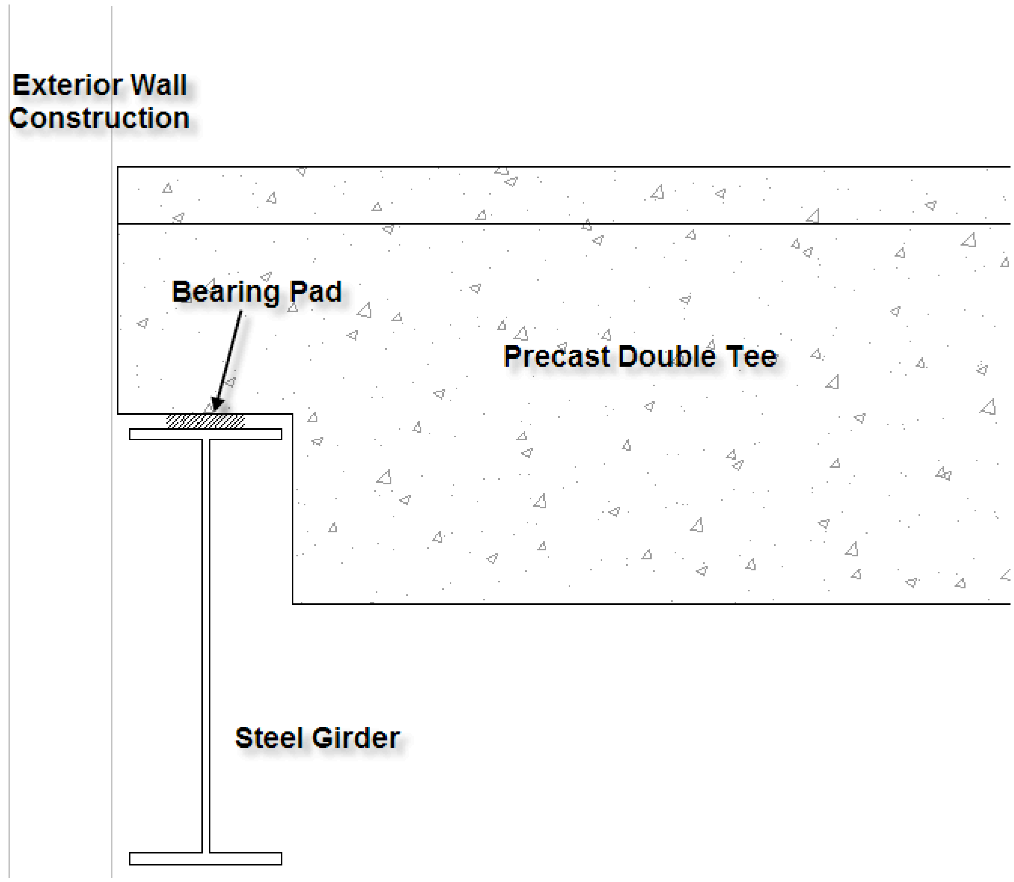


FIGURE 55: PRECAST DOUBLE TEE ON TOP OF STEEL GIRDER

GIRDER SELECTIONS

Table 17 contains the steel girders that were chosen for the steel framed parking garage. In designing these members, the factored positive moment acting on each girder was checked in comparison with the published values given in Table 3-2 of the *AISC Steel Design Manual*. Once an adequate beam size was selected for the moment, the overall deflection of the W shape was checked. The moment of inertia for each girder was used to determine a deflection when loaded under service conditions. All girders were also checked for shear strength and buckling. Table 39 of Appendix C provides a summary of the girders and the design loads acting on them.

TABLE 17: STEEL GARAGE GIRDER SELECTIONS

Steel Girder Selections			
Girder Type	Member Size	Length (ft)	Total # of Members
G1	W 27 x 94	36	8
G2	W 30 x 108	36	12
G3	W 30 x 99	36	12
G4	W 27 X 84	30	12
G5	W 24 x 68	40	8
G6	W 10 x 15	18	8
G7	W 10 x 15	12.5	16
G8	W 10 x 15	6	16

Using the girder designations from Figure 54, Table 18 displays the girders selected for the precast parking garage using the factored loads calculated in Table 40 of Appendix C. Girders G1 and G2 both support gravity loads and act as wall enclosures, as well. Standard L beam shapes were selected out of the *PCI Design Handbook* by comparing the factored design uniform load to the tabulated safe superimposed loads. The estimated weight of additional concrete necessary to make the wall a proper height of 6 feet was included in the factored design load in order to pick proper L beam sizes. Girders G3 and G6 don't support any gravity loads and just act as walls and bracing members. The designation 12RB72 means that they are rectangular beams 12 inches wide by 72 inches deep. Values for this type of beam aren't given in the PCI design Handbook, however by comparing beams of a smaller size and their span length; these girders are more than capable of supporting this frame. Girders G4 and G5 both lay on the interior of the building and only support dead loads. Inverted tee beam shapes were selected using the *PCI Design Handbook*. Girder G5 only spans 6 feet. To keep a uniform floor height, the same shape inverted tee beam selected for G4 is used. Figure 56 below shows the interaction between the girder and floor system.

TABLE 18: PRECAST GARAGE GIRDER SELECTIONS

Precast Girder Selections			
Girder Type	Member Size	Length (ft)	Total # of Members
G1	20LB36	36	8
G2	20LB44	36	12
G3	12RB72	40	8
G4	28IT36	30	9
G5	28IT36	6	8
G6	12RB72	12.5	8

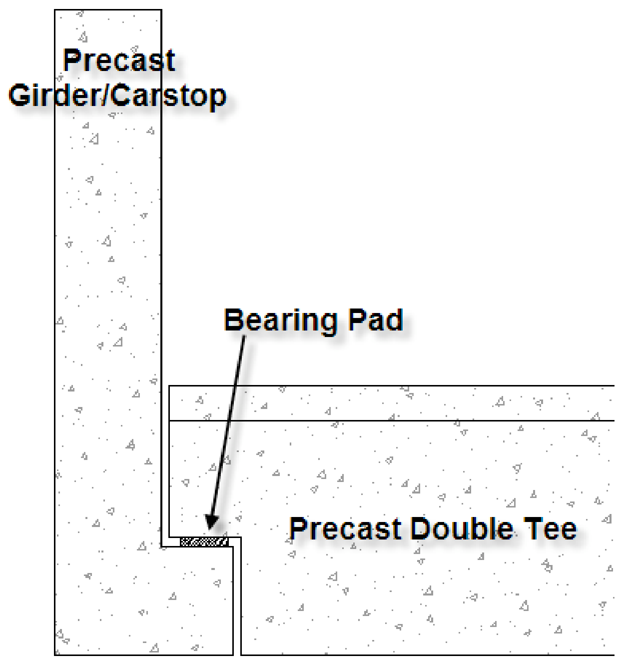


FIGURE 56: PRECAST GIRDER SUPPORTING DOUBLE TEE

COLUMN SELECTIONS

The steel columns selected for the parking garage can be seen in Table 19. The columns on the east side of the garage all have the same height of 25 feet. Column lengths on the west face increase as the slope of the garage increases. In the table below, column length values for the west face can be noted as running from south to north. Figures 45 and 53 are helpful in understanding this concept. The loads acting on each column were determined by using the tributary area around each column. Dead, live, and snow loads were all factored together to find an axial load in kips acting directly downward on each column. Then using Table 4-2 in the AISC *Steel Design Manual,* columns were selected by checking their available strength in axial compression versus their unbraced length. HP-type steel columns were used since they have a larger flange width to account for connections.

TABLE 19: STEEL GARAGE COLUMN SELECTIONS

Steel Column selections - East Side			
Column Type	Member Size	Height (ft)	Total # of Members
C1	HP 10 x 42	25	2
C2	HP 10 x 42	25	2
C3	HP 10 x 42	25	2
C4	HP 10 x 42	25	4
C5	HP 10 x 42	31	4
C6	HP 10 x 42	25	2
C7	HP 12 x 53	25	2
C8	HP 12 x 53	25	2
Steel Column selections - West Side			
Column Type	Member Size	Height (ft)	Total # of Members
C1	HP 10 x 42	19/23	2
C2	HP 10 x 42	19/23	2
C3	HP 10 x 42	20/22	2
C4	HP 10 x 42	19/23	4
C5	HP 10 x 42	31	4
C6	HP 10 x 42	19/23	2
C7	HP 12 x 53	19/23	2
C8	HP 12 x 53	20/22	2

Using Figure 54 as a reference, Table 20 lists the precast columns for the garage. The *PCI Design Handbook* was used to help determine the proper dimension for each precast column. For the design of the columns running along the exterior of the building, the largest axial load of 440.6 kips was used to develop symmetrical members. Higher column dimensions were also used to incorporate the installation of girders into these members. Figure 57 shows the column to girder interaction. For the columns on the interior of the building, a similar analysis was used. However, since no girders are installed directly into the column, corbels are used to transmit the load from the inverted tee beams. A compressive strength of 5,000 psi was used for all the concrete columns.

TABLE 20: PRECAST COLUMN SELECTIONS

Steel Column selections - East Side				
Column Type	Dimensions (in)	# of strands	Height (ft)	Total # of Members
C1	20 x 20	8	25	2
C2	20 x 20	8	25	2
C3	20 x 20	8	25	2
C4	12 x 12	4	25	4
C5	12 x 12	4	31	4
C6	12 x 12	4	25	2
Steel Column selections - East Side				
Column Type	Member Size	# of strands	Height (ft)	Total # of Members
C1	20 x 20	8	19/23	2
C2	20 x 20	8	19/23	2
C3	20 x 20	8	20/22	2
C4	12 x 12	4	19/23	4
C5	12 x 12	4	31	4
C6	12 x 12	4	19/23	2

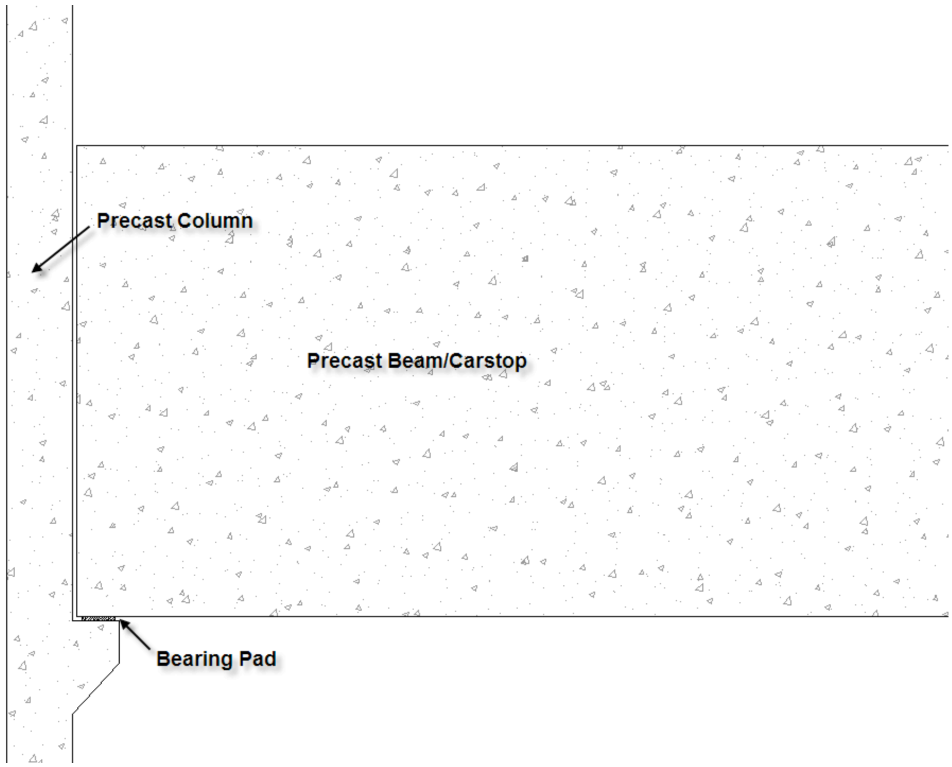


FIGURE 57: PRECAST COLUMN SUPPORTING PRECAST BEAM

LATERAL LOAD RESISTANCE

The final stages for both designs were to adequately support the frames against lateral loads. For the steel parking garage, lateral bracing is used along the interior columns and the access routes. Figure 8 of the background, shows a common way in which lateral forces are resisted for structures. X-bracing within the garage, provides an adequate amount of lateral resistance for design. Diagonal bracing can also be used within this scheme since it is only placed in areas where traffic flow won't be issue. Figure 58 shows where the lateral bracing should be placed between the columns to resist lateral forces.

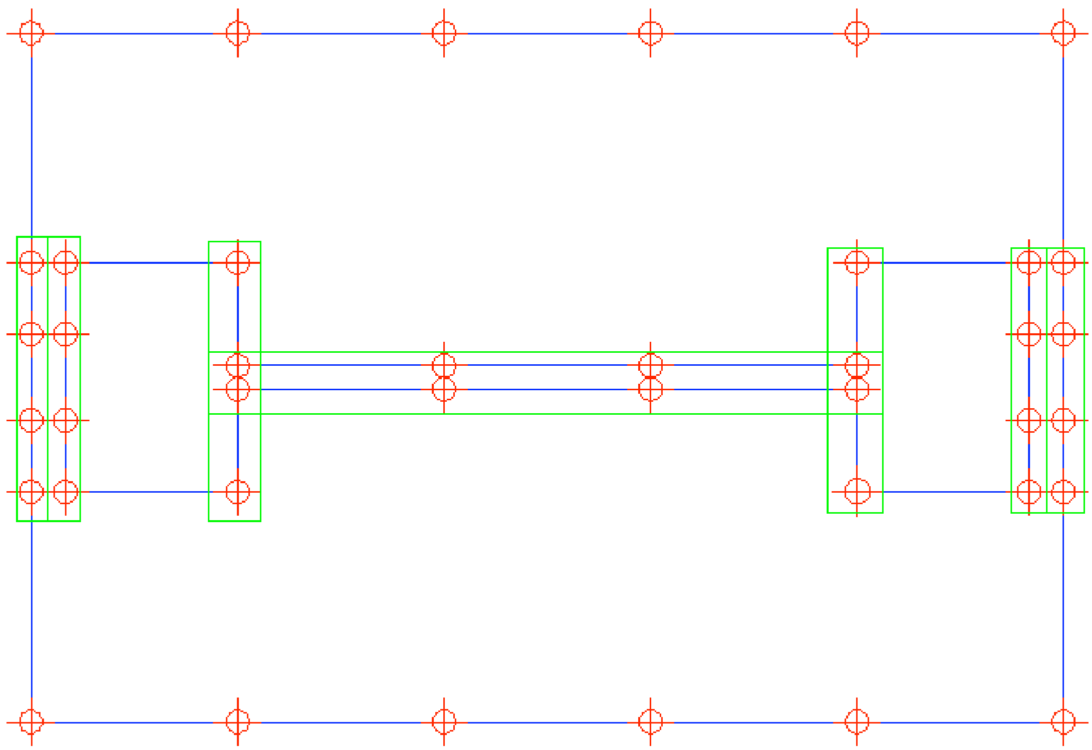


FIGURE 58: LOCATION OF LATERAL REINFORCEMENT IN THE STEEL FRAMED GARAGE

Since the precast parking garage will incorporate the use of shear walls as columns along interior span and access routes of the building only the design criteria for these members is mentioned here. There are nine shear walls along the interior of the garage each supporting the weight of two 12-foot double tees on each level. A total factored axial load at the base of 213.2 kips was calculated for these walls. These columns/shear walls are much smaller than those listed in the section above; however, adequate reinforcement is necessary within each wall to protect the frame against lateral shear. Since there are nine shear walls, the total wind force acting on the exterior face perpendicular to these walls is divided by nine to find the amount of shear resisted for each wall. Each shear wall has two corbels 8-inches wide by 8-inches deep spaced at 6-feet to support the two the tension members of the double-tee. The final dimensions of the wall are a 6.5 foot width and an 8 in depth, each having a height of 25 feet. The compressive force of the concrete used is 5,000 psi.

Chapter 5: Cost Estimate of Residence Hall Structure

In order to help compare each floor system, a cost estimate was performed on the structural elements of the building. This encompassed the entire substructure (excluding excavation and base courses) as well as all structural steel members and the elements of the floor and roof systems.

All costs were based on national average prices provided by *RSMeans Building Construction Cost Data 2008*. Therefore, it was necessary to use location indices, also provided by *RSMeans*, to adjust the national averages to typical prices in Worcester, MA. These indices can be seen in Table 21 below.

Table 21: Worcester location indices (RSMeans, 2008)

Division		Massachusetts Worcester 015-016		
		Materials	Installation	Total
015433	**Contractor Equipment**		100.6	100.6
0241, 31-34	**Site & Infrastructure, Demolition**	83.7	104.2	98.0
0310	Concrete Forming & Accessories	99.0	129.5	125.3
0320	Concrete Reinforcing	102.0	146.8	123.6
0330	Cast-in-Place Concrete	90.4	143.4	110.0
03	**Concrete**	101.0	136.6	117.5
04	**Masonry**	96.4	144.1	124.9
05	**Metals**	93.4	123.3	102.1
06	**Wood, Plastics, & Composites**	100.4	131.3	117.0
07	**Thermal & Moisture Protection**	99.5	135.2	113.5
08	**Openings**	105.3	133.7	112.3
0920	Plaster & Gypsum Board	105.1	131.3	121.3
0950, 0980	Ceilings & Acoustic Treatment	96.2	131.3	117.8
0960	Flooring	96.3	163.7	114.6
0970, 0990	Wall Finishes & Painting/Coating	91.6	132.4	116.1
09	**Finishes**	99.6	137.2	119.2
Covers	**Divs. 10-14, 25, 28, 41, 43, 44**	100.0	102.4	100.5
21, 22, 23	**Fire Suppression, Plumbing & HVAC**	100.1	107.2	103.1
26, 27, 3370	**Electrical, Communications & Util.**	98.1	98.5	98.3
MF2004	**Weighted Average**	98.7	120.8	108.1

These location indices are based on the national cost, which is indexed at 100. This means that for metals, the material cost in Worcester is 93.4% of the national average, and the labor cost is 123.3% of the national average labor cost. The totals are weighted depending on the relationship of material and labor costs for each division, and the weighted average indices are weighted based on the typical make-up of a construction project.

The following sections familiarize the reader with methods used to determine unit costs of the building materials and provide the final costs for each system.

STEEL OPEN-WEB JOISTS WITH METAL DECK AND CONCRETE TOPPING

The cost of the steel joist system was estimated at approximately $2.11 Million. The breakdown of the costs is summarized in Table 22. It is important to note that the unit costs presented in the cost breakdowns are not those used to calculate the costs, but rather the cost of the entire element in the most appropriate unit. The costs of some elements were estimated using several building materials. For instance, the cost of elevated slabs includes concrete with finish, and reinforcement.

TABLE 22: COST BREAKDOWN FOR JOIST SYSTEM

Building Element	Total Cost	Unit Cost	Unit of Measure
Cost of Joist System	$ 2,114,300	$ 21.14	SF of Building
Substructure	$ 198,400	$ 1.98	SF of Building
Slab on Grade	$ 70,000	$ 3.50	SF of Ground
Spread Footings	$ 43,800	$ 608	CYs
Concrete Pedestals	$ 20,600	$ 1056	CYs
Strip Footings	$ 25,100	$ 228	CYs
Frost Wall	$ 38,900	$ 250	CYs
Superstructure	$ 1,915,900	$ 19.15	SF of Building
Joists	$ 214,800	$ 2790	Tons
Beams (Roof)	$ 32,100	$ 3452	Tons
Girders	$ 498,800	$ 3098	Tons
Shear Studs: 3/4" x 3-3/8"	$ 18,000	$ 1.82	Each
Columns	$ 183,300	$ 2656	Tons
Steel Form Decking	$ 515,700	$ 5.16	SF of Elevated Slab
Steel Edge Forms	$ 25,200	$ 5.04	LF Perimeter for Slabs
Elevated Slabs	$ 428,000	$ 4.28	SF of Elevated Slabs

The greatest unique cost driver in this system was the steel joists themselves. Unfortunately, not all of the open-web joist sizes that were specified were priced in RSMeans. It was therefore necessary to understand what was driving the material and installation costs and use this knowledge to interpolate costs for the remaining joist sizes.

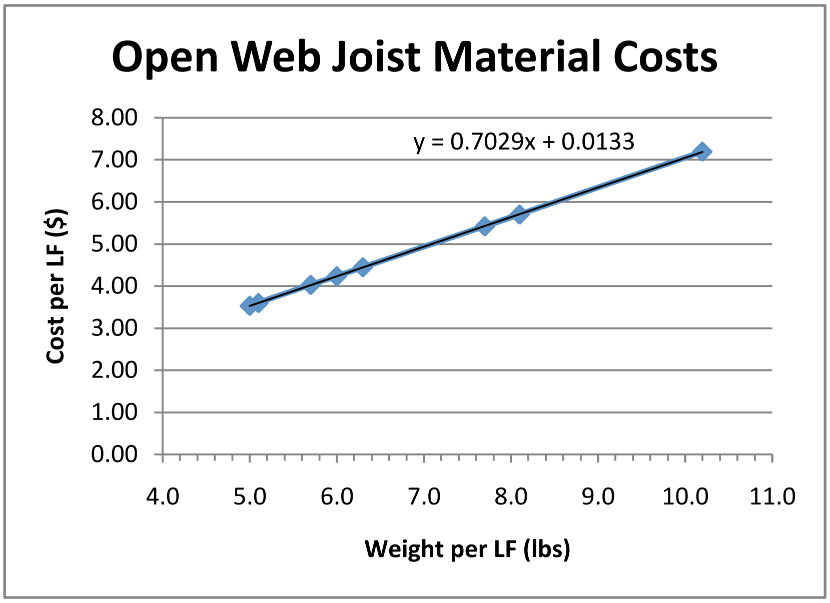


FIGURE 59: MATERIAL COST OF OPEN-WEB JOISTS

In order to determine the unknown material costs of open-web joists, the known prices were plotted against their weight per linear foot, and the relationship was found to be linear (see Figure 59). An equation representing the relationship was determined and used to interpolate the unknown costs. The installation cost was found to be dependent on the depth of the joist. For example, all joists of depth eight or ten inches had the same installation cost, as do joists of 12 and 14 inches in depth.

Another large expense, although not unique to this system, was the steel form decking. The available cost data included 24 gauge 1" deck, and this was used to determine the costs of the specified 20 gauge deck. The material cost was simply multiplied by the thickness ratio of 20 gauge to 24 gauge (equal to 1.5). The installation cost was not clearly based on any one x-variable, therefore it was necessary to make an educated guess based on the information known. Finally, the cost was escalated by assuming a 5% waste consideration.

ROLLED STEEL BEAMS WITH METAL DECK AND CONCRETE TOPPING

The final cost of this system's sub- and superstructure was estimated at about $2.07 Million. This is only about thirty thousand dollars less than the joist system. The largest unique cost driver is again the infill members, in this case rolled steel beams. Like the open-web joists, the material cost was solely dependent upon the weight per linear foot, and the linear equation was used to yield unknown values. The depth controlled the installation cost, but sometimes there were different costs for the heavier sections of the same depth beam. In these cases, if the beam to be interpolated was between the transition values, the higher, more conservative value was used.

TABLE 23: COST BREAKDOWN FOR BEAM SYSTEM WITH METAL DECK

Building Element	Total Cost	Unit Cost	Unit of Measure
Cost of SoMD with Beams	$ 2,068,800	$ 20.69	SF of Building
Substructure	$ 198,400	$ 1.98	SF of Building
Slab on Grade	$ 70,000	$ 3.50	SF of Ground
Spread Footings	$ 43,800	$ 608	CYs
Concrete Pedestals	$ 20,600	$ 1056	CYs
Strip Footings	$ 25,100	$ 228	CYs
Frost Wall	$ 38,900	$ 250	CYs
Superstructure	$ 1,870,400	$ 18.70	SF of Building
Beams	$ 237,800	$ 3359	Tons
Girders	$ 504,500	$ 2950	Tons
Shear Studs: 3/4" x 3-3/8"	$ 26,200	$ 1.82	Each
Columns	$ 183,300	$ 2657	Tons
Steel Form Decking	$ 539,200	$ 5.39	SF of Elevated Slab
Steel Edge Forms	$ 25,200	$ 5.04	LF of Slab Perimeter
Elevated Slabs	$ 354,200	$ 3.54	SF of Elevated Slab

The metal decking was also a large cost driver in this system, totaling more than half of a million dollars. The decking for this system was 20 ga. as well, but with a section of 2" in depth. The costs of this deck were determined in the same way as the 1" deck from the previous example, and found to have an additional cost about $0.23 per square foot. Still, this additional cost and the cost of the extra shear studs were compensated by the lower cost of the infill members.

ROLLED STEEL BEAMS WITH CAST-IN-PLACE CONCRETE SLAB

The cost of this system was the highest of the four, at about $2.17 Million. The breakdown can be seen in Table 24 below.

TABLE 24: COST BREAKDOWN FOR BEAM SYSTEM WITH NO METAL DECK

Building Element	Total Cost	Unit Cost	Unit of Measure
Cost of CIP (no deck) System	$ 2,171,300	$ 21.71	SF of Building
Substructure	$ 198,400	$ 1.98	SF of Building
Slab on Grade	$ 70,000	$ 3.50	SF of Ground
Spread Footings	$ 43,800	$ 608	CYs
Concrete Pedestals	$ 20,600	$ 1056	CYs
Strip Footings	$ 25,100	$ 228	CYs
Frost Wall	$ 38,900	$ 250	CYs
Superstructure	$ 1,972,900	$ 19.73	SF of Building
Beams	$ 237,800	$ 3359	Tons
Girders	$ 504,500	$ 2950	Tons
Shear Studs: 3/4" x 3-3/8"	$ 26,200	$ 1.82	Each
Columns	$ 183,300	$ 2657	Tons
Temporary Formwork	$ 667,000	$ 6.67	SF of Elevated Slab
Elevated Slabs	$ 354,100	$ 3.54	SF of Elevated Slab

The largest unique cost driver in this system was the temporary formwork for the elevated concrete slabs. The cost of formwork can be a very difficult thing to estimate because the final cost is dependent on so many variables. One of the most significant variables is the number of times the forms are used. When the cost of formwork can be spread out among several castings of concrete, it can have a large effect. In addition, sometimes the concrete subcontractor may have usable forms from a previous job that can be used at a discounted rate. It may seem then that the most economical approach would be to use the same formwork for all five elevated slabs. The problem is that when using plywood forms, the surfaces of the forms typically become too damaged after four uses. The cost was calculated for splitting the usage of the forms into three uses for one set and two uses for the other, and also for four and one. Four uses of one set and one of the other was the scheme used because the cost was calculated to be the lowest, and because the roof is best cast using its own formwork due to any subtle differences in the dimensional requirements.

The implications of requiring the same usage of formwork for up to eight uses can be seen in Figure 62. The cost for five uses is taken to be the cost of four uses plus one use, spread over five uses. Similarly, the cost of six uses is calculated as four and two uses, divided by the total of six uses, and so on. Once the cost of eight uses is reached, the value returns to that of four uses. Continuing this graph for additional uses, the price would jump up after every four uses, but would continue to flatten out toward that lower bound.

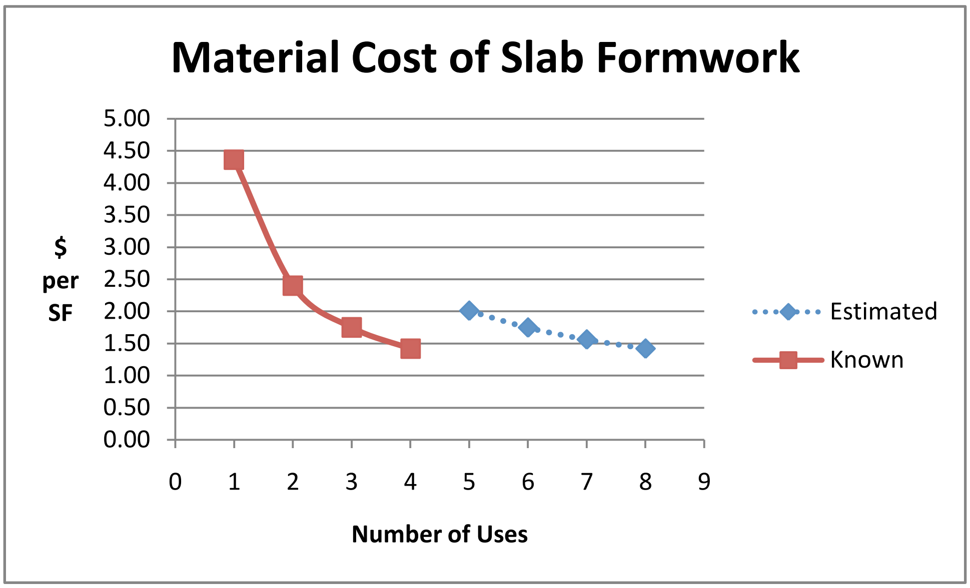


FIGURE 60: COST OF ELEVATED SLAB FORMWORK BY NUMBER OF USES

ROLLED STEEL BEAMS WITH HOLLOW CORE PRECAST CONCRETE SLABS

The cost of the precast system is driven almost exclusively by the unique cost of the slabs themselves. While the cost of the girders, columns, and foundations was slightly greater than that of the other systems, the governing cost factor was the precast elements along with the specified two inch topping of concrete. Since the cost of the hollow-core precast slabs was specified by RSMeans only for 8” and above, it was necessary to extrapolate the cost of a 6” hollow core slab. The 2” topping, for cost considerations, was considered an elevated slab without formwork or reinforcement. The material cost for this slab was linear in relationship to the thickness of the slab. The installation costs were nearly static, however, because of the cost associated with finishing the surface of the concrete, which does not change with the thickness of the slab. The final cost of the sub- and superstructures of the precast system can be seen in Table 25. It is interesting to note that despite the many differences with the precast system and the cast-in-place systems, the items necessary to the build-up of the slabs and infill beams are comparable, each hovering around the $1.2 Million mark.

TABLE 25: COST BREAKDOWN FOR PRECAST SLAB SYSTEM

Building Element	Total Cost	Unit Cost	Unit of Measure
Cost of Precast Slab System	$ 2,092,300	$ 20.92	SF of Building
Substructure	$ 199,900	$ 2.00	SF of Building
Slab on Grade	$ 70,000	$ 3.50	SF of Ground
Spread Footings	$ 45,000	$ 608	CYs
Concrete Pedestals	$ 20,600	$ 1056	CYs
Strip Footings	$ 25,400	$ 228	CYs
Frost Wall	$ 38,900	$ 250	CYs
Superstructure	$ 1,892,400	$ 18.92	SF of Building
Girders	$ 518,400	$ 2929	Tons
Columns	$ 212,800	$ 2660	Tons
Precast Slabs (with topping)	$ 1,161,200	$ 11.61	SF of Elevated Slab

TYPICAL DORMITORY SQUARE FOOT COSTS

To double check the costs calculated above, they were compared to typical square foot costs of a dormitory building. RSMeans publishes a book of typical square foot costs broken down by system. The most appropriate building in *RSMeans Square Foot Costs* is a six-story dormitory of 85,000 SF. The approximate square foot costs for sub- and superstructure are presented in Table 26.

TABLE 26: COMPARATIVE SF COSTS

	Estimated Costs (SoMD w/ beams)		Model Building Costs (RSMeans)	
Building System	Cost per SF of Building	% of total project[16]	Cost per SF of Building[17]	% of total project
Substructure (not including excavation)	$1.98	0.5%	$2.55	2.4%
Superstructure	$19.45[18]	5.3%	$20.19	20.5%

While small discrepancies exist between the cost estimate and the RSMeans model building SF costs, they are certainly within a reasonable range of each other. The cost discrepancy with the substructure is probably a product of the fact that the model building is six stories. These extra gravity loads could increase the required foundation size per SF of building. The large difference in the project percentages is easily explained by the fact that the new residence hall has a total cost of $350 per SF, while the model building has a cost of only $132 per SF. This large difference can be attributed to several factors. The largest factor is the fact that this building is an apartment-style building, meaning it includes a kitchen and bathroom for each suite. Also causing an increase in the SF costs are the high grade/institutional finishes and hardware, brick masonry enclosure, specialties and equipment, and the restrictive nature of the site to mention a few.

[16] Calculated using total project cost of $35 Million.

[17] Adjusted to Worcester using weighted average indices

[18] Seventy-five thousand dollar allowance for diagonal lateral bracing (10% of total structural steel costs).

Chapter 6: Environmental Study

LEED Credits

What follows are the nine credits that were researched in the Methodology and the reasons they were either chosen to be a goal of WPI's or not. The actual credit is shown, taken from LEED for New Construction Checklist, followed by the pros and cons of achieving or not achieving each.

Materials reuse

Materials Reuse (2 credits)

Intent: *Reuse building materials and products in order to reduce demand for virgin materials and to reduce waste, thereby reducing impacts associated with the extraction and processing of virgin resources.*

Requirements: *Use salvaged, refurbished or reused materials such that the sum of these materials constitutes at least 5% (for Credit 3.1) and 10% (for credit 3.2) based on cost, of the total value of materials on the project.*

The site before construction housed two structures made out of mainly concrete and a parking lot. The materials that would be salvaged out of their destruction would not be suitable for the construction of the residence hall, made out of steel and masonry, or the parking garage, created out of cast in place concrete planks. As an added factor the buildings that were torn down were very old and any materials out of them would not be guaranteed to be durable and usable for the new buildings. There would be brick facing and old cement that could potentially be reused from the old buildings, but as mentioned in the methodology this was not deeply looked into. Thus, these two credits did not seem to be possible.

Increased Ventilation

Increased Ventilation

Intent: *Provide additional outdoor air ventilation to improve indoor air quality for improved comfort, well-being and productivity.*

> ***Requirements:*** *For mechanically ventilated spaces increase breathing zone outdoor air ventilation rates to all occupied spaces by at least 30% above the minimum rates required by ASHRAE Standard 62.1-2004 as determined by EQ Prerequisite 1.*

The intent of this credit is to provide the occupants of a building with the best indoor air quality possible. A higher air quality has been proven to support a healthier and more comfortable well-being for the occupants. The process of how to achieve a ventilation system that improves the standard air quality by 30% uses the ASHRAE guidelines. In the *ASHRAE Standard 62.1-2004: Ventilation for Acceptable Indoor Air Quality* there are tables that break down different buildings and provide a set outdoor air flow, a default occupant density, etc. A section of Table 6-1 from ASHRAE Standard 62.1-2007 can be seen in Figure 61. From the values given in this table and the known facts about the HVAC system that will be installed in a building allow calculations to be performed that will determine what type of system and energy would be needed to sufficiently provide the building with a 30% increase in air quality. These calculations were not performed by this MQP as not enough sufficient information was had.

TABLE 6-1 MINIMUM VENTILATION RATES IN BREATHING ZONE
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values: Occupant Density (see Note 4)	Default Values: Combined Outdoor Air Rate (see Note 5)		Air Class
	cfm/person	L/s·person	cfm/ft²	L/s·m²		#/1000 ft² or #/100 m²	cfm/person	L/s·person	
Hotels, Motels, Resorts, Dormitories									
Bedroom/living room	5	2.5	0.06	0.3		10	11	5.5	1
Barracks sleeping areas	5	2.5	0.06	0.3		20	8	4.0	1
Laundry rooms, central	5	2.5	0.12	0.6		10	17	8.5	2
Laundry rooms within dwelling units	5	2.5	0.12	0.6		10	17	8.5	1
Lobbies/prefunction	7.5	3.8	0.06	0.3		30	10	4.8	1
Multipurpose assembly	5	2.5	0.06	0.3		120	6	2.8	1

ANSI/ASHRAE Standard 62.1-2007 13

Occupancy Category	cfm/person	L/s·person	cfm/ft²	L/s·m²	Notes	#/1000 ft² or #/100 m²	cfm/person	L/s·person	Air Class
Public Assembly Spaces									
Auditorium seating area	5	2.5	0.06	0.3		150	5	2.7	1
Places of religious worship	5	2.5	0.06	0.3		120	6	2.8	1
Courtrooms	5	2.5	0.06	0.3		70	6	2.9	1
Legislative chambers	5	2.5	0.06	0.3		50	6	3.1	1
Libraries	5	2.5	0.12	0.6		10	17	8.5	1
Lobbies	5	2.5	0.06	0.3		150	5	2.7	1
Museums (children's)	7.5	3.8	0.12	0.6		40	11	5.3	1
Museums/galleries	7.5	3.8	0.06	0.3		40	9	4.6	1

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values: Occupant Density (see Note 4)	Default Values: Combined Outdoor Air Rate (see Note 5)		Air Class
	cfm/person	L/s·person	cfm/ft²	L/s·m²		#/1000 ft² or #/100 m²	cfm/person	L/s·person	
Sports and Entertainment									
Sports arena (play area)	–	–	0.30	1.5	E	–			1
Gym, stadium (play area)	–	–	0.30	1.5		30			2
Spectator areas	7.5	3.8	0.06	0.3		150	8	4.0	1
Swimming (pool & deck)	–	–	0.48	2.4	C	–			2
Disco/dance floors	20	10	0.06	0.3		100	21	10.3	1
Health club/aerobics room	20	10	0.06	0.3		40	22	10.8	2
Health club/weight rooms	20	10	0.06	0.3		10	26	13.0	2
Bowling alley (seating)	10	5	0.12	0.6		40	13	6.5	1
Gambling casinos	7.5	3.8	0.18	0.9		120	9	4.6	1
Game arcades	7.5	3.8	0.18	0.9		20	17	8.3	1
Stages, studios	10	5	0.06	0.3	D	70	11	5.4	1

GENERAL NOTES FOR TABLE 6-1

1 **Related requirements:** The rates in this table are based on all other applicable requirements of this standard being met.
2 **Smoking:** This table applies to no-smoking areas. Rates for smoking-permitted spaces must be determined using other methods. See Section 6.2.9 for ventilation requirements in smoking areas.
3 **Air density:** Volumetric airflow rates are based on an air density of 0.075 lb_{da}/ft^3 (1.2 kg_{da}/m^3), which corresponds to dry air at a barometric pressure of 1 atm (101.3 kPa) and an air temperature of 70°F (21°C). Rates may be adjusted for actual density but such adjustment is not required for compliance with this standard.
4 **Default occupant density:** The default occupant density shall be used when actual occupant density is not known.
5 **Default combined outdoor air rate (per person):** This rate is based on the default occupant density.
6 **Unlisted occupancies:** If the occupancy category for a proposed space or zone is not listed, the requirements for the listed occupancy category that is most similar in terms of occupant density, activities and building construction shall be used.
7 **Health-care facilities:** Rates shall be determined in accordance with Appendix E.

ITEM-SPECIFIC NOTES FOR TABLE 6-1

A For high school and college libraries, use values shown for Public Assembly Spaces—Libraries.
B Rate may not be sufficient when stored materials include those having potentially harmful emissions.
C Rate does not allow for humidity control. Additional ventilation or dehumidification may be required to remove moisture.
D Rate does not include special exhaust for stage effects, e.g., dry ice vapors, smoke.
E When combustion equipment is intended to be used on the playing surface, additional dilution ventilation and/or source control shall be provided.
F Default occupancy for dwelling units shall be two persons for studio and one-bedroom units, with one additional person for each additional bedroom.
G Air from one residential dwelling shall not be recirculated or transferred to any other space outside of that dwelling.

FIGURE 61: TABLE 6-1 ASHRAE STANDARDS

Shown in Figure 61 are three sections of Table 6-1, one for dormitories, lobbies, and a fitness room. All of these uses will be present in the new residence hall thus it would be complicated to decide which one to use and follow. The knowledge of which one to use could potentially be found by speaking to a LEED professional. From there specific details would need to be known about the HVAC system that will be installed in the residence hall and with all this information it would be possible to see if this credit were achievable. Another complicating factor would be that the residence hall is planning on using both a mechanical ventilation system and a passive ventilation system, windows and doors that are operable. This in turn makes the amount of extra ventilation that would need to be done greater than if you were using just one because the system is dealing with two different air types and has to find a way to meld the two together in a successful and high quality air type. Since this group is missing much of the specific details needed for this credit it will not be considered for further use.

THERMAL COMFORT

THERMAL COMFORT

Intent: *Provide a high level of thermal comfort system control by individual occupants or by specific groups in multi-occupant spaces (ie. Classrooms or conference areas) to promote the productivity, comfort and well-being of building occupants.*

Requirements*: Provide individual comfort controls for 50% (minimum) of the building occupants to enable adjustments to suit individual task needs and preferences. Operable windows can be used in lieu of comfort controls for occupants of areas that are 20 feet inside of and 10 feet to either side of the operable part of the window. The areas of operable window must meet the requirements of ASHRAE 62.1-2004 paragraph 5.1 Natural Ventilation. AND Provide comfort system controls for all shared multi-occupant spaces to enable adjustments to suit group needs and preferences. Conditions for thermal comfort are described in ASHRAE Standard 55-2004 to include the primary factors of air temperature, radiant temperature, air speed and humidity. Comfort system control for the purposes of this credit is defined as the provision of control over at least one of these primary factors in the occupant's local environment.*

This seemed like it would be a rather easy credit to fulfill, and it would be possible to put a room specific thermostat in each suite. After further thought it does not seem like there would be much energy or heat saved because the students who keep their temperature high would most likely cancel out the students who kept their temperature at a lower value. Looking at it in a mechanical way it might also require a very complicated system that would be able to control 40 or 50 different temperatures. This complicated system would then require more maintenance than a regular system and if it broke could be hard to pinpoint where the mishap occurred.

A case study performed by LEED found in their *New Construction & Major Renovation Reference Guide* installed under-floor air systems that allowed air into the building through the floors. This succeeded very well in improving the air quality. For the residence hall this does not seem like a possible option considering that the systems already being installed in the building required penetrations through the steel beams in order to keep the overall height of the building minimized while still supplying the occupants with good-size rooms. The holes in the beams in turn then work to lessen the maximum amount of strength that beam can support and more must be added as reinforcement to ensure the building is safe.

RAPIDLY RENEWABLE MATERIALS

RAPIDLY RENEWABLE MATERIALS

Intent: *Reduce the use and depletion of finite raw materials and long-cycle renewable materials by replacing them with rapidly renewable materials.*

Requirements: *Use rapidly renewable building materials and products (made from plants that are typically harvested within a ten-year cycle or shorter) for 2.5% of the total value of all building materials and products used in the project, based on cost.*

This seems like it could be a possible option because though we are looking for tough and durable materials, this is a residence hall that will have a lot of use, and there are a couple of materials such as cork and linoleum that may stand up to that type of use. Cork is used to make floors that are very similar to hardwood floors, and they could be a possible option for the floors of the residence hall. Cork floors are durable and resistant to wear, and the maintenance required would be limited to repainting the varnish coat over the floor every couple of years. This is of course discounting any unexpected occurrences that might damage the floor. Linoleum could be used in the bathrooms and kitchen area flooring. Obviously this flooring needs to be made out of an easily cleaned surface and something that is waterproof since the bathroom and kitchen areas are more susceptible to spills and water damage. More information about the cost and maintenance issues pertaining to these options is available in the environmental results section.

The rapidly renewable credit would need to be chosen before the whole construction process begins to be successfully achieved. This would be because the materials that fulfilled the credit would need to be chosen and then ordered so that they would be ready to be installed at the correct time in the construction process. This MQP suggests three different types of renewable materials: cork flooring, linoleum, and glass countertops. The costs of each of these three options and their probable locations in the residence hall are shown in Table 27.

TABLE 27: COSTS OF RENEWABLE RESOURCES

Rapidly Renewable Materials						
Material	**Aquired From:**	**Use**	**Square Footage**	**Cost/sf**	**Total Cost**	**Approximate amount of total res hall area (103,383sf)**
Cork	~9 year hearvest time from Cork Oak Trees	Suite Flooring	69,000	$5-$10	$345,000-$690,000	2/3 of total area
Linoleum	Numerous materials harvested frequently	Kitchen/Bathroom Flooring	17,250	$3-$8	$51,750-$138,000	1/6 of total area
Glass	Recycled content	Countertops	8,615	Comparable to granite or stone $70-$100	$603,000-$861,500	1/12 of total area
				TOTAL	$999,750-$1,689,500	
				Actual Res Hall Cost	~35 million	
				%	2.8%-4.8%	

Viewing Table 27 the credit would be successfully achieved at both ends of the cost spectrum. These costs would be comparable to most others that are commonly used in public buildings materials, but would not harm the earth in any dire ways.

INNOVATIVE WASTEWATER TECHNOLOGIES

INNOVATIVE WASTEWATER TECHNOLOGIES

Intent: *Reduce generation of wastewater and potable water demand, while increasing the local aquifer recharge*

Requirements: *Reduce potable water use for building sewage conveyance by 50% through the use of water conserving fixtures (water closets, urinals) or non-potable water (captured rainwater, recycled greywater, and on-site or municipally treated wastewater).*

This credit is fairly self-explanatory. The ultimate goal of the innovative wastewater technologies is that the building will lessen its contribution of wastewater to the public wastewater treatment plan as well as reduce the amount of fresh water that is used to supply things such as toilets and urinals. These appliances use large amounts of water daily, but do not need to be supplied with fresh water that is in popular demand. If the residence hall were to introduce a rainwater harvesting system into the residence hall they could sufficiently provide rainwater to all the residence hall toilets and have a large amount left over for irrigation purposes. This in turn would achieve this credit.

The innovative wastewater technologies credit would be the hardest credit to achieve out of the five chosen because it would require installation of a rainwater harvesting system, which includes a storage facility and maintenance. For the rainwater harvesting, in our area of the world the average annual rainfall is 43.84 inches/year.[19] Multiply the average annual rainfall by the area of the building roof and the residence hall can obtain 910,425 cubic feet of water per year. This is approximately 7 million gallons of water per year. The easiest decision is that the residence hall uses the stored rainwater for just toilets and irrigation purposes; this is the

[19] Annual Rainfall for the United States. http://www.betweenwaters.com/etc/usrain.html

easiest choice because it doesn't require a cleaning process. The toilets of the residence hall would require approximately 700,000 gallons of water to sufficiently supply them for one year. This value is far surpassed by the amount the rainwater would give and leave ~300,000 gallons for irrigation purposes of the residence hall. The material of the roofing would want to be a type that does not absorb a large amount of excess water and instead allows the water to run off it with little loss.

The cost of a rainwater harvesting system would be substantial up front, but the savings found through not paying for toilet water or irrigation, which could require any amount WPI wanted, purposes would far surpass the larger initial cost. A more complex gutter system would be needed where the complexities would be in the fact that screens would need to be installed at the ends of the gutters so that large debris could be trapped before the water enters the storage tanks. Since the residence hall has two HVAC containers that sit on the roof it could be the decision of WPI to decide if they wanted a gutter system that was also on those as well as the other sections of roof, and funneled the water from up there down to the water at the normal height roof and then on. This gutter system would also require weekly maintenance to make sure that there are no blockages or large pieces of debris that are blocking the water and creating overflow.

The next cost would be for the storage containers for the captured rainwater. The best size tank for the residence hall would be around 15,000 gallons which would include a system of 3 or 4 tanks. This size would be good because WPI would need to be able to store a large amount of water at one time, but it does rain frequently enough that water does not need to be stored for long periods of time. The cost of this system would be approximately $10,000 plus and would depend upon whether they needed to be specially made for the residence hall or if they are available on demand. The material of the storage tanks would be what determined the cost and availability. For the residence hall, where there is limited space, the tanks would most likely be put underground so that would also affect the selection of material for the tank.

The last part of the rainwater harvesting would be plumbing that would bring the rainwater to the supply of water for the toilets of the residence hall. This would be the most complicated part of achieving this credit because it would require two separate plumbing systems in the building because the rainwater cannot run through the same pipes as drinking water for the residence hall. There would be pumps and other appliances needed that would get the water from the below ground tanks to the bottom floor of the facility into the plumbing. The pumps would be one of the more expensive parts of the system, but are obviously an essential. How much water would be required to supply the toilets of the residence hall follows.

The residence hall houses approximately 60 toilets. This includes all suite bathrooms and the public restrooms available on the first floor. Assume the average person uses the bathroom 5 times a day. Using the information from the background, conventional toilets use 1.6 gallons of water per flush. At 5 flushes a day that is 8 gallons of water per day per person. In the residence hall there are 4 people to a toilet so for 60 toilets we have a total of 1920 gallons of water used a day. WPI pays for their water per cubic foot, so 1,920 gallons equals 257 cubic feet of water per day. That means that in a typical year WPI pays for 93,500 cubic feet of toilet water per year. At approximately $1.50 per cubic foot that is $140, 250 per year. If WPI were to install dual-flush toilets the water usage would be about 4.8 gallons per day per person. That is assuming that 4 of the 5 flushes are the half flush (0.8 gallons) and the fifth is a full (1.6 gallons). That would be approximately 56,000 cubic feet of toilet water a year that would cost WPI $84,000. The comparison between how much water is used by regular toilets versus dual flush toilets can be seen in Figure 62.

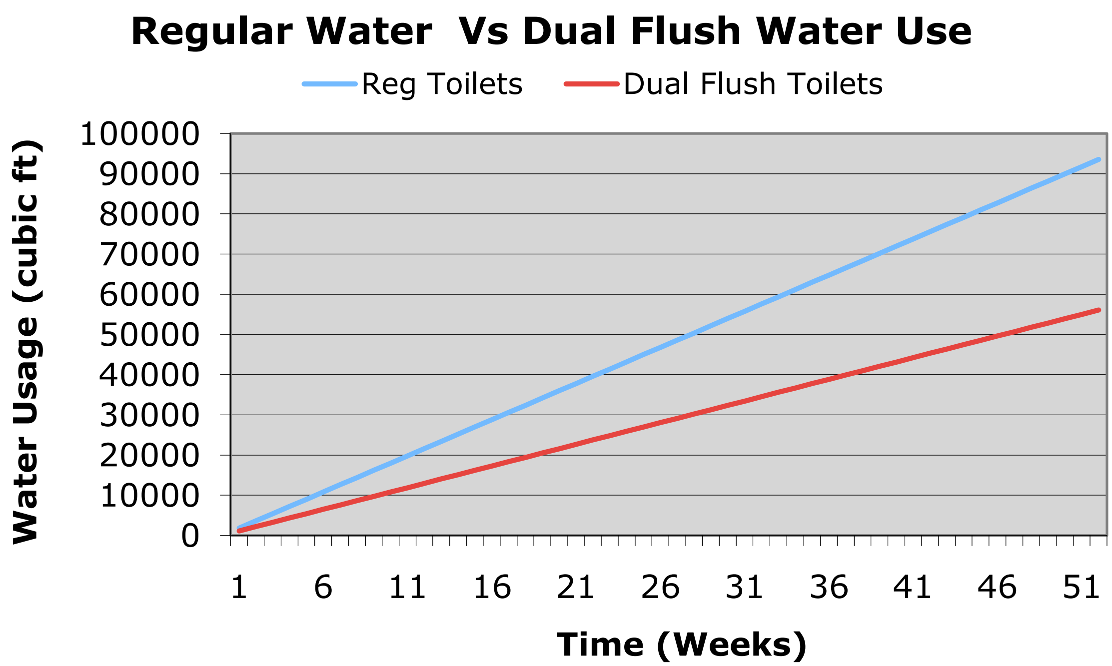


FIGURE 62: COMPARISON OF WATER USE GRAPH

That is a difference of $56,250 per year that WPI could potentially save if dual-flush toilets were used. Over a 5 year period that is a $281,000 savings in water cost and over 10 years a $562,000 savings just in toilet water use.

The cost of dual-flush toilets can run from 250 to 650 dollars to buy, and they have no extra installation or maintenance fee beyond that of conventional toilets. Thus if WPI chose to buy the most expensive dual-flush toilets, 60 toilets at $650 apiece costs $39,000. This more expensive upfront cost would be paid for in less than one year by the savings that would be seen in paying for water usage. It should also be considered that conventional toilets can cost approximately $100-$400 which is comparable to the cost of the dual-flush toilets. So in essence WPI would not be spending a much greater amount of money at first, but would be saving very large amounts through the decrease in water usage.

SITE SUSTAINABILITY

SITE DEVELOPMENT, MAXIMIZE OPEN SPACE

Intent: *Provide a high ratio of open space to development footprint to promote biodiversity*

Requirements: *Where a zoning ordinance exists, but there is no requirement for open space, provide vegetated open space equal to 20% of the projects site area.*

Note: For projects located in urban areas that earn SS Credit 2 (met), vegetated roof areas can contribute to credit compliance.

The amount of open space is limited in the surrounding residence hall area is already taken up for other buildings and planned parking spots and a garage. Though there is limited space there is a green roof being created on a section of the residence hall roof and there are some options where seating areas could be placed that would provide an open space for workers to take lunch or students to hang out.

The size of the open space that would be needed was calculated by multiplying the footprint of the building by 0.2. The project site area is 43,277 square feet. This means that the required open space needed to satisfy this credit would have to be 8,655 square feet. In a site this small it seems unreasonable to think that creating an open space of this size is possible. The one factor that may make this work is that the green roof, which is being constructed on a section of the hall's roof, can count towards the open space and would help to alleviate the size. The area of the green roof centered in the middle of the residence hall roof is about 6000 square feet which leaves the hall with a little less than 3000 SF of area left to successfully fulfill the required amount. There is an amount of space between the parking garage and the residence hall that is approximately 4000 SF of space, and it could potentially be turned into a pleasant outdoor area with some seating areas and green space. The space can be seen in Figure 63. Although there is already being a green roof installed on a section of the residence hall roof the occupants of the building won't

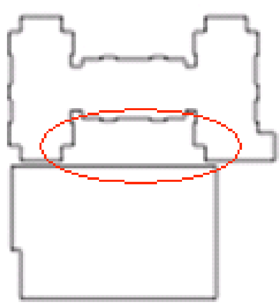


FIGURE 63: BIRDS EYE OF RESIDENCE HALL PROPOSED OPEN SPACE

be able to use the roof as a quiet outdoor space to relax. It would be better for all and ensure that this credit would be achieved if the green roof were available to occupants. The type of green roof being installed would not have to change, but given that it would be experiencing use there would be maintenance required. This maintenance would consist of ensuring that the levels of soil and grass stay consistent and that any repairs would be attended to quickly and correctly.

ALTERNATIVE TRANSPORTATION

ALTERNATIVE TRANSPORTATION, BICYCLE STORAGE & CHANGING ROOMS

Intent: *Reduce pollution and land development impacts from automobile use*

Requirements: *For commercial or institutional buildings, provide secure bicycle racks and/or storage (within 200 yards of a building entrance) for 5% or more of all building users (measured at peak periods), And provide shower and changing facilities in the building, or within 200 yards of a building entrance, for 0.5% of Full Time Equivalent occupants.*

This seemed like a reasonable goal because it seems typical to provide bike racks outside of a student dorm. Considering our specific college though, WPI's campus is very small when compared to others. Thus it is not essential for students who live on campus to have a mode of transportation that is not walking because no one campus building is very far away. The changing rooms are taken care of with private restrooms in each of the suites and public restrooms available to all other users of the building.

A commercial bike rack ranges from about $100 to $500 dollars. Both movable racks and fixed are around the same prices where the quality of the bike rack will be the deciding factor in how much the bike rack will cost. Overall the price of buying and installing bike racks for the new residence hall would not be even comparable to the cost of constructing the hall. Even though some may not like the looks of bike racks or think that there may not be room for one in front of the residence hall it would be perfectly fine to install one by the entrance to the garage or off to the side. A bike rack does not require more than 50 SF of space.

OPTIMIZE ENERGY PERFORMANCE

OPTIMIZE ENERGY PERFORMANCE

Intent: *Achieve increasing levels of energy performance above the baseline in the prerequisite standard to reduce environmental and economic impacts associated with excessive energy use*

Requirements: *Whole Building Energy Simulation (1-10pts)*

Demonstrate a percentage improvement in the proposed building performance rating compared to the baseline building performance rating per ASHRAE/IESNA Standard 90.1-2004 (without amendments) by a whole building project simulation using the Building Performance Rating Method in Appendix G of the Standard. The minimum energy cost savings percentage for each point threshold is as follows:

10.5%	*1 pt*
14%	*2 pt*
17.5%	*3 pt*
21%	*4 pt*
24.5%	*5 pt*
28%	*6 pt*
31.5%	*7 pt*
35%	*8 pt*
38.5%	*9 pt*
42%	*10 pt*

This seemed like it would be a good credit to go for at the beginning. It is one credit that allows you to get 1-10 points. This credit looks into all energy aspects of the building from lighting to mechanical systems, to water usage. LEED supplies the designer with a template that must be filled out.

The template shown is for the residence hall and was obtained from Lynne Deninger from Cannon Design. It should be noted that this is not considered a final document and any information obtained from it is not to be considered the actual amount of energy that the building will use in the future. This template shows all of the energy considerations that any building could have, and there is a place where the baseline amounts of energy for the specific type of energy a building can use may be put in. These baseline amounts can be taken from a similar building whose information is easily obtained or it can be taken from the LEED reference guide where typical amounts of energy used for certain types of buildings are provided. Once these areas have been filled in, there is an area where you put in the expected values for your proposed design.

Table 1.8.2 - Performance Rating Table - Performance Rating Method Compliance

End Use	Process?	Proposed Design Energy Type	Proposed Design Units	Proposed Building Results	Baseline Building Units	Baseline Building Results	Percent Savings
Exterior Lighting - Garage		Electricity	Energy Use (kWh)	47,657.5	Energy Use (kWh)	86,648.9	45 %
			Demand (kW)	7.7	Demand (kW)	14	44.7 %
Space Heating		Natural Gas	Energy Use (therms)	16,047.9	Energy Use (therms)	51,004.4	68.5 %
			Demand (MBH)	1,037.9	Demand (MBH)	2,562.9	59.5 %

FIGURE 64: OPTIMIZE ENERGY PERFORMANCE TEMPLATE 1

It can be seen from this section of the template how the proposed design specifies the type of energy and the expected consumption which is an estimated cost based off of similar buildings, and the baseline design then specifies the typical amount of that energy that is consumed and then the percent of energy saved is calculated in the last column on the right. Finally the total percent of energy saved after comparing the proposed building to the baseline building is found, and the number of points achieved is credited.

	Proposed Design		Baseline Design		Percent Savings	
	Energy Use	Cost	Energy Use	Cost	Energy	Cost
Total:	11,205 (MBtu/year)	$340,207	16,522 (MBtu/year)	$460,383	32.2 %	26.1 %

FIGURE 65: OPTIMIZE ENERGY PERFORMANCE TEMPLATE 2

As can be seen in Figure 65 the total energy savings was 32.2% which would be equal to 6 points. The correlation can be seen on the previous page. Now since we know that WPI is only achieving 4 points in this credit we can assume that this template is looking at the optimal point of view of the residence hall.

This credit became one of the final five credits to be chosen because from the information received by the Cannon Designer it seems that WPI was planning on potentially achieving 6 points in this category, proven in the template in Figure 65. Considering the present WPI is obtaining 4 points for this credit meaning that they have successfully planned for this building to save 21% total energy that the building uses. To gain just one extra point WPI only has to jump that percent up 3.5% and increase the amount of saved energy to 24.5% of the total energy use of the building. Though this MQP cannot talk about certain HVAC or mechanical systems that WPI could consider to achieve this because we don't know what WPI is planning on using, it does not seem like a far stretch to achieve that extra 3.5% and gain one extra point.

The extra costs associated with obtaining this credit would be that WPI would most likely have to look into potential solar systems or other more drastic energy saving systems. These energy saving systems would be very costly, but if WPI were to decide to go further in this direction then they might be able to cut out a few other credits because going this extreme for this credit would potentially allow WPI to achieve more than 1 extra point in this credit.

Shown in Table 28 is a succinct version of the results section that shows the five credits that this MQP believes should be pursued and the approximate cost they would incur. These credits have made use of the green building and material options that were reviewed and have formed a complete package of how WPI can achieve a higher level of LEED certification and be as environmentally friendly building as possible.

TABLE 28: COMPLETE COST REVIEW OF LEED CREDITS

Credit	Points Acquired	What to do	Cost	Installation/ Maintenance	Vendors
Alternative Transportation: Bicycles & Changing Rooms	1	Buy & Install commercial bike rack outside of residence hall	~$100-$500	Extra effort to install, no maintenance after installation	Dero: Innovative Bike Racks, Highland Product Groups, LLC
Innovative Wastewater Technologies	1	Rainwater Harvesting & Dual Flush Toilets	~$30,000	Weekly maintenance is required for the gutter systems and storage tanks	RainStay System Design and Installation, Rainwater Recovery Systems, New England Rain Barrel Company
Site Development: Maximize Open Space	1	Green Roof & Open space between parking garage and residence hall	~cost of maintenance of occupant available green roof and open space behind residence hall	Maintenance for the green roof, and then traditional landscaping/ maintenance for the open space	Roofscapes Inc. Tremco
Optimize Energy Performance	1pt-10pt	Consider other energy saving systems for the residence hall	~cost of whatever energy saving system is decided to install	Maintenance of the system	Horizon Energy Systems, Solar Electric Power Company
Rapidly Renewable Materials	1	Cork & Linoleum Flooring, Glass Countertops	$999,750-$1,689,500	No maintenance out of the ordinary, repainting of finishes every 2+ years	DuroDesign, Expanko, Topshield, Green Floors, Vetrazzo

CHAPTER 7: CONCLUSIONS & RECOMMENDATIONS

RESIDENCE HALL STRUCTURE

Based on the results of our structural designs and cost estimates, the most suitable system for the residence hall structure is a concrete slab and steel form deck atop rolled steel beams. This is in agreement with Cannon Design's choice for the actual structure, which uses a similar system. This section will cover some of the salient features of the chosen system, and will discuss briefly the reasons why the other systems did not satisfy the feasibility criteria as satisfactorily.

One of the most important aspects of a structural design, from WPI's perspective, is cost. Unlike other building materials such as finishes, enclosures, and opening, paying more for a structural system does not necessarily coincide with having a higher quality building. In comparing the cost estimates of the systems (Table 29), it was found that the chosen system was the least expensive of the four. Despite this, the values do not vary greatly. The difference between the least and most expensive option is about one-hundred thousand dollars, or about 5% of the total structural cost. This 5% is comparable to the accuracy of the cost estimates. Consequently, it cannot be said with certainty that the chosen system is the least expensive, but it is very likely that it is one of the more economically sound decisions.

TABLE 29: COST COMPARISON OF RESIDENCE HALL STRUCTURAL SYSTEMS

Building Element	Total Cost	Cost per SF
Joist System	$ 2,114,000	$ 21.14
Slab and deck with Beams	$ 2,069,000	$ 20.69
CIP (no deck) System	$ 2,171,000	$ 21.71
Precast Slab System	$ 2,092,000	$ 20.92

Another important consideration in choosing the most appropriate method is the depth of the floor systems. The overall depth of the building must be kept under 55' to avoid reaching high rise status. There are a number of implications with exceeding this height, and the result would be a higher project cost. From a site walk at the new residence hall with Project Manager Neil

Benner of Gilbane, it was found that in some areas of the building, the ceiling heights of the actual project are 7'-6" in some critical locations. This is typically the minimum allowable ceiling height for serviceability purposes. Both the slab thickness and the depth of the beams and girders were checked to make sure that at least the minimum ceiling height could be achieved in all areas of the building. Figure 66 shows half of the building with all beam and girder sizes for the chosen system.

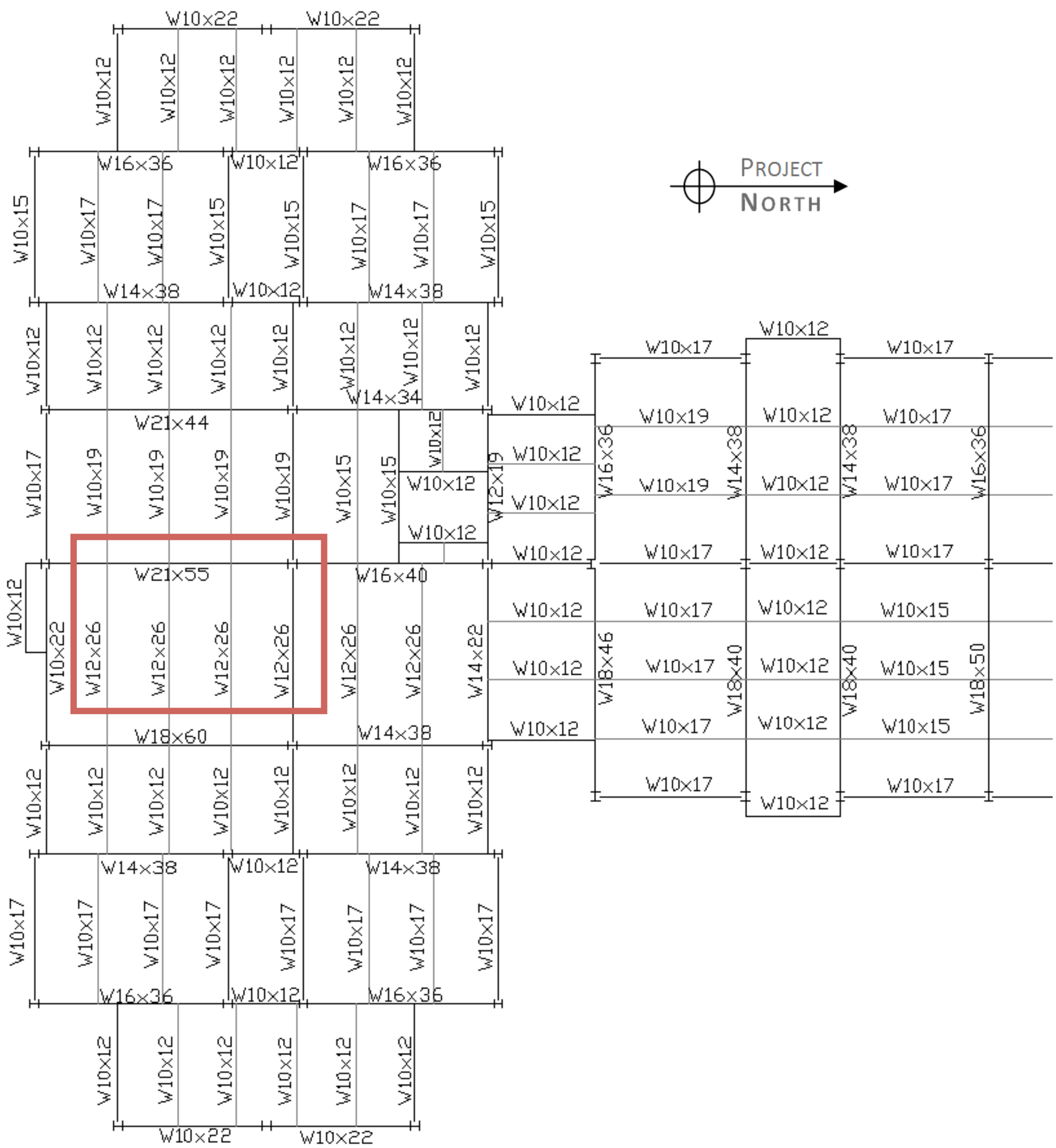


FIGURE 66: BEAM AND GIRDER SIZES FOR SLAB AND DECK SYSTEM (MOST CRITICAL AREA IN RED)

The most critical area of the building can be seen highlighted in red in Figure 66. The slab in this area totals 6” in depth, the beams about 12”, and the girder about 21”. An east-west interior elevation showing the most critical beams can be seen in Figure 67. The minimum ceiling height is a foot short of the depth of the beams, allowing adequate space for mechanical electrical and plumbing. Alternatively, the ceiling height may be raised, and beam penetrations may allow for the running of the MEP elements.

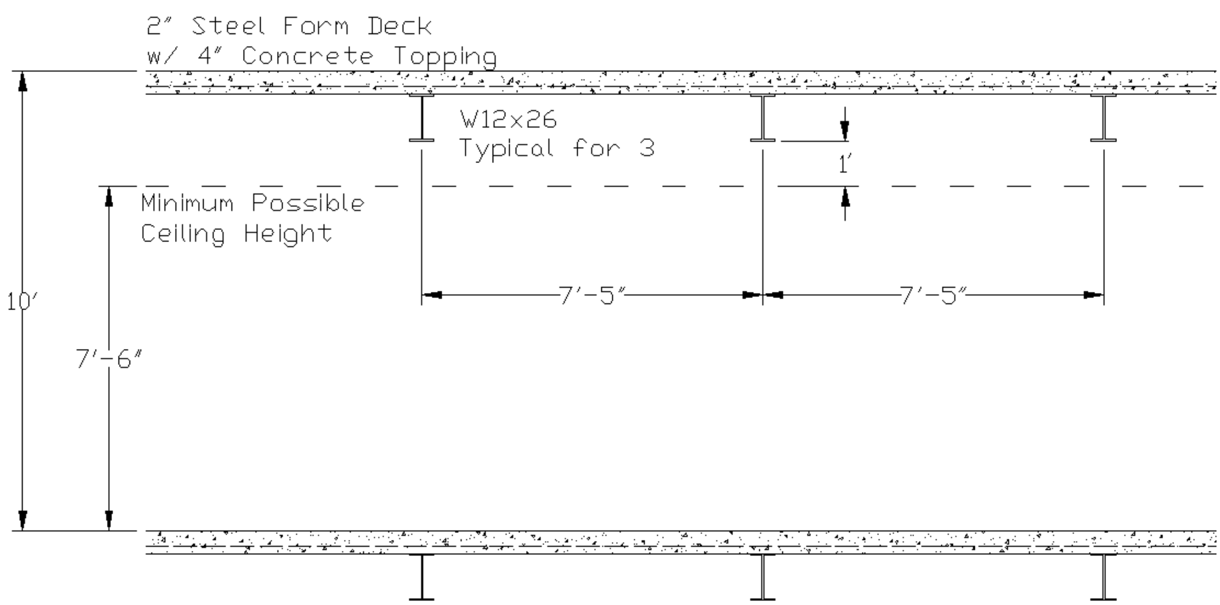


FIGURE 67: EAST-WEST INTERIOR ELEVATION OF THE MOST CRITICAL BEAM DEPTH

Figure 68 is an interior elevation of the most critical girder depth. Penetrations of the girder would be required in order to run MEP elements through the ceiling space in this area. If the ceiling height was set at 7’-6”, there would be 3” of space in which to place the ceiling. Alternatively, the ceiling height could be increased, and the girder could be encased in gypsum wall board so that it protrudes slightly from the ceiling. In either case, the dimensional requirements regarding ceiling height are met by the chosen system of concrete slab and steel deck on rolled steel beams.

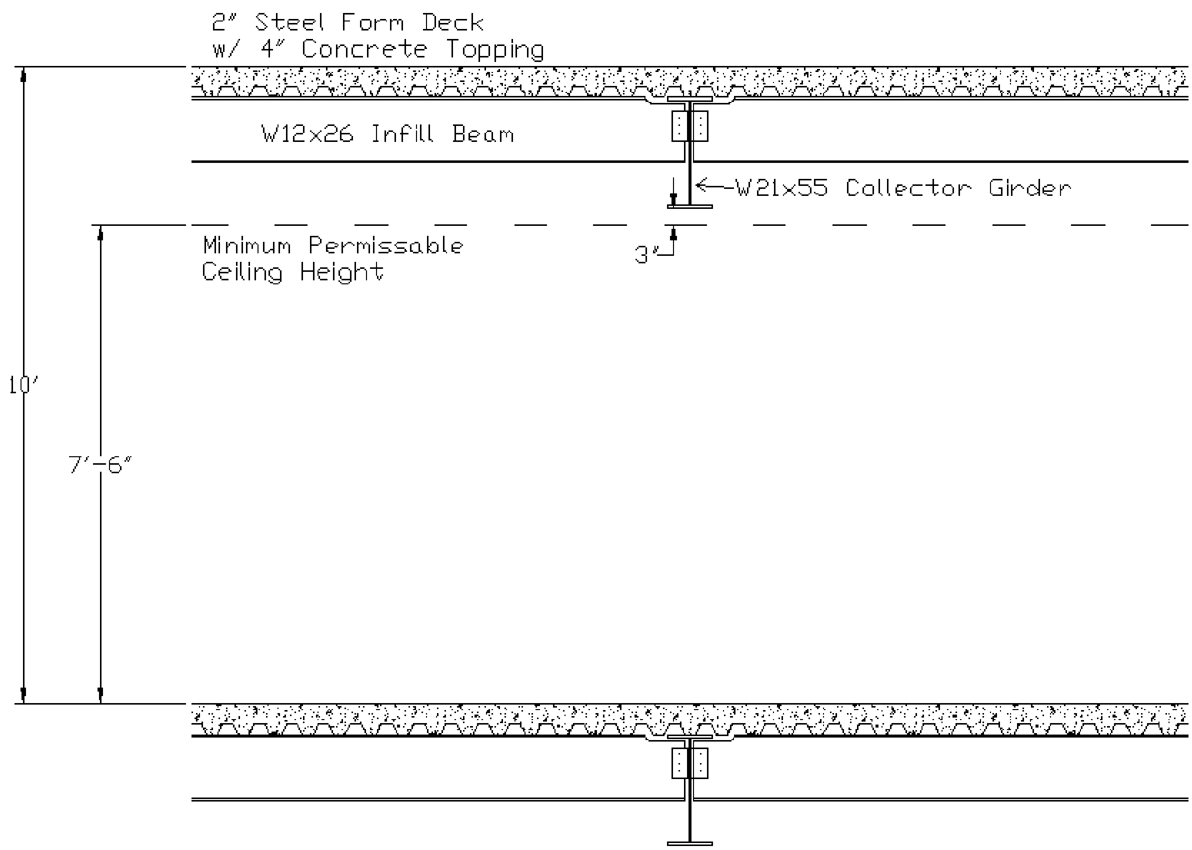


FIGURE 68: NORTH-SOUTH INTERIOR ELEVATION OF THE MOST CRITICAL GIRDER DEPTH

In the case of the cast-in-place deck without steel form deck, cost was the factor governing the decision not to choose the system. With the incorporation of the Worcester location index for formwork labor of 129.5, the cost of the formwork is about 20% higher than the alternative of metal decking. For this reason, cast-in-place construction has been almost completely phased out of construction in New England. With only one extra inch of ceiling height (5" vs. 6" slab), the dimensional benefits simply do not outweigh the extra costs.

With the precast slab system, the cost is so comparable to that of the chosen system that it is almost inconsequential. The deciding factor in not selecting this system was the slab thickness. The total slab thickness of 8" with a maximum girder size of 21" leaves only one inch for the ceiling in the most critical areas. While this is possible, the end effect is either a 2" reduction in either all-around ceiling height or space above the ceiling. Another factor weighing on the inappropriateness of this choice is the availability of precast in the Worcester area. Relatively low supply and high demand means that the waiting time involved in ordering precast slabs could be significant, and could have a negative effect, especially due to the fast-track nature of the project. On the positive side, the assembly of precast slabs is quick and simple and can be done despite inclement weather conditions, unlike cast-in-place concrete. But like the cast-in-place without steel deck system, the benefits do not outweigh the drawbacks.

Concerning the steel joist system, the reasons not to choose it was not as clearly cut. With a slab thickness only ½" shallower, the same critical girder depths, and a probable duration of construction very similar to the chosen beam system, the final choice came down to cost. The upside to using open-web steel joists is that there is no need to field-cut penetrations in the infill members. Penetrations would still have to be cut in the girders, however. It is possible that if the design choice of the beam system was to cut penetrations in the beams to raise the ceiling height, this added cost may bring the chosen system up to or over the cost of the joist system. With the information gathered in this report, though, the final decision was to recommend the cast-in-place slab and metal deck atop beams rather than joists.

PARKING GARAGE STRUCTURE

Based on the results from the parking garage design section, the best method for designing the parking garage is to use precast concrete. This is also the same design in which cannon design chose to go with. The following paragraphs describe why a precast parking garage instead of steel is best suited for this design.

There are several aspects to a steel framed garage that will encourage added costs to the design. An exterior masonry wall can be designed around the garage to make it visually appealing to its surroundings, but an added cost would be incurred. A steel guard rail can be placed between columns to enclose the parking bays, but this may not be visually appealing to pedestrians. The complexity of having two rows of columns running along the interior of the building not only decrease the span length of the main parking bays, but they require harder conditions in which members must fit. Using a steel framed garage encourages the use of more materials and resources when a simple yet effective design is most desirable in this situation.

The precast garage is much better suited in this design for several reasons. The benefit of only having one row of columns running down the interior of the garage makes the construction and framing process much easier. All precast concrete pieces are capable of being directly shipped to the site from the manufacturer and then erected within a matter of days. Each column can be place atop the foundation, joined together by the girders and then the floors systems can simply be lifted and dropped into place. No form of exterior wall is need and the only costs inquired in this process are manufacturing and erection. The precast parking garage will allow more room for the flow of traffic on each level, cut down on additional construction costs and visually acceptable for its environment.

ENVIRONMENTAL CONSIDERATIONS

The new residence hall has a very definite possibility to achieve a Gold level in the LEED certification process. From the checklist that the group received from Alfred Dimoero, Assistant VP of Facilities at WPI, there were sufficient credits checked off and planned for at the beginning of the project to achieve a gold level to start, but this MQP made the assumption that there were more than enough credits to check off. This meant that during the construction process if a credit would cause a delay in the schedule or cost more than expected it could be dropped at little to no cost and the building would still achieve the level that they had been publicly speaking about. Thus this MQP decided that the residence hall needed one more credit to achieve gold level, and that we would research five credits in depth to ensure that a Gold level was achieved.

Out of all the green research that was done throughout this MQP most of the credits seemed extremely possible to do and little extra cost would need to be invested by WPI. There are two credits that would require a large amount of extra effort and money to successfully complete.

The rainwater harvesting system is the first one. Since without this credit the residence hall would still be able to achieve Gold level certification, WPI would have to be whole-heartedly committed to trying to decrease the amount of resources they use in the residence hall. The rainwater harvesting system paired with the dual flush toilets would work to eliminate the use of fresh water for uses that do not need it at all.

The pros of including this system in the residence hall would be that WPI would be drastically reducing their use of fresh water and could hope to set a standard for all future buildings built here at WPI or in the City of Worcester. Even if WPI did not want to go as far as installing the rainwater system, the dual flush toilets would make a huge difference by themselves.

The cons of including this system in the residence hall are that it would have to be a decision made at the beginning of the process. It must be considered while designing the building and when the materials of the roof are chosen. Extra plumbing systems will be needed to bring the stored rainwater to the toilets, and those pipes must be separate from any that carry freshwater as the rainwater won't be purified or disinfected. The extra up-front cost will also have to be considered as it will be quite substantial, not only because of having to buy the materials for the system but as well as maybe having to install the storage tanks below ground which will cost extra labor fees. Lastly it would be a system that would require maintenance on a regular basis.

The second credit is the optimize energy performance credit. This credit could be a large amount of extra money or not too much extra effort at all. Because of the limited information available to this MQP they looked into the most time taking and more expensive option. This least optimal way that this credit would have to be achieved is if WPI had to install a system such as a solar option that would help to reduce their energy usage, but would require a large amount of upfront costs and installation as well as maintenance throughout its life. Even though this would be a drastic decision to make, it would be very beneficial to the environment as well as potentially allow WPI to reach an even higher level of LEED certification than was ever expected.

Over all WPI is entirely able to achieve a Gold LEED certification without a large amount of extra cost and that cost would be very easily discarded after a few years of the residence's hall's life. Overall the green systems and materials researched would be very beneficial to WPI in achieving not only certain credits, but in creating a total environmentally friendly building that has done the utmost to be as energy efficient and fresh water friendly as possible.

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Appendix A: MQP Proposal

Proposal of the Major Qualifying Project:

Residence Hall Construction

(Project Code: LDA-0806)

Submitted to:

Prof. Leonard Albano, Advisor

On October 4, 2007

By:

Michael Belsky

Matthew Desjardin

&

Hallie Schiess

Introduction

Over the last few years, the Worcester Polytechnic Institute has been involved in many construction projects as a part of their master plan. This plan calls for developing a vibrant lower campus linking WPI's main campus with the downtown Worcester area and Gateway Park, an 11-acre mixed-use life sciences-based campus. A new residence hall, arts walk, and parking garage are currently being constructed on a lot located between Dean St. and Boynton St, next to Founders Hall, and will be completed in the fall of 2008.

The new apartment-style residence hall will accommodate 232 upperclassmen with a variety of state-of-the-art facilities. Every student will live in a four-person apartment including a full kitchen, living room, compartmentalized bathrooms, and either a single or double bedroom. The building will also include a recreation and fitness facility, technology suits on every floor, music rooms, and full wireless Internet access. WPI alumni and friends will be the major source of funding for this project by a host of name giving opportunities for the various facilities within the building, the main lobby being the most expensive with a cost of two million dollars. The new residence hall will also be the second building on the WPI campus to receive certification from the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED).

The building's exterior finishes were designed to coincide with its neighboring buildings. The outside will consist of mainly glass and masonry concrete. The masonry will blend in with the surrounding brick buildings and the wide expanse of glass will compliment Founder's Building whose new restaurant has whole walls of windows.

The Gilbane Building Company was hired as the general contractor of this project and has just recently completed a parking garage at WPI's Gateway Park. Gilbane Incorporated is one of the largest privately helped family-owned companies in the construction industry with revenues topping three billion dollars.[20] They have 22 offices nation wide and base themselves on values

[20] http://www.gilbaneco.com/

such as integrity, teamwork, loyalty, and dedication to excellence.[21] Cannon Design of Boston, an international architectural, engineering, and planning firm, was hired as the project design team. Cannon was founded over 60 years ago. They have over 700 employees who work out of 15 offices. Projects are being completed in 42 states, 8 provinces, and in Europe and Asia.[22]

Scope of Work

This project will consist of three sub-sections of study all concerning the new WPI residence hall. The first section is considering possible structural alternatives for both the residence hall and parking garage. We will not be changing the footprint of the buildings or the existing layout of rooms. Depending on our discoveries however, we may choose to alter the frame's layout without changing the architecture. Alternative floor systems will be researched and designed for the residence hall. We will be choosing different column and girder sizes considering gravity loads, dead and live, as well as lateral loads, wind and seismic. A foundation will then be designed that successfully supports each of our chosen alternatives. A second structural activity will be to research two different scenarios for the parking garage: pre-cast concrete and steel frame with concrete decking.

The next section of our report will be a feasibility assessment of our structural work. This study will focus on cost, constructability, and scheduling. It will be performed on each of the alternative designs for the residence hall and parking garage. The construction cost estimates will include all structural costs, from the floor through the frame, and down to the foundations.

The final section of the project is an environmental study that will involve two parts. The first part concerns the US Green Building Council's LEED certification system. We will research how much more it might cost to achieve a higher level of LEED certification than is currently expected. The expected level is silver, which is the third level in succession to Gold and Platinum. This will include researching the requirements for achieving a gold level as well as

[21] http://www.gilbaneco.com/

[22] http://cannondesign.com/

what WPI is already doing and how much it costs. We will evaluate what that higher level will mean for WPI and the residence hall in the future, and if achieving that higher level warrants the additional cost.

The second part of the environmental study will involve researching alternative green building options that were open to WPI other than a green roof, such as rainwater harvesting or a grey water system. This effort will include noting the costs of each alternative and a look into how each option would affect the operating cost of the residence hall.

This MQP at the end will have looked into numerous other options that were open to WPI when deciding how to build the residence hall and will provide comparisons of the two and our conclusions as to the best decision.

Capstone Design

To achieve the capstone design needed to fulfill our degree requirements our project will consist of redesigning the new WPI residence hall in terms of structural and environmental alternatives. The project will address the following Capstone design considerations: economic, environmental, sustainability, social, health and safety, and constructability.

Economic

We will be researching different structural material and layout options. A complete cost estimate of the structural elements will be performed for every alternative for both the residence hall and parking garage, and will weigh on the appropriateness of each. The feasibility of any green options will be judged considering construction, operating, maintenance, and life-cycle costs.

Environmental

An in-depth analysis of LEED construction will be performed and different options will be investigated to see if a higher level of LEED could be achieved (silver is the current target level). Alternative green structures will be researched other than the existing green roof and compared. The environmental effect of these options will be explored and taken into account in our conclusions.

Sustainability

When the issues of LEED construction and the green roof are addressed, sustainability will be parallel with those. Several aspects of LEED focus on components of the building, such as alternative water sources, that have the ability to partially or fully sustain themselves. In addition, the alternative green structures will be considered in terms of their sustainability considering water, cost, amount of material used, etc.

Constructability

The alternate floor systems and structures we will be exploring will all be standard building techniques, but there are other considerations to take into account. The availability of the materials required for each alternative will be reviewed. In addition, the length of construction time will be noted. We will also explore any unique construction requirements a system may entail. These factors will be considered in our conclusions concerning best choice.

Social

In the background of our report we will research how the new residence hall and parking garage will affect the WPI campus in terms of its students and how it will affect the surrounding community. We will also look into how having more upperclassmen live on campus will affect the WPI community.

Health and Safety

To ensure the safety of all building residents, we will be abiding by all required building codes and doing a structural analysis and design of the building to ensure its safety. It will always be a goal during the project to provide the healthiest environment for the students to live in, through ensuring a sound structure and lessening the environmental impact.

Methodology

This project will take three terms to complete. It will culminate with a paper reporting our methods, findings, and analyses, and will include a segment describing how our work incorporates the requirements for capstone design. When appropriate, drawings will be made using AutoCAD to document our layout designs, while all sets of numerical data will be organized in spreadsheets for convenient reference.

Structural Design

Residence Hall

Using the plans for the new residence hall, we plan to design the columns and girders of the building without changing the footprint. The frame we choose to use may not match exactly the one designed by the architects and engineers, but it will not interfere with the building's functional design. This process will involve identifying the bays in the building and specifying the typical and atypical areas

Once we have selected our typical and atypical areas, the group will begin to explore alternate floor systems. The following systems will be designed using loads specified by the IBC: rolled steel beams with metal deck and concrete topping, open web joist with metal deck and concrete topping, rolled steel beams with cast-in-place concrete slab, and rolled steel beams with precast concrete slabs. When designing for the open-web joists, it will be necessary to examine each bay and apply spacing rules set by the Steel Joist Institute for joists and bridging, whether horizontal or diagonal. When substituting pre-cast planks or cast-in-place slab for the metal deck construction, it may be necessary to adjust the beam spacing to accommodate for maximum spans and available lengths. Once each system has been designed to our needs, the weight of each system will be computed.

The next step is to design the frame of the building. We will start our design by focusing on the gravitational loads in the building. These include the live loads obtained from the IBC, dead loads from the floor systems, dead load allowances from ASCE, any unique dead loads such as the green roof, and snow loads. Member sizes will be chosen for the gravitational loads. The columns of the building will then be analyzed and designed for lateral loading. This includes wind and seismic loading. Computer programs may be utilized to aid in our structural analyses. The most appropriate size of the structural members will then be chosen using the AISC LRFD Specification and a steel design manual as reference. The result of this section will be four unique frame designs, one for each of the floor systems.

During the design process for the new residence hall, focus will begin on the typical regions of the building. These are the simply shaped, often repeated bays within the structure. From there the design of atypical areas, for example the unique spacing of the columns on the first floor that allows for wide doors, will commence that requiring a more in depth and unique layout design.

A foundation for the residence hall will then be created that will successfully support the design loads of our building. The weight of the building will be calculated using the weight of each floor system and different foundations will be designed for each separate system that includes the weight of the columns and that specific floor system. The strength of the soil will be procured from an actual report to aid in proper design of the foundation and lateral loads.

Parking Garage

We propose to also develop a structural design for the parking garage as well. Two different construction possibilities will be considered, pre-cast concrete and a steel frame with concrete decking. The footprint of the building and all of the requirements such as clearances, capacities, and loads will be considered when designing the frame of the parking garage. Similar to the residence hall, computer programs may be utilized to analyze stresses, and concrete and steel design specification and reference manuals will be employed to choose appropriately sized members. Typical foundation elements for each structural option will be designed.

Cost, Constructability, and Scheduling

The feasibility of all structural alternatives will be evaluated in terms of cost, constructability, and scheduling effects. For the residence hall, a complete cost estimate of the structural elements will be performed for each of the alternate floor systems using data from R.S. Means construction cost data publications. This would include the elements of the floor systems, the girders and columns supporting them, and the foundation. The estimate will take into consideration all required materials, labor, and equipment, and will be adjusted by division for the Worcester area.

The methods of construction for each alternate will be reviewed to check for unique considerations. For example, with pre-cast concrete slabs, it may not be possible to continue building higher stories of the frame until all slabs are in place. The time required for construction may vary between systems as well. These considerations will have an effect on the scheduling, which could translate into a monetary effect, and must be considered when determining our conclusions regarding the most rational choice.

A similar study into the parking garage alternates will allow us to conclude which is more feasible.

Environmental study

USGBC's LEED certification

The new residence hall at WPI will be Leadership in Energy and Environmental Design (LEED) certified by the U.S. Green Building Council (USGBC). Out of the possible certified (minimum), silver, gold, and platinum, the building is expected to be ranked as silver. In a study of the sustainability and environmental friendliness of the building, we will examine possible ways to increase the ranking. This would be achieved by altering the design and construction methods to incorporate green practices specified by the USGBC, therefore increasing the number of points the building receives. The standard calls that for a Silver Rating the building must acquire 33-38 points and a Gold Rating requires 39-51. Thus at maximum, the new residence hall only needs to achieve 6 points extra to surpass the silver. These extra points may be obtained through numerous ways, examples include further improving an already green system or by adding in a new application that wasn't in the initial plan.

We propose to examine the list of how to gain points and decide on feasible practices that could be incorporated into the design of the new building. A multi-dimensional analysis of these "point-makers" will include variables such as constructability, initial cost, life-cycle costs, and benefits. The many benefits can include a boost of the school's public image, sustainability of the building, and better health and safety of the residents. The goal is to decide, based on these many factors, whether or not each practice could be considered sufficiently beneficial to justify the cost.

Alternative green structures

There are numerous green and environmentally friendly construction options that are becoming more and more acceptable in the construction industry. We will be researching these different options, including grey water systems, rainwater harvesting, dual-flush toilets, and geothermal heating. A cost analysis will be done for each to see how it compares to the green roof chosen by WPI for the new residence hall. This analysis will take into account future costs such as operating, maintenance, and life-cycle costs. These factors will be compared and evaluated against one another.

Group and individual goals

As a group, we plan to have a good foundation on which to build our individual efforts. This basis includes the layout of columns, beams, and girders, the design of the several floor systems, and the associated gravity load design for each. It will also include a good understanding of what makes a building environmentally friendly, and a basic understanding of the LEED rating system. We hope to have this group effort complete in the beginning of November. This will allow us ample time to focus our efforts on our individual research for the balance of B-term and much of C-term.

Beginning after Thanksgiving break at the latest, our focus will shift to our specific areas of interest. Michael will focus first on the lateral loads associated with the residence hall, and design structural frames for those loads. He will then focus on the parking garage, designing the entire structure for the two construction methods. Matthew's focus will be two-fold as well, designing the necessary foundations for the residence hall, and then performing the feasibility studies on the options for both the residence hall and the parking garage. These studies will involve a construction cost estimate of the structure as well as any constructability and scheduling considerations for each of the four residence hall and two parking garage alternates. Hallie will be focused primarily on the environmental and sustainability aspect, performing cost-benefit analyses of different systems and materials in an overall attempt to improve the building on all dimensions such as cost, public image, environmental impact, and health of the students. This encompasses the LEED and green building systems sections of the report.

Schedule

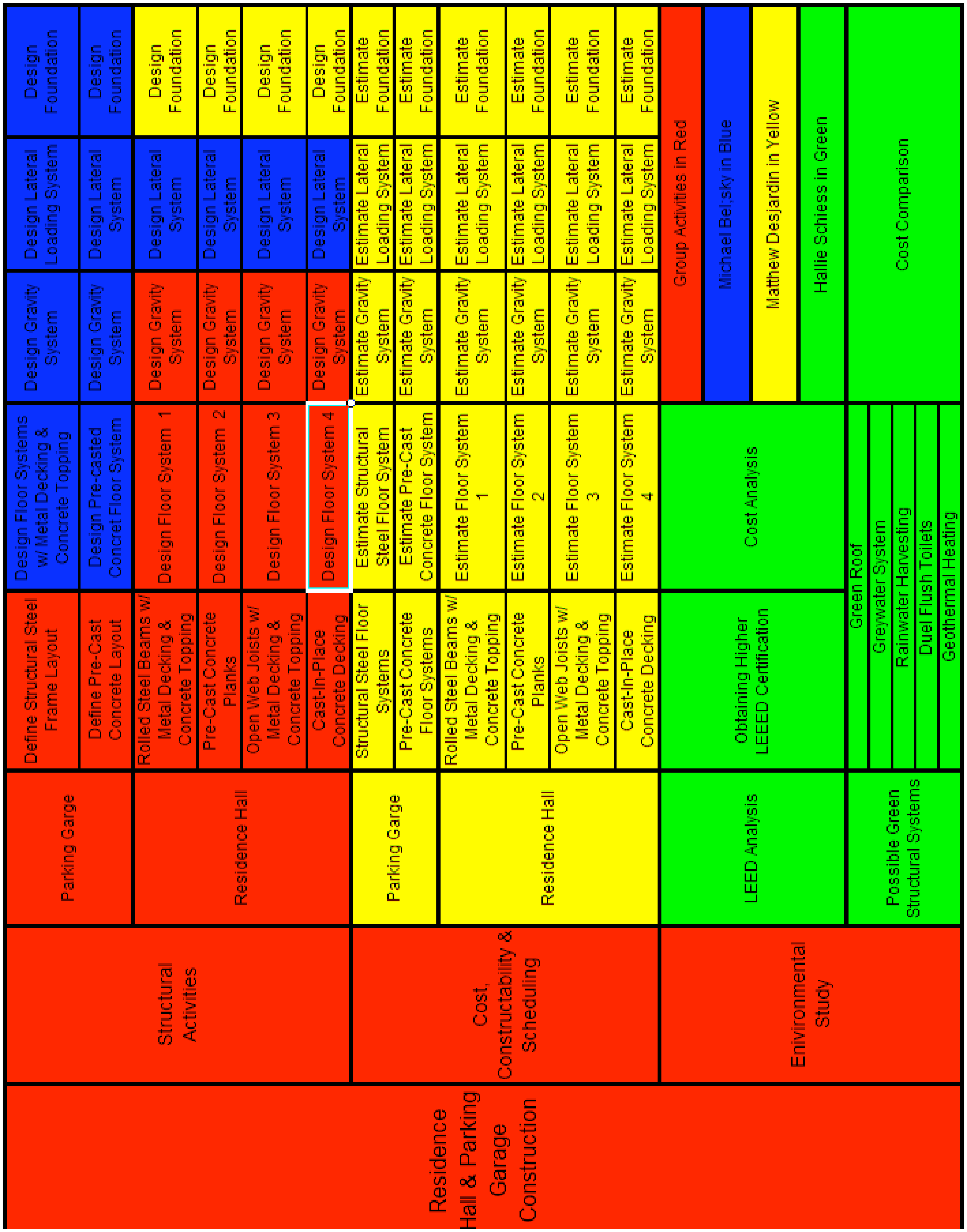
This project will be completed during the first three terms of the 2007-2008 school year. At the end of A-term we propose to have completed the proposal as well as the layout for our residence hall. All loads acting on and within the building will also be identified to begin our analysis of the gravity systems. Background research to support the group effort and the individual areas of investigation will be done throughout B-term. We propose to have each alternative floor system designed along with their gravity loads by Thanksgiving break, allowing us to focus on our individual tasks. By the end of B-term we will have made significant progress on our individual items. For Michael this will include finishing the lateral load design for the residence hall, as well as, beginning the framing systems for the parking garage. Matthew will have completed the cost estimates for all floor and gravity systems of the residence hall, and will have started on the foundations. Hallie will have completed the LEED half of her environmental study. The individual efforts will be completed by the middle of C-term, giving us time to wrap up our report and hand it in with time for comments and corrections to be made.

Deliverables

At the completion of this project in C-term, the group will present a report that includes all of our research, AutoCAD drawings, and a project layout. Our research will include a detailed analysis of designing steel and concrete structures, along with any implications necessary to attain a higher LEED certification. The structural design of the residence hall and parking garage will be displayed through a series of AutoCAD drawings and Microsoft Excel Spreadsheets. Cost estimations will be made for every phase of our project to ensure that our final product will meet the economic requirements of WPI.

PROJECT ORGANIZATION

On the following page is a table diagramming the way our project will be structured.


Residence Hall & Parking Garage Construction
Structural Activities
Parking Garge
Define Structural Steel Frame Layout
Design Floor Systems w/ Metal Decking & Concrete Topping
Design Gravity System
Design Lateral Loading System
Design Foundation
Define Pre-Cast Concrete Layout
Design Pre-casted Concret Floor System
Design Gravity System
Design Lateral System
Design Foundation
Residence Hall
Rolled Steel Beams w/ Metal Decking & Concrete Topping
Design Floor System 1
Design Gravity System
Design Lateral System
Design Foundation
Pre-Cast Concrete Planks
Design Floor System 2
Design Gravity System
Design Lateral System
Design Foundation
Open Web Joists w/ Metal Decking & Concrete Topping
Design Floor System 3
Design Gravity System
Design Lateral System
Design Foundation
Cast-In-Place Concrete Decking
Design Floor System 4
Design Gravity System
Design Lateral System
Design Foundation
Cost, Constructability & Scheduling
Parking Garge
Structural Steel Floor Systems
Estimate Structural Steel Floor System
Estimate Gravity System
Estimate Lateral Loading System
Estimate Foundation
Pre-Cast Concrete Floor Systems
Estimate Pre-Cast Concrete Floor System
Estimate Gravity System
Estimate Lateral Loading System
Estimate Foundation
Residence Hall
Rolled Steel Beams w/ Metal Decking & Concrete Topping
Estimate Floor System 1
Estimate Gravity System
Estimate Lateral Loading System
Estimate Foundation
Pre-Cast Concrete Planks
Estimate Floor System 2
Estimate Gravity System
Estimate Lateral Loading System
Estimate Foundation
Open Web Joists w/ Metal Decking & Concrete Topping
Estimate Floor System 3
Estimate Gravity System
Estimate Lateral Loading System
Estimate Foundation
Cast-In-Place Concrete Decking
Estimate Floor System 4
Estimate Gravity System
Estimate Lateral Loading System
Estimate Foundation
Enivironmental Study
LEED Analysis
Obtaining Higher LEEED Certification
Cost Analysis
Group Activities in Red
Michael Bel;sky in Blue
Matthew Desjardin in Yellow
Hallie Schiess in Green
Possible Green Structural Systems
Green Roof
Greywater System
Rainwater Harvesting
Duel Flush Toilets
Geothermal Heating
Cost Comparison

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Appendix B: Sample Calculations

Concrete slab calculations

Verifying thickness of slab

This bulleted list is simply calculations that were done to make sure that the slab thickness of 4.5” was enough to resist the forces. In the end, it was found that the thickness required for fire resistance rating governed.

- Thickness should be at least L/30 = 2.2”, 4.5” is adequate.
- Ultimate design load:

$$U = 1.2D \times 1.6L = 1.2 \times (35 + 65)\text{psf} + 1.6 \times 80\text{psf} = 248\text{psf}$$

- Maximum moment:

$$M_U = \frac{1}{10} UL^2 = \frac{1}{10}(248\text{plf})\left(3\, {}^{1}\!/_{12}\ \text{ft}\right)^2 = 574\ \text{ft lbs}$$

- Maximum moment resistance. This value represents the maximum possible moment resistance given the thickness of the slab and strength of steel. The depth of steel used was 3.375”, enough to provide a concrete cover of 1.125” in negative moment regions. R found to be 0.204 k-in, a pre-calculated value for balanced sections.

$$\Phi M_R = \Phi \cdot R \cdot b \cdot d^2 = (0.85)(0.204\ \text{kip in})(12")(3.375")^2 \left(\frac{1000\ {}^{\text{lbs}}\!/_{\text{kip}}}{12\ {}^{\text{in}}\!/_{\text{ft}}}\right) = 2091\ \text{ft lbs}$$

  The resistance is more than substantial.

- Maximum shear stress:

$$V = \frac{(1.15)UL}{2} = 1.15 \times \frac{248\ \text{plf}}{12\ \text{in/ft}} \times 64\ \text{in} \times {}^{1}\!/_{2} = 761\ \text{lbs}$$

$$v = \frac{V}{b \times d} = \frac{761\ \text{lbs}}{(12")(3.375")} = 18.8\ \text{psi}$$

- Shear resistance of concrete alone. f'_c is 3000 psi and phi for shear is 0.75

$$\Phi 1.1\sqrt{f'_c} = (0.75)(1.1)\sqrt{3000} = 60.\ \text{psi.}$$

The deck provides adequate shear resistance.

Computing required reinforcement

Now that the thickness of the slab has been found to be adequate, the steel reinforcement of the slab must now be calculated. The minimum amount of reinforcement allowed in each direction is given as a ratio of area of steel to area of the entire cross-section of the strip of slab. For grade 60 steel ρ_t = 0.0018.

$$A_s = \rho_t \times A_c = 0.0018 \times 60\text{in}^2 = 0.108\text{in}^2$$

The required reinforcement for the tension controlled sections of the slab is computed as follows:

$$\varphi A_s = \frac{M}{f_s jd}$$

Where:

- Φ is the ACI reduction factor, 0.9 for tension controlled sections
- M is the maximum moment, $(1/10)U_{max}L_{max}^2$
- f_s is the steel strength, $0.5f_y$, or 24 ksi, whichever is less
- j is a ratio of internal moment arm to d (pre-calculated, retrieved from *Simplified Design* (Alsamsam & Kamara, 2004)
- d is the effective depth of the steel

Using the maximum moment of 574 ft-kips, the required area of steel was calculated to be about 0.107 in^2. This means that for all areas typical of the building, temperature and shrinkage steel governs in both directions. The only area to be checked is the cantilever areas in Unit 3. The weight of the glazing walls was estimated as 15 psf (Parker & Ambrose, 1984). a concentrated load of 180 pounds was found to be acting on the ends of the cantilever, for a one foot slice. Once factored, that value became 216 lbs, not to be confused with the 216 psf value for U, which is also used in the following equation. The extension of the cantilever is 20”. The following equation was used to calculate the maximum moment:

$$M = \frac{UL^2}{2} + PL = \frac{(216\text{psf})(20")^2}{(2)(144\frac{\text{in}^2}{\text{ft}^2})} + (216\text{lbs})(20") = 4620 \text{ in lbs} = 385 \text{ ft lbs}$$

When this value was substituted into the area of steel equation, the result is 0.072 in^2, so the value for temperature and shrinkage still governed.

Beam Design

The design for composite steel beams is governed by the ASCE and IBC; each provided standard load information and design equations. With the help of Microsoft excel, spread sheets were made to make the design process more time efficient. The composite steel beam design process along with all assumptions is shown below followed by a sample calculation of a beam designed in Unit 2 – Bay 1.

Dead and live loads acting on the beam were identified and determined to have consistent uniform load throughout the structure. The dead and live loads are then multiplied by the tributary width of the beam, B_z, in order to find the total load acting per linear foot. Using load factor combinations 1 and 2, a dead and live load were considered to be acting on the beam. Each load combination puts an importance on the effect of different factored loads; and therefore, when the total live and dead loads are computed into the equation; the larger of the two values determines the critical load. Assuming the beams are simply supported, a maximum moment is determined. Table 3-19 in the *AISC Steel Construction Manuel* is used to identify an adequate beam that withstands the factored moment, M_U. The distance from the top of the concrete slab to the flange (Y_{con}) = 6”, and an assumed value of *a* = 2” are used to calculate Y2, the distance from the steel flange to the center of gravity in the concrete flange. The Y2 value and an Y1 value = 0” are used in table 3-19 to choose W shapes specific to our design. The beams nominal strength of shear connectors, ΣQ_n, is then used to find a new depth of *a*. Y2 is computed again with the new depth to select the actual value for flexural strength, ϕM_n, using

Table 3-19 in the *AISC Manuel*. As long as the flexural strength exceeds the factored moment, the beam is said to be "OK", and the next phase of design can proceed.

The number of steel studs running along the span of the beam acting in composite action with the concrete is now determined. A steel stud 3" long with a diameter of ¾" carrying a nominal strength of Q_n = 23.6 ksi is selected. Using table 3-19, the Y2 column was checked to see if a reduction in the number of studs can be made. Since the PNA value falls in the concrete flange, a new value of nominal strength for shear connections is used. The number of ¾" studs required is then determined by multiplying the nominal strength of the beam by two and then dividing by the nominal strength of the stud.

Several checks are made to ensure beam adequacy. The strength of the W sections before the concrete hardens is inspected to ensure safety during construction. Wet concrete acts as a live load during construction and consequently adds a construction live load of 20 psf. A new dead load consisting of all the existing dead load factors except the concrete and a new live load including the weight of the wet concrete are calculated to find a factored load and moment. The new computed moment capacity must be less than the maximum available flexural strength, $\phi_b M_p$, in order for the beam to be considered safe. Service load deflection is calculated to check for failure during construction with a total maximum deflection assumed to be 1" for spans under 20' and 1.5" for spans longer. A c_1 value is selected as a deflection expression in accordance to Figure 3-2 in the LRFD manual and the moment of inertia for the beam can found in the Manuel. Service live load deflection strength of the composite beam is also checked once the concrete has hardened. A new moment for the beam is computed using only the live load and the composite moment of inertia in table 3-20 of the manual. The deflection limit in this case is determined by dividing the span length in inches by 360. If the beam fails to meet deflection criteria or is very close to our maximum deflection, a new beam is selected out of the LRFD manual.

The shear strength of the beam is the last check for design. Since the beam is a doubly symmetric member with the shear plane in the web, equation G2-1 from the LRFD manual can be used to find the nominal shear strength, V_n, of the beam. Values of $\phi_v = 0.9$ and $C_{v\,=}$ 1.0 were specified by the manual to determine a design shear strength, $\phi_v V_n$. The original load factor calculated in the beginning of the design is used to compute the actual shear stress acting in the beam. This value is checked against the design shear strength for safety.

Load Combinations & Factored Moment

$$W_U = 1.4D = 1.4\left(760.76\frac{lb}{ft}\right) = 1069.53\ lb/ft$$

$$W_U = 1.2D + 1.6L + 0.5(L_r\ or\ S\ or\ R) = 1.2\left(760.76\frac{lb}{ft}\right) + 1.6\left(445.02\frac{lb}{ft}\right) = 1628.77\ lb/ft$$

$$M_U = \frac{W_u L^2}{8} = \frac{(1628.77)18.5^2}{8} = 69.68\ ft - K$$

Flexural Strength Design Values Using Table 3-19(AISC Manuel)

$$\Sigma Q_n = A \times F_y = (5.62in^2)(50ksi) = 281k \qquad a = \frac{\Sigma Q_n}{0.85 f_c' b_z} = \frac{281\,k}{0.85(3000\,psi)(7.417)} = 1.24in$$

$$Y2 = Y_{con} - \frac{a}{2} = 6" - \frac{1.24}{2} = 5.38in$$

*Using interpolation from Table 3-19

$\phi M_n > M_u = 220ft - k > 69.68ft - k$ (OK)

Number of Shear Studs

$$\#\ of\ studs = \frac{(2 \times \Sigma Q_n)}{Q_n} = \frac{2 \times 122k}{23.6k} = 10.34 = 12\ studs$$

Strength of W Section

$$NewD_L = D_L - ConcreteD_L = 763.95 - 482.11 = 281.85\ lb/ft$$

$$NewL_L = (20psf \times b_z) + L_L = (20psf \times 7.417) + 482.11\frac{lb}{ft} = 630.45\ lb/ft$$

$W_u = 1.2(NewD_L) + 1.6(NewL_L)$=1346.93 lb/ft

$$M_U = \frac{W_u L^2}{8} = 57.62\ ft - k$$

$\phi_b M_p > M_U = 81\ ft - k > 57.62\ ft - k$ (OK)

Service Dead Load Deflection

$$W_{DL} = D_L + b_z(20psf) = 760.76 + 7.417(20) = 912.3lb/ft$$

$$M_{DL} = \frac{W_{DL}L^2}{8} = 39.03ft - k$$

$$\Delta_{DL} = \frac{M_{DL} * L^2}{C_1 * I_x} = 0.862in < 1.0in \quad \text{(OK)}$$

Service Live Load Deflection

$$M_{LL} = \frac{L_L L^2}{8} = 19.04lb/ft$$

$$\Delta_{LL} = \frac{M_{LL} * L^2}{C_1 * I_x} = 0.862in < 1.0in \quad \text{(OK)}$$

Shear Strength

$$\phi_v V_n = (0.9)(0.6)F_y A_w C_v = (0.9)(0.6)(50ksi)(2.42in^2)(1.0) = 65.45k$$

$$V_u = \frac{L \times W_u}{2} = \frac{18.5' \times (\frac{1628.77}{1000})}{2} = 15.07k$$

$$\phi_v V_n > V_u = 65.45k > 15.07k \quad \text{(OK)}$$

Appendix C: Additional Results

Table 30: Strand designations for 4HC6+2 precast slabs across various spans

Span Designation[1]	Span Length[2] (ft)	Superimposed Load (psf)	Strand Designation[3]	Estimated Camber (in)
A to B	15	95	66-S	0.2
B to C	18	95	66-S	0.1
C to D	13	95	66-S	0.2
		115	66-S	0.2
D to E	19	95	66-S	0.0
		115	66-S	0.0
E to F	22	95	76-S	-0.2
		115	96-S	0.2
F to G	13	95	66-S	0.2
		115	66-S	0.2
G to H	18	95	66-S	0.1
H to I	15	95	66-S	0.2
5 to 6	13	95	66-S	0.2
		115	66-S	0.2
6 to 7	18	95	66-S	0.1
		115	66-S	0.1
7 to 8	12	95	66-S	0.2
		115	66-S	0.2
8 to 9	18	95	66-S	0.1
		115	66-S	0.1
9 to 10	18	95	66-S	0.1
		115	66-S	0.1
10 to 11	12	95	66-S	0.2
		115	66-S	0.2
11 to 12	18	95	66-S	0.1
		115	66-S	0.1
12 to 13	13	95	66-S	0.2
		115	66-S	0.2

[1] Refers to alphanumeric grid system from Figure 24.

[2] Not the exact length; rounded up for design purposes.

[3] The first number refers to the number of strands. The second number denotes the diameter in sixteenths of an inch. The S means straight.

Table 31: Open-web joist system girder selection (floors)

Girder	W shape	Length (ft)	# of Girders	# of studs	Girder	W Shape	Length (ft)	# of Girders	# of Studs
1-1	16 x 36	24'-7"	2	20	3-1	10 x 12	14' - 8"	4	8
1-2	14 x 38	24'-7"	2	18	3-2	10 x 12	14' - 8"	4	8
1-3	14 x 38	24'-7"	2	18	3-3	10 x 15	18'	4	10
1-4	16 x 36	24'-7"	1	20	3-4	10 X 15	18'	4	10
1-5	18 x 46	28'	2	28	3-5	10 X 15	18'	4	10
1-6	18 x 40	28'	2	24	3-6	10 x 15	18'	4	10
1-7	18 x 40	28'	2	24	3-7	10 x 12	12' - 11"	4	8
1-8	18 x 50	28'	1	26	3-8	10 x 12	12' - 11"	4	8
1-9	10 x 17	18'	2	10	3-9	10 x 12	12' - 11"	4	8
1-10	10 x 12	11'-5"	4	8	3-10	10 x 22	17'-10"	4	10
1-11	10 x 17	17'-9"	2	10	3-11	10 x 22	17'-10"	4	10
1-12	10 x 17	18'	2	10	3-12	16 x 36	23'-3"	4	20
1-13	10 x 12	11'-5"	2	8	3-13	10 x 12	9'	4	8
1-14	10 x 17	17'-9"	2	10	3-14	16 x 36	23'-5"	4	20
1-15	10 x 17	18'	2	10	3-15	14 X 38	23'-3"	4	18
1-16	10 x 12	11'-5"	4	8	3-16	10 x 12	9'	4	8
1-17	10 x 17	17'-9"	2	10	3-17	14 X 38	23'-5"	4	18
2-1	10 x 17	18'-6'	2	10	4-1	10 x 15	18'-6"	2	10
2-2	10 x 19	18'-6'	2	12	4-2	12 x 19	18'-6"	2	12
2-3	10 x 12	10'-9"	2	8	4-3	14 x 22	21'-11"	2	14
2-4	10 x 22	21'-11"	2	10	4-4	14 x 34	23'-4"	2	18
2-5	10 x 22	21'-11"	2	10	4-5	10 x 12	13'	2	8
2-6	21 x 44	29'-8"	2	32	4-6	10 x 12	10'-7"	2	8
2-7	21 x 55	29'-8"	2	34	4-7	10 x 12	10'-7"	2	8
2-8	18 x 60	29'-8"	2	32	4-8	16 x 40	23'-4"	2	20
					4-9	10 x 12	13'	2	8
					4-10	14 x 38	23'-4"	2	18
					4-11	10 x 12	13'	2	8

Table 32: Open-web joist system girder selection (roof)

Girder	W shape	Length (ft)	# of Girders	# of studs	Girder	W Shape	Length (ft)	# of Girders	# of Studs
1-1	16 x 40	24'-7"	2	20	3-1	10 x 12	14' - 8"	4	8
1-2	16 x 36	24'-7"	2	20	3-2	10 x 12	14' - 8"	4	8
1-3	16 x 36	24'-7"	2	20	3-3	10 x 15	18'	4	10
1-4	16 x 36	24'-7"	1	20	3-4	10 X 17	18'	4	10
1-5	18 x 50	28'	2	26	3-5	10 X 17	18'	4	10
1-6	18 x 46	28'	2	28	3-6	10 x 15	18'	4	10
1-7	18 x 46	28'	2	28	3-7	10 x 12	12' - 11"	4	8
1-8	18 x 55	28'	1	30	3-8	10 x 12	12' - 11"	4	8
1-9	10 x 17	18'	2	10	3-9	10 x 12	12' - 11"	4	8
1-10	10 x 12	11'-5"	2	8	3-10	10 x 19	17'-10"	4	12
1-11	10 x 17	17'-9"	2	10	3-11	10 x 19	17'-10"	4	12
1-12	10 x 19	18'	2	12	3-12	14 x 34	23'-3"	4	18
1-13	10 x 12	11'-5"	2	8	3-13	10 x 12	9'	4	8
1-14	10 x 19	17'-9"	2	12	3-14	14 x 34	23'-5"	4	18
1-15	10 x 17	18'	2	10	3-15	16 x 40	23'-3"	4	20
1-16	10 x 12	11'-5"	4	8	3-16	10 x 12	9'	4	8
1-17	10 x 17	17'-9"	2	10	3-17	16 x 40	23'-5"	4	20
2-1	10 x 15	18'-6'	2	10	4-1	12 x 16	18'-6"	2	12
2-2	10 x 22	18'-6'	2	10	4-2	10 x 17	18'-6"	2	10
2-3	10 x 12	10'-9"	2	8	4-3	12 x 22	21'-11"	2	14
2-4	10 x 19	21'-11"	2	12	4-4	16 x 36	23'-4"	2	20
2-5	10 x 26	21'-11"	2	12	4-5	10 x 12	13'	2	8
2-6	21 x 50	29'-8"	2	34	4-6	10 x 12	10'-7"	2	8
2-7	24 x 55	29'-8"	2	40	4-7	10 x 12	10'-7"	2	8
2-8	21 x 55	29'-8"	2	34	4-8	16 x 45	23'-4"	2	24
					4-9	10 x 12	13'	2	8
					4-10	16 x 40	23'-4"	2	20
					4-11	10 x 12	13'	2	8

Table 33: Steel beam systems (with and without metal deck) girder selection (floors)

Girder	W shape	Length (ft)	# of Girders	# of Studs	Girder	W Shape	Length (ft)	# of Girders	# of Studs
1-1	16 x 36	24'-7"	2	20	3-1	10 x 12	14' - 8"	4	8
1-2	14 x 38	24'-7"	2	18	3-2	10 x 12	14' - 8"	4	8
1-3	14 x 38	24'-7"	2	18	3-3	10 x 15	18'	4	10
1-4	16 x 36	24'-7"	1	20	3-4	10 X 15	18'	4	10
1-5	18 x 46	28'	2	28	3-5	10 X 15	18'	4	10
1-6	18 x 40	28'	2	24	3-6	10 x 15	18'	4	10
1-7	18 x 40	28'	2	24	3-7	10 x 12	12' - 11"	4	8
1-8	18 x 50	28'	1	26	3-8	10 x 12	12' - 11"	4	8
1-9	10 x 17	18'	2	10	3-9	10 x 12	12' - 11"	4	8
1-10	10 x 12	11'-5"	4	8	3-10	10 x 22	17'-10"	4	10
1-11	10 x 17	17'-9"	2	10	3-11	10 x 22	17'-10"	4	10
1-12	10 x 17	18'	2	10	3-12	16 x 36	23'-3"	4	20
1-13	10 x 12	11'-5"	2	8	3-13	10 x 12	9'	4	8
1-14	10 x 17	17'-9"	2	10	3-14	16 x 36	23'-5"	4	20
1-15	10 x 17	18'	2	10	3-15	14 X 38	23'-3"	4	18
1-16	10 x 12	11'-5"	4	8	3-16	10 x 12	9'	4	8
1-17	10 x 17	17'-9"	2	10	3-17	14 X 38	23'-5"	4	18
2-1	10 x 17	18'-6'	2	10	4-1	10 x 15	18'-6"	2	10
2-2	10 x 19	18'-6'	2	12	4-2	12 x 19	18'-6"	2	12
2-3	10 x 12	10'-9"	2	8	4-3	14 x 22	21'-11"	2	14
2-4	10 x 22	21'-11"	2	10	4-4	14 x 34	23'-4"	2	18
2-5	10 x 22	21'-11"	2	10	4-5	10 x 12	13'	2	8
2-6	21 x 44	29'-8"	2	32	4-6	10 x 12	10'-7"	2	8
2-7	21 x 55	29'-8"	2	34	4-7	10 x 12	10'-7"	2	8
2-8	18 x 60	29'-8"	2	32	4-8	16 x 40	23'-4"	2	20
					4-9	10 x 12	13'	2	8
					4-10	14 x 38	23'-4"	2	18
					4-11	10 x 12	13'	2	8

Table 34: Steel beam systems (with and without metal deck) girder selection (roof)

Girder	W shape	Length (ft)	# of Girders	# of studs	Girder	W Shape	Length (ft)	# of Girders	# of Studs
1-1	16 x 40	24'-7"	2	20	3-1	10 x 12	14' - 8"	4	8
1-2	16 x 36	24'-7"	2	20	3-2	10 x 12	14' - 8"	4	8
1-3	16 x 36	24'-7"	2	20	3-3	10 x 15	18'	4	10
1-4	16 x 36	24'-7"	1	20	3-4	10 X 17	18'	4	10
1-5	18 x 50	28'	2	26	3-5	10 X 17	18'	4	10
1-6	18 x 46	28'	2	28	3-6	10 x 15	18'	4	10
1-7	18 x 46	28'	2	28	3-7	10 x 12	12' - 11"	4	8
1-8	18 x 55	28'	1	30	3-8	10 x 12	12' - 11"	4	8
1-9	10 x 17	18'	2	10	3-9	10 x 12	12' - 11"	4	8
1-10	10 x 12	11'-5"	4	8	3-10	10 x 19	17'-10"	4	12
1-11	10 x 17	17'-9"	2	10	3-11	10 x 19	17'-10"	4	12
1-12	10 x 19	18'	2	12	3-12	14 x 34	23'-3"	4	18
1-13	10 x 12	11'-5"	2	8	3-13	10 x 12	9'	4	8
1-14	10 x 19	17'-9"	2	12	3-14	14 x 34	23'-5"	4	18
1-15	10 x 17	18'	2	10	3-15	16 x 40	23'-3"	4	20
1-16	10 x 12	11'-5"	4	8	3-16	10 x 12	9'	4	8
1-17	10 x 17	17'-9"	2	10	3-17	16 x 40	23'-5"	4	20
2-1	10 x 15	18'-6'	2	10	4-1	12 x 16	18'-6"	2	12
2-2	10 x 22	18'-6'	2	10	4-2	10 x 17	18'-6"	2	10
2-3	10 x 12	10'-9"	2	8	4-3	12 x 22	21'-11"	2	14
2-4	10 x 19	21'-11"	2	12	4-4	16 x 36	23'-4"	2	20
2-5	10 x 26	21'-11"	2	12	4-5	10 x 12	13'	2	8
2-6	21 x 50	29'-8"	2	34	4-6	10 x 12	10'-7"	2	8
2-7	24 x 55	29'-8"	2	40	4-7	10 x 12	10'-7"	2	8
2-8	21 x 55	29'-8"	2	34	4-8	16 x 45	23'-4"	2	24
					4-9	10 x 12	13'	2	8
					4-10	16 x 40	23'-4"	2	20
					4-11	10 x 12	13'	2	8

Table 35: Precast system girder selection (floors)

Girder	W shape	Length (ft)	# of Girders	Girder	W Shape	Length (ft)	# of Girders
1-1	16 x 40	24'-7"	2	3-1	10 x 12	14' - 8"	4
1-2	14 x 38	24'-7"	2	3-2	10 x 12	14' - 8"	4
1-3	14 x 38	24'-7"	2	3-3	10 x 15	18'	4
1-4	16 x 40	24'-7"	1	3-4	10 X 15	18'	4
1-5	18 x 50	28'	2	3-5	10 X 15	18'	4
1-6	18 x 46	28'	2	3-6	10 x 15	18'	4
1-7	18 x 46	28'	2	3-7	10 x 12	12' - 11"	4
1-8	18 x 50	28'	1	3-8	10 x 12	12' - 11"	4
1-9	10 x 17	18'	2	3-9	10 x 12	12' - 11"	4
1-10	10 x 12	11'-5"	4	3-10	10 x 22	17'-10"	4
1-11	10 x 17	17'-9"	2	3-11	10 x 22	17'-10"	4
1-12	10 x 19	18'	2	3-12	16 x 40	23'-3"	4
1-13	10 x 12	11'-5"	2	3-13	10 x 12	9'	4
1-14	10 x 19	17'-9"	2	3-14	16 x 40	23'-5"	4
1-15	10 x 17	18'	2	3-15	14 X 38	23'-3"	4
1-16	10 x 12	11'-5"	4	3-16	10 x 12	9'	4
1-17	10 x 17	18'	2	3-17	14 X 38	23'-5"	4
2-1	10 x 17	18'-6'	2	4-1	10 x 15	18'-6"	2
2-2	10 x 19	18'-6'	2	4-2	12 x 19	18'-6"	2
2-3	10 x 12	10'-9"	2	4-3	14 x 30	21'-11"	2
2-4	10 x 22	21'-11"	2	4-4	14 x 38	23'-4"	2
2-5	10 x 26	21'-11"	2	4-5	10 x 12	13'	2
2-6	21 x 50	29'-8"	2	4-6	10 x 12	10'-7"	2
2-7	21 x 55	29'-8"	2	4-7	10 x 12	10'-7"	2
2-8	18 x 60	29'-8"	2	4-8	16 x 40	23'-4"	2
				4-9	10 x 12	13'	2
				4-10	16 x 36	23'-4"	2
				4-11	10 x 12	13'	2

Table 36: Precast system girder selection (roof)

Girder	W shape	Length (ft)	# of Girders	Girder	W Shape	Length (ft)	# of Girders
1-1	16 x 45	24'-7"	2	3-1	10 x 12	14' - 8"	4
1-2	16 x 40	24'-7"	2	3-2	10 x 12	14' - 8"	4
1-3	16 x 40	24'-7"	2	3-3	10 x 15	18'	4
1-4	16 x 45	24'-7"	1	3-4	10 X 15	18'	4
1-5	18 x 55	28'	2	3-5	10 X 15	18'	4
1-6	18 x 50	28'	2	3-6	10 x 15	18'	4
1-7	18 x 50	28'	2	3-7	10 x 12	12' - 11"	4
1-8	18 x 55	28'	1	3-8	10 x 12	12' - 11"	4
1-9	10 x 19	18'	2	3-9	10 x 12	12' - 11"	4
1-10	10 x 12	11'-5"	4	3-10	10 x 22	17'-10"	4
1-11	10 x 19	17'-9"	2	3-11	10 x 22	17'-10"	4
1-12	10 x 19	18'	2	3-12	16 x 40	23'-5"	4
1-13	10 x 12	11'-5"	2	3-13	10 x 12	9'	4
1-14	10 x 19	17'-9"	2	3-14	16 x 40	23'-3"	4
1-15	10 x 19	18'	2	3-15	14 X 38	23'-5"	4
1-16	10 x 12	11'-5"	2	3-16	10 x 12	9'	4
1-17	10 x 19	17'-9"	2	3-17	14 X 38	23'-3"	4
2-1	10 x 17	18'-6'	2	4-1	10 x 17	18'-6"	2
2-2	10 x 22	18'-6'	2	4-2	12 x 16	18'-6"	2
2-3	10 x 12	10'-9"	2	4-3	14 x 34	21'-11"	2
2-4	10 x 22	21'-11"	2	4-4	16 x 40	23'-4"	2
2-5	12 x 22	21'-11"	2	4-5	10 x 12	13'	2
2-6	21 x 55	29'-8"	2	4-6	10 x 12	10'-7"	2
2-7	21 x 62	29'-8"	2	4-7	10 x 12	10'-7"	2
2-8	21 x 62	29'-8"	2	4-8	18 x 46	23'-4"	2
				4-9	10 x 12	13'	2
				4-10	16 x 45	23'-4"	2
				4-11	10 x 12	13'	2

TABLE 37: COLUMN SELECTION (ALL CAST-IN-PLACE SYSTEMS)

Column	Floors 1 & 2	Floors 3 & 4	Floor 5
Ax2	W 8x 31	W 8x 31	W 8x 31
Ax3.1	W 8x 31	W 8x 31	W 8x 31
Ax4	W 8x 31	W 8x 31	W 8x 31
Bx1.1	W 8x 31	W 8x 31	W 8x 31
BxS1	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
BxS2	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
Bx5.1	W 8x 31	W 8x 31	W 8x 31
Cx1.1	W 8x 31	W 8x 31	W 8x 31
CxS1	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
CxS2	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
Cx5.1	W 8x 31	W 8x 31	W 8x 31
D.1x6	W 8x 31	W 8x 31	W 8x 31
D.1x7	W 8x 31	W 8x 31	W 8x 31
D.1x8	W 8x 31	W 8x 31	W 8x 31
D.1x9	W 8x 31	W 8x 31	W 8x 31
Dx1	W 8x 31	W 8x 31	W 8x 31
Dx3	W 8x 48	W 8x 31	W 8x 31
Dx5	W 8x 31	W 8x 31	W 8x 31
Ex1	W 10x 45	W 8x 31	W 8x 31
Ex3	W 10x 54	W 10x 33	W 10x 33
Ex5	W 10x 45	W 10x 33	W 10x 33
Ex6	W 8x 48	W 8x 31	W 8x 31
Ex7	W 10x 45	W 10x 33	W 10x 33
Ex8	W 10x 45	W 10x 33	W 10x 33
Ex9	W 10x 49	W 10x 33	W 10x 33
Fx1	W 8x 35	W 8x 31	W 8x 31
Fx3	W 10x 49	W 10x 33	W 10x 33
Fx5	W 8x 35	W 8x 31	W 8x 31
F.1x6	W 8x 31	W 8x 31	W 8x 31
F.1x7	W 8x 31	W 8x 31	W 8x 31
F.1x8	W 8x 31	W 8x 31	W 8x 31
F.1x9	W 8x 31	W 8x 31	W 8x 31
Gx1.1	W 8x 31	W 8x 31	W 8x 31
GxS1	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
GxS2	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
Gx5.1	W 8x 31	W 8x 31	W 8x 31
Hx1.1	W 8x 31	W 8x 31	W 8x 31
HxS1	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
HxS2	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
Hx5.1	W 8x 31	W 8x 31	W 8x 31
Ix2	W 8x 31	W 8x 31	W 8x 31
Ix3.1	W 8x 31	W 8x 31	W 8x 31
Ix4	W 8x 31	W 8x 31	W 8x 31

Table 38: Precast system column selection

Column	Floors 1 & 2	Floors 3 & 4	Floor 5
Ax2	W 8x 31	W 8x 31	W 8x 31
Ax3.1	W 8x 31	W 8x 31	W 8x 31
Ax4	W 8x 31	W 8x 31	W 8x 31
Bx1.1	W 8x 31	W 8x 31	W 8x 31
BxS1	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
BxS2	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
Bx5.1	W 8x 31	W 8x 31	W 8x 31
Cx1.1	W 8x 31	W 8x 31	W 8x 31
CxS1	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
CxS2	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
Cx5.1	W 8x 31	W 8x 31	W 8x 31
D.1x6	W 8x 31	W 8x 31	W 8x 31
D.1x7	W 8x 31	W 8x 31	W 8x 31
D.1x8	W 8x 31	W 8x 31	W 8x 31
D.1x9	W 8x 31	W 8x 31	W 8x 31
Dx1	W 8x 35	W 8x 31	W 8x 31
Dx3	W 10x 49	W 10x 33	W 10x 33
Dx5	W 8x 31	W 8x 31	W 8x 31
Ex1	W 10x 45	W 10x 33	W 10x 33
Ex3	W 10x 54	W 10x 33	W 10x 33
Ex5	W 10x 45	W 10x 33	W 10x 33
Ex6	W 8x 48	W 8x 31	W 8x 31
Ex7	W 8x 48	W 8x 31	W 8x 31
Ex8	W 8x 48	W 8x 31	W 8x 31
Ex9	W 10x 49	W 10x 33	W 10x 33
Fx1	W 8x 35	W 8x 31	W 8x 31
Fx3	W 10x 49	W 10x 33	W 10x 33
Fx5	W 8x 35	W 8x 31	W 8x 31
F.1x6	W 8x 31	W 8x 31	W 8x 31
F.1x7	W 8x 31	W 8x 31	W 8x 31
F.1x8	W 8x 31	W 8x 31	W 8x 31
F.1x9	W 8x 35	W 8x 31	W 8x 31
Gx1.1	W 8x 31	W 8x 31	W 8x 31
GxS1	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
GxS2	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
Gx5.1	W 8x 31	W 8x 31	W 8x 31
Hx1.1	W 8x 31	W 8x 31	W 8x 31
HxS1	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
HxS2	HSS 8x 8x 1/4	HSS 8x 8x 3/16	HSS 8x 8x 1/8
Hx5.1	W 8x 31	W 8x 31	W 8x 31
Ix2	W 8x 31	W 8x 31	W 8x 31
Ix3.1	W 8x 31	W 8x 31	W 8x 31
Ix4	W 8x 31	W 8x 31	W 8x 31

TABLE 39: STEEL GARAGE GIRDER LOADS

Girder Design Loads						
Girder Type	Length (ft)	Superimposed Load (psf)	tw (ft)	Uniform Load on Girder (plf)	Add Weight of Exterior Wall (plf)	M_u (ft-kips)
G1	36	156	20	3120	3420	554.0
G2	36	156	29	4524	4824	781.5
G3	36	156	30	4524	4524	732.9
G4	30	152	40	6070	6070	682.9
G5	40	156	6	936	1236	247.2
G6	18	156	6	936	1236	50.1
G7	12.5	178	3	533	833	16.3
G8	6	178	26.5	4274	4274	19.2

TABLE 40: PRECAST GARAGE GIRDER DESIGN LOADS

Precast Girder Design Loads				
Girder Type	Length (ft)	Superimposed Load (psf)	tw (ft)	Uniform Load on Girder (plf)
G1	36	156	20	3120
G2	36	156	30	4680
G3	40	156	6	936
G4	30	151.75	40	6070
G5	6	177.5	26.5	1154
G6	12.5	177.5	3	533

Appendix D: LEED Project Checklist

Sustainable Sites — 14 Possible Points

Prereq 1	Construction Activity Pollution Prevention Required	Required
Credit 1	Site Selection	1
Credit 2	Development Density & Community Connectivity	1
Credit 3	Brownfield Redevelopment	1
Credit 4.1	Alternative Transportation, Public Transportation Access	1
Credit 4.2	Alternative Transportation, Bicycle Storage & Changing Rooms	1
Credit 4.3	Alternative Transportation, Low Emitting & Fuel Efficient Vehicles	1
Credit 4.4	Alternative Transportation, Parking Capacity	1
Credit 5.1	Site Development, Protect or Restore Habitat	1
Credit 5.2	Site Development, Maximize Open Space	1
Credit 6.1	Stormwater Design, Quantity Control	1
Credit 6.2	Stormwater Design, Quality Control	1
Credit 7.1	Heat Island Effect, Non-Roof	1
Credit 7.2	Heat Island Effect, Roof	1
Credit 8	Light Pollution Reduction	1

Water Efficiency — 5 Possible Points

Credit 1.1	Water Efficient Landscaping, Reduce by 50%	1
Credit 1.2	Water Efficient Landscaping, No Potable Use or No Irrigation	1
Credit 2	Innovative Wastewater Technologies	1
Credit 3.1	Water Use Reduction, 20% Reduction	1
Credit 3.2	Water Use Reduction, 30% Reduction	1

Energy & Atmosphere — 17 Possible Points

Prereq 1	Fundamental Commissioning of the Building Energy Systems	Required
Prereq 2	Minimum Energy Performance	Required
Prereq 3	Fundamental Refrigerant Management	Required
Credit 1	Optimize Energy Performance	1–10

(2 points mandatory for LEED for New Construction projects registered after June 26, 2007)

Credit 2	On-Site Renewable Energy	1–3
Credit 3	Enhanced Commissioning	1
Credit 4	Enhanced Refrigerant Management	1
Credit 5	Measurement & Verification	1
Credit 6	Green Power	1

Materials & Resources 13 Possible Points

Prereq 1	Storage & Collection of Recyclables	Required
Credit 1.1	Building Reuse, Maintain 75% of Existing Walls, Floors & Roof	1
Credit 1.2	Building Reuse, Maintain 95% of Existing Walls, Floors & Roof	1
Credit 1.3	Building Reuse, Maintain 50% of Interior Non-Structural Elements	1
Credit 2.1	Construction Waste Management, Divert 50% from Disposal	1
Credit 2.2	Construction Waste Management, Divert 75% from Disposal	1
Credit 3.1	Materials Reuse, 5%	1
Credit 3.2	Materials Reuse, 10%	1
Credit 4.1	Recycled Content, 10% (post-consumer + 1/2 pre-consumer)	1
Credit 4.2	Recycled Content, 20% (post-consumer + 1/2 pre-consumer)	1
Credit 5.1	Regional Materials, 10% Extracted, Processed & Manufactured Regionally	1
Credit 5.2	Regional Materials, 20% Extracted, Processed & Manufactured Regionally	1
Credit 6	Rapidly Renewable Materials	1
Credit 7	Certified Wood	1

Indoor Environmental Quality 15 Possible Points

Prereq 1	Minimum IAQ Performance	Required
Prereq 2	Environmental Tobacco Smoke (ETS) Control	Required
Credit 1	Outdoor Air Delivery Monitoring	1
Credit 2	Increased Ventilation	1
Credit 3.1	Construction IAQ Management Plan, During Construction	1

Credit 3.2	Construction IAQ Management Plan, Before Occupancy	1
Credit 4.1	Low-Emitting Materials, Adhesives & Sealants	1
Credit 4.2	Low-Emitting Materials, Paints & Coatings	1
Credit 4.3	Low-Emitting Materials, Carpet Systems	1
Credit 4.4	Low-Emitting Materials, Composite Wood & Agrifiber Products	1
Credit 5	Indoor Chemical & Pollutant Source Control	1
Credit 6.1	Controllability of Systems, Lighting	1
Credit 6.2	Controllability of Systems, Thermal Comfort	1
Credit 7.1	Thermal Comfort, Design	1
Credit 7.2	Thermal Comfort, Verification	1
Credit 8.1	Daylight & Views, Daylight 75% of Spaces	1
Credit 8.2	Daylight & Views, Views for 90% of Spaces	1

Innovation & Design Process 5 Possible Points

Credit 1.1	Innovation in Design	1
Credit 1.2	Innovation in Design	1
Credit 1.3	Innovation in Design	1
Credit 1.4	Innovation in Design	1
Credit 2	LEED Accredited Professional	1

Project Totals 69 Possible Points

Certified 26–32 points Silver 33–38 points Gold 39–51 points Platinum 52–69 points