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CitySquare Underground Parking Garage

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CitySquare Underground Parking Garage

Project Proposal

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 in Civil Engineering & Management Engineering by

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Sponsor: Consigli Construction

Approved by:

Professor Guillermo Salazar

Professor Walter Towner

Abstract

As the city of Worcester continues to attract more students and businesses, and with a central location to New England, the need to expand and develop the alienated downtown area has been identified. CitySquare, a $563 million multi-phased private/public development project, will include a steel structure underground parking garage managed by Consigli Construction which will accommodate over 500 cars and will aid with the increasing demand for parking space experienced during the past decade. This project examined the management of the construction by assessing the effectiveness of the schedule, cost, and communication as observed. An evaluation based on Lean Construction concepts was made in order to identify possible areas of improvement. Additionally, an alternative structural design was proposed using prestressed concrete to serve as an alternative to the actual design that uses steel framing and slab on deck. Environmental factors were considered and evaluated as well, by utilizing LEED concepts, embodied energy, and performing a life-cycle cost analysis. The concept of axiomatic design decomposition was then used to identify the most important functional design requirements and their respective design parameters.

Capstone Design Experience Statement

This project focused on the design and construction of a 2 story steel-structure underground parking garage in downtown Worcester, MA. The construction was executed by the general contractor, Consigli Construction of Milford Massachusetts, for the owner CitySquare II development Co. LLC, This facility will provide parking services to the city as well as the surrounding businesses such as Unum, St. Vincent's Hospital, a future Marriot Hotel, and the general public. The current structural design uses steel frame with slab on deck (provided by Arrowstreet Designers and Niesch & Goldstein Structural Engineering). The alternative design proposed in this study replaces the structural steel elements of the actual design with precast and prestressed members. The design process involved the identification of loads, the selection of an area of interest representative to the overall project, the design calculations for each component. The design process was paralleled with the creation of an axiomatic design that analyzed the relationships between the design parameters and functional requirements through aspects of economy, constructability, safety, and serviceability.

We fulfilled our Design Capstone by creating an independent design that is ruled by the actual conditions of the site, the geometry of the layout, the loading distribution of the project, and the owner's needs. To design our precast concrete structure, we first extracted the loading, framing, geometric, and serviceability requirements from the provided construction documents. We took into account constraints such as having a defined site layout, geotechnical properties of the location, traffic and pedestrian accessibility, among others. Using the Precast/Prestressed Concrete Institute's (PCI) Design Manual, we designed the structural components of a double tee beam, inverted tee beam, columns, and connections. To aid the design process and add analysis into the design, we used software such as Microsoft Excel, Procore, Concise Beam, and Primavera. Additionally, we applied an approach of Axiomatic Design using the software Acclaro in order to identify the key functional requirements of the alternative design and the design parameters of utmost importance for a successful prestressed bay.

The design problem that we addressed was the selection of the most cost effective, fast-tracked, sustainable and feasible construction material for a project in an urban environment rich in spatial, legal, safety, environmental, and monetary constraints. We approached this design problem by performing analysis on schedule, cost, communication, and sustainability on the steel-structure, which enabled us to compare its performance against our independent design based on prefabricated prestressed concrete. We performed a series of analysis using actual construction documents, attending meetings, documentation logs, and physical progress which allowed us to arrive at an alternative design that was economical (compared through Life Cycle analysis), constructability (through 3D visualization), safety (through adherence to loading requirements), and environmental (through embodied energy analysis and LEED parameters).

Professional Licensure Statement

Professional Licensure is a proof of competency that demonstrates that the engineer has the credentials and specialized skills to perform their practice. Licensure also protects the public by enforcing standards that restrict practice to qualify individuals who have met specific qualifications in education, work experience, and exams. (NSCPE, 2015) The requirements a

The National Society of Professional Engineers, states that the specific requirements for licensure can differ from state to state. However there are four major steps for licensure candidates to follow. The first step is to successfully complete the Fundamentals of engineering (FE) exam while or after graduating from an accredited engineering program. By passing this exam the candidate achieves Engineering Intern (EI) or Engineer in Training (EIT) status, which shows that, the candidate have mastered the fundamental requirements. The second step in the process is to complete four years of qualifying professional experience. However, obtaining a masters degree from an accredited program can shorten this experience requirement. After four years the individual can learn about your state's licensure requirements, as it is different for each state. Then the final step is to successfully completing the Principles and Practice of Engineers (PE) exam. (NSCPE, 2015)

Obtaining professional licensure is a prestigious title and a standard recognized by employers, clients, government, and by the public. It is also a sign of authority and responsibility since only PE's can "sign and seal engine, and submit engineering plans and drawings to a public authority for approval, or seal engineering work for public and private clients." (NSCPE, 2015) Having a PE license also gives the individual flexibility in their career by becoming a specialist or by expanding their opportunities beyond a company structure into becoming an independent consultant.

Our work in this project with the project management analysis and design of an alternative bay for the construction of the underground parking garage, has served as an initial step in the right direction to obtaining the Professional Licensure. It has allowed us to gain practical knowledge and apply concepts learned in class to a real-life project.

Acknowledgments

We would like to first thank our advisors, Professor Guillermo Salazar and Professor Walter Towner, for their invaluable guidance throughout the completion of this project. They provided us with direction, support, and constructive feedback which aided the completion of the project.

Likewise, we want to acknowledge the support and guidance of the members of Consigli Construction - Brent Kaizer, Kevin Beechman, Pat Condon, and Mike Gerdhard. They provided us with all the resources needed to complete this project, allowed us to observe the development of the parking garage, and made us feel part of the team.

Additionally, we would like to extend our appreciation to Professor Arsava, Professor Rahbar, and Jessica Rosewitz (PhD Candidate), from the WPI Civil Engineering department for their guidance on the capstone design requirement.

Lastly, we would like to thank Chris Fowler and David Wan from OldCastle Precast for their exceptional support with our alternative design.

Authorship

In general, all members contributed to the development of this project. The following list indicates the primary area of focus of each member in the report.

Jose A. Cueva – Project Management, Alternative Design, and Sustainability

Saadet Nur Yilmaz - Project Management and Alternative Design

Jean Pierre Miralda – Lean Construction, Axiomatic Design Decomposition, and Sustainability

The signatures below indicate the acceptance of the above.

Jose A. Cueva

Saadet Nur Yilmaz

Jean Pierre Miralda

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1.0 Introduction

Worcester is a city with a rich history, and in recent years, it has seen an exponential growth in its demand for business development partly due to its central location in New England. With the opening of the Worcester Center Galleria in 1971, the city intended to attract a big number of businesses and export the fashions of Boston to the suburbs while revitalizing the ailing downtown of Worcester. However, this has not been the case and by 2006 the mall was closed. Following the closure, the city of Worcester proposed a development project known as CitySquare, a $563 million multi-phased private/public project which is considered the largest development project in the Commonwealth excluding the Boston Area.

Small steps have been taken since 2007 – the demolition of the mall and the construction of Unum Building and St. Vincent Cancer Center have taken place. Residents of Worcester are losing their hopes that one day they will see downtown as a commercial and vivid location, with several retail stores and residential space. However, in recent years, CitySquare II Development Co. LLC took over the project and has redesigned the original space and layout, which will now include an underground parking garage with over 500 parking spaces and a multi-story hotel to accommodate for the influx of people. The garage is the first step of the new development phase, which will be followed by the hotel, retail space, and some residential areas.

Consigli Construction, has been involved as a general contractor during the past 5 years, overseeing several projects and improvements to the downtown area of the city of Worcester. They will now be in charge of the 2-story underground parking garage which will sit in the heart of the city. Nonetheless, this presents a big challenge for Consigli, given that the project is located in an area of high traffic, a street runs over the site, and three out of the four sides adjacent to the site have buildings already. The construction team will have to develop a plan to run the project as efficiently as possible to deliver it on time and within the allowable budget. This will require a lot of coordination and planning with the sub-contractors, site workers, the city manager, and the owners of the adjacent structures.

The current design of the parking garage consists of a steel structure with spread footings, slab on grade, and slab on deck at the upper levels. This project considered certain aspects which can potentially impact the current design and structure significantly including space, location, weather, and materials being utilized, amongst others. For this reason, our study investigated an alternative design to the parking garage, and evaluated the impact it may have on the cost, schedule, and delivery of the project. The alternative prestressed structure design presented in this project took into account current site and loading conditions as well as spatial constraints. A visual model of the alternative design was created by utilizing Concise Beam (a design software for precast) and Google SketchUp. Additionally, an analysis on a single modular bay of the alternative design was made by utilizing the Axiomatic Design Decomposition approach. This approach aimed to identify the critical components of the design and analyze the functional requirements and design parameters to determine their most critical aspects.

The management of this actual project was observed and analyzed based on their delivery in terms of scheduling, costs, and communication. The study also included an evaluation and analysis of the original design and its management based on Lean Construction concepts. The purpose of this evaluation was to identify the activities and aspects in which Lean concepts could be applied to make the process more efficient and reduce any waste that does not add value to the end-user. To accomplish this, the contractor's project members were surveyed at two different points in the development of the project and their responses were analyzed to determine the value on the applicability of Lean concepts to the project. Alongside, sustainability aspects were considered in the analysis including embodied energy, LEED, and the Life Cycle Cost Analysis.

The goal of this project was to create a sustainable and cost-effective alternative design that met all requirements indicated by the existing construction documents. The following report draws conclusions on the project management components of construction, the application of lean concepts to the project, a sustainable and cost-effective alternative design, and the application of the axiomatic design method to the proposed alternative design.

2.0 Background

The following chapter examines the purpose of the construction of the underground parking garage and introduces some of the concepts and analysis measures that were used in the project. The chapter starts with an overview of the history and future development of the CitySquare project, the main reason for the construction of the garage. The following sections provide an overview of the project management and the concepts that were important in the implementation and analysis of the project, including Lean Construction, software assisted analysis, and prestressed concrete.

2.1 CitySquare Project

The following section explains the history of CitySquare and its development in the last couple of years. Furthermore, it explains the next steps in the development of CitySquare and how this study relates to the purpose of this large-scale project in the city of Worcester.

2.1.1 CitySquare History

On July 29th, 1971 the Worcester Center Galleria opened for business in downtown Worcester, Massachusetts. This massive shopping center included 1,000,000 square feet of floor space and was intended to export the fashions of Boston to the suburbs while revitalizing the ailing downtown of Worcester. A 4,300-car parking structure was attached to building, and at the time being, it was the largest parking structure in the world. (Caldor, 2006) Figure 1 below shows the layout of the existing mall, parking garage, and adjacent buildings as it looked in 2012.

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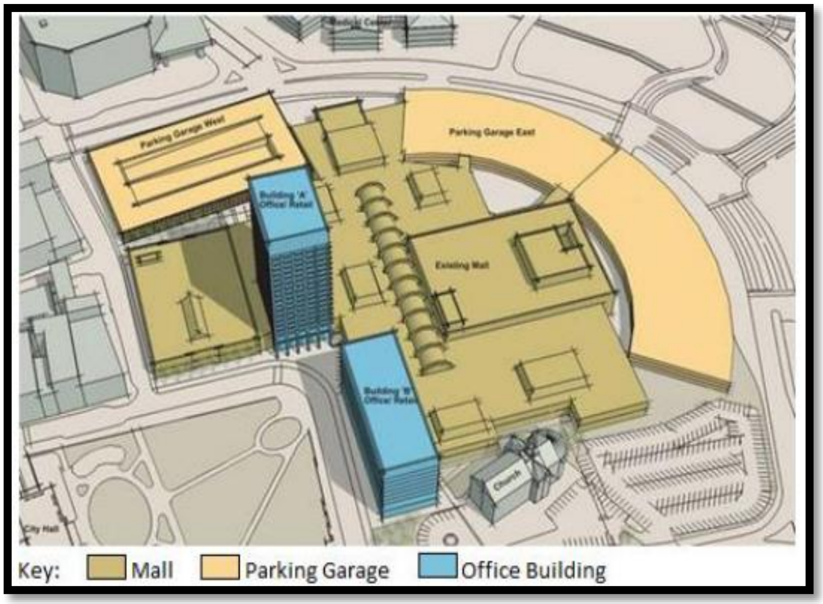

Figure 1 - Mall Site Plan (Huard, 2012)

Unfortunately, as early as 1973, the shopping center was already having issues of not being viable and losing its customers. Despite the numerous failed attempts by the city to revitalize the mall throughout the next decades, it was still considered New England's largest and most notorious dead mall. (Caldor, 2006) With the opening of the Wrentham Village Premium Outlets in 1997 the Worcester Common's area had no reason to attract any more customers and it slowly started losing businesses and stores with each passing year. However, in 2004 it was announced that Berkley Investments from Boston would be purchasing and demolishing the mall, in order to rebuild downtown Worcester in a project named CitySquare; and by 2006, the mall was closed. (Caldor, 2006)

CitySquare is a $563 million multi-phased private/public project and is considered the largest development project in the Commonwealth, without the inclusion of the Boston Area. The project's goal is to create more 2.2 million square feet of commercial, medical, retail, entertainment, and residential space. (Worcester, 2014) Figure 2 below, shows the proposed development for the area that was supposed to connect Worcester's downtown with the failed mall.

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Figure 2- City Square Development Plan (Huard, 2012)

However, Berkley Investments failed to comply with the General Development Agreement (GDA) between them and the City of Worcester, which required Berkley to secure a tenant for one of the designated buildings. Unum Group, a disability and life insurance based in Portland, Maine, signed a letter of intent in 2009 with the City of Worcester. In 2010, plans were revived with the backing of a new investor, the Hanover Insurance Group Inc. Since then, Unum and Vanguard Health Systems Inc., the operator of St. Vincent Hospital, have been the only two new developments in the area and no additional progress has been made as shown in Figure 3 (McCluskey, 2013).

Figure 3 - CitySquare Development in 2013 (McCluskey, 2013) (Source:T&G Staff, Rick Cinclair)

The demolition of the former outlet mall and parking garage had been completed, and was intended to help advance the project. However, no private investor had announced interest in the site for more than two years.

2.1.2 CitySquare Future Development

Since the demolition of the mall and a large portion of the original parking garage, no development has been seen in the area. Nonetheless, there have been several conversations and negotiations as to what is the future of the CitySquare project. CitySquare II Development Co. LLC, an entity managed by Leggat McCall and funded by Opus Investment Management Inc., a subsidiary of Hanover Insurance, is now working with Consigli Construction, the General Contractor, in the next phase of the project.

There have been several conversations about the use of the space, and the current vision includes commercial office space, housing, a 500+ space underground parking garage, and space for street-level retail stores. In addition, they are planning on adding another component to the project and building a multi-story Marriott Renaissance hotel that will go over the underground parking garage. Figure 4 illustrates the revised plans for the CitySquare project.

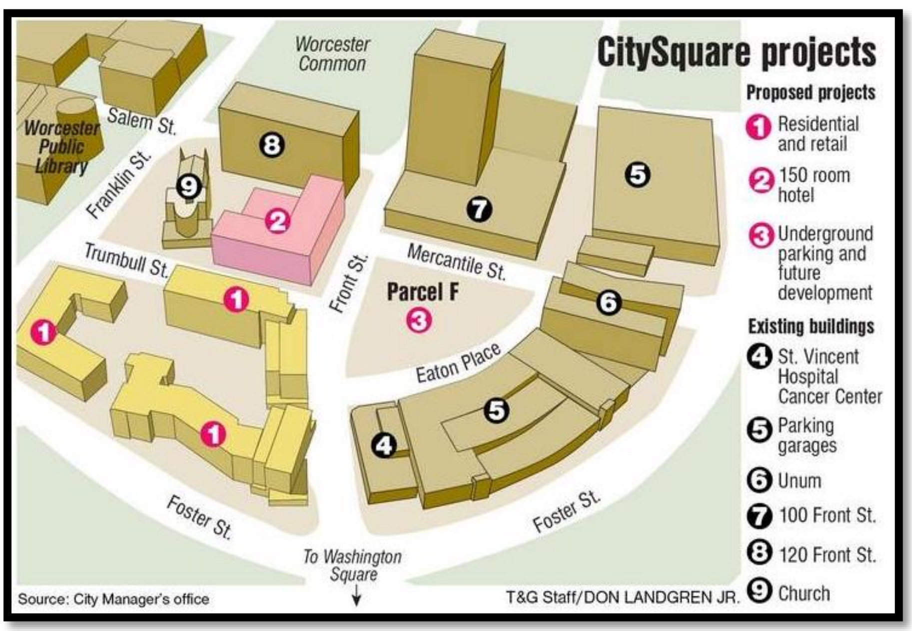

Figure 4 - CitySquare Revised Layout (Kotsopoulos, 2014) (Source: City Manager's office)

"I think the demand for hotel space in the city is at an all-time high right now," shared Craig L. Blais, president and chief executive officer of the private Worcester Business Development Corporation, with Worcester Telegram and Gazette. (McCluskey, 2013) The two-level underground parking garage will be built behind the Unum and St. Vincent buildings, in the area where the mall used to be. This parking garage is the next step to the development of CitySquare and once it is completed, the hotel, housing, and retail space will commence its development on top of it.

Minor amendments and details have been made to the design since then, with the addition of two surface entrances to the underground parking garage, so-called "head houses". These will be kept largely transparent and open, and bicycle racks will also be installed in each of them, with stairs and elevators to access the garage. (Kotsopoulos, 2014) Appendix A shows in detail some of the construction drawings with the proposed addition of the “head houses”. In May of 2014, the Planning Board approved modifications that reduce the size of the underground garage from the planned 1,025 spaces to 580. The parking garage will now encompass less space in the project site with the changes made. (Kotsopoulos, 2014)

2.2 Consigli Construction

Consigli Construction is a fourth generation, family-owned construction firm established in 1905. The company is experienced in serving academic, corporate, life science, health care, federal, and institutional clients throughout New England and New York. (Consigli, 2014) Grossing more than $743.8 million annually, in 2013 Consigli was ranked 77 among the top 400 construction firms by Engineering News Record. They are capable of providing several different construction delivery methods such as Construction Management at Risk, Design Build, Integrated Project Delivery, as well as Design-Bid-Build competitive bidding.

2.2.1 Consigli Construction’s involvement in CitySquare

Consigli Construction has been involved in the CitySquare Development Project starting from September 2010 with the demolition the former Worcester Common Fashion Outlets mall. Throughout the years, the projects have had various types of contracts, predominantly Guaranteed Maximum Price. A $110 million demolition job of the 215,000 sq. ft. building and selective demolition of an existing parking garage was completed in June 2012. Figure 5 illustrates the demolition of the mall which has brought down 4,000 tons of steel. The steel, concrete and brick from the mall have been recycled. (Dayal, 2011)

Figure 5 - Demolition of Worcester Commons Fashion Outlets (Grillo, 2013)

City Square's first building, Unum facility (Figure 6), was also constructed by Consigli Construction and was completed on January 2013. The energy efficient building system includes a high impact corporate lobby with advanced technology and executive offices. Consigli was both responsible for the core shell and interior fit-out of the building, while coordinating the owner's installation of finishes and equipment. The $72 Million facility has achieved LEED Silver Certification (Consigli, 2014), and has attracted a lot of business and public to the downtown Worcester area. After having a strong presence for years in the city, Consigli is currently working on the underground parking garage for CitySquare II.

Figure 6 - The UNUM Building in Downton Worcester (Grillo, 2013)

2.3 Project Management Parameters

2.3.1 Overview

Recent investments in infrastructure by both private and public funds in the downtown Worcester area have created a demand for increased parking spaces for daily commuters, visitors, professionals, and students. Limited available space downtown motivated the construction of a facility that would meet the parking needs of the city while minimizing its impact on potential future developments. As a result, the parking garage will be constructed entirely underground and will feature aboveground elements such as green space and head-houses that will add to Worcester's development.

2.3.2 Organizational Breakdown Structure (OBS) of City Square Underground Parking Garage

The organizational breakdown structure for the City Square Underground parking garage project is illustrated in the Figure 7 **- OBS for CitySquare Underground Parking Garage Project**below. The owner, City Square II, has a representative who oversees the entire project and delivers the project in a consulting capacity. Consigli Construction's organizational structure starts the with the president of the company who oversees the Projective Executive who leads, manages and coordinates the overall direction, completion, and financial outcome of the project. Additionally, he also mentors a team of project managers and engineers. The Project Manager, Superintendent, and MEP manger work together and are responsible for the safe completion of the project within the proposed budget and schedule, company's quality standards, and customer's satisfaction. (Consigli, 2014) The architecture firm, Arrowstreet Inc., coordinates and oversees the structural, civil and MEP/FP engineers to deliver their design aspects of the project, based on the owners' specifications.

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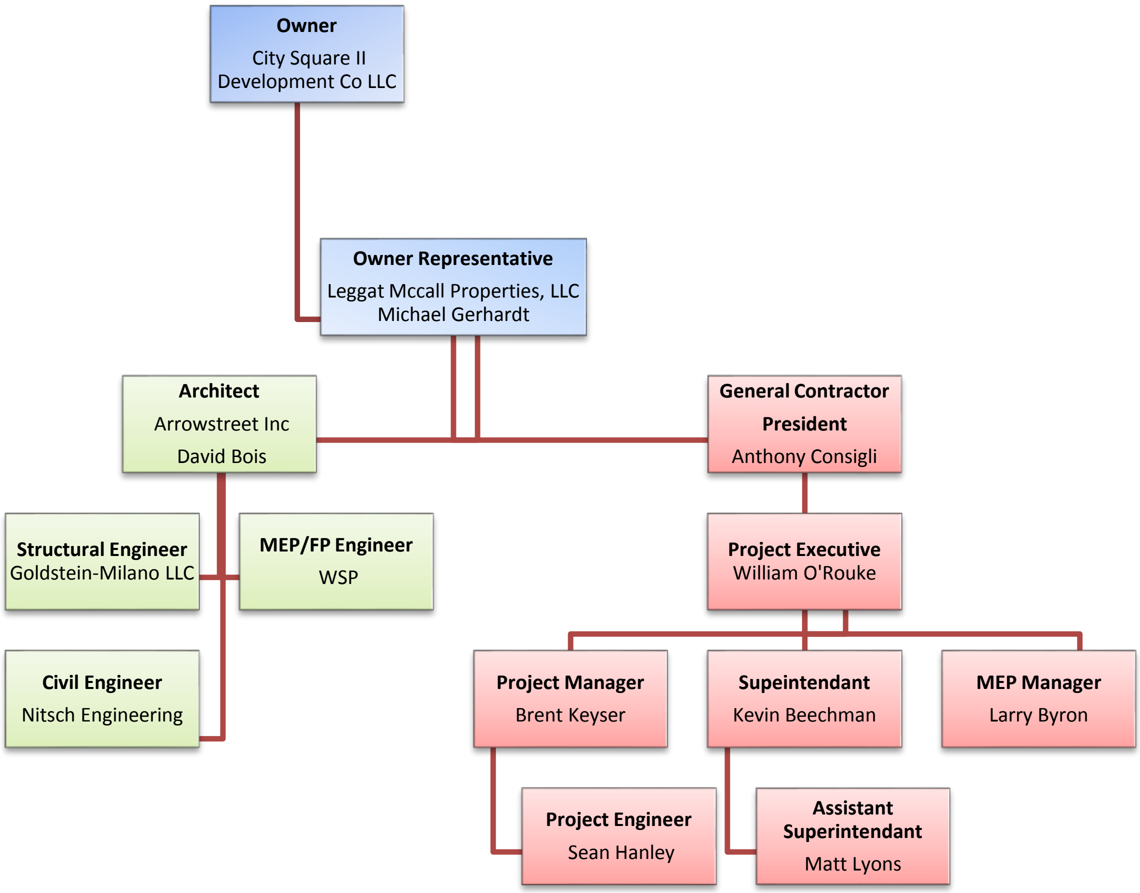


Figure 7 - OBS for CitySquare Underground Parking Garage Project

2.3.3 Scope

The project undertaken by Consigli Construction consists of building an underground parking garage as indicated in the final construction documents within a guaranteed maximum prized. The parking garage is to have 2 levels, housing over 500 vehicles and 2 entrances from the street level, as well as 2 head-houses on the street level and a green space over the “Ballpark” section of the parking garage. The garage features steel construction and extends under Front Street of the city of Worcester with its top level to be on grade. The parking garage will be adjacent to a preexisting above ground East Garage which services both Saint Vincent’s Hospital and Telegram and Gazette. The completed underground parking garage will block off the air flow for the lower level of East Garage, making it necessary for ventilation systems and sprinklers to be installed. All work related to the mitigation of East Garage is included in the scope of this project.

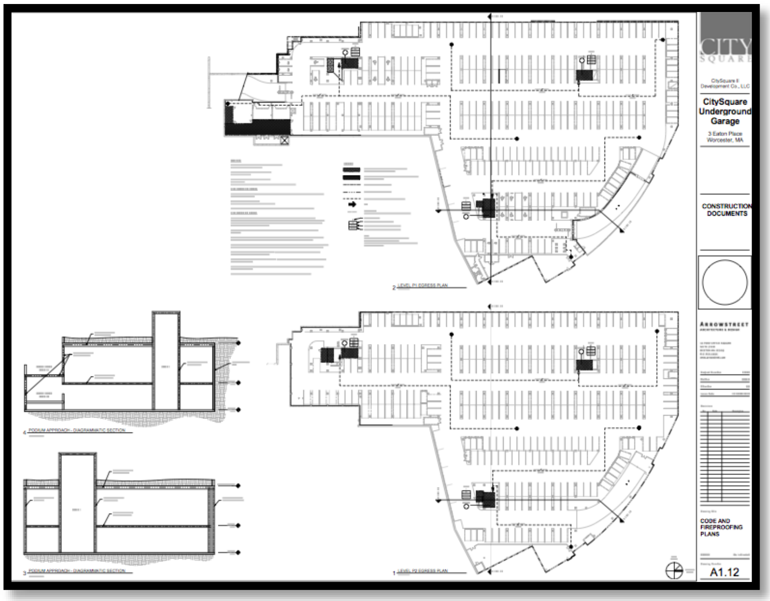


Figure 8 - Architectural drawings by levels and elevations of the underground parking garage (Gateway)

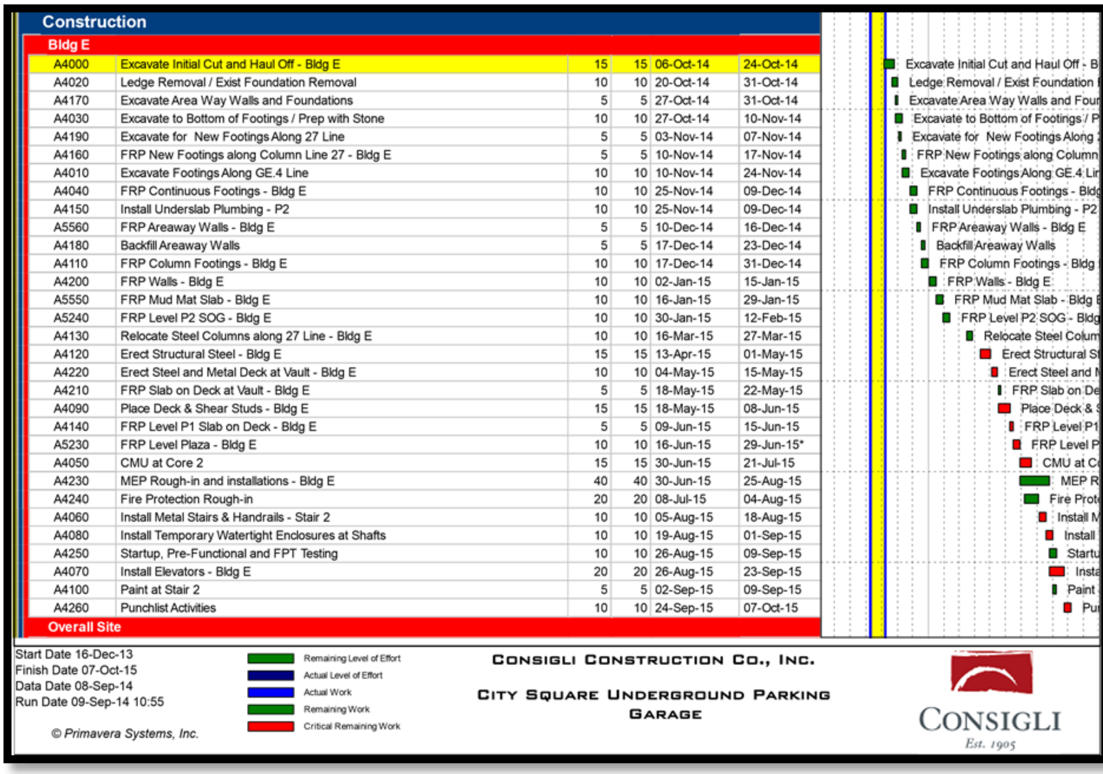
2.3.4 Cost

The contract called for a Guaranteed Maximum Price (GMP) for the project, also known as not-to-exceed price (NTE or NTX). Under this cost related contract, Consigli bills for the cost of the work performed plus a fixed fee or percentage without exceeded a predetermined allowance. (Cushman, 1999) The ceiling prices were negotiated between CitySquare II and Consigli, as well as the allowances providing flexibility in the contract. The total cost of the project as detailed in the finalized GMP was $34,299,152.00.

A cost component that played a critical role in this project was the use of change requests. Change requests are change management procedures whereby changes in the scope of work agreed to by the owner, contractor and architect/engineer are implemented. Change requests are typically more prominent towards the middle or end of the construction process, but in this project the CM used them as a means to expedite the start of construction.

2.3.5 Schedule

The schematic design of the underground parking garage was approved in January 24th, 2014 and construction documents were finalized and approved on July 21st, 2014. Consigli's involvement as General Contractor began on June 30th, 2014 and received notice to proceed on September 14th, 2014. The delay between the start of the project and the notice to proceed came as a consequence of setbacks on the guaranteed maximum price (GMP) negotiation between the owner, CitySquare II, and the general contractor, Consigli Construction. The planned completion date for the project is October 7th, 2015. All milestones, activities, and relevant dates were tracked using Primavera 6 (P6), a high-performance project management software. Figure 9 below shows the proposed a portion of the P6 schedule.



Construction					
Bldg E					
A4000	Excavate Initial Cut and Haul Off - Bldg E	15	15	06-Oct-14	24-Oct-14
A4020	Ledge Removal / Exist Foundation Removal	10	10	20-Oct-14	31-Oct-14
A4170	Excavate Area Way Walls and Foundations	5	5	27-Oct-14	31-Oct-14
A4030	Excavate to Bottom of Footings / Prep with Stone	10	10	27-Oct-14	10-Nov-14
A4190	Excavate for New Footings Along 27 Line	5	5	03-Nov-14	07-Nov-14
A4160	FRP New Footings along Column Line 27 - Bldg E	5	5	10-Nov-14	17-Nov-14
A4010	Excavate Footings Along GE.4 Line	10	10	10-Nov-14	24-Nov-14
A4040	FRP Continuous Footings - Bldg E	10	10	25-Nov-14	09-Dec-14
A4150	Install Underslab Plumbing - P2	10	10	25-Nov-14	09-Dec-14
A5560	FRP Areaway Walls - Bldg E	5	5	10-Dec-14	16-Dec-14
A4180	Backfill Areaway Walls	5	5	17-Dec-14	23-Dec-14
A4110	FRP Column Footings - Bldg E	10	10	17-Dec-14	31-Dec-14
A4200	FRP Walls - Bldg E	10	10	02-Jan-15	15-Jan-15
A5550	FRP Mud Mat Slab - Bldg E	10	10	16-Jan-15	29-Jan-15
A5240	FRP Level P2 SOG - Bldg E	10	10	30-Jan-15	12-Feb-15
A4130	Relocate Steel Columns along 27 Line - Bldg E	10	10	16-Mar-15	27-Mar-15
A4120	Erect Structural Steel - Bldg E	15	15	13-Apr-15	01-May-15
A4220	Erect Steel and Metal Deck at Vault - Bldg E	10	10	04-May-15	15-May-15
A4210	FRP Slab on Deck at Vault - Bldg E	5	5	18-May-15	22-May-15
A4090	Place Deck & Shear Studs - Bldg E	15	15	18-May-15	08-Jun-15
A4140	FRP Level P1 Slab on Deck - Bldg E	5	5	09-Jun-15	15-Jun-15
A5230	FRP Level Plaza - Bldg E	10	10	16-Jun-15	29-Jun-15*
A4050	CMU at Core 2	15	15	30-Jun-15	21-Jul-15
A4230	MEP Rough-in and installations - Bldg E	40	40	30-Jun-15	25-Aug-15
A4240	Fire Protection Rough-in	20	20	08-Jul-15	04-Aug-15
A4060	Install Metal Stairs & Handrails - Stair 2	10	10	05-Aug-15	18-Aug-15
A4080	Install Temporary Watertight Enclosures at Shafts	10	10	19-Aug-15	01-Sep-15
A4250	Startup, Pre-Functional and FPT Testing	10	10	26-Aug-15	09-Sep-15
A4070	Install Elevators - Bldg E	20	20	26-Aug-15	23-Sep-15
A4100	Paint at Stair 2	5	5	02-Sep-15	09-Sep-15
A4260	Punchlist Activities	10	10	24-Sep-15	07-Oct-15
Overall Site					

Figure 9 - Building E proposed schedule

2.3.6 Communication

Consigli used both Gateway and Procore online project management dashboards to track communication between the owner, architects, engineers and subcontractors. The project team stored and accessed all relevant documents on both cloud servers to make edits and expedite the process of communication. As the project progressed, the Gateway server only included the documentation of submittals. On the other hand the documentation of requests for information (RFI's), change requests (CR's), project schedule updates, construction drawings, meeting minutes, and specifications was stored in the Procore server. Both servers were useful tools to get updates on project documents and observe the communication between key players of the project. Figure 10 and Figure 11 below show the layout of the user-friendly Gateway and Procore servers.

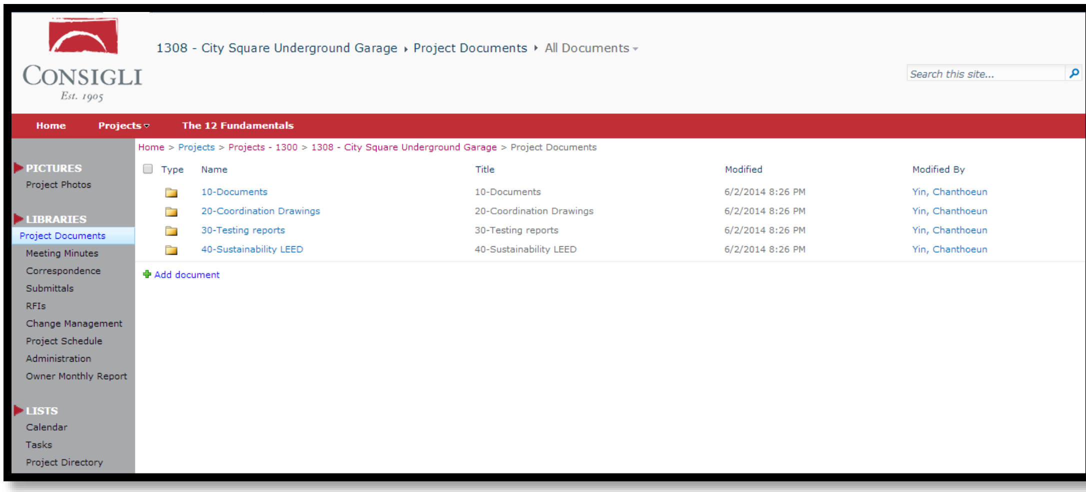


Figure 10 - Consigli Gateway for 1308 City Square Project

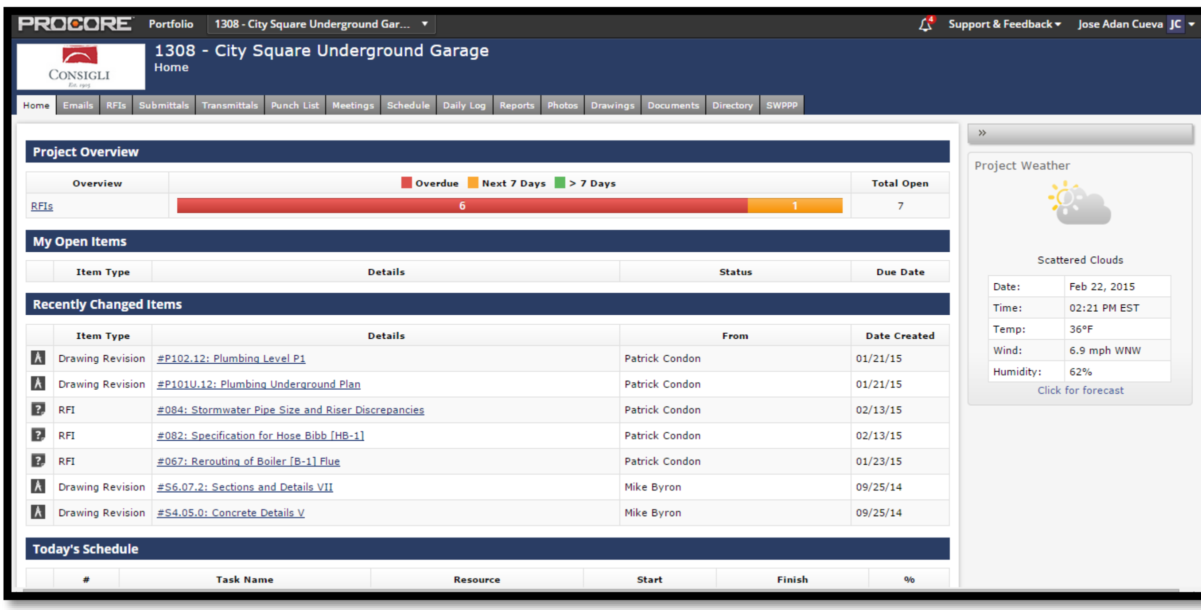


Figure 11 - Consigli Procore

2.4 Lean Construction

The term "Lean Construction" found its way into the construction industry in 1993. Two key organizations have led the leadership of the topic: The International Group for Lean Construction (IGLC) founded in 1993 and The Lean Construction Institute (LCI) founded in 1997". (Sayer, 2012) *Lean,* originated in the late 1980's from Toyota automotive manufacturing, and is a customer-focused methodology to deliver value to customers through the effective use of resources. "The aim of Lean is to deliver the customer's value when they want it, how they want it, where they want it, at a price they will pay, and using all resources most effectively – time, money, and people." (Sayer, 2012) The focus is on improving the overall performance and delivery of the project instead of reducing cost and time from certain activities.

Lean construction challenges the belief that there must always be a trade-off between time, cost, and quality. Table 1 below shows a comparison between a traditional project and a lean project.

	Traditional Projects	Lean Construction Projects
Operating System	Critical Path Management (push)	Last Planner (pull)
Organizational Model	Command and Control	Collaborate/Distribute Authority
Commercial Terms	Transactional	Relational - shared risk

Table 1 - Comparison of Traditional and Lean Projects (Sayer, 2012)

One important aspect to notice from Table 1 is that Lean Construction focuses on optimizing the overall project flow, unlike traditional projects which instead focus on optimizing individual pieces. Lean principles can be applied to several areas of a construction project, but they are only effective if they focus on improving the whole process. Some areas of focus may include the design, procurement, production planning, logistics, and the construction itself. Construction is the area that might be most applicable to Lean concepts as the physical putting together of structures/roadways/design elements is the goal of all projects. Some aspects to consider include: clear communication of project ideas, training, multitasking, progress reporting, and improving meetings. (Excellence, 2004)

There have been several successful groups and companies that have implemented Lean concepts to their projects. However, there is still a lot of opposition to institute a change in the industry because most of the players involved believe in the traditional approach they have operated in the past. This is reflected in the productivity in the US Construction Industry, which has stayed leveled or declined since 1964, depending on the study used, as shown in Figure 12 below. (Sayer, 2012) Despite the stagnant trend line below, many building owners are now expecting Lean concepts and practices to be applied in their projects and reflected in the Request for Proposals, thus potentially improving the industry's productivity.

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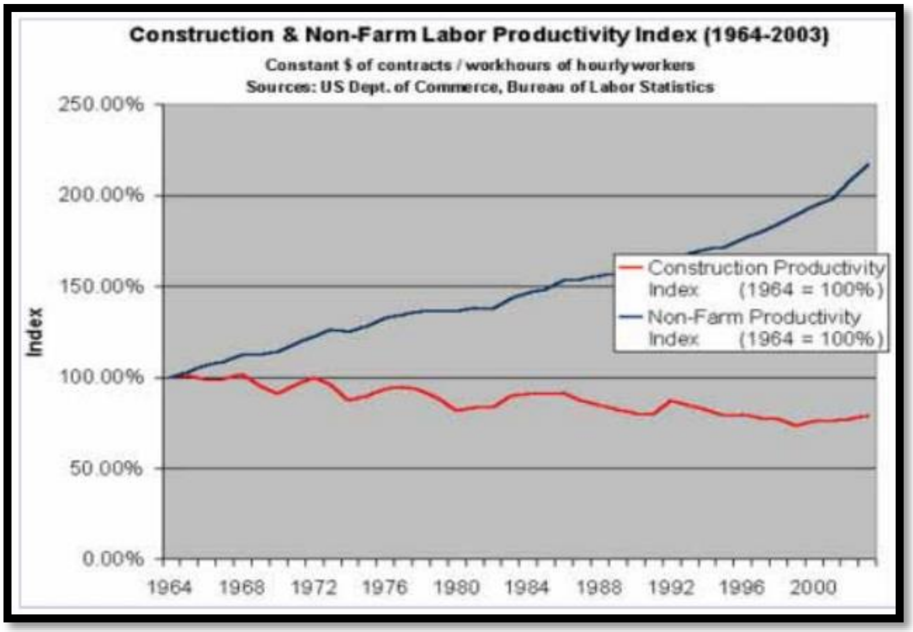

Figure 12 - Labor Productivity Index for the U.S. Construction Industry and all Non-farm Industries. (Sayer, 2012)
(Original Source: Teicholz, Paul. "Labor Productivity Declines in the Construction Industry" AECbytes Viewpoint. Issue 4. April 14, 2004)

Some of the benefits presented by using Lean Construction include better budget performance, higher on-time performance, fewer accidents, and better value delivered to the customer with the completion of the project. Beyond it being a different approach to the entire construction sequence, Lean fosters the use of advanced technology and software to support its core principals. The most important advancement is Building Information Modeling (BIM), a technology that allows the team to design multi-dimensional models of a facility, and enables Lean Project Delivery. With BIM, "the team can evaluate multiple design alternatives, make better design decisions, make better costing decisions, have more communication earlier in the project, and create production system plans directly into the model earlier in the process." (Sayer, 2012)

2.5 Pre-stressed Concrete

The selection of prestressed concrete as a viable alternative material for a typical bay design took into account available research on its benefits and limitations. The concept of prestressed concrete is bonding strands of steel which have been pre-tensioned with a concrete casted to a particular shape and dimensions. Once the concrete cures and the element is released from its mold, the tension in the strands remains, usually creating a camber. This applied tension force on the concrete member acts against the applied service loading of the structure, allowing the member to carry greater loads without cracking or failing.

Although prestressed concrete allows members to be cast into wide variety of shapes and sizes, using commonly produced designs and shapes is more advantageous in terms of speed and cost of the construction. (PCI, 2012) In Figure 13, two common components in building applications are illustrated. For parking structures double tee systems are more suitable due to their capacity to span longer distances and eliminate columns. Additionally, reducing columns and maximizing space allows for unobstructed views through the levels.

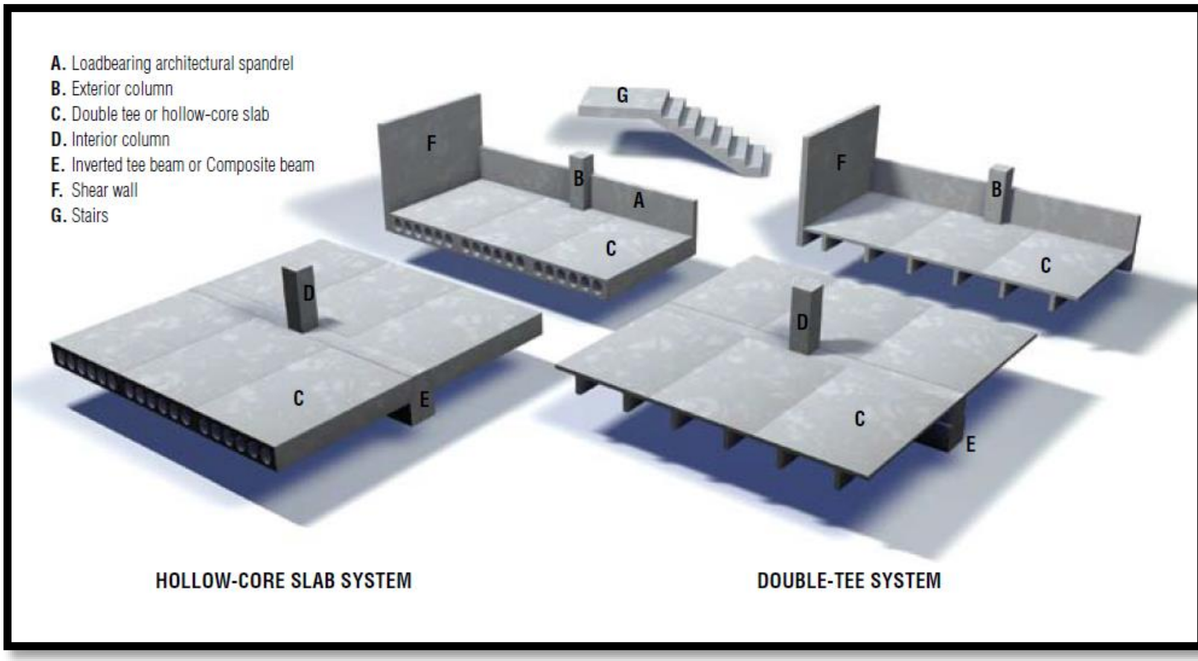

Figure 13 - Common Component Systems in Prestressed Concrete Design (Foster et. al., 1997)

Additional background information and research on underground parking garage structures can be found in Appendix B.

2.6 Summary

Throughout this chapter, relevant background research and concepts for the project were covered:

- CitySquare history and future development plans
- Consigli Construction overview and its involvement in the CitySquare
- The project management parameters of the underground parking garage project
- Overview on lean construction and its benefits
- Overview of prestressed concrete

The following chapters will discuss in depth the methodology and analysis done in the project including project management, lean construction, an alternative design, axiomatic design methodology, and sustainability concepts.

3.0 City Square Project Management

Observing a Consigli Construction project on real-time allowed for the observation, study, and analysis of the elements that are managed from start to finish. A large scale project such as an underground parking garage in a downtown setting requires expertise to keep time and cost under defined contractual parameters. Understanding how the project manager tackled this complicated task, as well as how the key players communicated in a multi-party effort, lead to the identification of focal points that can be improved to the benefit of the overall project or future work. This section discusses:

- how the project driving critical path of the schedule changed throughout the duration of construction
- how the original quantities, labor, and cost changed
- how these changes were recognized and dealt with
- the effectiveness of communication efforts both within the General Contractor and among all key player, and
- the coordination among trades and tasks throughout the interrelated process of construction.

3.1 Project Snapshot

Analysis of the construction progress was quantified through three major gages dependent on time: cost, schedule, and communication. This study observed changes in these factors between September 14th (Week 12) and February 8th, 2015 (Week 33), considering that Consigli's involvement in the project started on June 30th, 2014 (week 1). This time window allowed the collection of valuable information from diverse sources included but not limited to meetings, written communication, formal documents, records, construction documents, actual construction progress, and staff surveys. Different combinations of up to date data (analyzed in subsequent sections) allowed for an understanding of each of the three factors previously mentioned. Table 2 below provides a concise summary/report of cost, schedule and communication as of Week 33 (representing the extent of the data available to date report was written).

Project Management Parameter	Status
Cost (GMP vs Change orders vs Allowances)	Total Cost: *$34,299,152.00.* Change Requests submitted as of Week 33: *15*
Schedule	Start: June 30th 2014 End (Projected): October 13th 2015
Communication (RFI's and Submittals)	RFI's submitted as of Week 33: *67* Submittals submitted as of Week 33: *92*

Table 2: Underground Parking Garage Snapshot as of Week 33

3.2 Cost/Quantity Analysis

Construction projects can be delivered under several contractual agreements that directly influence the way costs and quantities are tracked. In this project, Consigli performed as the general contractor (CM) under a guaranteed maximum price (GMP). This contractual agreement, also known as Construction Manager (in this case the CM) at risk, required Consigli to provide to the owner a reasonable maximum pricing for the activities necessary to complete construction. The process through which the GMP was revised, negotiated, and adjusted had an impact on the cost of individual trades because of their dependence on sufficient information through construction documents and CM instruction, as well as lead time to prepare production. Figure 14 below breaks down the Guaranteed Maximum Pricing for the entire project by major bid package according to Construction Specifications Institute (CSI) Master Format classification system.

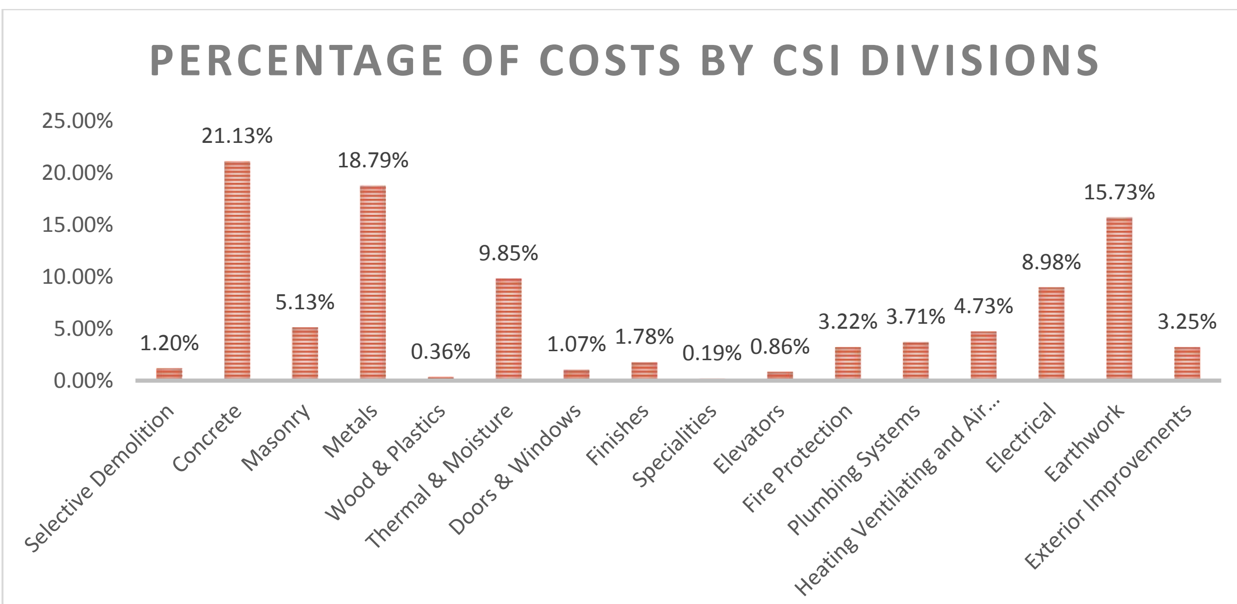

Figure 14- Percentage of Costs from GMP

The CSI divisions which included the work to be performed early in the project were Earthwork and Concrete, the 3rd and 1st highest in cost respectively. Earthwork involved the material movement through cut and fill of earthwork to adjust and prepare the site for construction. This process began prior to the completion of the GMP, as Consigli's involvement stemmed off an already established relationship with the City of Worcester and allowed for preliminary site work to begin early. The high cost of the all earthwork came as a result of the scope of the work, involving heavy excavation and voluminous movement of earth, and the pricing of the site work subcontractor, Marois Bros. Consigli had to balance the urgency to fuel the fast moving site work with the thorough creation of a GMP. The site work was the key to open up the schedule for concrete foundation work to follow, Consigli managed to get an early release change request approved months before the final GMP approval for a total value of just under $5,000,000. This change request came as the first financing step for the project to get underway and set the tone for project management measurements taken the following months. All change requests, including early release packages, are displayed below in Figure 15.

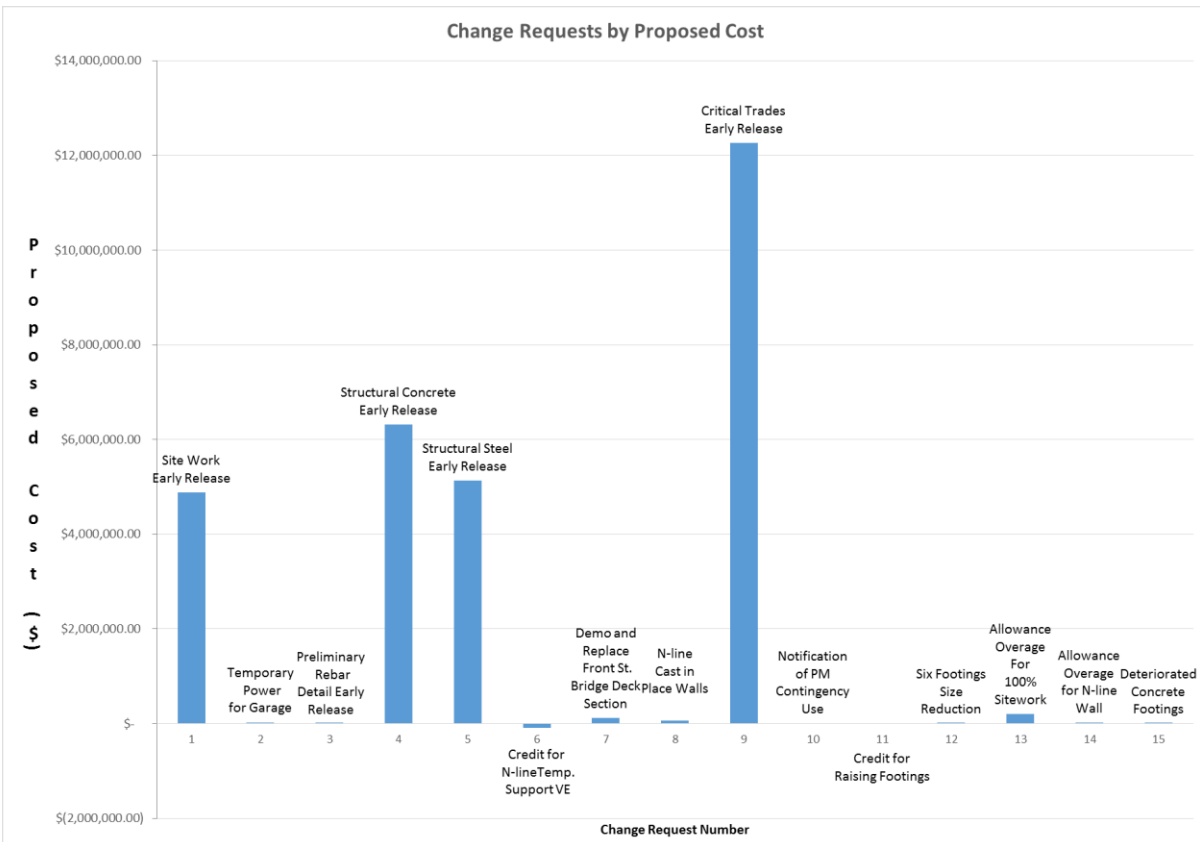

Figure 15 - Change Request by Cost

The second critical division of work which was affected by schedule and involving a high cost was Concrete. Foundation and footing work immediately followed the preparation of the site at the earliest availability. This came weeks prior the completion of the GMP, requiring another project management strategy from Consigli to ensure the continuity of construction work. Consigli issued Change Request 17-

005 titled Structural Concrete Package Early Release for a value of over $6,000,000 early September. This included the work necessary for structural concrete and the remainder of the preconstruction services costs by the CM. Beyond granting for work to continue, releasing concrete early also impacted the early release of the rebar detailing for the entire project, which immediately followed in the sequence of the change requests.

When compared to other change requests, both Structural Concrete Early Release and Site Work Early Release stand among the top for cost, especially when compared to later change requests. These change requests differed from the common nature of other CR's in that they represented the formal value of the work to be done defined and understood through the original project scope instead of accounting for later changes in scope and/or field conditions. These CR's would be included later in the GMP under their respective CSI Division and proportionally under any other cost category such as other CSI divisions, allowances or fees. Since the GMP approval came at a later time, the value of the early release change requests exceeded the CSI Divisions because they were inclusive to all the costs necessary to keep construction going, which are not necessarily captured by their respective division value. These figures are compared below in Table 3.

Type of Work	GMP CSI Division Value	Early Release Change Request Value
Concrete	$5,951,769.00	$6,322,294.00
Earthwork (Site Work)	$4,430,770.00	$4,879,314.00

Table 3 - Early Release and CSI

Analyzing the origin and nature of the Early Release Site Work and Concrete CR's sheds light on a broader analysis of the cost management for the overall project. Comparing the total value of the GMP against the value of submitted early release change requests shows that their sum amounted to 83.3% of the total GMP value ($28,752,937.00 in Submitted Early Release CR's out of a total GMP of $34,299,152.00). The full breakdown of the GMP can be found in Appendix C. This extremely high percentage proves that change requests were used as effective tools for early funding under schedule constraints in a negotiation were both owner and CM prioritized the ongoing progress of construction over contractual dealings.

Regardless of how effective change requests proved to be, the GMP could not be sidestepped, and the focus of much conversation and management efforts turned to finalizing the contract between weeks 15 and 25. A deeper analysis of the impact of the GMP negotiations is included in the following section. From a cost perspective, the concentrated efforts from the CM to get the GMP approved by the owner came in the form of Change Request 17-014 titled Early Release Critical Trades. This change request came in with a value of over $12,000,000 on week 19 (submitted on 11/5/14) and represented the work for trades that were on the critical path of the project in order to minimize the negative impact on the overall project schedule prior to the GMP signing. In comparison to all other early release change requests, this CR more than doubles the next highest in value (Refer to Figure 15 above).

Beyond the stated value of all early release change requests, especially CR 17-014 for critical trades, their submission dates allow for analysis considering project schedule. Figure 16 below plots the cumulative value of submitted change requests against time.

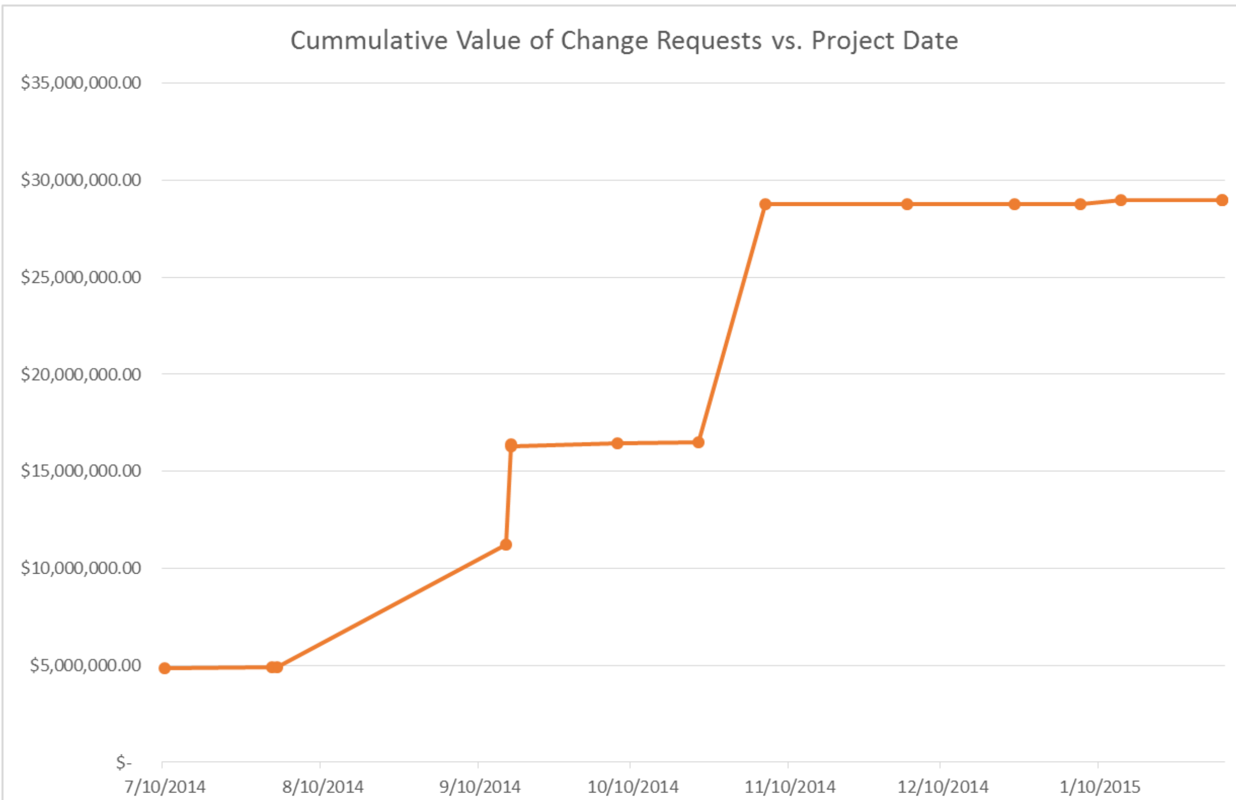

Figure 16 - Cumulative Value of Change Request vs Project Date

As previously discussed, the first change request CR 17-001 for Site Work came at a high value of around $5,000,000 and was followed by subsequent CR's. The graph above shows two rapid increases in cumulative CR value each immediately followed by plateaus. The first rapid increase comes as a result of the site work, structural concrete and structural steel early release CR's. Since these allowed for the continuation of work as defined by the critical path and the scope of construction, a first plateau was reached and lasted over a month for which labor, material, planning and management costs were covered for. Consigli made use of this time window to work towards to getting the GMP approved, which culminated in a second rapid increase in cumulative CR value as a result of CR 17-014 for critical trades.

When referring to both Figure 15 and Figure 16 it is clear that the value of change requests following CR 17-014 dropped dramatically. When plotted against time, this drop in CR value yielded a second plateau which was sustained at least until Week 33 (when this report was written). The significant reduction in CR value came with the final stages of the GMP negotiation around Week 20 and its final signing on Week 25. With the accomplishment of the GMP milestone, cost management shifted from change request based to maximum price and allowance management, which mirrors the change in CR nomenclature from “17-###” to “CR###” shown in detail in Appendix D. Comparing the total value of early release CR’s with post-GMP CR’s puts in perspective the contrast between traditional change requests as a function of added scope and/or change in field conditions and the unique way change requests were used in this project to expedite construction prior to a finalized contractual agreement. Figure 17 illustrates the magnitude of change requests prior to the signing the GMP compared to more recent change requests.

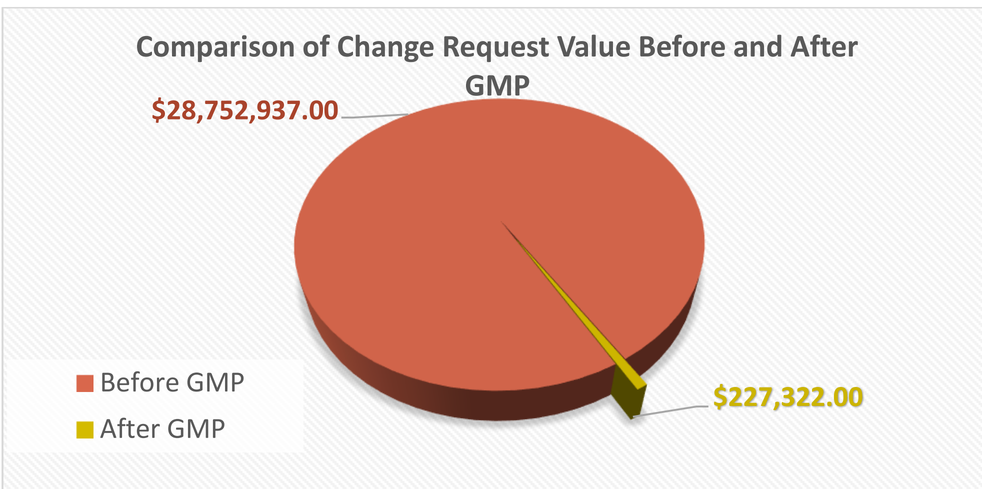

Figure 17 - Change Request Values before and after GMP

The value analysis of change requests was accompanied by an individual review of their content and nature. Studying the fifteen change requests (available to date) allowed a classification system by type, in the terms of the purpose of the change requests.

Table **4** below provides the full classification of CR’s.

Change Requests	
Types	**Amount**
Field Condition	4
Design Change	1
Alternative Solution	2
Early Release	6
Allowance Transfer	2
Total	15

Table 4 - Change Requests

From this table, it is evident that early release CR's were not only critical as earlier discussed, but were also prevalent. The second most prevalent type of CR was Field Condition, indicating a change or addition to scope due to field conditions unforeseen in contract documents. This type of CR reflects a more traditional use of change order management and will likely increase in number with the progress of construction. Contrastingly, the number of early release change requests will most likely remain the same given the GMP, with its prices by division, allowances, and fees, will cover all costs necessary (up to a guaranteed price) to complete the project. Applying this classification to Figure 18 which compares the value of all CR's adds depth to this analysis.

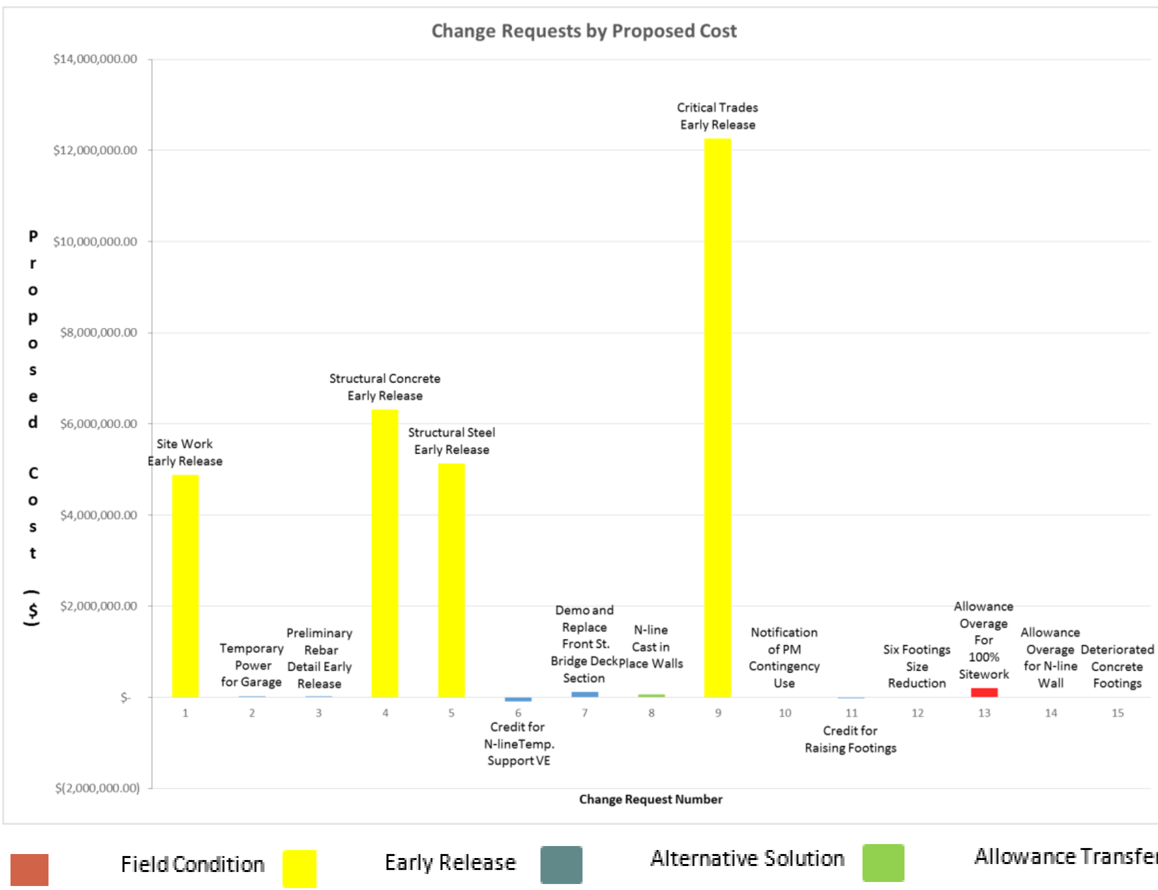

Figure 18 - Change Requests by Proposed Cost

Beyond change request management, an important aspect of cost management relates to approved allowances. These are approved line items for specific items or work for potential overruns or the unknown, with a set ceiling or limit. The full breakdown of all allowances can be found in Appendix C (GMP breakdown). The sum of all allowances represents a small percentage of the total cost of the project as illustrated by Figure 19 below.

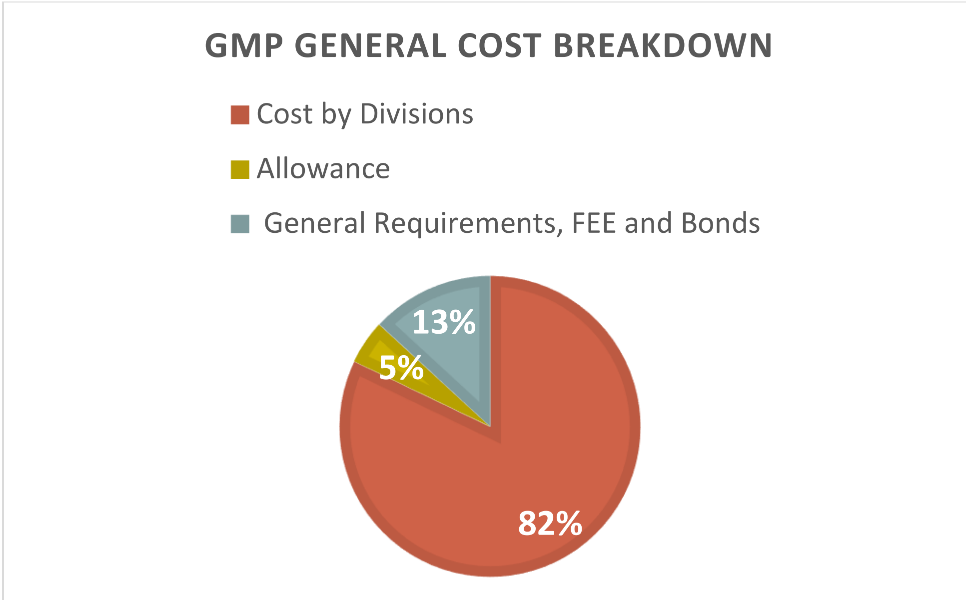

Figure 19 - GMP General Cost Breakdown

Even as allowances represent a small portion of the entire project cost, they were scrutinized by the owner who sought to approve and agree with the CM's argument and pricing for each. As in the case of change requests, allowances in this project served a different purposes including weather conditions (Police Detail Allowance and Winter Allowance), unexpected field conditions (Contaminated Soil Disposal and N-line Concrete Wall), and others. Most documentation for allowances is included in the communication analysis later in this chapter.

Fees and General Condition round of the pie chart for the total project cost with 13%. This category includes all costs unrelated to the work performed that allow the project to be executed such as insurance and bonds. Limited analysis can be done for these costs, as most of them are fixed and case specific.

3.3 Schedule Analysis

One of the most important elements in project management is the schedule. A comprehensive schedule should include all necessary activities in the precise order they need to take place, provide information into the duration of each activity, showcase various milestones throughout the project, and drive the day to day activities of the field.

Consigli managed the schedule using Primavera 6 software with detailed activities and milestones from the start of the project up to completion. This electronic schedule was the driver of monthly projections, 4-week look ahead with subcontractors, and ultimately the day to day activities to be performed. This process flow of time related information is best represented by Figure 20 below.

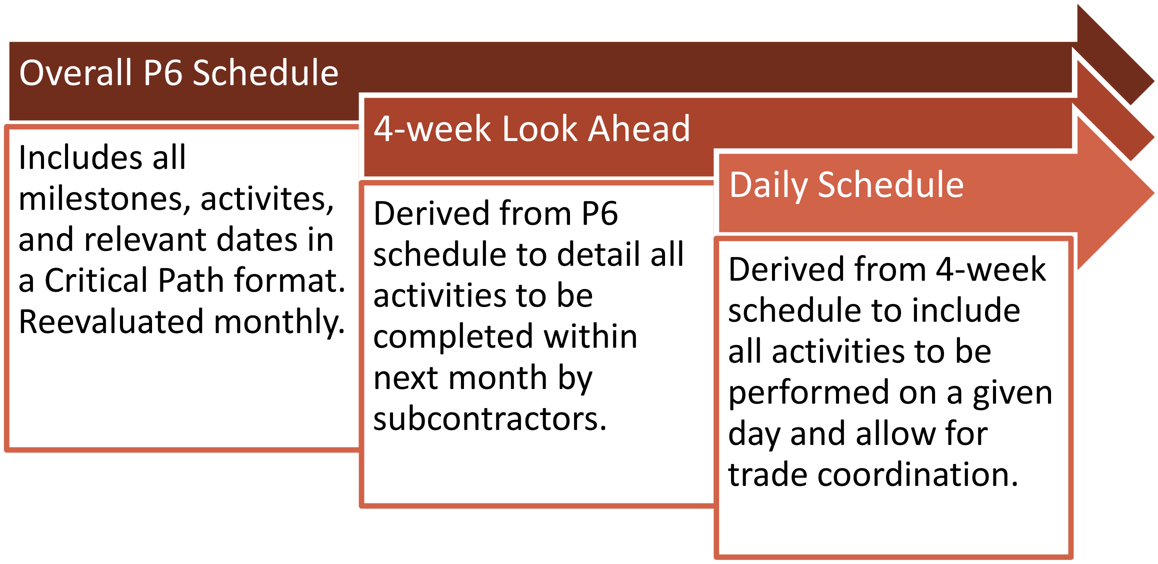

Figure 20 - Consigli Schedule Process Flow

An analysis was done on the changes to the overall P6 schedule from September to January. Studying the highest level of schedule provided the most comprehensive data revealing how integral certain activities and milestones were to the overall project management. To analyze the schedule effectively, an emphasis was put on finding the changes to the critical path of construction, which involved calculating how many activities became critical as a function of delays and the floats for all of them. Figure 21 below shows the format of Consigli's schedule from September. Both schedules used for this analysis can be found in full in Appendix E and Appendix F respectively.

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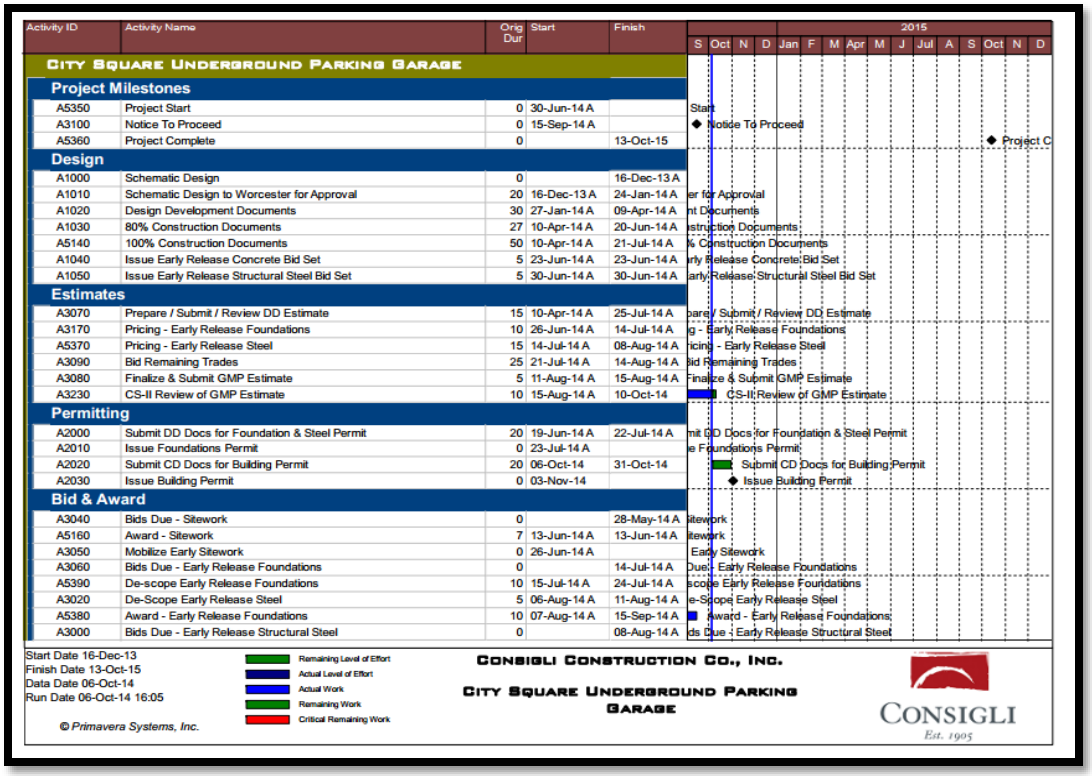

Activity ID	Activity Name	Orig Dur	Start	Finish
City Square Underground Parking Garage				
Project Milestones				
A5350	Project Start	0	30-Jun-14 A	
A3100	Notice To Proceed	0	15-Sep-14 A	
A5360	Project Complete	0		13-Oct-15
Design				
A1000	Schematic Design	0		16-Dec-13 A
A1010	Schematic Design to Worcester for Approval	20	16-Dec-13 A	24-Jan-14 A
A1020	Design Development Documents	30	27-Jan-14 A	09-Apr-14 A
A1030	80% Construction Documents	27	10-Apr-14 A	20-Jun-14 A
A5140	100% Construction Documents	50	10-Apr-14 A	21-Jul-14 A
A1040	Issue Early Release Concrete Bid Set	5	23-Jun-14 A	23-Jun-14 A
A1050	Issue Early Release Structural Steel Bid Set	5	30-Jun-14 A	30-Jun-14 A
Estimates				
A3070	Prepare / Submit / Review DD Estimate	15	10-Apr-14 A	25-Jul-14 A
A3170	Pricing - Early Release Foundations	10	26-Jun-14 A	14-Jul-14 A
A5370	Pricing - Early Release Steel	15	14-Jul-14 A	08-Aug-14 A
A3090	Bid Remaining Trades	25	21-Jul-14 A	14-Aug-14 A
A3080	Finalize & Submit GMP Estimate	5	11-Aug-14 A	15-Aug-14 A
A3230	CS-II Review of GMP Estimate	10	15-Aug-14 A	10-Oct-14
Permitting				
A2000	Submit DD Docs for Foundation & Steel Permit	20	19-Jun-14 A	22-Jul-14 A
A2010	Issue Foundations Permit	0	23-Jul-14 A	
A2020	Submit CD Docs for Building Permit	20	06-Oct-14	31-Oct-14
A2030	Issue Building Permit	0	03-Nov-14	
Bid & Award				
A3040	Bids Due - Sitework	0		28-May-14 A
A5160	Award - Sitework	7	13-Jun-14 A	13-Jun-14 A
A3050	Mobilize Early Sitework	0	26-Jun-14 A	
A3060	Bids Due - Early Release Foundations	0		14-Jul-14 A
A5390	De-scope Early Release Foundations	10	15-Jul-14 A	24-Jul-14 A
A3020	De-Scope Early Release Steel	5	06-Aug-14 A	11-Aug-14 A
A5380	Award - Early Release Foundations	10	07-Aug-14 A	15-Sep-14 A
A3000	Bids Due - Early Release Structural Steel	0		08-Aug-14 A

Figure 21 - Consigli's September Schedule

Although not part of the critical path, project milestones reveal the overall evolution of the schedule. The September schedule included only three milestones (Project Start, Notice to Proceed and Project complete), with a completion date for the project of October 13th 2015, thirteen months after the notice to proceed. The low number of milestones shows that the schedule was still being finalized, and only the three most critical milestones had been determined at the time. Contrastingly, the January schedule included 16 milestones detailing the progression of the construction from start to completion. The majority of the milestones were forthcoming through trades that had not begun yet. Structural steel for example had been detailed and its production ordered, but the assembly of steel beams, girders and columns would have to wait until March. With the addition of milestones also came the revision of the Project Complete date, which had been pushed back a little over two weeks to October 29th 2015. This slight delay carried through the entire project and caused the change of the critical path.

To determine a single cause for the delay of the schedule and its ripple effects across activities would be inaccurate, as it was a combination of factors and the interactions between key players that molded the progress of the project. However, the timeline of one particular element, the signing of the Guaranteed Maximum Price, can be used as a point of reference in the schedule analysis. The September schedule projected the review of the GMP to take place between mid-August and mid-October, but the

January schedule marked its actual completion as December 5th. In general, the almost two month delay of the GMP did not translate directly into an overall project delay of the same magnitude. This can be attributed in part to the string of high-value change requests that kept the project moving on schedule. Even as these bid awards CR's were completed more than a couple of weeks later than originally scheduled, their built in floats absorbed the impact on the overall project.

The scheduling of construction activities categorized by area of work (Building E and Ballfield) or by scope (Overall Site) was analyzed by means of the critical path. Activities within the Overall Site category were generally pushed back, but with no effect on the critical paths. These included work to be performed continuously throughout a long span of the project such as dewatering the early site and the footings, or activities far out enough on the schedule to remain uncritical such as installing site utilities. Similarly, all activities related to the mitigation plan for East Garage were rescheduled to later in the project without impacting the critical path. As the work on East Garage is to be done on its inside, there are no conflicts with any trades working on site.

Activities taking place on site for both the Building E and Ballfield areas had the biggest impact on the critical path. For Building E, 24 activities that had positive floats on the September schedule became critical on the January schedule. On average, the float for these activities became -9.5, meaning more than one week's time delay. A majority of the affected activities relate to the excavation and placing of footings in the area of the future hotel. Since this work encompassed demolition and removal of old structures, it was more dependent on unknown site conditions which resulted in setbacks. The first activity of this sequence, excavating the initial cut and hauling off, was delayed more than a month because of time consuming requests for information and added scope, became critical, and affected the path as the Figure 22 below shows.

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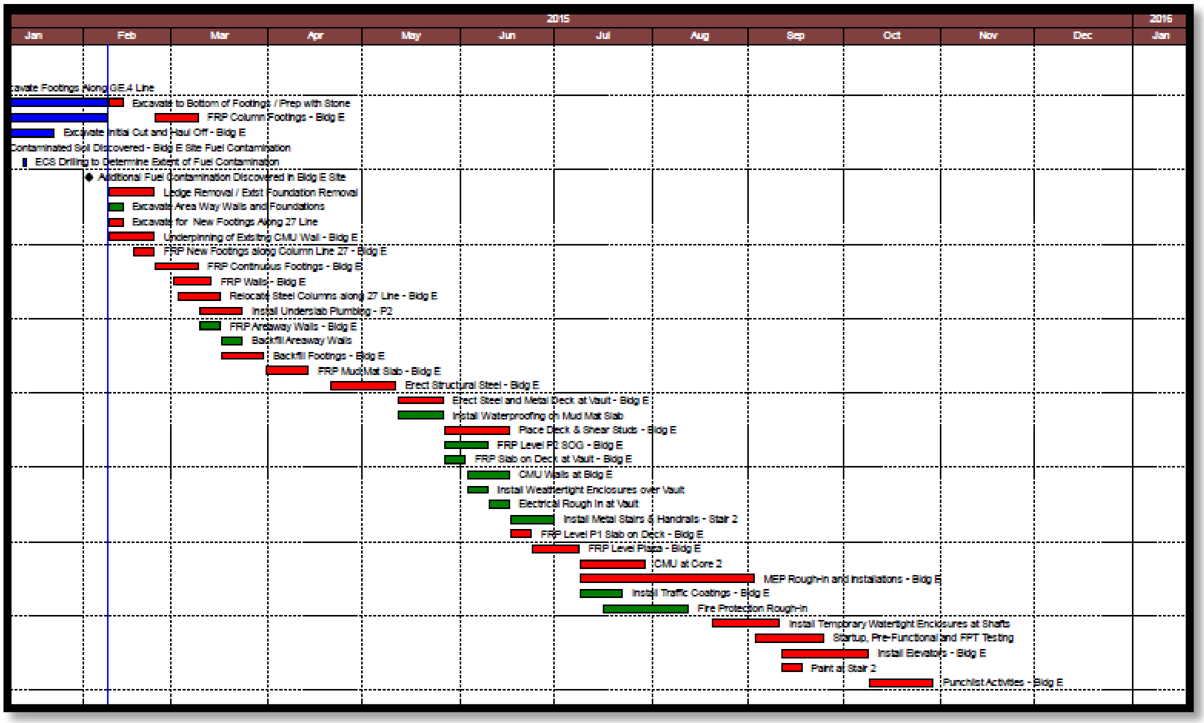

Figure 22 - Delay in Schedule

Over ten activities on the Ballfield area became critical with an average float of -7.75 days. Like on the Building E sequence, these changes stemmed off of excavation and foundation work delays and stretched across the project. Even with these changes, Consigli managed to keep individual delays from significantly impacting the overall project completion by using up the originally built in floats.

3.4 Communication

As the general contractor, Consigli was responsible for managing information exchanges and keeping organized records of changes or requests by party involved. While much of the internal communication happened on a daily basis at the field office and job site, the communication between key players was carefully documented and tracked electronically. Access to Consigli's Gateway and Pro Core servers, online project management dashboards, allowed the tracking of any formal exchanges of information and their progress in the communication chain. One thing to note is that Consigli originally was using Gateway as the only server. Mid-way through the project they launched the new server Pro Core, and began using both of them simultaneously. All Requests for Information (RFI's) and Submittals were monitored, documented and ultimately quantified and analyzed by using the functionalities of both online dashboards. Figure 23 below showcases the layout of the Pro Core dashboard for RFI's.

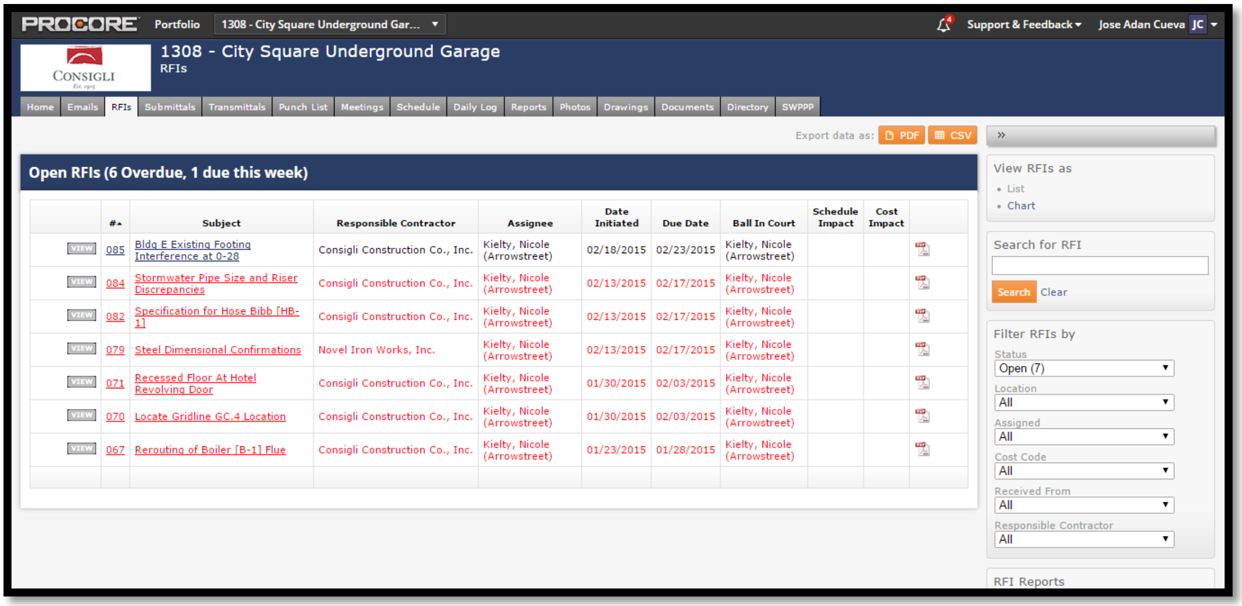

Figure 23 - Procore dashboard for RFI's

Requests for information, formal written documents expressing the need for the architect, engineer, or subcontractor to clarify construction documents, intent, or specifications, were quantified on a weekly or biweekly basis using the spreadsheet shown on Appendix G. To extract valuable prices of information for analysis, all documents attached to the request for information ranging from the official cover letter by the CM to the clarifying sketches and notes of the architect were reviewed. The key components which extend beyond individual RFI's and speak to the management of communication avenues were date submitted, turnover time, reasoning or type, and impact on schedule/cost expressed as a change of scope.

The analysis of the dates RFI's were submitted adds depth to the schedule analysis already discussed. By plotting the number of RFI's against time, it is evident that the project underwent periods of high RFI submission after periods of inactivity but with a consistent increase in number of RFI's over time. The plot for this trend is illustrated by Figure 24 below.

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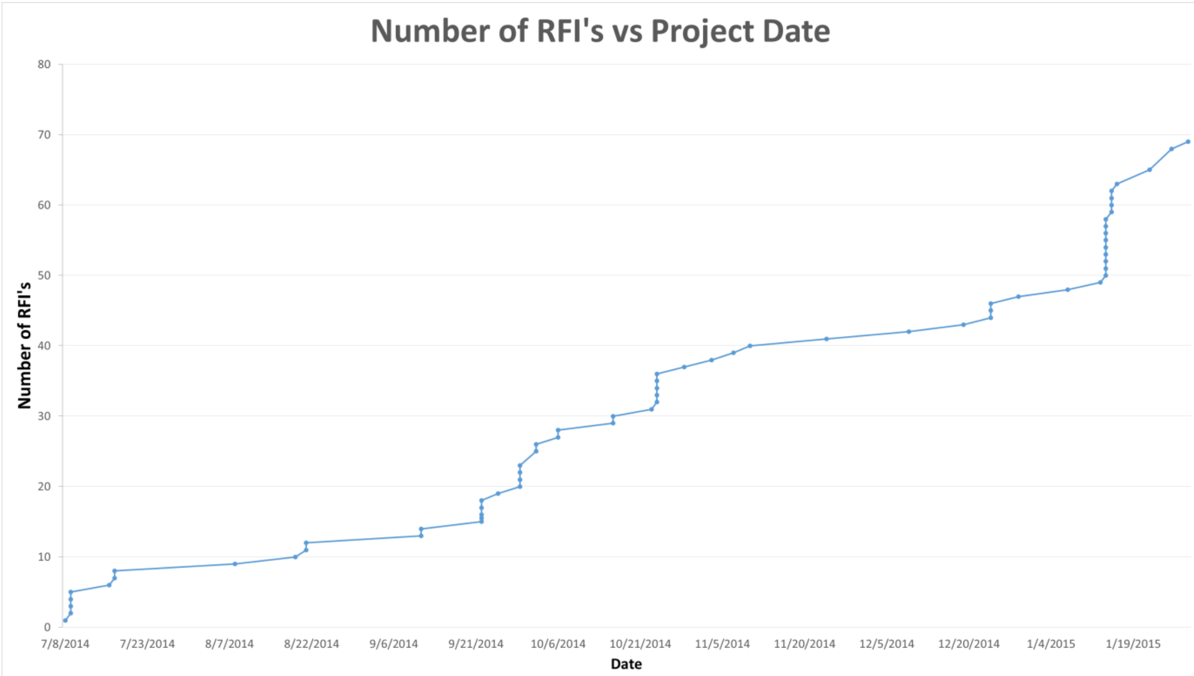

Figure 24 - Number of RFI's vs Project Date

Considering the trend for the submission of RFI's, it is valuable to understand how timely these were dealt with. Request for information typically originated from issues or uncertainties that subcontractors encountered on site who then communicated with Consigli. The flow of information then carried over to the architect, who consulted with the Engineers and then provided an official response to the CM. All communication was done on a standard RFI form provided by Consigli in addition to any clarifying documents, drawings or sketches tagged on by any key player to provide insight into the issue. An analysis was done to determine what percentage of the submitted RFI's were turned over within the expected 7-day turnover by Consigli's communication policy. Figure 25 and Figure 26 below graph the percentage of RFI's in compliance with this policy and a turnover time analysis in detail, respectively.

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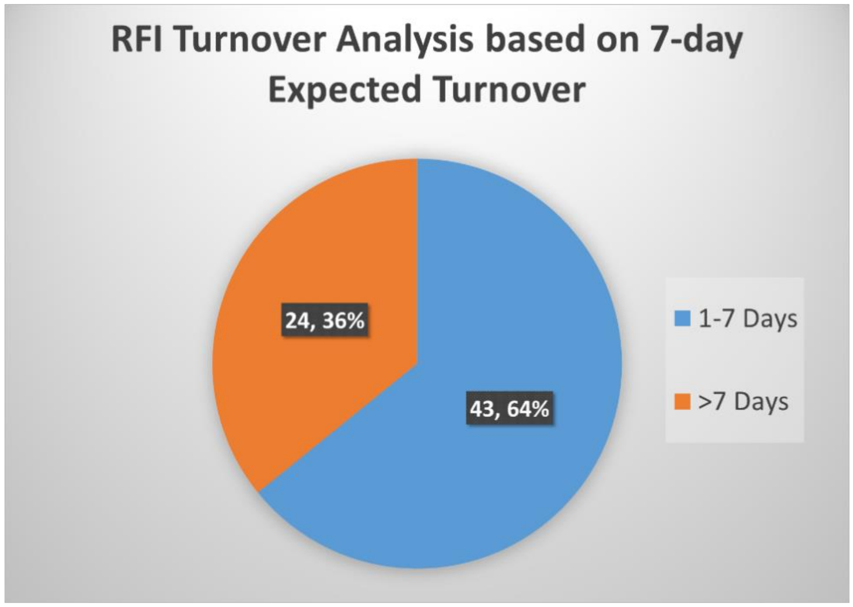


Figure 25 - RFI Turnover Analysis on a 7-Day Expected Turnover

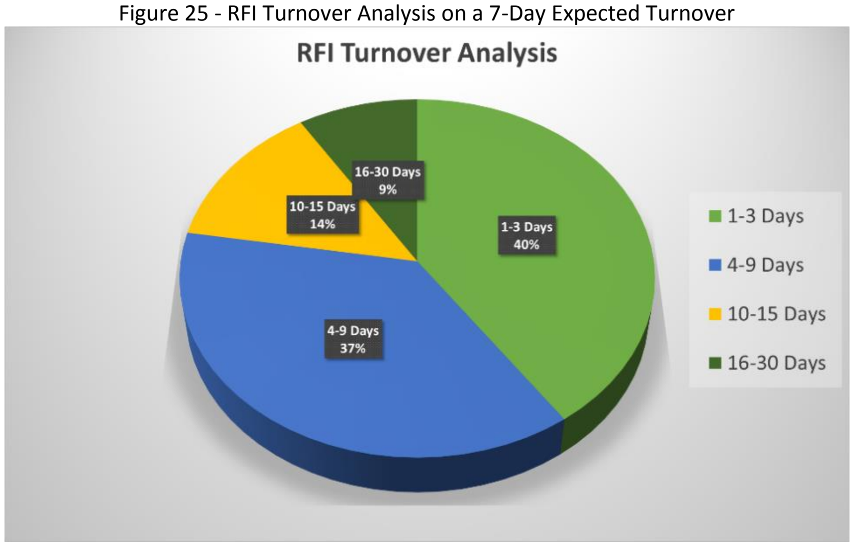


Figure 26 - RFI Turnover Analysis

Even with over a third of RFI's failing to comply with the 7-day turnover policy, RFI's generally did not have a profound impact on the project schedule. Whenever critical RFI's were pending, Consigli and the owner reviewed them verbally during the weekly owner's meetings. The project engineer was tasked with keeping an up to date RFI Log which detailed the status of upcoming, submitted, and returned RFI's and their details. When going over the log, most of the discussion around specific RFI's was done in a dynamic and collaborative fashion, having both the project manager and owner representative asking questions, searching through electronic correspondence, and making action items to follow through. Even as these verbal discussions contributed to effective communication, they were required to be followed by a formal write-up before the RFI could be closed. Given the large volume of information constantly being reviewed and exchanged amongst key players, keeping orderly official documentation carrying legal weight was imperative to the project. A full RFI log and a sample RFI can be found in Appendix H.

Beyond the relationship between RFI's and time, an analysis was done the type of information requested. Even as individual requests referred to different aspects of construction or related to specific subcontractors, they can collectively be classified into either clarification requests or changes in scope. In clarification RFI's, the CM or subcontractor typically proposed a means and method to go about a detailed piece of scope and asked for the owner, architect or engineer to approve. On the other hand, RFI's dealing with change of scope detailed new work to be done as a consequence of a field condition or coordination effort. These RFI's carried an important element of cost which sometimes carried over into change requests. The breakdown of RFI's by major type is displayed by Figure 27 below.

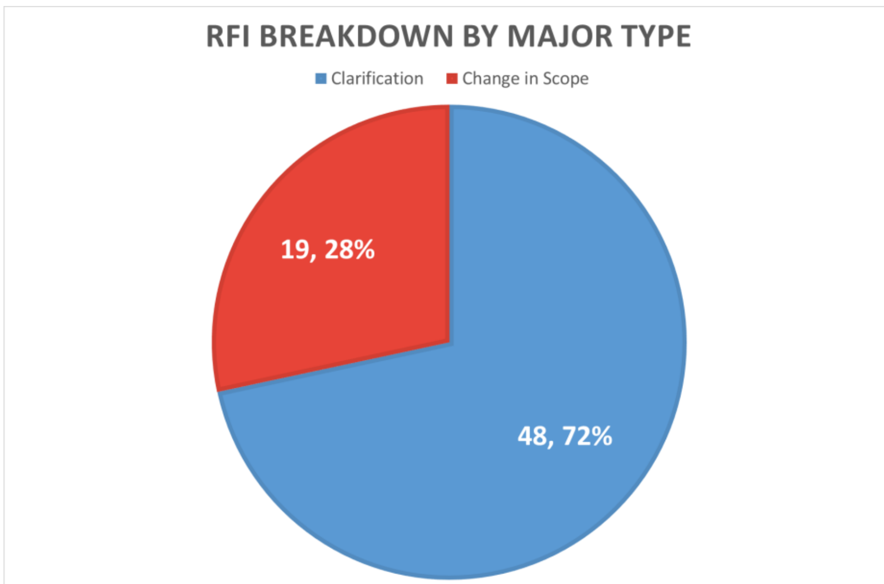


Figure 27 – RFI Breakdown by Major Type

Similarly, submittals were tracked by subcontractors, vendors, or other players and their effect on the schedule. Submittals were required to comply with the specifications for the project and were communicated to the City of Worcester before any work was done by specific subcontractors. Unlike RFI's which come up on a need basis, there is a set number of required submittals established with the scope of the project. The total number of required submittals was calculated to be 512 from the Submittal master list on the Gateway dashboard. The breakdown of the received/completed submittals is illustrated by Figure 28 below.

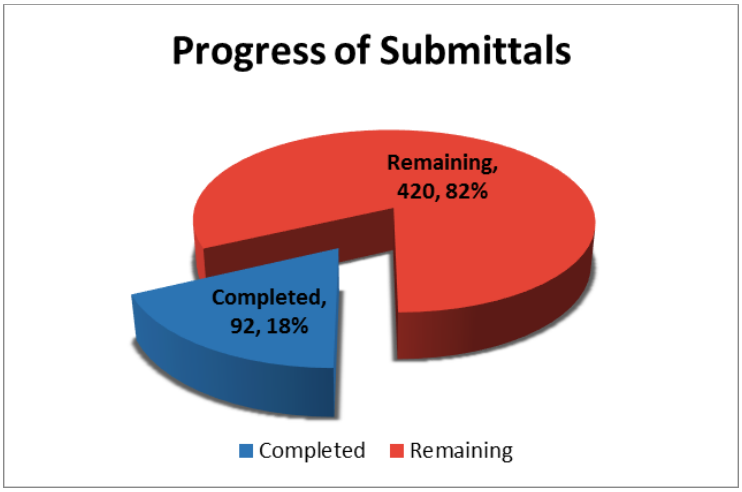


Figure 28 - Progress of Submittals

Completed submittals correspond mostly to trades coming in earlier into the schedule such as site work, concrete and steel. The full listing of completed submittals and analysis can be found in Appendix I. Comparing the percentage of completed submittals to the schedule shows that submittals have not come in at a rate proportional to elapsed project time. Even as the relationship between completed submittals and time is not entirely linear, it is valuable to understand how much lag required documentation can carry before impacting the critical path considering up to the writing of this report, submittals had no major negative impact on the overall schedule. Figure 29 shows this relationship.

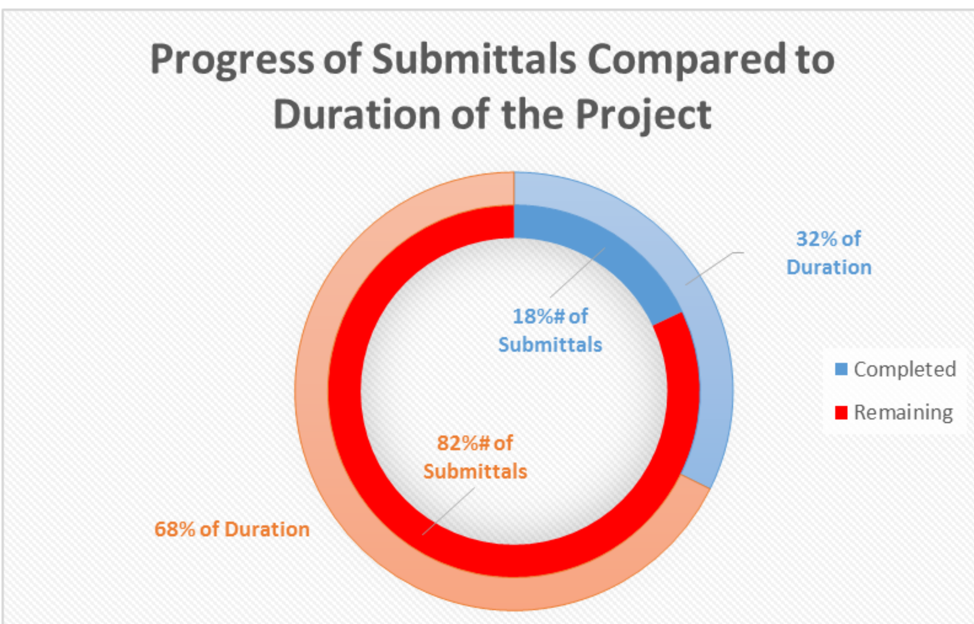


Figure 29 - Progress of Submittals Compared to Project Duration

For an added element of analysis, the turnover time for the approval/completion of submittals can be found in Appendix J.

4.0 Lean Construction

4.1 Overview

Lean construction is a process based on the concepts of lean manufacturing, which aims to remove all non-added value to the project, in order to deliver the customer needs in a more efficient, timely, and cost-effective manner. Lean concepts can be applied to different objectives and activities in a construction project to maximize value and minimize waste. Waste can be defined as anything that does not contribute to the value of the end user and is often categorized in 8 forms (n.a., 2010):

1. Under-utilized labor- not using people's skills and knowledge effectively
2. Waiting - wait time for an activity, material, etc. to be completed
3. Defects - rework or anything that needs to be discarded
4. Overproduction - having more than needed
5. Motion - movement that does not add value (trucks, materials, people, etc.)
6. Inventory - anything in excess that is not being utilized
7. Transportation - movement of people, information, and materials around the organization
8. Over-processing - additional effort that does not add value to the customer

In this study, Consigli's project management was analyzed based on six lean concepts that the team identified as directly relevant to the construction of the underground parking garage. The evaluation was accomplished by on-site observations of the project development and a series of questions that were addressed to the Project Engineer, Project Manager, and the Superintendent through a survey, as shown in Appendix K. The lean concepts which were utilized for the evaluation are described bellowed as they were outlined in the survey. Supplementary information on each of these concepts can be found on Appendix L.

(1)Communication and Level of Understanding - communication is defined as the interactions between the key players through various mediums (email, phone, face-to-face, intermediaries, etc.) which align them with their end goal of maximizing the end value and decreasing waste.

(2) Prefabrication - assembling outside of the project site to save time and space. Prefabrication can lead to better safety, a cleaner project site which reduces waste, and more space to assemble the parts; all which can benefit with the construction time and efficiency of certain activities.

(3) Inventory - all the materials that are not being utilized and stored on site. Lean aims to have only the materials that are required in order to accelerate the process, as well as, increase the working space and organization on site.

(4) Just in Time - the delivery of the materials at the right moment in order to reduce waste, time, and cost. The goal is to reduce the amount of inventory and deliver the materials when needed.

(5) Kitting and 5S - Kitting reduces the inventory levels and increases the operator's effectiveness. It decreases the space needed for supplies storage and ensures ease of access to supplies. 5S includes: (1) sorting, (2) straightening, (3) shining, (4) standardizing, and (5) sustaining. Sorting allows one to go through everything in the work area to keep what is necessary and discard the materials that are not used. Straightening and shining includes identifying items that go together, organize them, and arrange them for an effective retrieval. Standardizing and sustaining will allow one to determine the best practices to not fall into bad habits and educate people about maintaining those standards.

(6) Pull system - The pull system is perhaps the most common concept in Lean process improvement. This system is based on the "Last Planner Method" (LPM) instead of the common scheduling method using the Critical Path Instead of pushing the schedule out more in order to accommodate for more time to complete tasks, you act on the reasons for those failures and work with everyone to improve them and avoid repeating the same mistake to keep the project on schedule.

4.2 Data Gathered

In order to evaluate the lean concepts, a rating system was developed to determine the areas of improvement and identify key activities which were impacted. The evaluation includes a 1 for very bad performance, 2 for poor performance, 3 for an average performance, 4 for a very good performance, and 5 for an excellent performance. The Project Engineer, Project Manager, and the Superintendent were asked to provide a ranking to each of the activities based on each lean concept and how they felt the team had performed on each of those areas. The numerical responses from the respective members were then averaged for each lean concept in order to expedite the analysis of the data gathered and identify the areas showing lean concepts and the areas needing improvement.

The survey was conducted twice in order to better capture the progress of construction as responses could vary from one point in the project to another. The first survey responses were received on week 26 of the project (12/16/14) when the construction progress was slow as the GMP was not finalized yet. The second survey responses were received on week 33 of the project (02/04/15) when more activities were taking place on site by multiple subcontractors and the GMP had been finalized and signed. Table 5 and

Table 6 below illustrate the averaged responses of both surveys based on the topic, as well as the overall project rating that each member gave. The full set of responses to the surveys can be found on Appendix M.

Survey 1	Communication	Prefabrication	Inventory	Just in Time	Kitting & 5S	Pull
Project Engineer	4.17	1.00	3.75	3.50	3.33	2.80
Project Manager	4.08	2.00	3.50	3.75	4.00	2.00
Superintendent	4.17	1.83	3.75	3.50	3.67	1.00
Total Average	4.14	1.61	3.67	3.58	3.67	1.93

Overall Project Rating		
Project Manager	3.22	1
Project Engineer	3.09	2
Superintendent	2.99	3

Table 5 - Survey 1 Responses

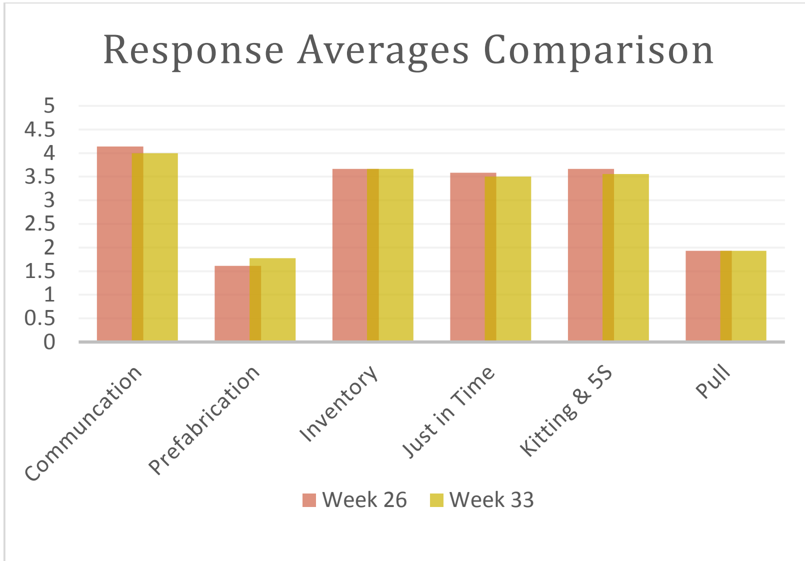
Survey 2	Communication	Prefabrication	Inventory	Just in Time	Kitting & 5S	Pull
Project Engineer	4.25	1.17	3.38	3.50	3.00	2.40
Project Manager	3.67	2.17	3.50	4.00	4.00	2.40
Superintendent	4.08	2.00	4.13	3.00	3.67	1.00
Total Average	4.00	1.78	3.67	3.50	3.56	1.93

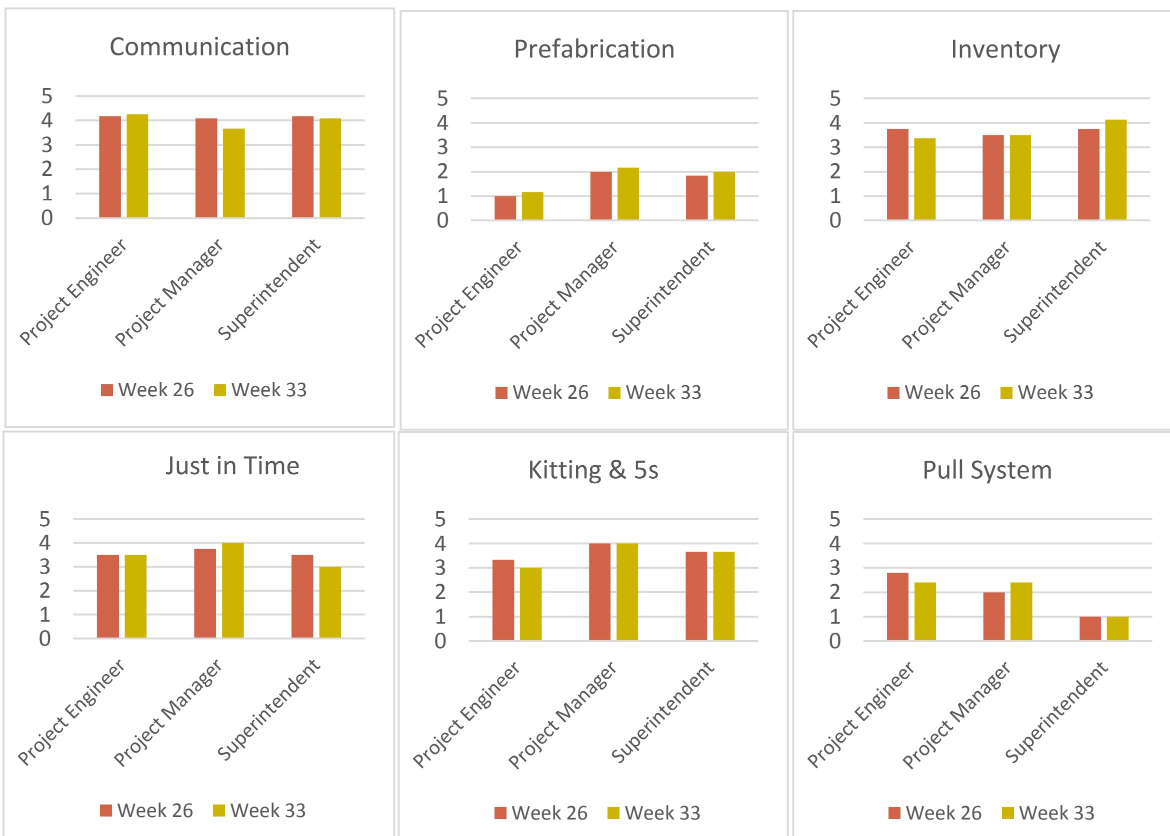
Overall Project Rating		
Project Manager	3.29	1
Project Engineer	2.95	3
Superintendent	2.98	2

Table 6 - Survey 2 Responses

4.3 Evaluation and Recommendations

After conducting both surveys the responses from each survey were compared to identify any major discrepancies or changes in the performance of each lean concept. Nonetheless, as shown in Graph 1 below and on Table 7, the response changes from one survey to the other were minimal.





Graph 1 – Lean Survey Response Comparison

Overall Project Rating Comparison		
Position	**Week 26**	**Week 33**
Project Manager	3.22	3.29
Project Engineer	3.09	2.95
Superintendent	2.99	2.98

Table 7 – Overall Project Rating Comparison

The graphs clearly illustrate that the responses did not vary much from week 26 to week 33 Overall, according to the project manager, project engineer, and superintendent, the project is performing "Fair" based on the lean concepts applied in this analysis. All three members gave the project an overall rating of about 3.0 as shown in Table 7 above, showing that there are areas in which they were very lean and efficient, and other areas which could be improved. Based on the observations from the field operations and on the survey responses, the following conclusions and recommendations with regards to each of the lean concepts were derived:

(1) **Communication and Level of Understanding** – The overall communication of the project was good as there was constant communication between Consigli Construction, CitySquare, and the Subcontractors throughout the development of the project. Weekly meetings were set-up with all the key members – owners, subcontractors, project manager, project engineer, superintendent, and architects – in order to discuss the progress of the project, GMP, RFI's, and anything else related to the management and development of the project. An in-depth analysis of the project management can be found in Chapter 3. These meetings were effective and efficient to discuss major concerns and address any issues, while maintaining everyone informed. Nonetheless, communication from the owners was not as efficient as expected, given that the GMP was signed almost 5 months after the project began, creating a major setback in the progress of the project.

(2) **Prefabrication** – this concept received the lowest rating of all due to the fact that minimal work and activities were being prefabricated or performed outside of the project site. This is partially due to the materials that were selected to build the parking structure. The steel structure does not allow for it to be assembled of-site and the concrete needs to be poured on site. Utilizing a pre-stressed concrete design as the one provided in this project would have allowed for the pre-fabrication of the parts off-site, allowing for more space on site, a quicker assemblage, and a cleaner project site. Although steel structures are also fabricated off-site, they are a lot more labor-intensive and require more space and time for installation.

(3) **Inventory** – Although inventory seemed like it was going to be a challenge for this project due to the surrounding features and buildings to the site, Consigli was able to use an empty site to store materials and inventory. During the period of observation, few materials were needed as the main activities included excavations and foundations. The steel frames were scheduled to arrive in March which will present a bigger challenge for Consigli and will require better organization of the delivery of materials. Overall, the project site was clean and organized but it was partially due

to additional space they had. It is important to note that Prestress members are also shipped to the site and may require some temporary storage, however the assembly process on site is less involved.

(4) **Just in Time** – As previously stated, materials required for the observed weeks were limited as it was mostly work done by machinery. Nonetheless, the project was able to stay on track with the proposed schedule and the concrete arrived on time to be poured for the foundations. A high level of communication between Consigli and the sub-contractors was required to get materials delivered on time. Although not considered a material, the GMP was delivered several weeks past the expected date. This stalled the development of the project and created bigger challenges for the management team.

(5) **Kitting & 5S** – This is a concept that management teams tend to forget about because it is so small, but it can have a huge impact on the efficiency. Although in construction the materials are managed by each subcontractor and they each have their own Conex box, labeling material, organizing them, and putting a sustaining plan to maintain it organized can improve the efficiency of the workers. Potentially, Consigli could look into having a larger Conex box were they maintain all the materials for the subcontractors and they can be shared. This can increase collaboration between subcontractors and would ease the organization of the tools. Appendix N illustrates one of the Conex boxes at the site.

(6) **Pull System** – A pull system was not utilized at all in this project as Consigli utilized the common scheduling method – CPM, instead of the "Last Planner Method" (LPM). After conversing with the Consigli team, they mentioned that in some projects they have a scheduling professional come in and create a Pull schedule for the project. However, this was not the case for the underground parking garage project.

Overall, Consigli did a very good job with maintaining an open communication with the owners and the subcontractors, always allowing all parties to be involved in the conversations. They also performed well with keeping their inventory low and managing the available space for the excavations and foundations. Although the GMP was delayed and the weather conditions presented a big challenge, the management team was able to maintain the progress without much deviation from the original schedule. Nonetheless, there are areas for future improvement to make the process leaner, including the use of prefabricated materials, organizing tools better, and utilizing a pull system for their schedule.

5.0 Alternative Design

5.1 Purpose

An alternative design for the parking garage using to prestressed concrete design was proposed and compared to the original steel design in terms of design, schedule, cost and sustainability. Good practices of Lean Construction discussed in the previous chapter were taken into account for all the work involved in the alternative design.

For more than 40 years, precast prestressed concrete has been the number one choice for underground parking garages due to concrete's greater strength, impermeability and superior durability. (High, 2014). Prestressed concrete also has major design advantages with long-span capabilities resulting larger open areas in buildings and greater span-to-depth ratios in components resulting less material usage. Using concrete reduces the potential for corrosion, which is a critical setback for steel structures. In terms of schedule, the speed of construction can be expedited due to the ability to begin casting components for the superstructure while foundation work is in progress, and being able to erect the superstructure year round without delays caused by harsh weather because it requires less labor in assembly or additional curing requirements. Prestressed concrete is also a sustainable material due to their minimal waste on construction site and lower life cycle cost in terms of construction, operation and maintenance since it does not require painting or tuck-pointing. This is further explored in Chapter 7.

This chapter outlines the steps taken to complete the alternative prestressed concrete design for a typical bay of the CitySquare Underground project. The progress started by identifying the loads that original structure carries. Then the prestressed concrete components and connections selected and calculated to support necessary loads. The last step was to check whether current foundation will be able to support the designed alternative structure.

5.2 Bay Design

The structural design of an underground parking structure includes the determination of loads, selection of framing system, the detailing and sizing of components and connections, and the analysis of foundations. Due to geometrical difficulties in the design of the CitySquare underground parking garage, the analysis of the prestressed design focused on a specific area representative of the project. To select the area of interest, the structural drawings were analyzed to select a section that showed high repetition. With this in consideration, the design focused on the analysis of the Ball field area, north of 27 line. This area is highlighted in green in Figure 30.

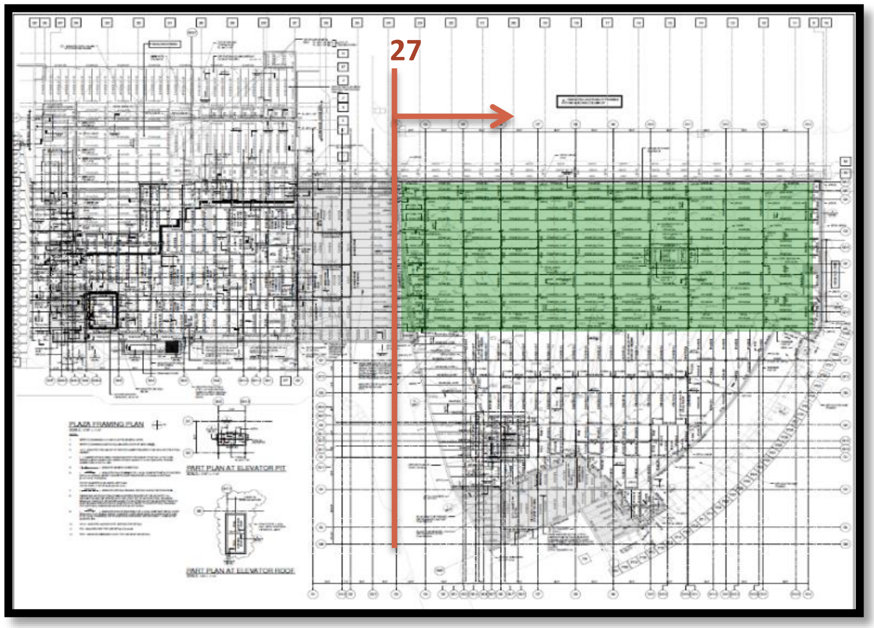
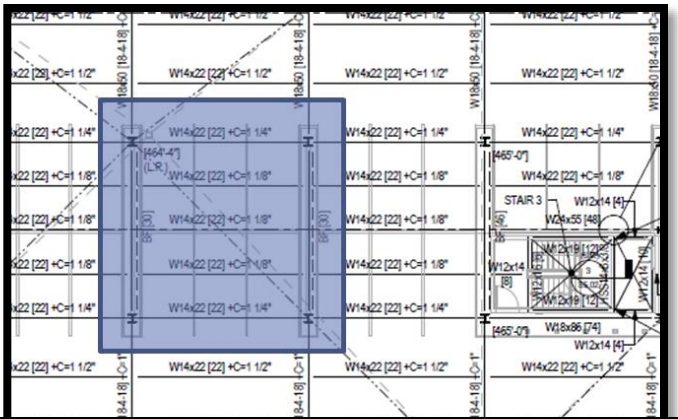


Figure 30 - The Focused Area for Prestressed Structural Design (Gateway)

From this focused area, a typical bay was selected with the goal of changing the steel design into prestressed concrete design. The selected typical steel bay is 30’ by 30’ and is highlighted in blue in

Figure 31. It comprises steel beams, steel girders, steel columns, and a metal deck concrete slab. The alternative bay design is repeatable throughout the highlighted area due to uniform loading conditions dominating the Ball field area. This repetition of size and shape allows using the same high-quality formwork, which will be more economical for overall project and will play into the cost analysis included in later sections.



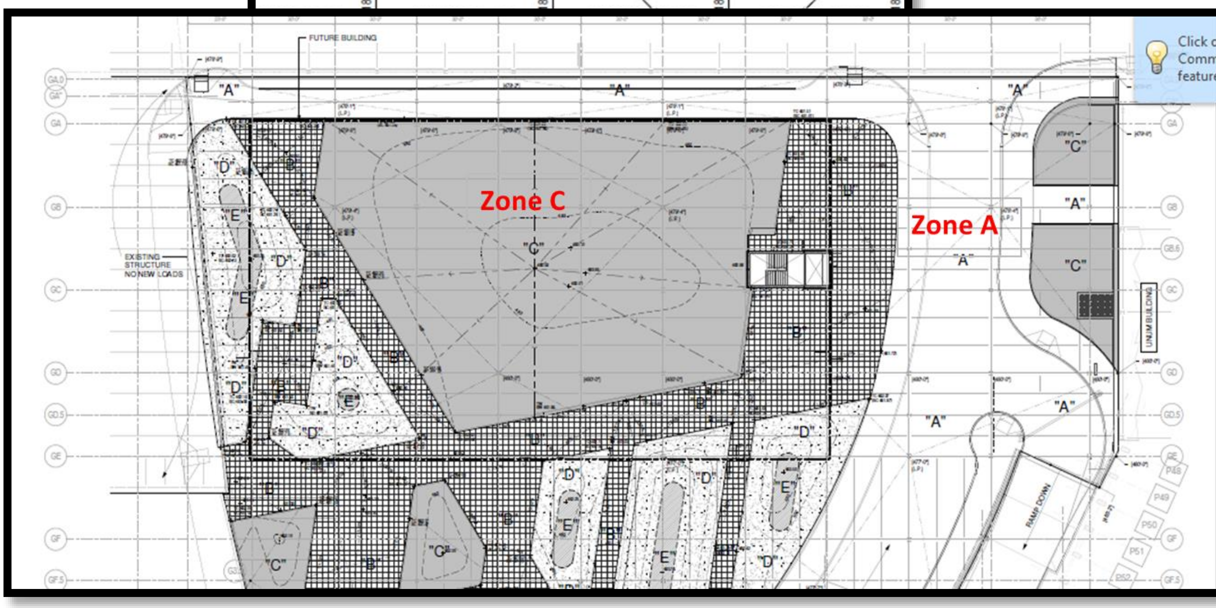


Figure 31 - Selected Steel Bay for Prestressed Design

5.2.1 Identify Loads

The initial step of the alternative design was to identify the loads that are necessary for each component to carry. This information was gathered by looking at the structural drawings provided by Arrowstreet Inc. and Consigli Construction. In the plaza load diagram plan (S1.03) the loadings are divided into different zones due to their different conditions as it is illustrated in Figure 32. The area of interest encompassed both Zone A and Zone C which have different loadings because Zone A includes the roadway and sidewalks bearing higher load due to extra weight of asphalt and gravel.

Figure 32 - Loading Conditions at the Plaza Level with Area of Interest Highlighted in red. (Gateway)

The design of each component is related to each other because they are superimposed onto each other when assembled, leading to the addition of dead loads from the self-weight of individual components. The overall process is summarized in Figure 33, indicating the first step to have been identifying load the loading distribution. The next step was calculating the dead and live loads applied on plaza level by converting uniformly distributed loads by square feet into kips per feet and calculating the loading applied on the surface area of the double tee (Surface Area = 15' x 30'). This was also calculated for the inverted tee and applied to its calculated tributary area (Tributary Area = 30' x 30') in addition to the dead load from the self-weight of the double tees. Similarly the live load on column was calculated from the loads applied on plaza level to the tributary area of column (Tributary Area = 30' x 30'). Additionally, the dead load was calculated to be the applied load from plaza level as well as the self-weight of two double tee beams and one inverted tee beam due the tributary area of the column. The final step of the process was to check whether the original foundation would carry the alternative prestressed concrete design. All of the loadings from the plaza level and the total self-weight of the complete bay were compared to the all of the loadings from original steel bay.

The dead load, live load, wind load and seismic load on plaza level, double tee, inverted beam, and column components are illustrated below in Table 8. Since the parking garage is an underground structure the wind load assumed to be zero.

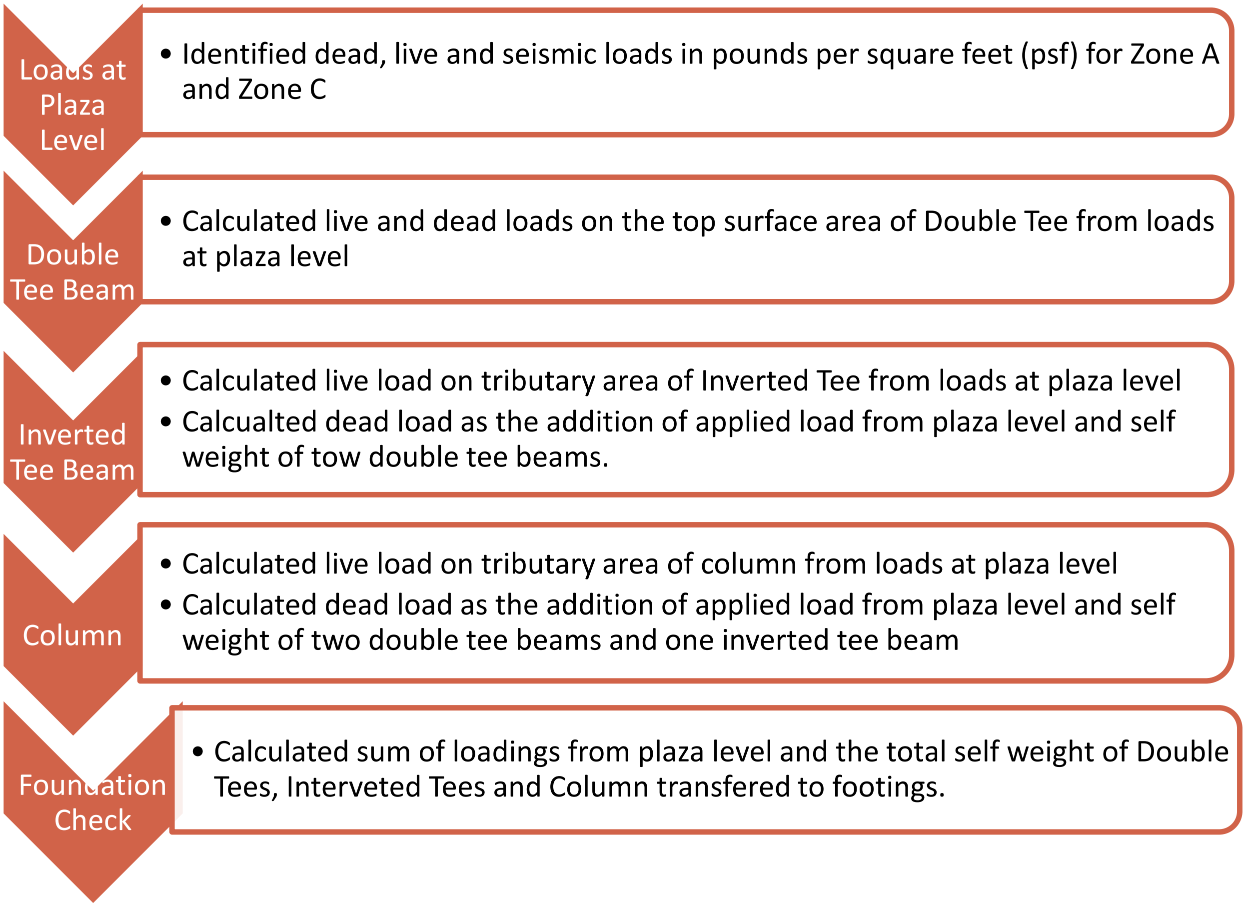


Figure 33 - Alternative Prestressed Design Process through Load Calculations

	Plaza Level		Double Tee		Inverted Beam		Column	
	Zone A (psf)	Zone C (psf)	Zone A (k/ft)	Zone C (k/ft)	Zone A (k/ft)	Zone C (k/ft)	Zone A (psf)	Zone C (psf)
Dead Load	225	225	3.375	3.375	6.75	6.75	340	340
Live Load	250	100	3.75	1.5	7.5	3	250	100
Wind Load	0	0	0	0	0	0	0	0
Seismic Load	42	42	0.63	0.63	1.26	1.26	42	42

Table 8 - Design Load Calculations at Plaza Level

5.2.2 Double Tee Beam Design

Double tee beams were designed to replace the four W18 x 40 steel beams from the selected typical steel bay illustrated in Figure 34. Due to the two different load requirements from Zones A and C, two different double tee beams were designed. In order to achieve maximum economy the section properties of both alternative double tee beam designs were kept the same, only adjusting the numbers of prestressed strands to the different load requirements. The process of designing the double tee beam is outlined in Figure 35.

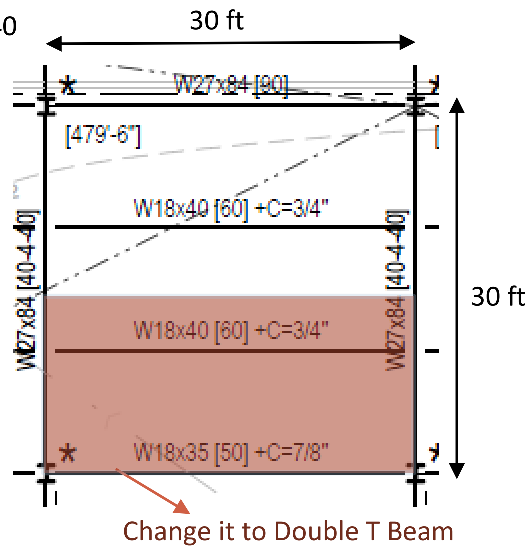


Figure 34 – Typical Steel Bay Beam

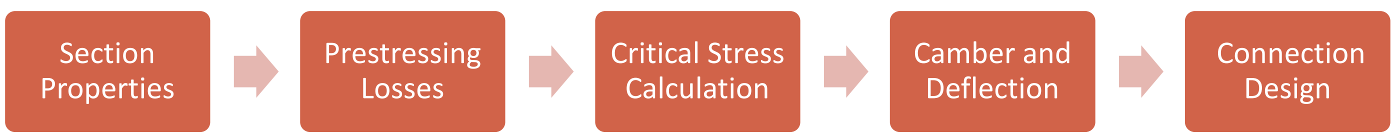


Figure 35 - Double Tee Beam Design Process

The design process for the double tee was iterative in nature because several trials were necessary to arrive at the final design. All calculations for the design process were done using the excel sheet found in Appendix O. The following sections include only the results for the final design.

Section Properties

Even though the prestressed concrete components can be manufactured in a variety of customized sizes and shapes, it was more economical to use common products used in the industry. (PCI, 2004) Double tees were selected for the alternative design because they are most commonly used members in parking garage construction due to their efficient shape for longer spans as compared to hollow-core slabs.

Even though the section properties for both double tee designs (Zone A and Zone B) are identical, the design of prestressing strands differed in order to support required loadings for each zone. The section properties can be found below in Table 9 along with a section view of the double tee beam in Figure 36 Zone A has of higher live loading required 16 strands, while Zone C of lower loading required only 12 stands.

Width, W (in) =	180
Height, H (in) =	30
b	7.75
a	9.75
h	4
H-h	26
Length (in) =	360
cb	22.38
Ct	7.61
Area (in^2) =	1175
Inertia (in^4) =	85138.07
Section Modulus,Sb (in^3) =	3803.65
Section Modulus,St (in^3) =	11177.76
Volume/Surface (in) =	2.60

Table 9 – Double Tee Section Properties

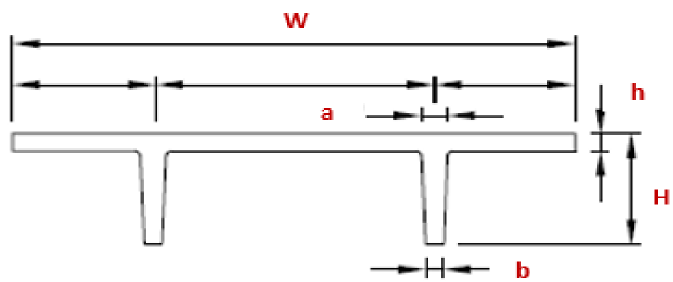


Figure 36 – Double Tee beam section view

Prestressing Losses

The prestressing force in a prestressed concrete member continuously decreases over time. There are several factors which contribute to the loss of prestress: instantaneous loss caused by the elastic shortening of concrete (ES), which happens right after the release of prestressing tendons and long term factors such as the creep of concrete, shrinkage of concrete and relaxation of strands. Table 10 below compares the prestress losses by different factors for the two different double tee designs.

	Double T Beam Zone A (psi)	Double T Beam Zone C (psi)
Elastic Shortening	7071.30	4964.78
Creep of Concrete	5850.88	2155.79
Shrinkage of Concrete	4931.41	4931.41
Relaxation of Tendons	3214.39	3388.44
Total Loss	21067.98	15440.42
Jacking Force after Losses (k)	583.06	451.95
Prestress Loss Percentage	**11.15%**	**8.17%**

Table 10 - Prestressing Losses in Double T Beam Designs for Zone A and Zone C

The differences in total loss between the two designs are directly related to the number of strands. The elastic shortening is much larger in Zone A since the initial prestress force (the jacking force) much higher due to higher number of stands. Similarly, the creep of concrete loss is doubled in Zone A as more stress is maintained over a period of time causing the concrete element to shorten. However, the shrinkage of concrete shows the same loss since the volume over surface area is equivalent in both designs, thus the reduction in volume due to the evaporation of water on the surface of concrete is the same. The loss due to relaxation of tendons have similar values since the same constant strain is applied in both cases. This causes gradual decrease in stress in the strands. These losses were calculated using the formulas outlined in Appendix O.

Critical Stress Calculation

In order to check the serviceability of prestressed concrete components, critical stress calculations were investigated in two different time periods. The first period of interest was after releasing the strands when the concrete would be fresh and there would be no service loads. Within this period, the transfer region was checked under initial prestress loads to keep cracking within the acceptable limit, and mid span region was checked to calculate tension zone due to initial camber. The second period of interest was under service loading to calculate the critical stress at mid-span. The formula's for calculating critical stress is listed in Appendix O.

The double tees were checked under loads primarily for serviceability, but also to keep cracking within acceptable PCI limit codes. PCI assumes three different kinds behavior in terms of design requirements. (PCI Manual 2012). First one is class U which stands for uncracked member. This is the optimum scenario which proves that the design is successful and will be able to carry the loads without any cracks. Class T stands for a transition between uncracked and cracked section. Under service loads PCI allows to use Class U and Class T. The worst scenario is Class C which stands for cracked section and it is not allowed in flexural members. Critical stress calculations are the determining factor to check whether selected concrete, steel properties and prestressing losses are acceptable. Several trials were necessary for the design of the double tee beams to be uncracked under service loading.

The summarized results for critical stress calculations for Zone A and Zone C are illustrated in Table 11. The critical stress at release in transfer and mid span as well as at service are in limits and uncracked (shown on Limit Check Row).

[Blank Space left intentionally]

	Transfer @ Release		Mid span @ Release		Mid span @ Service	
	fb	**ft**	**fb**	**ft**	**fb**	**ft**
PCI Limits	0.70 f'ci	-7.5 √f'ci	0.70 f'ci	-7.5 √f'ci	-12.0 √f'c	0.70 f'c

	3500.00	-530.33	3500.00	-530.33	-967.47	4550.00
Double Tee Beam Zone A (psi)						
Total	2121.48	-4.93	1846.86	92.05	-830.28	956.20
Limit Check	In Limits	Class U	In Limits	Compression OK	Class U	In Limits
Double Tee Beam Zone C (psi)						
Total	1573.77	8.46	1296.35	-480.65	-564.95	1318.89
Limit Check	In Limits	Compression OK	In Limits	Class U	Class U	In Limits

Table 11 - Critical Stress Calculations for Zone A and Zone C Double Tee Beams

Camber and Deflection

The next step in the procedure was to check whether camber and deflection were under acceptable limits. In prestressed concrete design, flexural components have an upward camber at the time of transfer of prestressed caused by the eccentricity of the prestressing force. (PCI, 2004) The reason behind is that when the stands are cut the concrete goes into compression and the beam takes on a camber. Since the designed member was uncracked, the camber and deflection is in elastic behavior. The behavior of prestressed concrete is illustrated in Figure 37 which shows during erection the dead load causes the double tee get flatter. After release of tendons the camber and self-weight of the component was calculated using uncracked moment of inertia.

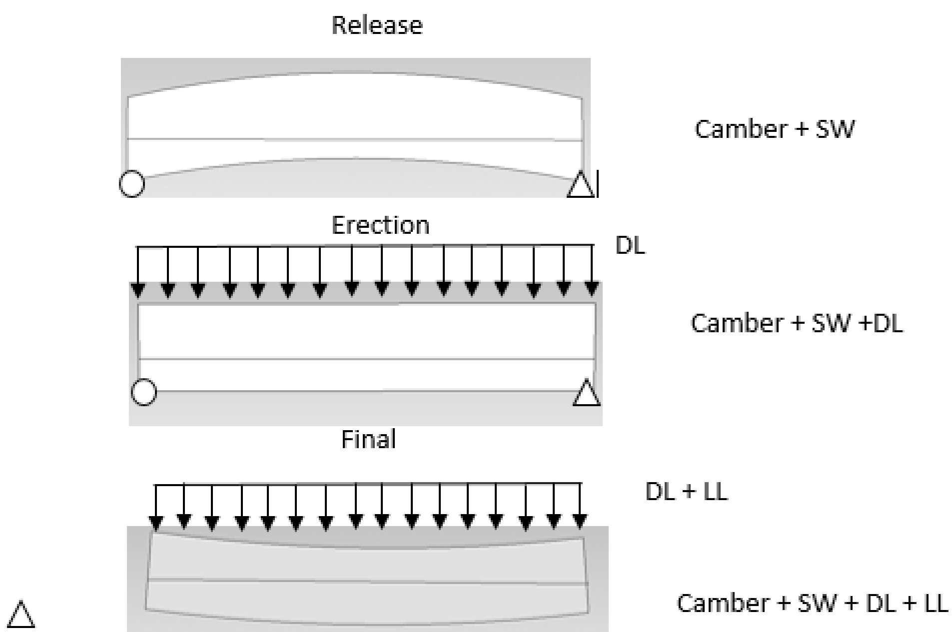


Figure 37 – Behavior of prestressed concrete

The total deflection of the double tee was calculated by subtracting the upward initial camber from the sum of the downward deflections caused by the member's self-weight, and the imposed dead and live loads. The total deflection was calculated to be 0.32 inches for Zone A and 0.27 inches for Zone C. The limitation on the immediate deflection for the double tee member was ℓ/180 based on the live load. The designed member came under the limitations, thus proving the deflection and camber for both zones to be acceptable. The detailed calculations and formulas for this section can be found in Appendix O and in Appendix P respectively.

Connection Design

The connections are important consideration in the structural design of a prestressed concrete structure since it transfers load, restrains movement and provides stability to the components. The double tee beams were designed as dapped-end, which is structural element with abruptly reduced depth of its end in order to provide the necessary seating without impacting the clear height between floors. The dapped end connection design required investigation of several potential failure modes listed Figure 38 along with the required reinforcements.

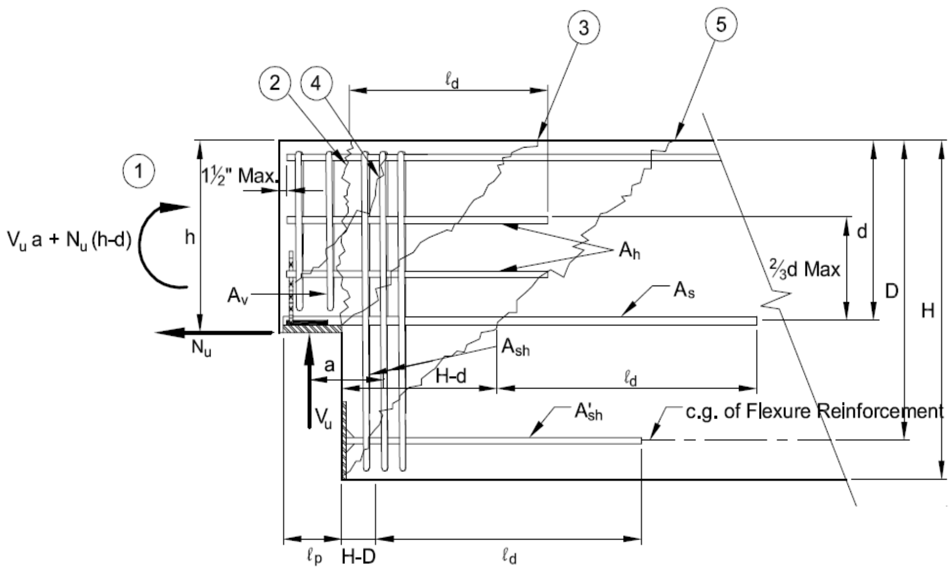


Figure 38 - Potential Failure Modes and Required Reinforcement in Dapped-end Connections

The direct shear at the junction of dap was avoided by providing shear friction reinforcement composed of Avf and Ah. The diagonal tension originating from the re-entrant corner was avoided by adding shear reinforcement, Ash. The Diagonal tension in the extended end was avoided through shear reinforcement composed of Ah and AV. Because both double tee designs have the same section properties, one dapped end design was able to serve both. Figure 39 below illustrates all types of reinforcements needed and the selected size and number of bars for each (diagonal tension did not required any additional stirrup reinforcement due to the negative A_v value). All of the reinforcing bars selected to be size of #8's in order to achieve maximum economy as well as easier production. The placement of stands and bars are illustrated in Figure 40.

Reinforced Concrete Bearing

a (in) =	8	
h (in) =	18.5	$A_S = \frac{1}{\phi f_y}\left[V_U \frac{a}{d} + N_U \frac{h}{d}\right]$
d (in) =	17	
As (in) =	3.103941176	
M =	1	Table 5.3.1
Me =	12.3059867	$\mu_e = \frac{\phi \times 1000 \times \lambda \times b \times h \times \mu}{V_U \times 1000}$
Me =	2.9	
Max Me =	2.9	Table 5.3.1 $A_S' = \frac{2V_U}{3\phi f_y \mu_e} + \frac{N_U}{\phi f_y}$
As' (in^2) =	1.938781609	
Critical As (in^2)	3.103941176	
Use ____#____ BARS	5 # 8	
As practical (in^2)=	3.95	Ok $A_h = 0.5\left[A_S - \frac{N_U}{\phi f_y}\right]$
Ah (in^2) =	1.524	
Use ____#____ U BARS	2 # 8	
Ah practical (in^2)=	1.58	Ok
Ash (in^2) =	4.51	$A_{sh} = \frac{V_U}{\phi f_y}$
Use ____#____ STIRRUPS	6 # 8	
Ash practical (in^2)=	4.74	Ok
Av (in^2) =	-1.856751452	$A_V = \frac{1}{2f_y}\left[\frac{V_U}{\phi} - \frac{2bd\lambda\sqrt{f_c'}}{1000}\right]$
Use ____#____STIRRUPS		
Av practical (in^2)=	0	Ok
Chech Vn (k) =	441.1576306	$V_N = \phi\left(A_V f_y + A_h f_y + \frac{2bd\sqrt{f_c'}}{1000}\right)$
	Ok	
Ld Ah (in) =	22.5	Design Aid 15.4.4
Ld As (in) =	37.5	Design Aid 15.4.4
Anchor for As (in) =	50.5	$L_d = H - d + l_d$

Figure 39 - Dapped-end Connection Calculation for Reinforced Concrete Bearing

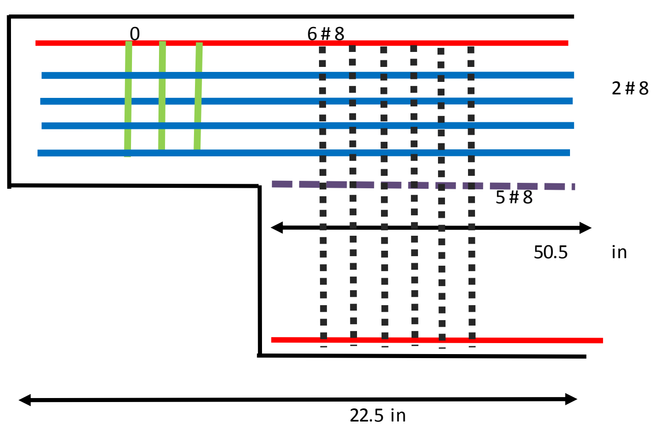


Figure 40 - Dapped End Connection for Double T and Inverted T Beams

5.2.3 Inverted Tee Beam Design

Inverted tee beams were designed to replace the W27 x 84 steel girders from the selected steel illustrated in Figure 41.Due to the two different load requirements from Zones A and C, two different inverted tee beams were designed. In order to achieve maximum economy, section properties of both alternative inverted tee beam designs were kept the same, only adjusting the numbers of prestressed strands to the different load requirements. Mirroring the design process of double tee beams, the outline for the design of the inverted tees is outlined in Figure 42.

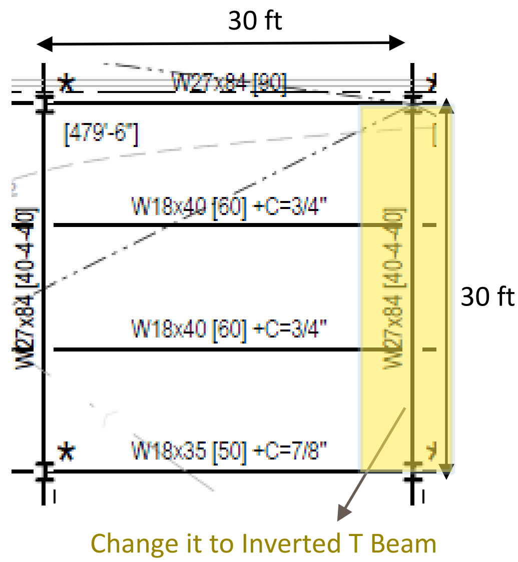


Figure 41 – Typical Steel Bay Girder

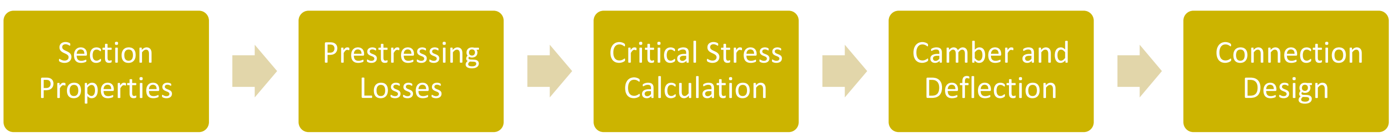


Figure 42 - Inverted Tee Beam Design Process

The design process for the inverted tee was iterative in nature because several trials were necessary to arrive at the final design. All calculations for the design process were done using the excel sheet found in Appendix Q. The following sections include only the results for the final design.

Section Properties

Inverted tees were selected for the alternative design because they are most commonly used in parking garage construction as structural framing to support deck components such as double tees. The section properties of Inverted tee beam for Zone A and Zone C are outlined in Table 12 with a section view of the inverted tee beam in Figure 43.

[Blank Space left intentionally]

Width, b (in) =	40
Height, H (in) =	30
b 1	28
h2	14
h1	16
b2	6
Length (in) =	344
cb	13.66667
Ct	16.33333
Area (in^2) =	1008
Inertia (in^4) =	74704
Section Modulus, Sb (in^3) =	5466.146
Section Modulus, St (in^3) =	4573.714
Volume/Surface (in) =	7.2

Table 12 – Inverted Tee beam Section Properties

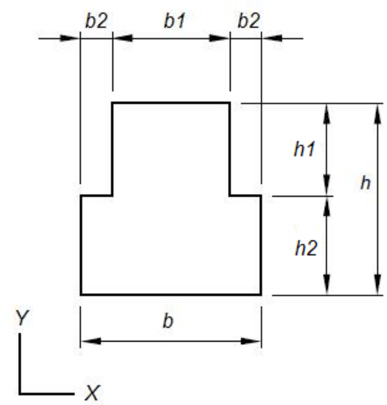


Figure 43 – Inverted Tee beam section view

Even though the section properties for both inverted tee designs (Zone A and Zone B) are identical, the design of prestressing strands differed in order to support required loadings for each zone and the weight of the double tees. Zone A has of higher live loading required 45 strands, while Zone C of lower loading required only 30 stands.

Prestressing Losses

Mirroring the prestress loss calculations for double tees, losses in prestressing force were calculated for both the short and long term. Table 13 below compares the prestress losses between the two different designs by zone.

	Inverted T Beam Zone A (psi)	Inverted T Beam Zone C (psi)
Elastic Shortening	15947.54	11326.13
Creep of Concrete	17354.19	7477.76
Shrinkage of Concrete	3318.54	3318.54
Relaxation of Tendons	2654.39	3086.33
Total Loss	39274.66	25208.76
Jacking Force after Losses (k)	1494.59	1066.28
Prestress Loss Percentage	**20.79%**	**13.34%**

Table 13 - Prestressing Losses in Inverted Tee Beam Designs for Zone A and Zone C

Compared to double tee beams, inverted tee beam had higher total loss and jacking force resulting in a higher prestress loss percentage. The differences in total loss between the two component designs are directly related to the number of strands. According to PCI Manual the range of values for total loss for normal weight concrete components are from about 30,000 psi to 55,000 psi, thus the designed inverted tee beam were within this range.

As with the already covered prestress losses of double tee beams, the inverted tee design for Zone A shows a larger elastic shortening and creep of concrete as a consequence of the higher number of prestressing strands. However, the loss for shrinkage of concrete is the same for both designs since the volume over surface is equivalent remained unchanged. Losses were calculated by using the formulas outlined in Appendix Q.

Critical Stress Calculation

The inverted tees were checked under loads primarily for serviceability criteria but also to keep cracking within acceptable PCI limits. Critical stress calculations were the determining factor to check whether the selected concrete, steel properties and prestressing losses were acceptable And required iteration to determine a design that would remain uncracked under both release and services stages. The summarized results for critical stress calculations for Zone A and Zone C inverted tee designs are illustrated in Table 14. The critical stress at release in transfer and mid span as well as at service are all in limits and uncracked.

	Transfer @ Release		Midspan @ Release		Midspan @ Service	
	f_b	f_t	f_b	f_t	f_b	f_t
PCI Limits	0.70 f'ci	-7.5 √f'ci	0.70 f'ci	-7.5 √f'ci	-7.0 √f'c	0.70 f'c
	3500.00	-530.33	3500.00	-530.33	-604.67	4550.00
Inverted Tee Beam Zone A (psi)						
Total	3445.28615	-439.3031	3301.94	-258.5264	-531.2246	4205.894
Limit Check	In Limits	Class U	In Limits	Class U	Class U	In Limits
Inverted Tee Beam Zone C (psi)						
Total	2536.66	-520.13	2391.92	-96.96	-470.88	2668.01
Limit Check	In Limits	Class U	In Limits	Class U	Class U	In Limits

Table 14 - Critical Stress Calculations for Zone A and Zone C Double Tee Beams

Camber and Deflection

Since the designed beam was in Class U, the camber and deflection was in elastic behavior. The total deflection of the double tee was calculated by subtracting the upward initial camber from the sum of the downward deflections caused by the member's self-weight, and the imposed dead and live loads, and the weight of the supported double tees. The total deflection was calculated to be 0.82 inches for Zone A and 0.69 inches for Zone C. The designed member came limits (ℓ/180), thus proving the deflection and camber for both zones to be acceptable. The detailed calculations and formulas for this section can be found in Appendix Q and in Appendix R respectively.

Connection Design

The connection between the inverted tee beams and columns was determined to be a corbel design. Corbels are used to resist moments by providing fixity to columns and at the top of the beam. The design of corbel connections for both Zone A and Zone C are identical due to their section properties. All of the failure modes were considered to determine the minimum required reinforcements illustrated below in Table 15.

Corbel Design

Φ	0.75
a	10
h	20
d	17
As (in^2)	5.699555556
As' (in^2)	6.651124952
Critical As (in^2)	6.651124952
Use _____#_____ BARS	6 # 10
As practical (in^2)=	7.62
Ah (in^2)	2.613118032
Use _____#_____ U BARS	3 # 6
Ah practical (in^2)=	2.64
2/3 d	11.33333333

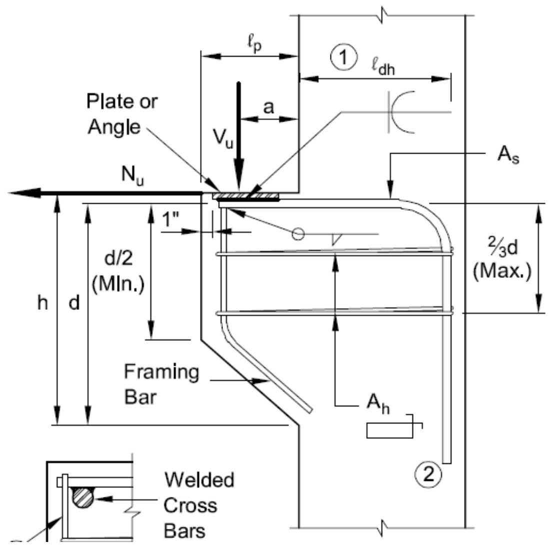


Table 15 - PCI MNL Chp 5: Design of Concrete Corbels

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5.2.4 Column Design

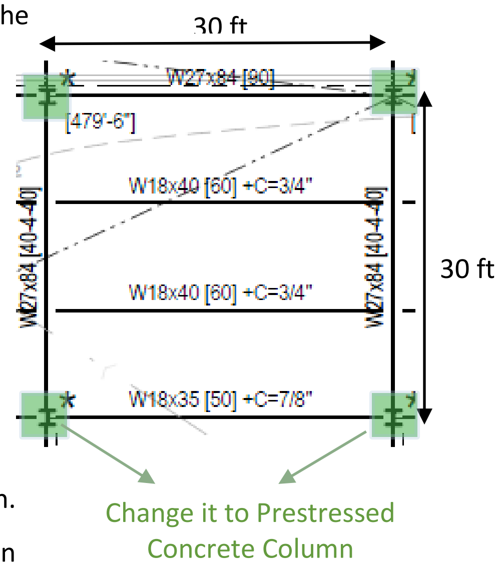

Figure 44 – Typical Steel Bay Column

As illustrated by Figure 44, the size of steel columns in as the selected steel bay was W14 x 233. Column size for the alternative design was to be kept equivalent to the original steel design to avoid impacting the available parking and maneuverability space for vehicles in the garage. Further inspection into the steel column indicated that it includes fire protection coating as well 2 inch minimum all-around concrete encasement. This led to the design of square tied concrete 16" by 16" columns. To determine axial loading, the loads identified for the Plaza Level were multiplied by tributary area of the column. Based on industry practice, eccentricity was assumed to be ten percent of the width of each column to calculate to moment caused by axial loading. The results for these calculations illustrated in Table 16.

Factored Loading - LL (psf)	400.0
Factored Loading DL (psf)	409.9
Tributary Area (ft2)	900.0
Axial Load (P) (kips)	728.9
e - eccentricity (in)	1.6
Moment (Mu) (kips)	1166.3

Table 16: Alternative Column Design Parameters

The calculations detailed above were complement with insight provided by David Wan from OldCastle Concrete who provided the team with resources from CRSI (Concrete Reinforcing Steel Institute) found in Table 17 from which a reinforcement design was selected to meet loading requirements. The selected reinforcement is highlighted below.

[Blank Space left intentionally]

SQUARE TIED COLUMNS 16″ × 16″

Short columns – no sidesway f'_c = 6,000 psi f_y = 60,000 psi
Bars symmetrical in 4 faces ϕM in inch-kips ϕP in kips

BARS	RHO	Max Cap		0% f_y		25% f_y		50% f_y		100% f_y		$.1f'_c$ Ag		Zero Axial Load
		ϕM	ϕP	ϕM	ϕP	ϕM	ϕP	ϕM	ϕP	ϕM	ϕP	ϕM	ϕP	ϕM
4-# 8	1.23	1317	828	2029	644	2248	542	2351	462	2434	340	1752	154	1138
4-# 9	1.56	1352	854	2121	658	2359	551	2483	467	2610	337	1936	154	1398
4-#10	1.98	1395	887	2236	676	2499	564	2650	474	2830	332	2168	154	1722
4-#11	2.44	1430	923	2352	689	2629	573	2800	478	2997	320	2383	154	2041
4-#14	3.52	1525	1008	2620	736	2958	606	3193	497	3482	302	2931	154	2799
4-#18	6.25	1738	1223	3247	859	3733	694	4085	541	4575	249	4226	154	4562
8-# 6	1.38	1292	839	1967	659	2181	553	2276	473	2336	345	1816	154	1265
8-# 7	1.88	1332	879	2075	682	2312	569	2432	483	2545	342	2060	154	1666
8-# 8	2.47	1380	925	2200	709	2465	588	2616	496	2791	338	2337	154	2127
8-# 9	3.13	1431	977	2334	739	2631	610	2814	509	3058	334	2629	154	2616
8-#10	3.97	1500	1043	2504	778	2840	637	3064	527	3389	327	2989	154	3225
8-#11	4.88	1551	1115	2669	814	3033	661	3291	541	3645	308	3300	154	3743
8-#14	7.03	1699	1285	3065	914	3525	732	3883	587	4375	279	4110	154	4826
12-#10	5.95	1667	1200	2848	881	3255	720	3565	572	4078	322	3802	154	4348
12-#11	7.31	1746	1307	3076	938	3522	761	3882	594	4443	296	4218	154	5041

Table 17 - CRSI Design Handbook Column Criteria

The values from the table were used to plot the Column Interaction Curve as shown in Figure 45. Given the calculated moment and load plotted inside the column interaction curve, the column reinforcement and size proved acceptable. The detailed calculation for column design can be found in Appendix S.

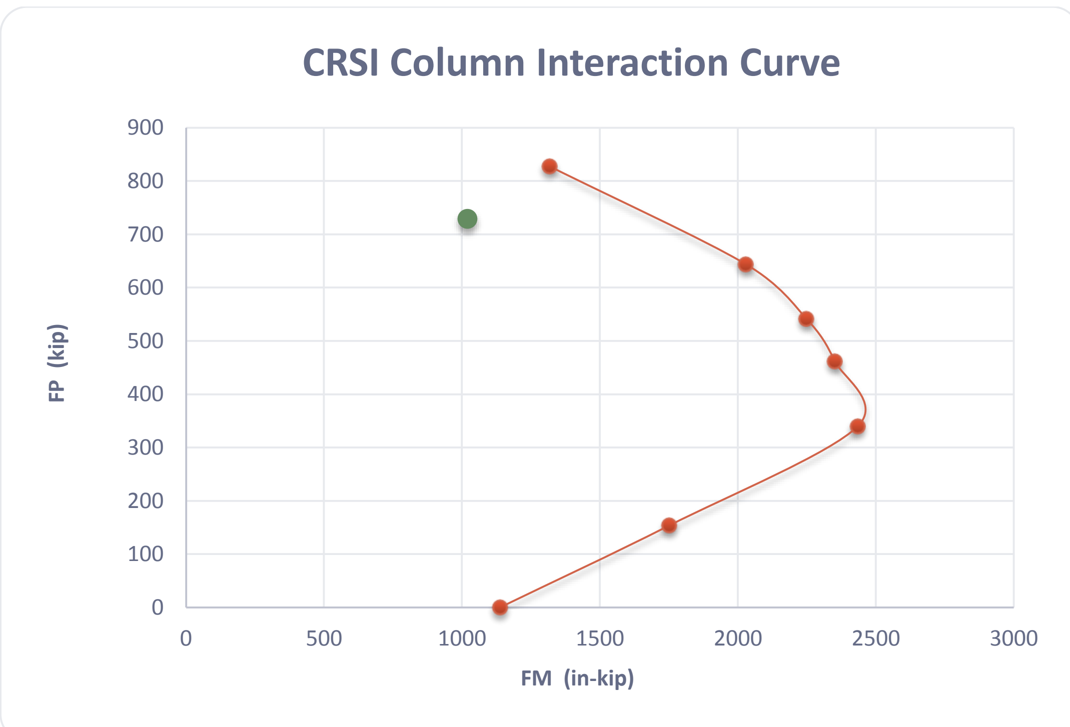

Figure 45 - Prestressed Column Interaction Curve

5.2.5 Foundation Check

As it is shown in Figure 46 below, all of the foundations in this project are shallow. Shallow foundations are spread footings that a single column bears on a rectangular pad to distribute the load over a bigger area or combined footings where multiple columns bear on a rectangular footing. (Nichols, 2013)

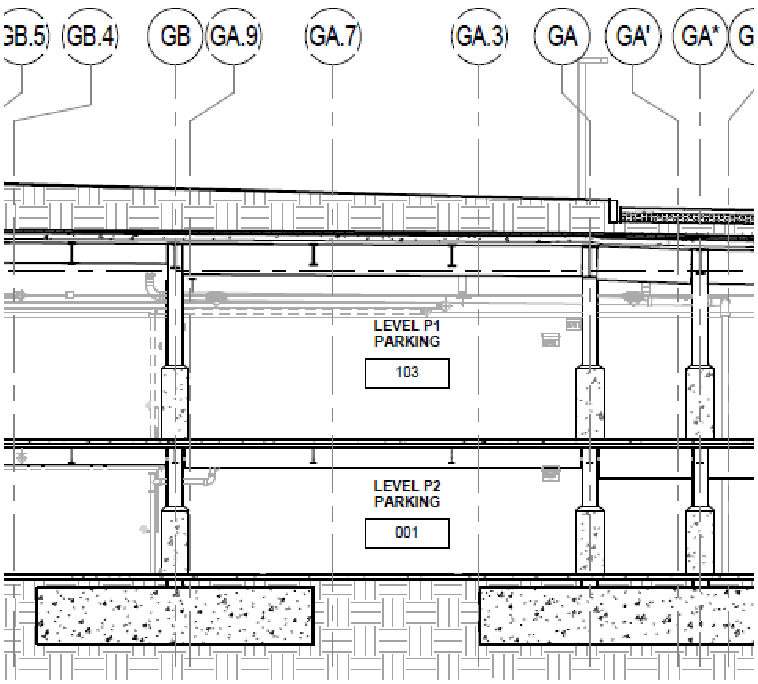

Figure 46 - Partial Elevation in Architectural Drawings, (Gateway)

The allowable bearing pressure of the foundations in our area of focus is documented as 2 tons per square foot in the structural documents. The full foundation details as well as the volume and loading calculations are presented in Table 18.

Footing Details	
Footing 21.0	20 - #10
Length (in)	252.00
Width (in)	252.00
Depth (in)	50.00
Volume of the Foundation (CF)	1837.50
Soil Bearing Capacity (tsf)	2.00
Total Soil Capacity	882.00
Loading (lbs)	41562.50
Loading (tons)	20.78

Table 18 - Footing Details for City Square Underground Parking Garage

With soil conditions identified, the next step was to calculate the total weight of the original steel bay and compare it to the weight of designed prestressed concrete bay. (Detailed weight calculations can be found in Appendix T). In order to check whether the alternative bay design would be supported by the original footings. As Table 19 shows, the designed prestressed concrete bay is much heavier than the original steel bay. To draw a basis a comparison, the volume of the foundation was divided by the weight of each design in order to define the "foundation strength ratio". The foundation strength ratio represents the weight a spread footing would carry under each bay design.

	Original Steel Typical Bay	Designed Prestressed Concrete Bay
Weight of the Bay (lbs)	72,551.17	105,381.85
Foundation Strength Ratio (lbs/ft^3)	39.48	57.35

Table 19 - Weight and Foundation Strength Ratio for Original Steel Bay and Alternative Prestressed Concrete Bay Designs

The steel bay design had a lower foundation strength ratio due to the lower self-weight of the bay structure. This comparison shows that the alternative design would possibly need bigger footings to support the additional weight. Considering the high soil bearing capacity previously mentioned, an alternative solution could be as simple as increasing the depth of the footings, but further analysis by geotechnical engineering is necessary to arrive at a specific solution. Advanced geotechnical analysis is beyond the scope of this project.

5.2.6 Software Assisted Analysis

A wide range of innovative software has been developed to assist the design and construction of engineering projects. For civil engineering projects including parking garages, most software applies to either the structural design of individual elements, the visualization and coordination of the individual elements, or the overall management of the project. A series of software were used to complete this project including the already mentioned project management software Primavera 6 and the online management dashboards Gateway and Procore used by Consigli. The goal to design a feasible, sustainable, and cost-effective alternative to a typical steel bay required the exploration of software with structural design capabilities. The first option considered was Building Information Modeling (BIM) because of the interconnectedness of the elements in management and design being analyzed. Several software belonging to the collective body known as BIM were considered (Autocad, Revit, SAP200, etc), but proved to either lack the functionality needed for the design or presented technical issues such as expensive licenses (unavailable for WPI at the time). Albeit the decision to find a structural design software, research was done on BIM and its benefits, and a summary can be found in Appendix W. Structural design functionality was particularly of interest so as to provide a computer generated check for the calculations performed by hand and on Microsoft Excel spreadsheets (Appendix O-U) Thus, the program Concise Beam by Black Mint Software was selected.

Concise Beam is a program for the design of precast concrete beams available for download on the web. It allows for different beam types to be designed using different design standards, which include the American Standard (ACI), and Canadian Standard (CSA). Figure 47 below shows the user interface of the software as advertised on their website. (Concise Beam Home, n.d.)

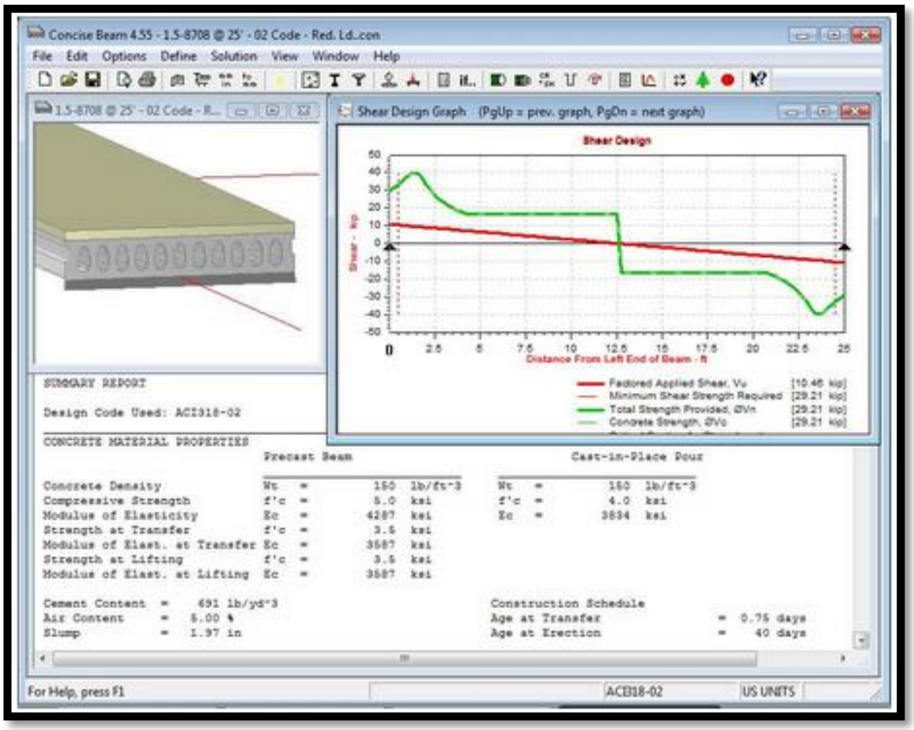

Figure 47- Concise Beam User Interface

The built-in functionality allowing the input of all relevant elements in detail including concrete, steel reinforcement, prestressing strands, support layout, loading, and production was used to replicate the chosen design for double tee beam and inverted tee beam for Zone A. The software allowed for a more detailed design for steel reinforcement for both concrete beams, but all other elements mirrored those used in the design process detailed in earlier sections. Finally, axial, shear, and torsion analysis were performed to check the validity of the designs. A detailed report expanding on deflection, cracks and moment results for the double tee and inverted tee can be found in Appendix X and Appendix Y respectively. A summary of the critical stress analysis for the double tee can be found below in Figure 48.

Location	x ft	Stress psi	Limit psi	Overstress Notice	
STRESSES AT TRANSFER					
Critical Compression					
Top of Beam	15.00	12	3000	0%	
Bottom of Beam	2.70	2347	3000	0%	
					Longitudinal Tensile Rebar Needed (in^2) Required Provided Additional
Critical Tension					
Top of Beam	5.40	-47	-213	0%	
Bottom of Beam	0.00	2	-426	0%	
STRESSES DURING INITIAL LIFTING					
Critical Compression					
Top of Beam	15.00	12	3000	0%	
Bottom of Beam	2.70	2347	3000	0%	
					Longitudinal Tensile Rebar Needed (in^2) Required Provided Additional
Critical Tension					
Top of Beam	5.40	-47	-213	0%	
Bottom of Beam	0.00	2	-426	0%	
STRESSES DURING ERECTION LIFTING					
Critical Compression					
Top of Beam	15.00	17	3900	0%	
Bottom of Beam	2.70	2178	3900	0%	
					Longitudinal Tensile Rebar Needed (in^2) Required Provided Additional
Critical Tension					
Top of Beam	5.40	-40	-243	0%	
Bottom of Beam	0.00	2	-485	0%	
STRESSES IN SERVICE					
Critical Compression					
Top of Beam	15.00	638	3900	0%	
Bottom of Beam	2.70	1433	3900	0%	
Critical Tension					
Top of Beam	0.00	0	-485 *	0%	Not cracked
Bottom of Beam	0.00	2	-485 *	0%	Not cracked
STRESSES IN SERVICE (SUSTAINED LOADS ONLY)					
Critical Compression					
Top of Beam	15.00	638	2925	0%	
Bottom of Beam	2.70	1433	2925	0%	

Figure 48: Critical Stresses Summary for Double Tee Design

The summarized results for critical stresses (shown above) are broken up by the stress acting on the member (compression or tension) and by time period (transfer, initial lift, erection, service). The Overstress Notice column indicates with zeros for all categories that the stresses for the double tee are within limits (report shows default CSA standard) and the design works.

A summary of the critical stress analysis for the inverted tee can be found below in Figure 49.

[Blank Space left intentionally]

Location	x ft	Stress psi	Limit psi	Overstress Notice	
STRESSES AT TRANSFER					
Critical Compression					
Top of Beam	0.00	-1	3000	0%	
Bottom of Beam	26.09	3887	3000	30%	
Critical Tension					Longitudinal Tensile Rebar Needed (in^2): Required 2.7, Provided 2.8, Additional 0.0
Top of Beam	26.37	-999	-426	135%	
Bottom of Beam	0.00	4	-426	0%	
STRESSES DURING INITIAL LIFTING					
Critical Compression					
Top of Beam	0.00	-1	3000	0%	
Bottom of Beam	26.09	3887	3000	30%	
Critical Tension					Longitudinal Tensile Rebar Needed (in^2): Required 2.7, Provided 2.8, Additional 0.0
Top of Beam	26.37	-999	-426	135%	
Bottom of Beam	0.00	4	-426	0%	
STRESSES DURING ERECTION LIFTING					
Critical Compression					
Top of Beam	0.00	-1	3900	0%	
Bottom of Beam	26.09	3550	3900	0%	
Critical Tension					Longitudinal Tensile Rebar Needed (in^2): Required 2.5, Provided 2.8, Additional 0.0
Top of Beam	26.37	-910	-485	87%	
Bottom of Beam	0.00	4	-485	0%	
STRESSES IN SERVICE					
Critical Compression					
Top of Beam	14.33	1229	3900	0%	
Bottom of Beam	26.37	2719	3900	0%	
Critical Tension					
Top of Beam	26.37	-247	-485 *	0%	Not cracked
Bottom of Beam	0.00	3	-485 *	0%	Not cracked
STRESSES IN SERVICE (SUSTAINED LOADS ONLY)					
Critical Compression					
Top of Beam	14.33	1229	2925	0%	
Bottom of Beam	26.37	2719	2925	0%	

Figure 49: Critical Stresses Summary for Inverted Tee Design

For the inverted tee, the Overstress Notice column indicates non-zero values for both stresses at transfer and stressed during initial lifting. However, the notes to the right of the Overstress Notice column indicate that the tensile rebar provided exceeds the required longitudinal bar. Thus, the stresses caused by the prestressing strands before the member is in service are controlled by the provided steel reinforcement, and the design is valid.

The results found using Concise Beam mirrored those obtained using hand calculations and Excel spreadsheets. However, Concise Beam offered a greater level of detail in the analysis of torsion and shear which were not the critical aspects of the alternative design.

Beyond its design functionality, Concise Beam offered a visual component responsive to the specific design parameters of each design element. The software created a basic 3-D representation of the double tee and inverted tee beams on an x-y-z plane, which can be found in Figure 50 and Figure 51 respectively.

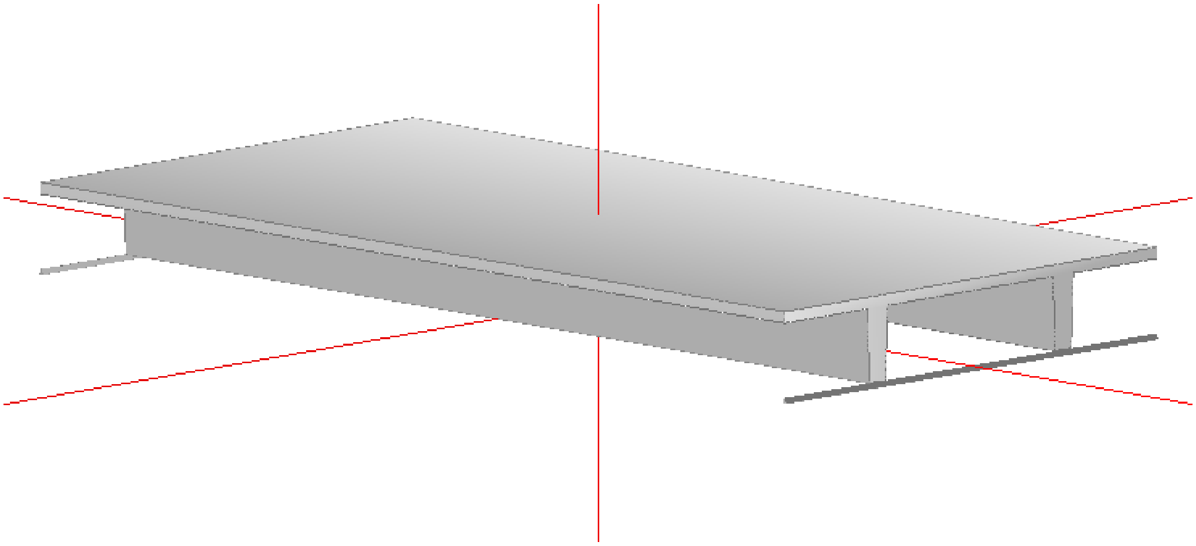

Figure 50: 3-D Model of Double Tee Design without Connection Details

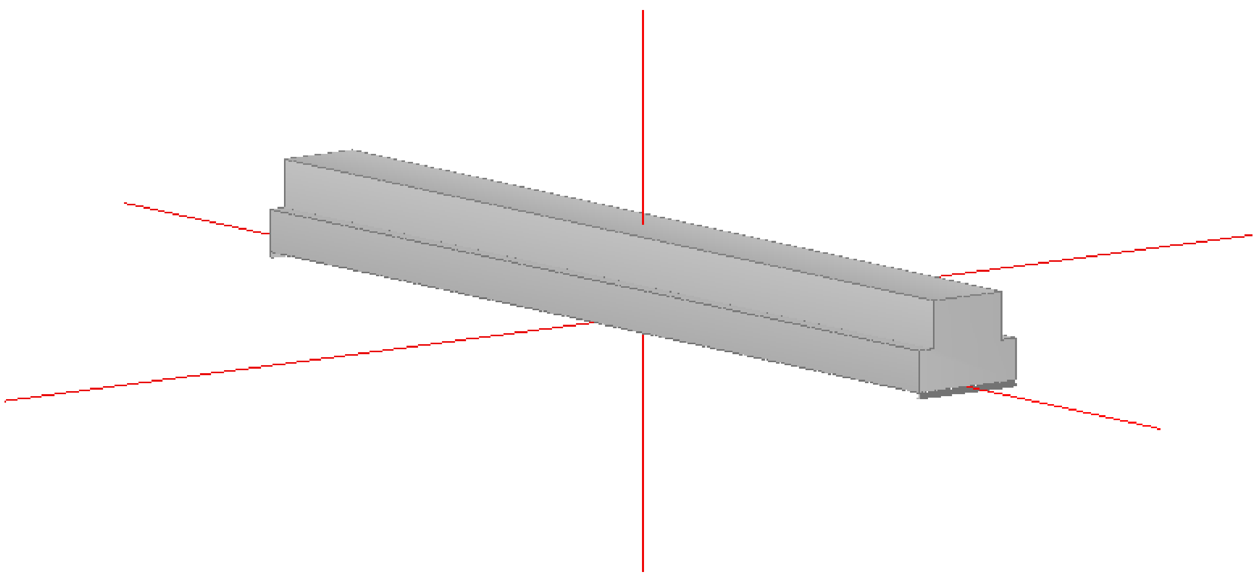

Figure 51: Model of Inverted Tee Design without Connection Details

The model was useful for clarification of the design, as it allowed shifting and panning 360 °. Unfortunately, the 3-D models presented limitations to model connection designs mentioned in earlier sections and could not communicate with each other. Hence, supplementary software, Google SketchUp, was used to generate accurate 3-D visualizations of the alternative design. Figure 52 and Figure 53 below provide a comprehensive visualization of the alternative bay.

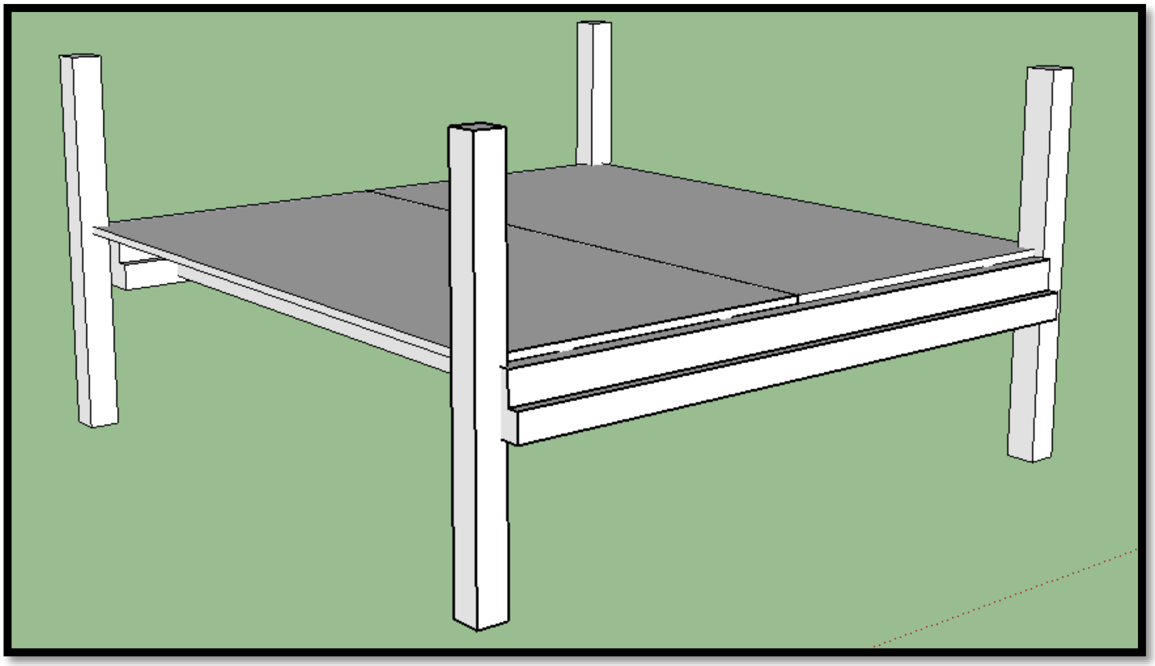

Figure 52: Isometric View Alternative Prestressed Concrete Bay Design

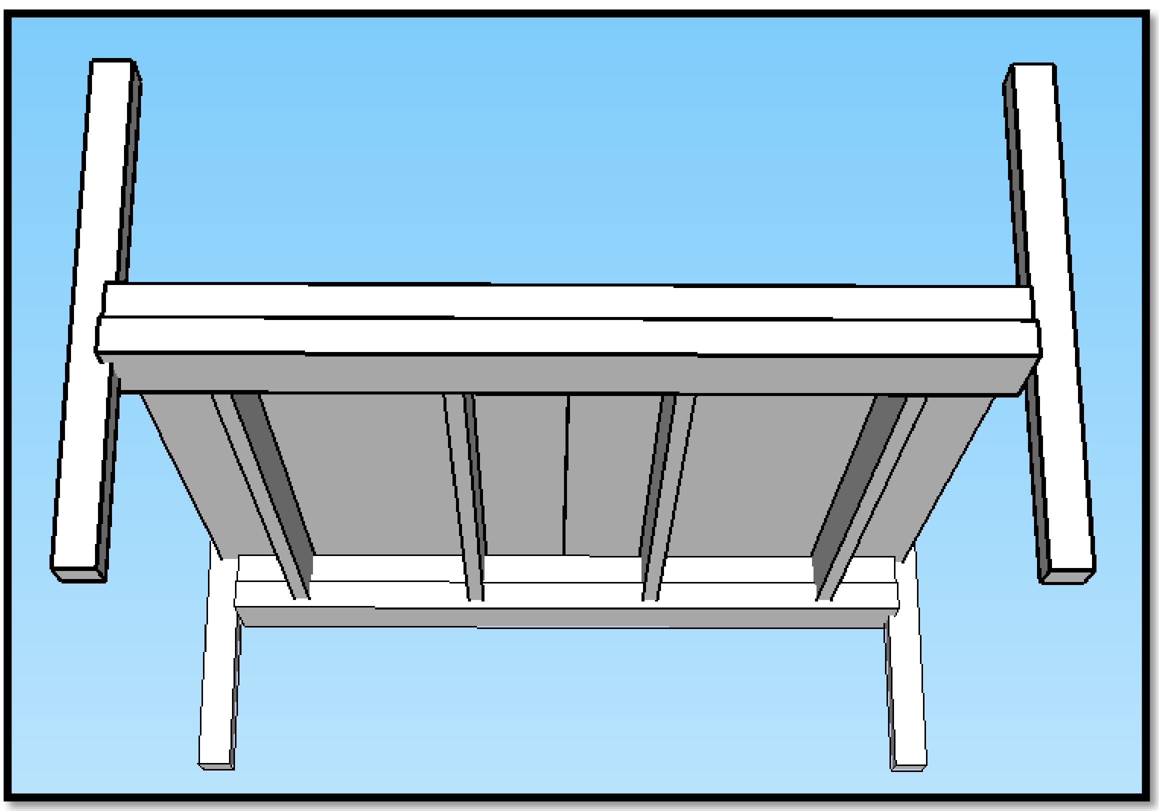

Figure 53: Bottom of Alternative Prestressed Concrete Bay Design

6.0 Axiomatic Design Decomposition of Alternative Prestressed Concrete Bay

6.1 Overview

Axiomatic Design is an approach to engineering design based on two axioms, or laws, which assure that the most effective design process is being utilized. It can be applied to the entire design process of a project, including the planning or manufacturing. In its essence, it aims to identify a design which (1) maximizes the independence of the functional elements and (2) minimizes the information content. (Brown, 2013) Figure 54 below outlines the Axiomatic Design process which, according to Suh, correlates four domains, with the left representing "what we want to achieve" and the right domain representing the solution to "how we want to achieve those goals". (Angwafo, 2014) (2001)

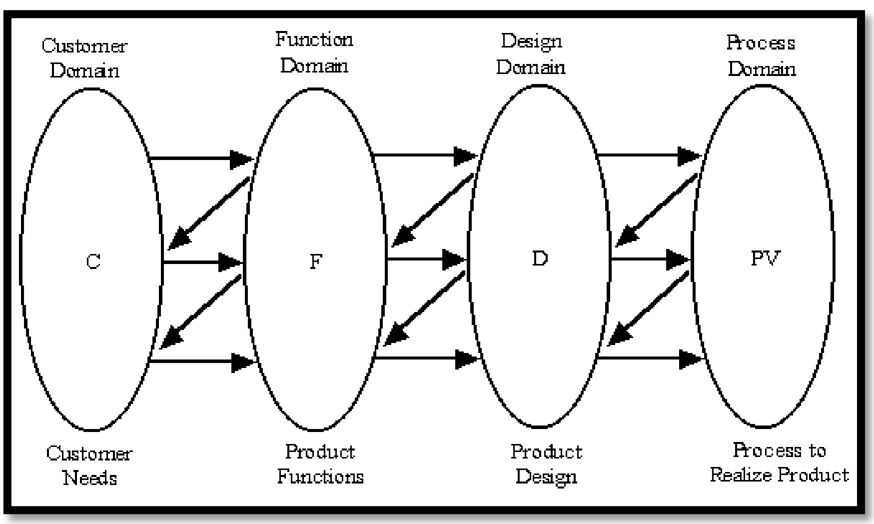

Figure 54 – Axiomatic Design Process (Sohlenius, 1998)

Axiomatic Design was first identified by Nam P. Suh, president of KAIST and MIT professor, in the late 70's in Cambridge, MA. Suh was able to develop this concept which is now applied across industries and has identified three essential components for it:

- Axioms (independence and information)
- Structure (lateral and vertical decomposition)

- Process (zigzagging decomposition)

This approach helps identify the best design solution from a conceptual stage and ensures that the customer is receiving the most added value. According to Suh, the goal of the design is to maintain the independence of the functional elements and minimize the information content in order to maximize the probability of success. (Suh, 2005) Furthermore, axiomatic design decomposition demands that the list of FRs satisfying the customer be collectively exhaustive, mutually exclusive and stated in a minimum form. The design axioms are also subject to additional theorems and corollaries that are described by Suh to further support an analysis (Suh 1990).

6.2 Decomposition

In this project, Suh's axiomatic design method is used to decompose and determine all the functional requirements that the alternative prestressed design had to meet. More specifically, it is focused on the bay dimensions, installation requirements, and the functionality of the design. The axiomatic design decomposition was used to guide the decision-making process to create the most effective bay structure. Additionally, the axiomatic design approach was made from a management and civil perspective in order to ensure a cost effective bay which met the proper construction requirements. This analysis was made by utilizing *Acclaro* Software.

The first step was to identify the customer needs for the bay in order to determine the functional requirements. Table 20 below outlines the customer needs from both, a civil and management perspective.

Civil Perspective	Management Perspective
1. Constructible	1. Low maintenance cost
2. Allow parking and movement of cars	2. Low cost, but durable material
3. Ability to support heavy loads	3. Repeatable and constructible design
4. Transfer loads down to the footings	4. Low installation cost and time
5. Support and connect the double tee beams and inverted tee beams	5. Efficient delivery of materials
	6. Quality Assurance of assemblage
6. Columns that connect with inverted tee beams	

Table 20 - Civil and Management customer needs

The following step after identifying the customer requirements was to determine the overarching functional requirement (FR0) – fabricate a modular pre-stressed concrete typical bay for an underground parking garage. This was then broken down into six main functional requirements outline below. The twelve customer requirements identified below have been consolidated into these six main requirements:

FR1 – Span 30’ x 30’ space

FR2 – Accommodate motion of vehicles

FR3 – Allow for structure to be reproducible

FR4 – Support structure and vehicle load

FR5 – Produce a financially viable modular bay

FR6 – Provide for easy field assembly

These were paired to their respective design parameters. The breakdown of the functional and design parameters, as well as further subsections, can be seen below in Figure 55 **- Axiomatic Design Decomposition**, as shown in the Acclaro Software. The full breakdown of the axiomatic design decomposition can be found in Appendix Z.

#	[FR] Functional Requirements	[DP] Design Parameters
0	Fabricate a modular pre-stressed concrete "Parking Bay"	System to fabricate a modular pre-stressed concrete "Parking Bay"
1	Support structure and vehicle load	Design for supporting the structure and vehicle loads
1.1	Support the double tee beams and the load	Design of the inverted tee beam (girder)
1.2	Connect beam and girder to allow the transfer of loads	Design of dapped end
1.3	Support the axial and seismic loading for the tributary area	Design of Columns
1.4	Connect the columns and inverted tee beam (girder)	Corbel Connection
1.5	Transfer load down to the footings	Foundations
2	Accomodate motion of vehicles	Design that allows motion of vehicles
2.1	Distance between columns	Double tee beam with 30' x 30' dimensions
2.2	Allow 8' 6" height for motion of vehicles	Column design and height
3	Allow for structure to be reproducible	System for producing structures on demand
3.1	Create a mold for the bay reproduction	Fabricate a mold for the bay reproduction
3.2	Design that fits site space	Design of the bay
4	Provide for easy field assembly	Method for field assembly
4.1	Pre-stage and transport materials to site	System of pre-staging and transporting bay parts
4.2	Deliver materials in proper order	Delivery schedule and timing
4.3	Monitor quality of structure assemblage	Method of monitoring quality assurance
4.4	Have machinery/labor necessary to assemble	Arrange machinery/labor schedule according to each activity
5	Produce a finacially viable modular bay	Cost of production, assembly, and maintenance
5.1	Select material with low cost	Type of material slected
5.2	Mantain a low assembly cost	System of assembly
5.3	Sustain a low maintenance cost	System for maintenance of the structure
6	Span 30' x 30' space	Method to span 30' x 30' space
6.1	Dimensions of 30' x 30'	dimensions of double tee beam
6.2	Maximize load capacity and minimize self weight	cross-sectional area of double tee beam
6.3	Sufficient strength to carry load	type of concrete
6.4	Sufficient pre-stress force	number of pre-stressing strands
6.5	Un-cracked when casting	eccentricity of pre-stressing strands
6.6	Remain uncracked under service	number of pre-stressing strands

Figure 55 - Axiomatic Design Decomposition

6.3 Results - Matrix

After identifying the functional requirements and the respective design parameters, these were all compared to each other to determine which design parameters would impact multiple functional requirements. This can be seen in the decomposition matrix below, were the "x" marks the relation mentioned above. The first matrix (Figure 56) represents the initial representation of the axiomatic design. The second matrix (Figure 57) represents the results of the matrix after being optimized by the Acclaro software.

	DP0- System to fabricate a modular pre-stressed concrete "Parking Bay"	DP1- Method to span 30' x 30' space	DP2- Design that allows motion of vehicles	DP3- System for producing structures on demand	DP4- Design for supporting the structure and vehicle loads	DP5- Cost of production, assembly, and maintenance	DP6- Method for field assembly
FR0- Fabricate a modular pre-stressed concrete "Parking Bay"	X						
FR1- Span 30' x 30' space		X	X	O	X	O	X
FR2- Accomodate motion of vehicles		O	X	O	X	O	O
FR3- Allow for structure to be reproducible		O	X	X	X	O	O
FR4- Support structure and vehicle load		O	O	O	X	O	O
FR5- Produce a finacially viable modular bay		O	O	X	O	X	O
FR6- Provide for easy field assembly		O	O	O	O	X	X

Figure 56 - Axiomatic Design Matrix (without optimization)

	DP0- System to fabricate a modular pre-stressed concrete "Parking Bay"	DP1- Design for supporting the structure and vehicle loads	DP2- Design that allows motion of vehicles	DP3- System for producing structures on demand	DP4- Method for field assembly	DP5- Cost of production, assembly, and maintenance	DP6- Method to span 30' x 30' space
FR0- Fabricate a modular pre-stressed concrete "Parking Bay"	X						
FR1- Support structure and vehicle load		X	O	O	O	O	O
FR2- Accomodate motion of vehicles		X	X	O	O	O	O
FR3- Allow for structure to be reproducible		X	X	X	O	O	O
FR4- Provide for easy field assembly		O	O	X	X	O	O
FR5- Produce a finacially viable modular bay		O	O	X	X	X	O
FR6- Span 30' x 30' space		X	X	O	X	O	X

Figure 57 - Axiomatic Design Matrix (optimized)

After optimizing the matrix, the result is a “decoupled” matrix. This is considered a decoupled matrix given that the Design Parameters’ (more than one) affect more than a single Functional Requirement and it satisfies the Independence Axiom. If the design was coupled, meaning that the “x” was to the right of the Independence Axiom, new choices of DP’s would be necessary in order to find an uncoupled or decoupled design. Hence, the order of the functional requirements is important which is why the matrix was optimized. After completing the optimization, the FR’s were arranged in order of importance from the bottom-up. In this case, the functional requirement of a 30’x30’ span is the most critical since it is affected by four different design parameters. This approach can be applied to the other FR’s to determine their importance. Essentially, the more DP’s that affect the FR the more critical it is. Similarly, the most critical design parameter is the design for supporting the structure and vehicle loads, given that it affects four FR’s.

Applying Suh’s axiomatic design method to any project can prove to be very useful because it helps the decision-making process for the activities that need to be accomplished. It creates a graphical representation of all the functions that need to be accomplished in order to deliver the end product or service and includes all the parameters throughout the process that may affect it; hence providing metrics that can be used to differentiate between competing design concepts. More specifically to a construction project, it can aid the project manager and superintendent identify the key functions that the structure needs to meet and which are the critical activities that may have an impact end-product that needs to be delivered to the owners. Additionally, it can serve as a methodology to identify which type of design, material, and activities would optimize the construction while meeting the expectations of the owners.

7.0 Sustainability

Efforts to reduce the impact of the construction industry have led to advancements in a diverse range of sustainability concepts that are being gradually adopted more. Additional to environmental considerations, sustainability efforts encompass variables such as the durability of construction materials to reduce additional costs to projects. According to WRAP, an agency for the waste management of the UK, lifetime maintenance and management costs of buildings can be five times greater than the cost of construction itself. (Optimizing durability and lifespan, 2014) In this project, a quick assessment on the durability of a steel design against the precast design was performed through methods such as embodied energy analysis and LEED assessment.

The useable life of a construction material depends on its properties, its manufacturing, its usage, and its maintenance/management. All these variables can be tracked and quantified, allowing for comparisons between materials that shed light into the sustainable practices and resources. In this project, a life cycle assessment for both structural steel and precast concrete was performed, guided by the principles listed in the life cycle assessment diagram below:

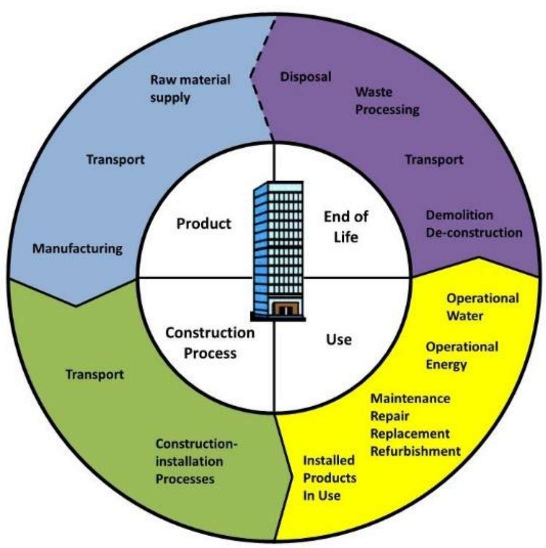

Figure 58 - Life Cycle Assessment Diagram

7.1 Embodied Energy

Interrelated with the Life Cycle Assessment, an embodied energy analysis can add basis for comparison between construction materials. All of the activities prior to receiving a material amount to a sum of costs, transactions, logistics, and handling which require energy. The concept referred to as embodied energy, can be defined as the total energy inputs consumed throughout a product's life-cycle (Cannon Design, 2013). Unlike the life cycle assessment, which evaluates all of the impacts over the whole life of a material, embodied energy does not include the operation or disposal of materials and only considers the front-end aspect of the impact of a building material. When selecting building materials, the embodied energy should be considered with respect to the durability of building materials, how easily materials can be separated, the use of locally sourced materials, and the use of recycled materials, amongst other considerations. (n.a. 2014)

For this project, the focus was on the embodied energy encompassed in construction materials used for the parking garage at their arrival for assembly. The analysis consisted on comparing the embodied energy of the construction materials specified by the project's construction document (structural steel and reinforced concrete) and the energy encompassed in precast concrete, the material for the alternative design. The embodied energy of the building materials is averaged based on the two widely referenced embodied energy coefficient databases - Alcorn and Wood, 1998 and Hammond and Jones, 2008.

The first analysis of embodied energy was conducted on the current design to be built by Consigli. In order to narrow down the scope of the analysis, the team decided to complete the embodied energy analysis of a single typical bay for Zone C (ball field area). Table 21 represents the embodied energy calculations for the steel bay.

Typical Bay Element	Bay Measurement for Embodied Energy	Unit	Embodied Energy	Unit	Total Embodied Energy	Unit
Steel Beam	2177.24	kg	34.57	MJ/kg	**75259.98**	**MJ**
Steel Girder	2286.10	kg	34.57	MJ/kg	**79022.98**	**MJ**
Steel Column	898.34	kg	34.57	MJ/kg	**31052.58**	**MJ**
Composite Metal Decking	83.61	m^2	560.00	MJ/m^2	**46823.112**	**MJ**
				Total	**232,158.66**	**MJ**

Table 21 - Steel Bay embodied energy calculations

The second analysis of embodied energy was conducted on the alternative design being proposed in this project. The embodied energy of *2.0 MJ/kg* used in this analysis was derived from the data provided in the Australian guide to environmentally sustainable homes for "precast steam-cured concrete". (Milne, 2013) Although embodied energy numbers may vary by country and region in the world, our team made the assumption that *2.0 MJ/kg* was a close representation of the embodied energy of prestressed concrete in the United States. Table 22 represents the embodied energy calculations for a single typical bay of the precast alternative design.

Alternative Bay Element	Dimensions	Unit	Qt.	Bay Measurement for Embodied Energy	Unit	Embodied Energy	Unit	Total Embodied Energy	Unit
Double Tee	30	LF	2	33202.93	kg	2.00	MJ/kg	**66405.87**	**MJ**
Inverted Tee	28.67	LF	1	13654.71	kg	2.00	MJ/kg	**27309.41**	**MJ**
Concrete Column	8.5	LF	1	836.58	kg	2.00	MJ/kg	**1673.16**	**MJ**
							Total	**95,388.45**	**MJ**

Table 22 - Precast Concrete embodied energy calculations

After conducting both analysis, the team was able to determine that the embodied energy for the prestressed concrete bay is significantly lower than that of the steel bay. The total embodied energy for a steel bay is *232,158.66 MJ*, whereas for the precast concrete bay is *95,388.45 MJ.* The graph below in Figure 59 visually represents the difference between one material and the other.

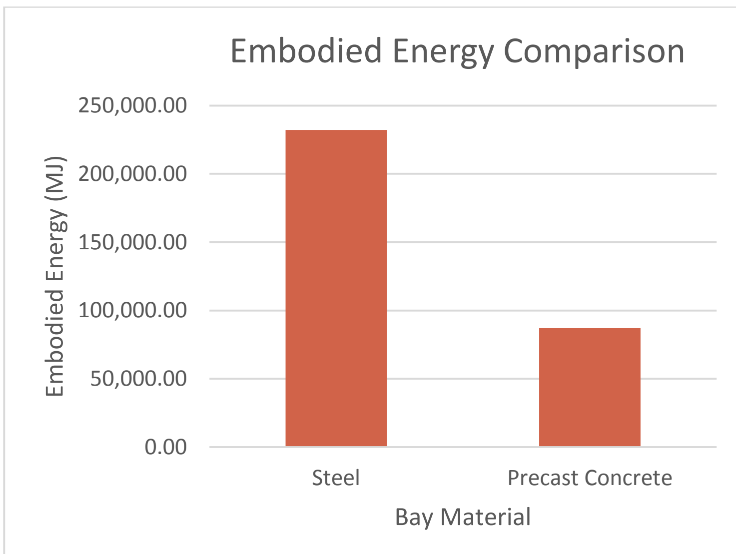

Figure 59 – Embodied Energy Comparison Graph

The results from the embodied energy calculations reflect the assumptions that the team made about the benefits precast concrete over steel. As the figure shows above, there is a significant difference between both materials which, in the long-run, can have a big impact in the environment.

7.2 LEED

Leadership in Energy and Environmental Design is a voluntary rating system that assess the level of sustainability in buildings and motivates owners to be environmentally responsible by using resources efficiently. (PCI, 2009) This point- based system has 7 environmental categories: Sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environment quality, innovation in design, and regional priority. "In LEED 2009, the allocation of points between credits is based on the potential environmental impacts and human benefits of each credit with respect to a set of impact categories. The impacts are defined as the environmental or human effect of the design, construction, operation, and maintenance of the building, such as greenhouse gas emissions, fossil fuel use, toxins and carcinogens, air and water pollutants, indoor environmental conditions. A combination of approaches, including energy modeling, life-cycle assessment, and transportation analysis, is used to quantify each type of impact." (PCI, 2009) A building is LEED certified with silver, gold or platinum when ratings are awarded for at least 50, 60 or 80 point out of 110 points, respectively.

For this project, certain LEED concepts were evaluated based on the LEED checklist provided in Appendix AA. A full LEED evaluation was not conducted on the project given that the team did not have the expertise required to provide an in depth analysis of each concept and most of the concepts did not apply to an underground parking garage structure. However, it was deemed relevant to consider certain LEED concepts, given that sustainability is such an important component of every construction project. The team was able to identify areas in which the project was performing really well and other areas which needed improvement. These areas are explained and divided below into aspects in which the project performances well in accordance with LEED standards and areas that need improvement.

AREAS OF COMPLIANCE WITH LEED

Site Selection

Intent → *"to avoid the development of inappropriate sites and reduce the environmental impact from the location of a building on a site."* (PCI, 2009)

It requires that buildings are not developed in prime farmland areas, land identified as habitat for any endangered species, and previously undeveloped land within 50 feet of water body, amongst other. The construction of the underground parking garage does not interfere with any of the project areas stated in LEED checklist, hence making the site selection of the project a great location for it.

Development Density and Community Connectivity

Intent → "*To channel development to urban areas with existing infrastructure, protect green fields, and preserve habitat and natural resources."* (PCI, 2009)

According to this requirement, the construction has to be located on a previously developed site, is within 1/2 mile of a residential area, and is within ½ mile of at least 10 basic services, all requirements which it meets. The parking garage is being developed on the grounds where a mall used to be and is located in downtown Worcester, locating it near more than 10 basic services for the community.

Construction Waste management

Intent → *"To divert construction and demolition debris from disposal in landfills and incineration facilities. Redirect recyclable recovered resources back to the manufacturing process and reusable materials to appropriate sites."* (PCI, 2009)

This requirement is to promote the recycling and proper disposal of materials and waste from a construction. Consigli developed a waste management plan to properly dispose of materials from the demolition of the mall and excavations by sorting the materials prior to being sent to specific sites for material disposal/reuse.

Material Reuse

Intent → *"To reuse building materials and products to reduce demand for virgin materials and reduce waste, thereby lessening impacts associated with the extraction & processing of resources."* (PCI, 2009)

The requirement is for a project to use salvaged, refurbished or reused materials, which sum at least 5% or 10%, based on cost, of the total value of materials on the project. The team has identified this as an area of improvement for Consigli as materials for parking garage were not reused. For instance, steel was being bought from a mill and materials from the previous site were not reused, not reflecting sustainable practices.

Alternative Transportation – Low-Emitting and Fuel-Efficient Vehicles

Intent → *"To reduce pollution and land development impacts from automobile use."* (PCI, 2009)

Although the team was not able to observe the finalized construction of the parking garage, this is an important requirement to consider and implement. If Consigli provides preferred parking areas or discounted parking rate for low-emitting and fuel-efficient vehicles, it could potentially serve as an incentive for more sustainable transportation vehicles, which will reduce pollution.

Although Consigli is not working towards being LEED certified for this project, it is important to consider best practices for sustainability and identify materials which can reduce the impact in the environment. Identifying materials and resources which can be reused, encouraging alternative transportation methods such as bikes, optimizing energy usage, and using low-emitting materials are just some of the things that Consigli should consider prior to the development of the project. This will not only benefit the company and end-users, but the environment as well.

7.3 Life Cycle Cost Analysis

When evaluating the sustainability of a project, it is essential to consider the life-cycle cost of the materials and the financial implications it might bring. In this project, a cost analysis is made on a single bay for both designs and their individual net present value was calculated. The first aspect that was analyzed with regards to cost was in relation to the GMP once it was finalized. It was important to look at the big picture and analyze the total cost of the project in relation to similar projects. Figure 60 below gives a breakdown of the numbers that were provided in the GMP.

Total cost of Project:	**$34,299,152**
Total number of Spaces:	547
Cost per space:	**$62,704.12***
National Average cost/space:	$15K-$21K**

*have to consider that it's two stories, it's underground, and it is structurally sound to support the construction of a future hotel and it includes the mitigation plan for the adjacent East Garage.
** (Litman, 2012)

Figure 60 - Project Cost Analysis

As noted above, the total cost per space of this project is about $62,000, almost three times as much as the national average cost per space, according to Todd Littman of the Victoria Transport Policy Institute. Although this might seem alarming at first, it is important to note that it is a number derived from dividing the total GMP by the number of parking spots which does not only considers the cost of materials and labor for each spot. Instead, it encompasses all the activities that were part of the construction of the project which ultimately delivers parking space for 547 vehicles in conjunction with the additional work requested by the owner to prepare the site to enable the future construction of a superimposed hotel on the Building E area and the above grade finishes for the common area atop the Ball field area.

After drawing some general cost analysis on the GMP, the next step was to calculate the total cost of producing a single modular bay. Given that the scope of this project was narrowed down to creating an alternative design for a single modular bay, it was deemed appropriate to do the cost analysis on a single modular bay for the steel design and the prestressed concrete design. The breakdown of the costs for each of the designs is shown below inTable 23 and Table 24 respectively.

Size	Weight per bay	Unit	Dim.	Unit	Qt	Material Cost/Unit	Labor/Install Cost per Unit	Equipment Cost per Unit	Trucking Cost	Total Cost
W18x40	4799.95	lbs	30.00	LF	4	$58.50	$4.25	$1.73	$500.00	$8,237.60
W27x84	5039.94	lbs	30.00	LF	2	$122.00	$3.51	$1.39	$250.00	$7,864.00
W14x233	1980.48	lbs	8.50	LF	1	$346.64	$4.20	$2.20	$250.00	$3,250.84
3" Metal Decking	-	-	900.00	SF	1	$2.34	$0.57	$0.05	$250.00	$2,914.00
6" slab 4000 psi	-	-	900.00	SF	1	$2.09	$0.91	$0.28	$3.28	$2,955.28
									TOTAL	**$25,221.72**

Table 23 - Cost Breakdown of Steel Modular Bay

Alternative Bay Element	L	Unit	W	Unit	D	Unit	Qt./ bay	Dim./ bay	Unit	Material Cost/Unit	Material Cost/ bay
Double Tee	30.00	LF	15.00	LF	2.50	LF	2	900.00	SF	$10.00	$9,000.00
Inverted Tee	28.67	LF	3.33	LF	2.50	LF	1	28.67	LF	$225.00	$6,450.75
Concrete Column	8.50	LF	8.50	LF	1.17	LF	1	8.50	LF	$200.00	$1,700.00

Alternative Bay Element	Trucking Layout	Trucking Cost	Labor/Install Cost	Total Cost
Double Tee	1 per truck	$1,000.00	$2,000.00	$12,000.00
Inverted Tee	2 per truck	$500.00	$1,000.00	$7,950.75
Concrete Column	2 per truck	$500.00	$1,000.00	$3,200.00
			TOTAL	**$23,150.75**

Table 24 - Cost Breakdown of Prestressed Concrete Modular Bay

The cost for the modular steel bar were calculated using a combination of information obtained from the GMP and project with RSMeans 2015. These costs were adjusted to the city of Worcester using RSMeans location factors. The specific costs for steel element were calculated based on average costs based size and dimensions. It must be noted that the cost of steel fluctuates with respect to time, and pricing for individual beams differs from large-scale orders from mills which roll to order. Despite these factors, the total cost of the steel bay represents an accurate approximation providing a basis of comparison.

The cost calculation and breakdown for each of the components of the prestressed concrete bay were obtained by contacting David Wan, Chief Engineer at Oldcastle Precast, a leading manufacturer of precast concrete in the U.S. Through his guidance and recommendations, it was possible to calculate the approximate industry cost of the material based on the dimensions of the design, as well as the installation, trucking, and labor cost. As a result from these calculations and additional research, the team was able to conclude that the prestressed concrete bay would have a lower total cost of about $2000. Although it may not seem as a significant cost difference at first, this is just the cost of a single bay and the parking garage would have multiple of them, adding into the cost and potential savings.

Additionally, a net present value calculation was made on both designs in order to analyze the profitability of the investment in this project. "The purpose of net present value is to help analysts and managers decide whether or not new projects are financially viable. Essentially, net present value measures the total amount of gain or loss a project will produce compared to the amount that could be earned simply by saving the money in a bank or investing it in some other opportunity that generates a return equal to the discount rate." (Hamel, n.d.) In order to calculate the net present value of the investment in each bay, the Net Cash Inflow (NCI) had to be calculated. It is important to note that it is hard to determine the net cash inflow of this specific project as there are many variables that may affect the cash inflow and general assumptions were made for purposes of this analysis. In order to calculate the Net Cash Inflow, a parking cost, pricing, and revenue spreadsheet created by Todd Litman of the Victoria Transport Policy Institute was utilized. (Litman, 2012) Table 25 below shows the calculations for the NCI for a year considering that each bay holds six parking spots.

	Monthly Rate per spot	**Total per Bay (6 spots)**	**Load Factor**	**Gross Annual Revenue**	**Total Annual costs**	**Net Annual Revenue**	**Profit Margin**
Steel	$150.00	$900.00	80%	$8,640.00	$6,200.00	$2,440.00	39%
Prestressed	$150.00	$900.00	80%	$8,640.00	$4,400.00	$4,240.00	96%
	Monthly Rates Charged Users	Monthly Income for 6 spots	Portion of parking rented any month, or portion thereof.	Total revenue.	Annual costs of maintenance + $2000 (facilities, operations, and pricing expenses).	Gross revenue minus costs.	

Table 25 - Net Cash inflow/year (C_t)

For purposes of this net cash inflow analysis, these are the assumptions that were made:

- The monthly rate per parking spot will be $150 a month
- No rate per hour was considered
- 80% of the parking spots were being rented/producing income every month
- Maintenance cost per parking spot for the Steel design is $700 annually
- Maintenance cost per parking spot for the Prestressed design is $400 annually
- Facilities, operations, and pricing expenses annually are $2000

The following step to calculate the Net Present Value (NPV) was to put the values for all the variables of the NPV formula. The NPV formula is defined as:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

where:

C_t = net cash inflow during the period	r = discount rate

C_o= initial investment	t = number of time periods

For this project, the team utilized Microsoft Excel embedded formulas to calculate the net present value of both designs. However, instead of doing a single calculation, the team made 3 different scenarios with different discount rates in order to analyze what type of scenario would benefit or impact the investment more. A life-expectancy of 50 years was considered for both designs, although research claims that prestressed concrete parking structures can have a durability of up to 100 years with good maintenance, compared to the 50-70 years of a steel design. Table 26 below illustrates the three scenarios that were considered for this project.

				steel	prestressed		
Discount Rate [r]	5.00%		**Initial Investment (C_o)**	$25,221.72	$23,150.75		
Total Life of Project	50		**Net Cash inflow/year (C_t)**	$2,440.00	$4,240.00		

(t)	**1 year**	**2 years**	**5 years**	**10 years**	**25 years**	**35 years**	**40 years**	**50 years**
steel	($22,897.91)	($20,684.76)	($14,657.80)	($6,380.69)	$9,167.50	$14,731.31	$16,646.45	$14,731.31
prestressed	($19,112.65)	($15,266.85)	($4,793.77)	$9,589.41	$36,607.57	$46,275.83	$49,603.78	$54,254.37

				steel	prestressed		
Discount Rate [r]	8.00%		**Initial Investment (C_o)**	$25,221.72	$23,150.75		
Total Life of Project	50		**Net Cash inflow/year (C_t)**	$2,440.00	$4,240.00		

(t)	**1 year**	**2 years**	**5 years**	**10 years**	**25 years**	**35 years**	**40 years**	**50 years**
steel	($22,962.46)	($20,870.55)	($15,479.51)	($8,849.12)	$824.73	$3,215.43	$3,874.34	$3,215.43
prestressed	($19,224.82)	($15,589.71)	($6,221.66)	$5,300.00	$22,110.30	$26,264.62	$27,409.61	$28,719.22

				steel	prestressed		
Discount Rate [r]	12.00%		**Initial Investment (C_o)**	$25,221.72	$23,150.75		
Total Life of Project	50		**Net Cash inflow/year (C_t)**	$2,440.00	$4,240.00		

(t)	**1 year**	**2 years**	**5 years**	**10 years**	**25 years**	**35 years**	**40 years**	**50 years**
steel	($23,043.15)	($21,098.00)	($16,426.07)	($11,435.18)	($6,084.46)	($5,273.49)	($5,106.90)	($5,273.49)
prestressed	($19,365.04)	($15,984.93)	($7,866.50)	$806.20	$10,104.16	$11,513.39	$11,802.86	$12,060.32

Table 26 - Net Present Value Calculation

After calculating the NPV for the three different discount rates, it is clear that the higher the discount rate the less economically feasible is the project. Given that there is no target rate of return for this project, it was decided to use a low, a medium, and a high rate of return to account for the risk, opportunity cost, and other factors. Although the prestressed design does have a positive return of investment with all three discount rates, the steel design only has a positive NPV with the 5.00% and 8.00% discount rate. The following plot graphs in Figure 61 clearly illustrate the results from the NPV calculations.

Figure 61 – Discount Rate plot graphs

Essentially, a positive net present value is measuring the total amount of gain which this project can produce compared to simple saving the money in the bank or investing it in another opportunity with the same discount rate. Given that this is a long-term project and with a lower discount rate it has a positive NPV, it means that Consigli should go ahead with the project. However, with a higher rate of return such as 12%, the project would not be a financially smart decision if the design is made out of steel. (Hamel, *n.d.)* Table 27 below summarizes the results from the various NPV calculations and shows if the project would be a sound investment.

Discount Rate	Steel NPV	Invest?	Prestressed NPV	Invest?
5.00%	+	✓	+	✓
8.00%	+	✓	+	✓
12.00%	-	✗	+	✓

Table 27 - Net Present Value Summary

Although calculating the NPV seems like a reasonable way to measure the value of an investment, it is important to consider that it is limited by guesses of what might happen in the future. The usefulness of NPV relies on the accuracy of the expected income of a project and the discount rate. In this case, assumptions have been made to determine the expected income and three different discount rates were considered in order to account for these undetermined variables. An optimistic expected income or a low discount rate can simply return a net present value which might reflect an overestimation of a project's potential; hence, these numbers include several assumptions and are not an exact reflection of the potential of the project. Nonetheless, it serves as an example of the positive impact the NPV can have during the decision-making process of a project.

8.0 Conclusions & Future Work

The goal of this project was to create a sustainable and cost-effective alternative design that met all requirements indicated by the existing construction documents. This study on the Underground Parking Garage built by Consigli Construction, contains an analysis on the project management components of construction, the application of lean concepts to the project, a sustainable and cost-effective alternative design, and the application of the axiomatic design method to the proposed alternative design. The following conclusions and future steps can be drawn from each of these steps:

Project Management

Overall, the management of three main components of cost, schedule, and communication was done effectively with a spirit of collaboration amongst most key players. However, various analysis presented in this report indicate several areas of improvement and shed light into the intricate and complex nature of underground construction in a downtown area. Evaluating the project management as both effective both in need of improvement poses somewhat of a contradiction, but its true value comes through when considering the difference between the negative ramifications generated by the delayed signing of the GMP and the quality of Consigli's overall management. In this context, it is fair to say Consigli attempted and usually succeeded in applying good project management practice under the shadow of a major financial and logistical hurdle. As for immediate action to further improve communications, it is recommendable for Consigli to expedite the issuing of formal documents like change requests to draw weekly conversations and efforts into the issues that may have a negative impact on the overall schedule.

As for future work, much depth could be added to any of the analysis presented in this report with an extension of the data collection phase. Even as the duration of this project allowed the team to arrive at interesting all-encompassing conclusions, the conditions and progress of construction may to change with the passing of project time. Because of this changing nature of construction projects, a longer-spanning study could solidify general conclusions and have more data to interconnect the reviewed area of focus such as project management, design, and sustainability.

Lean Construction

Overall, Consigli performed well in the six lean concepts which were analyzed in this report. The communication between all parties involved was very good and the inventory and materials were maintained low, which increase the efficiency of the project. Nonetheless, a big part of being Lean is the use of a "pull system" or "pull schedule". For future projects, it would be beneficial to involve a member who can devise a pull schedule for the project. This may help increase the effectiveness of the activities performed and potentially lower the cost and delivery time of the project. The application of lean practices are important throughout the duration of the project, but a clear implementation plan and setting up metrics are essential prior to the start of the project.

Alternative Design

The design of a typical bay using prestressed concrete members resulted in a feasible and constructible alternative to steel construction. The success of the overall bay depended on the soundness in design of the individual pieces in addition to constructability, serviceability, and sustainability considerations for the underground parking garage as a whole. The design process proved to be challenging and at times foreign, but the reliance on available WPI and external (industry) resources allowed for a detailed design that met all project-specific criteria. This process was expedited greatly by the decision of focusing on one loading zone and general area of the garage, as it allowed for the kind of repetition and practicality which underlay successful construction projects.

In terms of future work, this project is ripe with opportunities to continue the developed design methodology to cover a greater area of the parking garage, if not all. This report includes extensive research in the design process of prestressed concrete members which in addition to valuable tools could be utilized to develop a full alternative design for a complex underground parking structure. Additionally, there remains a great potential for the development of data-rich building information modeling that could allow the exploration of other critical construction aspects such as site logistics, labor coordination, and client interactions.

Axiomatic Design methodology

Applying the axiomatic design to any project can prove to be very useful because it helps the decision-making process for the activities that need to be accomplished. It creates a graphical representation of all the functions that need to be accomplished in order to deliver the end product or service, and includes all the parameters throughout the process that may affect it; hence providing metrics that can be used to differentiate between competing design concepts. Although it is not commonly used in construction projects, this methodology can aid the project manager and superintendent identify the key functions that the structure needs to meet and which are the critical activities that may have an impact end-product that needs to be delivered to the owners. Applying this thought process during the planning phase of the project may prove to be the most useful, as it will help guide the decision-making and thought process of the key players involved.

Sustainability

In terms of sustainability the team looked at the embodied energy of the two designs and the alternative prestressed design proved to have a lower embodied energy than the current steel structure. Similarly, the alternative design had a higher positive net present value proving to be a more financially viable option in the long-run. Although the parking garage was already under construction and the design was not going to be changed, the team recommends that for future projects sustainability should be an important factor considered during the design phase. A sustainability assessment prior to the start of the project and finalization of the design should be done to ensure that a sustainable design and practices are being utilized. Moreover, parking garage structures are no longer LEED certified but applying some of the LEED concepts can ensure that sustainability efforts are met and considered.

Overall, having the opportunity to observe the Consigli Team that worked in the construction of the underground parking garage for the CitySquare development was a great experience. It served as a chance to apply concepts learned at WPI to a real-life project and have hands-on exposure to the development of the construction. Although Consigli will not use the alternative design proposed in this report or the conclusion drawn from the project to change the current construction, the report will serve as an assessment and evaluation tool for future projects. More specifically to this project, it would have been more beneficial for our team to be present during the planning phase prior to the start of the project and during the erection of the steel structure to better apply the concepts covered in this report. Images of the site development during the project duration can be found in Appendix BB .However, the time frame for the construction of the entire aligned partially with the time of execution of this study making it somewhat challenging. Nonetheless, it was a great experience and served as an opportunity to learn new concepts and apply the ones learned in class at WPI.

<u>Note:</u> All the electronic files utilized during this Major Qualifying Project are listed in Appendix CC. An explanation to each file and the calculations and information they contain can be found there as well. The MQP proposal submitted in A-Term can be found in Appendix DD.

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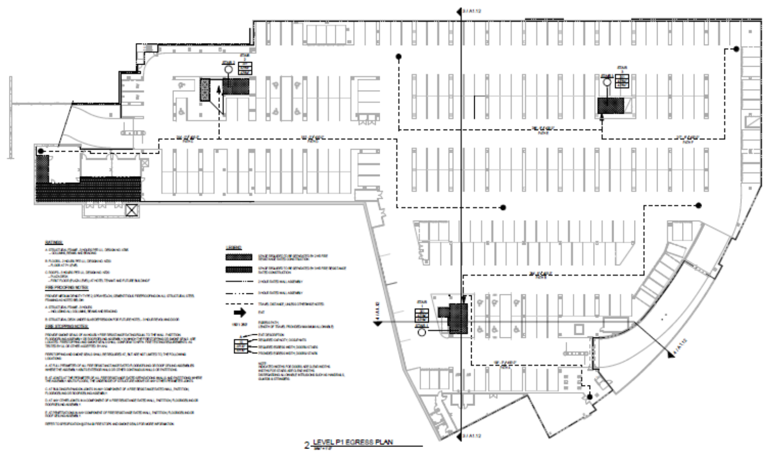
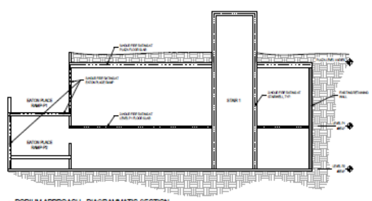
Appendix

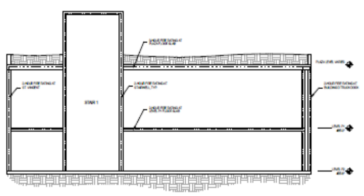
Appendix A: Construction Drawings of "Head Houses"



2 LEVEL P1 EGRESS PLAN

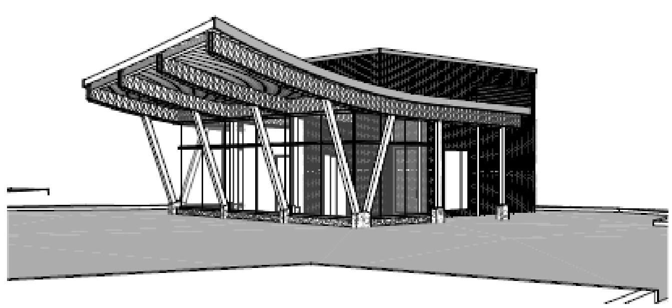


4 PODIUM APPROACH - DIAGRAMMATIC SECTION



3 PODIUM APPROACH - DIAGRAMMATIC SECTION

1 LEVEL P2 EGRESS PLAN



6 CORE 1 3D VIEW SW CORNER
REFER TO ELEVATIONS FOR DETAILED INFORMATION

7 CORE 1 3D VIEW NE CORNER
REFER TO ELEVATIONS FOR DETAILED INFORMATION

Appendix B: Underground Parking Structures Background

Underground construction is a common way of maximizing subsurface space and accommodating facilities of diverse functionalities. The functionality of underground construction is mostly limited by the geological conditions of the site, but even so geological advancements and modern construction methods enable a broad spectrum of usages for investors, cities, and industries to explore.

To better understand the diversity of underground spaces, a classification system with groupings by function, geometry, origin, site feature and project feature can be developed. **Table 28** provides the major categories for underground space.

Function	Geometry	Origin	Site Feature	Project Feature
Residential	Type of space	Natural	Geography	Rationale
Nonresidential	Fenestration	Mined	Climate	Design
Infrastructure	Relationship to surface	End use	Land use	Construction
Military	Depth dimension to Scale of project		Ground conditions building relationships	Age

Table 28 - Major Classification Groupings of Underground Space (Goel, et. all., 2012)

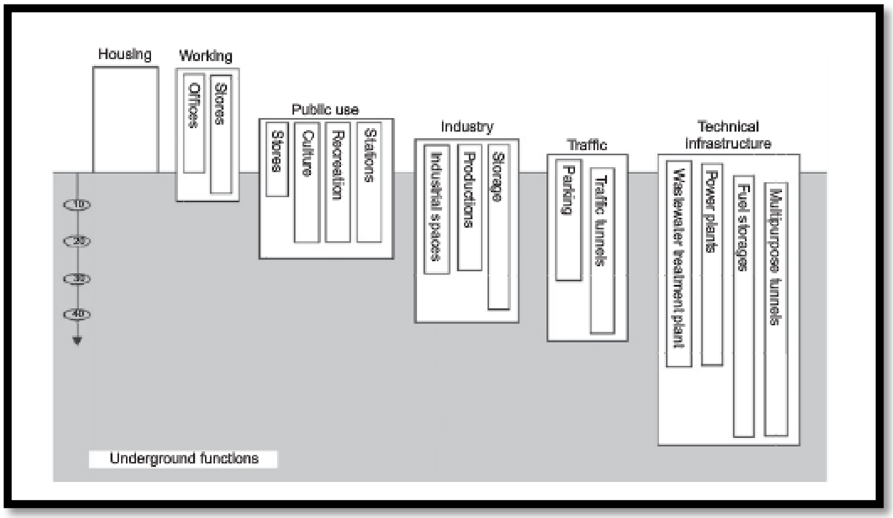
Further classification can be done using any of the groupings displayed above, but a closer look at geometry and site feature, more specifically on the relationship between structure and ground surface, provides a comprehensive classification for underground construction in the civil realm.

Classification by the vertical dimension of the underground space, or its depth, allows all underground spaces to be studied from a geotechnical and structural view. Table 29 below provides this overview.

Term	Typical Range of Depth Implied According to Use (m)			
	Local Utilities	**Buildings**	**Regional Utilities/Urban Transit**	**Mines**
Shallow	0-2	1-10	0-10	0-100
Moderate	2-4	10-30	10-50	100-1000
Deep	>4	>30	>50	>1000

Table 29 - Classification of Underground Space by Depth (Goel, et. all., 2012)

Beyond the geotechnical and structural considerations of underground structures, attention must be given to the level-wise planning of underground space. With increasing depth, considerations such as ventilation, lighting, acoustics and space distribution become more critical. Because of this, the depth of the underground structure is reflective of its intended use and purpose. The figure below provides a graphical depiction of the uses of underground space based on depth.



Feasible depths of different activities in urban structures. (Goel, et. all., 2012)

Considering the relationship of the underground space to the surface in addition to a dimensional classification provides a better understanding of the use or functionality of underground structures. These classifications are not exclusive of each other, and can be used in conjunction to reach a full understanding of underground spaced.

Table below provides four main categories under this consideration.

Description of Type of Underground Structure	Relationship between structure and Ground Surface	Main Uses	Effects on Aboveground Environment
Totally underground	Structure totally below surface	Shelter, storage, urban facilities, supply management facilities	Preserves open space
Some floors aboveground and some floors underground	Structure uses both aboveground and underground space	Offices, pedestrian walkways, parking, warehouses, industry substations	Aboveground allows for sunlight, but is restricted by height limitations
Atrium-type structures	Structure incorporates atrium(s), skylight(s), to connect surface with underground	Pedestrian walkaways, residences, sports facilities	Effective at preserving scenery and space aboveground
Underground structures with shafts	Depends on shaft; structures mainly suited to an inclined plane	Storage facilities, residences	Preserves natural scenery

Classification of Underground Space by Relationship between Structure and Ground Surface

Appendix C: Guaranteed Maximum Pricing for Underground Parking Garage by Consigli

Division	Description	Value	% of Total Project	% by Division
2	Selective Demolition	$ 337,645.00	0.98%	1.20%
3	Concrete	$ 5,951,769.00	17.35%	21.13%
4	Masonry	$ 1,444,800.00	4.21%	5.13%
5	Metals	$ 5,292,900.00	15.43%	18.79%
6	Wood & Plastics	$ 101,826.00	0.30%	0.36%
7	Thermal & Moisture	$ 2,773,868.00	8.09%	9.85%
8	Doors & Windows	$ 302,035.00	0.88%	1.07%
9	Finishes	$ 502,702.00	1.47%	1.78%
10	Specialities	$ 54,646.00	0.16%	0.19%
14	Elevators	$ 241,700.00	0.70%	0.86%
21	Fire Protection	$ 908,195.00	2.65%	3.22%
22	Plumbing Systems	$ 1,046,260.00	3.05%	3.71%
23	Heating Ventilating and Air Conditioning	$ 1,332,525.00	3.89%	4.73%
26	Electrical	$ 2,530,599.00	7.38%	8.98%
31	Earthwork	$ 4,430,770.00	12.92%	15.73%
32	Exterior Improvements	$ 914,952.00	2.67%	3.25%
Total Cost by Divisions		$ 28,167,192.00	82.12%	100.00%
Allowance	N-Line Concrete Wall	$ 58,529.00	0.17%	
Allowance	ASI #1 Irrigation Allowance	$ 90,000.00	0.26%	
Allowance	Addeddum #2 Allowance	$ 20,000.00	0.06%	
Allowance	Police Detail Allowance	$ 50,000.00	0.15%	
Allowance	Winter Conditions (NTE Allowance)	$ 500,000.00	1.46%	
Allowance	Bldg E Storm Pipe Removal Through J/K Allowance	$ 25,000.00	0.07%	
Allowance	Light Pole Base Repair on Front Street Allowance	$ 15,000.00	0.04%	
Allowance	BUD Material Disposal Allowance	$ 25,000.00	0.07%	
Allowance	ASI #2 Allowance	$ 40,000.00	0.12%	
Allowance	ASI #3 Allowance	$ 50,000.00	0.15%	
Allowance	100% CD's-Sitework	$ 587,757.00	1.71%	
Allowance	Contaminated Soil Disposal - Out of State Landfill	$ 160,000.00	0.47%	
Total Allowance		$ 1,621,286.00	4.73%	
	SDI (Subcontractor Bonds)	$ 357,462.00	1.04%	
	Construction Contingency	$ 904,378.00	2.64%	
	GC-Precon	$ 70,000.00	0.20%	
	General Requirements	$ 567,705.00	1.66%	
	General Conditions	$ 1,190,673.00	3.47%	
	General Liability Insurance	$ 328,787.00	0.96%	
	Payment & Performance Bond	$ 222,490.00	0.65%	
	FEE	$ 869,179.00	2.53%	
Total General Requirement, FEE and Bonds		$ 4,510,674.00	13.15%	
	Total Cost	**$ 34,299,152.00**		

Appendix D: Tracking Sheet for Change Requests

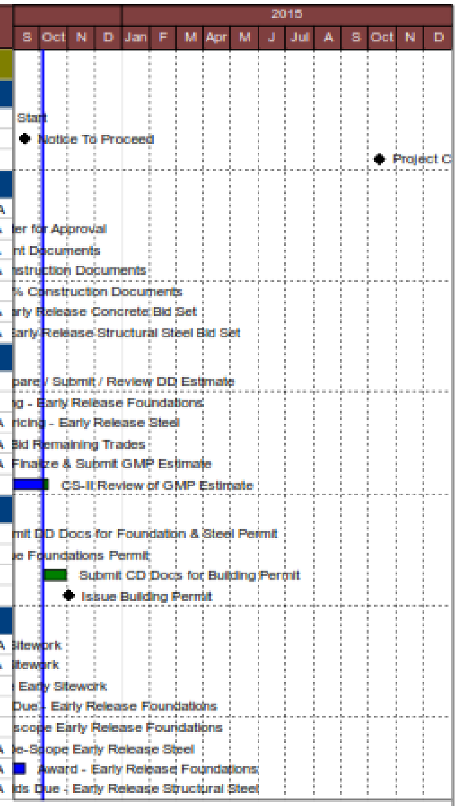
Nomenclature	Title	Summary	Type of CR	Description
17-001	City Square Underground Parking Garage - Early Release Sitework	Early release sitework for the project	Early Release	Site work activities to prepare for construction
17-002	Temporary Power for Parking Garage	Early release site work temp. power request	Early Release	Parking garage currently getting power req. from portable generator to run dewatering pumps. Request for temp. power source for overall proejct scope.
17-003	Rebar Detailing Early Release	Early release rebar shop drawings.	Early Release	Need to issue early reinforcing steel package in order to get shop drawings underway for structural concrete foundations of parking garage. No intent to buy materials and start fabrication because the concrete package has not been released yet.
17-005	Structural Concrete Package Early Release	Early release structural concrete with current drawings and includes site work costs.	Early Release	Need to issue early release for structural concrete to get other detailing underway (i.e., rebar). Change request also includes the remainder of the Preconstruction services costs needed for the project.
17-006	Structural Steel Package/Early Release	Early release for structural steel	Early Release	Release of the structural steel to enable project to advance while contract and GMP are completed. Value of the change will be reversed once a contract is finalized.
17-008	Install Temporary Soil Support along N-line in lieu of Underpinning Existing Footings	Credit for original method of underpinning in Marois Bros. subcontract and additional cost for alternative design	Alternative Solution	Consigli directed Marois Bros. to come up with the most effective and economical solution to support along N-line. The proposed solution of soldier piles instead of underpinning represented cost savings reflected in this change request. This change request is a credit to the owner.
17-011	Demo and Replace Section of Front St. Bridge	Demo and later replace section of Front St. bridge for construction access	Alternative Solution	Most effective logistical plan for construction is to remove an intermediate deck from a single bay of Front St. Bridge. Cost includes demo, removal and replacement of structural steel.
17-012	Cast in place walls along N-line	Costs for labor, materials, and equipment to build cast-in-place walls under existing slab or grade beams of truck tunnel.	Allowance Transfer	Scope for work was excluded from Structural Concrete Subcontract, so scope had not been bought. The work was described as "underpinning" and was excluded from the Sitework scope.
17-014	Early Release Critical Trades	Work across trades (MEP, HVAC, Fireproofing, Masonry, etc.) in case GMP approval was further delayed	Early Release	Work for trades that are on the critical path of the project. Step forward ro minimize the overall project schedule prior to the GMP signing.
CR001	RFI 043- Top of Column Detail at Plaza Level	Formal notification of contingency use.	Allowance Transfer	Notification of use of construction manager's project contingency to revise structural steel design.
CR002	RFI 037- Raise Footings	Work to raise footings so that they are above the water table.	Field Condition	Raise the elevation of the footings around the ground water ejector pits per RFI 037.
CR003	RFI 039 and 040R- Footing Encroachments	Work to reduce approximately 6 footings in size to avoid encroaching from UNUM columns and footings.	Field Condition	Work to either revise footing size or build new footing to conform with existing footings from UNUM to avoid encroaching.
CR004	Allowance Overage 100% Sitework	Allowance overage and allowance utilization notification	Design Change	Sitework package was released early prior to GMP approval when construction documents were not 100%. The now completed 100% documents have addeed scope from the original package. An allowance carried in the GMP will be used to purchase this new scope.
CR005	Allowance Overage N-line Wall	Overage for N-line work Allowance.	Field Condition	An alllowance for the N-line wall work was included in the GMP, but field conditions created an overage.
CR008	ASI-008 Detereriorated Concrete at East Garage	Manafort is proposing new 4000 psi concrete underpinning at deteriorated concrete areas.	Field Condition	Manafort is proposing new 4000 psi concrete underpinning at deteriorated concrete areas in the East Garage.

Nomenclature	Date Proposed by GC	Date Approved by Owner	Turnover Time	Proposed Cost	# of Revisions	Final Cost	Reasoning for Cost Revision
17-001	7/10/2014	7/11/2014	1	$ 4,879,314.00	0	$ 4,879,314.00	N/A
17-002	7/31/2014	9/24/2014	55	$24,928.00	1	$24,065.00	Negotiated price decrease by remoing cost of material tax
17-003	8/1/2014	8/12/2014	11	$23,360.00	1	$23,360.00	N/A
17-005	9/15/2014	9/15/2014	1	$6,322,294.00	1	$6,322,294.00	N/A
17-006	9/16/2014	10/1/2014	15	$5,138,243.00	1	$5,076,793.00	Removed scope of removing and replacing Front St. Bridge Steel & Deck, added scope for G90 Deck
17-008	9/16/2014	9/30/2014	14	-$84,419.00	1	-$84,419.00	N/A
17-011	10/7/2014	10/16/2014	9	$119,583.00	0	$119,583.00	N/A
17-012	10/23/2014	Pending	N/A	$65,107.00	0	$65,107.00	N/A
17-014	11/5/2014	Pending	N/A	$12,264,527.00	0	$12,264,527.00	N/A
CR001	1/6/2015	Pending	N/A	$0.00	0	$0.00	Use of pre-existing contingency, no addded cost.
CR002	12/3/2014	Pending	N/A	-$2,037.00	0	-$2,037.00	N/A
CR003	12/24/2014	Pending	N/A	$5,771.00			N/A
CR004	2/3/2015	Pending	N/A	$205,149.00			N/A
CR005	2/3/2015	Pending	N/A	$12,012.00			N/A
CR008	1/14/2015	Pending	N/A	$6,427.00			N/A

Nomenclature	Increase in Contract Time	Resolution	Category	Type	Funded	Terms of Action
17-001	0		Major Change	Public Work	N/A	N/A
17-002	0	Voided/GMP	Minor Change	Public Work	Other	N/A
17-003	Meet CPM	Voided/GMP	Minor Change	Public Work	N/A	N/A
17-005	Meet CPM and allow for Preconstruction Services	Voided/GMP	Major Change	Public Work	N/A	N/A
17-006	0	Voided/GMP	Major Change	Public Work	N/A	As directed, GC will not proceed until formal direction from owner
17-008	0	Voided/GMP	Minor Change	Public Work	N/A	As directed, GC will not proceed until formal direction from owner
17-011	0	Voided/GMP	Minor Change	Public Work	N/A	N/A
17-012	Change in Schedule	Voided/Allowance Transfer	N/A	N/A	N/A	N/A
17-014	Meet CPM	Voided/GMP	Major Change	Public Work	N/A	N/A
CR001	0	Pending	N/A	N/A	N/A	As directed, GC will not proceed until formal direction from owner
CR002	0	Pending	N/A	N/A	N/A	As directed, GC will not proceed until formal direction from owner
CR003	0	Pending	N/A	N/A	N/A	As directed, GC will not proceed until formal direction from owner
CR004	0	Pending	Major Change	Public Work	N/A	N/A
CR005	0	Pending	N/A	N/A	N/A	N/A
CR008	0	Pending	N/A	N/A	N/A	N/A

Appendix E: Full Project Schedule Updated September 2014

Activity ID	Activity Name	Orig Dur	Start	Finish
CITY SQUARE UNDERGROUND PARKING GARAGE				
Project Milestones				
A5350	Project Start	0	30-Jun-14 A	
A3100	Notice To Proceed	0	15-Sep-14 A	
A5360	Project Complete	0		13-Oct-15
Design				
A1000	Schematic Design	0		16-Dec-13 A
A1010	Schematic Design to Worcester for Approval	20	16-Dec-13 A	24-Jan-14 A
A1020	Design Development Documents	30	27-Jan-14 A	09-Apr-14 A
A1030	60% Construction Documents	27	10-Apr-14 A	20-Jun-14 A
A5140	100% Construction Documents	50	10-Apr-14 A	21-Jul-14 A
A1040	Issue Early Release Concrete Bid Set	5	23-Jun-14 A	23-Jun-14 A
A1050	Issue Early Release Structural Steel Bid Set	5	30-Jun-14 A	30-Jun-14 A
Estimates				
A3070	Prepare / Submit / Review DD Estimate	15	10-Apr-14 A	25-Jul-14 A
A3170	Pricing - Early Release Foundations	10	26-Jun-14 A	14-Jul-14 A
A5370	Pricing - Early Release Steel	15	14-Jul-14 A	08-Aug-14 A
A3090	Bid Remaining Trades	25	21-Jul-14 A	14-Aug-14 A
A3080	Finalize & Submit GMP Estimate	5	11-Aug-14 A	15-Aug-14 A
A3230	CS-II Review of GMP Estimate	10	15-Aug-14 A	10-Oct-14
Permitting				
A2000	Submit DD Docs for Foundation & Steel Permit	20	19-Jun-14 A	22-Jul-14 A
A2010	Issue Foundations Permit	0	23-Jul-14 A	
A2020	Submit CD Docs for Building Permit	20	06-Oct-14	31-Oct-14
A2030	Issue Building Permit	0	03-Nov-14	
Bid & Award				
A3040	Bids Due - Sitework	0		28-May-14 A
A5160	Award - Sitework	7	13-Jun-14 A	13-Jun-14 A
A3050	Mobilize Early Sitework	0	26-Jun-14 A	
A3060	Bids Due - Early Release Foundations	0		14-Jul-14 A
A5390	De-scope Early Release Foundations	10	15-Jul-14 A	24-Jul-14 A
A3020	De-Scope Early Release Steel	5	06-Aug-14 A	11-Aug-14 A
A5380	Award - Early Release Foundations	10	07-Aug-14 A	15-Sep-14 A
A3000	Bids Due - Early Release Structural Steel	0		08-Aug-14 A



Start Date 16-Dec-13
Finish Date 13-Oct-15
Data Date 06-Oct-14
Run Date 06-Oct-14 16:05

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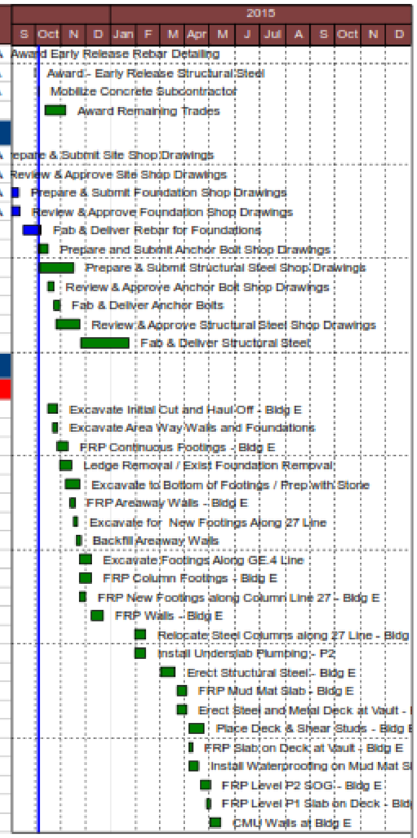
Remaining Level of Effort
Actual Level of Effort
Actual Work
Remaining Work
Critical Remaining Work

CONSIGLI CONSTRUCTION CO., INC.

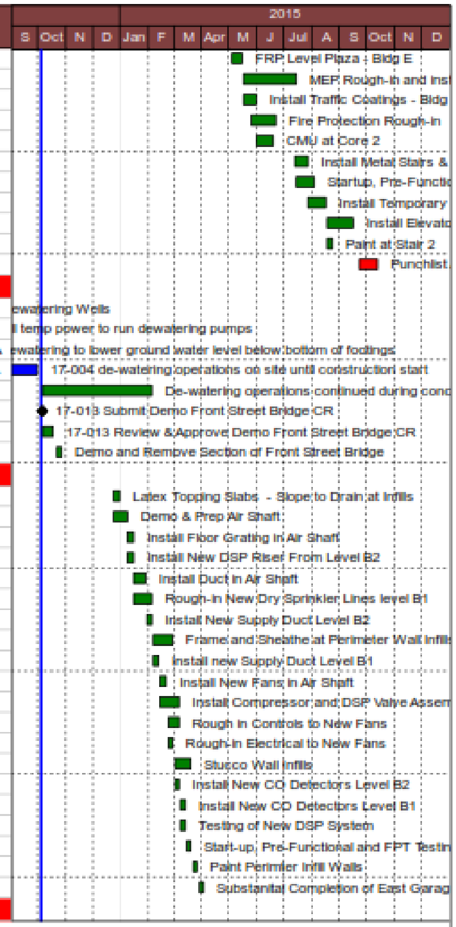
CITY SQUARE UNDERGROUND PARKING GARAGE

CONSIGLI
Est. 1905

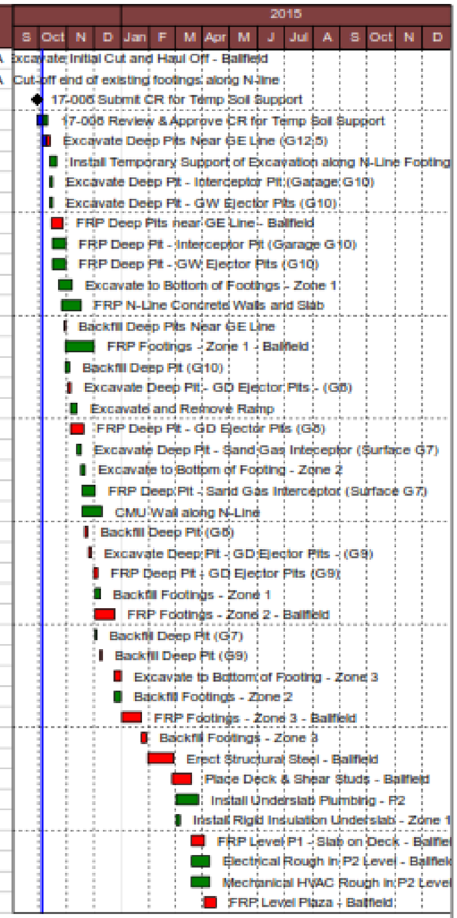
Activity ID	Activity Name	Orig Dur	Start	Finish
A5820	Award Early Release Rebar Detailing	5	18-Aug-14 A	18-Aug-14 A
A5150	Award - Early Release Structural Steel	1	01-Oct-14 A	01-Oct-14 A
A3180	Mobilize Concrete Subcontractor	5	06-Oct-14 A	06-Oct-14 A
A3190	Award Remaining Trades	20	13-Oct-14	07-Nov-14
Submittals				
A3120	Prepare & Submit Site Shop Drawings	10	23-Jun-14 A	05-Aug-14 A
A3160	Review & Approve Site Shop Drawings	10	05-Aug-14 A	15-Aug-14 A
A3110	Prepare & Submit Foundation Shop Drawings	10	28-Aug-14 A	11-Sep-14 A
A3150	Review & Approve Foundation Shop Drawings	15	28-Aug-14 A	12-Sep-14 A
A3130	Fab & Deliver Rebar for Foundations	10	17-Sep-14 A	08-Oct-14
A3200	Prepare and Submit Anchor Bolt Shop Drawings	10	06-Oct-14 A	16-Oct-14
A3010	Prepare & Submit Structural Steel Shop Drawings	30	06-Oct-14 A	17-Nov-14
A3210	Review & Approve Anchor Bolt Shop Drawings	5	17-Oct-14	23-Oct-14
A3220	Fab & Deliver Anchor Bolts	5	24-Oct-14	30-Oct-14
A3140	Review & Approve Structural Steel Shop Drawings	20	27-Oct-14	24-Nov-14
A3030	Fab & Deliver Structural Steel	40	25-Nov-14	22-Jan-15
Construction				
Bldg E				
A4000	Excavate Initial Cut and Haul Off - Bldg E	7	17-Oct-14	27-Oct-14
A4170	Excavate Area Way Walls and Foundations	5	22-Oct-14	28-Oct-14
A4040	FRP Continuous Footings - Bldg E	10	28-Oct-14	10-Nov-14
A4020	Ledge Removal / Exist Foundation Removal	10	31-Oct-14	14-Nov-14
A4030	Excavate to Bottom of Footings / Prep with Stone	10	07-Nov-14	24-Nov-14
A5560	FRP Areaway Walls - Bldg E	5	12-Nov-14	18-Nov-14
A4190	Excavate for New Footings Along 27 Line	5	17-Nov-14	21-Nov-14
A4180	Backfill Areaway Walls	5	19-Nov-14	25-Nov-14
A4010	Excavate Footings Along GE.4 Line	10	24-Nov-14	05-Dec-14
A4110	FRP Column Footings - Bldg E	10	24-Nov-14	05-Dec-14
A4160	FRP New Footings along Column Line 27 - Bldg E	5	24-Nov-14	01-Dec-14
A4200	FRP Walls - Bldg E	10	09-Dec-14	22-Dec-14
A4130	Relocate Steel Columns along 27 Line - Bldg E	10	30-Jan-15	12-Feb-15
A4150	Install Underslab Plumbing - P2	10	30-Jan-15	12-Feb-15
A4120	Erect Structural Steel - Bldg E	15	02-Mar-15	20-Mar-15
A5550	FRP Mud Mat Slab - Bldg E	10	23-Mar-15	03-Apr-15
A4220	Erect Steel and Metal Deck at Vault - Bldg E	10	23-Mar-15	03-Apr-15
A4090	Place Deck & Shear Studs - Bldg E	15	06-Apr-15	24-Apr-15
A4210	FRP Slab on Deck at Vault - Bldg E	5	06-Apr-15	10-Apr-15
A6060	Install Waterproofing on Mud Mat Slab	10	06-Apr-15	17-Apr-15
A5240	FRP Level P2 SOG - Bldg E	10	20-Apr-15	01-May-15
A4140	FRP Level P1 Slab on Deck - Bldg E	5	27-Apr-15	01-May-15
A6040	CMU Walls at Bldg E	10	01-May-15	14-May-15



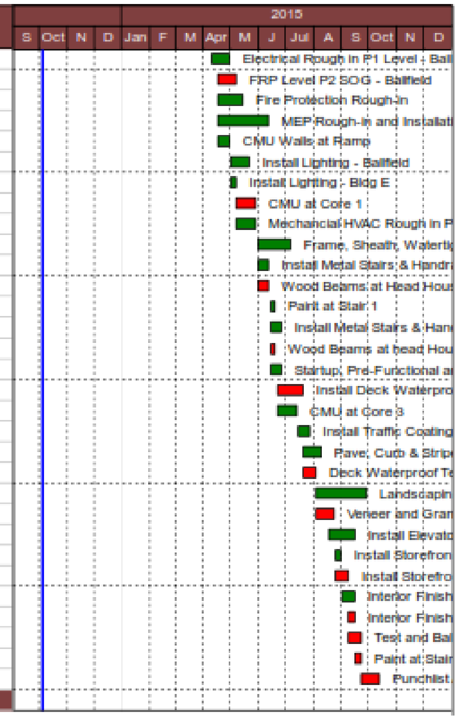
Activity ID	Activity Name	Orig Dur	Start	Finish
A5230	FRP Level Plaza - Bldg E	10	04-May-15	15-May-15
A4230	MEP Rough-In and Installations - Bldg E	40	18-May-15	14-Jul-15
A4270	Install Traffic Coatings - Bldg E	10	18-May-15	01-Jun-15
A4240	Fire Protection Rough-In	20	26-May-15	22-Jun-15
A4050	CMU at Core 2	15	01-Jun-15	19-Jun-15
A4060	Install Metal Stairs & Handrails - Stair 2	10	14-Jul-15	27-Jul-15
A4250	Startup, Pre-Functional and FPT Testing	15	15-Jul-15	04-Aug-15
A4080	Install Temporary Watertight Enclosures at Shafts	15	28-Jul-15	17-Aug-15
A4070	Install Elevators - Bldg E	20	18-Aug-15	15-Sep-15
A4100	Paint at Stair 2	5	18-Aug-15	24-Aug-15
A4260	Punchlist Activities - Bldg E	15	23-Sep-15	13-Oct-15
Overall Site				
A5060	Drill Dewatering Wells	5	30-Jun-14 A	08-Jul-14 A
A5410	Install temp power to run dewatering pumps	5	14-Jul-14 A	16-Jul-14 A
A5400	Dewatering to lower ground water level below bottom of footings	20	17-Jul-14 A	05-Aug-14 A
A5830	17-004 de-watering operations on site until construction start	30	05-Aug-14 A	01-Oct-14 A
A5840	De-watering operations continued during concrete operations	85	06-Oct-14	05-Feb-15
A5860	17-013 Submit Demo Front Street Bridge CR	0	06-Oct-14 A	
A5870	17-013 Review & Approve Demo Front Street Bridge CR	10	06-Oct-14	17-Oct-14
A5850	Demo and Remove Section of Front Street Bridge	5	22-Oct-14	28-Oct-14
East Garage Mitigation				
A5630	Latex Topping Slabs - Slope to Drain at Infills	5	24-Dec-14	31-Dec-14
A5650	Demo & Prep Air Shaft	10	24-Dec-14	08-Jan-15
A5660	Install Floor Grating in Air Shaft	5	09-Jan-15	15-Jan-15
A5700	Install New DSP Riser From Level B2	5	09-Jan-15	15-Jan-15
A5670	Install Duct in Air Shaft	10	16-Jan-15	29-Jan-15
A5690	Rough-in New Dry Sprinkler Lines level B1	15	16-Jan-15	05-Feb-15
A5720	Install New Supply Duct Level B2	5	30-Jan-15	05-Feb-15
A5320	Frame and Sheathe at Perimeter Wall Infills	15	06-Feb-15	27-Feb-15
A5730	Install new Supply Duct Level B1	5	06-Feb-15	12-Feb-15
A5680	Install New Fans in Air Shaft	5	13-Feb-15	20-Feb-15
A5710	Install Compressor and DSP Valve Assemblies	15	13-Feb-15	06-Mar-15
A5760	Rough in Controls to New Fans	10	23-Feb-15	06-Mar-15
A5780	Rough-in Electrical to New Fans	5	23-Feb-15	27-Feb-15
A5640	Stucco Wall Infills	15	02-Mar-15	20-Mar-15
A5740	Install New CO Detectors Level B2	5	02-Mar-15	06-Mar-15
A5750	Install New CO Detectors Level B1	5	09-Mar-15	13-Mar-15
A5810	Testing of New DSP System	5	09-Mar-15	13-Mar-15
A5770	Start-up, Pre-Functional and FPT Testing	5	16-Mar-15	20-Mar-15
A5790	Paint Perimter Infill Walls	5	23-Mar-15	27-Mar-15
A5800	Substanital Completion of East Garage	5	30-Mar-15	03-Apr-15
Ballfield				



Activity ID	Activity Name	Orig Dur	Start	Finish
A5000	Excavate Initial Cut and Haul Off - Ballfield	20	07-Jul-14 A	12-Aug-14 A
A5170	Cut-off end of existing footings along N-line	5	11-Aug-14 A	19-Aug-14 A
A5880	17-006 Submit CR for Temp Soil Support	0	30-Sep-14 A	
A5890	17-006 Review & Approve CR for Temp Soil Support	5	30-Sep-14 A	10-Oct-14
A5450	Excavate Deep Pits Near GE Line (G12.5)	3	06-Oct-14 A	13-Oct-14
A5010	Install Temporary Support of Excavation along N-Line Footings	7	13-Oct-14	21-Oct-14
A5420	Excavate Deep Pit - Interceptor Pit (Garage G10)	3	14-Oct-14	16-Oct-14
A5900	Excavate Deep Pit - GW Ejector Pits (G10)	3	14-Oct-14	16-Oct-14
A5460	FRP Deep Pits near GE Line - Ballfield	10	15-Oct-14	28-Oct-14
A5940	FRP Deep Pit - Interceptor Pit (Garage G10)	10	17-Oct-14	30-Oct-14
A5950	FRP Deep Pit - GW Ejector Pits (G10)	10	17-Oct-14	30-Oct-14
A5020	Excavate to Bottom of Footings - Zone 1	10	24-Oct-14	06-Nov-14
A6050	FRP N-Line Concrete Walls and Slab	15	27-Oct-14	17-Nov-14
A5470	Backfill Deep Pits Near GE Line	3	29-Oct-14	31-Oct-14
A5030	FRP Footings - Zone 1 - Ballfield	20	31-Oct-14	01-Dec-14
A5440	Backfill Deep Pit (G10)	2	31-Oct-14	03-Nov-14
A5920	Excavate Deep Pit - GD Ejector Pits - (G8)	3	03-Nov-14	05-Nov-14
A5490	Excavate and Remove Ramp	5	05-Nov-14	12-Nov-14
A5970	FRP Deep Pit - GD Ejector Pits (G8)	10	06-Nov-14	20-Nov-14
A5930	Excavate Deep Pit - Sand Gas Inteceptor (Surface G7)	3	13-Nov-14	17-Nov-14
A5190	Excavate to Bottom of Footing - Zone 2	5	17-Nov-14	21-Nov-14
A5980	FRP Deep Pit - Sand Gas Interceptor (Surface G7)	10	18-Nov-14	02-Dec-14
A5430	CMU Wall along N-Line	15	18-Nov-14	09-Dec-14
A6000	Backfill Deep Pit (G8)	2	21-Nov-14	24-Nov-14
A5910	Excavate Deep Pit - GD Ejector Pits - (G9)	3	25-Nov-14	28-Nov-14
A5960	FRP Deep Pit - GD Ejector Pits (G9)	5	01-Dec-14	05-Dec-14
A5500	Backfill Footings - Zone 1	5	02-Dec-14	08-Dec-14
A5130	FRP Footings - Zone 2 - Ballfield	15	03-Dec-14	23-Dec-14
A6010	Backfill Deep Pit (G7)	2	03-Dec-14	04-Dec-14
A5990	Backfill Deep Pit (G9)	2	08-Dec-14	09-Dec-14
A5480	Excavate to Bottom of Footing - Zone 3	5	24-Dec-14	31-Dec-14
A5510	Backfill Footings - Zone 2	5	24-Dec-14	31-Dec-14
A5160	FRP Footings - Zone 3 - Ballfield	15	02-Jan-15	22-Jan-15
A5520	Backfill Footings - Zone 3	5	23-Jan-15	29-Jan-15
A5250	Erect Structural Steel - Ballfield	20	30-Jan-15	27-Feb-15
A5270	Place Deck & Shear Studs - Ballfield	15	27-Feb-15	19-Mar-15
A5310	Install Underslab Plumbing - P2	20	02-Mar-15	27-Mar-15
A5540	Install Rigid Insulation Underslab - Zone 1 - ballfield	5	02-Mar-15	06-Mar-15
A5340	FRP Level P1 - Slab on Deck - Ballfield	10	20-Mar-15	02-Apr-15
A6060	Electrical Rough in P2 Level - Ballfield	15	20-Mar-15	09-Apr-15
A6110	Mechanical HVAC Rough in P2 Level - Ballfield	15	20-Mar-15	09-Apr-15
A5330	FRP Level Plaza - Ballfield	10	03-Apr-15	16-Apr-15



Activity ID	Activity Name	Orig Dur	Start	Finish
A6090	Electrical Rough in P1 Level - Ballfield	15	10-Apr-15	30-Apr-15
A5300	FRP Level P2 SOG - Ballfield	15	17-Apr-15	07-May-15
A5530	Fire Protection Rough-In	20	17-Apr-15	14-May-15
A5260	MEP Rough-in and Installations	40	17-Apr-15	12-Jun-15
A6020	CMU Walls at Ramp	10	17-Apr-15	30-Apr-15
A6120	Install Lighting - Ballfield	15	01-May-15	21-May-15
A6130	Install Lighting - Bldg E	5	01-May-15	07-May-15
A5040	CMU at Core 1	15	08-May-15	29-May-15
A6100	Mechancial HVAC Rough in P1 Level - Ballfield	15	08-May-15	29-May-15
A5050	Frame, Sheath, Watertight Enclosures at Shafts	25	01-Jun-15	06-Jul-15
A5060	Install Metal Stairs & Handrails - Stair 1	10	01-Jun-15	12-Jun-15
A5570	Wood Beams at Head House - Core 1	10	01-Jun-15	12-Jun-15
A5120	Paint at Stair 1	5	15-Jun-15	19-Jun-15
A5200	Install Metal Stairs & Handrails - Stair 3	10	15-Jun-15	26-Jun-15
A5580	Wood Beams at head House Core 3	5	15-Jun-15	19-Jun-15
A5280	Startup, Pre-Functional and FPT Testing	10	15-Jun-15	26-Jun-15
A5090	Install Deck Waterproofing at Upper Deck Only	20	22-Jun-15	20-Jul-15
A5220	CMU at Core 3	15	22-Jun-15	13-Jul-15
A6070	Install Traffic Coating - Ballfield	10	15-Jul-15	28-Jul-15
A5110	Pave, Curb & Stripe at Eaton Place	15	21-Jul-15	10-Aug-15
A6150	Deck Waterproof Testing	10	21-Jul-15	03-Aug-15
A5100	Landscaping and Site Improvements	40	04-Aug-15	29-Sep-15
A6030	Veneer and Granite at Headhouses	15	04-Aug-15	24-Aug-15
A5070	Install Elevators - Ballfield	20	18-Aug-15	15-Sep-15
A5590	Install Storefront at Head House - Core 1	5	25-Aug-15	31-Aug-15
A5600	Install Storefront at head House - Core 3	10	25-Aug-15	08-Sep-15
A5610	Interior Finishes at Head House - Core 1	10	01-Sep-15	15-Sep-15
A5620	Interior Finishes at Head House - Core 3	5	09-Sep-15	15-Sep-15
A6140	Test and Balance	10	09-Sep-15	22-Sep-15
A5210	Paint at Stair 3	5	16-Sep-15	22-Sep-15
A5290	Punchlist Activities - Ballfield	15	23-Sep-15	13-Oct-15
seperate				



Appendix F: Full Project Schedule Updated January 2015

City Square Underground Parking Garage

Activity ID	Activity Name	Orig Dur	Rem Dur	Start	Finish	Total Float
Project Milestones						
A5350	Project Start	0	0	06/30/14 A		
A3100	Notice To Proceed	0	0	09/15/14 A		
A6240	First Foundation Placement Complete	0	0		10/20/14 A	
A6270	MEP Coordination Complete	0	0		02/09/15	185
A6290	Buyout Complete	0	0		02/13/15	180
A6260	Start Structural Steel	0	0	03/03/15		170
A6250	Start Underground MEP Rough In	0	0	03/10/15		165
A6300	Start MEP Overhead Rough In	0	0	05/19/15		115
A6310	Building Weathertight	0	0		07/29/15	65
A6320	Permanent Power Live	0	0		07/29/15	65
A6280	Start Exterior Facade - Headhouses	0	0	09/03/15		40
A6220	Substantial Completion	0	0		10/08/15	15
A6330	Building Commissioned	0	0		10/08/15	15
A6340	Complete Elevators	0	0		10/08/15	15
A6350	Sitework/Landscape Complete	0	0		10/08/15	15
A5360	Project Complete	0	0		10/29/15*	-12
Design						
A1000	Schematic Design	0	0		12/16/13 A	
A1010	Schematic Design to Worcester for Approval	20	0	12/16/13 A	01/24/14 A	
A1020	Design Development Documents	30	0	01/27/14 A	04/09/14 A	
A1030	60% Construction Documents	27	0	04/10/14 A	06/20/14 A	
A5140	100% Construction Documents	50	0	04/10/14 A	07/21/14 A	
A1040	Issue Early Release Concrete Bid Set	5	0	06/23/14 A	06/23/14 A	
A1050	Issue Early Release Structural Steel Bid Set	5	0	06/30/14 A	06/30/14 A	
Estimates						
A3070	Prepare / Submit / Review DD Estimate	15	0	04/10/14 A	07/25/14 A	
A3170	Pricing - Early Release Foundations	10	0	06/26/14 A	07/14/14 A	
A5370	Pricing - Early Release Steel	15	0	07/14/14 A	08/08/14 A	
A3090	Bid Remaining Trades	25	0	07/21/14 A	08/14/14 A	
A3080	Finalize & Submit GMP Estimate	5	0	08/11/14 A	08/15/14 A	
A3230	CS-II Review of GMP Estimate	10	0	08/15/14 A	12/05/14 A	
A3270	Execute GMP and Contract	0	0		12/05/14 A	
Permitting						
A2000	Submit DD Docs for Foundation & Steel Permit	20	0	06/19/14 A	07/22/14 A	
A2010	Issue Foundations Permit	0	0	07/23/14 A		
A2020	Submit CD Docs for Building Permit	20	0	10/21/14 A	11/13/14 A	
A2030	Issue Building Permit	0	0	11/13/14 A		
Bid & Award						
A3040	Bids Due - Sitework	0	0		05/28/14 A	
A5160	Award - Sitework	7	0	06/13/14 A	06/13/14 A	
A3050	Mobilize Early Sitework	0	0	06/26/14 A		
A3060	Bids Due - Early Release Foundations	0	0		07/14/14 A	
A5390	De-scope Early Release Foundations	10	0	07/15/14 A	07/24/14 A	
A3020	De-Scope Early Release Steel	5	0	08/06/14 A	08/11/14 A	
A5380	Award - Early Release Foundations	10	0	08/07/14 A	09/15/14 A	
A3000	Bids Due - Early Release Structural Steel	0	0		08/08/14 A	
A5820	Award Early Release Rebar Detailing	5	0	08/18/14 A	08/18/14 A	
A5150	Award - Early Release Structural Steel	1	0	10/01/14 A	10/01/14 A	
A3180	Mobilize Concrete Subcontractor	5	0	10/06/14 A	10/06/14 A	
A3240	CS-II Review Early Release CR for N-Line Walls	5	0	10/29/14 A	12/05/14 A	
A3260	CS-II Review of Early Release CR Critical Path Trades	5	0	11/03/14 A	12/05/14 A	
A3190	Award Remaining Trades	20	5	12/08/14 A	02/13/15	-7
A3250	Award Critical Path Trades - Early Release CR	1	0	12/08/14 A	12/12/14 A	
Submittals						
A3120	Prepare & Submit Site Shop Drawings	10	0	06/23/14 A	08/05/14 A	
A3160	Review & Approve Site Shop Drawings	10	0	08/05/14 A	08/15/14 A	
A3110	Prepare & Submit Foundation Shop Drawings	10	0	08/28/14 A	09/11/14 A	
A3150	Review & Approve Foundation Shop Drawings	15	0	08/28/14 A	09/12/14 A	
A3130	Fab & Deliver Rebar for Foundations	10	0	09/17/14 A	10/08/14 A	
A3200	Prepare and Submit Anchor Bolt Shop Drawings	10	0	10/06/14 A	10/23/14 A	
A3010	Prepare & Submit Structural Steel Shop Drawings	30	0	10/06/14 A	12/19/14 A	
A3210	Review & Approve Anchor Bolt Shop Drawings	5	0	10/17/14 A	10/23/14 A	
A3220	Fab & Deliver Anchor Bolts	5	0	10/24/14 A	11/06/14 A	
A3140	Review & Approve Structural Steel Shop Drawings	30	0	11/13/14 A	01/29/15 A	
A3030	Fab & Deliver Structural Steel	40	20	01/02/15 A	03/09/15	3

Start Date 12/16/13
Finish Date 10/29/15
Data Date 02/09/15
Run Date 02/09/15 08:43

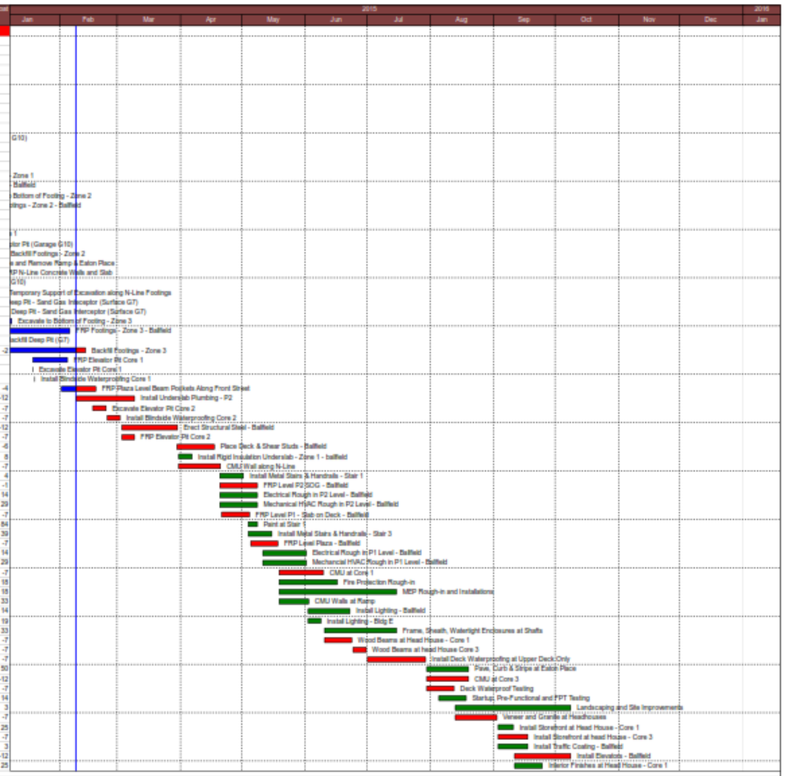
Legend: Remaining Level of Effort; Actual Level of Effort; Actual Work; Remaining Work; Critical Remaining Work; ◆ Milestone

CONSIGLI CONSTRUCTION CO., INC.
CITY SQUARE UNDERGROUND PARKING GARAGE
PROJECT SCHEDULE - JANUARY 2015 UPDATE

CONSIGLI Est. 1905

Activity ID	Activity Name	Orig Dur	Rem Dur	Start	Finish	Total Float
Construction						
Bldg E						
A4010	Excavate Footings Along GE.4 Line	10	0	11/06/14 A	01/02/15 A	
A4030	Excavate to Bottom of Footings / Prep with Stone	10	5	11/24/14 A	02/13/15	-7
A4110	FRP Column Footings - Bldg E	10	10	11/26/14 A	03/09/15	-7
A4000	Excavate Initial Cut and Haul Off - Bldg E	7	0	12/30/14 A	01/23/15 A	
A4320	Contaminated Soil Discovered - Bldg E Site Fuel Contamination	0	0		01/05/15 A	
A4330	ECS Drilling to Determine Extent of Fuel Contamination	2	0	01/13/15 A	01/14/15 A	
A4340	Additional Fuel Contamination Discovered in Bldg E Site	0	0		02/03/15 A	
A4020	Ledge Removal / Exist Foundation Removal	10	10	02/09/15	02/23/15	-7
A4170	Excavate Area Way Walls and Foundations	5	5	02/09/15	02/13/15	43
A4190	Excavate for New Footings Along 27 Line	5	5	02/09/15	02/13/15	-7
A4310	Underpinning of Existing CMU Wall - Bldg E	10	10	02/09/15	02/23/15	-7
A4160	FRP New Footings along Column Line 27 - Bldg E	5	5	02/17/15	02/23/15	-7
A4040	FRP Continuous Footings - Bldg E	10	10	02/24/15	03/09/15	-7
A4200	FRP Walls - Bldg E	10	10	03/02/15	03/13/15	-1
A4130	Relocate Steel Columns along 27 Line - Bldg E	10	10	03/03/15	03/16/15	-12
A4150	Install Underslab Plumbing - P2	10	10	03/10/15	03/23/15	-7
A5560	FRP Areaway Walls - Bldg E	5	5	03/10/15	03/16/15	28
A4180	Backfill Areaway Walls	5	5	03/17/15	03/23/15	48
A4280	Backfill Footings - Bldg E	10	10	03/17/15	03/30/15	-12
A5550	FRP Mud Mat Slab - Bldg E	10	10	03/31/15	04/13/15	-12
A4120	Erect Structural Steel - Bldg E	15	15	04/21/15	05/11/15	-12
A4220	Erect Steel and Metal Deck at Vault - Bldg E	10	10	05/12/15	05/26/15	-12
A6060	Install Waterproofing on Mud Mat Slab	10	10	05/12/15	05/26/15	8
A4090	Place Deck & Shear Studs - Bldg E	15	15	05/27/15	06/16/15	-12
A5240	FRP Level P2 SOG - Bldg E	10	10	05/27/15	06/09/15	8
A4210	FRP Slab on Deck at Vault - Bldg E	5	5	05/27/15	06/02/15	33
A6040	CMU Walls at Bldg E	10	10	06/03/15	06/16/15	33
A4290	Install Weathertight Enclosures over Vault	5	5	06/03/15	06/09/15	65
A4300	Electrical Rough In at Vault	5	5	06/10/15	06/16/15	65
A4060	Install Metal Stairs & Handrails - Stair 2	10	10	06/17/15	06/30/15	23
A4140	FRP Level P1 Slab on Deck - Bldg E	5	5	06/17/15	06/23/15	-12
A5230	FRP Level Plaza - Bldg E	10	10	06/24/15	07/08/15	-12
A4050	CMU at Core 2	15	15	07/09/15	07/29/15	-12
A4230	MEP Rough-in and installations - Bldg E	40	40	07/09/15	09/02/15	-12
A4270	Install Traffic Coatings - Bldg E	10	10	07/09/15	07/22/15	43
A4240	Fire Protection Rough-in	20	20	07/16/15	08/12/15	3
A4080	Install Temporary Watertight Enclosures at Shafts	15	15	08/20/15	09/10/15	-12
A4250	Startup, Pre-Functional and FPT Testing	15	15	09/03/15	09/24/15	-12
A4070	Install Elevators - Bldg E	20	20	09/11/15	10/08/15	-12
A4100	Paint at Stair 2	5	5	09/11/15	09/17/15	-2
A4260	Punchlist Activities - Bldg E	15	15	10/09/15	10/29/15	-12
Overall Site						
A5080	Drill Dewatering Wells	5	0	06/30/14 A	07/08/14 A	
A5410	Install temp power to run dewatering pumps	5	0	07/14/14 A	07/16/14 A	
A5400	Dewatering to lower ground water level below bottom of footings	20	0	07/17/14 A	08/05/14 A	
A5830	17-004 de-watering operations on site until construction start	30	0	08/05/14 A	10/01/14 A	
A5870	17-013 Review & Approve Demo Front Street Bridge CR	10	0	10/06/14 A	10/30/14 A	
A5840	De-watering operations continued during concrete operations	85	22	10/06/14 A	03/11/15	11
A5860	17-013 Submit Demo Front Street Bridge CR	0	0	10/06/14 A		
A6230	National Grid Raise Conduit Under Front Street	5	0	11/10/14 A	11/13/14 A	
A5850	Demo and Remove Section of Front Street Bridge	5	0	11/14/14 A	11/19/14 A	
A6380	Install Site Utilities - Sanitary Sewer	10	10	03/31/15	04/13/15	58
A6370	Install Site Utilities - Storm	10	10	04/07/15	04/20/15	58
A6360	Install Site Utilities - Water	15	15	04/14/15	05/04/15	58
East Garage Mitigation						
A5630	Latex Topping Slabs - Slope to Drain at Infills	5	5	03/31/15	04/06/15	93
A5650	Demo & Prep Air Shaft	10	10	03/31/15	04/13/15	68
A5660	Install Floor Grating in Air Shaft	5	5	04/14/15	04/20/15	73
A5700	Install New DSP Riser From Level B2	5	5	04/14/15	04/20/15	68
A5670	Install Duct in Air Shaft	10	10	04/21/15	05/04/15	73
A5690	Rough-in New Dry Sprinkler Lines level B1	15	15	04/21/15	05/11/15	68
A5720	Install New Supply Duct Level B2	5	5	05/05/15	05/11/15	73
A5320	Frame and Sheathe at Perimeter Wall Infills	15	15	05/12/15	06/02/15	68
A5730	Install new Supply Duct Level B1	5	5	05/12/15	05/18/15	73
A5680	Install New Fans in Air Shaft	5	5	05/19/15	05/26/15	73
A5710	Install Compressor and DSP Valve Assemblies	15	15	05/19/15	06/09/15	78
A5760	Rough in Controls to New Fans	10	10	05/27/15	06/09/15	78
A5780	Rough-in Electrical to New Fans	5	5	05/27/15	06/02/15	73
A5640	Stucco Wall Infills	15	15	06/03/15	06/23/15	68
A5740	Install New CO Detectors Level B2	5	5	06/03/15	06/09/15	73
A5750	Install New CO Detectors Level B1	5	5	06/10/15	06/16/15	73
A5810	Testing of New DSP System	5	5	06/10/15	06/16/15	78
A5790	Paint Perimeter Infill Walls	5	5	06/24/15	06/30/15	68
A5770	Start-up, Pre-Functional and FPT Testing	5	5	07/09/15	07/15/15	58
A5800	Substantial Completion of East Garage	5	5	07/16/15	07/22/15	58

Activity ID	Activity Name	Orig Dur	Rem Dur	Start	Finish	Total Float
Ballfield						
A5000	Excavate Initial Cut and Haul Off - Ballfield	20	0	07/07/14 A	08/12/14 A	
A5170	Cut-off end of existing footings along N-line	5	0	08/11/14 A	08/19/14 A	
A5880	17-008 Submit CR for Temp Soil Support	0	0	09/30/14 A		
A5890	17-008 Review & Approve CR for Temp Soil Support	5	0	09/30/14 A	10/16/14 A	
A5450	Excavate Deep Pits Near GE Line (G12.5)	3	0	10/06/14 A	10/15/14 A	
A5900	Excavate Deep Pit - GW Ejector Pits (G10)	3	0	10/09/14 A	10/13/14 A	
A5950	FRP Deep Pit - GW Ejector Pits (G10)	10	0	10/14/14 A	10/20/14 A	
A5460	FRP Deep Pits near GE Line - Ballfield	10	0	10/15/14 A	10/22/14 A	
A5470	Backfill Deep Pits Near GE Line	3	0	10/27/14 A	10/30/14 A	
A5910	Excavate Deep Pit - GD Ejector Pits - (G9)	3	0	10/29/14 A	10/30/14 A	
A5420	Excavate Deep Pit - Interceptor Pit (Garage G10)	3	0	10/30/14 A	11/03/14 A	
A5920	Excavate Deep Pit - GD Ejector Pits - (G8)	3	0	10/31/14 A	11/03/14 A	
A5960	FRP Deep Pit - GD Ejector Pits (G9)	5	0	10/31/14 A	11/07/14 A	
A5970	FRP Deep Pit - GD Ejector Pits (G8)	10	0	11/03/14 A	11/10/14 A	
A5020	Excavate to Bottom of Footings - Zone 1	10	0	11/04/14 A	11/20/14 A	
A5030	FRP Footings - Zone 1 - Ballfield	20	0	11/06/14 A	12/02/14 A	
A5190	Excavate to Bottom of Footing - Zone 2	5	0	11/07/14 A	12/20/14 A	
A5130	FRP Footings - Zone 2 - Ballfield	15	0	11/10/14 A	12/24/14 A	
A5990	Backfill Deep Pit (G9)	2	0	11/10/14 A	11/12/14 A	
A6000	Backfill Deep Pit (G8)	2	0	11/14/14 A	11/17/14 A	
A5500	Backfill Footings - Zone 1	5	0	11/17/14 A	12/03/14 A	
A5940	FRP Deep Pit - Interceptor Pit (Garage G10)	10	0	11/17/14 A	12/02/14 A	
A5510	Backfill Footings - Zone 2	5	0	11/21/14 A	01/05/15 A	
A5490	Excavate and Remove Ramp & Eaton Place	15	0	12/04/14 A	12/24/14 A	
A6050	FRP N-Line Concrete Walls and Slab	15	0	12/05/14 A	01/02/15 A	
A5440	Backfill Deep Pit (G10)	2	0	12/08/14 A	12/11/14 A	
A5010	Install Temporary Support of Excavation along N-Line Footings	7	0	12/18/14 A	12/26/14 A	
A5930	Excavate Deep Pit - Sand Gas Inteceptor (Surface G7)	3	0	12/19/14 A	12/20/14 A	
A5980	FRP Deep Pit - Sand Gas Interceptor (Surface G7)	10	0	12/22/14 A	12/29/14 A	
A5480	Excavate to Bottom of Footing - Zone 3	5	0	12/29/14 A	01/08/15 A	
A5180	FRP Footings - Zone 3 - Ballfield	15	0	12/30/14 A	02/06/15 A	
A6010	Backfill Deep Pit (G7)	2	0	01/03/15 A	01/03/15 A	
A5520	Backfill Footings - Zone 3	5	5	01/05/15 A	02/13/15	-2
A6160	FRP Elevator Pit Core 1	5	0	01/19/15 A	02/05/15 A	
A6180	Excavate Elevator Pit Core 1	5	0	01/19/15 A	01/19/15 A	
A6200	Install Blindside Waterproofing Core 1	5	0	01/20/15 A	01/20/15 A	
A6390	FRP Plaza Level Beam Pockets Along Front Street	7	7	02/02/15 A	02/18/15	-4
A5310	Install Underslab Plumbing - P2	20	20	02/09/15	03/09/15	-12
A6190	Excavate Elevator Pit Core 2	5	5	02/17/15	02/23/15	-7
A6210	Install Blindside Waterproofing Core 2	5	5	02/24/15	03/02/15	-7
A5250	Erect Structural Steel - Ballfield	20	20	03/03/15	03/30/15	-12
A6170	FRP Elevator Pit Core 2	5	5	03/03/15	03/09/15	-7
A5270	Place Deck & Shear Studs - Ballfield	15	15	03/30/15	04/17/15	-6
A5540	Install Rigid Insulation Underslab - Zone 1 - ballfield	5	5	03/31/15	04/06/15	8
A5430	CMU Wall along N-Line	15	15	03/31/15	04/20/15	-7
A5060	Install Metal Stairs & Handrails - Stair 1	10	10	04/20/15	05/01/15	4
A5300	FRP Level P2 SOG - Ballfield	15	15	04/20/15	05/08/15	-1
A6080	Electrical Rough in P2 Level - Ballfield	15	15	04/20/15	05/08/15	14
A6110	Mechanical HVAC Rough in P2 Level - Ballfield	15	15	04/20/15	05/08/15	29
A5340	FRP Level P1 - Slab on Deck - Ballfield	10	10	04/21/15	05/04/15	-7
A5120	Paint at Stair 1	5	5	05/04/15	05/08/15	84
A5200	Install Metal Stairs & Handrails - Stair 3	10	10	05/04/15	05/15/15	39
A5330	FRP Level Plaza - Ballfield	10	10	05/05/15	05/18/15	-7
A6090	Electrical Rough in P1 Level - Ballfield	15	15	05/11/15	06/01/15	14
A6100	Mechancial HVAC Rough in P1 Level - Ballfield	15	15	05/11/15	06/01/15	29
A5040	CMU at Core 1	15	15	05/19/15	06/09/15	-7
A5530	Fire Protection Rough-in	20	20	05/19/15	06/16/15	18
A5260	MEP Rough-in and Installations	40	40	05/19/15	07/15/15	18
A6020	CMU Walls at Ramp	10	10	05/19/15	06/02/15	33
A6120	Install Lighting - Ballfield	15	15	06/02/15	06/22/15	14
A6130	Install Lighting - Bldg E	5	5	06/02/15	06/08/15	19
A5050	Frame, Sheath, Watertight Enclosures at Shafts	25	25	06/10/15	07/15/15	33
A5570	Wood Beams at Head House - Core 1	10	10	06/10/15	06/23/15	-7
A5580	Wood Beams at head House Core 3	5	5	06/24/15	06/30/15	-7
A5090	Install Deck Waterproofing at Upper Deck Only	20	20	07/01/15	07/29/15	-7
A5110	Pave, Curb & Stripe at Eaton Place	15	15	07/30/15	08/19/15	50
A5220	CMU at Core 3	15	15	07/30/15	08/19/15	-12
A6150	Deck WaterproofTesting	10	10	07/30/15	08/12/15	-7
A5280	Startup, Pre-Functional and FPT Testing	10	10	08/05/15	08/18/15	14
A5100	Landscaping and Site Improvements	40	40	08/13/15	10/08/15	3
A6030	Veneer and Granite at Headhouses	15	15	08/13/15	09/02/15	-7
A5590	Install Storefront at Head House - Core 1	5	5	09/03/15	09/10/15	25
A5600	Install Storefront at head House - Core 3	10	10	09/03/15	09/17/15	-7
A6070	Install Traffic Coating - Ballfield	10	10	09/03/15	09/17/15	3
A5070	Install Elevators - Ballfield	20	20	09/11/15	10/08/15	-12
A5610	Interior Finishes at Head House - Core 1	10	10	09/11/15	09/24/15	25



Activity ID	Activity Name	Orig Dur	Rem Dur	Start	Finish	Total Float
A5620	Interior Finishes at Head House - Core 3	5	5	09/18/15	09/24/15	-7
A5210	Paint at Stair 3	5	5	09/25/15	10/01/15	-7
A6140	Test and Balance	10	10	09/25/15	10/08/15	-12
A5290	Punchlist Activities - Ballfield	15	15	10/09/15	10/29/15	-12

Appendix G: Tracking Sheet for Requests for Information (RFI's)

Doc. #	Document Name	Date Submitted	Turnover time (Calendar Days)	Sequencing	Reasoning	Response	Impact on Schedule	Projected Cost
1	Concrete to remain at Truck Tunnel	7/8/2014	9	GC>DES>GC>SUB	GC noticed concrete to remain near truck tunnel had not support under it because ground had eroded. GC asked to cut concrete up to where it met foundations to avoid it failing later.	Concrete to remain in place if possible. If not, remove it.	No impact. Minor issue	Within the scope.
2	Existing future slab	7/9/2014	8	GC>DES>GC>Included in SUB scope	Conflicting notes on drawing S2.01 indicating "extent of slab on grade" and another "future slab by others". Question who will do future slab?	All new slab on grade west of foundation wall is indicated as future work.	No impact. Minor issue	Work to be included in scope for Concrete Bid Set.
3	New Footings at 0/31 and GB.4/GH5	7/9/2014	8	GC>DES>GC	Drawings indicate footing to go in area where slab exists. GC wants confirmation slab has to be removed to perform footings work, and slab replacement is future work.	Footins will be replaced later by others.	No impact. Minor issue	Slab replacement outside of Concrete Bid Set scope.
4	Footing at GE/G11	7/9/2014	8	GC>DES>GC	Footing shoen at GE/G11 does not scall off to match. GC wants to confirm designation.	Don't scale drawings. Footing designation correct.	No impact. Minor issue	Clarification
5	Detail 10/S5.09 Callout	7/9/2014	8	GC>DES>GC	Detail references S2.04, but no callout found.	Callout can be found in S2.04 near GJ.1-GC.5	No impact. Minor issue	Clarification
6	Cut Footing prior to underpinning	7/16/2014	1	GC>DES>GC>Included in SUB scope	GC wants to cut and remove outside of footing prior to underpinning.	No underpinning shown at column footings for N line, but footings must be cut for access.	No impact. Minor issue	Clarification
7	Sump Pit to Precast Units	7/17/2014	1	GC>DES>GC>SUB>GC>DES>GC	GC suggesting to change deep pits from cast in place as shown in drawings to precast to avoid problems with dewatering operations as the water table is below the top of the structure.	Substitution to precast is acceptable. Submit precast drawings for approval.	Precast units to be cast ahead of time.	Change in cost from cast in place to precast.
8	Ground Rod from St. Vincent's Parking Garage	7/17/2014	12	GC>DES>GC>SUB>GC>DES>GC	GC asking for suggestions as to how Electric SUB can connect ground cable to rod.	Suggestion to extent grounding rods downward. Electrical drawings will be upgraded to cover this scope and issues as part of Addendum 1.	Additional time for added scope.	Addendum 1 cost.
9	Sawcut 30" Footings	8/8/2014	10	SUB>GC>DES>GC>SUB	GC asking to allow footings along N line to be cut using 24" blade instead of 30" blade indicated on drawings due to availability from SUB.	Footings must be cut with 30" blade.	At least 1 additional week for SUB to get 30" blade on site.	No change in cost, just delay.
10	Supply Duct Reconfiguration	8/19/2014	3	GC>DES>GC	1) GC recommending changing duct shape. 2) GC requesting to add horizontal shaft wall to adhere to recommendation of keeping plenums internal and meet 2 hour fire proofing. 3) DOT approved reflective warning strips for ductwork. GC wants direction.	1) Acceptable. 2) Acceptable. 3)AST needs more time to review.	Additional time for added scope. Additional wait for AST review for 3).	2)Additional cost for added scope.
11	Front Street Deck Removal	8/21/2014	13	GC>DES>GC>Included in SUB scope	In order to access the "ballfield" portion of the site, GC proposed and has included within the GMP provisions to remove and replace a section of the existing Front Street bridge deck. This will reduce the amount of time Front Street will be required to be closed or impacted to support the construction activities. Provide any details and or descriptions or requirements for the demolition and subsequent replacement of the steel and concrete deck.	Reference Addendum No. 2 for supplemental information regarding the removal and replacement of structure below Front Street.	Added time for Access to Site operations, but savings in the time that Front Street traffic would be affected and support of construction activities.	Addendum 2 cost.
12	Vertical Pipe Found During Excavation	8/21/2014	7	GC>DES>SUB of DES>DES>GC>SUB	A vertical pipe connected to a tank was found during excavation at the bottom of the access ramp. Tank was emptied by third party, and GC is requesting to remove pipe as needed and leave tank undisturbed.	Remove pipe as soon as possible to avoid re-infiltration as directed by ESC (SUB of DES).	Additional time to remove pipe.	Added cost based on T&M pricing.
13	Drains "PD" and "SPD" Revisions	9/11/2014	7	GC>DES>SUB of DES>DES>GC	1) Plaza Drains on Roadway: Request to clarify the specifications for the drains and keep the specifications provided for "Early Sitework Phase" drawings. 2) Sub-surface Drains: Request to clarify the specifications for the drains and keep the specifications provided for "Early Sitework Phase" drawings. 3) Typo in model number. Request to clarify.	1) Accept recommendation 2) Accept recommendation 3) Follow up after waterproof detailing.	No impact.	Clarification
14	Telephone Building Entry Charges	9/11/2014	4	GC/OWN/SUB>DES> GC	After coodination meeting with Verizo/CCC/LMP, revisions of quantity of telephone conduits to be reduced , addition of bushings at conduit ends, and addition of grounding. GC asking for comment and direction.	Accepted recommendations, no direction.	Change in scope of electrical SUB	Change in scope of electrical SUB
15	Second 15" RCP ST Leaving Building	9/22/2014	3	GC>DES>GC	GC asking if second storm water draininage pipe is needed for future provision as it is not tied to anything and is not collecting water as designed	Second pipe not needed.	Reduced quantity.	Reduced quantity.

15.5	Second 15" RCP ST Leaving Building	9/22/2014	18	DES>GC	New reply to RFI 15	Second pipe needed for future provisions	Added scope.	Added scope.
16	Domestivc Water Pressure Regulating Valve Station	9/22/2014	22		Clarification on need for water pressure regulating valve that is shown on drawings but not on plumbing detials.	Confirmed need of valve and directed them to forthcoming S1 #2	Clarification	Within the scope.
17	Underpinning at 4 Footing Locations	9/22/2014	3	GC>DES>GC>SUB >DES	Consigli wants to use temp soil support sheet instead of underpinning shown on drawgings.	Change is acceptable, but need a detailed submital calculated the deflection of the earth around the footing.	Clarification	Within the scope.
18	R&D Existing Pump Chamber	9/22/2014	2		Consigli wants do temo and remo a pump chamber below slab evaluation and infilling instead of removing and demo the entire pump chamber.	Recommended to proceed as indicated in design but alternative could be use if work is not in the influence zone of the adjacent footing.	Clarification	Within the scope.
19	NEMA Enclosures for VFDs	9/25/2014	12	GC>DES>SUB of DES>GC	Clarification on NEMA enclosures for VFDs.	Confirmed detials on enclosures.	Clarification	Within the scope.
20	Temp Generator Stack Condition	9/29/2014	21	GC>DES>GC	Clarification on interim installation of generator stack to be used in the future hotel project.	Confirmed interim installation details.	Clarification	Within the scope.
21	Temp Elevator 2 and 3 Vent Condition	9/29/2014	17	GC>DES>GC	Clarification on elevator exhaust fan for future hotel proejct. Consigli proposed alternative design.	Confirm to carry out as designed and provide value analysis of alternative design.	Clarification	Within the scope.
22	Missing Exhaust Fan for Fan Room 202	9/29/2014	1	GC>DES> SUB of DES>GC	Clarification on need for ventialation for Fan Room 202.	Exhaust fan is not required unless VFDs are moved into room.	Clarification	Within the scope.
23	Missing Vent for GRD-1	9/29/2014	7	GC>DES>GC	Drawings missing 4" vent pipe for GRD-1.	Added vent to drawings.	Clarification	Correction. Within the scope.
25	Existing conditions reveals area between existing precast and new CMU.	10/2/2014	4	GC>DES>GC	Clarification on fire protection requirements for gap between existing precast and CMU wall.	Confirmed waterproofing to be carried using standard method.	Clarification	Within the scope.
26	N line Existing Conditions	10/2/2014	1	GC>DES>GC	Field conditions along N line vary from drawings. Clarification on wall specifcations.	Confirmed proposed wall specifications.	Clarification	Within the scope.
27	Plaza Granite Curb	10/6/2014	7	GC>DES>SUB of DES>GC >SUB	Additional detials requested on granite thermal finish and sawn or split surfaces.	Provided detials on thermal and surface finishes.	Clarification	Within the scope.
28	CMU Clarification of Exisint CMU along N line	10/6/2014	1	SUB>GC>DES>GC >SUB	Confirm that drawings show an additional CMU wall along N line.	Confirmed new CMU wall is needed.	Added scope for masonry sub.	Added cost to Masonry Bid.
29	Cottom of wall rebar dowls at Building E Area and N line	10/16/2014	1	SUB>GC>DES>GC >SUB	Confirm that drilling at epoxing 4 dowels is acceptable.	Confirmed that bars could be drilled and epoxy.	Clarification	Within the scope.
30	Backfill Procedures of Deep Pit Foundations	10/16/2014	1	GC>DES>GC	1) Confirm that deep pit foundations can being to be backfilled without waiting for conrete to gain full deign strength. 2)Confirm that dead weight of concrete walls and slab will resist against buoyancy effect of rising water table.	1) Confirmed 2) Confirmed	Clarification	Within the scope.
31	Spray Fire Proofing Clarification	10/23/2014	4	GC>DES>GC	Clarification on fire rating for structural steel and location where 3h, 2h, or 1.5h ratings are acceptable.	Confirmed 3h rating is required for all structural steel, 2h rating could be used in some locaitons and 1.5h was not acceptable.	Clarification	Within the scope.
32	Intumescent Fireproofing at Core 3 Steel	10/24/2014	3	GC>DES>GC	Clarification on intumescent fireproofing on tubes running Core 3 stair tower.	Provided specifications for fireproofing.	Clarification	Within the scope.
33	East Garage - Cement Board at Stucco infill	10/24/2014	3	GC>DES>GC	Clarification on required number of layers of cement board to receive Stucco finish.	Use one layer on each side.	Clarification	Within the scope.
34	Ramp Radius Work Point	10/24/2014	3	SUB>GC>DES>GC > SUB	Request for radius work point off gridlines to locate ramp radius.	Provided gridlines to find radius.	Clarification	Within the scope.
35	E.O.S. and Beam Locations on Drawing E1	10/24/2014	3	SUB>GC>DES>GC > SUB	Clarification on E.O.S. dimensions around air shaft and dimensions for beams at Stairs 2, and Elevator 2 and 3.	Provided dimensions and beam size but requested confirmation from MEP coordination drawings.	Clarification	Within the scope.
36	Column Elevations along Griline GB.7	10/24/2014	3	SUB>GC>DES>GC > SUB	Provide information if leveling plates and anchor bolts will be provided sloping with the foundation wall or flat.	Base plates can be flat.	Clarification	Within the scope.
37	Footings along GE line Groundwater Ejector Pit	10/29/2014	2	GC>DES>GC	Propose to raise the bottom of the footing elevation so that footings are above water table.	No. Cannot raise elevation because elevation is set low so as to not be impacted by adjacent pits.	Clarification	Within the scope.
38	Plumbing Invert Elevations at Ejector Pits	11/3/2014	14	GC>DES>Sub of DES>GC	Request invert elevations at the ejector pits.	Provided list of elevations.	Missing information.	Clarification
39	Existing Unum Building Footing Encroachment	11/7/2014	7	GC>Sub of DES>GC	Request to change footing dimensions next to Unum building to avoid encroaching into existing Unum footings	Confirmed.	No impact	Added cost for extra volume of concrete.
40	East Garage Existing Footing Encroachment	11/10/2014	2	GC>Sub of DES>GC	Confirm the resizing of the footings adjacent to East Garage.	Confirmed.	No impact	Added cost for bond breaker between citysquare
41	GH11.5-GJ.4 Footing Interference	11/24/2014	1	GC>Sub of DES>GC	Confirm the direction from Structural Engineer to have a resolution to the footing interference without cutting the existing footing.	Confirmed.	Clarification	Within scope.
42	Domestic Water Reduce Pressure Station	12/9/2014	1	GC>Sub of DES>GC	Advise if a reduce pressure station is needed given water service pressure into building will be 150PSI.	Addressed in SI#002.	Clarification	N/A
43	Top of Column Detail at Future Building	12/19/2014	19	GC>DES>Sub of DES>GC>Sub	grade in the future hotel area should be fireproofed and treated or cut. Order put on for longer length already	Provide pricing to proceed with option 1 as shown in A/S6.03	Clarification	Added cost to remidiate extra length of steel columns.
44	Ramp Geometry	12/24/2014	7	Sub>GC>DES>GC	Provide work point locations for angle degrees marked in ramp drawings.	Attached drawings with comments and mark up	Missing information	Within scope.
45	Existing Walls to New Expansion Joints	12/24/2014	5	Sub>GC>DES>GC	Advise if bent place can remain straight or skewed along G.14 line and GA.0	Bent plate can be run straight as long as min. 4" expansion joint is provided.	Clarification	Within scope.

46	Ramp CMU Wall Locations	12/24/2014	5	Sub>GC>DES>GC	Provide dimensions of angles and of CMU Wall along ramp.	Attached drawings with comments and mark up	Clarification	Within scope.
47	Base Plate Elevation Changes	12/29/2014	2	Sub>GC>DES>GC	Confirm that elevation of base plates is 1' below what is shown on drawings and other elevations as shown in returned Submittal 051200-001.	Confirmed both.	Clarification	Within scope.
48	Non-Galvanized Dry Sprinkler Piping	1/7/2015	1	Sub>GC>DES>GC	Confirm that it is acceptable to use non-galvinized instead of galvanized sprinkler dry piping and fittings. Cost savings associated.	Not acceptable. Proceed with galvinized.	Clarification	Within scope.
49	Stair 1 Wall and Shelf Elevations	1/13/2015	1	Sub>GC>DES>GC	Provide elevations for the top of walls and shelves at Stair 1 on the Upper Plaza Level.	Attached drawings with comments and mark up	Missing information	Within scope.
50	Field Applied Jacketing	1/14/2015	7	Sub>GC>DES>subs of DES>GC	Provide guidance as to which, if any, jacketing apply to piping within th parking garage. Different options for jacketing depend on considering the parking garagean open or an underground structure.	No additional jacket or coating required for plumbing pipe.	Clarification	Within scope.
51	Level P2 St and SAN Piping between GH-6 and GH-3 Clarifications	1/14/2015	8	GC>DES>GC	Confirm that two sanitary pipes on the drawings were mislabled. Confirm the pipe should be 4".	Confirmed.	Clarification	Within scope.
52	Missing and Mislabled GV Piping	1/14/2015	8	GC>DES>GC	Confirm that a 4" pipe was mislabled in the drawings and that there was mising detial on the connection between GV piping and GV piping slated.	Confirmed.	Clarification	Within scope.
53	Missing Sanitary Vents	1/14/2015	10	Sub>GC>DES>GC>Sub	Provide information on missing vents for sanitary system from the plumbing drawings.	Attached drawings with comments and mark up	Clarification	Within scope.
54	Inverts for Sand and Gas interceptor	1/14/2015	1	Sub>GC>DES>GC	Confirm that due to approved changes in RFI 38, the dimensions of the Sand and Gas Interceptor inverts can be 32" and 26".	Not Acceptable. Code does not recognize proposed dimensions. Suggest additonal excavation to meet dimensions.	Clarification	Extra cost due to additional work
55	Inverts for Sand and Gas Interceptor (Surface)	1/14/2015	1	Sub>GC>DES>GC	Confirm that due to approved changes in RFI 38, the elevations of the Sand and Gas Interceptor inverts can be modified.	Not Acceptable. Please indicate on coordination drawing.	Clarification	Within scope.
56	Reconfiguration of GVs at P-28 level P1	1/14/2015	8	GC>DES>GC	Confirm that to maximum headroom in garage, lines of STVs can be deleted and reconfigured.	Confirmed	Clarification	Within scope.
57	GRD-1 and 2 Discharge Piping Size Calculation	1/14/2015	1	Sub>GC>DES>GC>Sub	Confirm that discharge of pipe in the drawings is mislabled and should be 3".	Confirmed	Clarification	Within scope.
58	Reconfiguration of ST Piping at Building Exit	1/14/2015	1	Sub>GC>DES>GC>Sub	Confirm that reconfiguration of ST Piping at building exit is acceptable.	Confirmed with comments	Clarification	Within scope.
59	Elevation of GV for Level P1 GDs at GF/G5 & GF/G9	1/15/2015	21	Sub>GC>DES>GC>Sub	Confirm that although the inverts of the pipes are lower than the elevations shown on drawings, the fact that the elevation is acceptable at the crossing makes this viable.	Confirmed with comments	Clarification	Within scope.
60	Missing PD at Plaza Level	1/15/2015	7	GC>DES>GC	Confirm if drain shown on Drainage Plan (L3.01), but not on plumbing drawings is needed.	Provide plaza drain and piping.	Missing information	Added scope for drain and pipe.
61	Cl Locations off of Column Line for All Surface Drainage	1/15/2015	8	GC>DES>GC	Provide dimensional information not shown on drawing in regards to CL locations off of column line for all Surface Drainage.	See attached sketch.	Missing information	Within scope.
62	Reolcation of 4" GV to Stair 3	1/15/2015	4	GC>DES>GC	Confirm that proposed relocation of GV to stair 3 based on the length of the run and the pitch required is acceptable.	Provide coordination drawings to clarify issue.	Clarification	Within scope.
63	Revised Top Footings Elevations	1/16/2015	4	GC>DES>Sub of DES>DES>GC	Confirm that changes made by the attached Sk are to be incorporated into the construction documents.	Confirmed	Clarification	Within scope.
65	Precast Hatch Detail	1/22/2015	11	Sub>GC>DES>GC>Sub	Confirm that drawings for precast hatch are acceptable.	Confirmed with comments	Clarification	Within scope.
68	Missing Piping for (2) DDs at Eaton Place	1/26/2015	10	GC>DES>GC	Confirm if two roadway deck drains are required are they are not shown on plumbing drawings. If required, reference attached sketches of porposed modification.	Confirmed drains required.	Clarification	Added scope for drains.
69	Building E Column Foundation Obstruction	1/29/2015	6	GC>DES>Sub of DES>DES>GC	Advise on Building E existing Column foundation @29 interferes with new wall line at 2'-11 3/4 west of column centerline.	Select alternative: Shore column, remove pier and footing, pour new "tall footing"	Clarification	Added scope for alternative.

CONSIGLI
Est. 1905

Request for Information

To: Stefan Chaires
Arrowstreet, Inc.
10 Post Office Square
Suite 700N
Boston,, MA 02019
Ph: (617)666-7136 Fax: (617)625-4646

RFI #: 9
Date: 8/8/2014
Job: 1308 City Square Underground Garage
Phone:

CC:

Subject: Sawcut 30" Footings

Drawing: S2.01

Spec Section:

Request:

Date Required:

Please reference S2.01. It was verified in the field that 7 of the 13 footings on N line from G14-G4 are 30" deep. It was noted by the sitework contractor that only a 24" blade is available at the moment for cutting. Due to the fact that it would take at least a week to get a 30" blade on site, we would like to know if it is acceptable to cut the footings with the 24" blade and wedge or gently apply pressure to snap off the final 6" of the footings. Please confirm.

*The remaining 6 footings measure 24" and will be cut with no problem.

Requested by: Mario Reed
Consigli Construction Co., Inc

Response:

Footings must be cut with 30" blade.

Stefan Chaires

Answered By
Arrowstreet, Inc.
Company

8/18/2014
Date

Forward: Marois, David (MAROIS BROS., INC.)

Page 1 of 1

Consigli Construction Co., Inc. Construction Managers and General Contractors
72 Sumner Street, Milford, Massachusetts 01757 phone 508.473.2580 fax 508.473.3588 web www.consigli.com

Hartford, CT • Portland, ME • Milford, MA

Appendix I: Submittals Tracking Sheet

Document #	Document Name	Type	Date	Turnover time (Days)	Sequencing	Response	Reasoning
051200-001	Anchor Bolts	SD	10/17/2014	8	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop drawings for anchor bolts
051200-002	Embeds	SD	11/3/2014	4	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved with comments: Check for elevation	Shop drawings fro embeds
051200-003	Erection Drawings	SD	11/13/2014	11	SUB>GC>DES>Sub of DES>DES>GC	Approved as noted. Resubmission required.	Fabrication of steel. Need to coordinate with fan, generator, elevator, and freight lift approved submittals.
312000-003	Temporary Earth Support System Calcs	SD	10/17/2014	12	ENG>GC>DES>Sub of DES>DES>GC	Revise and Resubmit.	Design calculations for temporary earth support (soldier piles) as alternative solution.
312000-003R	Temporary Earth Support System Calcs	SD	10/30/2014	4	ENG>GC>DES>Sub of DES>DES>GC	Approved as noted.	Resubmitted design calculations for temporary earth support (soldier piles) using factor of safety of 1.5.
033100-001	Rebar fabrication	SD	8/28/2014	1	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop drawings calling for coordination with plmbing subcontractor
033100-002	Ballfield Foundation Reinforcing	SD	9/11/2014	1	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop drawings for reinforments calling GC to verify quantities
033100-003	Alternate Mix Design for Early Strength	PD	10/22/2014	1	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specification for mix design to provide early strength for backfilling purposes
033100-004	Building E Area Foundation Reinforcing	SD	10/3/2014	6	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop drawings for reinforments calling GC to verify quantities and coordinate
033100-005	Hotel Slab Area Foundation Reinforcing	SD	10/8/014	1	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop drawings for reinforcements calling for GC to coordinate with waterproofing
033100-006	Form Release Compound	PD	10/13/2014	2	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved pending use per manufacturer's requirements	Product information for a release agent for concrete forms
033100-007	Expansion Joint	PD	10/13/2014	2	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Product information for joint filler called for use where filler required
033100-008	Asphalt Expansion Joint	PD	10/13/2014	2	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Product information for asphalt expansion joint called for exterior use only
033100-009	Expansion Water Stop	PD	10/13/2014	2	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved pending use per manufacturer's requirements	Product information for waterstop for nonmoving concrete joints
033100-010	Dumbbell Waterstop	PD	10/13/2014	2	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Product information for waterstop embedded in concrete between joints
033100-011	Nonshrink Grout	PD	10/13/2014	2	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Product information for grouting for structural elements
033100-012	Injectable Epoxy	PD	10/16/2014	1	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Product information for injectable epoxy for the installation of threaded rods into concrete
033100-013	Hotel Reinforcing	SD	10/28/2014	2	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop drawings for reinforcements requesting information on a specific location

KEY: PD= Product Data   SD= Shop Drawings

033100-014	Reinforcing Steel N-Line	SD	10/29/2014	1	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop drawings for reinforcement along N-line
033100-015	Concrete Mix Design	PD	10/29/2014	1	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Product information for 4000 psi concrete mix
033100-016	Elevated Pits 2 & 3	SD	10/29/2014	1	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop drawings for pit reinforcement calling GC to veryfy requirements with approved elevator manufacturer
331000-001	Service Tubing	PD	7/17/2014	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved.	Product data of plumbing and refrigeration service tubes.
331000-002	Resilient Wedge Gate Valves	PD	7/17/2014	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Product data of resilient wedge gate valves for service tubing.
331000-003	Curb and Corporation Stops	PD	7/17/2014	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Product data of curb and corporation metal stops for service tubing.
333000-001	PVC Pipe	PD	7/17/2014	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Product data of PVC pipes and connections for service tubing.
033100-017	Polyethelyne Moisture Barrier and Seam Tape	PD	12/24/2014	12	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Product data for vapor barrier for slabs.
033100-018	P1 SOD Reinforcing	SD	1/5/2015	3	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Shop drawings for slab on deck reinforcement.
033100-019	Slab Placement Plan	SD	1/16/2015	4	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop drawings for slab plavcement with additional notes.
033100-020	Reinforcing of Existing Wall on Plaza Level	SD	1/16/2015	3	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop drawings to reinforce wall at plaza level.
033100-021	Added reinforcement at GB-3 for Pen	SD	1/21/2014	1	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Additional reinforcement for concrete being penetrated by shaft.
051200-004	Piece Drawing PH.2-6	SD	11/25/2014	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted - Resubmission Required	Shop Drawings for steel members along with phasing plan. Resubmission based upon coordination and beam penetration locations.
051200-005	Piece Drawing PH.7-11	SD	12/8/2014	22	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop Drawings for steel members along with phasing plan.
051200-006	Piece Drawing PH.12-16	SD	12/22/2015	9	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop Drawings for steel members along with phasing plan.
051200-007	Piece Drawing PH.17-20	SD	1/12/2015	7	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop Drawings for steel members along with phasing plan.
051200-008	Piece Drawing PH.21-24	SD	1/26/2015	14	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop Drawings for steel members along with phasing plan.
053000-001	Metal Decking	SD	12/10/2015	26	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Shop drawings for the metal decking of the concrete slab. GC to coordinate with MEP.
071425-001	Procore Fluid Applied Waterproofing	PD	1/26/2015	7	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Fluid applied waterproofing for below grade structures.
071425-002	Procore Fluid Applied Waterproofing	PD	1/26/2015	7	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Pre-fabricated geocomposite drain for us as combined drainage and protection layer with Grace waterproofing membranes.

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071816-001	AutoGuard Traffic Deck Coating	PD	1/26/2015	7	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Base coating for concrete.
072100-001	Thermal Rigid Insulation	PD	12/24/2015	5	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specification for rigid insulation.
072700-001	CCW 705 Self Adhesive Membrane	PD	1/26/2015	7	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on air, water, and vapor barriers.
072700-002	Auxiliary Materials	PD	1/26/2015	7	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Accesory product used in conjunction with Air & Moisture Barrier.
079000-001	Sealants	PD	1/26/2015	7	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on silicon sealant for joint applications.
096500-004	Latex Underlayment Ardex Geather Finish	PD	1/29/2015	8	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on self-drying, cement-based finish underlayment
096500-005	Vinyl Tile	PD	1/29/2015	7	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on vinyl composition tile for flooring.
096500-006	Adhesives	PD	1/29/2015	7	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on clear thin spread adhesive for tile flooring.
096500-007	VCT Maintenace Data and Warranty	PD	1/29/2015	8	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Warranty for vinyl composition tile flooring.
096500-009	Johnsonite Reducer Molding	PD	1/29/2015	8	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on reducer moldings for flooring.
096500-010	Johnsonite Rubber Wall Base	PD	1/29/2015	8	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on rubber wall base.
211000-001	Pipe and Fittings	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications for fire sprinkle pipe and fittings.
211000-002	Sprinkler Heads	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specifications on automated sprinkler heads with a note indicating chrome plated finish.
211000-003	Valves - Butterfly Valve w/ Tamper	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on weatherproof actuator valve.
211000-004	Check Valve	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on checking valves for water pressure.
211000-005	Valves - Dry Alarm Check Valve and Trim	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on low, differential, latched clapper valve to separate water supplies from dry-pipe systems.
211000-006	Valves - Pre-Action Valves and Smoke Detector	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specifications on valve controlling water into pre-action sprinklers, and smoke detectors. Note sequencing of operation.
211000-007	Valves - Ball Valve	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specifications on brass valves for piping.
211000-008	Valves - Test N Drain	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on brass valves for piping.
211000-009	Valves - Double Check Valve Assembly	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on Bbackflow preventerv valve.

KEY: PD= Product Data SD= Shop Drawings

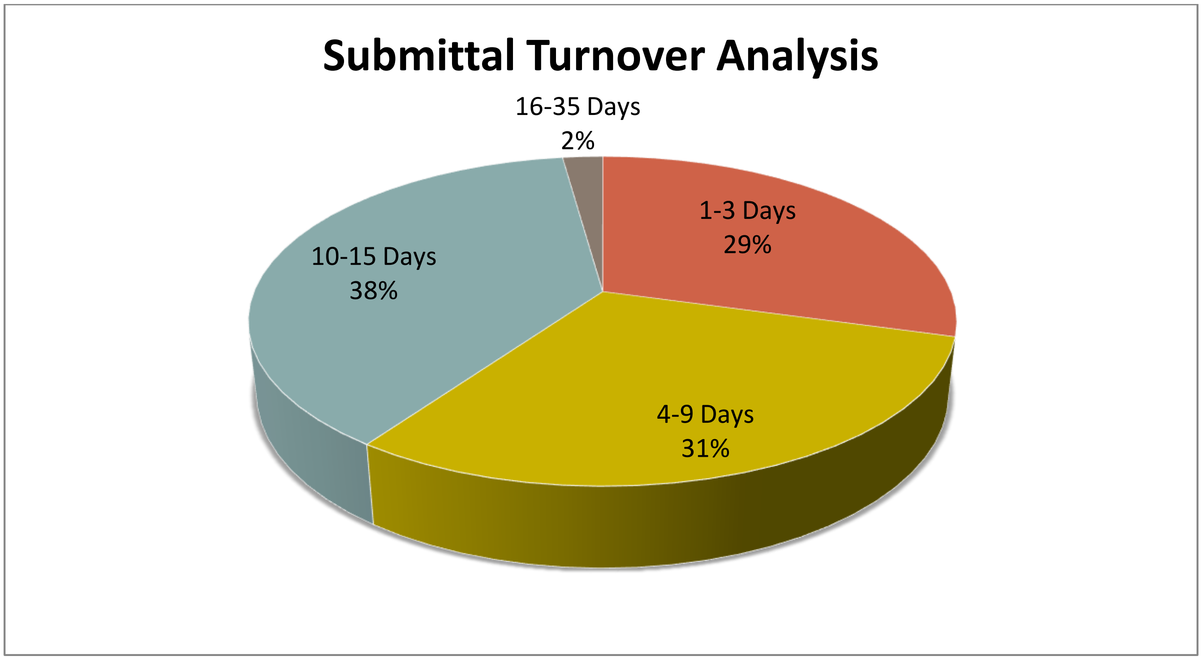
211000-010	Hangers and Supports	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on hangers to hold piping.
211000-011	Initiating Devices - Supv and Alarm Pressure Switches	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on alams for pressure switches to indicate discharge by sprinkler.
211000-012	Initiating Devices - Water Flow Switch	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on water flow detector.
211000-013	Notification Devices - Electric Bell	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specfication on low current electric alarm bells.
211000-014	Hose Connections	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specification on adaptors, bushings, angle valves.
211000-015	Hose Connections - Fire Department Connection	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted - Resubmission Required	Specifications on inlet connections for water supply system. Resubmission to comply to City standards.
211000-016	Air Compressor	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specifications on oilless tank mounted compressors.
211000-017	FireStopping	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on intumescent sealant for connections.
211000-018	Wall Plates and Escutcheons	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on settl hinged wall plate for pipe penetrations.
211000-019	Pipe and Fittings - Underground Service Entrace	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on ductile iron pipes.
211000-021	Pipe and Fittings - East Garage	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications for fire sprinkler pipe and fittings.
211000-022	East Garage Sprinkler Heads	PD	2/6/2015	3	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specifications on automated sprinkler heads with a note indicating chrome plated finish.
211000-023	Valves - East Garage Butterfly Valve w/ Tamper	PD	2/6/2015	3	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on weatherproof actuator valve.
211000-024	Valves - East Garage Dry Alarm Check Valve and Trim	PD	2/6/2015	3	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on low, differential, latched clapper valve to separate water supplies from dry-pipe systems.
211000-025	Valves - East Garage Ball Valve	PD	2/6/2015	3	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specifications on brass valves for piping.
211000-026	Valves - East Garage Test N Drain	PD	2/6/2015	3	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on brass valves for piping.
211000-027	East Garage Hangers and Supports	PD	2/6/2015	3	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on hangers to hold piping.
211000-028	East Garage Initiating Devices - Water Flow Switch	PD	2/6/2015	3	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on water flow detector.
211000-029	East Garage Initiating Devices - Supv and Alarm Pressure Switches	PD	2/6/2015	3	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on alams for pressure switches to indicate discharge by sprinkler.
211000-030	East Garage Air Compressor	PD	2/6/2015	3	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specifications on oilless tank mounted compressors.

KEY: PD= Product Data SD= Shop Drawings

211000-031	East Garage FireStopping	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on intumescent sealant for connections.
221000-001	Pipe and Fittings - Service Weight	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on cast iron soil pipe and fittings for underground applications.
221000-002	Pipe and Fittings - No Hub	PD	1/7/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on cast iron soil pipe and fittings for above ground applications.
221000-004	Sub-service Drain	PD	1/30/2015	6	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on overflow standpipe roof drain.
221000-007	Trench Drain	PD	1/30/2015	6	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specifications on interlocking drain system.
221000-008	Promenade Drain	PD	1/30/2015	10	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specifications on heavy duty floor drain.
221000-009	Floor Cleanout	PD	1/30/2015	6	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved	Specficications on floor cleanouts with adjustable tops.
223000-001	Drainage Ejector Pump	PD	2/5/2015	4	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specifications on bronze waste water pump.
223000-002	Ground water ejector Pump	PD	2/5/2015	4	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specifications on 4" submersible heavy duty pump
223000-003	Garage Drainage Ejector Pump	PD	2/5/2015	4	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specifications on 2" submersible heavy duty pump
223000-004	Sewer Ejector Pump	PD	2/5/2015	4	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specifications on 3" submersible slicer pump
261000-001	Vector Mapping Handhole	PD	1/21/2015	13	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted	Specficications on electrical vector mapping hanhole. Noted to confirm size and quantity.
314000-001	Underpinning - at C.L. N	SD	7/30/2014	14	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted - Resubmission Required	Shop drawings for underpinning excavation and support for initial work.
314000-002	Schnabel Hotel Area Underpinning	SD	1/21/2015	6	SUB>GC>DES>Sub of DES>DES>GC>SUB	Approved as noted - Resubmission Required	Shop drawings for hand excavating underpinning piers.

KEY: PD= Product Data   SD= Shop Drawings

Appendix J: Submittals Turnover Analysis



Appendix K: Lean Survey Questions

Q1.
In order to evaluate the lean concepts, our team has created this evaluation system to look at different aspects including communication, prefabrication, inventory, just in time delivery, kitting and 5S, and pull system. We would really appreciate it if you could take 15 minutes to take the survey and evaluate the concepts based on your knowledge and experience.

Q9. Please provide the position you hold in the project

test

COMMUNICATION: Please evaluate the communication* for the different activities by using a rating of 1 to 5, with 1 meaning very poor communication and 5 being excellent communication.

*In lean concepts, communication is defined as the interactions between the key players through various mediums (email, phone, face-to-face, intermediaries, etc.) which align them with their end goal of maximizing the end value and decreasing waste.

	N/A	Very Poor	Poor	Fair	Good	Excellent
How effective have you been communicating with all parties to create your CPM Schedule?	○	○	○	○	○	○
How effective have you been communicating with all parties to create your 4 Week Look-Ahead?	○	○	○	○	○	○
How effective have you been communicating with all your Subcontractors?	○	○	○	○	○	○
How would you rate your submittal process?	○	○	○	○	○	○
How would you rate your RFI process?	○	○	○	○	○	○
How would you rate your Change Request process?	○	○	○	○	○	○
How much influence did the delay in GMP approval influence your response above?	○	○	○	○	○	○
How effective have your communications been with vendors, suppliers, and subcontractors, in terms of material deliveries?	○	○	○	○	○	○
How effectively have you communicated your safety goals to your subcontractors?	○	○	○	○	○	○
How effectively have your subcontractors communicated their safety requirements and issues?	○	○	○	○	○	○
How effective have your been communicating during your procurement process? (vendors, suppliers, subcontractors)	○	○	○	○	○	○

How would you rate the overall

How would you rate the overall communication of this project?	○	○	○	○	○	○

PREFABRICATION: Please evaluate the impact of prefabrication* in each activity by using a rating of 1 to 5, with 1 meaning very low and 5 being very high.

*Prefabrication is defined as assembling outside of the project site to save time and space.

	N/A	very low	low	medium	high	very high
How much prefabrication did the design of the garage include?	○	○	○	○	○	○
How much prefabrication did the design of the garage allow for?	○	○	○	○	○	○
How much savings in time has prefabrication allowed in your CPM schedule?	○	○	○	○	○	○
How much savings in money has prefabrication allowed in your CPM schedule?	○	○	○	○	○	○
How much savings in space has prefabrication allowed for on site?	○	○	○	○	○	○
How much prefabrication do you anticipate to do with the shell construction (steel)?	○	○	○	○	○	○

INVENTORY: Please evaluate the use of inventory* by using a rating of 1 to 5, with 1 meaning very low and 5 being very high.

*In lean terms, inventory refers to all the materials that are not being utilized and stored on site. Lean aims to have only the materials that are required in order to accelerate the process, as well as, increase the working space and organization on site.

	N/A	very low	low	medium	high	very high
How much effort do you put into having only the necessary inventory on site for the next 4 weeks at a time?	○	○	○	○	○	○
How efficiently has the inventory been organized on site?	○	○	○	○	○	○
How much inventory are you storing/keeping on site?	○	○	○	○	○	○
How much effort do you put into having all the necessary equipment on site?	○	○	○	○	○	○
Have submitals caused to fall behind with the materials needed on site?	○	○	○	○	○	○
How effective have you been on having all the concrete necessary for foundations; on site, on spec, and on time?	○	○	○	○	○	○
How important will inventory (as defined above) be during the shell (steel) construction?	○	○	○	○	○	○
How effective was the coordination for trucking materials in and out of site during the site work phase?	○	○	○	○	○	○

JUST IN TIME: Please evaluate the efficiency of the just in time* delivery of materials by using a rating of 1 to 5, with

1 meaning very poor and 5 being excellent efficiency.

*In Lean, Just in Time is defined as the delivery of the materials at the right moment in order to reduce waste, time, and cost. The goal is to reduce the amount of inventory and deliver the materials when needed.

	N/A	very poor	Poor	Fair	Good	Excellent
With limited space to work on site, how has just in time delivery of materials impacted the staging on site?	○	○	○	○	○	○
How much have you considered just in time deliveries to minimize negative impacts with your accessibility on site?	○	○	○	○	○	○
What impact has just in time delivery had on the equipment you have rented?	○	○	○	○	○	○
What impact has just in time delivery had on the equipment Consigli owns?	○	○	○	○	○	○

KITTING & 5S: Please evaluate the organization of supplies based on the concept of Kitting* and 5S** by using a rating of 1 to 5, with 1 meaning very poor and 5 being excellent organization.

*Kitting reduces the inventory levels and increases the operator's effectiveness. It decreases the space needed for supplies storage and ensures ease of access to supplies.
**5S includes: (1) sorting, (2) straightening, (3) shining, (4) standardizing, and (5) sustaining.

	N/A	very poor	Poor	Fair	Good	Excellent
How effective have you been applying these concepts when storing supplies in your conex boxes on site?	○	○	○	○	○	○
How effective have you been applying these concepts when storing supplies in your field office?	○	○	○	○	○	○
How effective do you think your contractors have been at applying the concepts above?	○	○	○	○	○	○

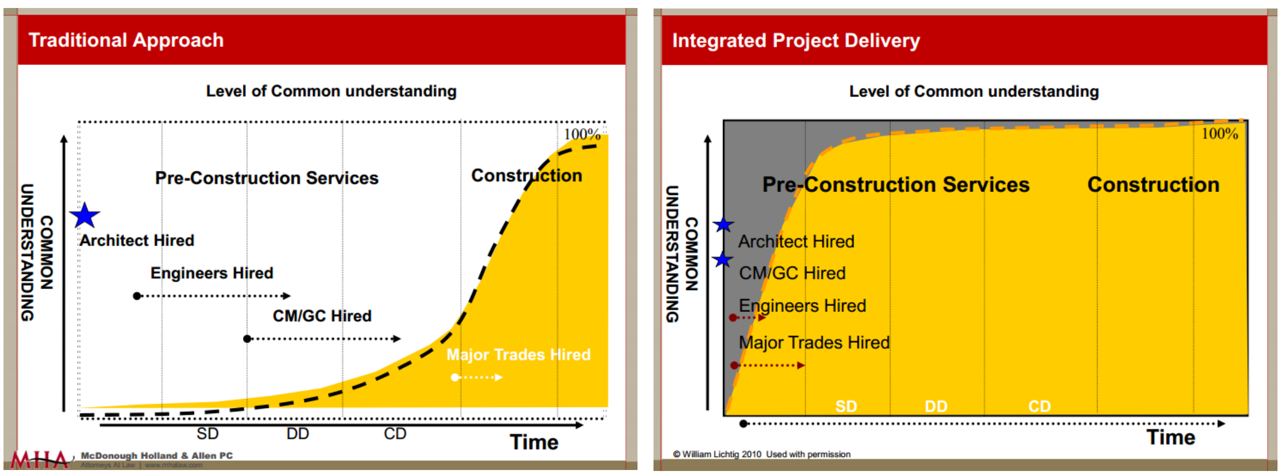
PULL SYSTEM: Please evaluate the use of the "Pull System"* in the various activities by using a rating of 1 to 5, with 1 meaning very low and 5 being very high.

*This system is based on the "Last Planner Method" (LPM) instead of the common scheduling method of CPM. Instead of pushing the schedule out more in order to accommodate for more time to complete tasks, you act on the reasons for those failures and work with everyone to improve them and avoid repeating the same mistake to keep the project on schedule.

	N/A	very low	low	medium	high	very high
How much have you utilized pull on your CPM schedule?	○	○	○	○	○	○
How much have you utilized pull on your 4 week look ahead?	○	○	○	○	○	○
How much do you enforce/require your subcontractors to utilize the pull system?	○	○	○	○	○	○
How much did you integrate your staging on site with the pull system?	○	○	○	○	○	○
How much impact have change requests had on your ability to	○	○	○	○	○	○

Appendix L: Lean Concepts Research

(1)Communication and Level of Understanding - Often times, effective communication between the different counterparts in a construction project is lacking, which leads to setbacks in the production, delivery of materials, and goal completion, amongst others. The current practice encourages participants to perform in their own silos and areas of work, but sometimes it does not align them towards the end goal of maximizing the end value and decreasing waste. In many cases, productivity improvements in each silo lead to even more unpredictable workflow because collaboration is limited and as mentioned before, lean construction should be applied to the entire process of a project, and not just a specific section. The figure below shows the traditional approach (left) to a project where the different silos are hired as the project progresses. However, a lean project would involve all the key players since the first phase in order to reduce waste in the overall project, as depicted in the graph on the right.



Traditional Approach vs Lean Approach

Our team will evaluate the current project design and management based on this concept to determine the best practices for communication and understanding across all the key players in the project. Recommendations for improvement on this aspect will be provided.

(2) Prefabrication - In many projects, pre-fabricating certain objects or using materials that can be assembled outside of the project site, can significantly save time and space. Prefabrication can lead to better safety, a cleaner project site which reduces waste, and more space to assemble the parts; all which can benefit with the construction time and efficiency of certain activities. The construction of the parking garage is facing a big challenge with the space available at the project site to hold materials and progress on the construction, due to its location in downtown. The team will evaluate the impact that utilizing prefabricated concrete can have on the time and space at the project site, as well as the improvement on efficiency it may have.

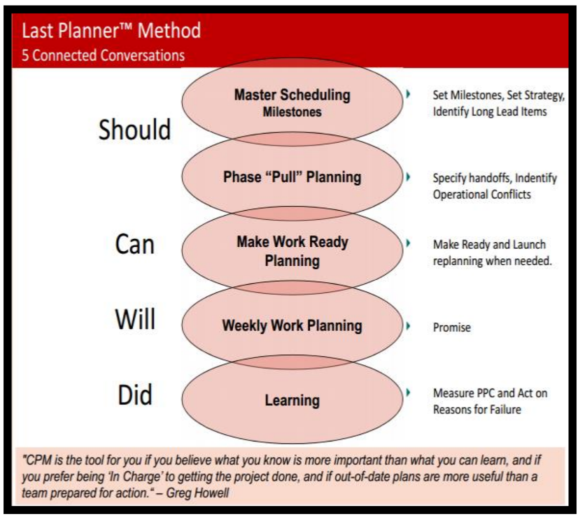
(3) Inventory - Having too much inventory is always an issue because it is considered waste and reduces the workspace available. With the current design of steel, many of the materials will be received and stored on site as they get used and placed on their respective location. However, with the alternative design of prestressed concrete, prefabrication will be an advantage and can potentially improve and reduce the amount of inventory. The site does not have much space available to hold the materials and machinery, and still operate efficiently while not disturbing the operations in the downtown area. The team will analyze the inventory on-site based on the two designs and determine which one is more effective.

(4) Just in Time - Delivery of the materials at the right moment is crucial for the efficiency of the project and to reduce waste, time, and cost. With the goal of reducing the amount of inventory, just in time delivery of materials will be essential to utilize the materials when needed (pull), rather than having them on site. This would give us no laydown and no truck staging outside of the site, a crucial element in this project due to its location. With a material such as prestressed concrete, the delivery of the slabs when needed will impact the efficiency and progress of the project. We will evaluate the delivery of materials for both designs and determine which are the critical elements for each activity.

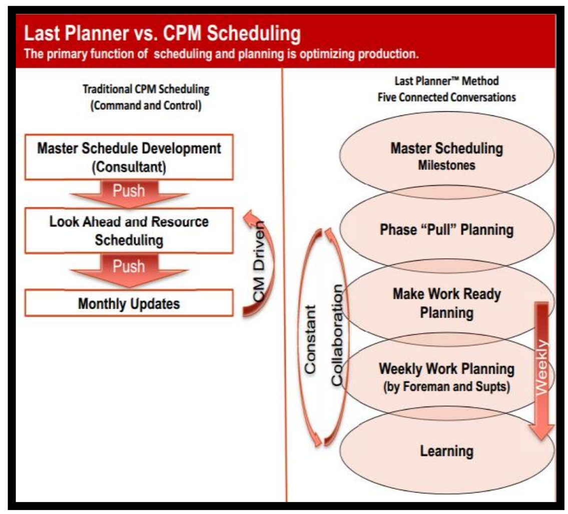
(5) Kitting and 5S - When applying lean concepts to a process, 5S can be a simple solution to a lot of drawbacks. The five S's include: (1) sort, (2) straighten, (3) shine, (4) standardize, and (5) sustain. Sorting allows you to go through everything in the work area to keep what is necessary and discard the materials that are not used. Straightening and shining includes identifying items that go together, organize them, and arrange them for an effective retrieval. Standardizing and sustaining will allow you to determine the best practices to not fall into old habits and educate people about maintaining those standards. Kitting reduces the inventory levels and increases the operator's effectiveness. It decreases the space needed for material storage, reduces the overall deliveries, and ensures ease of access to materials. Our team will evaluate the project site in terms of their effectiveness of usage and storage of materials on site. Based on the outcomes and performance, we will provide recommendations to improve such practices. Better storage and organization of their materials can impact the staging on site, accessibility to the site, and the equipment usage and rental.

(6) Pull system - The pull system is perhaps the most common concept in Lean process improvement. This system is based on the "Last Planner Method" (LPM) instead of the common scheduling method of CPM. This method is designed to "integrate 'should-can-will-did' planning and activity delivery of a project". (Sayer, 2012) The LPM empowers the person who is making the job assignments to direct and communicate with the workers, enabling a constant communication vehicle with everyone. One of the key

components to the LPM is the learning aspect of it, where you identify any failures and the reasons behind it. Instead of pushing the schedule out more in order to accommodate for more time to complete tasks, you act on the reasons for those failures and work with everyone to improve them and avoid repeating the same mistake to keep the project on schedule. Our team will be doing an evaluation of the current and proposed schedule based on the LPM concepts to identify what type of system is being utilized and if there are any areas for improvement in the schedules. The figures below illustrate the Last Planner Method and compares it to the traditional CPM scheduling.



The Last Planner Method outline (n.a., 2009)



Last Planner Method vs. Traditional CPM Scheduling (n.a., 2009)

Appendix M: Lean Survey Responses

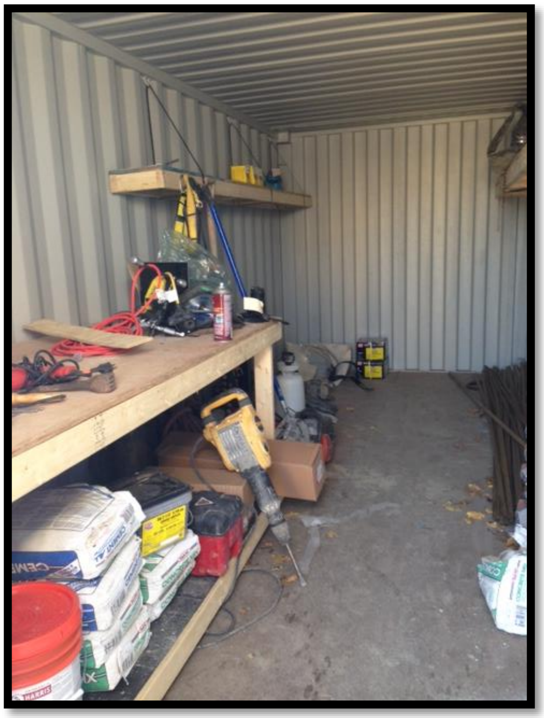
...cation		
very low	very low	low
low	low	medium
low	low	low
1	1	2
2	2	3
2	2	2
1.67	1.67	2.33
		1.777778

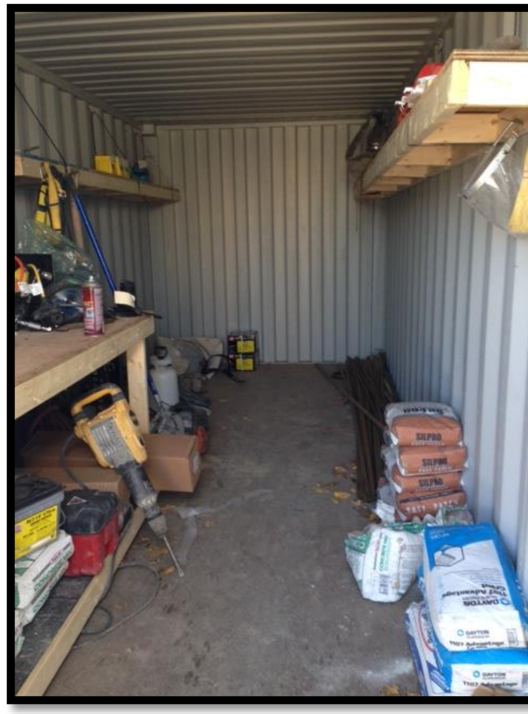
	Communication												Prefabrication					
Project Engineer	Excellent	Excellent	Excellent	Good	Good	Good	Poor	Good	Excellent	Good	Good	Good	very low	very low	very low	very low	very low	very low
Project Manager	Good	Good	Good	Good	Good	Good	Fair	Excellent	Excellent	Good	Good	Good	low	low	low	low	low	low
SUPERINTENDENT	Good	Good	Good	Excellent	Excellent	Excellent	Excellent	Good	Good	Fair	Good	Good	high	low	very low	very low	very low	low
Project Engineer	5	5	5	4	4	4	2	4	5	4	4	4	1	1	1	1	1	1
Project Manager	4	4	4	4	4	4	3	5	5	4	4	4	2	2	2	2	2	2
SUPERINTENDENT	4	4	4	5	4	5	5	4	4	3	4	4	4	2	1	1	1	2
AVERAGE	4.33	4.33	4.33	4.33	4.00	4.33	3.33	4.33	4.67	3.67	4.00	4.00	2.33	1.67	1.33	1.33	1.33	1.67
TOTAL AVERAGE PER CONCEPT												4.138889						1.611111

Pull System		
low	medium	medium
low	low	medium
very low	very low	very low
2	3	3
2	2	3
1	1	1
1.67	2.00	2.33
		1.933333

	Inventory								Just in Time				KITTING & 5S			Pull System				
Project Engineer	medium	high	low	very high	very low	very high	very high	very high	Fair	Good	Good	Fair	Fair	Good	Fair	low	medium	high	medium	low
Project Manager	high	high	medium	high	very low	high	high	high	Good	Good	Good	Fair	Good	Good	Good	low	low	low	low	low
SUPERINTENDENT	high	medium	medium	high	very low	very high	very high	very high	Fair	Good	Good	Fair	Excellent	Fair	Fair	very low	very low	very low	very low	very low
Project Engineer	3	4	2	5	1	5	5	5	3	4	4	3	3	4	3	2	3	4	3	2
Project Manager	4	4	3	4	1	4	4	4	4	4	4	3	4	4	4	2	2	2	2	2
SUPERINTENDENT	4	3	3	4	1	5	5	5	3	4	4	3	5	3	3	1	1	1	1	1
AVERAGE	3.67	3.67	2.67	4.33	1.00	4.67	4.67	4.67	3.33	4.00	4.00	3.00	4.00	3.67	3.33	1.67	2.00	2.33	2.00	1.67
TOTAL AVERAGE PER CONCEPT								3.666667				3.583333			3.666667					1.933333

Appendix N: Conex Boxes



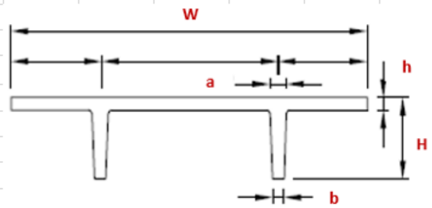


Inside the Conex Box

Outside the Conex Box

Appendix O: Alternative Design – Prestressed Double Tee Beam Zone A

Width,W (in) =	180
Height,H (in) =	30
b	7.75
a	9.75
h	4
H-h	26
Length (in) =	360
cb	22.38326
Ct	7.616738
Area (in^2) =	1175
Inertia (in^4) =	85138.07
Section Modulus,Sb (in^3) =	3803.649
Section Modulus,St (in^3) =	11177.76
Volume/Surface (in) =	2.599035



Shape	I	A	y	A*y	d	A*d²
	in⁴	in²	in	in³	in	in³
Flange	960	720	28	20160	5.616738	22714.37
Web 1	12760.04	227.5	13.49524	3070.167	8.888024	17971.81
Web 2	12760.04	227.5	13.49524	3070.167	8.888024	17971.81
Sum =	26480.07	1175		26300.33		58658

1969520

e @ transfer Length (in) =	1.195
Msw @ transfer length (k-in)	565.2648

Properties of Concrete

fc'(psi)=	6500	
fci(psi)=	5000	
Density of Conrete (lb/ft^3) =	150	
Ec' =	4887733.37	$33 \times w_c^{1.5}\sqrt{f_c'}$
Eci =	4286825.749	$33 \times w_c^{1.5}\sqrt{f_c'}$

Properties of Prestressing Steel

fpu (ksi) =	270	
Number of Strands =	16	
Aps (in^2) =	0.217	
Eps (psi) =	2.85E+07	$0.7 * A_{ps} * \#of\ strands * f_{pu}$
Pi (k) =	656.208	

Section Properties

Rectangular Beam

Width,b (in) =	180				
Height,h (in) =	30				
Length (in) =	360				
Area (in^2) =	1175	$b \times h$			
Inertia (in^4) =	85138.07083		$\frac{1}{12}bh^3$		
cb=ct (in) =	22.38326241	$\frac{I}{h/2}$		ct=	7.616737589
Section Modulus,Sb (in^3) =	3803.648872			St=	11177.7608
Volume/Surface (in) =	2.599035058				

Loads

Live Load (k/f) =	3.75
Dead Load (k/f) =	3.375
Self Weight (k/ft) =	1.223958333

Prestress Losses

Elastic Shortening

Kes=	1	
Kcir=	0.9	
e (in)=	10.5	
Msw (k-in) = $\frac{w_{sw} \times L^2}{8}$	1652.34375	
fcir (psi)=	1063.629421	$f_{cir} = K_{cir}\left(\frac{P_i}{A_g} + \frac{P_i e^2}{I_g}\right) - \frac{M_{sw}e}{I_g}$
ES (psi) = $ES = \frac{K_{ES}E_{PS}f_{cir}}{E_{ci}}$	7071.301768	

Creep of Concrete

Kcr=	2	
Mdl (kp-in) =	4556.25	
fcds (psi) =	561.9181235	$\frac{M_{DL}e}{I}$
CR (psi) =	5850.880517	$CR = K_{CR}\left(\frac{E_{PS}}{E_c'}\right)(f_{cir} - f_{cds})$

Shrinkage of Concrete

Ksh =	1	
Relative Humidity (RH) =	75	Design Aid 4.11.12
SH (psi) =	4931.408261	

$SH = (8.2 \times 10^{-6})K_{SH}E_{PS}(1 - 0.06V/S)(100 - RH)$

Relaxation of Tendons

Kre=	5000	From Table 5.7.1
J=	0.04	From Table 5.7.1
fpi=Pi/Aps	189	
fpi/fpu	0.7	
C=	0.75	Table 5.7.2
RE (psi) =	3214.392284	$RE = [K_{RE} - J(ES + CR + SH)]C$

TOTAL LOSS (PSI)=	21067.98283	11.14708086
JACKING FORCE AFTER LOSSES (k) =	583.0599636	

$P_i - (TL * \#\ of\ strands * A_{ps})$

Critical Stress Calculations

Fse = (0.7 x fpu) ksi	189	
Tl= (Transfer Length -in) =	34	Design Aid 15.3.4

Ps forces after losses

Transfer @ Release		
Msw,T (k-in)=	565.2647569	$\frac{W_{sw} \times T_L}{2} \times (L - T_L) * 12$
fcir(ksi)=	1.197697874	$f_{cir} = K_{cir}\left(\frac{P_i}{A_g} + \frac{P_i e^2}{I_g}\right) - \frac{M_{sw,T} e}{I_g}$
EST (ksi)=	7.962625821	
Loss EST (k)	27.64623685	$(ES_T \times A_{ps} \times \#of\ strands)$
Po1(k)=	628.5617631	$P_i - ES_T$

Midspan @ Release		
Msw,M (k-in)=	1652.34375	
ESM (ksi)=	7.071301768	
Loss ESM (k)	24.55155974	$ES_M \times A_{ps} \times \#of\ strands$
Po2(k)=	631.6564403	

Midspan @ Service	
Msw (k-in)=	1652.34375
MSDL (k-in)=	4556.25
MLL (k-in)=	5062.5
Po3(k)=	590.5872

	Transfer @ Release		Midspan @ Release		Midspan @ Service	
****units are in psi*****	fb	ft	fb	ft	fb	ft
Po/A	534.9461814	534.9461814	537.5799492	537.5799492	502.6274043	502.6274043
Po.e/S	1735.149257	-590.449074	1743.692135	-593.3561062	1630.320203	-554.777089
Msw/S	-148.6111826	50.57048251	-434.4101692	147.8242181	-434.4101692	147.8242181
Msdl/S	0	0	0	0	-1197.862935	407.6174184
Mll/S	0	0	0	0	-1330.958816	452.9082427
Total	2121.484255	-4.932410128	1846.861915	92.04806109	-830.284313	956.2001942
PCI Limits	3500	-530.3300859	3500	-530.3300859	-967.4709298	4550
Limit Check	In Limits	Class U	In Limits	Compression OK	Class U	In Limits

Deflection Calculations

Camber (in)=	0.29439173	$\frac{P_{02} e L^2}{8E_{ci} I_g}$
Def due to SW (in) =	0.06111876	$\frac{5w_{sw} L^4}{384E_{ci} I_g}$
Def due to SDL (in) =	0.147812105	$\frac{5w_{DL} L^4}{384E_c' I_g}$
If Uncracked		
Def due to LL (in) =	0.164235672	$\frac{5w_{LL} L^4}{384E_c' I_g}$

If Uncracked

	(1) Release	Multiplier	(2) Erection	Multiplier	(3) Final
Camber	0.294	1.800	0.530	2.450	0.721
wsw	-0.061	1.850	-0.113	2.700	-0.165
wsd			-0.148	3.000	-0.443
wll					-0.164
			0.269		-0.051
Total Deflection	0.320				

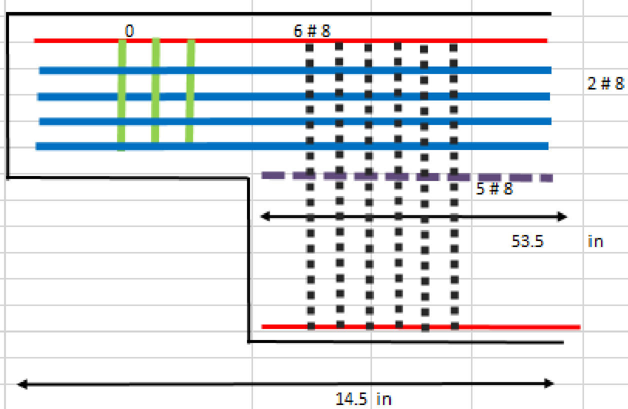
Connection Design

fy (ksi) =	60	Assume
fys (ksi) =	60	
wu (k/f) =	13.53	See Load Calculations
Vu (k) =	202.95	
Nu (k) =	40.59	$V_U = \frac{W_U \times L}{2}$ $\quad N_U = 0.2 \times V_U$
Lambda =	1	

$$W_U = 1.2(SW + DL) + 1.6LL$$

Reinforced Concrete Bearing

a (in) =	8			
h (in) =	15.5		$A_S = \frac{1}{\phi f_y}\left[V_U \frac{a}{d} + N_U \frac{h}{d}\right]$	1/2 in Grout for connection
d (in) =	14			
As (in) =	3.575785714			
M =	1	Table 5.3.1		
Me =	10.31042129		$\mu_e = \frac{\phi \times 1000 \times \lambda \times b \times h \times \mu}{V_U \times 1000}$	
Me =	2.9			
Max Me =	2.9	Table 5.3.1		
As' (in^2) =	1.938781609		$A'_S = \frac{2V_U}{3\phi f_y \mu_e} + \frac{N_U}{\phi f_y}$	
Critical As (in^2)	3.575785714			
Use ____#____ BARS	5 # 8			
As practical (in^2)=	3.95	Ok	$A_h = 0.5\left[A_S - \frac{N_U}{\phi f_y}\right]$	
Ah (in^2) =	1.524			
Use ____#____ U BARS	2 # 8			
Ah practical (in^2)=	1.58	Ok		
Ash (in^2) =	4.51		$A_{sh} = \frac{V_U}{\phi f_y}$	
Use ____#____ STIRRUPS	6 # 8			
Ash practical (in^2)=	4.74	Ok		
Av (in^2) =	-1.131148254		$A_V = \frac{1}{2f_y}\left[\frac{V_U}{\phi} - \frac{2bd\lambda\sqrt{f_c'}}{1000}\right]$	
Use ____#____STIRRUPS				
Av practical (in^2)=	0	Ok		
Chech Vn (k) =	375.8533429		$V_N = \phi\left(A_V f_y + A_h f_y + \frac{2bd\sqrt{f_c'}}{1000}\right)$	
	Ok			
Ld Ah (in) =	14.5	Design Aid 15.4.4		
Ld As (in) =	37.5	Design Aid 15.4.4		
Anchor for As (in) =	53.5		$L_d = H - d + l_d$	



Appendix P: Alternative Design – Prestressed Double Tee Beam Zone C

Properties of Concrete

fc'(psi)=	6500	
fci(psi)=	5000	
Density of Conrete (lb/ft^3) =	150	
Ec' =	4887733.37	$33 \times w_c^{1.5}\sqrt{f_c'}$
Eci =	4286825.75	$33 \times w_c^{1.5}\sqrt{f_c'}$

Properties of Prestressing Steel

fpu (ksi) =	270	
Number of Strands =	12	
Aps (in^2) =	0.217	
Eps (psi) =	2.85E+07	$0.7 * A_{ps} * \#of\ strands * f_{pu}$
Pi (k) =	492.156	

Section Properties

Rectangular Beam

Width,b (in) =	180		
Height,h (in) =	30		
Length (in) =	360		
Area (in^2) =	1175	$b \times h$	
Inertia (in^4) =	85138.0708		$\frac{1}{12}bh^3$
cb=ct (in) =	22.3832624		ct= 7.616737589
Section Modulus,Sb (in^3) =	3803.64887	$\frac{I}{h/2}$	St= 11177.7608
Volume/Surface (in) =	2.59903506		

Loads

Live Load (k/f) =	1.5
Dead Load (k/f) =	3.375
Self Weight (k/ft) =	1.22395833

Prestress Losses

Elastic Shortening

Kes=	1	
Kcir=	0.9	
e (in)=	10.5	
Msw (k-in) =	1652.34375	$\frac{w_{sw} \times L^2}{8}$
fcir (psi)=	746.776557	$f_{cir} = K_{cir}\left(\frac{P_i}{A_g}+\frac{P_i e^2}{I_g}\right)-\frac{M_{sw}e}{I_g}$
ES (psi) =	4964.77653	$ES = \frac{K_{ES}E_{ps}f_{cir}}{E_{ci}}$

Creep of Concrete

Kcr=	2	
Mdl (kp-in) =	4556.25	
fcds (psi) =	561.918124	$\frac{M_{DL}e}{I}$
CR (psi) =	2155.79081	$CR = K_{CR}\left(\frac{E_{PS}}{E_c'}\right)(f_{cir} - f_{cds})$

Shrinkage of Concrete

Ksh =	1	
Relative Humidity (RH) =	75	Design Aid 4.11.12
SH (psi) =	4931.40826	

$$SH = (8.2 \times 10^{-6})K_{SH}E_{ps}(1 - 0.06V/S)(100 - RH)$$

Relaxation of Tendons

Kre=	5000	From Table 5.7.1
J=	0.04	From Table 5.7.1
fpi=Pi/Aps	189	
fpi/fpu	0.7	
C=	0.75	Table 5.7.2
RE (psi) =	3388.44073	$RE = [K_{RE} - J(ES + CR + SH)]C$

TOTAL LOSS (PSI)=	15440.4163	8.169532453
JACKING FORCE AFTER LOSSES (k) =	451.949156	$P_i - (TL * \#\ of\ strands *\ A_{ps})$

Critical Stress Calculations

Fse = (0.7 x fpu) ksi	189	
Tl= (Transfer Length -in) =	34	Design Aid 15.3.4

Ps forces after losses

Transfer @ Release

Msw,T (k-in)=	565.264757	$\frac{W_{sw} \times T_L}{2} \times (L - T_L) * 12$
fcir(ksi)=	0.88084501	$f_{cir} = K_{cir}\left(\frac{P_i}{A_g}+\frac{P_i e^2}{I_g}\right)-\frac{M_{sw,T}e}{I_g}$
EST (ksi)=	5.85610058	
Loss EST (k)	15.2492859	$(ES_T \times A_{ps} \times \#of\ strands)$
P01(k)=	476.906714	$P_i - ES_T$

Midspan @ Release

Msw,M (k-in)=	1652.34375	
ESM (ksi)=	4.96477653	
Loss ESM (k)	12.9282781	$ES_M \times A_{ps} \times \#of\ strands$
P02(k)=	479.227722	

Midspan @ Service

Msw (k-in)=	1652.34375
MsDL (k-in)=	4556.25
MLL (k-in)=	2025
P03(k)=	442.9404

	Transfer @ Release		Midspan @ Release		Midspan @ Service	
****units are in psi*****	fb	ft	fb	ft	fb	ft
Po/A	405.878055	405.8780545	407.8533804	407.8533804	376.9705532	376.970553
Po.e/S	1316.50441	-447.9895919	1322.911564	-1322.911564	1222.740152	-1222.7402
Msw/S	-148.611183	50.57048251	-434.4101692	434.4101692	-434.4101692	434.410169
Msdl/S	0	0	0	0	-1197.862935	1197.86293
Mll/S	0	0	0	0	-532.3835265	532.383526
Total	1573.77128	8.458945185	1296.354776	-480.6480149	-564.945925	1318.88703
PCI Limits	3500	-530.3300859	3500	-530.3300859	-604.6693311	4550
Limit Check	In Limits	Compression OK	In Limits	Class U	Class U	In Limits

Deflection Calculations

Camber (in)=	0.22335034	$\frac{P_{02}eL^2}{8E_{ci}I_g}$
Def due to SW (in) =	0.06111876	$\frac{5w_{sw}L^4}{384E_{ci}I_g}$
Def due to SDL (in) =	0.14781211	$\frac{5w_{DL}L^4}{384E_c'I_g}$

If Uncracked

Def due to LL (in) =	0.06569427	$\frac{5w_{LL}L^4}{384E_c'I_g}$

If Uncracked

	(1) Release	Multiplier	(2) Erection	Multiplier	(3) Final
Camber	0.223	1.800	0.402	2.450	0.547
wsw	-0.061	1.850	-0.113	2.700	-0.165
wsd			-0.148	3.000	-0.443
wll					-0.066
			0.141		-0.127
Total Deflection	0.268				

Connection Design

fy (ksi) =	60	Assume
fys (ksi) =	60	
wu (k/f) =	13.53	See Load Calculations
Vu (k) =	202.95	
Nu (k) =	40.59	
Lambda =	1	

$$V_U = \frac{W_U \times L}{2} \qquad N_U = 0.2 \times V_U$$

$$W_U = 1.2(SW + DL) + 1.6LL$$

Reinforced Concrete Bearing

a (in) =	8	
h (in) =	18.5	
d (in) =	17	
As (in) =	3.10394118	
M =	1	Table 5.3.1
Me =	12.3059867	
Me =	2.9	
Max Me =	2.9	Table 5.3.1
As' (in^2) =	1.93878161	
Critical As (in^2)	3.10394118	
Use ____#____BARS	5 # 8	
As practical (in^2)=	3.95	Ok
Ah (in^2) =	1.524	
Use ____#____U BARS	2 # 8	
Ah practical (in^2)=	1.58	Ok
Ash (in^2) =	4.51	
Use ____#____STIRRUPS	6 # 8	
Ash practical (in^2)=	4.74	Ok
Av (in^2) =	-1.85675145	
Use ____#____STIRRUPS		
Av practical (in^2)=	0	Ok
Chech Vn (k) =	441.157631	
	Ok	
Ld Ah (in) =	22.5	Design Aid 15.4.4
Ld As (in) =	37.5	Design Aid 15.4.4
Anchor for As (in) =	50.5	

$$A_S = \frac{1}{\phi f_y}\left[V_U \frac{a}{d} + N_U \frac{h}{d}\right]$$

$$\mu_e = \frac{\phi \times 1000 \times \lambda \times b \times h \times \mu}{V_U \times 1000}$$

$$A_S' = \frac{2V_U}{3\phi f_y \mu_e} + \frac{N_U}{\phi f_y}$$

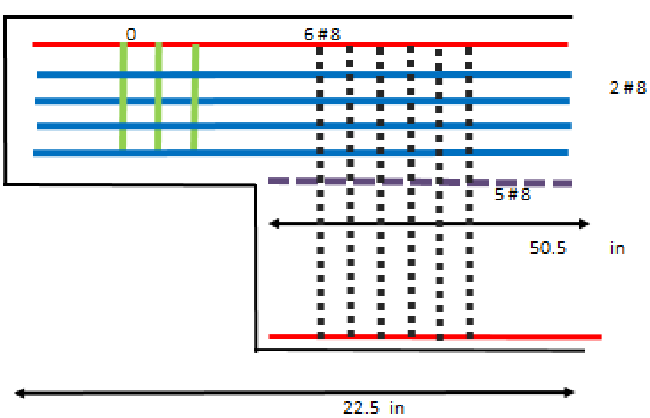
$$A_h = 0.5\left[A_S - \frac{N_U}{\phi f_y}\right]$$

$$A_{sh} = \frac{V_U}{\phi f_y}$$

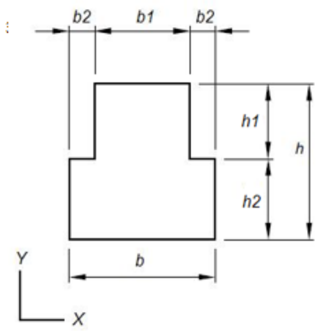
$$A_V = \frac{1}{2f_y}\left[\frac{V_U}{\phi} - \frac{2bd\lambda\sqrt{f_c'}}{1000}\right]$$

$$V_N = \phi\left(A_V f_y + A_h f_y + \frac{2bd\sqrt{f_c'}}{1000}\right)$$

$$L_d = H - d + l_d$$



Appendix Q: Alternative Design – Prestressed Inverted Tee Beam Zone A



Width,b (in) =	40
Height,H (in) =	30
b 1	28
h2	14
h1	16
b2	6
Length (in) =	344
cb	13.6667
Ct	16.3333
Area (in^2) =	1008
Inertia (in^4) =	74704
Section Modulus,Sb (in^3) =	5466.15
Section Modulus,St (in^3) =	4573.71
Volume/Surface (in) =	7.2

Perimeter	
28.00	web top
32	web sides
12.00	flange top
28.00	flange sides
40.00	flange bottom
140.00	sum

Shape	I	A	y	A*y	d	A*d²
	in⁴	in²	in	in³	in	in⁵
Flange	9146.67	560	7	3920	-6.6667	24888.9
Web	9557.33	448	22	9856	-8.3333	31111.1
Sum =	18704	1008		13776		56000

Properties of Concrete

fc'(psi)=	6500	
fci(psi)=	5000	
Density of Conrete (lb/ft^3) =	150	
Ec' =	4887733.37	$33 \times w_c^{1.5}\sqrt{f_c'}$
Eci =	4286825.749	$33 \times w_c^{1.5}\sqrt{f_c'}$

Properties of Prestressing Steel

fpu (ksi) =	270	
Number of Strands =	45	
Aps (in^2) =	0.217	
Eps (psi) =	2.85E+07	$0.7 * A_{ps} * \#of\ strands * f_{pu}$
Pi (k) =	1845.585	

Section Properties

Rectangular Beam

Width,b (in) =	40		
Height,h (in) =	30		
Length (in) =	344		
Area (in^2) =	1008	$b \times h$	
Inertia (in^4) =	74704		$\frac{1}{12}bh^3$
cb=ct (in) =	13.66666667	$\frac{I}{h/2}$	
Section Modulus,Sb (in^3) =	5466.146341		
Volume/Surface (in) =	7.2		

ct= 16.33333333

St= 4573.714286

Loads

Live Load (k/f) =	7.5
Dead Load (k/f) =	9.19791667
Self Weight (k/ft) =	1.05

Prestress Losses

Elastic Shortening

Kes=		1	
Kcir=		0.9	
e (in)=		6	
Msw (k-in) =	$\frac{w_{sw} \times L^2}{8}$	1294.3	
fcir (psi)=		2344.341314	$f_{cir} = K_{cir}\left(\frac{P_i}{A_g} + \frac{P_i e^2}{I_g}\right) - \frac{M_{sw}e}{I_g}$
ES (psi) =	$ES = \frac{K_{ES}E_{PS}f_{cir}}{E_{ci}}$	15585.82769	

Creep of Concrete

Kcr=	2	
Mdl (kp-in) =	11337.9653	
fcds (psi) =	910.63118	$\frac{M_{DL}e}{I}$
CR (psi) =	16719.7086	$CR = K_{CR}\left(\frac{E_{PS}}{E_c'}\right)(f_{cir} - f_{cds})$

Shrinkage of Concrete

Ksh =	1	
Relative Humidity (RH) =	75	Design Aid 4.11.12
SH (psi) =	3318.54	

$SH = (8.2 \times 10^{-6})K_{SH}E_{PS}(1 - 0.06V/S)(100 - RH)$

Relaxation of Tendons

Kre=	5000	From Table 5.7.1
J=	0.04	From Table 5.7.1
fpi=Pi/Aps	189	
fpi/fpu	0.7	
C=	0.75	Table 5.7.2
RE (psi) =	2681.27771	$RE = [K_{RE} - J(ES + CR + SH)]C$

TOTAL LOSS (PSI)=	38305.35399	20.26738306
JACKING FORCE AFTER LOSSES (k) =	1471.533218	

Critical Stress Calculations

Fse = (0.7 x fpu) ksi	189	
Tl= (Transfer Length -in) =	34	Design Aid 15.3.4

Ps forces after losses

Transfer @ Release		
Msw,T (k-in)=	461.125	$\frac{W_{sw} \times T_L}{2} \times (L - T_L) * 12$
fcir(ksi)=	2.411259417	$f_{cir} = K_{cir}\left(\frac{P_i}{A_g} + \frac{P_i e^2}{I_g}\right) - \frac{M_{sw,T} e}{I_g}$
EST (ksi)=	16.0307177	
Loss EST (k)	156.5399583	$(ES_T \times A_{ps} \times \#of\ strands)$
P01(k)=	1689.045042	$P_i - ES_T$

Midspan @ Release		
Msw,M (k-in)=	1294.3	
ESM (ksi)=	15.58582769	
Loss ESM (k)	152.1956074	$ES_M \times A_{ps} \times \#of\ strands$
P02(k)=	1693.389393	

Midspan @ Service	
Msw (k-in)=	1294.3
MsDL (k-in)=	11337.96528
MLL (k-in)=	9245
P03(k)=	1661.0265

	Transfer @ Release		Midspan @ Release		Midspan @ Service	
****units are in psi*****	fb	ft	fb	ft	fb	ft
Po/A	1675.639922	1675.639922	1679.949794	1679.949794	1647.84375	1647.84375
Po.e/S	1854.006391	-2215.763735	1858.775035	-2221.462846	1823.251406	-2179.0078
Msw/S	-84.3601637	100.8206834	-236.7847326	282.9866317	-236.7847326	236.784733
Msdl/S	0	0	0	0	-2074.215465	2478.94043
Mll/S	0	0	0	0	-1691.319519	2021.33308
Total	3445.286149	-439.3031296	3301.940096	-258.5264204	-531.2245613	4205.89422
PCI Limits	3500	-530.3300859	3500	-530.3300859	-604.6693311	4550
Limit Check	In Limits	Class U	In Limits	Class U	Class U	In Limits

Deflection Calculations

Camber (in)=	0.469305124	$\frac{P_{02} e L^2}{8 E_{ci} I_g}$
Def due to SW (in) =	0.049819678	$\frac{5 w_{sw} L^4}{384 E_{ci} I_g}$
Def due to SDL (in) =	0.382762525	$\frac{5 w_{DL} L^4}{384 E_c' I_g}$
If Uncracked		
Def due to LL (in) =	0.312105344	$\frac{5 w_{LL} L^4}{384 E_c' I_g}$

If Uncracked

	(1) Release	Multiplier	(2) Erection	Multiplier	(3) Final
Camber	0.469	1.800	0.845	2.450	1.150
wsw	-0.050	1.850	-0.092	2.700	-0.135
wsd			-0.383	3.000	-1.148
wll					-0.312
			0.370		-0.445
Total Deflection	0.815				

Connection Design

fy (ksi) =	60	
fys (ksi) =	60	
wu (k/f) =	24.2975	$W_U = 1.2(SW + DL) + 1.6LL$
Vu (k) =	320.6	$V_U = \frac{W_U \times L}{2}$
Nu (k) =	64.12	$N_U = 0.2 \times V_U$
Lambda =	1	

Corbel Design

Φ	0.75
a	10
h	20
d	17
As (in^2)	5.699555556
As' (in^2)	6.651124952
Critical As (in^2)	6.651124952
Use ____#____ BARS	6 # 10
As practical (in^2)=	7.62
Ah (in^2)	2.613118032
Use ____#____ U BARS	3 # 6
Ah practical (in^2)=	2.64
2/3 d	11.33333333

Appendix R: Alternative Design – Prestressed Inverted Tee Beam Zone C

Properties of Concrete

fc'(psi)=	6500	
fci(psi)=	5000	
Density of Conrete (lb/ft^3) =	150	
Ec' =	4887733.37	$33 \times w_c^{1.5}\sqrt{f_c'}$
Eci =	4286825.749	$33 \times w_c^{1.5}\sqrt{f_c'}$

Properties of Prestressing Steel

fpu (ksi) =	270	
Number of Strands =	30	
Aps (in^2) =	0.217	
Eps (psi) =	2.85E+07	$0.7 * A_{ps} * \#of\ strands * f_{pu}$
Pi (k) =	1230.39	

Section Properties

Rectangular Beam

Width,b (in) =	40				
Height,h (in) =	30				
Length (in) =	344				
Area (in^2) =	1008	$b \times h$			
Inertia (in^4) =	74704		$\frac{1}{12}bh^3$		
cb=ct (in) =	13.66666667	$\frac{I}{h/2}$		ct=	16.33333333
Section Modulus,Sb (in^3) =	5466.146341			St=	4573.714286
Volume/Surface (in) =	7.2				

Loads

Live Load (k/f) =	3
Dead Load (k/f) =	9.19791667
Self Weight (k/ft) =	1.05

Prestress Losses

Elastic Shortening

Kes=	1	
Kcir=	0.9	
e (in)=	7	
Msw (k-in) = $\frac{w_{sw} \times L^2}{8}$	1294.3	
fcir (psi)=	1703.618441	$f_{cir} = K_{cir}\left(\frac{P_i}{A_g} + \frac{P_i e^2}{I_g}\right) - \frac{M_{sw}e}{I_g}$
ES (psi) = $ES = \frac{K_{ES}E_{PS}f_{cir}}{E_{ci}}$	11326.1253	

Creep of Concrete

Kcr=	2	
Mdl (kp-in) =	11337.9653	$\frac{M_{DL}e}{I}$
fcds (psi) =	1062.40304	
CR (psi) =	7477.75602	$CR = K_{CR}\left(\frac{E_{PS}}{E_c'}\right)(f_{cir} - f_{cds})$

Shrinkage of Concrete

Ksh =	1	
Relative Humidity (RH) =	75	Design Aid 4.11.12
SH (psi) =	3318.54	

$SH = (8.2 \times 10^{-6})K_{SH}E_{PS}(1 - 0.06V/S)(100 - RH)$

Relaxation of Tendons

Kre=	5000	From Table 5.7.1
J=	0.04	From Table 5.7.1
fpi=Pi/Aps	189	
fpi/fpu	0.7	
C=	0.75	Table 5.7.2
RE (psi) =	3086.32736	$RE = [K_{RE} - J(ES + CR + SH)]C$

TOTAL LOSS (PSI)=	25208.74868	13.33796227
JACKING FORCE AFTER LOSSES (k) =	1066.281046	

Critical Stress Calculations

Fse = (0.7 x fpu) ksi	189	
Tl= (Transfer Length -in) =	34	Design Aid 15.3.4

Ps forces after losses

Transfer @ Release		
Msw,T (k-in)=	461.125	$\frac{W_{sw} \times T_L}{2} \times (L - T_L) * 12$
fcir(ksi)=	1.781689561	$f_{cir} = K_{cir}\left(\frac{P_i}{A_g} + \frac{P_i e^2}{I_g}\right) - \frac{M_{sw,T}e}{I_g}$
EST (ksi)=	11.84516364	
Loss EST (k)	77.11201531	$(ES_T \times A_{ps} \times \#of\ strands)$
P01(k)=	1153.277985	$P_i - ES_T$

Midspan @ Release		
Msw,M (k-in)=	1294.3	
ESM (ksi)=	11.3261253	
Loss ESM (k)	73.73307569	$ES_M \times A_{ps} \times \#of\ strands$
P02(k)=	1156.656924	

Midspan @ Service	
Msw (k-in)=	1294.3
MsDL (k-in)=	11337.96528
MLL (k-in)=	3698
P03(k)=	1107.351

	Transfer @ Release		Midspan @ Release		Midspan @ Service	
****units are in psi*****	fb	ft	fb	ft	fb	ft
Po/A	1144.124985	1144.124985	1147.477107	1147.477107	1098.5625	1098.5625
Po.e/S	1476.898968	-1765.074377	1481.226071	-1481.226071	1418.084427	-1418.08443
Msw/S	-84.3601637	100.8206834	-236.7847326	236.7847326	-236.7847326	236.784733
Msdl/S	0	0	0	0	-2074.215465	2074.21547
Mll/S	0	0	0	0	-676.5278075	676.527808
Total	2536.66379	-520.1287086	2391.918446	-96.96423115	-470.8810791	2668.00608
PCI Limits	3500	-530.3300859	3500	-530.3300859	-604.6693311	4550
Limit Check	In Limits	Class U	In Limits	Class U	Class U	In Limits

Deflection Calculations

Camber (in)=	0.373981236	$\frac{P_{02}eL^2}{8E_{ci}I_g}$
Def due to SW (in) =	0.049819678	$\frac{5w_{sw}L^4}{384E_{ci}I_g}$
Def due to SDL (in) =	0.382762525	$\frac{5w_{DL}L^4}{384E_c'I_g}$
If Uncracked		
Def due to LL (in) =	0.124842137	$\frac{5w_{LL}L^4}{384E_c'I_g}$

If Uncracked

	(1) Release	Multiplier	(2) Erection	Multiplier	(3) Final
Camber	0.374	1.800	0.673	2.450	0.916
wsw	-0.050	1.850	-0.092	2.700	-0.135
wsd			-0.383	3.000	-1.148
wll					-0.125
			0.198		-0.491
Total Deflection	0.690				

Connection Design

fy (ksi) =	60	
fys (ksi) =	60	
wu (k/f) =	17.0975	$W_U = 1.2(SW + DL) + 1.6LL$
Vu (k) =	320.6	
Nu (k) =	64.12	$V_U = \frac{W_U \times L}{2}$ $N_U = 0.2 \times V_U$
Lambda =	1	

Corbel Design	
Φ	0.75
a	10
h	20
d	17
As (in^2)	5.699555556
As' (in^2)	6.651124952
Critical As (in^2)	6.651124952
Use ____#____ BARS	6 # 10
As practical (in^2)=	7.62
Ah (in^2)	2.613118032
Use ____#____ U BARS	3 # 6
Ah practical (in^2)=	2.64
2/3 d	11.33333333

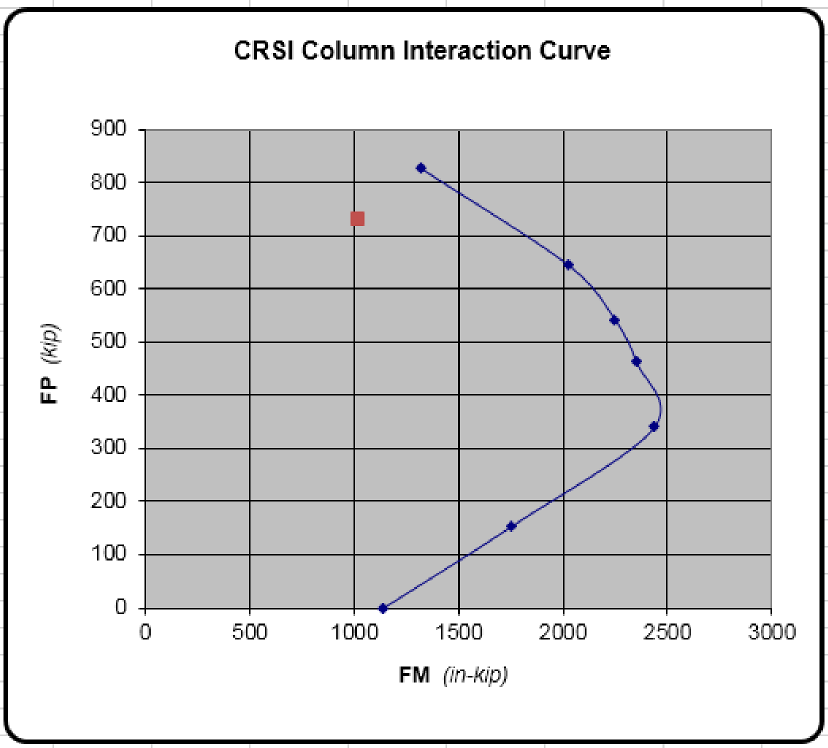
Appendix S: Alternative Design – Prestressed Column Design

Lateral Load Calc		Factored - Load Combination 2
LL (psf)	250	400
DL (psf)	341.5972	409.9166667
S (psf)	42	21
Tributary Area (ft2)	900	900
Axial Load (P) (kips)	532.4375	728.925
e - eccentricity (in)	1.4	
Mu	1020.495	

Column Size:	14	***in dia.***
Concrete F'c:	6000	***psi***
Rebar fy:	60,000	***psi***
BARS:	4 - # 8	

Design Pu:	728.925	***kip***
Design Mu:	1020.495	***in-kip***

	FM (in-kip)	FP (kip)
Max Cap	1317	828
0% fy	2029	644
25% fy	2248	542
50% fy	2351	462
100% fy	2434	340
0.1 f'cAg	1752	154
Zero Axial	1138	0



Appendix T: Alternative Design – Foundation Check

Weight Calculation of Original Bay						
Typical Bay Element	**Size**	**Dimensions**	**Unit**	**Quantity**	**Weight**	**Unit**
Steel Beam	W18x40	30.00	LF	4	4800.00	lbs
Steel Girder	W27x84	30.00	LF	2	5040.00	lbs
Steel Column + Encasing	W14x233	8.50	LF	1	4247.17	lbs
Composite Metal Decking	5" slab on 3" Metal Decking 2.46 psf	900.00	SF	1	58464.00	lbs
				Total:	**72551.17**	**lbs**

Weight Calculation of Alternative Prestressed Concrete Design						
Alternative Bay Element	**Length (ft)**	**Self Weight (k/ft)**	**Weight**	**Quantity**	**Total Weight**	**Unit**
Double Tee	30.00	1.22	36718.75	2	73437.50	lbs
Inverted Tee	28.67	1.05	30100.00	1	30100.00	lbs
Column	8.50	216.98	1844.35	1	1844.35	lbs
				Total:	**105381.85**	**lbs**

	Original Steel Typical Bay	**Designed Prestressed Concrete Bay**
Weight of the Bay (lbs)	72551.17	105381.85
Foundation Strength Ratio (lbs/ft^3)	39.48	57.35

Footing Details	
Footing 21.0	20 - #10
Length (in)	252.00
Width (in)	252.00
Depth (in)	50.00
Volume of the Foundation (CF)	1837.50
Soil Beraing Capacity (tsf)	2.00
Total Soil Capacity	882.00
Loading (lbs)	41562.50
Loading (tons)	20.78

Section Properties

$A_g = b \times h$ Trapezoid = $A_g = \cancel{\frac{h(2a+b)}{3(a+b)}} = \frac{a+b}{2} h$

$c_g = \Sigma y_i \frac{A_i}{A_g}$

$c_g = \frac{(y_1 \cdot A_1) + (y_2\, A_2)}{A_g}$

$c_g = c_b$

$c_t = h - c_g$ Trapezoid = $y_i = \frac{h(2a+b)}{3(a+b)}$

$S_b = \frac{I_g}{c_b}$ $S_t = \frac{I_g}{c_t}$

$I_g = \frac{1}{12} b h^3$ rectangular

$I_g = \frac{h^3(a^2+4ab+b^2)}{36(a+b)}$ Trapezoid

$I_g = \sum_{i=1}^{n} I_i + A_i (c_g - y_i)^2$

$V/S = \frac{A_g}{\text{Perimeter}}$

Calculating Prestress Losses

1) Elastic Shortening of Concrete (ES)

⑤ $ES = K_{es} \frac{E_{ps}}{E_{ci}} f_{cir}$

① $E_{ci} = 33\, w_c^{1.5} \sqrt{f_{ci}}$

④ $f_{cir} = K_{cir} \left(\frac{P_i}{A_g} + \frac{P_i e^2}{I_g} \right) - \frac{M_g \cdot e}{I_g}$ (→ k·in)

③ $P_i = 0.7$ (# of strands × Aps × Fpu)

② $M_g = M_{sw} = \frac{W_{sw} L^2}{8}$ = k.f = k.in $w_{sw} = \frac{A_g}{144} \times \frac{w_c}{150}$

2) Creep of Concrete (CR)

$CR = K_{CR} \left(\frac{E_{ps}}{E_c'} \right) (f_{cir} - f_{cds})$ (→ psi)

$E_c' = 33\, w_c^{1.5} \sqrt{f'_c}$

$f_{cds} = \frac{M_{sd} \times e}{I_g}$ (→ k·in) $M_{sd} = \frac{w_{dl} L^2}{8}$ - k.f ⇒ k.in

3) Shrinkage of Concrete (SH)   Design Aid → 4.11.12

$SH = (8.2 \times 10^{-6}) K_{SH} E_{ps} (1 - 0.06 \frac{V}{S})(100 - RH)$

4) Relaxation of Tendons (RE)

$RE = [K_{RE} - J(SH + CR + ES)] C$ (K_{RE} → Table 5.71, J → Table 5.71, C → Table 5.72)

Total Loss = TL = ES + CR + SH + RE

Jacking Force after losses = $P_o = P_i - (TL \times \#$ of strands × Aps)

P_i	100
P_o	x

x = Y

100 − Y = 2% Loss

Calculating Critical Stress

① Transfer @ Release

T_L = Design aid 15.3.4 $= \frac{0.7 f_{pu}}{3} d_b$ (in) $\left(\frac{f_{py}}{...} \times 150\right)/1000$

$M_{sw,t} = \frac{w_{sw} T_L}{2}(L - T_L)$ = k-ft

$f_{cir,T} = K_{cir}\left(\frac{P_i}{A_g} + \frac{P_i e^2}{I_g}\right) - \frac{M_{sw,t}\, e}{I_g}$ (k-in) (K_{cir} = 0.9)

$ES_{,T} = K_{ES}\left(\frac{E_{ps}}{E_{ci}}\right) f_{cir,T}$ (K_{ES} = 1)

$P_{o1} = P_i - (ES_{,T} \times \#\text{ of strands} \times A_{ps})$

② Midspan @ Release

$ES_{M} = K_{ES}\left(\frac{E_{ps}}{E_{ci}}\right) f_{cir,M}$ ($M_{sw} = \frac{w_{sw} L^2}{8}$)

f_{cir} will be calculated by using midspan moment (previous/prestress loss calculation)

$P_{o2} = P_i - (ES_M \times A_{ps} \times \#\text{ of strands})$

③ Midspan @ Service

$P_{o3} = P_i - (TL \times A_{ps} \times \#\text{of strands})$

$M_{DL} = \frac{w_{DL} L^2}{8}$ $M_{LL} = \frac{w_{LL} L^2}{8}$

(psi)	Transfer @ Release		Midspan @ Release		Midspan @ Service	
	f_b	f_t	f_b	f_t	f_b	f_t
$\frac{P}{A}$	$+\frac{P_{o1}}{A}$	$+\frac{P_{o1}}{A}$	$+\frac{P_{o2}}{A}$	$+\frac{P_{o2}}{A}$	$+\frac{P_{o3}}{A}$	$+\frac{P_{o3}}{A}$
$\frac{Pe}{S}$	$+\frac{(P_{o1})e}{S_b}$	$-\frac{(P_{o1})e}{S_t}$	$+\frac{(P_{o2})e}{S_b}$	$-\frac{(P_{o2})e}{S_t}$	$+\frac{(P_{o3})e}{S_b}$	$-\frac{(P_{o3})e}{S_t}$
$\frac{M_{sw}}{S}$	$-\frac{(M_{sw})_1}{S_b}$	$+\frac{(M_{sw})_1}{S_t}$	$-\frac{(M_{sw})_M}{S_b}$	$+\frac{M_{sw,M}}{S_t}$	$-\frac{M_{sw,M}}{S_b}$	$+\frac{M_{sw,M}}{S_t}$
$\frac{M_{DL}}{S}$	0	0	0	0	$-\frac{M_{DL,M}}{S_b}$	$+\frac{M_{DL,M}}{S_t}$
$\frac{M_{LL}}{S}$	0	0	0	0	$-\frac{M_{LL,M}}{S_b}$	$+\frac{M_{LL,M}}{S_t}$
TOTAL						
PCI Limits	$0.7f_{ci}$	$-7.5\sqrt{f_{ci}}$	$0.7f_{ci}$	$-7.5\sqrt{f_{ci}}$	$-7.5\sqrt{f_{ci}}$	$0.7f_c'$
	compression	tension				

Class U	Class T	Class C
Uncracked	Transition	Cracked
$\le 7.5\sqrt{f_c'}$	$7.5\sqrt{f_c'} < x < 12\sqrt{f_c'}$	$x \ge 12\sqrt{f_c'}$

* PCI allows Class U and Class T @ service

Connections

① Reinforced Concrete Connection

Step ① ⇒ Calculate Connection Load

For simply supported beam ⇒ $V_u = \frac{w_u L}{2}$ $w_u = 1.2(SW + DL) + 1.6(LL)$

$N_u = 0.2(V_u)$

Step ② ⇒ Check the Shear capacity of Concrete, V_n $(V_n > V_u)$

By using Table 5.3.1,

Concrete to Concrete cast monolithically	concrete to hardened concrete with roughedened surfhase
$V_n = 1000\lambda A_{cr}$	$V_n = 1000\lambda A_{cr}$
$\mu = 1.4\lambda$	$\mu = 1.0\lambda$
$\mu_{e\,max} = 3.4$	$\mu_{e\,max} = 2.9$

Step ③ ⇒ Calculate μ_e

$$\mu_e = \frac{\phi 1000 \lambda A_{cr} \mu}{V_u}$$

$\phi = 0.75$ (Shear factor)
$\lambda = 1$ for normal weight concrete
$A_{cr} = b \times d$

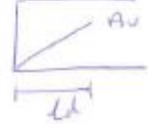
(if calculated μ_e is larger than the max μ_e in Table 5.3.1 use max μ_e)

Step ④ ⇒ Calculate A_{vn}

f_y = tensile strengthe of rebar (60ksi)

$$A_{vn} = \underbrace{\frac{V_u}{\phi f_y \mu_e}}_{\text{Vertical Stress}} + \underbrace{\frac{N_u}{\phi f_y}}_{\text{horizontal stress}}$$

- Then assign the bar size for A_{vn} using design aid 15.4.1
- Calculate l_d (Developent lenght) using design aid 15.4.4

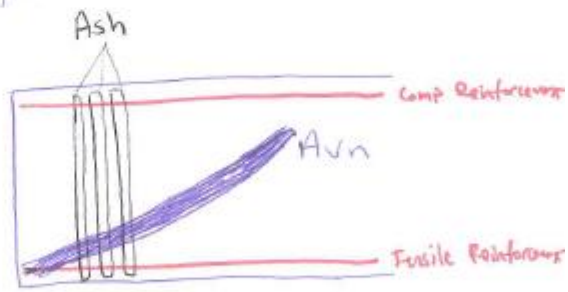


Step ⑤ ⇒ Calculate Ash, repeat the process in step 3. Instead of A_{cr} use A_{cr}'

$A_{cr}' = b\,l_d$

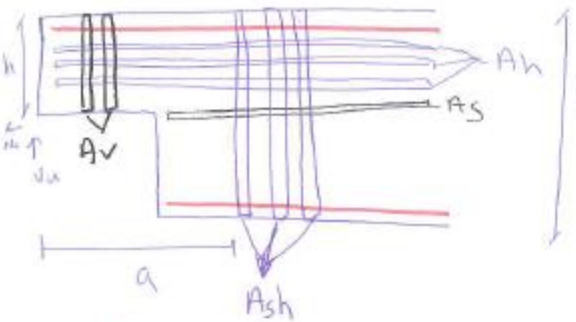
$$\mu_e = \frac{\phi 1000 \lambda A_{cr}' \mu}{A_{vn} f_y}$$

$$A_{sh} = \frac{A_{vn} f_y}{\mu_e f_{ys}}$$



Then assign bar size for stirrups
$2 \times (\#\text{of bar}) \times (\text{area})$

② Dapped-End Beam Connection



d = distance from the center of As
h = depth of component
a = distance from shear load to center of Ash

Step ①
$V_u = \frac{w_u L}{2}$ $N_u = 0.2(V_u)$

Step ② ⇒ Calculate As

$$A_s = \frac{1}{\phi f_y}\left[V_u\left(\frac{a}{d}\right) + N_u\left(\frac{h}{d}\right)\right]$$

(vertical stresses) (horizontal stresses)

$\phi = 0.75$ $\frac{a}{d} < 1$ OK

Step ③ ⇒ Calculate As'

$$\mu_e = \frac{\phi 1000 \lambda (b \times h)\mu}{V_u}$$

$$A_s' = \frac{2V_u}{3\phi f_y \mu_e} + \frac{N_u}{\phi f_y}$$

if μ_e > Max μ_e use max μ_e → Table 5.3.1

- Compare previously calculated As with the As'
  → Use the critical one
- Assign bar size (15.4)

Step ④ ⇒ Calculate Ah

$$A_h = 0.5\left(A_s - \frac{N_u}{\phi f_y}\right)$$

- Assign bar size Ubars

Step ⑤ ⇒ Calculate Av - stirrups

$$A_v = \frac{1}{2f_y}\left(\frac{V_u}{\phi} - 2bd\lambda\sqrt{f'_c}\right)$$

Step ⑥ ⇒ Calculate Ash - Ubar

$$A_{sh} = \frac{V_u}{\phi f_y}$$

- Assign bar size (2 × (# of bars) × (area) (Ubars)

Check $V_n = \phi(A_v f_y + A_h f_y + 2bd\sqrt{f'_c}) > V_u$

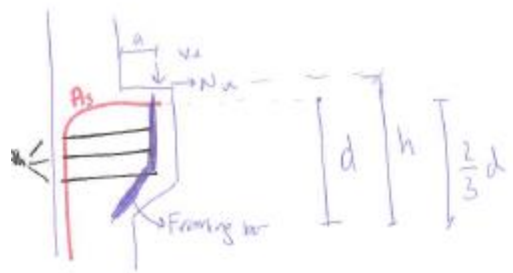
if not increase Av or Ah

Step ⑦ ⇒ Calculate ld for As and Ah

As ⇒ $l_{d_{As}} = H - d + l_d$

Ah ⇒ l_d = table value 15.4.4

Corbel Design



$\frac{a}{d} \leq 1 \quad \frac{N_u}{V_u} \leq 1$

Step ① ⇒ Calculate A_s

$$A_s = \underbrace{\frac{2}{3}\left(\frac{V_u}{\phi f_y \mu}\right)}_{\text{to resist shear friction}} + \underbrace{\frac{N_u}{\phi f_y}}_{\text{to resist horizontal stress}}$$

μ = table 5.3.1

Step ② ⇒ Calculate A_s'

$$A_s' = \frac{V_u(a) + N_u(h-d)}{\phi f_y \, 0.85\, d} + \frac{N_u}{\phi f_y}$$

- Compare A_s with A_s' & choose the critical one
- Assign bar size

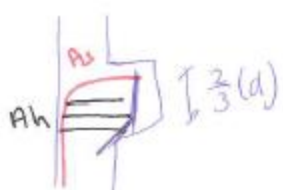
Step ③ ⇒ Calculate A_h – stirrups

if critical A_s is A_s (step 1) ⇒ $A_h = \frac{V_u}{3\phi f_y \mu}$

if critical A_s is A_s' (step 2) ⇒ $A_h = \frac{V_u(a) + N_u(h-d)}{2\phi f_y (0.85) d}$

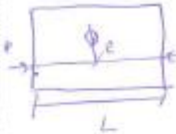
- Asign bar size ($2 \times$ (# of bar) $\times$ area) stirrups

Step ④ Draw the Corbel

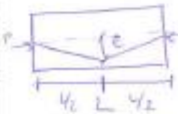


Camber Deflection

① Calculate initial Camber (@ midspan @ release)

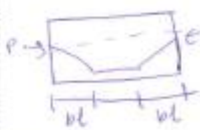


$$\Delta_c = \frac{P_{o2}\, e\, L^2_{in}}{8 E_{ci} I_g}$$



$$\Delta_c = \frac{P_{o2}\, e L^2}{12 E_{ci} I_g}$$

$$\Delta_c = \frac{5 P_{o2}\, e L^2}{48 E_{ci} I_g}$$



$$\Delta_c = \frac{b(3-4b^2)\left(\frac{P_e}{bL}\right)\ell^3}{24 E_{ci} I_g}$$

② Deflection due to self weight

$$\Delta_{SW} = \frac{5 w_{SW} L^4}{384 E_c' I_g}$$

($\frac{w_{SW}}{12}$ = k-in)

③ Deflection due to dead load

$$\Delta_{DL} = \frac{5 w_{DL} (L^4)}{384 E_c' I_g}$$

④ Deflection due to Live Load

$$\Delta_{LL} = \frac{5 w_{LL} L^4}{384 E_c' I_g}$$

if section is class U

If it is Class T (started to crack)

- Midspan@service f_b Total − Limit of Midspan@service = the additional stress that cause cracking (S)
- $\frac{M_{LL}}{S}$ (midspan @ release) − S ⇒ in limit (class U)

→ if $\frac{M_{LL}}{S}$ (midspan @ release) is 100%

in limit value is X ∴ 100−Y of the live load stays in Class U

S is Y

Elastic behaviour

$$w_{WLL,unc} = \frac{100-Y}{100} \times W_{LL}$$

$$w_{WLL,cr} = -w_{WLL,unc} + W_{LL} \quad (W_{LL} - w_{WLL,uncr})$$

For uncracked part ⇒ $\Delta_{uncr,LL} = \frac{5(w_{LL,unc})L^4}{384 E_c' I_g}$

Bilinear Region

$$I_{cr} = C\, b\, d_p^3$$

$d_p = e + C_t$ (addition of n.a. e)

C = design aid 5.14.11

b = width of beam

→ $q_p = \frac{A_{ps} \times \#\text{ of strands}}{b \times d_p}$

$$\Delta_{cr,LL} = \frac{5\, W_{LL,cr}\, L^4}{384 E_{ci} I_{cr}}$$

$$\Delta_{LL} = \Delta_{unc,LL} + \Delta_{cr,LL}$$

Short Term Long Term Multipliers

	Release	Multiplier	Erection	Multiplier	Final
Camber	Δ_c ↑	1.8	$\Delta_c \times 1.8$ ↑	2.45	$\Delta_c \times 2.45$ ↑
SW	Δ_{SW} ↓	1.85	$\Delta_{SW} \times 1.85$ ↓	2.7	$\Delta_{SW} \times 2.7$ ↓
DL			Δ_{DL} ↓	3	$\Delta_{DL} \times 3$ ↓
LL					Δ_{LL} ↓
			+ $\Delta_{Erection}$		+ Δ_{Final}

$$\Delta_{TOTAL} = \Delta_{Final} - \Delta_{Erection} < \frac{\ell}{180}$$

Methods to Control Camber

① Delaying strand cut

→ it will change E_{ci}

$$\Delta_{camber} = \frac{P_{o2}\, e L^2}{8 E_{ci} I_g} \qquad E_{ci} \uparrow \ \Delta_c \downarrow$$

② Changing the eccentricity

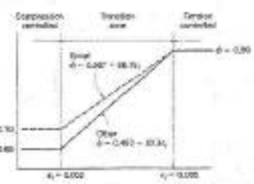
$e \uparrow \quad \Delta_c \uparrow$

Columns

- Lateral Tie Sizes
  - $< \#10 \Rightarrow \#3$
  - $7 \#10 \Rightarrow \#4$
- Spacing Must not exceed

$$S_{max}\ \text{min of} \begin{cases} 48 \cdot \frac{tie}{8} \\ 16 \cdot \frac{bar}{8} \\ \text{smallest of } b/h \end{cases}$$

- Spiral more ductile than tied
- Φ factor



$\alpha = 0.80$ for tied columns

$\alpha = 0.85$ for spirally columns

Ex: Steps - Developing P-M Diagram

1) Balanced Condition ($\varepsilon_s = \varepsilon_y$)

$$C_b = d\left(\frac{\varepsilon_u}{\varepsilon_u + \varepsilon_y}\right) \quad \varepsilon_y = \frac{f_y}{E_s(29000)}$$

$\varepsilon_u \to 0.003$

$$a_b = \beta_1 C_b$$

$\beta_1 \to 0.85$

$f_s = f_y$ (balanced cond.)

$$\varepsilon'_s = \varepsilon_u\left(\frac{c-d'}{c}\right)$$

$$f'_s = E\,\varepsilon_u\left(\frac{c-d'}{c}\right) \leq f_y$$

if f'_s is greater than f_y then $f'_s = f_y$

$$C = 0.85 f'_c\, a\, b$$

$$P_b = C + A'_s f'_s - A_s f_s$$

$$M_b = C\left(\frac{h}{2} - \frac{a}{2}\right) + A'_s f'_s\left(\frac{h}{2} - d'\right) + A_s f_s\left(d - \frac{h}{2}\right)$$

$$e_b = \frac{M_b}{P_b}$$

2) A point in the tension failure
- select c smaller than C_b

$f_s = f_y$ b/c steel yields

$f'_s < f_y$ so just use f'_s

3) A point in the compression controlled region
- select c larger than C_b

find a, C, f_s

$$f_s = E_s \varepsilon_u\left(\frac{d-c}{c}\right)$$

$f'_s > f_y \therefore f'_s = f_y$

4) Find P_o = axial strength

$e = 0 \quad (c = \infty)$

$$P_o = 0.85 f'_c\, h\, b + (A'_s + A_s) f_y$$

5) Design transverse reinforcement
- pick lateral tie size
- find spacing

6) Plot the Points

Example: Select Reinforcement

1) Calculate Factor Loads

$$P_u = 1.2\, D_{DL} + 1.6\, P_{LL}$$

$$M_u = 1.2\, M_{DL} + 1.6\, M_{LL}$$

$$e = \frac{M_u}{P_u}$$

2) Design Aids

Assume cover and h

calculate $\gamma = \frac{\gamma h}{h}$

$$K_n = \frac{P_u}{\Phi f'_c A_g}$$

$$R_n = \frac{M_u}{\Phi f'_c A_g h}$$

3) Look up K_n, R_n, γ, f'_c, f_y in the graph and find ρ_g

$$A_s = \rho_g\, b\, h$$

4) Choose Reinforcement by using A_s

5) Check to see if one row fits by using spacing conditions

Example: Select Column Size

1) Select h and cover (2.5")

$\frac{\gamma h}{h} = 0.8$ Assume $\rho_g = 0.03$

2) Design Aids

$$e = \frac{M_u}{P_u}$$

Look up in the graph K_n

$$K_n = \frac{P_u}{\Phi f'_c b h} \Rightarrow \text{find } b$$

3) Find area, choose reinforcement

$$A_s = \rho_g (b)(h)$$

Example - Circular Spiral Column

1) Select h, cover,

$\frac{\gamma h}{h} \Rightarrow$ calc. γ

Assume $\rho_g = 0.015$

$f'_c = 4$ ksi

$f_y = 60$ ksi

2) Design Aids

$\frac{e}{h} \Rightarrow$ use graph to find $K_n = \frac{P_u}{\Phi f'_c A_g}$, $A_g = \frac{\pi h^2}{4}$

$$h = \sqrt{\frac{P_u}{\Phi f'_c\left(\frac{\pi}{4}\right)}}$$

3) Design Reinforcement

$A_s = \rho_g \frac{\pi h^2}{4} \Rightarrow$ reinforcement

$\to$ select # spiral

4) Check h

(clear cover) + (d_{spiral}) + $\frac{1}{2} d_{bar}$ < 2.7

(1.5")

$$D_c = h - 2\left(C - \frac{spiral}{8} - \frac{bar}{2 \cdot 8}\right)$$

$$\rho_s = 0.45\left(\frac{A_g}{A_c} - 1\right)\frac{f'_c}{f_{yt}}$$

$A_g = \frac{\pi h^2}{4}$, $A_c = \frac{\pi D_c^2}{4}$

Pitch

$$S = \frac{4\, a_s (D_c - d_b)}{D_c^2\, \rho_s}$$

Appendix V: Alternative Design – Conference Call with David from Old Castle Precast

1/20/2015

David,

Thanks again for scheduling a conference call with us tomorrow—we are sure it will prove invaluable to our project.

This document will give you an overview of our project, our design goals, our concerns, and our questions.

Overview

Our project is concerned with the study and analysis of the construction and design of an underground parking garage in downtown Worcester. The garage is fit for +500 cars and is split up into two connected sections: a "hotel section" over which a 6-story hotel will be built on in the future and a "ballpark section" with lighter loading coming from a green area/park on top of it. The General Contractor for the project is Consigli Construction, who has generously incorporated us into their team and provided access to all construction and project documents.

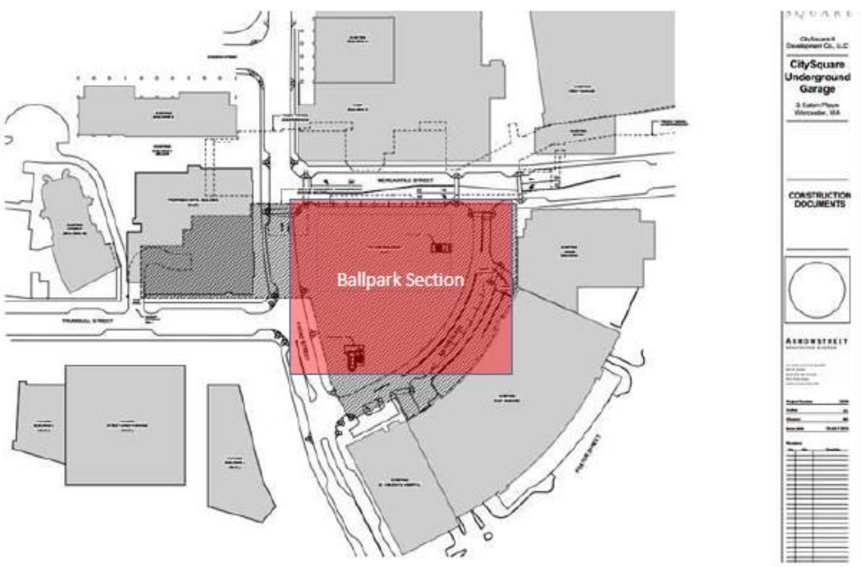


Figure 1: Underground Garage Layout

Our focus is the "ballpark section" which features a more repetitive steel bay design which is more suitable for our alternative prestressed concrete bay design. This is depicted above in Figure 1.

Design Goals

Our goal is to design a structurally sound and feasible alternative solution in prestressed concrete to the typical steel bay we have identified for the "ballpark section". The typical steel bay can be found in Figure 2.

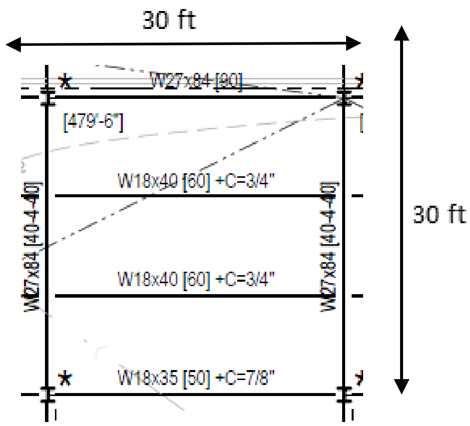


Figure 2: Typical Steel Bay Design

The design requirements we want to meet for our alternative solution include:

- Maintaining a 30ft x 30ft Bay size
- Maintaining a 8'-6" design height
- Maintaining column size so as to retain same number of parking spots and maneuverability
- Maintaining column locations

The alternative design would be able to support its self-weight and the loading parameters given by the construction documents. The design calculations we have done so far can be found in the excel file titled "MQP Design Calculations" which includes the loading, double tee beam, inverted T beam and connection calculations. Our alternative solution features prestressed double tee beams acting as floor slabs, prestressed inverted tees as girders supporting the dapped-end double tees, and prestressed columns supporting the inverted tees with a corbel connection. This is illustrated in Figure 3 below.

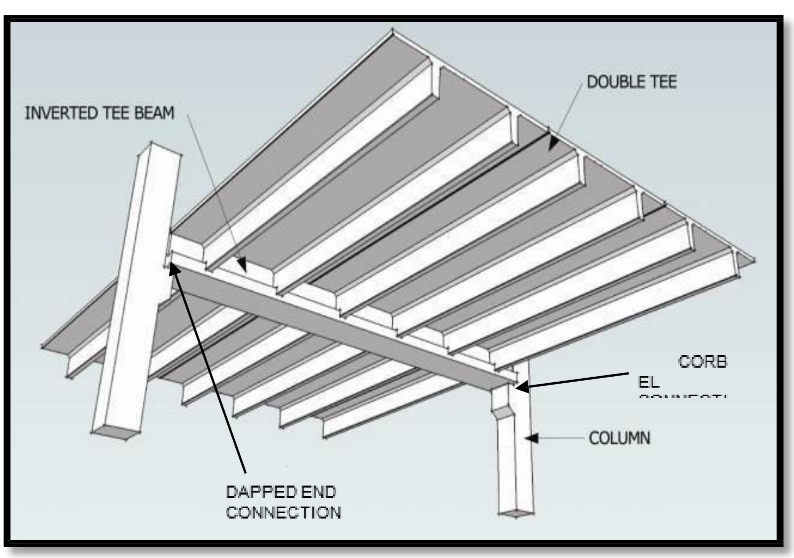


Figure 3: Visualization of Alternative Design

Questions and Concerns

Due to the self-driven nature of our project, all of the work we have completed so far in terms of design was enabled by the knowledge we gained from a 7-week full undergraduate course on prestressed concrete design. Even as the course was extremely beneficial and pointed us to valuable resources such as PCI Manual and publications, we believe we need guidance from a professional in the field with a high level of expertise. The points we want to address in our conference call tomorrow 1/21/2014 are listed below:

1. Design Concern: Column Design.
   Given our class did not involve in-depth column design, we are not confident in which steps to take in order to design a suitable prestressed column for our Inverted tee beams and loadings. We hope to get the necessary tools such as excel sheets or software that can help us come up with a design.

2. Design Concern: Foundation Check
   After completing a column design and having a structurally sound full bay design, how would you suggest we check whether the original spread footings will be able to support our alternative prestressed design?

3. Software with Visual and Structural Functionalities
   Is there any software you would suggest that would be able to verify our design calculations for our members (double tee, inverted tee, and columns) and/or would provide a 3D visualization of our alternative design.

4. Cost Estimating for Alternative Design
   Once we have a completed alternative design, would you be able to provide us with rough estimates for the production costs of our alternative bay design? We tried to select members that resembles the dimensions of common designs featured in the PCI Manual in hopes of reducing the hypothetical production cost.

5. Sustainability: Embodied Energy
   Our project also features a comparison between the sustainability of the original steel design and our alternative prestressed design. One metric we will use is Embodied Energy meaning the total energy used for the extraction of the raw materials, transportation to factory, processing and manufacturing, as well as transportation to site and construction. We have already done research on this topic and have found energy measurements for most common materials (steel, rebar, concrete, etc.), but we would like to know if you have data on this kind of analysis for your plant's production.

6. Sustainability: Maintenance
   Another comparison we want to include are the difference in maintenance costs between a traditional steel construction + cast-in-place concrete and prestressed construction. Do you have any data or research on the life-cycle costs of these materials?

We look forward to our conference call tomorrow and we again thank you for your time.

Sincerely,

-Jose Cueva and Saadet Nur Yilmaz

Jose & Saadet,

Attached information from our GotoMeeting this morning.

1. CRSI Column Tables & CRSI excel file for column design
2. Compare steel & precast weight for one bay. Precast will be heavier. Then propose proportionate footing size increase if geotechnical engineer says the soil bearing capacity has been exceeded.
3. Bentley Presto precast design software – images from Bentley web site and internet
   PCI preliminary design tables for inverted tee beams & double tees
4. Precast cost = material component cost + trucking cost + field installation cost
   Double tee = $10/SF (1 per load)
   Column = $200 / LF (2 per load) but only 1 per bay
   InvT Beam = $225 /LF (2 per load)
   Trucking = $900 / Load for example
   Crane = $3000 per day + Crew = $7000 per day = $10,000 day (can erect 10 pcs precast per day) $10,000 / 10 pcs = $1,000 field installation cost per piece
5. Sustainability
   a) Replace 20% cement with fly ash (cement is 70% of total embodied energy per PCI LCA "Life cycle analysis" study)
   b) Minimize size of sections
   c) Maximize pcs on truck loads and find local precaster to reduce transportation distance – fuel use
   d) Prefabrication – less construction waste on site
   e) Precast – reuse metal formwork in plant
   f) Casting in late spring & summer – no applied heat needed for curing
6. Maintenance – PCI Parking Structures Maintenance Manual
   Steel structure requires repainting every few years

David Wan, P.E., LEED AP
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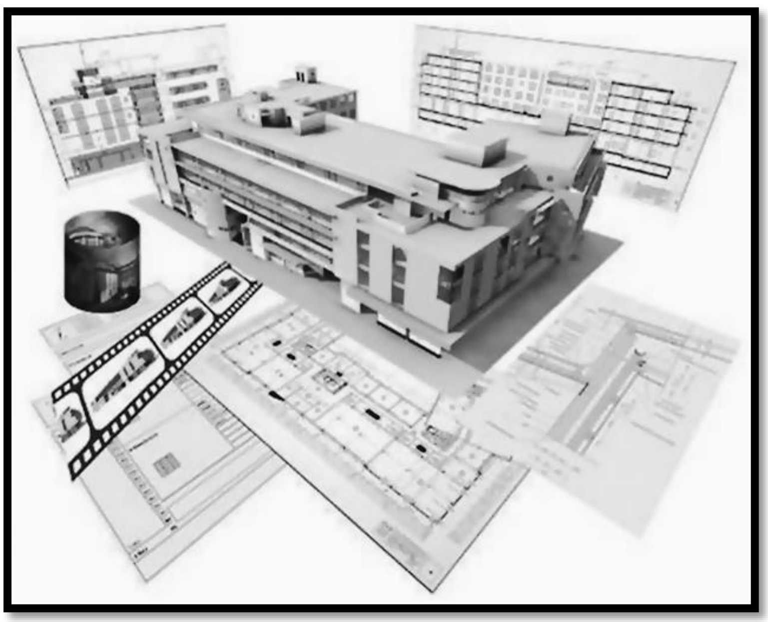
Appendix W: Building Information Modeling and Its Benefits

The term building information modeling (BIM) has been present in the construction industry's vocabulary since 2002. When it was first introduced, industry analysts debated over the meaning of the three letter acronym, but all agreed that this was the "next generation of design software" after computer-aided design (CAD) (Smith, et. all. 2009). Autodesk, a world leader in 3D design software for entertainment, natural resources, manufacturing, engineering, construction, and civil infrastructure, defines BIM as an "intelligent model-based process that provides insight to help you plan, design, construct, and manage buildings and infrastructure" (Autodesk, 2014). The key word to note in this definition is "process", for it qualifies BIM not as a product or a tool, but a sequence of actions that involve participation from the different parties involved. The figure below shows a visual representation of the information used on building information modelling.



BIM graphic showing various types of information being derived from a 3D model, e.g., plans, sections, etc., and component information. (Smith, et. all. 2009)

A second definition for BIM from an academic standpoint defines it as a "*project* as well as a *process* simulation", thus emphasizing the visualization capabilities of the technology (Kymmel, 2008). Creating a computer modelled construction process much like the real construction work is labor intensive and rich in information. The planning process to create a comprehensive simulation requires the same considerations the constructors at the field would be concerned about: time, space, cost, and scheduling. Like the work it parallels, BIM modeling requires constant reevaluation and adaptation as conditions change throughout the life of the project. This gives the interactive computer model relevance and accuracy as a projection that is weeks if not months ahead of the tangible construction work, thus potentially resolving issues during construction before they materialize.

BIM models are most beneficial when created as both as a tool for coordination among all parties involved (designers, construction managers, owner, subcontractor, and trades) and as a vehicle to increase understanding on the intricacies of any project. When used as a medium through which all parties further the understanding of their individual role and their role as team members in a largely coordinated time-spanning effort, these computerized simulations represent the most accurate and detailed account of the building, tower, or structure that is to be built. By having one master simulation that incorporates all parties, sometimes referred to as a composite model, construction documents are more transparent, detailed, and living than their predecessors in paper or in 2-D (Smith, 2009). Building this comprehensive model is a unique opportunity in the construction process to become intimately familiar with the project and all of its components.

The benefits of using BIM technology in construction projects come through the facilitation of updated information to all parties, reduced field coordination problems, more accurate construction schedule, and multidimensional display of activities. According to an article published in the International Journal of Project Management, "The most frequently reported benefit related to the cost reduction and control through the project life cycle" along with time savings (Bryde, et. all. 2013). A case study on the same publication reviewed 35 case studies which mentioned positive and negative benefits of the use of BIM using success criteria related to the output of the project, including meeting time, cost and quality objectives and also objectives related to the management of the process, such as effective scope management and communications. (Bryde, et. all. 2013) The table below summarizes its findings in terms of percentages.

	Positive benefit			**Negative benefit**		
Success criterion	Total instances	Total number of projects	% of total projects	Total instances	Total number of projects	% of total projects
Cost reduction or control	29	21	**60.00%**	3	2	5.71%
Time reduction or control	17	12	**34.29%**	4	3	8.57%
Communication improvement	15	13	**37.14%**	0	0	0.00%
Coordination improvement	14	12	**34.29%**	7	3	8.57%
Quality increase or control	13	12	**34.29%**	0	0	0.00%
Negative risk reduction	8	6	**17.14%**	2	1	2.86%
Scope clarification	3	3	**8.57%**	0	0	0.00%
Organization improvement	2	2	**5.71%**	2	2	**5.71%**
Software issues	0	0	0.00%	9	7	**20.00%**

BIM Success Case Study Data (Bryde, et. all. 2013)

The success criterion of this case study highlights the benefits of BIM in construction project while indicating which benefits are most prominent. A direct comparison between the percentages of total projects that positively benefited from BIM against the percentage of total projects that experienced negative benefits stresses the value of this technology and its main areas of provided improvement.

Appendix X: Double Tee Beam Deflections

Summary Report

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Project:
Problem:

SUMMARY REPORT

Design Code Used: CSA A23.3-94

CONCRETE MATERIAL PROPERTIES

		Precast Beam	
Concrete Density	Wt	= 150	lb/ft^3
Compressive Strength	f'c	= 6500.0	psi
Modulus of Elasticity	Ec	= 4.490E+6	psi
Strength at Transfer	f'c	= 5000.0	psi
Modulus of Elast. at Transfer	Ec	= 4.069E+6	psi
Strength at Lifting	f'c	= 5000.0	psi
Modulus of Elast. at Lifting	Ec	= 4.069E+6	psi

Cement Content = 691 lb/yd^3
Air Content = 5.00 %
Slump = 1.97 in
Aggregate Mix = 0.40 (fine to total aggregate ratio)
Aggregate Size = 0.79 in
Basic Shrinkage Strain = 780.000E-6

Construction Schedule
Age at Transfer = 0.75 days
Age at Erection = 40 days
Age at Cast-in-Place Pour = 50 days
Age Cast-in-Place is Composite = 53 days
Age Construction is Complete = 143 days

Curing Method = Moist
Relative Humidity in Service = 70 %
Ambient Temperature in Service = 20 deg C

PRECAST BEAM LAYOUT

No	Segment/Length From ft	To ft	Length ft	Section Identification Folder Name	Section Name	Section Type	Offset Z in	Y in
1	0.00	30.00	30.00	DoubleTee	DoubleTeePretopped	Double Tee	0.00	0.00

Span Length at Transfer = 30.00 ft, Centre of Supports, Left @ 0.00 ft, Right @ 30.00 ft
Span Length in Service = 30.00 ft, Centre of Supports, Left @ 0.00 ft, Right @ 30.00 ft
Total Beam Length = 30.00 ft, Bearing Length, Left = 0.00 in, Right = 0.00 in

The cast-in-place pour, if defined, has been turned off (not included).

GROSS PRECAST SECTION PROPERTIES (NON-COMPOSITE)
(based on Ec of the precast beam - transformed area of rebar and strand NOT included)

Seg. No.	Section Properties A in^2	I in^4	yb in	Section Height in	Section Width in	Shear Width in	Volume / Surface in	Section Moduli Sb in^3	St in^3
1	1175.0	85138	22.38	30.00	180.00	17.50	2.51	-3804	11173

UNCRACKED SECTION PROPERTIES SUMMARY

	Net Precast Section at Transfer (based on Eci) (include rebar,deduct strand)			Transformed Precast Section at Transfer (based on Eci) (include rebar and strand)			Transformed Precast Section in Service (based on Ec) (include rebar and strand)		
x ft	A in^2	I in^4	yb in	A in^2	I in^4	yb in	A in^2	I in^4	yb in
0.00	1172	84647	22.42	1175	85141	22.38	1175	85141	22.38
3.00	1181	84931	22.46	1205	88398	22.21	1202	88046	22.23
6.00	1181	84931	22.46	1205	88398	22.21	1202	88046	22.23
9.00	1181	84931	22.46	1205	88398	22.21	1202	88046	22.23
12.00	1181	84931	22.46	1205	88398	22.21	1202	88046	22.23
15.00	1181	84931	22.46	1205	88398	22.21	1202	88046	22.23
18.00	1181	84931	22.46	1205	88398	22.21	1202	88046	22.23
21.00	1181	84931	22.46	1205	88398	22.21	1202	88046	22.23
24.00	1181	84931	22.46	1205	88398	22.21	1202	88046	22.23
27.00	1181	84931	22.46	1205	88398	22.21	1202	88046	22.23
30.00	1172	84647	22.42	1175	85141	22.38	1175	85141	22.38

These section properties can used to calculate uncracked concrete stresses using the following guidelines.

Net Precast Section at Transfer properties are used with the initial prestress after transfer (after elastic shortening loss).
Transformed Precast Section at Transfer properties are used with the precast beam self-weight.
Transformed Precast Section in Service properties are used with external loads applied to the non-composite precast beam.

PRESTRESSING STEEL TENDONS

ID	Qty	Grade ksi	Type *	Strand Size	Offsets x ft	y in	End Offset & Type Left ** ft	Right ** ft	Tendon Area in^2	Jacking Force Pj kip	%fpu
1	16	270.0	LRS	0.6" (3/5)	0.00	10.50	0.00 B	0.00 B	3.472	656.2	0.70
					30.00	10.50					

note: * Type = LRS - Low-Relaxation Strand, SRS - Stress-Relieved Strand, PB - Plain Bar,
DB - Deformed Bar, SW - Single Wire
** End Types = B - Fully Bonded, D - Debonded, C - Cut, A - Anchored (fully developed)

Calculated Losses: Initial = 5.1%, Final = 12.8%

Project:
Problem:

Maximum Total Prestress Forces: Pj(jacking) = 656.2 kip,
Pi(transfer) = 623.0 kip,
Pe(effective) = 572.5 kip @ x = 15.00 ft,

See the "Development Length" text report for details of the strand transfer and development lengths

LONGITUDINAL REINFORCING STEEL

Reinforcing Steel Groups

ID	Qty	Steel Grade ksi	Bar Size	Bar Area in^2	End Location & Type From ft	*	To ft	*	Bar Spacing in		Cross Spacing in	Vertical Offset in	Offset ** Reference
1	30	65	D 5	1.5	0.00	SE	30.00	SE	6.00	Mesh	6.00	2.00	Top of Precast Beam

* End Types: SE - Straight Embeddment, FD - Fully Developed, SH - Standard Hook, HB - Headed Bar
** Offsets are measured up from the bottom or down from the top

See the "Development Length" text report for details of the bar and wire development lengths

SHEAR STIRRUPS

From ft	To ft	Stirrup Grade ksi	Stirrup Size	Number of Legs Stirrup in Beam	Number of Legs Interface Ties	Total Stirrup Area Stirrup in^2	Total Stirrup Area Interface in^2	Stirrup Spacing Stirrup in	Stirrup Spacing Interface in
0.00	30.00	65.0	D 4	2	0	0.08	0.00	10.00	0.00

TORSION PARAMETERS

Seg. Torsion Parameters

No.	Aoh in^2	Ph in
1	0.00	0.00

Aoh is the area enclosed by the centerline of the outermost closed transverse torsional reinforcement.
Ph is the perimeter of the area defined as Aoh.

PRECAST BEAM AND CAST-IN-PLACE POUR SELF-WEIGHT

No.	Segment/Length From ft	Segment/Length To ft	Linear Weight Beam kip/ft	Linear Weight Cast-in-Place kip/ft
1	0.00	30.00	1.2239	0.0000

EXTERNALLY APPLIED LOADS

Load Case	Type	Label	Description	Distribution
SDL BT	D	Load #1	Vertical: 2.25 kip/ft full length	No Load Distribution
LL Sustain	L	Load #1	Vertical: 2.92 kip/ft full length	No Load Distribution

Load Combinations
Factored Combination 1 = 1.25D
Factored Combination 2 = 1.25D + 1.50L + 1.50SR + 1.50F
Factored Combination 3 = 1.25D + 1.50W
Factored Combination 4 = 1.25D + 1.05L + 1.05SR + 1.05F + 1.05W
Factored Combination 8 =

ANALYSIS RESULTS SUMMARY - IN SERVICE

x ft	Total Unfactored Moments Total kipft	Total Unfactored Moments Sustained kipft	Total Factored Effects Shear kip	[*]	Moment kipft	[*]	Torsion kipft	[*]
0.00	0.0	0.0	130.8	[2]	0.0	[1]	0.0	[1]
3.00	259.0	259.0	104.7	[2]	353.3	[2]	0.0	[1]
6.00	460.4	460.4	78.5	[2]	628.0	[2]	0.0	[1]
9.00	604.2	604.2	52.3	[2]	824.3	[2]	0.0	[1]
12.00	690.5	690.5	26.2	[2]	942.0	[2]	0.0	[1]
15.00	719.3	719.3	0.0	[1]	981.3	[2]	0.0	[1]
18.00	690.5	690.5	-26.2	[2]	942.0	[2]	0.0	[1]
21.00	604.2	604.2	-52.3	[2]	824.3	[2]	0.0	[1]
24.00	460.4	460.4	-78.5	[2]	628.0	[2]	0.0	[1]
27.00	259.0	259.0	-104.7	[2]	353.3	[2]	0.0	[1]
30.00	0.0	0.0	-130.8	[2]	0.0	[1]	0.0	[1]

* Critical ULS Load Combination

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Project:
Problem:

SUPPORT REACTIONS (kip)
(+ve = upwards)

Unfactored Support Reactions

Load Case	In Service Left	In Service Right	During Lifting Left	During Lifting Right	During Transport Left	During Transport Right
Beam Weight	18.4	18.4	18.4	18.4	18.4	18.4
SDL BT	33.8	33.8				
CIP Weight	0.0	0.0				
SDL AT	0.0	0.0				
LL Sustain	43.8	43.8				
Live Load	0.0	0.0				
Roof Load	0.0	0.0				
Fluid Wgt	0.0	0.0				
Wind	0.0	0.0				
Seismic	0.0	0.0				
Constrct LL	0.0	0.0				
SLS Maximum	95.9	95.9	18.4	18.4	18.4	18.4
SLS Max DL	52.1	52.1				
SLS Min DL	52.1	52.1				
SLS Max Sus	95.9	95.9				

ULS Support Reactions

Load Combo.	Left	[*]	Right	[*]
ULS Maximum	130.8	[2]	130.8	[2]
ULS Minimum	44.3	[7]	44.3	[7]

* Critical Factored Load Combination

CONCRETE STRESS RESULTS (UNCRACKED ANALYSIS)
(+ve = compression, -ve = tension)

Location	x ft	Stress psi	Limit psi	Overstress Notice	
STRESSES AT TRANSFER					
Critical Compression					
Top of Beam	15.00	12	3000	0%	
Bottom of Beam	2.70	2347	3000	0%	
					Longitudinal Tensile Rebar Needed (in^2) Required Provided Additional
Critical Tension					
Top of Beam	5.40	-47	-213	0%	
Bottom of Beam	0.00	2	-426	0%	
STRESSES DURING INITIAL LIFTING					
Critical Compression					
Top of Beam	15.00	12	3000	0%	
Bottom of Beam	2.70	2347	3000	0%	
					Longitudinal Tensile Rebar Needed (in^2) Required Provided Additional
Critical Tension					
Top of Beam	5.40	-47	-213	0%	
Bottom of Beam	0.00	2	-426	0%	
STRESSES DURING ERECTION LIFTING					
Critical Compression					
Top of Beam	15.00	17	3900	0%	
Bottom of Beam	2.70	2178	3900	0%	
					Longitudinal Tensile Rebar Needed (in^2) Required Provided Additional
Critical Tension					
Top of Beam	5.40	-40	-243	0%	
Bottom of Beam	0.00	2	-485	0%	
STRESSES IN SERVICE					
Critical Compression					
Top of Beam	15.00	638	3900	0%	
Bottom of Beam	2.70	1433	3900	0%	
Critical Tension					
Top of Beam	0.00	0	-485 *	0%	Not cracked
Bottom of Beam	0.00	2	-485 *	0%	Not cracked
STRESSES IN SERVICE (SUSTAINED LOADS ONLY)					
Critical Compression					
Top of Beam	15.00	638	2925	0%	
Bottom of Beam	2.70	1433	2925	0%	

* Tensile stress limit in service is for a non-corrosive environment. For a corrosive environment halve the limit.
Beyond this limit crack control is required.

	At Transfer	During Lifting	In Service
Modulus of Rupture, fr =	-511 psi	-511 psi	-583 psi

Strength Required for Transfer, f'c = 3911.6 psi (f'c specified = 5000 psi)
Strength Required for Initial Lifting, f'c = 3911.6 psi (f'c assumed = 5000 psi)

CRACK CONTROL
(+ve = tension, -ve = compression)

Beam not cracked, cracking is controlled, or crack depth is less than concrete cover.

DEFLECTION ESTIMATE AT ALL STAGES

Design Code Used: CSA A23.3-94

A. Deflections at All Stages
(-ve = deflection down, +ve = camber up)

Location x ft Column	Net Deflection: Net @ Transfer in A	Net @ Erection in B	Net @ Completion in C	Net DL @ Final in D	Net Total @ Final in E	Change in Deflection: DL growth + LL in E - C	LL alone in E - D	Span/Deflection: DL growth + LL	LL alone
0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0
3.00	0.103	0.151	0.181	0.022	0.022	-0.159	0.000	2263	0
6.00	0.183	0.266	0.317	0.014	0.014	-0.303	0.000	1187	0
9.00	0.239	0.343	0.409	-0.008	-0.008	-0.417	0.000	862	0
12.00	0.272	0.388	0.461	-0.029	-0.029	-0.490	0.000	734	0
15.00	0.283	0.403	0.479	-0.036	-0.036	-0.515	0.000	698	0
18.00	0.272	0.388	0.461	-0.029	-0.029	-0.490	0.000	734	0
21.00	0.239	0.343	0.409	-0.008	-0.008	-0.417	0.000	862	0
24.00	0.183	0.266	0.317	0.014	0.014	-0.303	0.000	1187	0
27.00	0.103	0.151	0.181	0.022	0.022	-0.159	0.000	2263	0
30.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0

Col. A: Net deflection at transfer includes prestressing and beam weight on temporary supports.
Col. B: Net deflection at erection includes prestressing and all dead loads applied before the cast-in-place pour plus long-time deflection growth of the prestressing and beam weight up to erection
Col. C: Net deflection at completion of construction includes prestressing and all dead loads plus long-time deflection growth of the prestressing and dead load up to completion
Col. D: Net DL deflection at final includes prestressing, all dead loads, and sustained live loads,. plus long-time deflection growth.
Col. E: Net total deflection at final includes prestressing, all dead loads, and all live loads, plus long-time deflection growth.

Live load includes roof load, and fluid weight. Wind and earthquake are not included.
Deflection growth is estimated by use of the PCI suggested multipliers - see the Deflection Multipliers report.

Span/Deflection Limits: DL growth + LL = L / 480 for non-structural attachments
L / 240 otherwise
LL alone = L / 360 for floors
L / 180 for roofs

SUPPORT ROTATIONS, AND CHANGE OF LENGTH AT ALL STAGES

Design Code Used: CSA A23.3-94

B. Unrestrained Support Rotations at All Stages
(-ve = counter-clockwise rotation, +ve = clockwise rotation)

Support Location Column	Net Rotation: Net @ Transfer degrees A	Net @ Erection degrees B	Net @ Completion degrees C	Net DL @ Final degrees D	Net Total @ Final degrees E	Change in Rotation: DL growth + LL degrees E - C	LL alone degrees E - D
Left	-0.0067	-0.0100	-0.0120	-0.0019	-0.0019	0.0101	0.0000
Right	0.0067	0.0100	0.0120	0.0019	0.0019	-0.0101	0.0000

C. Unrestrained Longitudinal Change of Length Due to Creep and Shrinkage
(-ve = shortening, +ve = elongation)

Elastic Shortening = -0.0425 in

	Total Change of Length (after elastic shortening): Erection in B	Completion in C	Final in D	Difference in Change: to Compl. in C - B	to Final in D - C	to Final in D - B
Creep	-0.0261	-0.0394	-0.0798	-0.0134	-0.0404	-0.0538
Shrink.	-0.0786	-0.1271	-0.1860	-0.0485	-0.0589	-0.1074
Total	-0.1047	-0.1666	-0.2659	-0.0619	-0.0993	-0.1612

FLEXURAL DESIGN CHECK

Design Code Used: CSA A23.3-94
β used: for precast beam = 0.858
α used: for precast beam = 0.783
Material Resistance Factors Used: precast concrete = 0.65
cast-in-place concrete = 0.60
reinforcing steel = 0.85
prestressing steel = 0.90

Modulus of Rupture of Precast Concrete, fr = 583 psi (tension)

x ft	Factored Moment Mf kipft	Provided Resistance Mr kipft	Cracking Moment Mcr kipft	Minimum Required Resistance kipft	Depth in Compression c in	Compression Depth Ratio c / d	Notes & Warnings
0.00	0.0	0.8	185.3	0.0	0.04	0.002	
3.00	353.3	816.4	903.3	471.0	1.16	0.060	
6.00	628.0	1101.3	923.9	837.3	1.47	0.075	
9.00	824.3	1296.9	938.7	1099.0	1.65	0.085	
12.00	942.0	1296.9	947.5	1137.0	1.65	0.085	
15.00	981.3	1296.9	950.5	1140.6	1.65	0.085	
18.00	942.0	1296.9	947.5	1137.0	1.65	0.085	
21.00	824.3	1296.9	938.7	1099.0	1.65	0.085	

24.00	628.0	1101.3	923.9	837.3	1.47	0.075	
27.00	353.3	816.4	903.3	471.0	1.16	0.060	
30.00	0.0	0.8	185.3	0.0	0.04	0.002	
Points of Maximum and Minimum Factored Moment							
15.00	981.3	1296.9	950.5	1140.6	1.65	0.085	
0.00	0.0	-0.4	542.3	0.0	0.03	0.001	
Points of Maximum Ratio of Factored Moment to Provided Resistance							
15.00	981.3	1296.9	950.5	1140.6	1.65	0.085	
0.00	0.0	-0.4	542.3	0.0	0.03	0.001	
Points of Maximum Ratio of Minimum Resistance to Provided Resistance							
15.00	981.3	1296.9	950.5	1140.6	1.65	0.085	
0.00	0.0	-0.4	542.3	0.0	0.03	0.001	

SHEAR DESIGN CHECK

Design Code Used: CSA A23.3-94

x ft	Design Shear Vf kip	Prestress Component Vp kip	Concrete Resistance Vc kip	Resistance Provided Stirrups Vs kip	Resistance Provided Total Vr kip	Min. Resistance Req'd Stirrups Vs kip	Min. Resistance Req'd Total Vr kip	Notes & Warnings
0.00	119.9	0.0	119.4	11.9	131.3	23.4	142.8	5
3.00	104.7	0.0	154.5	9.5	164.1	18.7	173.2	
6.00	78.5	0.0	107.8	9.5	117.3	18.7	126.5	
9.00	52.3	0.0	62.6	9.5	72.1	18.7	81.3	
12.00	26.2	0.0	40.6	9.5	50.1	18.7	59.3	
15.00	0.0	0.0	40.6	9.5	50.1	0.0	40.6	
18.00	-26.2	0.0	-40.6	-9.5	-50.1	-18.7	-59.3	
21.00	-52.3	0.0	-62.6	-9.5	-72.1	-18.7	-81.3	
24.00	-78.5	0.0	-107.8	-9.5	-117.3	-18.7	-126.5	
27.00	-104.7	0.0	-154.5	-9.5	-164.1	-18.7	-173.2	
30.00	-119.9	0.0	-119.4	-11.9	-131.3	-23.4	-142.8	5

Notes & Warnings
5 - Note: Design shear force limited to critical section near support.

TORSION DESIGN CHECK

Design Code Used: CSA A23.3-94

x ft	Design Torsion Tcr/4 kipft	Threshold Torsion Stress kipft	Combined Shear and Torsion Limit psi	Combined Shear and Torsion Tf psi	Torsion Resistance Provided Tr kipft	Torsion Resistance Required Tr kipft	Notes & Warnings
0.00	0.0	15.5	0	0	0.0	0.0	2
3.00	0.0	25.4	0	0	0.0	0.0	
6.00	0.0	25.6	0	0	0.0	0.0	
9.00	0.0	25.8	0	0	0.0	0.0	
12.00	0.0	25.9	0	0	0.0	0.0	
15.00	0.0	25.9	0	0	0.0	0.0	
18.00	0.0	25.9	0	0	0.0	0.0	
21.00	0.0	25.8	0	0	0.0	0.0	
24.00	0.0	25.6	0	0	0.0	0.0	
27.00	0.0	25.4	0	0	0.0	0.0	
30.00	0.0	15.5	0	0	0.0	0.0	2

Notes & Warnings
2 - Note: Design torsion force limited to critical section near support.

SHEAR/TORSION TRANSVERSE REINFORCING DESIGN CHECK

Design Code Used: CSA A23.3-94

x ft	Shear Steel Total (Av+2At)/s in^2/ft	Required Torsion* At/s in^2/ft	Shear Steel Provided Av/s in^2/ft	Stirrup Provided Av+2At in^2	Stirrup Spacing Provided s in	Stirrup Spacing Required s in	Additional Long. Steel for Torsion, Al Total in^2	Additional Long. Steel for Torsion, Al Reduction** in^2	Notes & Warnings
0.00	0.19	0.00	0.10	0.08	10.00	5.10	0.00	0.00	1 2 5
3.00	0.19	0.00	0.10	0.08	10.00	5.10	0.00	0.00	1 2
6.00	0.19	0.00	0.10	0.08	10.00	5.10	0.00	0.00	1 2
9.00	0.19	0.00	0.10	0.08	10.00	5.10	0.00	0.00	1 2
12.00	0.19	0.00	0.10	0.08	10.00	5.10	0.00	0.00	1 2
15.00	0.00	0.00	0.10	0.08	10.00	15.12	0.00	0.00	
18.00	0.19	0.00	0.10	0.08	10.00	5.10	0.00	0.00	1 2
21.00	0.19	0.00	0.10	0.08	10.00	5.10	0.00	0.00	1 2
24.00	0.19	0.00	0.10	0.08	10.00	5.10	0.00	0.00	1 2
27.00	0.19	0.00	0.10	0.08	10.00	5.10	0.00	0.00	1 2
30.00	0.19	0.00	0.10	0.08	10.00	5.10	0.00	0.00	1 2 5

Notes & Warnings
1 - WARNING: The shear stirrup spacing is too wide.
2 - Note: Amount of shear steel required represents minimum code requirements.
5 - Note: Design torsion force limited to critical section near support.
Note: Additional long. steel in compression side of section has been reduced.
* Portion of the total stirrup area required to resist torsional shear flow (one leg around periphery).
** The allowable reduction in Al within the flexural compression zone.

Appendix Y: Inverted Tee Beam Deflections

Summary Report

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Problem:

SUMMARY REPORT

Design Code Used: CSA A23.3-04

CONCRETE MATERIAL PROPERTIES

		Precast Beam
Concrete Density	Wt	= 150 lb/ft^3
Compressive Strength	f'c	= 6500.0 psi
Modulus of Elasticity	Ec	= 4.490E+6 psi
Strength at Transfer	f'c	= 5000.0 psi
Modulus of Elast. at Transfer	Ec	= 4.069E+6 psi
Strength at Lifting	f'c	= 5000.0 psi
Modulus of Elast. at Lifting	Ec	= 4.069E+6 psi

Cement Content = 691 lb/yd^3
Air Content = 5.00 %
Slump = 1.97 in
Aggregate Mix = 0.40 (fine to total aggregate ratio)
Aggregate Size = 0.79 in
Basic Shrinkage Strain = 780.000E-6

Construction Schedule
Age at Transfer = 0.75 days
Age at Erection = 40 days
Age at Cast-in-Place Pour = 50 days
Age Cast-in-Place is Composite = 53 days
Age Construction is Complete = 143 days

Curing Method = Moist
Relative Humidity in Service = 70 %
Ambient Temperature in Service = 20 deg C

PRECAST BEAM LAYOUT

No	Segment/Length From ft	To ft	Length ft	Section Identification Folder Name	Section Name	Section Type	Offset Z in	Y in
1	0.00	28.67	28.67	Inverted-Tee MQP	28IT34	Inverted Tee	0.00	0.00

Span Length at Transfer = 28.67 ft, Centre of Supports, Left @ 0.00 ft, Right @ 28.67 ft
Span Length in Service = 28.67 ft, Centre of Supports, Left @ 0.00 ft, Right @ 28.67 ft
Total Beam Length = 28.67 ft, Bearing Length, Left = 0.00 in, Right = 0.00 in

The cast-in-place pour, if defined, has been turned off (not included).

GROSS PRECAST SECTION PROPERTIES (NON-COMPOSITE)
(based on Ec of the precast beam - transformed area of rebar and strand NOT included)

Seg. No.	Section Properties A in^2	I in^4	yb in	Section Height in	Section Width in	Shear Width in	Volume / Surface in	Section Moduli Sb in^3	St in^3
1	1008.0	74704	13.67	30.00	40.00	28.00	7.20	-5465	4575

UNCRACKED SECTION PROPERTIES SUMMARY

	Net Precast Section at Transfer (based on Eci) (include rebar,deduct strand)			Transformed Precast Section at Transfer (based on Eci) (include rebar and strand)			Transformed Precast Section in Service (based on Ec) (include rebar and strand)		
x ft	A in^2	I in^4	yb in	A in^2	I in^4	yb in	A in^2	I in^4	yb in
0.00	998	74127	13.75	1008	74711	13.67	1008	74710	13.67
2.87	1015	77551	13.99	1085	81704	13.47	1077	80945	13.49
5.73	1015	77551	13.99	1085	81704	13.47	1077	80945	13.49
8.60	1015	77551	13.99	1085	81704	13.47	1077	80945	13.49
11.47	1015	77551	13.99	1085	81704	13.47	1077	80945	13.49
14.33	1015	77551	13.99	1085	81704	13.47	1077	80945	13.49
17.20	1015	77551	13.99	1085	81704	13.47	1077	80945	13.49
20.07	1015	77551	13.99	1085	81704	13.47	1077	80945	13.49
22.93	1015	77551	13.99	1085	81704	13.47	1077	80945	13.49
25.80	1015	77551	13.99	1085	81704	13.47	1077	80945	13.49
28.67	998	74127	13.75	1008	74711	13.67	1008	74710	13.67

These section properties can used to calculate uncracked concrete stresses using the following guidelines.

Net Precast Section at Transfer properties are used with the initial prestress after transfer (after elastic shortening loss).
Transformed Precast Section at Transfer properties are used with the precast beam self-weight.
Transformed Precast Section in Service properties are used with external loads applied to the non-composite precast beam.

PRESTRESSING STEEL TENDONS

ID	Qty	Grade ksi	Type *	Strand Size	Offsets x ft	y in	End Offset & Type Left ** ft	Right ** ft	Tendon Area in^2	Jacking Force Pj kip	%fpu
1	45	270.0	LRS	0.6" (3/5)	0.00	6.00	0.00 B	0.00 B	9.765	1845.6	0.70
					28.67	6.00					

note: * Type = LRS - Low-Relaxation Strand, SRS - Stress-Relieved Strand, PB - Plain Bar,
DB - Deformed Bar, SW - Single Wire
** End Types = B - Fully Bonded, D - Debonded, C - Cut, A - Anchored (fully developed)

Calculated Losses: Initial = 11.3%, Final = 22.6%

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Maximum Total Prestress Forces: Pj(jacking) = 1845.6 kip,
Pi(transfer) = 1637.2 kip,
Pe(effective) = 1427.6 kip @ x = 14.33 ft,

See the "Development Length" text report for details of the strand transfer and development lengths

LONGITUDINAL REINFORCING STEEL

Reinforcing Steel Groups

ID	Qty	Steel Grade ksi	Bar Size	Bar Area in^2	End Location & Type From ft	*	To ft	*	Bar Spacing in		Cross Spacing in	Vertical Offset in	Offset ** Reference
1	14	65	W20	2.8	0.00	SE	28.67	SE	4.00	Mesh	4.00	2.00	Top of Precast Beam

* End Types: SE - Straight Embeddment, FD - Fully Developed, SH - Standard Hook, HB - Headed Bar
** Offsets are measured up from the bottom or down from the top

See the "Development Length" text report for details of the bar and wire development lengths

SHEAR STIRRUPS

From ft	To ft	Stirrup Grade ksi	Stirrup Size	Number of Legs Stirrup in Beam	Number of Legs Interface Ties	Total Stirrup Area Stirrup in^2	Total Stirrup Area Interface in^2	Stirrup Spacing Stirrup in	Stirrup Spacing Interface in
0.00	28.67	65.0	W20	2	0	0.40	0.00	12.00	0.00

TORSION PARAMETERS

Seg. Torsion Parameters

No.	Aoh in^2	Ph in
1	0.00	0.00

Aoh is the area enclosed by the centerline of the outermost closed transverse torsional reinforcement.
Ph is the perimeter of the area defined as Aoh.

PRECAST BEAM AND CAST-IN-PLACE POUR SELF-WEIGHT

No.	Segment/Length From ft	Segment/Length To ft	Linear Weight Beam kip/ft	Linear Weight Cast-in-Place kip/ft
1	0.00	28.67	1.0499	0.0000

EXTERNALLY APPLIED LOADS

Load Case	Type	Label	Description	Distribution
SDL BT	D	Deadload	Vertical: 4.7 kip/ft full length	No Load Distribution
LL Sustain	L	Liveload	Vertical: 2.92 kip/ft full length	No Load Distribution

Load Combinations
Factored Combination 1 = 1.40D
Factored Combination 2 = 1.25D + 1.50L + 0.50SR + 1.50F
Factored Combination 3 = 1.25D + 1.50L + 1.50F + 0.40W
Factored Combination 4 = 1.25D + 0.50L + 1.50SR + 0.50F
Factored Combination 8 = 1.00D + 0.50L + 0.25SR + 0.50F + 1.00E

ANALYSIS RESULTS SUMMARY - IN SERVICE

x ft	Total Unfactored Moments Total kipft	Total Unfactored Moments Sustained kipft	Total Factored Effects Shear kip	[*]	Moment kipft	[*]	Torsion kipft	[*]
0.00	0.0	0.0	165.8	[2]	0.0	[1]	0.0	[1]
2.87	320.5	320.5	132.6	[2]	427.7	[2]	0.0	[1]
5.73	569.9	569.9	99.5	[2]	760.3	[2]	0.0	[1]
8.60	747.9	747.9	66.3	[2]	997.9	[2]	0.0	[1]
11.47	854.8	854.8	33.2	[2]	1140.5	[2]	0.0	[1]
14.33	890.4	890.4	0.0	[1]	1188.0	[2]	0.0	[1]
17.20	854.8	854.8	-33.2	[2]	1140.5	[2]	0.0	[1]
20.07	747.9	747.9	-66.3	[2]	997.9	[2]	0.0	[1]
22.93	569.9	569.9	-99.5	[2]	760.3	[2]	0.0	[1]
25.80	320.5	320.5	-132.6	[2]	427.7	[2]	0.0	[1]
28.67	0.0	0.0	-165.8	[2]	0.0	[1]	0.0	[1]

* Critical ULS Load Combination

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SUPPORT REACTIONS (kip)
(+ve = upwards)

Unfactored Support Reactions

Load Case	In Service Left	In Service Right	During Lifting Left	During Lifting Right	During Transport Left	During Transport Right
Beam Weight	15.0	15.0	15.0	15.0	15.0	15.0
SDL BT	67.3	67.3				
CIP Weight	0.0	0.0				
SDL AT	0.0	0.0				
LL Sustain	41.9	41.9				
Live Load	0.0	0.0				
Roof Load	0.0	0.0				
Fluid Wgt	0.0	0.0				
Wind	0.0	0.0				
Seismic	0.0	0.0				
Constrct LL	0.0	0.0				
SLS Maximum	124.2	124.2	15.0	15.0	15.0	15.0
SLS Max DL	82.4	82.4				
SLS Min DL	82.4	82.4				
SLS Max Sus	124.2	124.2				

ULS Support Reactions

Load Combo.	Left	[*]	Right	[*]
ULS Maximum	165.8	[2]	165.8	[2]
ULS Minimum	74.1	[9]	74.1	[9]

* Critical Factored Load Combination

CONCRETE STRESS RESULTS (UNCRACKED ANALYSIS)
(+ve = compression, -ve = tension)

Location	x ft	Stress psi	Limit psi	Overstress Notice
STRESSES AT TRANSFER				
Critical Compression				
Top of Beam	0.00	-1	3000	0%
Bottom of Beam	26.09	3887	3000	30%
Critical Tension				
Top of Beam	26.37	-999	-426	135%
Bottom of Beam	0.00	4	-426	0%
STRESSES DURING INITIAL LIFTING				
Critical Compression				
Top of Beam	0.00	-1	3000	0%
Bottom of Beam	26.09	3887	3000	30%
Critical Tension				
Top of Beam	26.37	-999	-426	135%
Bottom of Beam	0.00	4	-426	0%
STRESSES DURING ERECTION LIFTING				
Critical Compression				
Top of Beam	0.00	-1	3900	0%
Bottom of Beam	26.09	3550	3900	0%
Critical Tension				
Top of Beam	26.37	-910	-485	87%
Bottom of Beam	0.00	4	-485	0%
STRESSES IN SERVICE				
Critical Compression				
Top of Beam	14.33	1229	3900	0%
Bottom of Beam	26.37	2719	3900	0%
Critical Tension				
Top of Beam	26.37	-247	-485 *	0% Not cracked
Bottom of Beam	0.00	3	-485 *	0% Not cracked
STRESSES IN SERVICE (SUSTAINED LOADS ONLY)				
Critical Compression				
Top of Beam	14.33	1229	2925	0%
Bottom of Beam	26.37	2719	2925	0%

Longitudinal Tensile Rebar Needed (in^2) — Transfer

Required	Provided	Additional
2.7	2.8	0.0

Longitudinal Tensile Rebar Needed (in^2) — Initial Lifting

Required	Provided	Additional
2.7	2.8	0.0

Longitudinal Tensile Rebar Needed (in^2) — Erection Lifting

Required	Provided	Additional
2.5	2.8	0.0

* Tensile stress limit in service is for a non-corrosive environment. For a corrosive environment halve the limit.
Beyond this limit crack control is required.

	At Transfer	During Lifting	In Service
Modulus of Rupture, fr =	-511 psi	-511 psi	-583 psi

Strength Required for Transfer, f'c = 6478.3 psi (f'c specified = 5000 psi)
Strength Required for Initial Lifting, f'c = 6478.3 psi (f'c assumed = 5000 psi)

CRACK CONTROL
(+ve = tension, -ve = compression)

Beam not cracked, cracking is controlled, or crack depth is less than concrete cover.

DEFLECTION ESTIMATE AT ALL STAGES

Project:
Problem:

Design Code Used: CSA A23.3-04

A. Deflections at All Stages
(-ve = deflection down, +ve = camber up)

Location x ft Column	Net Deflection: Net @ Transfer in A	Net @ Erection in B	Net @ Completion in C	Net DL @ Final in D	Net Total @ Final in E	Change in Deflection: DL growth + LL in E - C	LL alone in E - D	Span/Deflection: DL growth + LL	LL alone
0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0
2.87	0.200	0.297	0.357	0.186	0.186	-0.171	0.000	2017	0
5.73	0.358	0.526	0.629	0.302	0.302	-0.327	0.000	1053	0
8.60	0.470	0.684	0.816	0.365	0.365	-0.451	0.000	762	0
11.47	0.537	0.777	0.925	0.394	0.394	-0.531	0.000	647	0
14.33	0.559	0.807	0.961	0.402	0.402	-0.559	0.000	615	0
17.20	0.537	0.777	0.925	0.394	0.394	-0.531	0.000	647	0
20.07	0.470	0.684	0.816	0.365	0.365	-0.451	0.000	762	0
22.93	0.358	0.526	0.629	0.302	0.302	-0.327	0.000	1053	0
25.80	0.200	0.297	0.357	0.186	0.186	-0.171	0.000	2017	0
28.67	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0

Col. A: Net deflection at transfer includes prestressing and beam weight on temporary supports.
Col. B: Net deflection at erection includes prestressing and all dead loads applied before the cast-in-place pour plus long-time deflection growth of the prestressing and beam weight up to erection
Col. C: Net deflection at completion of construction includes prestressing and all dead loads plus long-time deflection growth of the prestressing and dead load up to completion
Col. D: Net DL deflection at final includes prestressing, all dead loads, and sustained live loads,. plus long-time deflection growth.
Col. E: Net total deflection at final includes prestressing, all dead loads, and all live loads, plus long-time deflection growth.

Live load includes roof load, and fluid weight. Wind and earthquake are not included.
Deflection growth is estimated by use of the PCI suggested multipliers - see the Deflection Multipliers report.

Span/Deflection Limits: DL growth + LL = L / 480 for non-structural attachments
L / 240 otherwise
LL alone = L / 360 for floors
L / 180 for roofs

SUPPORT ROTATIONS, AND CHANGE OF LENGTH AT ALL STAGES

Design Code Used: CSA A23.3-04

B. Unrestrained Support Rotations at All Stages
(-ve = counter-clockwise rotation, +ve = clockwise rotation)

Support Location Column	Net Rotation: Net @ Transfer degrees A	Net @ Erection degrees B	Net @ Completion degrees C	Net DL @ Final degrees D	Net Total @ Final degrees E	Change in Rotation: DL growth + LL degrees E - C	LL alone degrees E - D
Left	-0.0137	-0.0206	-0.0247	-0.0134	-0.0134	0.0113	0.0000
Right	0.0137	0.0206	0.0247	0.0134	0.0134	-0.0113	0.0000

C. Unrestrained Longitudinal Change of Length Due to Creep and Shrinkage
(-ve = shortening, +ve = elongation)

Elastic Shortening = -0.1249 in

	Total Change of Length (after elastic shortening)	Erection in B	Completion in C	Final in D		Difference in Change: to Compl. in C - B	to Final in D - C	to Final in D - B
Creep		-0.0894	-0.1240	-0.1871		-0.0346	-0.0631	-0.0977
Shrink.		-0.0413	-0.0622	-0.0775		-0.0209	-0.0152	-0.0361
Total		-0.1307	-0.1862	-0.2645		-0.0555	-0.0783	-0.1339

FLEXURAL DESIGN CHECK

Design Code Used: CSA A23.3-04
β used: for precast beam = 0.858
α used: for precast beam = 0.783
Material Resistance Factors Used: precast concrete = 0.70
cast-in-place concrete = 0.65
reinforcing steel = 0.85
prestressing steel = 0.90

Modulus of Rupture of Precast Concrete, fr = 583 psi (tension)

x ft	Factored Moment Mf kipft	Provided Resistance Mr kipft	Cracking Moment Mcr kipft	Minimum Required Resistance kipft	Depth in Compression c in	Compression Depth Ratio c / d	Notes & Warnings
0.00	0.0	2.4	266.7	0.0	0.04	0.002	
2.87	427.7	2038.8	1936.0	570.2	13.54	0.564	
5.73	760.3	2276.8	1974.2	1013.8	16.54	0.689	
8.60	997.9	2285.2	2001.3	1330.6	16.65	0.694	
11.47	1140.5	2290.1	2017.6	1520.6	16.73	0.697	
14.33	1188.0	2291.7	2023.0	1584.0	16.75	0.698	
17.20	1140.5	2290.1	2017.6	1520.6	16.73	0.697	
20.07	997.9	2285.2	2001.3	1330.6	16.65	0.694	

22.93	760.3	2276.8	1974.2	1013.8	16.54	0.689	
25.80	427.7	2038.8	1936.0	570.2	13.54	0.564	
28.67	0.0	2.4	266.7	0.0	0.04	0.002	
Points of Maximum and Minimum Factored Moment							
14.33	1188.0	2291.7	2023.0	1584.0	16.75	0.698	
0.00	0.0	-0.6	221.8	0.0	0.03	0.001	
Points of Maximum Ratio of Factored Moment to Provided Resistance							
14.33	1188.0	2291.7	2023.0	1584.0	16.75	0.698	
0.00	0.0	-0.6	221.8	0.0	0.03	0.001	
Points of Maximum Ratio of Minimum Resistance to Provided Resistance							
14.33	1188.0	2291.7	2023.0	1584.0	16.75	0.698	
0.00	0.0	-0.6	221.8	0.0	0.03	0.001	

SHEAR DESIGN CHECK

Design Code Used: CSA A23.3-04

x ft	Design Shear Vf kip	Prestress Component Vp kip	Concrete Resistance Vc kip	Resistance Provided Stirrups Vs kip	Resistance Provided Total Vr kip	Min. Resistance Req'd Stirrups Vs kip	Min. Resistance Req'd Total Vr kip	Notes & Warnings
0.00	144.9	0.0	293.2	95.1	388.3	71.6	364.8	5
2.87	132.6	0.0	234.9	76.1	311.0	57.3	292.2	
5.73	99.5	0.0	234.9	76.1	311.0	57.3	292.2	
8.60	66.3	0.0	234.9	76.1	311.0	57.3	292.2	
11.47	33.2	0.0	234.9	76.1	311.0	57.3	292.2	
14.33	0.0	0.0	234.9	76.1	311.0	57.3	292.2	
17.20	-33.2	0.0	-234.9	-76.1	-311.0	-57.3	-292.2	
20.07	-66.3	0.0	-234.9	-76.1	-311.0	-57.3	-292.2	
22.93	-99.5	0.0	-234.9	-76.1	-311.0	-57.3	-292.2	
25.80	-132.6	0.0	-234.9	-76.1	-311.0	-57.3	-292.2	
28.67	-144.9	0.0	-293.2	-95.1	-388.3	-71.6	-364.8	5

Notes & Warnings
5 - Note: Design shear force limited to critical section near support.

TORSION DESIGN CHECK

Design Code Used: CSA A23.3-04

x ft	Design Torsion Tcr/4 kipft	Threshold Torsion Stress kipft	Combined Shear and Torsion Limit psi	Combined Shear and Torsion Tf psi	Torsion Resistance Provided Tr kipft	Torsion Resistance Required Tr kipft	Notes & Warnings
0.00	0.0	39.1	0	0	0.0	0.0	2
2.87	0.0	94.8	0	0	0.0	0.0	
5.73	0.0	95.7	0	0	0.0	0.0	
8.60	0.0	96.3	0	0	0.0	0.0	
11.47	0.0	96.7	0	0	0.0	0.0	
14.33	0.0	96.9	0	0	0.0	0.0	
17.20	0.0	96.7	0	0	0.0	0.0	
20.07	0.0	96.3	0	0	0.0	0.0	
22.93	0.0	95.7	0	0	0.0	0.0	
25.80	0.0	94.8	0	0	0.0	0.0	
28.67	0.0	39.1	0	0	0.0	0.0	2

Notes & Warnings
2 - Note: Design torsion force limited to critical section near support.

SHEAR/TORSION TRANSVERSE REINFORCING DESIGN CHECK

Design Code Used: CSA A23.3-04

x ft	Shear Steel Total (Av+2At)/s in^2/ft	Required Torsion* At/s in^2/ft	Shear Steel Provided Av/s in^2/ft	Stirrup Provided Av+2At in^2	Stirrup Spacing Provided s in	Stirrup Spacing Required s in	Notes & Warnings
0.00	0.30	0.00	0.40	0.40	12.00	15.94	2 5
2.87	0.30	0.00	0.40	0.40	12.00	15.12	2 6
5.73	0.30	0.00	0.40	0.40	12.00	15.12	2 6
8.60	0.30	0.00	0.40	0.40	12.00	15.12	2 6
11.47	0.30	0.00	0.40	0.40	12.00	15.12	2 6
14.33	0.30	0.00	0.40	0.40	12.00	15.12	2 6
17.20	0.30	0.00	0.40	0.40	12.00	15.12	2 6
20.07	0.30	0.00	0.40	0.40	12.00	15.12	2 6
22.93	0.30	0.00	0.40	0.40	12.00	15.12	2 6
25.80	0.30	0.00	0.40	0.40	12.00	15.12	2 6
28.67	0.30	0.00	0.40	0.40	12.00	15.94	2 5

Notes & Warnings
2 - Note: Amount of shear steel required represents minimum code requirements.
5 - Note: Design torsion force limited to critical section near support.
6 - Note: Required stirrup spacing represents maximum code requirements.
* Portion of the total stirrup area required to resist torsional shear flow (one leg around periphery).

LONGITUDINAL REINFORCING COMBINED DESIGN CHECK

Design Code Used: CSA A23.3-04

Longitudinal Tensile Forces due to Flexure, Shear, and Torsion

Summary Report

Concise Beam, Version 4.59s, Copyright 2002-2014 Black Mint Software, Inc.
Licensed to: DEFAULT - EVALUATION USE ONLY
Project:
Problem:

x ft	Bottom of Beam Applied Tension kip	Bottom of Beam Resistance kip	Top of Beam Applied Tension kip	Top of Beam Resistance kip	Notes & Warnings
0.00	0.0	0.0	0.0	0.0	
2.87	418.5	1972.0	0.0	0.0	
5.73	539.9	2372.9	0.0	0.0	
8.60	617.8	2372.9	0.0	0.0	
11.47	660.0	2372.9	0.0	0.0	
14.33	660.0	2372.9	0.0	0.0	
17.20	660.0	2372.9	0.0	0.0	
20.07	617.8	2372.9	0.0	0.0	
22.93	539.9	2372.9	0.0	0.0	
25.80	418.5	1972.0	0.0	0.0	
28.67	0.0	0.0	0.0	0.0	

Appendix Z: Axiomatic Design Breakdown (Full)

#	[FR] Functional Requirements	[DP] Design Parameters
0	Fabricate a modular pre-stressed concrete "Parking Bay"	System to fabricate a modular pre-stressed concrete "Parking Bay"
1	Support structure and vehicle load	Design for supporting the structure and vehicle loads
1.1	Support the double tee beams and the load	Design of the inverted tee beam (girder)
1.2	Connect beam and girder to allow the transfer of loads	Design of dapped end
1.3	Support the axial and seismic loading for the tributary area	Design of Columns
1.4	Connect the columns and inverted tee beam (girder)	Corbel Connection
1.5	Transfer load down to the footings	Foundations
2	Accomodate motion of vehicles	Design that allows motion of vehicles
2.1	Distance between columns	Double tee beam with 30' x 30' dimensions
2.2	Allow 8' 6" height for motion of vehicles	Column design and height
3	Allow for structure to be reproducible	System for producing structures on demand
3.1	Create a mold for the bay reproduction	Fabricate a mold for the bay reproduction
3.2	Design that fits site space	Design of the bay
4	Provide for easy field assembly	Method for field assembly
4.1	Pre-stage and transport materials to site	System of pre-staging and transporting bay parts
4.2	Deliver materials in proper order	Delivery schedule and timing
4.3	Monitor quality of structure assemblage	Method of monitoring quality assurance
4.4	Have machinery/labor necessary to assemble	Arrange machinery/labor schedule according to each activity
5	Produce a finacially viable modular bay	Cost of production, assembly, and maintenance
5.1	Select material with low cost	Type of material slected
5.2	Mantain a low assembly cost	System of assembly
5.3	Sustain a low maintenance cost	System for maintenance of the structure
6	Span 30' x 30' space	Method to span 30' x 30' space
6.1	Dimensions of 30' x 30'	dimensions of double tee beam
6.2	Maximize load capacity and minimize self weight	cross-sectional area of double tee beam
6.3	Sufficient strength to carry load	type of concrete
6.4	Sufficient pre-stress force	number of pre-stressing strands
6.5	Un-cracked when casting	eccentricity of pre-stressing strands
6.6	Remain uncracked under service	number of pre-stressing strands

LEED 2009 for New Construction and Major Renovations

Project Checklist

Project Name

Date

Sustainable Sites — Possible Points: 26

Y	?	N	Item	Description	Points
Y			Prereq 1	Construction Activity Pollution Prevention	
			Credit 1	Site Selection	1
			Credit 2	Development Density and Community Connectivity	5
			Credit 3	Brownfield Redevelopment	1
			Credit 4.1	Alternative Transportation—Public Transportation Access	6
			Credit 4.2	Alternative Transportation—Bicycle Storage and Changing Roon	1
			Credit 4.3	Alternative Transportation—Low-Emitting and Fuel-Efficient Ve	3
			Credit 4.4	Alternative Transportation—Parking Capacity	2
			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 — Possible Points: 10

Y	?	N	Item	Description	Points
Y			Prereq 1	Water Use Reduction—20% Reduction	
			Credit 1	Water Efficient Landscaping	2 to 4
			Credit 2	Innovative Wastewater Technologies	2
			Credit 3	Water Use Reduction	2 to 4

Energy and Atmosphere — Possible Points: 35

Materials and Resources, Continued

Y	?	N	Item	Description	Points
			Credit 4	Recycled Content	1 to 2
			Credit 5	Regional Materials	1 to 2
			Credit 6	Rapidly Renewable Materials	1
			Credit 7	Certified Wood	1

Indoor Environmental Quality — Possible Points: 15

Y	?	N	Item	Description	Points
Y			Prereq 1	Minimum Indoor Air Quality Performance	
Y			Prereq 2	Environmental Tobacco Smoke (ETS) Control	
			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 and Sealants	1
			Credit 4.2	Low-Emitting Materials—Paints and Coatings	1
			Credit 4.3	Low-Emitting Materials—Flooring Systems	1
			Credit 4.4	Low-Emitting Materials—Composite Wood and Agrifiber Product	1
			Credit 5	Indoor Chemical and 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 and Views—Daylight	1
			Credit 8.2	Daylight and Views—Views	1

Appendix BB: Site Visit Photos

Underground Parking Garage Site from Front St. View

Building E Area from Trumble St. View

Front St. bridge

Ball field area from Front St. View

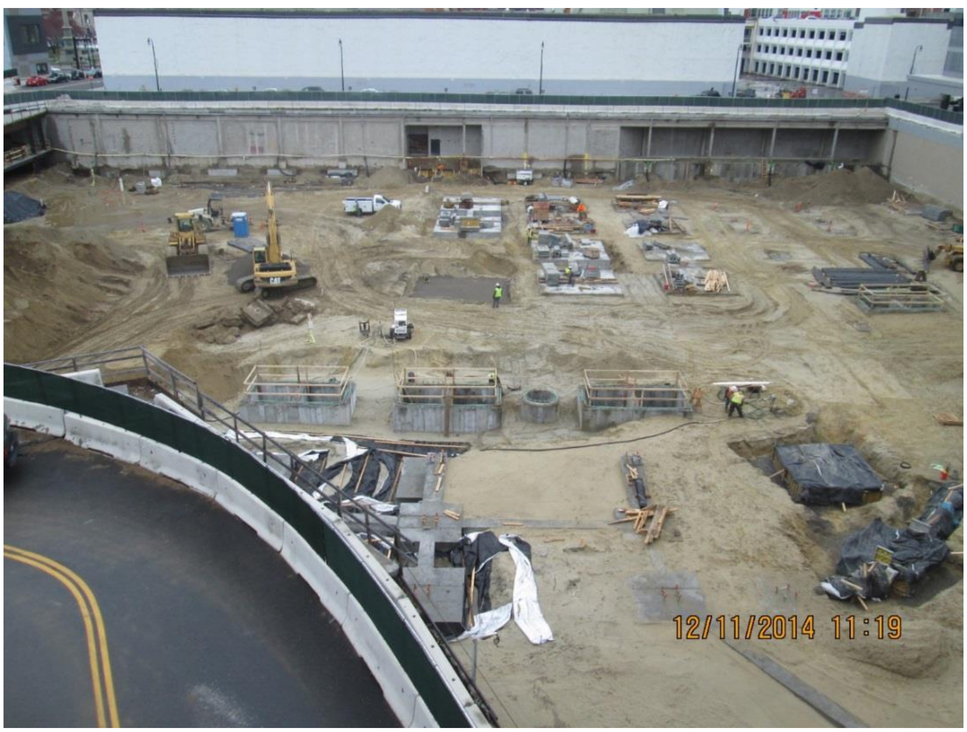
East Garage Mitigation area from Ball field area view

Ball Field Area Time Lapse


11/19/2014 13:03


11/25/2014 16:11


12/04/2014 08:38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12/18/2014 09:33

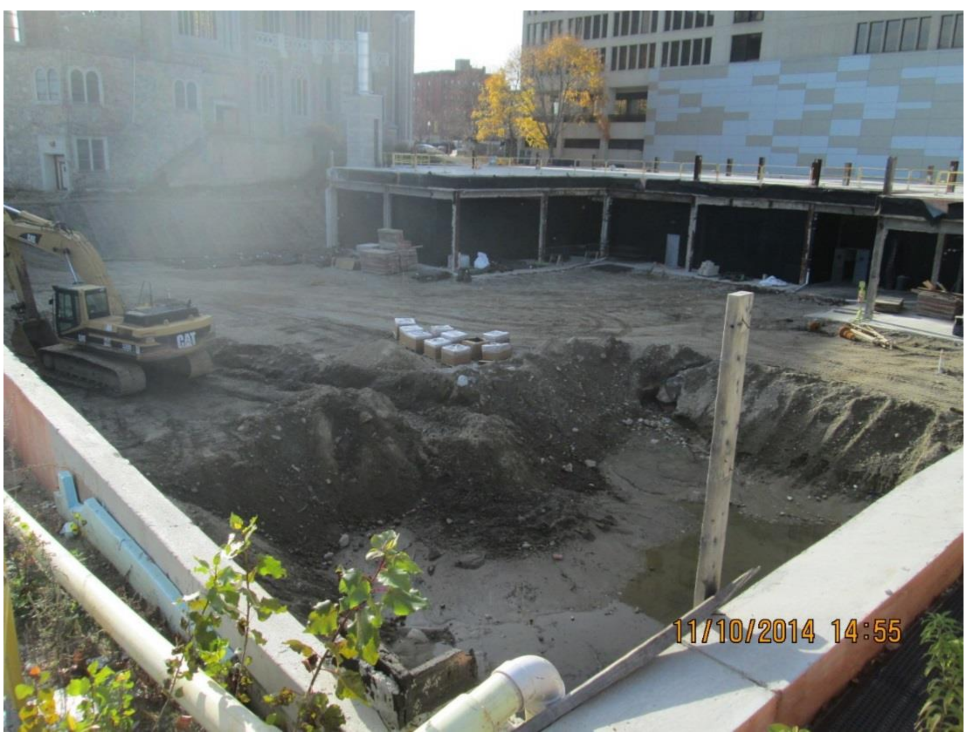

12/26/2014 12:17


01/12/2015 13:52


01/21/2015 15:37


01/30/2015 12:12

Hotel Area Time Lapse

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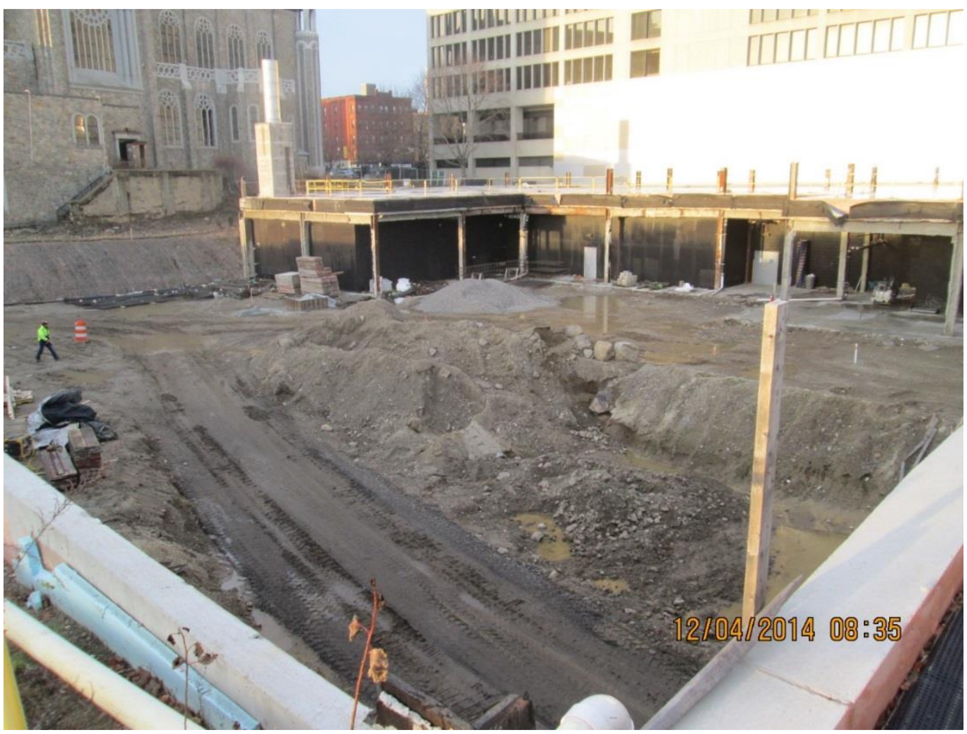
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01/15/2015 16:22


01/21/2015 15:44


01/22/2015 14:36


01/30/2015 12:19


02/10/2015 13:36

Appendix CC: Electronic Files

Outlined below are all the files that contain all the calculations made for each of the chapters of the report. These files can be found in the "E-Files" folder in the my.wpi site for the project. For further details on each of the calculations please refer to the respective chapter and file.

Project Management Analysis

- **Project Management Tracking Sheets – File: "Project Management Tracking Sheets 3.6.15"**
  Spreadsheets containing data on all RFI's, Submittals, Change Requests, and GMP.
  - Tab 1 – Miscellaneous Graph
  - Tab 2 – RFI's
  - Tab 3 – Submittals
  - Tab 4 – Change Requests
  - Tab 5 – GMP

Lean Construction

- **Lean Survey – File: "Lean Survey"**
  - Tab 1 – Survey #1 Responses
    Contains the responses from all 3 members of Consigli during the first round and includes tables comparing the responses.
  - Tab 2 – Survey #2 Responses
    Response Comparison
    Contains the responses from all 3 members of Consigli during the second round and includes tables comparing the responses of the first and second survey.

Alternative Design Calculations

- **Project Drawings – File: "03-Architectural, 04 Structural"**
  - *Contains construction drawings for the CitySquare Underground Parking Garage.*
- **Alternative Design Calculations – File: "MQP Final Prestressed Calculations"**
  The design process broken up by components based on load calculations in Tab 1.
  - Tab 1 – Load Calculations
  - Tab 2 – Double T Beam Zone A
  - Tab 3 – Double T Beam Zone C
  - Tab 4 – Inverted T Beam Zone A
  - Tab 5 – Inverted T Beam Zone C
  - Tab 6 – Column Design
  - Tab 7 – Foundation Check
- **Concise Beam Calculations for Double Tee– File: "Double Tee-concisedesign"**
  - *Contains in depth structural calculations for designed prestressed double tee.*
- **Concise Beam Calculations for Inverted Tee– File: "Inverted T Beem concisedesign"**
  - *Contains in depth structural calculations for designed prestressed inverted tee.*
- **Google Sketchup Alternative Bay– File: "Double Tee-concisedesign"**
  - *Contains 3-D model for alternative design bay.*

Axiomatic Design

- **Non-optimized AD – File: "02.17.15 NOT optimized"**
  Contains the Axiomatic Design breakdown and matrix of without the optimization.

- **Optimized AD – File: "02.17.15 optimized"**
  Contains the Axiomatic Design breakdown and matrix of with the optimization.

Sustainability

- **Embodied Energy Calculations – File: "Sustainability Calculations"**
  - Tab 1 – Steel Bay
    Contains the calculations for the embodied energy of the steel bay.
  - Tab 2 – Alternative Bay
    Contains the calculations for the embodied energy of the prestressed alternative bay.
- **Cost Analysis – File: "Sustainability Calculations"**
  - Tab 3 – LCCA Steel
    Contains the life cycle cost analysis for a single bay of the steel design.
  - Tab 4 – LCCA Prestressed
    Contains the life cycle cost analysis for a single bay of the alternative prestress design.
  - Tab 5 – Cost Analysis and NPV
    Contains a full analysis and calculation breakdown of the NPV for both bays.

Miscellaneous

- **Final Presentation – File: "MQP C Term Final"**
  Contains the final presentation that outlines our results and conclusions for the entire project.

- **Revit Files for the Underground Garage – File: "City Square – Revit Files"**
  Contains the Revit files for the structural design of the City Square Parking Garage.

Appendix DD: MQP Proposal (10/17/2014)

CitySquare Underground Parking Garage

Project Proposal

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 in Civil Engineering & Management Engineering by

____

Jose A. Cueva

____

Jean Pierre Miralda

____

Saadet Nur Yilmaz

10/15/2014

Sponsor: Consigli Construction

Approved by:

____

Professor Guillermo Salazar

____

Professor Walter Towner

Abstract

As the city of Worcester continues to attract more students and businesses, and with a central location to New England, it has identified the need to expand and develop the alienated downtown area. CitySquare, a $563 million multi-phased private/public development project, will include a steel structure underground parking garage which will accommodate over 500 cars and will aid with the unanswered high demand for parking space during the past decade. We will be examining the management of the project and the alternative design of using prestressed concrete, as well as applying the concept of axiomatic design decomposition to the span length of the alternative design. To support our prestressed concrete analysis, Building Information Modeling software will be used.

Capstone Design Statement

This project focuses on the construction of a 2 story steel-structure underground parking garage in downtown Worcester, MA. The construction will be executed by the general contractor, Consigli Construction, for the owner CitySquare II development Co. LLC, and the structure will service surrounding businesses such as Unum, St. Vincent's Hospital, a future Marriot Hotel, and the general public. Given the start of the major construction activities aligns with our WPI timeline for the completion of our Major Qualifying Project, we will perform a series of analysis using actual construction documents, meeting meetings, documentation logs, and physical progress. Having access to all of these sources will allow us not only to develop a section on project management with relevant insights into the current practices of the construction industry, but will also allow us to fulfill our Design Capstone by creating an independent design that is ruled by the actual conditions of the site, the geometry of the layout, the loading distribution of the project, and the owner's needs.

To complete our Design Capstone we will create an independent structural design that replaces structural steel elements of the actual design (provided by Arrowstreet Designers and Niesch & Goldstein Structural Engineering) with precast and prestressed members. The design problem that we will address is the selection of the most cost effective, fast-tracked, sustainable and feasible construction material for a project in an urban environment rich in spatial, legal, and monetary constraints. We will approach this design problem by performing analysis on schedule, cost, communication, and sustainability on the current steel-structure design to enable us to compare its performance against our independent design based on prefabricated prestressed concrete.

To analyze the current design, we will use all the information made available by Consigli as well as our site visits and inclusion in owner's meeting to compare the expected progression of construction against the actual work completed by focusing on the relationship between construction documents and schedule or cost impacting communications such as submittals, requests for information (RFI's), and change orders. We will supplement readily available information with research to gain insight into the most up to date methods for construction sustainability, allowing us to perform analysis such as life cycle assessment and embodied energy calculations. These considerations will also be applied to our independent structural design, and will ultimately allow us to compare the two different designs.

To design our precast concrete structure, we will first extract the loading, framing, geometric, and serviceability requirements from the provided construction documents. We will take into account constraints such as having a defined site layout, geotechnical properties of the location, traffic and pedestrian accessibility, among others. Using the Precast/Prestressed Concrete Institute's (PCI) Design Manual, we will design the structural components of double T beam, inverted t beam, columns and connections. To aid the design process and add analysis into the design, we will use software such as Microsoft Autocad, Revit, and Primavera.

Table of Contents

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1.0 Introduction

Worcester is a city with a lot of history, and in recent years, it has seen an exponential growth in its demand for business development partly due to its central location in New England. With the opening of the Worcester Center Galleria in 1971, the city intended to attract a big number of businesses and export the fashions of Boston to the suburbs while revitalizing the ailing downtown of Worcester. However, this was not the case and by 2006 the mall was closed. Following the closure, the city of Worcester proposed a development project known as CitySquare, a $563 million multi-phased private/public project which is considered the largest development project in the Commonwealth excluding the Boston Area.

Small steps have been taken since 2007 – the demolition of the mall and the construction of Unum Building and St. Vincent Cancer Center. Residents of Worcester are losing their hopes that one day they will see downtown as a commercial and vivid location, with several retail stores and residential space. However, in recent years, CitySquare II Development Co. LLC took over the project and has redesigned the original space and layout, which will now include an underground parking garage with over 500 parking spaces and an 8-story hotel to accommodate for the influx of people. The garage is the first step of the new development phase, which will be followed by the hotel, retail space, and some residential areas.

Consigli Construction, has been involved in the past 5 years with several projects and improvements to the downtown area of the city of Worcester. They will now be in charge of leading the 2-story underground parking garage which will sit in the heart of the city. Nonetheless, this presents a big challenge for Consigli, given that the project is located in an area of high traffic, a street runs over the site, and three out of the four sides adjacent to the site have buildings already. The construction team will have to develop a plan to run the project as efficiently as possible to deliver it on time and within the allowable cost. This will require a lot of communication and planning with the sub-contractors, site workers, the city manager, and the owners of the adjacent structures.

The current design of the parking garage consists of a steel structure with spread footings and slab on deck at each level. Our team is considering certain aspects which can potentially impact the project and structure significantly which include space, location, weather, and materials being utilized, amongst others. For this reason, our study will investigate an alternative design to the parking garage, and will evaluate the impact it may have on the cost, schedule, and delivery of the project. We will design an alternative prestressed structure which will take into account current site and loading conditions as well as spatial constraints. Our team will create a 3D model of the alternative design by utilizing Building Information Modeling software such as Autodesk and Primavera.

Our study will also include an evaluation and analysis of the two designs (original and alternative) based on Lean Construction concepts. The purpose of this evaluation will be to identify the activities and aspects in which Lean concepts can be applied to make the process more efficient and reduce any waste that does not add value to the end-user. A compare and contrast analysis will be made in order to identify which design is more efficient and can potentially lead to a decrease in cost and time of completion of the project.

The goal of this project is create an alternative design that still meets the criteria of CitySquare II, and determine if it is a better option. The CitySquare project management will be observed and analyzed based on their delivery in terms of scheduling, cost/quantity, and communication. The prestressed concrete alternative design will be developed and then evaluated based on lean concepts, which will include a time value of money analysis. Finally we will draw our conclusions and present our results and recommendations on the most effective structural design that could potentially offer more benefits to the project and end-user.

2.0 Background

The following chapter examines the purpose of the construction of the underground parking garage and introduces some of the concepts and analysis measures that will be used in the project. The chapter starts with an overview of the history and future development of the CitySquare project, the main reason for the construction of the garage. The following sections provide an overview of the project management and the concepts that will be important in the implementation and analysis of the project, including Lean Construction, Building Information Modeling (BIM), Axiomatic Design Decomposition, and the classification of underground spaces.

2.1 CitySquare Project

The following section explains the history of CitySquare and its development in the last couple of years. Furthermore, it explains the next steps in the development of CitySquare and how this MQP relates to the purpose of this large scale project in the city of Worcester.

2.1.1 CitySquare History

On July 29th, 1971 the Worcester Center Galleria opened for business in downtown Worcester, Massachusetts. This massive shopping center included 1,000,000 square feet of floor space and was intended to export the fashions of Boston to the suburbs while revitalizing the ailing downtown of Worcester. A 4,300-car parking structure was attached to building, and at the time being, it was the largest parking structure in the world. (Caldor, 2006) Figure **1** below shows the layout of the existing mall, parking garage, and adjacent buildings.

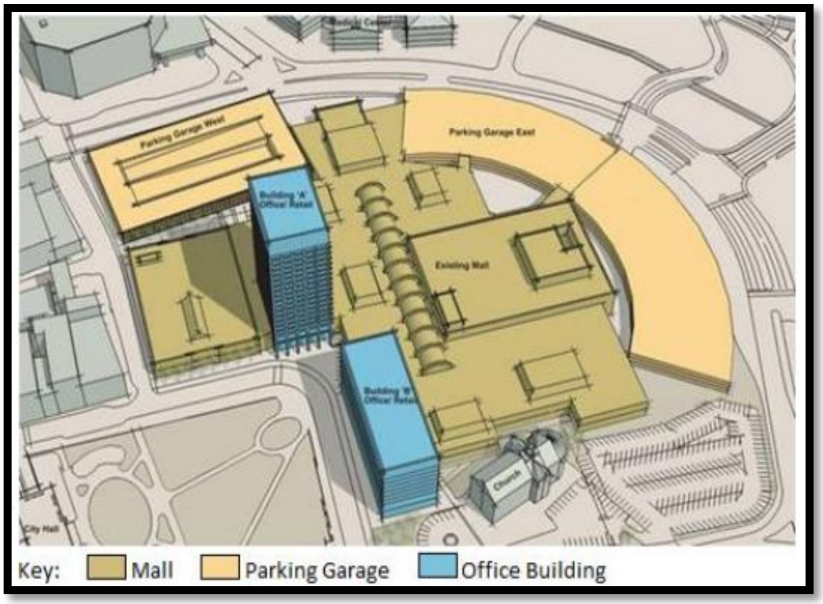


Figure 1 - Mall Site Plan (Huard, 2012)

Unfortunately, as early as 1973, the shopping center was already having issues of not being viable and losing its customers. Despite the numerous failed attempts by the city to revitalize the mall throughout the next decades, it was still considered New England's largest and most notorious dead mall. (Caldor, 2006) With the opening of the Wrentham Village Premium Outlets in 1997 the Worcester Common's area had no reason to attract any customers and it slowly started losing businesses and stores with each passing year. However, in 2004 it was announced that Berkley Investments from Boston would be purchasing and demolishing the mall, in order to rebuild downtown Worcester in a project named CitySquare; and by 2006, the mall was closed. (Caldor, 2006)

CitySquare is a $563 million multi-phased private/public project and is considered the largest development project in the Commonwealth, without the inclusion of the Boston Area. The project's goal is to create more 2.2 million square feet of commercial, medical, retail, entertainment, and residential space. (Worcester, 2014) Figure 2 below, shows the proposed development for the area that was supposed to connect Worcester's downtown with the failed mall.

Figure 2- City Square Development Plan (Huard, 2012)

However, Berkley Investments failed to comply with the General Development Agreement (GDA) between them and the City of Worcester, which required Berkley to secure a tenant for one of the designated buildings. Unum Group, a disability and life insurance based in Portland, Maine, signed a letter of intent in 2009. In 2010, plans were revived with the backing of a new investor, the Hanover Insurance Group Inc. Since then, Unum and Vanguard Health Systems Inc., the operator of St. Vincent Hospital, have been the only two developments in the area and no additional progress has been made as shown in Figure 3 (McCluskey, 2013).

Figure 3 - CitySquare Development in 2013 (McCluskey, 2013) (Source:T&G Staff, Rick Cinclair)

The demolition of the former outlet mall and parking garage has been completed, and is intended to help advance the project. However, no private investor has announced interest in the site for more than two years.

2.1.2 City Square Future Development

Since the demolition of the mall and parking garage, no development has been seen in the area. Nonetheless, there have been several conversations and negotiations as to what is the future of the CitySquare project. CitySquare II Development Co. LLC, an entity managed by Leggat McCall and funded by Opus Investment Management Inc., a subsidiary of Hanover Insurance, is now working with Consigli Construction in the next phase of the project.

There have been several conversations about the use of the space, and the vision includes commercial office space, housing, an underground parking garage, and space for street-level retail stores. In addition, they are planning on adding another component to the project and building an 8-story Marriott Renaissance hotel that will go over the underground parking garage. Figure 4 illustrates the revised plans for the CitySquare project.

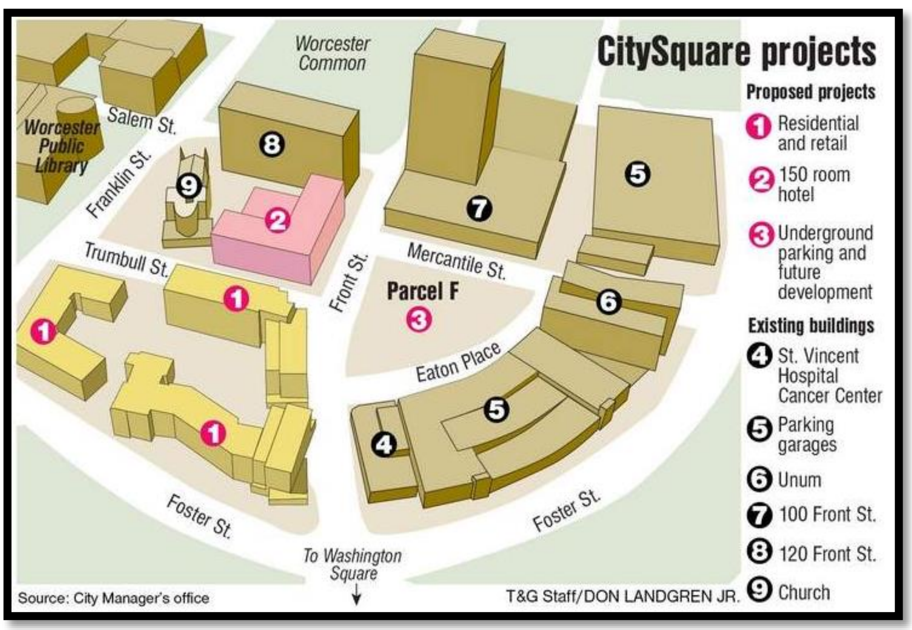


Figure 4 - CitySquare Revised Layout (Kotsopoulos, 2014) (Source: City Manager's office)

"I think the demand for hotel space in the city is at an all-time high right now," shared Craig L. Blais, president and chief executive officer of the private Worcester Business Development Corporation, with Worcester Telegram and Gazette. (McCluskey, 2013) The two-level underground parking garage will be built behind the Unum and St. Vincent buildings, in the area where the mall used to be. This parking garage is the next step to the development of CitySquare and once it is completed, the hotel, housing, and retail space will commence its development on top of it.

Minor amendments and details have been made to the design since then, with the addition of two surface entrances to the underground parking garage, so-called "head houses". These will be kept largely transparent and open, and bicycle racks will also be installed in each of them, with stairs and elevators to access the garage. (Kotsopoulos, 2014) Appendix E illustrates the construction drawings with the proposed addition of the “head houses”. In many of 2014, the Planning Board approved modifications that reduce the size of the underground garage from the planned 1,025 spaces to 580. The parking garage will now encompass less space in the project site with the changes made. (Kotsopoulos, 2014)

2.2 Consigli Construction

Consigli Construction is a fourth generation, family-owned construction firm established in 1905. The company is experienced in serving academic, corporate, life science, health care, federal, and institutional clients throughout New England and New York. (Consigli, 2014) Grossing more than $743.8 million annually, Consigli has been ranked 77 among the top 400 construction firms by Engineering News Record. They are capable of providing several different construction delivery methods such as Construction Management at Risk, design build, integrated project delivery and hard bids.

2.2.1 Consigli Construction’s involvement in City Square

Consigli Construction has been involved in the CitySquare Development Project starting from September 2010 with the demolition the former Worcester Common Fashion Outlets mall. A $110 million job of the 215,000 sq. ft. building and selective demolition of an existing parking garage was completed in June 2012. Figure 5 illustrates the demolition of the mall which has brought down 4,000 tons of steel. The steel, concrete and brick from the mall have been recycled. (Dayal, 2011)

Figure 5 - Demolition of Worcester Commons Fashion Outlets (Grillo, 2013)

City Square's first building, Unum facility (Figure 6), was also constructed by Consigli Construction and was completed on January 2013. The energy efficient building system includes a high impact corporate lobby with advanced technology and executive offices. Consigli was both responsible for the core shell and interior fit-out of the building, while coordinating the owner's installation of finishes and equipment. The $72 Million facility has achieved LEED Silver Certification (Consigli, 2014), and has attracted a lot of business and public to the downtown Worcester area. After having a strong presence for years in the city, Consigli is currently working on the underground parking garage for CitySquare II.

Figure 6 - The UNUM Building in Downton Worcester (Grillo, 2013)

2.2.2 Consigli Gateway Server

Consigli uses *Gateway* software which acts as a bridge between multiple networks to allow communication between the owner, architects, engineers and subcontractors. The project team is able access all of the project documents under one cloud as well as adding and editing documents to expedite the communication speed. The server includes the documentation of the following information; construction drawings, meeting minutes, submittals, RFI's, change management and project schedule. This is a great tool for our project to get updates on the project documents and observe the communication between key players of the project. The figure below shows the layout of the user friendly gateway page.

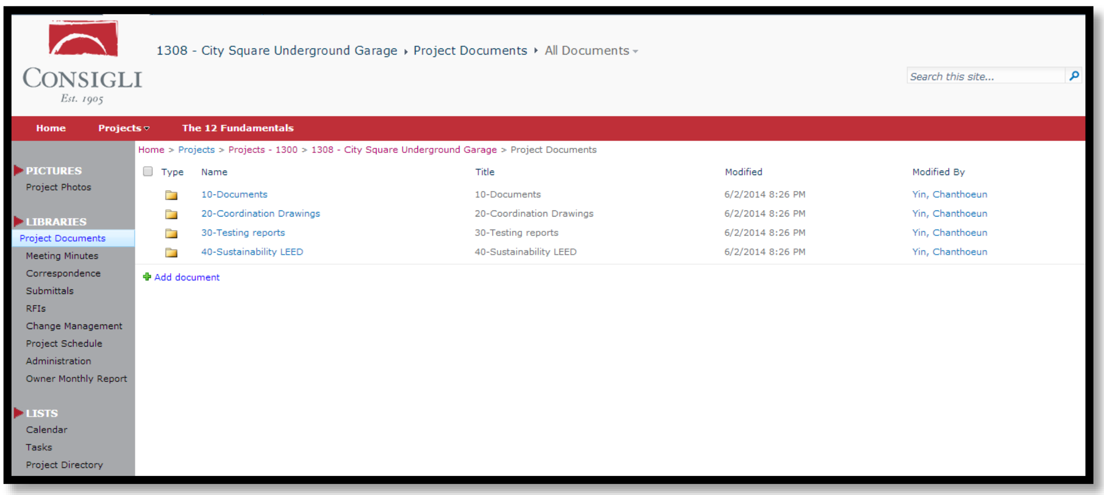


Figure 7 - Consigli Gateway for 1308 City Square Project

2.3 Project Specifications

2.3.1 Overview

Recent investments in infrastructure by both private and public funds in the downtown Worcester area have created a demand for increased parking spaces for daily commuters, visitors, professionals, and students. Limited available space downtown motivated the construction of a facility that would meet the parking needs of the city while minimizing its impact on potential future developments. As a result, the parking garage will be constructed entirely underground and will feature aboveground elements such as green space and head-houses that will add to Worcester's development.

2.3.2 Scope

The project undertaken by Consigli Construction consists of building an underground parking garage as indicated in the final construction documents within a guaranteed maximum prized. The parking garage is to have 2 levels, housing over 500 vehicles and 2 entrances from the street level, as well as 2 head-houses on the street level and a green space over the "Ballpark" section of the parking garage. The garage features steel construction and extends under Front Street of the city of Worcester.

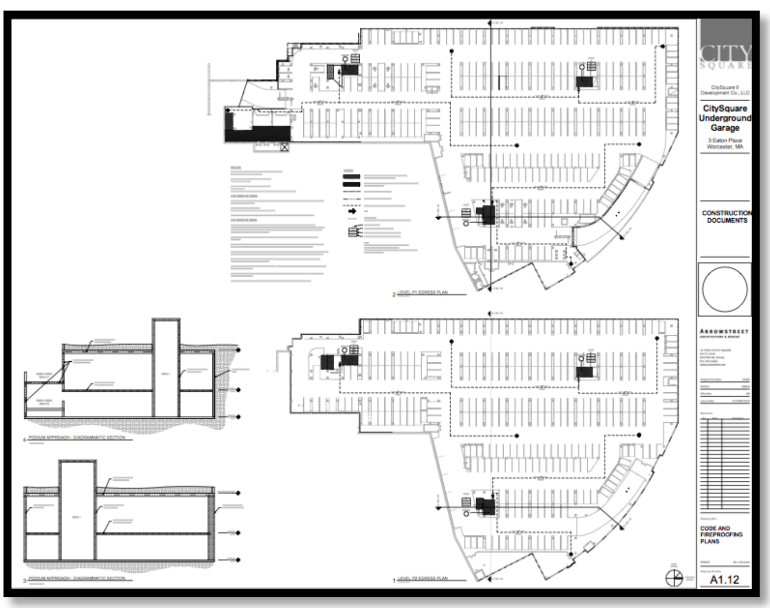


Figure 8 - Architectural drawings by levels and elevations of the underground parking garage (Gateway)

2.3.3 Organizational Breakdown Structure (OBS) of Consigli Construction

The organizational breakdown structure for the City Square Underground parking garage project is illustrated in the Figure 9 below. The owner, City Square II, has a representative who oversees the entire project and delivers the project in a consulting capacity. Consigli Construction's organizational structure starts the with the president of the company who oversees the Projective Executive who leads, manages and coordinates the overall direction, completion, and financial outcome of the project. Additionally, he also mentors a team of project managers and engineers. The Project Manager, Superintendent, and MEP manger work together and are responsible for the safe completion of the project within the proposed budget and schedule, company's quality standards, and customer's satisfaction. (Consigli, 2014) The architecture firm, Arrowstreet Inc., coordinates and leads the structural, civil and MEP/FP engineers to deliver the design aspect of the project more efficiently.

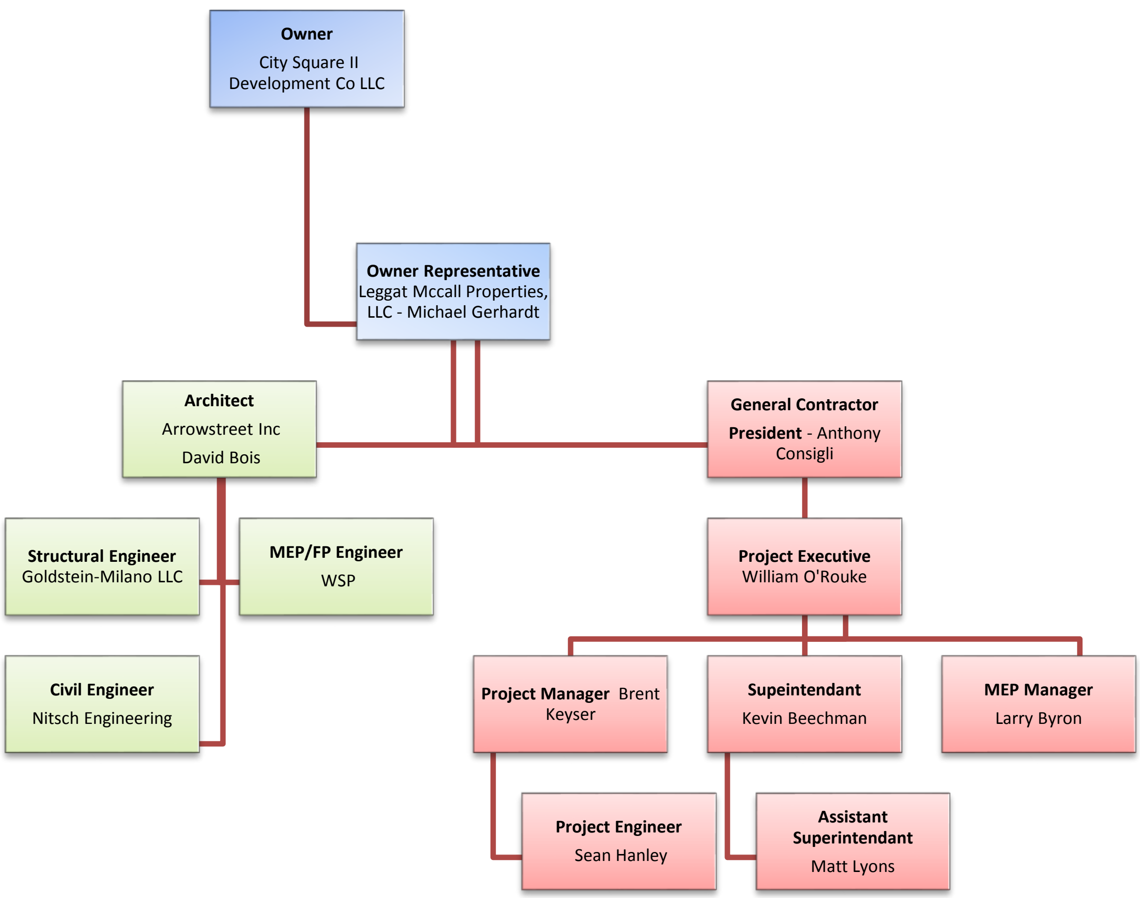
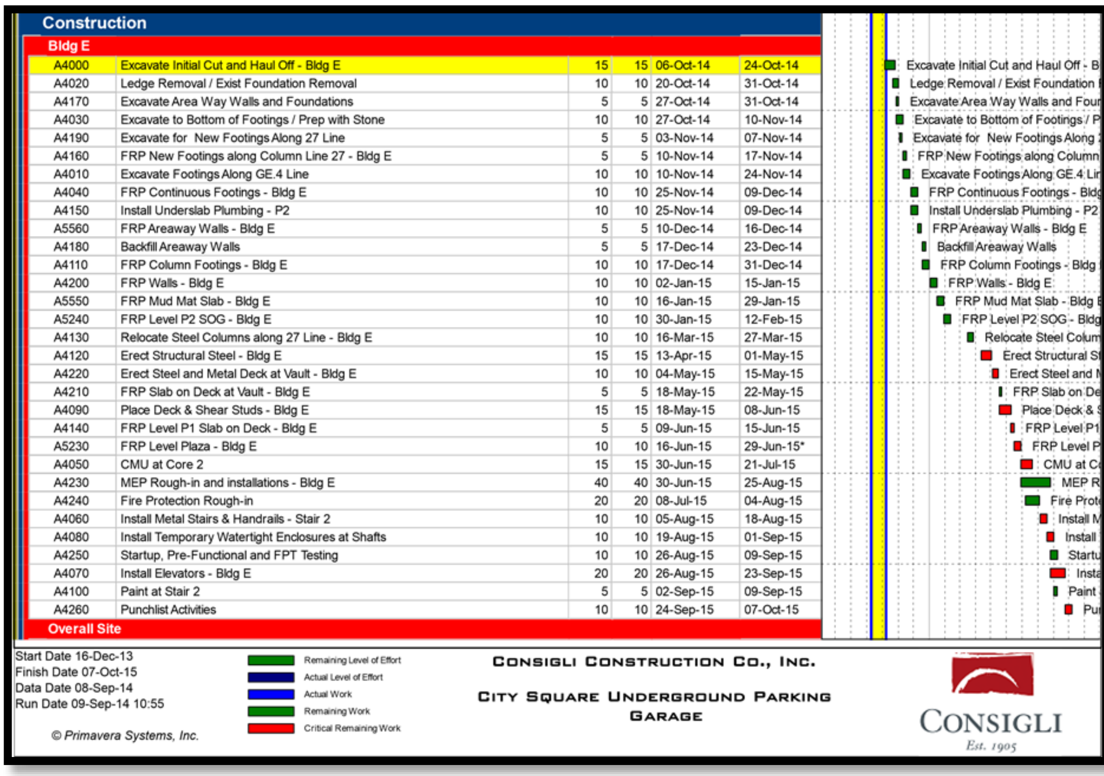


Figure 9 - OBS for CitySquare Underground Parking Garage Project

2.3.4 Schedule

The schematic design of the underground parking garage was approved in January 24, 2014 and construction documents were finalized and approved on July 21st, 2014. Consigli's involvement began on June 30th, 2014 and received notice to proceed on September 14th, 2014. The delay between the start of the project and the notice to proceed came as a consequence of setbacks on the guaranteed maximum price (GMP) negotiation between the owner, CitySquare II, and the general contractor, Consigli Construction. The planned completion date for the project is October 7th, 2015.



Construction					
Bldg E					
A4000	Excavate Initial Cut and Haul Off - Bldg E	15	15	06-Oct-14	24-Oct-14
A4020	Ledge Removal / Exist Foundation Removal	10	10	20-Oct-14	31-Oct-14
A4170	Excavate Area Way Walls and Foundations	5	5	27-Oct-14	31-Oct-14
A4030	Excavate to Bottom of Footings / Prep with Stone	10	10	27-Oct-14	10-Nov-14
A4190	Excavate for New Footings Along 27 Line	5	5	03-Nov-14	07-Nov-14
A4160	FRP New Footings along Column Line 27 - Bldg E	5	5	10-Nov-14	17-Nov-14
A4010	Excavate Footings Along GE.4 Line	10	10	10-Nov-14	24-Nov-14
A4040	FRP Continuous Footings - Bldg E	10	10	25-Nov-14	09-Dec-14
A4150	Install Underslab Plumbing - P2	10	10	25-Nov-14	09-Dec-14
A5560	FRP Areaway Walls - Bldg E	5	5	10-Dec-14	16-Dec-14
A4180	Backfill Areaway Walls	5	5	17-Dec-14	23-Dec-14
A4110	FRP Column Footings - Bldg E	10	10	17-Dec-14	31-Dec-14
A4200	FRP Walls - Bldg E	10	10	02-Jan-15	15-Jan-15
A5550	FRP Mud Mat Slab - Bldg E	10	10	16-Jan-15	29-Jan-15
A5240	FRP Level P2 SOG - Bldg E	10	10	30-Jan-15	12-Feb-15
A4130	Relocate Steel Columns along 27 Line - Bldg E	10	10	16-Mar-15	27-Mar-15
A4120	Erect Structural Steel - Bldg E	15	15	13-Apr-15	01-May-15
A4220	Erect Steel and Metal Deck at Vault - Bldg E	10	10	04-May-15	15-May-15
A4210	FRP Slab on Deck at Vault - Bldg E	5	5	18-May-15	22-May-15
A4090	Place Deck & Shear Studs - Bldg E	15	15	18-May-15	08-Jun-15
A4140	FRP Level P1 Slab on Deck - Bldg E	5	5	09-Jun-15	15-Jun-15
A5230	FRP Level Plaza - Bldg E	10	10	16-Jun-15	29-Jun-15*
A4050	CMU at Core 2	15	15	30-Jun-15	21-Jul-15
A4230	MEP Rough-in and installations - Bldg E	40	40	30-Jun-15	25-Aug-15
A4240	Fire Protection Rough-in	20	20	08-Jul-15	04-Aug-15
A4060	Install Metal Stairs & Handrails - Stair 2	10	10	05-Aug-15	18-Aug-15
A4080	Install Temporary Watertight Enclosures at Shafts	10	10	19-Aug-15	01-Sep-15
A4250	Startup, Pre-Functional and FPT Testing	10	10	26-Aug-15	09-Sep-15
A4070	Install Elevators - Bldg E	20	20	26-Aug-15	23-Sep-15
A4100	Paint at Stair 2	5	5	02-Sep-15	09-Sep-15
A4260	Punchlist Activities	10	10	24-Sep-15	07-Oct-15
Overall Site					

Figure 10 - Building E proposed schedule

2.3.5 Cost

The contract calls for a guaranteed maximum price (GMP) for the project, also known as not-to-exceed price (NTE or NTX). Under this cost related contract, the Consigli bills for the cost of the work performed plus a fixed fee or percentage without exceeded a predetermined allowance. (Cushman, 1999) The ceiling prices were negotiated between CitySquare II and Consigli, as well as the allowances providing flexibility in the contract. The total cost of the project is expected to be around $28,000,000.00

2.4 Lean Construction

The term "Lean Construction" found its way into the construction industry in 1993. Two key organizations have led the thought leadership of the topic: The International Group for Lean Construction (IGLC) founded in 1993 and The Lean Construction Institute (LCI) founded in 1997". (Sayer, 2012) *Lean,* originated in the late 1980's from Toyota automotive manufacturing, and is a customer-focused methodology to deliver value to customers through the effective use of resources. "The aim of Lean is to deliver the customer's value when they want it, how they want it, where they want it, at a price they will pay, and using all resources most effectively – time, money, and people." (Sayer, 2012) Lean construction is a management-based approach to project delivery, and focuses on changing the delivery process of it. The focus is on improving the overall performance and delivery of the project instead of reducing cost and time from certain activities.

Lean construction challenges the belief that there must always be a trade between time, cost, and quality. The table below shows a comparison between a traditional project and a lean project.

	Traditional Projects	**Lean Construction Projects**
Operating System	Critical Path Management (push)	Last Planner (pull)
Organizational Model	Command and Control	Collaborate/Distribute Authority
Commercial Terms	Transactional	Relational - shared risk

Table 1 - Comparison of Traditional and Lean Projects (Sayer, 2012)

One important aspect to notice from Table 1 is that Lean Construction focuses on optimizing the overall project flow, unlike traditional projects which instead focus on optimizing individual pieces. Lean principles can be applied to several areas of a construction project, but they are only effective if they focus on improving the whole process. Some areas of focus may include the design, procurement, production planning, logistics, and the construction itself. Construction is the area that might be most applicable to Lean concepts as the physical putting together of structures/roadways/design elements is the goal of all projects. Some aspects to consider include: clear communication of project ideas, training, multitasking, progress reporting, and improving meetings. (Excellence, 2004)

There have been several successful groups and companies that have implemented Lean concepts to their projects. However, there is still a lot of opposition to institute a change in the industry because most of the players involved believe in the traditional approach they have operated in the past.

This is reflected in the productivity in the US Construction Industry, which has stayed leveled or declined since 1964, depending on the study used, as shown in Figure 11 below. (Sayer, 2012) Despite the stagnant trend line below, many building owners are now expecting Lean concepts and practices to be applied in their projects and reflected in the Request for Proposals, thus potentially improving the industry's productivity.

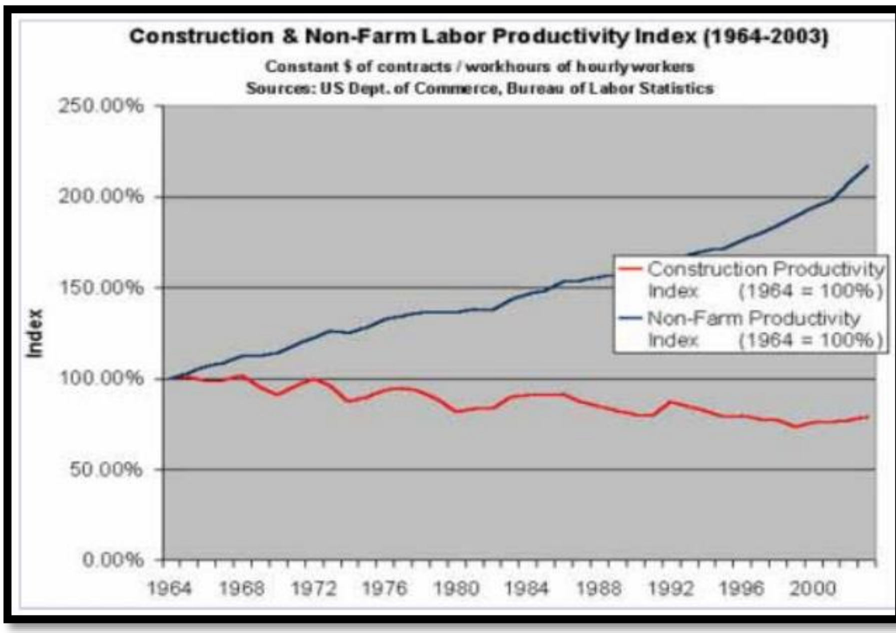


Figure 11 - Labor Productivity Index for the U.S. Construction Industry and all Non-farm Industries. (Sayer, 2012)
(Original Source: Teicholz, Paul. "Labor Productivity Declines in the Construction Industry" AECbytes Viewpoint. Issue 4. April 14, 2004)

Some of the benefits presented by using Lean Construction include better budget performance, higher on-time performance, fewer accidents, and better value delivered to the customer with the completion of the project. Beyond it being a different approach to the entire construction sequence, Lean fosters the use of advanced technology and software to support its core principals. The most important advancement is Building Information Modeling (BIM), a technology that allows the team to design multi-dimensional models of a facility, and enables Lean Project Delivery. With BIM, "the team can evaluate multiple design alternatives, make better design decisions, make better costing decisions, have more communication earlier in the project, and create production system plans directly into the model earlier in the process." (Sayer, 2012) This technology will be used in this project and will allow for the analysis and delivery of Lean Construction principles to this project.

2.5 Axiomatic Design

Axiomatic Design is an approach to engineering design based on two axioms, or laws, which assure that the most effective design is being utilized. It can be applied to the entire design process of a project, including the planning or manufacturing. In its essence, it aims to identify a design which (1) maximizes the independence of the functional elements and (2) minimizes the information content. (Brown, 2013) Figure 12 below outlines the Axiomatic Design process which correlates four domains, with the left representing "what we want to achieve" and the right domain representing the solution to "how we want to achieve those goals". (Angwafo, 2014)

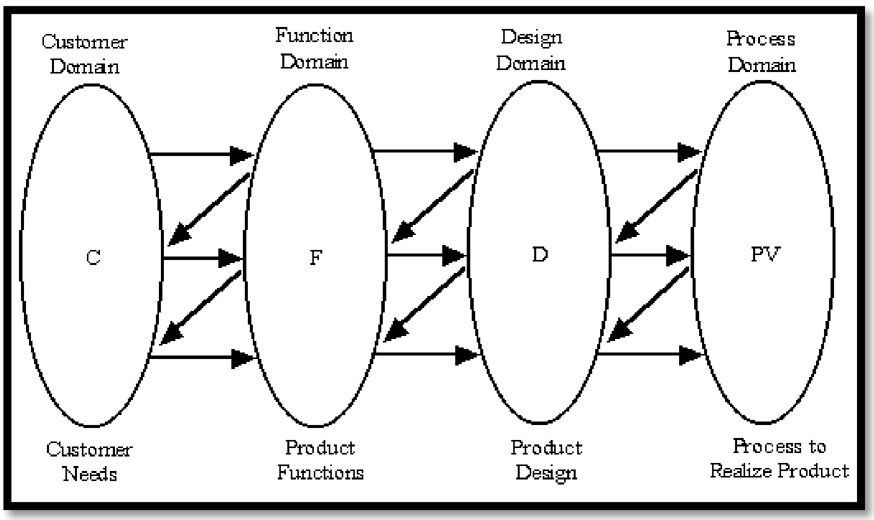


Figure 12 – Axiomatic Design Process (Sohlenius, 1998)

Axiomatic Design was first identified by Nam P. Suh, president of KAIST and MIT professor, in the late 70's in Cambridge, MA. Suh was able to develop this concept which is now applied across industries and has identified three essential components for it:

- Axioms (independence and information)
- Structure (lateral and vertical decomposition)
- Process (zigzagging decomposition)

This approach helps identify the best design solution from a conceptual stage and ensures that the customer is receiving the most added value. The section on axiomatic design decomposition in Chapter 4, will elaborate more on the application of this method to the construction project.

2.6 Building Information Modeling (BIM)

The term building information modeling (BIM) has been present in the construction industry's vocabulary since 2002. When it was first introduced, industry analysts debated over the meaning of the three letter acronym, but all agreed that this was the "next generation of design software" after computer-aided design (CAD) (Smith, et. all. 2009). (Building Information Modeling: A Strategic Implementation Guide for Architects, Engineers, Constructors, and Real Estate Asset Managers) Autodesk, a world leader in 3D design software for entertainment, natural resources, manufacturing, engineering, construction, and civil infrastructure, defines BIM as an "intelligent model-based process that provides insight to help you plan, design, construct, and manage buildings and infrastructure" (Autodesk, 2014). The key word to note in this definition is "process", for it qualifies BIM not as a product or a tool, but a sequence of actions that involve participation from the different parties involved.

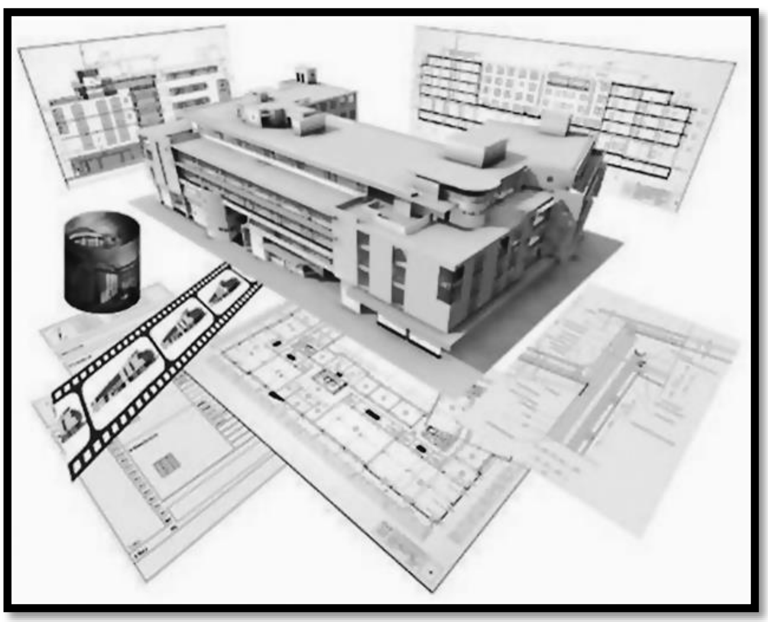


Figure 13 - BIM graphic showing various types of information being derived from a 3D model, e.g., plans, sections, etc., and component information. (Smith, et. all. 2009)

A second definition for BIM from an academic standpoint defines it as a "*project* as well as a *process* simulation", thus emphasizing the visualization capabilities of the technology (Kymmel, 2008). Creating a computer modelled construction process much like the real construction work is labor intensive and rich in information. The planning process to create a comprehensive simulation requires the same considerations the constructors at the field would be concerned about: time, space, cost, and scheduling. Like the work it parallels, BIM modeling requires constant reevaluation and adaptation as conditions change throughout the life of the project. This gives the interactive computer model relevance and accuracy as a projection that is weeks if not months ahead of the tangible construction work, thus potentially resolving issues before they materialize.

BIM models are most beneficial when created as both as a tool for coordination among all parties involved (designers, construction managers, owner, subcontractor, and trades) and as a vehicle to increase understanding on the intricacies of any project. When used as a medium through which all parties further the understanding of their individual role and their role as team members in a largely coordinated time-spanning effort, these computerized simulations represent the most accurate and detailed account of the building, tower, or structure that is to be built. By having one master simulation that incorporates all parties, sometimes referred to as a composite model, construction documents are more transparent, detailed, and living than their predecessors in paper or in 2-D. (Smith, 2009) Building this comprehensive model is a unique opportunity in the construction process to become intimately familiar with the project and all of its components.

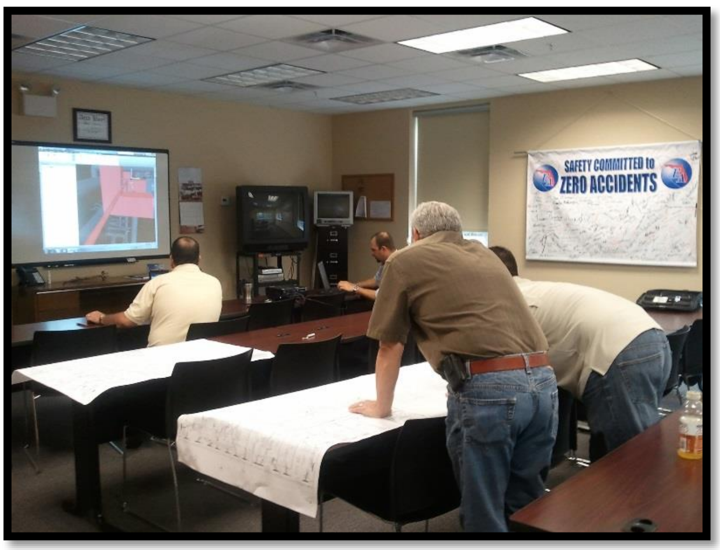


Figure 14 - Representatives from different trades gather to review BIM simulation for potential clashes (Energy Air, 2012).

Benefits of BIM

The benefits of using BIM technology in construction projects come through the facilitation of updated information to all parties, reduced field coordination problems, more accurate construction schedule, and multidimensional display of activities. According to an article published in the International Journal of Project Management, "The most frequently reported benefit related to the cost reduction and control through the project life cycle" along with time savings (Bryde, et. all. 2013). A case study on the same publication reviewed 35 case studies which mentioned positive and negative benefits of the use of BIM using success criteria related to the output of the project, including meeting time, cost and quality objectives and also objectives related to the management of the process, such as effective scope management and communications. (Bryde, et. all. 2013) The following table summarizes its findings in terms of percentages.

Success criterion	Positive benefit			Negative benefit		
	Total instances	Total number of projects	% of total projects	Total instances	Total number of projects	% of total projects
Cost reduction or control	29	21	**60.00%**	3	2	5.71%
Time reduction or control	17	12	**34.29%**	4	3	8.57%
Communication improvement	15	13	**37.14%**	0	0	0.00%
Coordination improvement	14	12	**34.29%**	7	3	8.57%
Quality increase or control	13	12	**34.29%**	0	0	0.00%
Negative risk reduction	8	6	**17.14%**	2	1	2.86%
Scope clarification	3	3	**8.57%**	0	0	0.00%
Organization improvement	2	2	**5.71%**	2	2	**5.71%**
Software issues	0	0	0.00%	9	7	**20.00%**

Table 2 - BIM Success Case Study Data (Bryde, et. all. 2013)

The success criterion of this case study highlights the benefits of BIM in construction project while indicating which benefits are most prominent. A direct comparison between the percentages of total projects that positively benefited from BIM against the percentage of total projects that experienced negative benefits validates the value of this technology and its main areas of provided improvement.

2.7 Underground Structures

Underground construction is a common way of maximizing subsurface space and accommodating facilities of diverse functionalities. The functionality of underground construction is mostly limited by the geological conditions of the site, but even so geological advancements and modern construction methods enable a broad spectrum of usages for investors, cities, and industries to explore.

To better understand the diversity of underground spaces, a classification system with groupings by function, geometry, origin, site feature and project feature can be developed. **Error! Reference ource not found.** provides the major categories for underground space.

Function	Geometry	Origin	Site Feature	Project Feature
Residential	Type of space	Natural	Geography	Rationale
Nonresidential	Fenestration	Mined	Climate	Design
Infrastructure	Relationship to surface	End use	Land use	Construction
Military	Depth dimension to Scale of project		Ground conditions building relationships	Age

Table 3 - Major Classification Groupings of Underground Space (Goel, et. all., 2012)

Further classification can be done using any of the groupings showcased above, but a closer look at geometry and site feature, more specifically on the relationship between structure and ground surface, provides a comprehensive classification for underground construction in the civil realm.

Classification by the vertical dimension of the underground space, or its depth, allows all underground spaces to be studied from a geotechnical and structural view. Table 4 below provides this overview.

Term	Typical Range of Depth Implied According to Use (m)			
	Local Utilities	Buildings	Regional Utilities/Urban Transit	Mines
Shallow	0-2	1-10	0-10	0-100
Moderate	2-4	10-30	10-50	100-1000
Deep	>4	>30	>50	>1000

Table 4 - Classification of Underground Space by Depth (Goel, et. all., 2012)

Beyond the geotechnical and structural considerations of underground structures, attention must be given to the level-wise planning of underground space. With increasing depth, considerations such as ventilation, lighting, acoustics and space distribution become more critical. Because of this, the depth of the underground structure is reflective of its intended use and purpose. Figure 15 provides a graphical depiction of the uses of underground space based on depth.

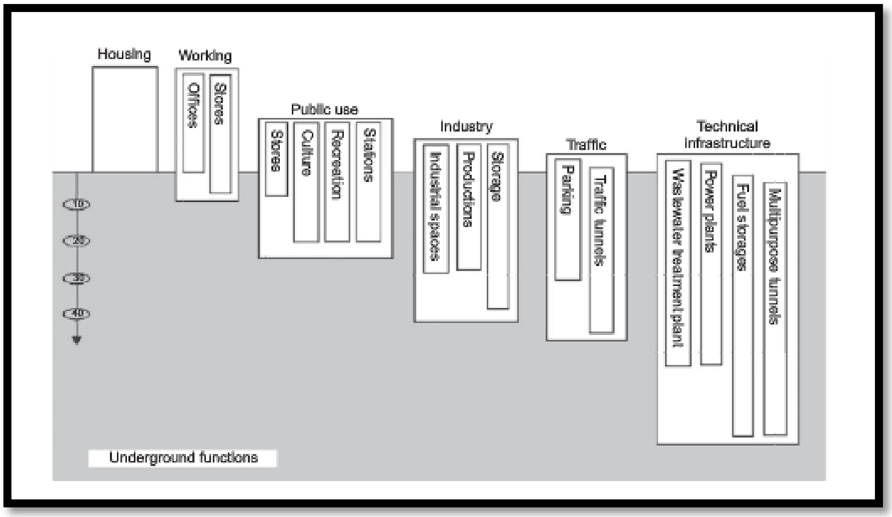


Figure 15 - Feasible depths of different activities in urban structures. (Goel, et. all., 2012)

Considering the relationship of the underground space to the surface in addition to a dimensional classification provides a better understanding of the use or functionality of underground structures. These classifications are not exclusive of each other, and can be used in conjunction to reach a full understanding of underground spaced.

Table 5 below provides four main categories under this consideration.

Description of Type of Underground Structure	Relationship between structure and Ground Surface	Main Uses	Effects on Aboveground Environment
Totally underground	Structure totally below surface	Shelter, storage, urban facilities, supply management facilities	Preserves open space
Some floors aboveground and some floors underground	Structure uses both aboveground and underground space	Offices, pedestrian walkways, parking, warehouses, industry substations	Aboveground allows for sunlight, but is restricted by height limitations
Atrium-type structures	Structure incorporates atrium(s), skylight(s), to connect surface with underground	Pedestrian walkaways, residences, sports facilities	Effective at preserving scenery and space aboveground
Underground structures with shafts	Depends on shaft; structures mainly suited to an inclined plane	Storage facilities, residences	Preserves natural scenery

Table 5 - Classification of Underground Space by Relationship between Structure and Ground Surface

3.0 Methodology

The methodology chapter presents the proposed activities and tasks that our team will be performing during this MQP, and how these will be accomplished. Throughout the project, our team will focus on analyzing and evaluating four aspects:

1. City Square Project Management – schedule, cost/quantity, and communication analysis
2. Prestressed Alternative Design
3. Lean Construction
4. Axiomatic Design Decomposition

The execution of some of the activities mentioned above will require the use of software such as *Revit, Primavera, Acclaro,* and *Consigli's Gateway system*. For a timeline of when the team will be performing each of the above-mentioned activities, refer to Chapter 4.0.

3.1 City Square Project Management

Working with Consigli Construction on a real-time construction project allows for the observation, study, and analysis of the elements that are managed from start to finish. A large scale project such as an underground parking garage in a downtown setting requires expertise to keep time and cost under defined contractual parameters. Understanding how the project manager tackles this complicated task, as well as how the key players communicate in a multi-party effort lead to the identification of focal points that can be improved to the benefit of the overall project. This section discusses how will the project schedule be analyzed as it changes throughout the duration of construction, how the original agreed to quantities, labor, and cost change with the unexpected and how are these changes recognized and dealt with, the effectiveness of the web of communication both internally to the General Contractor and among all key player, and the coordination among trades and tasks throughout the interrelated process of construction.

3.1.1 Schedule Analysis

One of the most important elements of a construction is its schedule. A comprehensive schedule should include all necessary activities in the precise order they need to take place, provide information into the duration of each activity, showcase various milestones throughout the project, and drive the day to day activities of the field.

A master schedule was created for our project using software (Primavera 6) to include all activities necessary for its completion along with their duration and sequencing. As schedules constantly change to reflect the effects of site conditions, subcontractor coordination, and material deliveries among others, an analysis needs a control schedule against which the changes in time can be measured. We have selected the full project schedule updated September 15th to be the control schedule (Appendix A), and will measure the time delta on a weekly basis against the 4-week look-ahead issued at the owner's meetings. Once we have a total delta, we will identify major reasons behind the delays, analyze their impact, and provide recommendations as to how to minimize their negative effects for future projects. A sample 4-week schedule can be found below:

CONSIGLI

Look Ahead Schedule
10/7/2014

SUBCONTRACTOR	ACTIVITY ID	UnderGround Garage 1308	10/6 - 10/10					10/13 - 10/17					10/20 - 10/24					10/27 - 10-31				
			M	T	W	T	F	M	T	W	T	F	M	T	W	T	F	M	T	W	T	F
Marois	A5830	Dewatering Operations	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
CCC / CS-II	A3100	Anticipated NTP - execution GMP			X																	
Novel	A3200	Prepare & Submit Anchor Bolt Shop Drawings	X	X	X	X	X	X	X	X	X										X	X
CS-II	A3210	Review & Approve Anchor Bolt Shop Drawings										X	X	X	X	X						
Novel	A3220	Fab & Deliver Anchor Bolts															X	X	X	X	X	X
BSC		Survey Control	X																		X	X
Marois	A5450	Excavate for Deep Pit Near GE Line (GRND WTR EJCTRS)	X	X	X																	X
Marois	A5170	Cut Off end of Existing Footings (N-Line) 2 Each			X																	
Marois	A5420	Excavate for Deep Pit Near GG Line (GRND WTR EJCTRS)				X	X		X	X												
Manafort-Precision	Manafort	Mobilize Concrete Subcontractor	X	X	X	X	X															
Manafort-Precision	A5460	FRP Deep Pits Near GE Line (GRND WTR EJCTRS)				X	X		X	X	X	X	X	X	X	X	X	X	X			
Marois	A5470	Backfill Deep Pit Near GE Line (GRND WTR EJTRS)																				
Manafort-Precision	A5420	FRP Deep Pits Near GG Line (GRND WTR EJCTRS)								X	X	X	X	X	X	X	X	X	X	X	X	X
CS-II	A5870	Review & Approve Removal of Front Street Bridge (Pricing)	X	X	X	X	X		X	X	X	X	X	X							X	X
Costello	A5850	Demo & Remove Section of Front Street Bridge													X	X	X	X	X			
Marois	A4000	Initial Cut & Haul Off Bldg. E										X	X	X	X	X	X	X				
Marois	A4170	Excavate Areaway Ftgs and Walls													X	X	X	X	X			
Manafort-Precision	A4040	FRP Continuous Ftgs - Bldg. E																	X	X	X	X

Figure 16 - 10/07/14 Look Ahead Schedule from Owner's Meeting

Additionally, we will analyze the logistics behind trades with a specific timeframe in the overall construction. We will monitor how closely the trade manages to meet the schedule, how it works with other trades and parties involved, the consistency with which materials and equipment needed are available and ready to go on site, and how it manages or avoids potential coordination problems.

3.1.2 Cost/Quantity Analysis

Construction projects can be completed under several contractual agreements that directly influence the way costs and quantities are tracked. In this project, Consigli will deliver as the general contractor GC under a guaranteed maximum price (GMP). This GMP allots dollar amounts for each activity necessary to the project, as well as allowances for potential overruns or the unknown, with a set ceiling or limit. The way Consigli tracks the progress of construction directly affects its cash flow and billings, and is critical to the health of the GC, subcontractors, and project in general.

While tracking every activity provides an overview of the progress of the project, it would lack depth in order to perform a critical analysis of the relationship between schedule, quantities, and cost. Instead, we will focus on change requests and change orders and their impact on the cost of the project. Change orders are written and approved orders for billable work not included in the scope of a project. (US Legal, 2014) Change orders follow a process starting from identifying the need for wok to the billing of the work performed. The following flowchart illustrates how change orders are managed in this project:

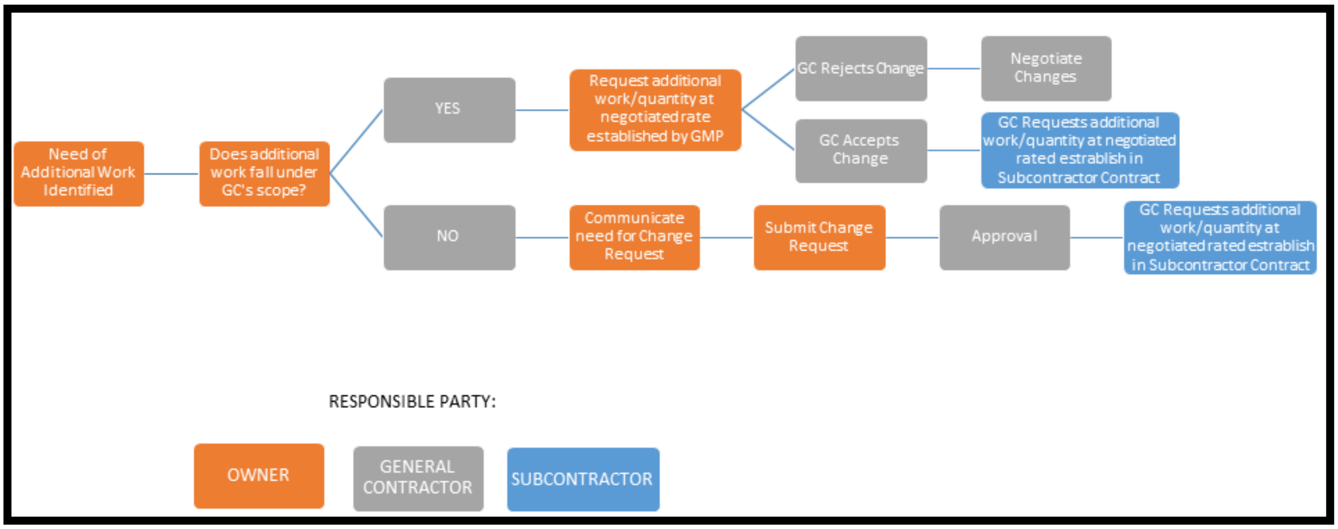


Figure 17 – Change Orders Flowchart (enlarged version in Appendix B)

To analyze the impact of change orders we will use both weekly meeting minutes that includes the updated Change Request Log by Status, and the logs stored on Consigli's Gateway Server. A sample weekly log can be found below:

CONSIGLI

Change Request Log by Status

Date: 10/08/14

1308 City Square Underground Garage

Number	Date	Description	Amount	Change Order
:HANGE REQUESTS				
Not issued				
17-007	9/3/14	Addendum 2 Drawings and Specs		
17-009	9/12/14	ASI #1 - Plaza Level Irrigation System		
17-010	10/1/14	GMP Reconciliation for Early Release Work		
		Not issued Total	0.00	
Submitted				
17-002	7/31/14	Temporary Power for Parking Garage	24,928.00	
17-004	8/26/14	Continue De-watering operations until ready for Concrete	114,092.19	Gmp
17-008	9/16/14	Install temporary soil support along N-line in lieu of underpinning exisitng footings	-84,419.00	
17-011	10/7/14	Demo and Replace section of Front Street bridge for access into site	119,583.00	
		Submitted Total	174,184.19	

Figure 18 - 10/08/14 Change Request Log from Owner's Meeting

3.1.3 Communication

As the general contractor, Consigli is responsible for filtering information and keeping organized records of changes or requests by any other party involved. While much of the internal communication happens on a daily basis at the field office and job site, the communication between key players is carefully documented and tracked. For our project, we will analyze the system used for documenting important communication (RFI's and Submittals) by looking at the turn over time between engagements, the resolution of requests, and the impact to communication on the field.

Access to Consigli's Gateway server will allow us to track any requests for information and their progress throughout the project. Requests for information are particularly critical as they often represent the need for a key player to clarify construction documents, intent, or specifications that can hinder the physical progression of the project. All parties have different time tolerances for the resolution of RFI's, and this must be taken into consideration by the general contractor executing the construction process. Similarly, we will be able to track submittals by subcontractors, vendors, or other players and their effect on the schedule. Submittals are required by the inspecting agency, in this case the City of Worcester, before any work can be done by specific trades or with specific materials. As a part of the life-cycle of the project, submittals are integral links between planning and execution that are easily traceable and identifiable. The following flowcharts represent the life-cycles of both RFI's and Submittals in this project.

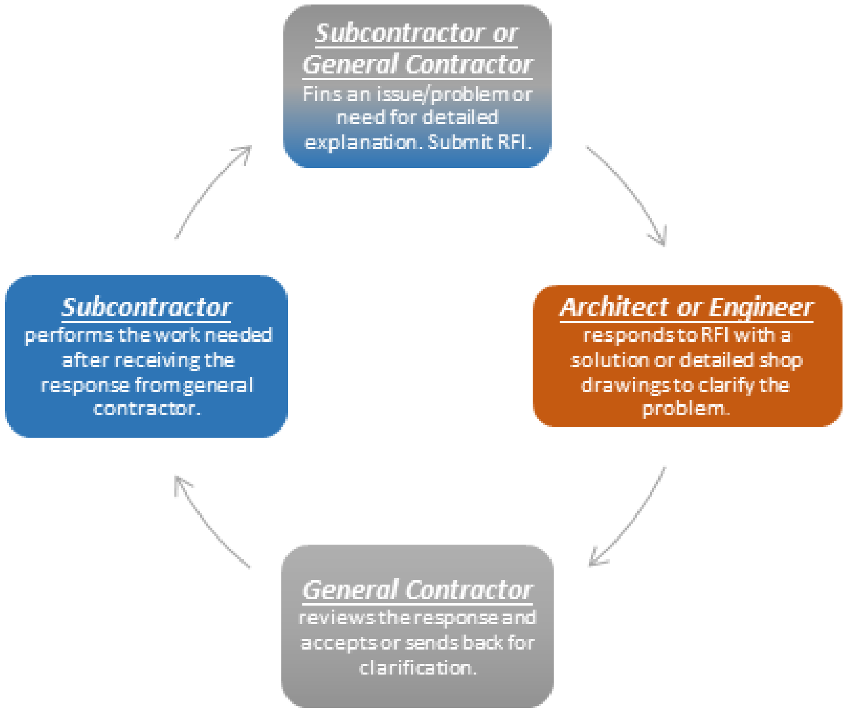


Figure 19 - Life Cycle for RFI's

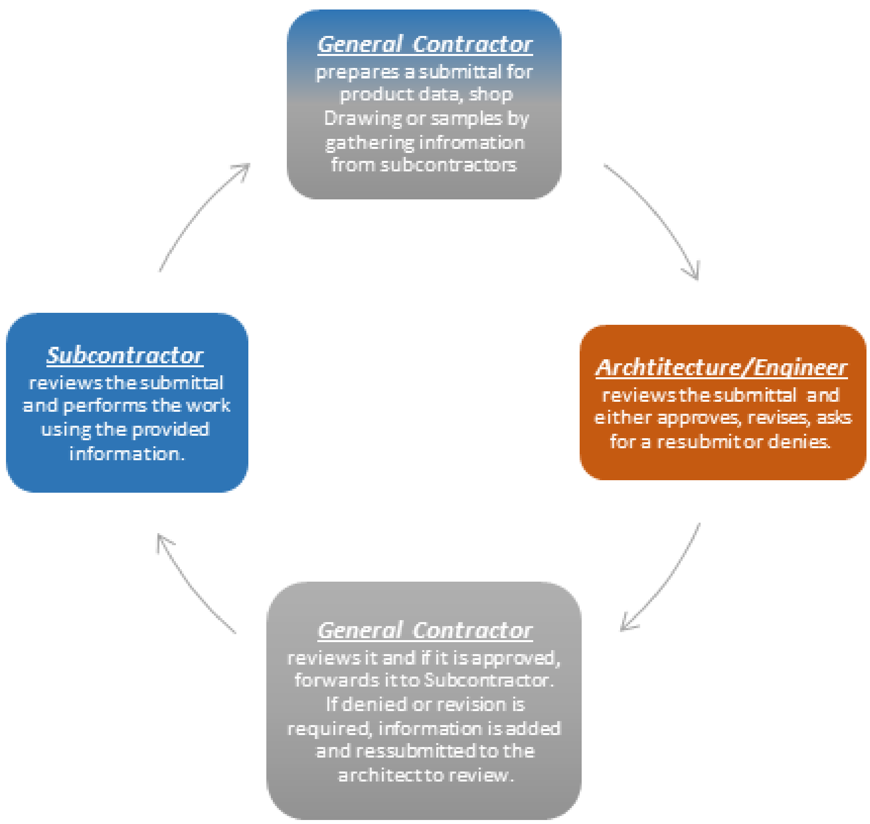


Figure 20 - Life Cycle of Submittals

To analyze the communications in the forms of RFI's and Submittals by key players, we will use two tracking charts, for RFI's and Submittals respectively, in which we track their turnover time, requirements, and impact on schedule. These can be found in Appendix C. We will use both weekly meeting minutes that detail the updated A/E Outstanding Submittal Log and RFI Question and Answer Log, and the logs stored on Consigli's Gateway Server. A sample weekly log can be found below.

Consigli Construction Co., Inc.

RFI Question and Answer Log 10/8/2014

1308 City Square Underground Garage Page 1

RFI #		Status	Date Sent	Answered Date
16	Domestic Water Pressure Regulating Valve Station	Open	9/22/2014	

Question: Currently there is an un-numbered detail on P3.00 depicting a pressure regulating valve station. Plumbing Drawings do not currently depict the use of this station. Note, building water feed is off of the high pressure water service which averages 150PSI static. Please advise whether a pressure regulating valve station is desired.

Answer:

CC:

Forward:

RFI #		Status	Date Sent	Answered Date
19	NEMA Enclosures for VFDs	Open	9/25/2014	

Question: Underground Garage Specifications dictate the use of NEMA 1 enclosures for interior located VFDs and NEMA 4X enclosures for exterior located VFDs; however they do not specifically assign the enclosure type to specific piece equipment.

East Garage Mitigation Specifications dictate the use of NEMA 4X enclosures for VFDs.

Please confirm the following:
- NEMA 1 Enclosure for GEF-1.1, 1.2, 2.1, and 2.2; provided VDFs located in Fan rooms 202/203.
- NEMA 1 Enclosure for GSF-1; provided VDF located in Garage Main Electrical Room 127.
- NEMA 1 Enclosure for VSF-1; provided VDF located in Garage Emergency Electrical Room 129.
- NEMA 4X Enclosure for East Garage GSF-1 and 2; regardless of location due to existing condensation issues.

Answer:

CC:

Forward:

Figure 21 - 10/08/14 RFI Q&A Log from Owner's meeting

3.2 Alternative Design

For more than 40 years, precast prestressed concrete has been the number one choice for underground parking garages due to concrete's greater strength, impermeability and superior durability. (High, 2014. Using concrete reduces the potential for corrosion which is a critical setback for steel structures. It is also a sustainable material due to their minimal waste and lower life cycle cost in terms of construction, operation and maintenance since it does not require painting or tuck pointing

The structural design of an underground parking structure includes the determination of loads, selection of framing system, the detailing and sizing of components and connections. Due to geometrical difficulties in the design of the CitySquare underground parking garage, the analysis of the prestressed design will focus on the north of 27 line. The focused area is highlighted in green in Figure 22.

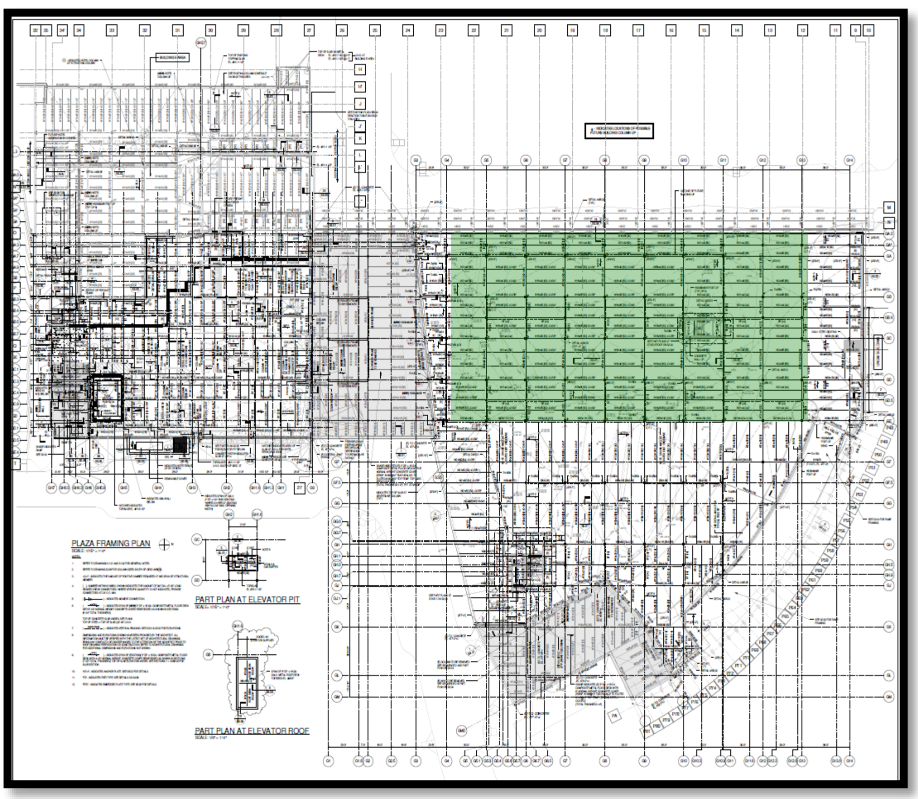


Figure 22 - The Focused Area for Prestressed Structural Design (Gateway)

Although prestressed concrete allows it to be cast into wide variety of shapes and sizes, using routinely produced custom designs and shapes will be more advantageous in terms of speed and cost of the construction. (PCI, 2012) In Figure 23, the two common components in building applications are illustrated. For parking structures double tee systems is more suitable due to longer span distances to eliminate columns and provide unobstructed views through the levels.

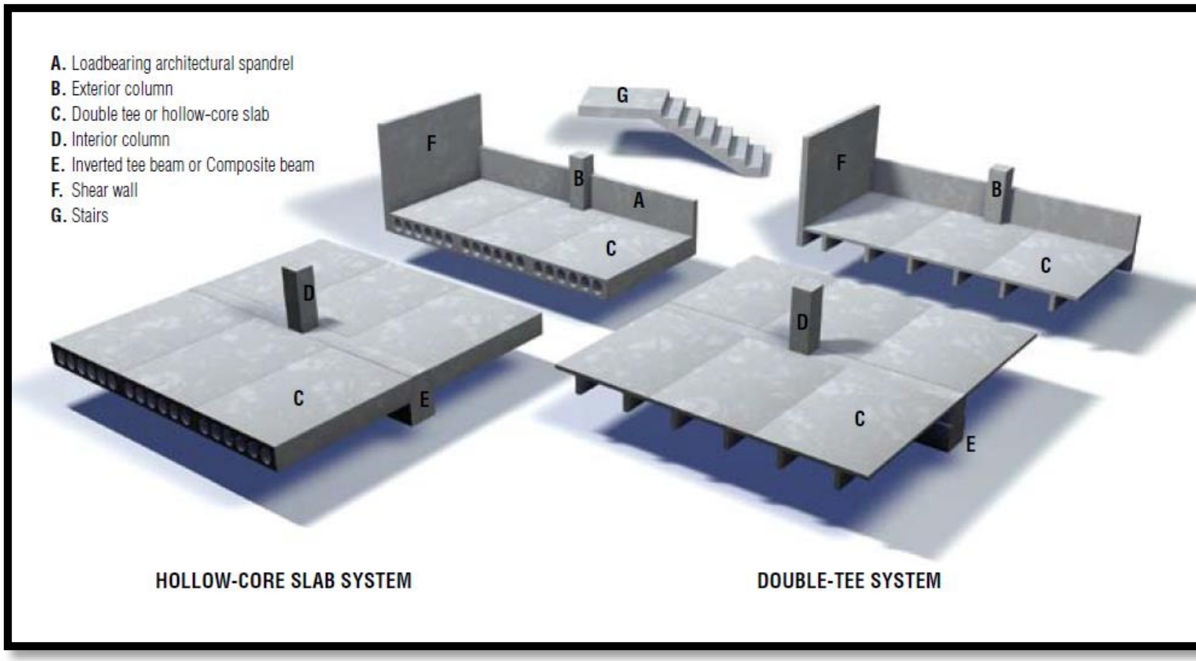


Figure 23 - Common Component Systems in Prestressed Concrete Design (Foster et. al., 1997)

The steps for calculating the structural design of a prestressed structure is outlined as following:

Step 1: Identify Loads

- Identify dead loads, live loads, snow loads, seismic loads used in provided construction drawings.
- Calculate the load combinations for each level using the formulas provided in Figure 24.
- Use the maximum load combination for designing prestressed members.
- Assume maximum uniform loading per level.
    - This conservative approach will lead to repetitiveness of prestressed member and will have positive impact on cost and schedule.
    - For example at the plaza level the maximum loading condition will be assumed for the area of interest highlighted in red in Figure 25.

Load Combinations

1. $1.4(D + F)$
2. $1.2(D + F + T) + 1.6(L + H) + 0.5(L_r \text{ or } S \text{ or } R)$
3. $1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (L \text{ or } 0.8W)$
4. $1.2D + 1.6W + L + 0.5(L_r \text{ or } S \text{ or } R)$
5. $1.2D + 1.0E + L + 0.2S$
6. $0.9D + 1.6W + 1.6H$
7. $0.9D + 1.0E + 1.6H$

D = dead load
D_i = weight of ice
E = earthquake load
F = load due to fluids with well-defined pressures and maximum heights
F_a = flood load
H = load due to lateral earth pressure, ground water pressure, or pressure of bulk materials
L = live load
L_r = roof live load
R = rain load
S = snow load
T = self-straining force
W = wind load
W_i = wind-on-ice determined in accordance with Chapter 10

Figure 24 - PCI Load Combination Formulas (PCI, 2004)

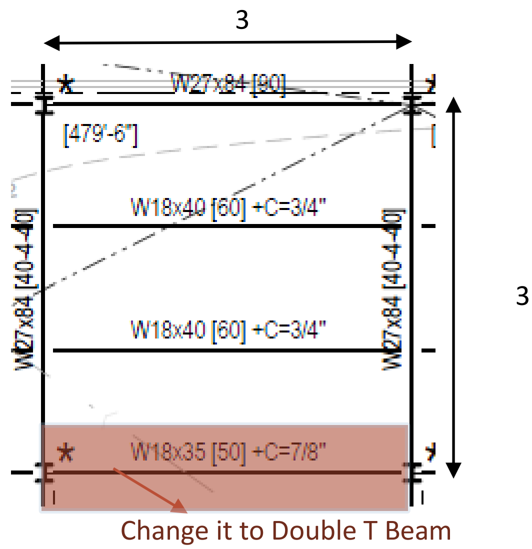
Figure 25 - Loading Conditions at the Plaza Level with Area of Interest Highlighted in red. (Gateway)

PLAZA LOAD DIAGRAM KEY

LABEL	DESCRIPTION	DESIGN SUPERIMPOSED DEAD LOAD	DESIGN LIVE LOAD	
-	EXISTING STRUCTURE	225 PSF	250 PSF NOTE 4	
"A"	ROADWAYS AND SIDEWALKS - TOTAL WEIGHT OF ASPHALT OR CONCRETE WITH GRAVEL SUB-BASE ≤ 225 PSF (SEE CIVIL)	225 PSF	250 PSF NOTE 4	SEE NOTES 1 THRU 3 BELOW
"B"	PAVERS AT PLAZA - PAVERS .... 25 PSF - BITUMINOUS BED .... 25 PSF - 6" GRAVEL .... 50 PSF	100 PSF	250 PSF	SEE NOTES 1 THRU 3 BELOW
"C"	GRASS AREAS AND GROUND COVER PLANTERS - 18" MAXIMUM DEPTH OF SOIL .... 175 PSF - 6" GRAVEL .... 50 PSF	225 PSF	100 PSF	SEE NOTES 1 THRU 3 BELOW
"D"	TREE PLANTERS - OUTER - AVERAGE SOIL DEPTH ≤ 24" .... 240 PSF - 6" GRAVEL .... 50 PSF	290 PSF	100 PSF	SEE NOTES 1 THRU 3 BELOW
"E"	TREE PLANTERS - AROUND TREES - MAXIMUM SOIL DEPTH ≤ 42" .... 420 PSF - 6" GRAVEL .... 50 PSF	470 PSF	50 PSF	- AREA "E" EXTENDS 4'-0" FROM TREE TRUNK ON ALL SIDES AS SHOWN ON PLAN. - SEE NOTES 1 THRU 3 BELOW

Figure 26- Loading Diagram Key for Plaza Level, Assumed Maximum Loading Conditions Highlighted in Yellow (Gateway)

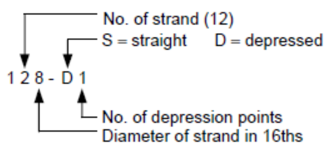
Step 2: Preliminary Double T Beam Design



- Use the existing beam frame layout dimensions 30ft. by 30ft.
- Select a shape and prestressing layout from the PCI Design Handbook load table shown in Figure **27**.
- Check if the selected design can carry the calculated service load.
- Test selected double tee beam for critical stress analysis and deflections.
  - Keep constant eccentricity throughout the beam
  - Use Excel spreadsheets for design process. (Appendix D)

Figure 27 - PCI-MNL Ch3 10DT24 Load Table (PCI, 2004)

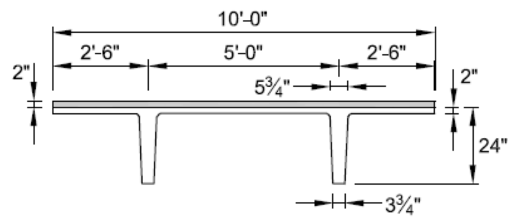
Strand Pattern Designation



Safe loads shown include dead load of 10 psf for untopped members and 15 psf for topped members. Remainder is live load. Long-time cambers include superimposed dead load but do not include live load.

Key
171 – Safe superimposed service load, psf
0.6 – Estimated camber at erection, in.
0.8 – Estimated long-time camber, in.

DOUBLE TEE
10'-0" x 24"
Normal Weight Concrete



$f'_c = 5{,}000$ psi
$f_{pu} = 270{,}000$ psi

Section Properties

	Untopped		Topped	
A =	449	in.^{2}	–	
I =	22,469	in.^{4}	29,396	in.^{4}
y_b =	17.77	in.	19.89	in.
y_t =	6.23	in.	6.11	in.
S_b =	1,264	in.^{3}	1,478	in.^{3}
S_t =	3,607	in.^{3}	4,812	in.^{3}
wt =	468	plf	718	plf
DL =	74	psf	72	psf
V/S =	1.35	in.		

10DT24

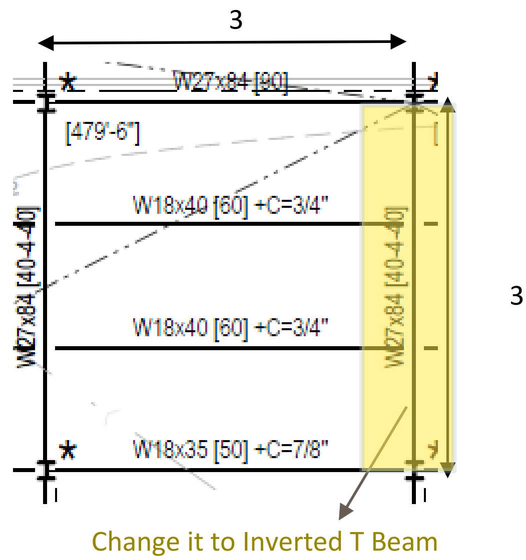
Table of safe superimposed service load (psf) and cambers (in.) **No Topping**

Strand Pattern	y_s(end) in. y_s(center) in.	Span, ft 30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	62	64	66	68	70	72	74	76	78
68-S	4.00	171	146	126	109	94	82	71	62	54	47	41	35	30	26											
	4.00	0.6	0.7	0.7	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.7	0.6											
		0.8	0.9	0.9	1.0	1.0	1.0	1.0	1.0	0.9	0.8	0.7	0.5	0.3	0.0											
88-S	5.00		193	167	146	127	112	98	87	77	68	60	53	47	41	36	32	27								
	5.00		0.9	1.0	1.1	1.1	1.2	1.3	1.3	1.4	1.4	1.4	1.4	1.3	1.3	1.2	1.0	0.9								
			1.2	1.3	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.2	1.0	0.8	0.5	0.1								
108-S	6.00				177	156	137	121	108	96	85	76	68	61	54	48	43	38	33	29						
	6.00				1.2	1.3	1.4	1.5	1.6	1.7	1.7	1.8	1.8	1.8	1.8	1.8	1.7	1.6	1.4	1.2						
					1.6	1.7	1.8	1.9	1.9	2.0	2.0	2.0	1.9	1.9	1.8	1.6	1.4	1.1	0.7	0.3						
128-S	7.00						159	141	125	112	100	90	80	72	64	58	52	46	41	36	31	26				
	7.00						1.6	1.7	1.8	1.9	1.9	2.0	2.0	2.1	2.1	2.1	2.1	2.0	1.9	1.8	1.6	1.4				
							2.0	2.1	2.2	2.3	2.3	2.3	2.3	2.2	2.2	2.1	1.9	1.7	1.4	1.1	0.6	0.1				
128-D1	11.67												100	90	80	72	64	57	51	46	41	37	33	30	26	
	3.25												2.3	2.4	2.5	2.5	2.5	2.5	2.4	2.3	2.2	2.0	1.8	1.5	1.2	
													2.7	2.7	2.6	2.5	2.4	2.2	1.9	1.6	1.3	0.9	0.4	–0.2	–0.9	
148-D1	12.86																	68	61	55	49	43	39	36	32	29
	3.50																	2.9	2.9	2.9	2.8	2.7	2.6	2.4	2.1	1.8
																		2.9	2.7	2.5	2.2	1.8	1.4	0.9	0.3	–0.3

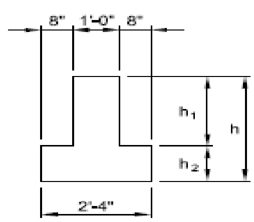
Figure 28 - PCI-MNL Ch3 10DT24 Load Table (PCI, 2004)

Step 3: Inverted T beam Design

- Select a shape and prestressing layout from the PCI load table shown in Figure 29.
- Check if the selected design can carry the calculated service load.
- Test selected double tee beam for critical stress analysis and deflections.
  - Use Excel spreadsheets for the design process. (Appendix D)



INVERTED TEE BEAMS



f'_c = 5,000 psi
f_{pu} = 270,000 psi
½ in. diameter
low-relaxation strand

Normal Weight Concrete

Section Properties								
Designation	h in.	h_1/h_2 in./in.	A in.^{2}	I in.^{4}	y_b in.	S_b in.^{3}	S_t in.^{3}	wt plf
28IT20	20	12/8	368	11,688	7.91	1,478	967	383
28IT24	24	12/12	480	20,275	9.60	2,112	1,408	500
28IT28	28	16/12	528	32,076	11.09	2,892	1,897	550
28IT32	32	20/12	576	47,872	12.67	3,778	2,477	600
28IT36	36	24/12	624	68,101	14.31	4,759	3,140	650
28IT40	40	24/16	736	93,503	15.83	5,907	3,869	767
28IT44	44	28/16	784	124,437	17.43	7,139	4,683	817
28IT48	48	32/16	832	161,424	19.08	8,460	5,582	867
28IT52	52	36/16	880	204,884	20.76	9,869	6,558	917
28IT56	56	40/16	928	255,229	22.48	11,354	7,614	967
28IT60	60	44/16	976	312,866	24.23	12,912	8,747	1,017

1. Check local area for availability of other sizes.
2. Safe loads shown include 50% superimposed dead load and 50% live load. 800 psi top tension has been allowed, therefore, additional top reinforcement is required.
3. Safe loads can be significantly increased by use of structural composite topping.

Key
6511 – Safe superimposed service load, plf.
0.2 – Estimated camber at erection, in.
0.1 – Estimated long-time camber, in.

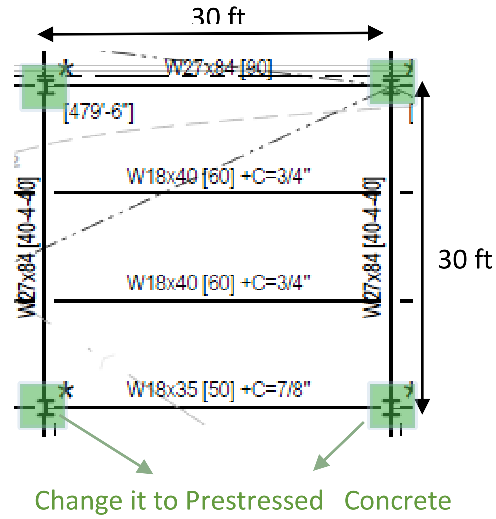
Table of safe superimposed service load (plf) and cambers (in.)

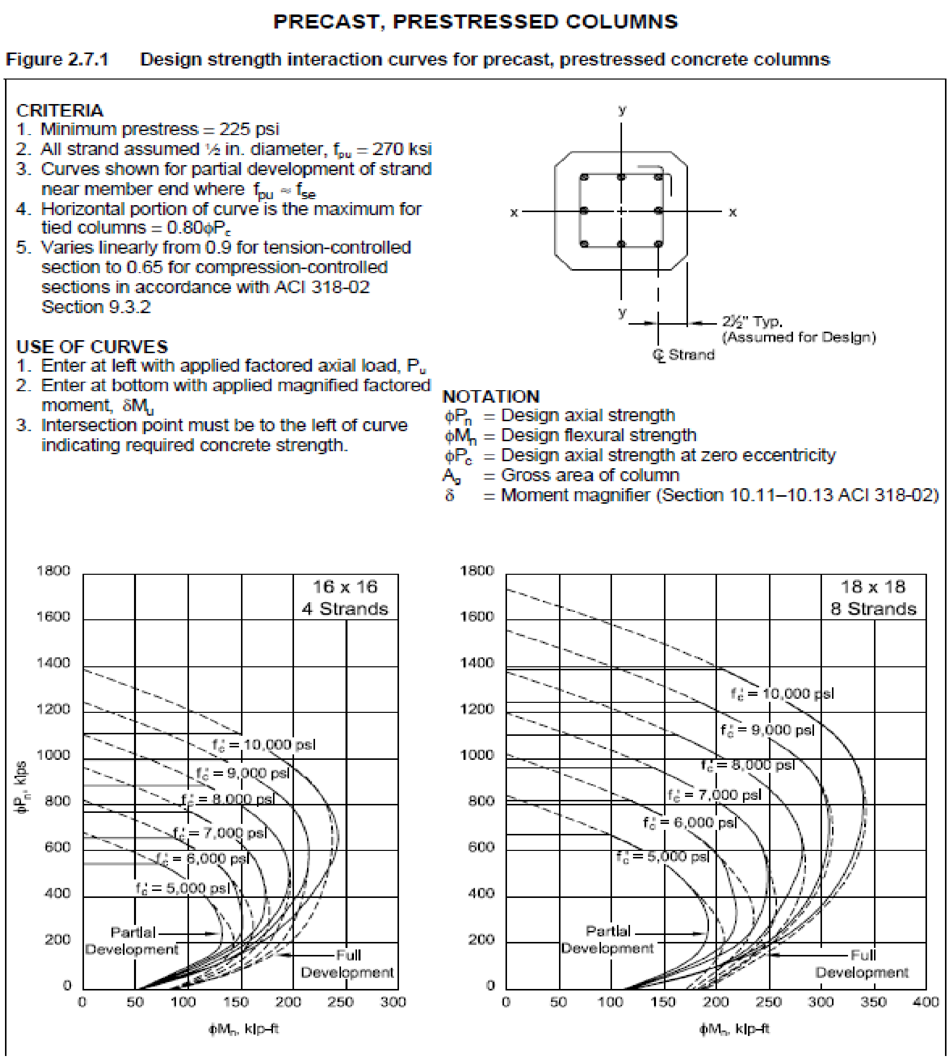
Desig-nation	No. Strand	y_s(end) in. y_s(center) in.	Span, ft 16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
28IT20	98-S	2.44 2.44	6511 0.2 0.1	5076 0.3 0.1	4049 0.4 0.1	3289 0.4 0.1	2711 0.5 0.1	2262 0.5 0.1	1905 0.6 0.0	1617 0.7 0.0	1381 0.7 0.0	1186 0.7 0.0	1022 0.8 –0.1							
28IT24	188-S	2.73 2.73	9612 0.2 0.1	7504 0.3 0.1	5997 0.3 0.1	4882 0.4 0.1	4034 0.4 0.1	3374 0.5 0.1	2850 0.6 0.1	2427 0.6 0.1	2081 0.7 0.1	1795 0.7 0.1	1555 0.7 0.0	1351 0.8 0.0	1178 0.8 –0.1	1029 0.8 –0.2				
28IT28	138-S	3.08 3.08			8353 0.3 0.1	6822 0.3 0.1	5657 0.4 0.1	4750 0.5 0.1	4031 0.5 0.1	3451 0.6 0.1	2976 0.6 0.1	2582 0.7 0.1	2252 0.7 0.1	1973 0.8 0.1	1735 0.8 0.0	1530 0.8 0.0	1352 0.9 –0.1	1197 0.8 –0.2	1061 0.8 –0.2	
28IT32	158-S	3.47 3.47				9049 0.3 0.1	7521 0.4 0.1	5333 0.4 0.1	5389 0.5 0.1	4628 0.5 0.1	4006 0.6 0.1	3490 0.6 0.1	3057 0.7 0.1	2691 0.7 0.1	2379 0.8 0.1	2110 0.8 0.1	1876 0.9 0.0	1673 0.9 0.0	1495 0.9 0.0	1337 0.9 –0.1
28IT36	168-S	3.50 3.50					9832 0.3 0.1	8295 0.4 0.1	7075 0.4 0.1	6092 0.5 0.1	5287 0.5 0.1	4619 0.6 0.1	4060 0.6 0.1	3587 0.7 0.1	3183 0.7 0.1	2835 0.8 0.1	2534 0.8 0.0	2271 0.9 0.0	2040 0.9 0.0	1836 0.9 –0.1
28IT40	198-S	4.21 4.21							8638 0.4 0.1	7440 0.5 0.1	6460 0.5 0.1	5647 0.6 0.1	4966 0.6 0.1	4390 0.7 0.1	3898 0.7 0.1	3474 0.8 0.1	3107 0.8 0.1	2787 0.8 0.1	2506 0.9 0.1	2258 0.9 0.1
28IT44	208-S	4.40 4.40								9186 0.4 0.1	7989 0.5 0.1	6997 0.5 0.1	6165 0.6 0.1	5462 0.6 0.1	4861 0.7 0.1	4344 0.7 0.1	3896 0.7 0.1	3505 0.8 0.1	3162 0.8 0.1	2859 0.8 0.0
28IT48	228-S	4.55 4.55									9719 0.4 0.1	8525 0.5 0.1	7523 0.5 0.1	6676 0.6 0.1	5953 0.6 0.1	5330 0.7 0.1	4791 0.7 0.1	4320 0.8 0.1	3907 0.8 0.1	3542 0.9 0.1
28IT52	248-S	5.17 5.17										9987 0.5 0.1	8823 0.5 0.1	7838 0.6 0.1	6998 0.6 0.1	6274 0.6 0.1	5647 0.7 0.1	4100 0.7 0.1	4619 0.8 0.1	4196 0.8 0.1
28IT56	268-S	5.23 5.23												9307 0.5 0.2	8319 0.6 0.2	7469 0.6 0.2	6731 0.7 0.2	6088 0.7 0.2	5524 0.8 0.2	5026 0.8 0.2
28IT60	288-S	5.57 5.57													9645 0.6 0.2	8668 0.6 0.2	7820 0.7 0.2	7081 0.7 0.2	6432 0.8 0.2	5859 0.8 0.2

Figure 29 - PCI-MNL Ch2 Inverted Tee Members Load Table (PCI, 2004)

Step 4: Column Design

- Select a shape and prestressing layout from the PCI Design Handbook load table shown in Figure 30.
- Calculate axial and flexural strength (P_n, M_n)
- Check that the design is within the limits of strength interaction curve in Figure 30.





PRECAST, PRESTRESSED COLUMNS

Figure 2.7.1 Design strength interaction curves for precast, prestressed concrete columns

CRITERIA
1. Minimum prestress = 225 psi
2. All strand assumed ½ in. diameter, f_{pu} = 270 ksi
3. Curves shown for partial development of strand near member end where $f_{pu} \approx f_{se}$
4. Horizontal portion of curve is the maximum for tied columns = $0.80\phi P_c$
5. Varies linearly from 0.9 for tension-controlled section to 0.65 for compression-controlled sections in accordance with ACI 318-02 Section 9.3.2

USE OF CURVES
1. Enter at left with applied factored axial load, P_u
2. Enter at bottom with applied magnified factored moment, δM_u
3. Intersection point must be to the left of curve indicating required concrete strength.

NOTATION
ϕP_n = Design axial strength
ϕM_n = Design flexural strength
ϕP_c = Design axial strength at zero eccentricity
A_g = Gross area of column
δ = Moment magnifier (Section 10.11–10.13 ACI 318-02)

Figure 30 - PCI MNL Design Strength Interaction curves for prestressed concrete columns (PCI, 2004)

Step 5: Connection Design

The connections are important consideration in the structural design of a prestressed concrete structure since it transfers load, restrains movement and provides stability to the components.

1. Dapped- End Beam Connection

- The beams are designed as dapped-end which requires the investigation of several potential failure modes. These failure modes are numbered and shown in Figure 31.
- The direct shear at the junction of dap will be avoided by providing shear friction reinforcement composed of A_{vf} and A_h. The diagonal tension originating from the re-entrant corner will be avoided through adding shear reinforcement, A_{sh}. The Diagonal tension in the extended end will be avoided through shear reinforcement composed of A_h and A_V.
- The reinforcement sizes are designed separately using the Figure 32 in order to configure the bar sizes and number. Use Excel spreadsheets for the design process (Appendix D).

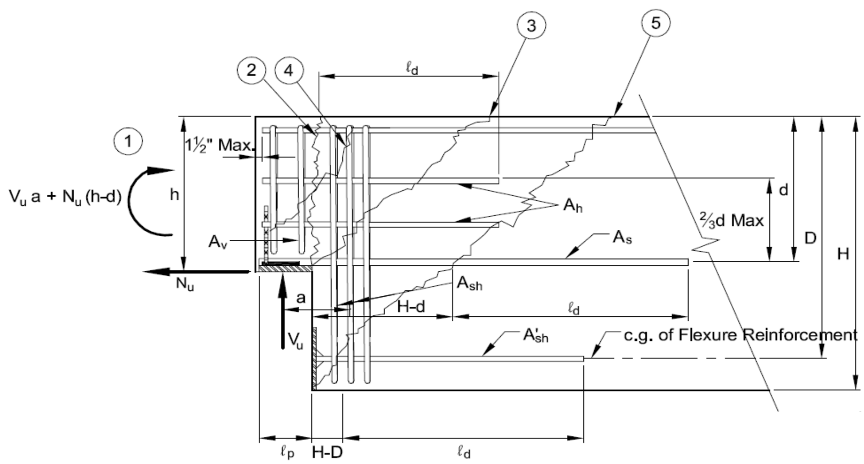


Figure 31 - PCI MNL Potential Failure Modes and Required Reinforcement in Dapped-end Connections, Design Aid 4.6.3.1 (PCI, 2004)

ASTM STANDARD REINFORCING BARS							
BAR SIZE[a] DESIGNATION		NOMINAL DIMENSIONS					
		DIAMETER		AREA		WEIGHT OR MASS	
U.S. CUSTOMARY	SI	in.	mm	in.^{2}	mm^2	lb/ft	kg/m
#3	#10	0.375	9.5	0.11	71	0.376	0.560
#4	#13	0.500	12.7	0.20	129	0.668	0.994
#5	#16	0.625	15.9	0.31	199	1.043	1.552
#6	#19	0.750	19.1	0.44	284	1.502	2.235
#7	#22	0.875	22.2	0.60	387	2.044	3.042
#8	#25	1.000	25.4	0.79	510	2.670	3.973
#9	#29	1.128	28.7	1.00	645	3.400	5.060
#10	#32	1.270	32.3	1.27	819	4.303	6.404
#11	#36	1.410	35.8	1.56	1006	5.313	7.907
#14	#43	1.693	43.0	2.25	1452	7.650	11.380
#18	#57	2.257	57.3	4.00	2581	13.600	20.240

a. Many mills will mark and supply bars only with metric (SI) designation, which is a soft conversion. Soft conversion means that the metric (SI) bars have exactly the same dimensions and properties as the equivalent U.S. customary designation.

Figure 32 - PCI MNL Reinforcing Bar Data, Design Aid 11.2.7 (PCI, 2004)

2. Corbel Design

- Corbels are used to resist moments by providing fixity to columns and at the top of the beam.
- The area of steel, A_s, is calculated to resist shear friction and horizontal stress.
- The area of shear reinforcement parallel to flexural tension reinforcement is calculated using the formulas in (Appendix D).

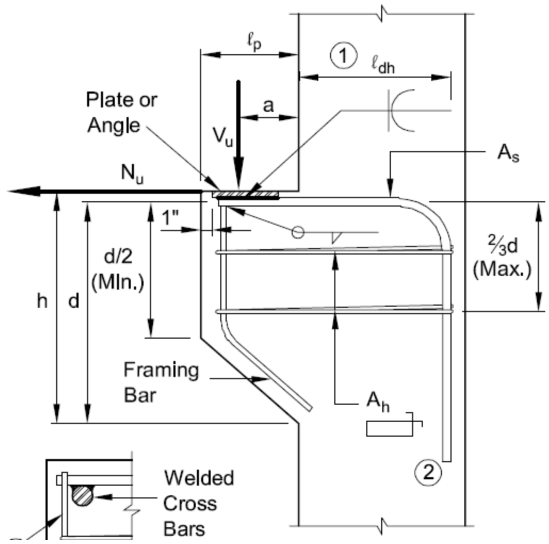


Figure 33 - PCI MNL Chp 5: Design of Concrete Corbels

Figure 34 illustrates the integration of the prestressed components; double tee beams, inverted tee beams, columns, corbel connections and dapped end connections.

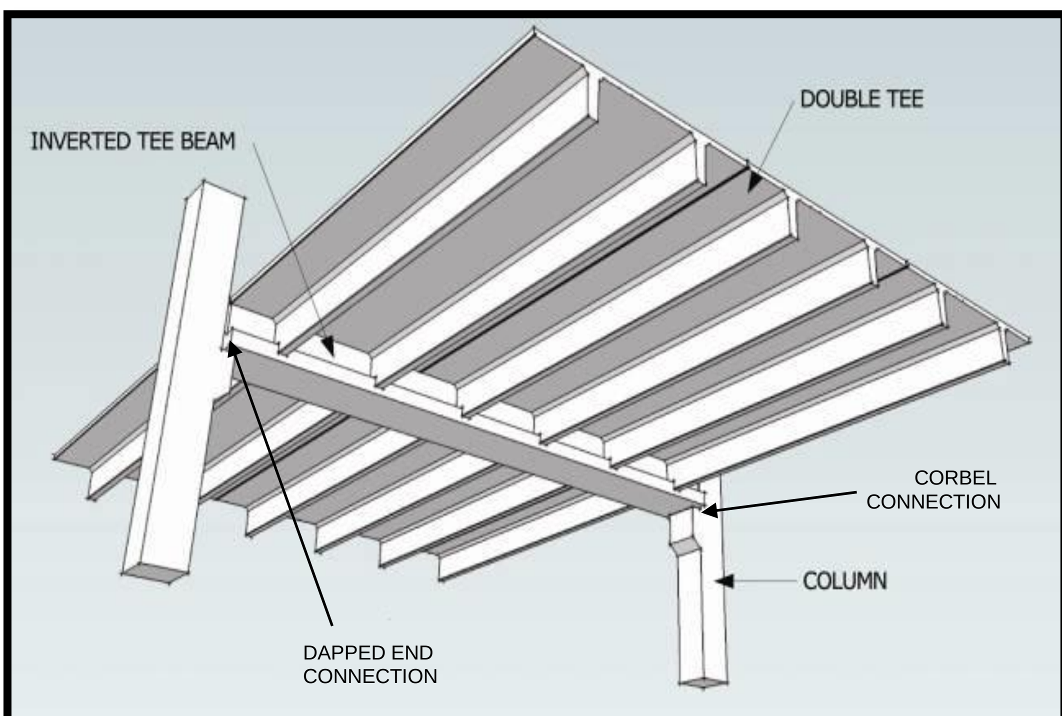


Figure 34 - Prestressed Component Illustration (WEI, 2010)

Step 6: Checking Footing Size

- As it is shown in Figure 35, all of the foundations in this project are shallow. Majority of the shallow foundations are either spread footings that a single column bears on a rectangular pad to distribute the load over a bigger area or combined footings where multiple columns bear on a rectangular footing. (Nichols, 2013)
- The allowable bearing pressure of the foundations in our focus area is documented as 2 tons per square foot in the structural documents.
- With the new loads of prestressed structure, the contact pressure and stability needs to be recalculated.
- The footing size can be altered by checking the closeness to the allowable bearing pressure.

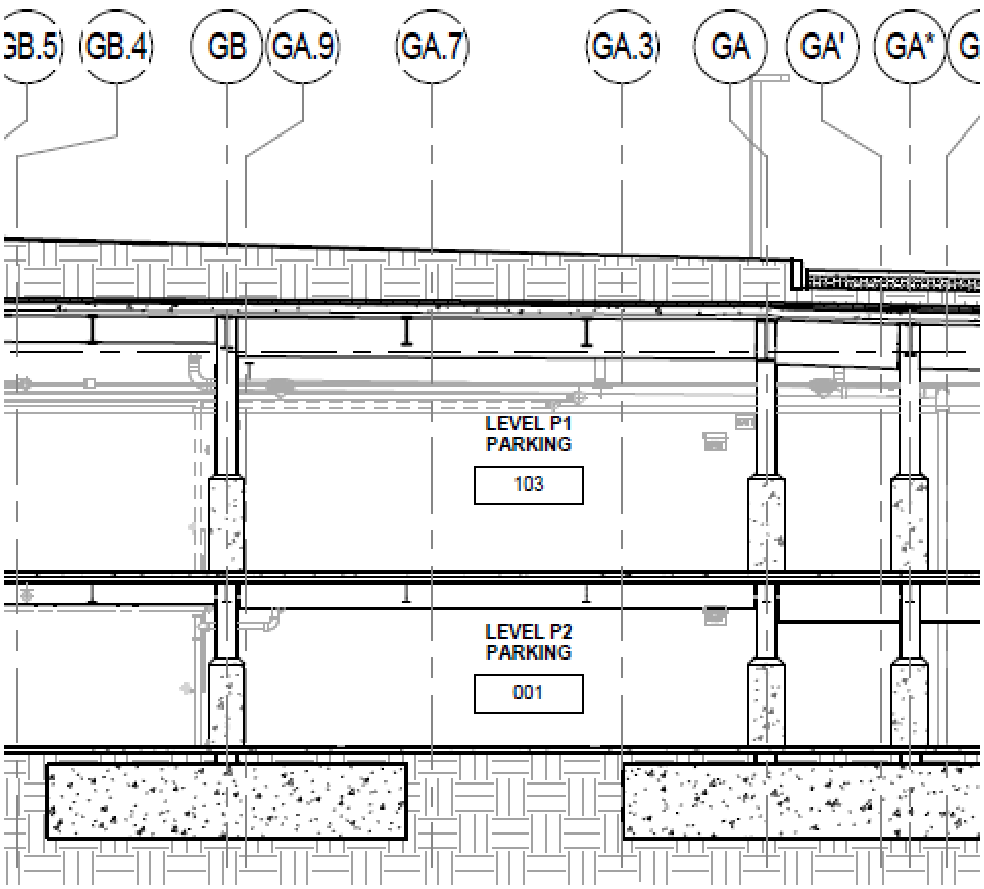


Figure 35 - Partial Elevation in Architectural Drawings, (Gateway)

Step 7: Altering the design for optimization

The preliminary design can be altered to optimize a better alternative design. Some of the changes can be altering the bay or footing size in order to find the most cost efficient solution. The size changes can be tested using the prepared spreadsheets in (Appendix D).

Step 8: BIM Visualization

- The final optimized prestressed concrete design will be illustrated in 3D digital model using Revit software.
- The design will start with the drawing of foundations and spread footings using the calculated foundation wall thicknesses, slab thickness and footing depths.
- The next step is erecting columns with designed sizes and attaching the corbel connections.
- Then the double t beams and inverted t beams will be connected using the dapped end bearing.
- The final design in Revit will look similar to the Figure 36 when all of the components are added and connected.

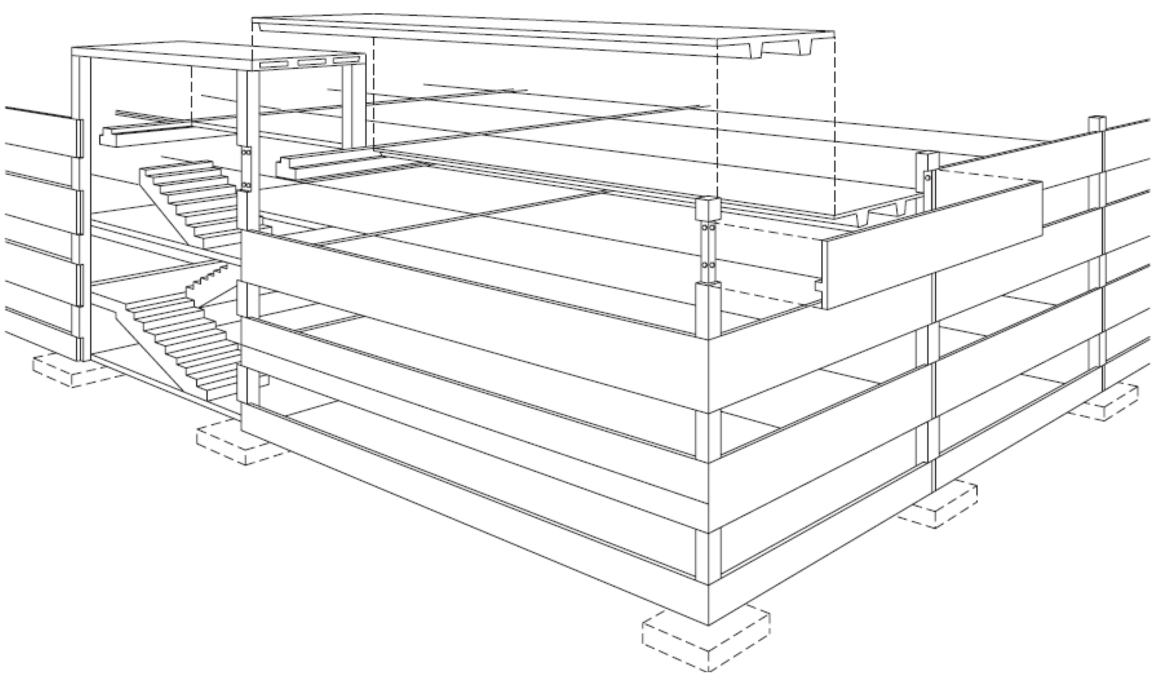


Figure 36 - Example Revit Design of the Prestressed Parking Garage (Force et. al., 1997)

3.3 Sustainability

Efforts to reduce the impact of the construction industry have led to advancements in a diverse range of sustainability concepts that are being gradually adopted more. This is particularly relevant as our industry consumes about 60% of the raw materials of the US excluding food and fuel and generates around the same amount of non-industrial, non-hazardous solid waste. (Choosing Green Materials and Products, 2012) Additional to environmental considerations, sustainability efforts encompass variables such as the durability of a construction materials to reduce additional cost to projects. According to WRAP, an agency for the waste management of the UK, lifetime maintenance and management costs of buildings can be five times greater than the cost of construction itself. (Optimizing durability and lifespan, 2014) Our project will focus on performing a quick assessment on the durability of a steel design against our precast design through methods such as life-cycle assessment (LCA) and embodied energy analysis.

3.3.1 Durability

The useable life of a construction material depends on its properties, its manufacturing, its usage, and its maintenance/management. All these variables can be tracked and quantified, allowing for comparisons between materials that shed light into the sustainable practices and resources. This type of tracking can be burdensome and convoluted for large scale construction processes that involve materials from different locations, in different conditions, at different times, and for different purposes. Thus, the right way to compare materials regarding their sustainability is by conducting a Life Cycle Assessment (LCA) of a functional unit, e.g. a square meter of a concrete. (EUPave, 2014) For our project, we will perform a life cycle assessment for both structural steel and precast concrete and then draw comparisons between them. A diagram providing an overview of life cycle assessment can be found in Figure 37.

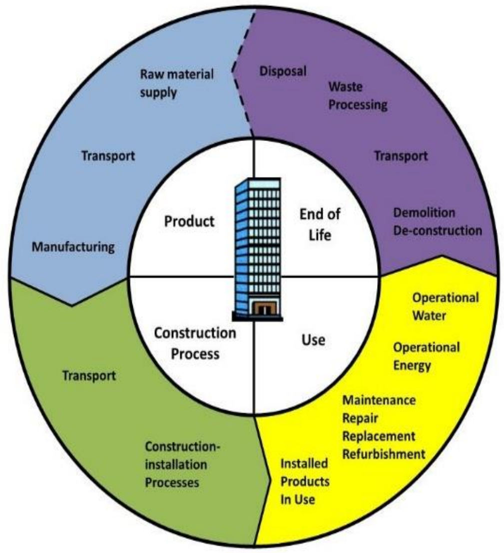


Figure 37 - Life Cycle Assessment Flow Chart (EUPave, 2014)

3.3.2 Embodied Energy

Interrelated with Life Cycle Assessment, an embodied energy analysis can add basis for comparison between construction materials. All of these have to be sourced, manufactured, processed, and then shipped before they are used on site. All of the activities prior to receiving a material amount to a sum of costs, transactions, logistics, and handling that requires energy. With the rise in popularity of the concept of sustainability across societies and industries worldwide, there has been an interest in quantifying the energy consumed by all the different processes and steps leading up to a construction material being available. This concept referred to as embodied energy can be defined as the total energy inputs consumed throughout a product's life-cycle. (Cannon Design, 2013).

For this project, our focus is on the embodied energy encompassed in construction materials used for the parking garage at their arrival for assembly. Thus, a more specific concept of Initial embodied energy representing the energy used for the extraction of raw materials, transportation to factory, processing and manufacturing, transportation to site, and construction will be analyzed.

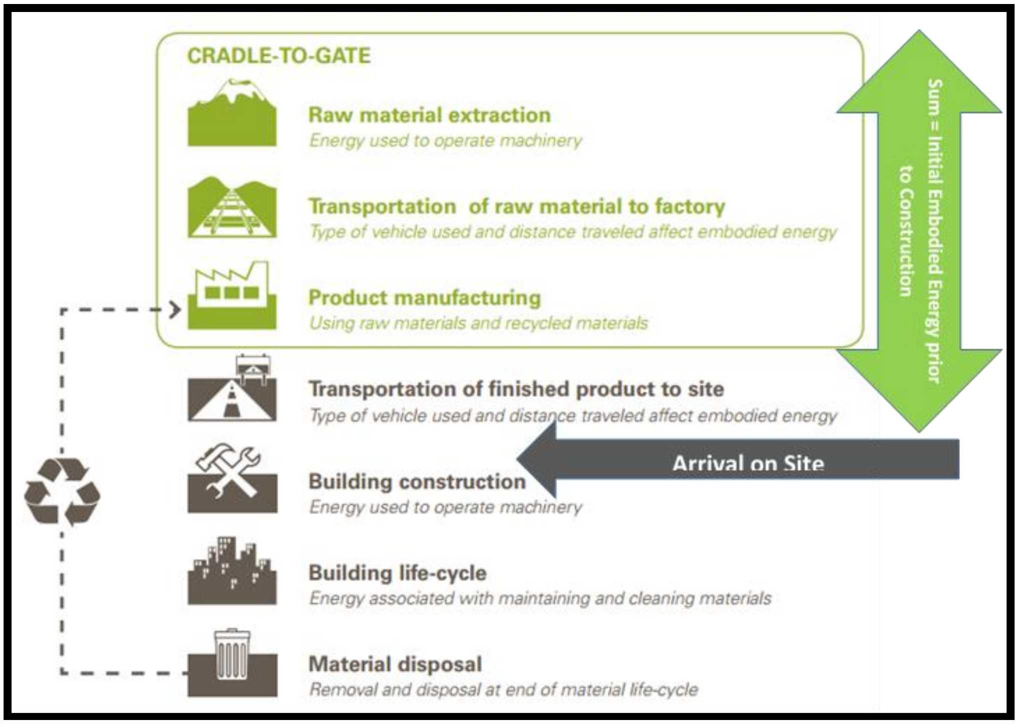


Figure 38 - Embodied Energy Analysis through Product or Material Life Cycle (Cannon Design, 2013)

Our analysis will consist in studying the difference between the embodied energy of the construction materials currently selected for the construction of the parking garage, primarily structural steel and concrete, and the energy encompassed in precast and prestressed members. To do this we will research the extraction and manufacturing processes of both alternatives and will recur to common industry sources and individual plants. We will use averages across the industry as a starting point, and then will do more specific research for our project location and criteria. (Cole et. al., 1996)

	EMBODIED ENERGY	
MATERIAL	MJ/kg	MJ/m3
Aggregate	0.10	150
Straw bale	0.24	31
Soil-cement	0.42	819
Stone (local)	0.79	2030
Concrete block	0.94	2350
Concrete (30 Mpa)	1.3	3180
Concrete precast	2.0	2780
Lumber	2.5	1380
Brick	2.5	5170
Cellulose insulation	3.3	112
Gypsum wallboard	6.1	5890
Particle board	8.0	4400
Aluminum (recycled)	8.1	21870
Steel (recycled)	8.9	37210
Shingles (asphalt)	9.0	4930
Plywood	10.4	5720
Mineral wool insulation	14.6	139
Glass	15.9	37550
Fiberglass insulation	30.3	970
Steel	32.0	251200
Zinc	51.0	371280
Brass	62.0	519560
PVC	70.0	93620
Copper	70.6	631164
Paint	93.3	117500
Linoleum	116	150930
Polystyrene Insulation	117	3770
Carpet (synthetic)	148	84900
Aluminum	227	515700

NOTE: Embodied energy values based on several international sources - local values may vary.

Table 6 - Construction Materials Embodied Energy

3.3.3 LEED

Leadership in Energy and Environmental Design is a voluntary rating system that asses the level of sustainability in buildings and motivates owners to be environmentally responsible by using resources efficiently. (PCI, 2009) This point- based system has 5 environmental categories: Sustainable sites, water efficiency energy and atmosphere, materials and resources, and indoor environment quality. Points awarded when a specific intent is met. A building is LEED certified with silver, gold or platinum when ratings are awarded for at least 50, 60 or 80 point out of 110 points, respectively. (PCI, 2009)

Comparing possible LEED points between steel structures and prestressed concrete structures, will be an adequate way to assess the levels of sustainability. When more points are earned, the lesser the environmental impact of the building to its surroundings. For structural design, LEED project checklist can be created by using submittals from the CitySquare parking garage project or obtaining general contractor's documentation of LEED points. For alternative design, an analysis like in Table 7 will be created and applicable points will added up for comparison.

LEED Category	Credit or Prerequisite	Potential Points
Sustainable Sites	Credit 5.1: Site Development—Protect or Restore Habitat	1
Sustainable Sites	Credit 5.2: Site Development—Maximize Open Space	1
Sustainable Sites	Credit 7.1: Heat Island Effect—Non-Roof	1
Sustainable Sites	Credit 7.2: Heat Island Effect—Roof	1
Energy and Atmosphere	Prerequisite 2: Minimum Energy Performance	—
Energy and Atmosphere	Credit 1: Optimize Energy Performance	1–19
Materials and Resources	Credit 1.1: Building Reuse	1
Materials and Resources	Credit 2: Construction Waste Management	1–2
Materials and Resources	Credit 4: Recycled Content	1–2
Materials and Resources	Credit 5: Regional Materials	1–2
Indoor Environmental Quality	Credit 3.1: Construction Indoor Air Quality Management Plan–During Construction	1
Indoor Environmental Quality	Credit 4.6: Low-Emitting Materials–Ceiling and Wall Systems	1‡
Indoor Environmental Quality	Credit 8.1: Daylight and Views–Daylight	1
Indoor Environmental Quality	Credit 8.2: Daylight and Views–Views	1
Indoor Environmental Quality	Credit 9: Enhanced Acoustical Performance	1‡
Indoor Environmental Quality	Credit 10: Mold Prevention	1‡
Innovation in Design	Credit 1: Innovation in Design	1–5
Innovation in Design	Credit 2: LEED Accredited Professional	1
Regional Priority	Credit 1: Regional Priority	1

Table 7 - LEED Project Checklist: Precast Concrete Potential Points (PCI, 2009)

3.4 Lean Construction

Lean construction is a process based on the concepts of lean manufacturing, which aims to remove all non-added value to the project, in order to deliver the customer needs in a more efficient, timely, and cost-effective manner. Lean concepts can be applied to different objectives and activities in a construction project to maximize value and minimize waste. Waste can be defined as anything that does not contribute to the value of the end user and is often categorized in 8 forms (n.a., 2010):

1. Under-utilized people - not using people's skills and knowledge effectively
2. Waiting - wait time for an activity, material, etc. to be completed
3. Defects - rework or anything that needs to be discarded
4. Overproduction - having more than needed
5. Motion - movement that does not add value (trucks, materials, people, etc.)
6. Inventory - anything in excess that is not being utilized
7. Transportation - movement of people, information, and materials around the organization
8. Over-processing - additional effort that does not add value to the customer

Our team will evaluate the current project management and design, as well as the alternative design that we will propose, based on specific lean concepts to reduce waste. This evaluation will be accomplished by on-site observations of the project development and a series of questions that will be address to the Project Engineer, Project Manager, and the Superintendent.

Following the evaluation of each component, we will develop a compare and contrast analysis to determine which aspects of each design are utilizing lean concepts in an effective way, and which ones could be improved. This will allow us to formulate recommendations for further improvement on the project and removal of non-added value operations. The lean concepts that will be used for this evaluation are: (1) communication and level of understanding, (2) prefabrication, (3) Inventory, (4) Just in Time, (5) Kitting and five S's, and (6) Pull system. These are explained below:

<u>(1)Communication and Level of Understanding</u> - Often times, effective communication between the different counterparts in a construction project is lacking, which leads to setbacks in the production, delivery of materials, and goal completion, amongst others. The current practice encourages participants to perform in their own silos and areas of work, but sometimes it does not align them towards the end goal of maximizing the end value and decreasing waste. In many cases, productivity improvements in each silo lead to even more unpredictable workflow because collaboration is limited and as mentioned before, lean construction should be applied to the entire process of a project, and not

just a specific section. Figure 39 shows the traditional approach (left) to a project where the different silos are hired as the project progresses. However, a lean project would involve all the key players since the first phase in order to reduce waste in the overall project, as depicted in the graph on the right.

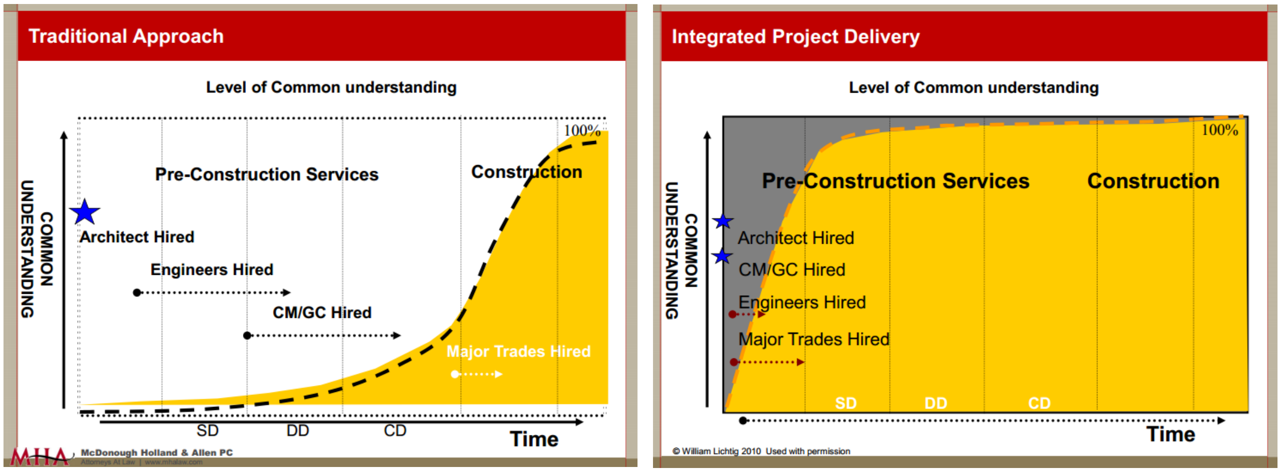


Figure 39 - Traditional Approach vs Lean Approach

Our team will evaluate the current project design and management based on this concept to determine the best practices for communication and understanding across all the key players in the project. Recommendations for improvement on this aspect will be provided.

(2) Prefabrication - In many projects, pre-fabricating certain objects or using materials that can be assembled outside of the project site, can significantly save time and space. Prefabrication can lead to better safety, a cleaner project site which reduces waste, and more space to assemble the parts; all which can benefit with the construction time and efficiency of certain activities. The construction of the parking garage is facing a big challenge with the space available at the project site to hold materials and progress on the construction, due to its location in downtown. The team will evaluate the impact that utilizing prefabricated concrete can have on the time and space at the project site, as well as the improvement on efficiency it may have.

(3) Inventory - Having too much inventory is always an issue because it is considered waste and reduces the workspace available. With the current design of steel, many of the materials will be received and stored on site as they get used and placed on their respective location. However, with the alternative design of prestressed concrete, prefabrication will be an advantage and can potentially improve and reduce the amount of inventory. The site does not have much space available to hold the materials and machinery, and still operate efficiently while not disturbing the operations in the downtown area. The team will analyze the inventory on-site based on the two designs and determine which one is more effective.

(4) Just in Time - Delivery of the materials at the right moment is crucial for the efficiency of the project and to reduce waste, time, and cost. With the goal of reducing the amount of inventory, just in time delivery of materials will be essential to utilize the materials when needed (pull), rather than having them on site. This would give us no laydown and no truck staging outside of the site, a crucial element in this project due to its location. With a material such as prestressed concrete, the delivery of the slabs when needed will impact the efficiency and progress of the project. We will evaluate the delivery of materials for both designs and determine which are the critical elements for each activity.

(5) Kitting and 5S - When applying lean concepts to a process, 5S can be a simple solution to a lot of drawbacks. The five S's include: (1) sort, (2) straighten, (3) shine, (4) standardize, and (5) sustain. Sorting allows you to go through everything in the work area to keep what is necessary and discard the materials that are not used. Straightening and shining includes identifying items that go together, organize them, and arrange them for an effective retrieval. Standardizing and sustaining will allow you to determine the best practices to not fall into old habits and educate people about maintaining those standards. Kitting reduces the inventory levels and increases the operator's effectiveness. It decreases the space needed for material storage, reduces the overall deliveries, and ensures ease of access to materials. Our team will evaluate the project site in terms of their effectiveness of usage and storage of materials on site. Based on the outcomes and performance, we will provide recommendations to improve such practices. Better storage and organization of their materials can impact the staging on site, accessibility to the site, and the equipment usage and rental.

(6) Pull system - The pull system is perhaps the most common concept in Lean process improvement. This system is based on the "Last Planner Method" (LPM) instead of the common scheduling method of CPM. This method is designed to "integrate 'should-can-will-did' planning and activity delivery of a project". (Sayer, 2012) The LPM empowers the person who is making the job assignments to direct and communicate with the workers, enabling a constant communication vehicle with everyone. One of the key components to the LPM is the learning aspect of it, where you identify any failures and the reasons behind it. Instead of pushing the schedule out more in order to accommodate for more time to complete tasks, you act on the reasons for those failures and work with everyone to improve them and avoid repeating the same mistake to keep the project on schedule. Our team will be doing an evaluation of the current and proposed schedule based on the LPM concepts to identify what type of system is being utilized and if there are any areas for improvement in the schedules. Figure 40 and Figure 41 below illustrate the Last Planner Method and compares it to the traditional CPM scheduling.

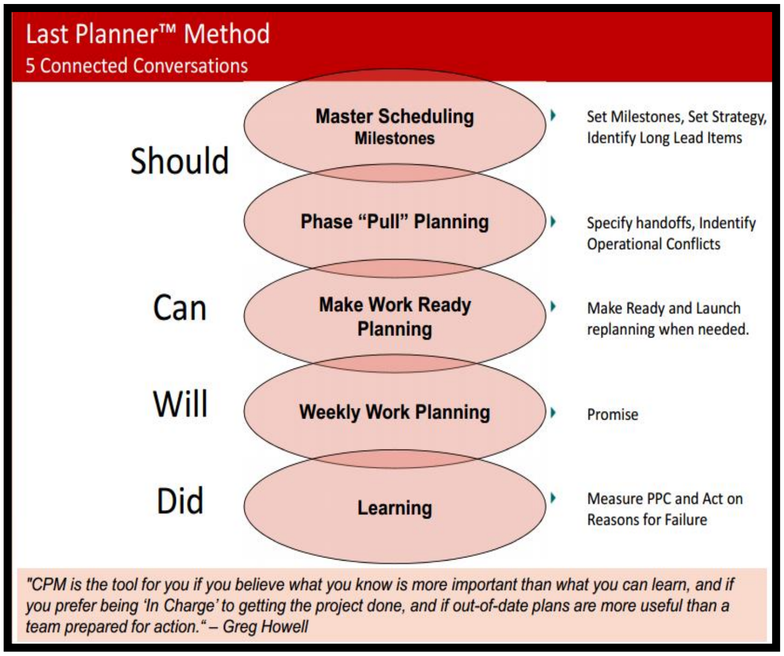


Figure 40 - The Last Planner Method outline (n.a., 2009)

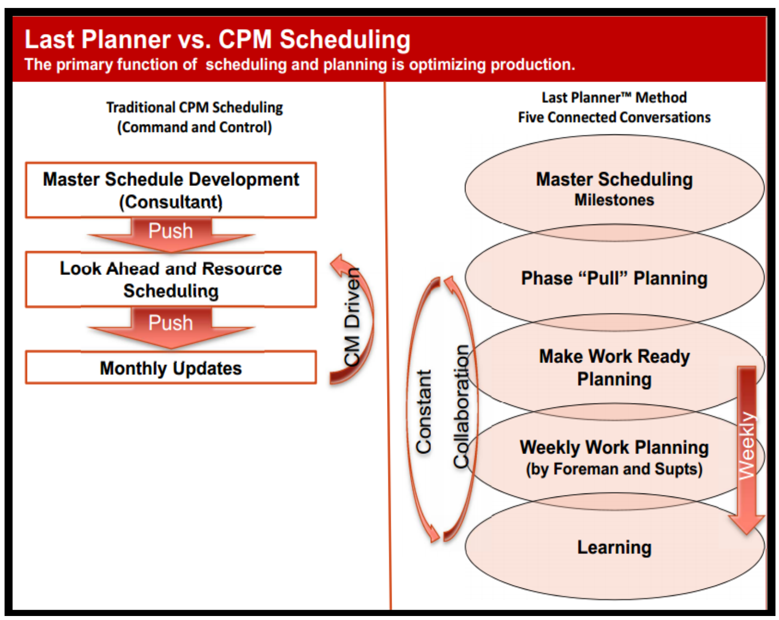


Figure 41 - Last Planner Method vs. Traditional CPM Scheduling (n.a., 2009)

Based on the six Lean concepts that have been outlined above, our team will conduct a compare and contrast analysis between the two methods to better understand the areas of improvement in each method based on the Lean concepts. It will also allow us to capture those key activities in which the current construction method is already being efficient and has low waste.

On Table 8 below, our team has created a chart which includes the six Lean concepts described above and the areas in which we believe these will have the most impact and influence. After conducting our evaluation, we will revisit the chart to determine if there are any other areas of high impact.

Activity	Coomunication	Prefabrication	Inventory	Just in Time	Kitting & 5S	Pull System	Total
Design Phase	X	X					2
CPM Schedule	X	X				X	3
4 Week Look Ahead	X		X			X	3
Subcontractor Preliminary Bidding	X					X	2
Descoping Subcontractor						X	1
Staging on Site		X	X	X	X	X	5
Accesibility to Site				X	X		2
Equipment Rental/Usage			X	X	X		3
Submittals	X		X				2
RFI's	X						1
Change Request	X					X	2
Substructure Construction			X				1
Shell Construction		X	X				2
Site Work			X		X		2
Services (HVAC, Electrical, Plumbing)			X				1
Finishes			X				1
Total	7	4	9	3	4	6	

Table 8 - Lean concepts' impact on project

3.5 Axiomatic Design Decomposition

In this section of the paper, our team will utilize the concepts of axiomatic design decomposition to analyze a specific problem of the project or design. Axiomatic Design is an approach to engineering design based on two axioms, or laws, which assures that the most effective design is being utilized. Our team will implement this concept to the construction project to look at the potential impact on the new alternative design. The section will include an introduction and state of the art for the concept and will explain its relatability to a construction project.

The first step will be to identify the specific problem, which could be a financial aspect with the GNP, logistics in the site, delivering materials, or any other key activity in the project. Currently, our team is evaluating the possibility of applying the axiomatic design concepts to the span length of the alternative prestressed design that will be developed. This is a critical component in the alternative design, as it may impact the existing dead loads and foundations. Since concrete is heavier than steel, we will utilize the axiomatic design decomposition to guide our decision-making process to create the most effective parking structure, in terms of maneuverability, cost, and schedule.

The second step will be to decompose the problem, to essentially determine the parameters of the design based on "what we want to achieve" and "how we want to achieve those goals". This will be accomplished by looking at the functional domains of the design and determining the design parameters based on them. It will be essential to identify functional requirements which are independently adjustable and will not require further decomposition. Likewise, they will have to be collectively exhaustive.

The final step will be to create a matrix to determine where the FR's interact with each other in a positive or negative way. The matrix will allow our team to have a visual representation of the design and determine if it will be the best alternative or not. In order to conduct the axiomatic design decomposition our team will utilize *Acclaro,* a software designed for this purpose. This will aid with the decomposition of the problem. The end goal of the axiomatic design decomposition is to utilize this method to decompose a problem or activity in a construction project and demonstrate the application of its method and usability to different fields.

Deliverables

Over the course of the next two terms, our team plans on completing all of our methods to provide an alternative design for the underground parking garage. We will conduct an analysis of the current project management, focusing mainly on the effectiveness of completion of the schedule, cost, organizational leadership, and logistics of the project. The team will create an alternative design for the project, utilizing prestressed concrete instead of steel. A schedule, cost, and sustainability analysis will be done for this alternative design, and will be compared to the actual construction of CitySquare's underground parking garage.

Moreover, Lean Construction concepts will serve as a benchmark to evaluate the current project management and design proposed, as well as the alternative design that the team will create. By evaluating both designs based on the same criteria and concepts, we will be able to identify areas of improvement were lean concepts can be applied increase the efficiency and remove any waste. A comparative table with both designs will be created to provide a more illustrative demonstration of the analysis conducted and results gathered.

Finally, the axiomatic design method will be utilized to identify a key activity in the alternative design and apply the methodology behind it to decompose the problem. The proposed activity to which it can be applied is the span length of the alternative design, a critical component which can impact the total cost and scheduling of the project. The end goal will be to demonstrate the application of its method and usability to the construction management field.

After completion of our methods, our team will present the results, recommendations, and conclusions of our project with a report and final presentation, which will be delivered to our project advisors and sponsors.

MQP Timeline

The following timeline depicts the milestones and steps that our team will be working on for the next two terms. Although the schedule may fluctuate a little as the project progresses, we will work to the best of our ability to remain within the proposed timeline in order to deliver the project report and presentation in a timely manner.

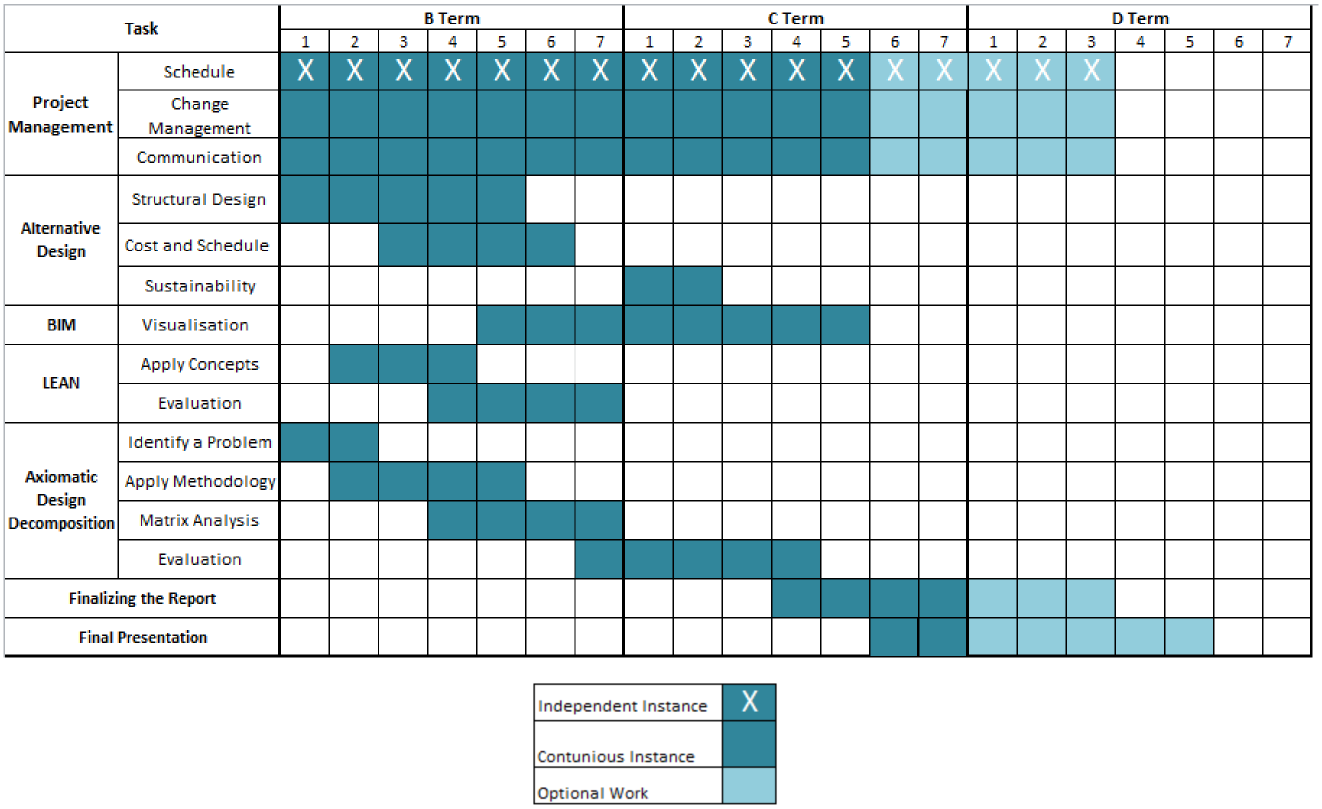


Figure 42 - Project Timeline

From the proposed timeline, we can identify that B-term and the first weeks of C-term will be focused on gathering data, conducting observations, and doing the evaluations. During the final weeks of C-term, the team will work on drawing the conclusion and recommendations and finalizing the report as our final deliverable. This will then be presented to our project advisors and sponsor.

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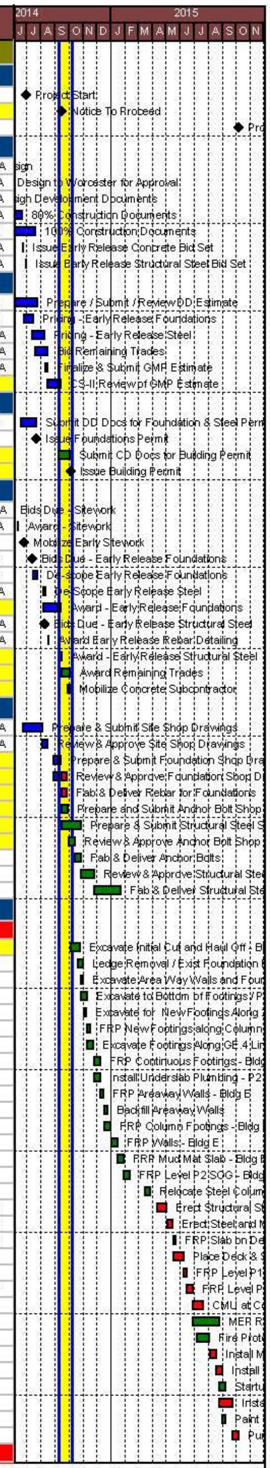
Appendix

Activity ID	Activity Name	Orig Dur	Rem Dur	Start	Finish
CITY SQUARE UNDERGROUND PARKING GARAGE					
Project Milestones					
A5350	Project Start	0	0	30-Jun-14 A	
A3100	Notice To Proceed	0	0	15-Sep-14	
A5360	Project Complete	0	0		07-Oct-15
Design					
A1000	Schematic Design	0	0		16-Dec-13 A
A1010	Schematic Design to Worcester for Approval	20	0	16-Dec-13 A	24-Jan-14 A
A1020	Design Development Documents	30	0	27-Jan-14 A	09-Apr-14 A
A1030	80% Construction Documents	27	0	10-Apr-14 A	20-Jun-14 A
A5140	100% Construction Documents	50	0	10-Apr-14 A	21-Jul-14 A
A1040	Issue Early Release Concrete Bid Set	5	0	23-Jun-14 A	23-Jun-14 A
A1050	Issue Early Release Structural Steel Bid Set	5	0	30-Jun-14 A	30-Jun-14 A
Estimates					
A3070	Prepare / Submit / Review DD Estimate	15	0	10-Apr-14 A	25-Jul-14 A
A3170	Pricing - Early Release Foundations	10	0	26-Jun-14 A	14-Jul-14 A
A5370	Pricing - Early Release Steel	15	0	14-Jul-14 A	08-Aug-14 A
A3090	Bid Remaining Trades	25	0	21-Jul-14 A	14-Aug-14 A
A3080	Finalize & Submit GMP Estimate	5	0	11-Aug-14 A	15-Aug-14 A
A3230	CS-II Review of GMP Estimate	10	5	15-Aug-14 A	12-Sep-14
Permitting					
A2000	Submit DD Docs for Foundation & Steel Permit	20	0	19-Jun-14 A	22-Jul-14 A
A2010	Issue Foundations Permit	0	0	23-Jul-14 A	
A2020	Submit CD Docs for Building Permit	20	20	08-Sep-14	03-Oct-14
A2030	Issue Building Permit	0	0	06-Oct-14	
Bid & Award					
A3040	Bids Due - Sitework	0	0		28-May-14 A
A5160	Award - Sitework	7	0	13-Jun-14 A	13-Jun-14 A
A3050	Mobilize Early Sitework	0	0	26-Jun-14 A	
A3060	Bids Due - Early Release Foundations	0	0		14-Jul-14 A
A5390	De-scope Early Release Foundations	10	0	15-Jul-14 A	24-Jul-14 A
A3020	De-Scope Early Release Steel	5	0	06-Aug-14 A	11-Aug-14 A
A5380	Award - Early Release Foundations	10	5	07-Aug-14 A	12-Sep-14
A3000	Bids Due - Early Release Structural Steel	0	0		08-Aug-14 A
A5820	Award Early Release Rebar Detailing	5	0	18-Aug-14 A	18-Aug-14 A
A5150	Award - Early Release Structural Steel	1	1	15-Sep-14	15-Sep-14
A3190	Award Remaining Trades	15	15	15-Sep-14	03-Oct-14
A3180	Mobilize Concrete Subcontractor	5	5	29-Sep-14	03-Oct-14
Submittals					
A3120	Prepare & Submit Site Shop Drawings	10	0	23-Jun-14 A	05-Aug-14 A
A3160	Review & Approve Site Shop Drawings	10	0	05-Aug-14 A	15-Aug-14 A
A3110	Prepare & Submit Foundation Shop Drawings	10	5	28-Aug-14 A	12-Sep-14
A3150	Review & Approve Foundation Shop Drawings	15	10	28-Aug-14 A	26-Sep-14
A3130	Fab & Deliver Rebar for Foundations	10	10	15-Sep-14	26-Sep-14
A3200	Prepare and Submit Anchor Bolt Shop Drawings	10	10	16-Sep-14	29-Sep-14
A3010	Prepare & Submit Structural Steel Shop Drawings	30	30	16-Sep-14	27-Oct-14
A3210	Review & Approve Anchor Bolt Shop Drawings	10	10	30-Sep-14	13-Oct-14
A3220	Fab & Deliver Anchor Bolts	10	10	14-Oct-14	27-Oct-14
A3140	Review & Approve Structural Steel Shop Drawings	20	20	28-Oct-14	25-Nov-14
A3030	Fab & Deliver Structural Steel	40	40	26-Nov-14	23-Jan-15
Construction					
Bldg E					
A4000	Excavate Initial Cut and Haul Off - Bldg E	15	15	06-Oct-14	24-Oct-14
A4020	Ledge Removal / Exist Foundation Removal	10	10	20-Oct-14	31-Oct-14
A4170	Excavate Area Way Walls and Foundations	5	5	27-Oct-14	31-Oct-14
A4030	Excavate to Bottom of Footings / Prep with Stone	10	10	27-Oct-14	10-Nov-14
A4190	Excavate for New Footings Along 27 Line	5	5	03-Nov-14	07-Nov-14
A4160	FRP New Footings along Column Line 27 - Bldg E	5	5	10-Nov-14	17-Nov-14
A4010	Excavate Footings Along GE.4 Line	10	10	10-Nov-14	24-Nov-14
A4040	FRP Continuous Footings - Bldg E	10	10	25-Nov-14	09-Dec-14
A4150	Install Underslab Plumbing - P2	10	10	25-Nov-14	09-Dec-14
A5560	FRP Areaway Walls - Bldg E	5	5	10-Dec-14	16-Dec-14
A4180	Backfill Areaway Walls	5	5	17-Dec-14	23-Dec-14
A4110	FRP Column Footings - Bldg E	10	10	17-Dec-14	31-Dec-14
A4200	FRP Walls - Bldg E	10	10	02-Jan-15	15-Jan-15
A5550	FRP Mud Mat Slab - Bldg E	10	10	16-Jan-15	29-Jan-15
A5240	FRP Level P2 SOG - Bldg E	10	10	30-Jan-15	12-Feb-15
A4130	Relocate Steel Columns along 27 Line - Bldg E	10	10	16-Mar-15	27-Mar-15
A4120	Erect Structural Steel - Bldg E	15	15	13-Apr-15	01-May-15
A4220	Erect Steel and Metal Deck at Vault - Bldg E	10	10	04-May-15	15-May-15
A4210	FRP Slab on Deck at Vault - Bldg E	5	5	18-May-15	22-May-15
A4090	Place Deck & Shear Studs - Bldg E	15	15	18-May-15	08-Jun-15
A4140	FRP Level P1 Slab on Deck - Bldg E	5	5	09-Jun-15	15-Jun-15
A5230	FRP Level Plaza - Bldg E	10	10	16-Jun-15	29-Jun-15*
A4050	CMU at Core 2	15	15	30-Jun-15	21-Jul-15
A4230	MEP Rough-in and installations - Bldg E	40	40	30-Jun-15	25-Aug-15
A4240	Fire Protection Rough-in	20	20	08-Jul-15	04-Aug-15
A4060	Install Metal Stairs & Handrails - Stair 2	10	10	05-Aug-15	18-Aug-15
A4080	Install Temporary Watertight Enclosures at Shafts	10	10	19-Aug-15	01-Sep-15
A4250	Startup, Pre-Functional and FPT Testing	10	10	26-Aug-15	09-Sep-15
A4070	Install Elevators - Bldg E	20	20	26-Aug-15	23-Sep-15
A4100	Paint at Stair 2	5	5	02-Sep-15	09-Sep-15
A4260	Punchlist Activities	10	10	24-Sep-15	07-Oct-15
Overall Site					



Start Date 16-Dec-13
Finish Date 07-Oct-15
Data Date 08-Sep-14
Run Date 09-Sep-14 10:55

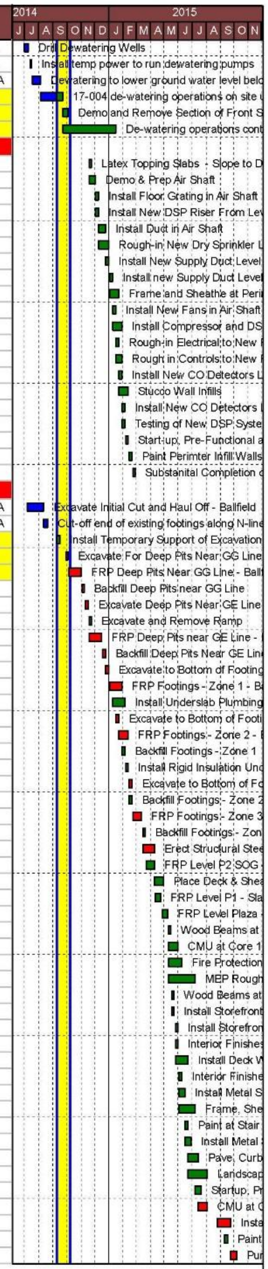
Remaining Level of Effort
Actual Level of Effort
Actual Work
Remaining Work
Critical Remaining Work

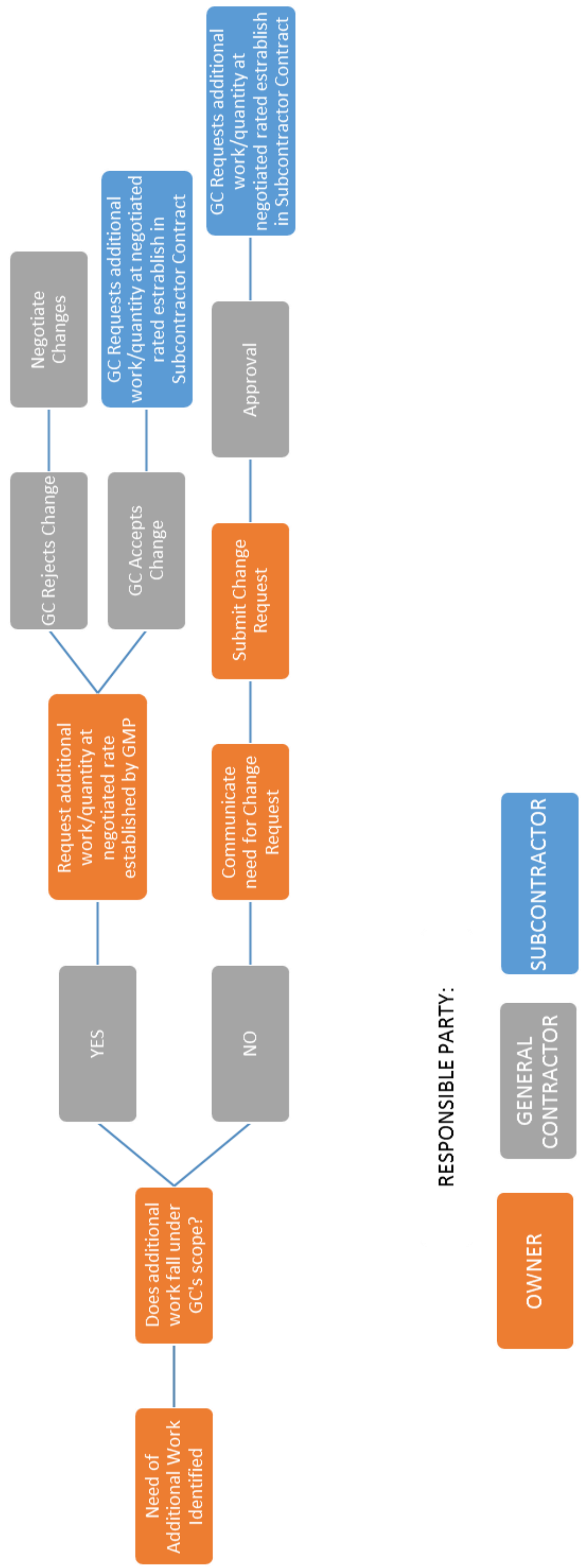
CONSIGLI CONSTRUCTION CO., INC.

CITY SQUARE UNDERGROUND PARKING GARAGE

CONSIGLI
Est. 1905

Activity ID	Activity Name	Orig Dur	Rem Dur	Start	Finish
A5080	Drill Dewatering Wells	5	0	30-Jun-14 A	08-Jul-14 A
A5410	Install temp power to run dewatering pumps	5	0	14-Jul-14 A	16-Jul-14 A
A5400	Dewatering to lower ground water level below bottom of footings	20	0	17-Jul-14 A	05-Aug-14 A
A5830	17-004 de-watering operations on site until construction start	30	15	05-Aug-14 A	22-Sep-14
A5850	Demo and Remove Section of Front Street Bridge	10	10	22-Sep-14	03-Oct-14
A5840	De-watering operations continued during concrete operations	80	80	23-Sep-14	16-Jan-15
East Garage Mitigation					
A5630	Latex Topping Slabs - Slope to Drain at Infills	5	5	18-Nov-14	24-Nov-14
A5650	Demo & Prep Air Shaft	10	10	18-Nov-14	02-Dec-14
A5660	Install Floor Grating in Air Shaft	5	5	03-Dec-14	09-Dec-14
A5700	Install New DSP Riser From Level B2	5	5	03-Dec-14	09-Dec-14
A5670	Install Duct in Air Shaft	10	10	10-Dec-14	23-Dec-14
A5690	Rough-in New Dry Sprinkler Lines level B1	15	15	10-Dec-14	31-Dec-14
A5720	Install New Supply Duct Level B2	5	5	24-Dec-14	31-Dec-14
A5730	Install new Supply Duct Level B1	5	5	02-Jan-15	08-Jan-15
A5320	Frame and Sheathe at Perimeter Wall Infills	15	15	02-Jan-15	22-Jan-15
A5680	Install New Fans in Air Shaft	5	5	09-Jan-15	15-Jan-15
A5710	Install Compressor and DSP Valve Assemblies	15	15	09-Jan-15	29-Jan-15
A5780	Rough-in Electrical to New Fans	5	5	16-Jan-15	22-Jan-15
A5760	Rough in Controls to New Fans	10	10	16-Jan-15	29-Jan-15
A5740	Install New CO Detectors Level B2	5	5	23-Jan-15	29-Jan-15
A5640	Stucco Wall Infills	15	15	23-Jan-15	12-Feb-15
A5750	Install New CO Detectors Level B1	5	5	30-Jan-15	05-Feb-15
A5810	Testing of New DSP System	5	5	30-Jan-15	05-Feb-15
A5770	Start-up, Pre-Functional and FPT Testing	5	5	06-Feb-15	12-Feb-15
A5790	Paint Perimter Infill Walls	5	5	13-Feb-15	20-Feb-15
A5800	Substanital Completion of East Garage	5	5	23-Feb-15	27-Feb-15
Ballfield					
A5000	Excavate Initial Cut and Haul Off - Ballfield	20	0	07-Jul-14 A	12-Aug-14 A
A5170	Cut-off end of existing footings along N-line	5	0	11-Aug-14 A	19-Aug-14 A
A5010	Install Temporary Support of Excavation along N-Line Footings	7	7	08-Sep-14	16-Sep-14
A5420	Excavate For Deep Pits Near GG Line	5	5	29-Sep-14	03-Oct-14
A5430	FRP Deep Pits Near GG Line - Ballfield	20	20	06-Oct-14	31-Oct-14
A5440	Backfill Deep Pits near GG Line	5	5	03-Nov-14	07-Nov-14
A5450	Excavate Deep Pits Near GE Line	5	5	10-Nov-14	17-Nov-14
A5490	Excavate and Remove Ramp	5	5	18-Nov-14	24-Nov-14
A5460	FRP Deep Pits near GE Line - Ballfield	20	20	18-Nov-14	16-Dec-14
A5470	Backfill Deep Pits Near GE Line	5	5	17-Dec-14	23-Dec-14
A5020	Excavate to Bottom of Footings - Zone 1	5	5	24-Dec-14	31-Dec-14
A5030	FRP Footings - Zone 1 - Ballfield	20	20	02-Jan-15	29-Jan-15
A5310	Install Underslab Plumbing - P2	20	20	09-Jan-15	05-Feb-15
A5190	Excavate to Bottom of Footing - Zone 2	5	5	16-Jan-15	22-Jan-15
A5130	FRP Footings - Zone 2 - Ballfield	15	15	23-Jan-15	12-Feb-15
A5500	Backfill Footings - Zone 1	5	5	30-Jan-15	05-Feb-15
A5540	Install Rigid Insulation Underslab - Zone 1 - ballfield	5	5	06-Feb-15	12-Feb-15
A5480	Excavate to Bottom of Footing - Zone 3	5	5	13-Feb-15	20-Feb-15
A5510	Backfill Footings - Zone 2	5	5	13-Feb-15	20-Feb-15
A5180	FRP Footings - Zone 3 - Ballfield	15	15	23-Feb-15	13-Mar-15
A5520	Backfill Footings - Zone 3	5	5	16-Mar-15	20-Mar-15
A5250	Erect Structural Steel - Ballfield	20	20	16-Mar-15	10-Apr-15
A5300	FRP Level P2 SOG - Ballfield	15	15	23-Mar-15	10-Apr-15
A5270	Place Deck & Shear Studs - Ballfield	15	15	10-Apr-15	30-Apr-15
A5340	FRP Level P1 - Slab on Deck - Ballfield	10	10	13-Apr-15	24-Apr-15
A5330	FRP Level Plaza - Ballfield	10	10	27-Apr-15	08-May-15
A5570	Wood Beams at Head House - Core 1	5	5	11-May-15	15-May-15
A5040	CMU at Core 1	15	15	11-May-15	01-Jun-15
A5530	Fire Protection Rough-in	20	20	11-May-15	08-Jun-15
A5260	MEP Rough-in and Installations	40	40	11-May-15	07-Jul-15
A5580	Wood Beams at head House Core 3	5	5	18-May-15	22-May-15
A5590	Install Storefront at Head House - Core 1	5	5	18-May-15	22-May-15
A5600	Install Storefront at Head House - Core 3	5	5	26-May-15	01-Jun-15
A5610	Interior Finishes at Head House - Core 1	5	5	26-May-15	01-Jun-15
A5090	Install Deck Waterproofing at Upper Deck Only	20	20	26-May-15	22-Jun-15
A5620	Interior Finishes at Head House - Core 3	5	5	02-Jun-15	08-Jun-15
A5060	Install Metal Stairs & Handrails - Stair 1	10	10	02-Jun-15	15-Jun-15
A5050	Frame, Sheath, Watertight Enclosures at Shafts	25	25	02-Jun-15	07-Jul-15
A5120	Paint at Stair 1	5	5	16-Jun-15	22-Jun-15
A5200	Install Metal Stairs & Handrails - Stair 3	10	10	16-Jun-15	29-Jun-15
A5110	Pave, Curb & Stripe at Eaton Place	15	15	23-Jun-15	14-Jul-15
A5100	Landscaping and Site Improvements	30	30	23-Jun-15	04-Aug-15
A5280	Startup, Pre-Functional and FPT Testing	10	10	08-Jul-15	21-Jul-15
A5220	CMU at Core 3	15	15	15-Jul-15	04-Aug-15
A5070	Install Elevators - Ballfield	20	20	26-Aug-15	23-Sep-15
A5210	Paint at Stair 3	5	5	10-Sep-15	16-Sep-15
A5290	Punchlist Activities	10	10	24-Sep-15	07-Oct-15




Need of Additional Work Identified
Does additional work fall under GC's scope?
YES
NO
Request additional work/quantity at negotiated rate established by GMP
GC Rejects Change
GC Accepts Change
Negotiate Changes
GC Requests additional work/quantity at negotiated rated estrablish in Subcontractor Contract
Communicate need for Change Request
Submit Change Request
Approval
GC Requests additional work/quantity at negotiated rated estrablish in Subcontractor Contract
RESPONSIBLE PARTY:
OWNER
GENERAL CONTRACTOR
SUBCONTRACTOR

RFI Tracking Shee	Column1	Column	Column3	Column4	Column5	Column6	Column7
Document #	**Document Name**	**Status**	**Turnover time (Days)**	**Sequencing**	**Reasoning**	**Impact on Schedule**	**Projected Cost**
#1234	Sample RFI for Connection Details	Resolved	25	SUB>GC>DS/ENG>GC >SUB	Connection details unclear on required epoxy for bolted connections	Steel subcontractor held off 4 days to select required epoxy coated connection bolts	Assumed unit cost of bolts: $2 Unit cost of bolts confirmed in RFI: $3.50 Total Added Cost: 425 bolts x $1.5/delta per bolt = $637.50

Key: SUB= Subcontractor - OWN= Owner - GC= General Contractor - DES= Designer - ENG= Engineer

Submittals Tracking Sheet	Column1	Column	Column3	Column4	Column5	Column6	Column7
Document #	**Document Name**	**Status**	**Turnover time (Days)**	**Sequencing**	**Reasoning**	**Impact on Schedule**	**Projected Cost**
#1234	Sample Submittal for Bolt Resistance	Approved	35	SUB>GC>DES/ENG> GC>OWN	Mechanical capacities of Epoxy coated bolts needed to be verified to meet designers requirements	None. Submittal was approved in time for Steel Subcontractor to acquire necessary materials	No changes.

Key: SUB= Subcontractor - OWN= Owner - GC= General Contractor - DES= Designer - ENG= Engineer

Properties of Concrete

fc'(psi)=	6500	
fci(psi)=	5000	
Density of Conrete (lb/ft^3) =	150	
Ec' =	4887733.4	$33 \times w_c^{1.5}\sqrt{f_c'}$
Eci =	4286825.7	$33 \times w_c^{1.5}\sqrt{f_c'}$

Properties of Prestressing Steel

fpu (ksi) =	270	
Number of Strands =	48	
Aps (in^2) =	0.217	
Eps (psi) =	2.85E+07	
Pi (k) =	1968.624	$0.7 * A_{ps} * \#of\ strands * f_{pu}$

Section Properties

Rectangular Beam

Width,b (in) =	160		
Height,h (in) =	42		
Length (in) =	840		
Area (in^2) =	2368	$b \times h$	
Inertia (in^4) =	334920.6		$\frac{1}{12}bh^3$
cb=ct (in) =	29	$\frac{I}{h/2}$	
Section Modulus,Sb (in^3) =	11548.986		
Volume/Surface (in) =	5.182		

ct=	13
St=	25763.12308

Loads

Live Load (k/f) =	2
Dead Load (k/f) =	2.5
Self Weight (k/ft) =	2.466667

Prestress Losses

Elastic Shortening

Kes=	1	
Kcir=	0.9	
e (in)=	19	
Msw (k-in) = $\frac{w_{sw} \times L^2}{8}$	18130	
fcir (psi)=	1629.4218	$f_{cir} = K_{cir}\left(\frac{P_i}{A_g} + \frac{P_i e^2}{I_g}\right) - \frac{M_{sw} e}{I_g}$
ES (psi) = $ES = \frac{K_{ES} E_{PS} f_{cir}}{E_{ci}}$	10832.846	

Creep of Concrete

Kcr=	2	
Mdl (kp-in) =	18375	
fcds (psi) =	1042.411	$\frac{M_{DL} e}{I}$
CR (psi) =	6845.627	$CR = K_{CR}\left(\frac{E_{PS}}{E_c'}\right)(f_{cir} - f_{cds})$

Shrinkage of Concrete

Ksh =	1	
Relative Humidity (RH) =	75	Design Aid 4.11.12
SH (psi) =	4025.9499	

$SH = (8.2 \times 10^{-6}) K_{SH} E_{ps} (1 - 0.06V/S)(100 - RH)$

Relaxation of Tendons

Kre=	5000	From Table 5.7.1
J=	0.04	From Table 5.7.1
fpi=Pi/Aps	189	
fpi/fpu	0.7	
C=	0.75	Table 5.7.2
RE (psi) =	3098.867	$RE = [K_{RE} - J(ES + CR + SH)]C$

TOTAL LOSS (PSI)=	24803.29	13.12343391
JACKING FORCE AFTER LOSSES (k) =	1710.2729	

$P_i - (TL * \#\ of\ strands * A_{ps})$

Criticatl Stress Calculations

Fse = (0.7 x fpu) ksi	189	
Tl= (Transfer Length -in) =	34	Design Aid 15.3.4

Ps forces after losses

Transfer @ Release

Msw,T (k-in)=	2816.5222	$\frac{W_{sw} \times T_L}{2} \times (L - T_L) * 12$
fcir(ksi)=	2.4981533	$f_{cir} = K_{cir}\left(\frac{P_i}{A_g} + \frac{P_i e^2}{I_g}\right) - \frac{M_{sw,T} e}{I_g}$
EST (ksi)=	16.608412	
Loss EST (k)	172.99322	$(ES_T \times A_{ps} \times \#of\ strands)$
Po1(k)=	1795.6308	$P_i - ES_T$

Midspan @ Release

Msw,M (k-in)=	18130	
ESM (ksi)=	10.832846	
Loss ESM (k)	112.83492	$ES_M \times A_{ps} \times \#of\ strands$
Po2(k)=	1855.7891	

Midspan @ Service

Msw (k-in)=	18130
MsDL (k-in)=	18375
MLL (k-in)=	14700
Po3(k)=	1771.7616

	Transfer @ Release		Midspan @ Release		Midspan @ Service	
****units are in psi*****	f_b	f_t	f_b	f_t	f_b	f_t
Po/A	758.29002	758.2900247	783.6947133	783.6947133	748.2101351	748.2101
Po.e/S	2954.1108	-1324.256562	3053.081189	-3053.081189	2914.84203	-2914.842
Msw/S	-243.8761	109.3237886	-1569.834761	1569.834761	-1569.834761	1569.835
Msdl/S	0	0	0	0	-1591.048744	1591.049
Mll/S	0	0	0	0	-1272.838995	1272.839
Total	3468.5247	-456.6427486	2266.941141	-699.5517148	-770.670335	2267.091
PCI Limits	3500	-530.3300859	3500	-530.3300859	-604.6693311	4550
Limit Check	In Limits	Class U	In Limits	Class T	Class T	In Limits

Deflection Calculations

Camber (in)=	2.1660731	$\frac{P_{02}eL^2}{8E_{ci}I_g}$
Def due to SW (in) =	0.9281271	$\frac{5w_{sw}L^4}{384E_{ci}I_g}$
Def due to SDL (in) =	0.8250216	$\frac{5w_{DL}L^4}{384E_c'I_g}$

If Uncracked

Def due to LL (in) =	0.6600173	$\frac{5w_{LL}L^4}{384E_c'I_g}$

If Cracked

dp (in) =	48	$d_p = e + c_t$
Pp =	0.00135625	$\frac{A_{ps} \times \#of\ strands}{b \times d_p}$
C=	0.037	Design Aid 5.14.11
Icr (in^4)=	654704.64	$I_{cr} = C \times b \times d_b{}^3$
Exceeding stress (psi) =	166.0010039	
Live load in limit (psi) =	1106.837991	
Percentage of the LL in limit	86.95820881	
live load in Class U (kip/ft) =	1.739164176	
Def. Ig (in)=	0.573939205	$\frac{5w_{unc,LL}L^4}{384E_c'I_g}$
Percentage of the exceedin LL	13.04179119	
Exceeding live load (kip/ft) =	0.260835824	
Def. Ic (in)=	0.044034086	$\frac{5w_{cr,LL}L^4}{384E_c'I_{CR}}$
total def due to LL (in) =	0.617973292	

If Uncracked

	(1) Release	Multiplier	(2) Erection	Multiplier	(3) Final
Camber	2.166	1.800	3.899	2.450	5.307
wsw	-0.928	1.850	-1.717	2.700	-2.506
wsd			-0.825	3.000	-2.475
wll					-0.660
			1.357		-0.334
Total Deflection	1.691				

If Cracked

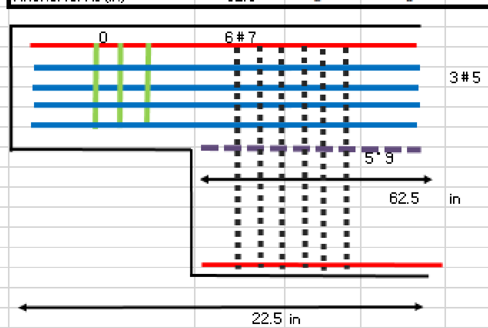
	(1) Release	Multiplier	(2) Erection	Multiplier	(3) Final
Camber	2.166	1.800	3.899	2.450	5.307
wsw	-0.928	1.850	-1.717	2.700	-2.506
wsd			-0.825	3.000	-2.475
wll					-0.618
			1.357		-0.292
Total Deflection	1.648977				

Connection Design

fy (ksi) =	60	
fys (ksi) =	60	
wu (k/f) =	9.16	$W_U = 1.2(SW + DL) + 1.6LL$
Vu (k) =	320.6	$V_U = \frac{W_U \times L}{2}$
Nu (k) =	64.12	$N_U = 0.2 \times V_U$
Lambda =	1	

Reinforced Concrete Bearing

a (in) =	8	
h (in) =	18.5	$A_S = \frac{1}{\phi f_y}\left[V_U \frac{a}{d} + N_U \frac{h}{d}\right]$
d (in) =	17	
As (in) =	4.9032941	
M =	1	Table 5.3.1
Me =	6.9245165	$\mu_e = \frac{\phi \times 1000 \times \lambda \times b \times h \times \mu}{V_U \times 1000}$
Me =	2.9	
Max Me =	2.9	Table 5.3.1
As' (in^2) =	3.0626922	$A_S' = \frac{2V_U}{3\phi f_y \mu_e} + \frac{N_U}{\phi f_y}$
Critical As (in^2)	4.9032941	
Use ____#____ BARS	5 " 9	
As practical (in^2)=	5	Ok
Ah (in^2) =	1.7875556	$A_h = 0.5\left[A_S - \frac{N_U}{\phi f_y}\right]$
Use ____#____ U BARS	3 # 5	
Ah practical (in^2)=	1.86	Ok
Ash (in^2) =	7.1244444	$A_{sh} = \frac{V_U}{\phi f_y}$
Use ____#____ STIRRUPS	6 # 7	
Ash practical (in^2)=	7.2	Ok
Av (in^2) =	-0.092668	$A_V = \frac{1}{2f_y}\left[\frac{V_U}{\phi} - \frac{2bd\lambda\sqrt{f_c'}}{1000}\right]$
Use ____#____STIRRUPS		
Av practical (in^2)=	0	Ok
Chech Vn (k) =	412.64012	$V_N = \phi\left(A_V f_y + A_h f_y + \frac{2bd\sqrt{f_c'}}{1000}\right)$
	Ok	
Ld Ah (in) =	22.5	Design Aid 15.4.4
Ld As (in) =	37.5	Design Aid 15.4.4
Anchor for As (in) =	62.5	$L_d = H - d + l_d$



Appendix E: Site Visit Photos


SAINT VINCENT
CANCER & WELLNESS CENTER
United Rentals
MQ POWER

Appendix F: Construction Drawings - CitySquare Underground Parking Garage