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Track Alternative Design and Construction Management Software

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WPI Recreation Center:
Track Alternative Design and Construction Management Software

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

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Abstract

This project created an alternative support system for the suspended track in WPI's new Recreation Center. The development of the alternative design primarily addressed structural integrity. A comparative analysis between the existing and alternative design was completed for the design, cost, and schedule. Two Building Information Modeling software applications: *Autodesk Robot* and *Revit* were used in supporting the study. *Robot* was explored as a new program in structural analysis and *Revit* was used to create 4-D models of both designs.

Capstone Design Statement

The capstone design requirements were met in this Major Qualifying Project through studying the new Recreation Center at WPI. This project focused on creating an alternative design for the suspended track system that is on the top floor of the new building and creating a cost estimate and a schedule that would allow the group to complete a comparative analysis of the existing and alternative designs. Finally, the schedule was integrated into BIM to create a 4-D model. The alternative design used cantilever and simple beams to replace the suspension.

In order to meet the specified requirements for a capstone design experience, this project addressed certain constraints set forth by the American Society of Civil Engineers. These constraints include economic, health and safety, ethical, manufacturability, and social.

The economic constraint was addressed by looking at the effects of the alternative design through a cost perspective. A cost estimate was created to compare the two designs. Also, the project looked into construction contracts and studied the different types as well as the economic benefits and differences of each type.

This project looked at the Health and Safety constraint through the alternative design. The alternative design used the *Massachusetts State Building Code: 7th Edition* as the building code and the *AISC Steel Construction Manual* for design considerations and specifications. These both are accepted standards that take health and safety into account.

Ethically, the alternative design was designed under the same ethical considerations taken by Cannon Design. Cannon stated many of their assumptions on the cover sheet of the structural package. All of these constraints were followed throughout the design process.

The next constraint studied was manufacturability. This project looked at how feasible it would be to have an alternate design for the track system. Similar sized beams and columns were used to ensure that the design was of comparable constructability to the original design. Construction of the alternative design does not require any extra major equipment, material, or labor. This approach allowed for guaranteed manufacturability and constructability. The constructability was also looked at through the schedule comparison and the creation of the 4-D model.

All aspects of this MQP addressed the social constraint. The Recreation Center is a social place that will be open for public use. The indoor track that is being installed is an important aspect of the Recreation Center and will most likely be a widely used portion of the building. In creating the alternative design, it had to be designed to meet all of the needs of the WPI community in their wants for an indoor track. The project meetings gave insight into how necessary the Recreation Center is and the social impact it will have on the campus. This project also provided educational opportunities for the WPI community by allowing students of many projects to be involved in the construction and development of the Recreation Center.

Authorship Page

All aspects of this project were equally worked on by the four members of the team. The following list outlines the areas of focus in the report for each member of the team.

John Flynn - Cost and Schedule Analyses of the Existing and Alterative design, 4-D *Revit* model

Kathryne Kulzer - Cost and Schedule Analyses of the Existing and Alterative design, 4-D *Revit* model

Sean Minor - Cantilever Beam Approach, Corner Design of the Simple Beam Approach.

Suzanne Najem - Simple Beam Approach, Column Design, *Robot*.

The signatures below indicate acceptance of above.

John Flynn

Kathryne Kulzer

Sean Minor

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Acknowledgements

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Chapter 1 - Introduction

Construction is an everyday activity that to a varying extent is part of our lives. The construction industry is continuously growing with new projects and the development of new infrastructures. Large-scale and small-scale construction projects alike are accomplished through multiple inter-disciplinary fields of work coming together to complete the project. Architects, structural engineers, project managers, and contractors are just a few of the many parties that can be involved in any project at one time. These parties come together and must work efficiently and collaboratively to design and build a facility based on the client's or owner's vision and that meets his/her needs.

Two major parties involved in construction projects are the design and project management teams. The design team usually includes architects and structural engineers, as well as other specialty engineers and design professionals. The architect works to take the owner's vision and provide a realistic design to meet the owner's needs. Structural engineers are responsible for the structural integrity of the project. Project managers are usually involved in construction, coordinating the involvement of supplies and trades, tracking the development of the project and assisting the owner throughout the entire project development process.

In early 2008, Worcester Polytechnic Institute decided to undertake the construction of a new Recreation Center for its community. WPI has a great need for a new Recreation Center because its community of students, faculty, and staff has grown so much in the past five years that the current facilities are no longer sufficient. The new Recreation Center is comprised of two floors which include an Olympic-sized swimming pool, a four-court gymnasium, a suspended jogging track, a 14,000 square foot fitness center, multi-purpose spaces, a Robotics pit and new offices for personnel in the Department of Physical Education and Athletics. This project investigated the structural implications for an alternative design of the fourth and fifth floors of the new Recreation Center as shown in areas A and B of Figure 1 below.

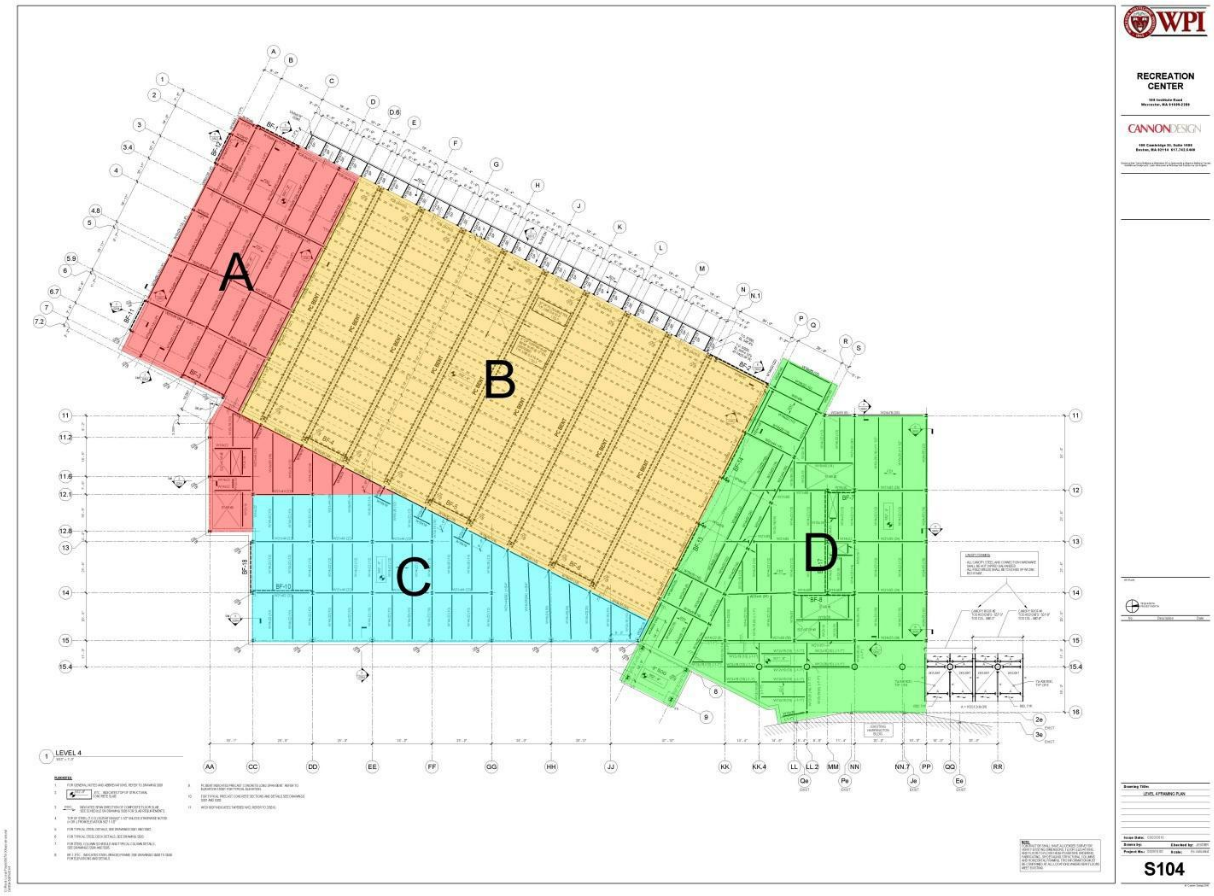

Figure 1: Construction Sections of the Recreation Center

The fourth and fifth floors of the Recreation Center these areas contain a four-court gymnasium and a suspended track. The suspended track is supported by steel rods that attach to the sides of the track and hang down from the roof trusses. This study investigated some alternative designs to the current suspended track using project management principles as well as structural engineering concepts. The first alternative design attempted to replace the steel rods with only cantilever beams and the second alternative design successfully replaced the supports with alternating cantilever beams to a simply supported beam. An evaluation of the loading changes that affect the roofing system for the alternative design was also completed. A comparative analysis including the effects of and construction schedule was also completed between the two designs.

To facilitate integration of the structural and project management aspects of the project, computer-aided engineering tools were utilized. *Autodesk Robot Structural Analysis (Robot)* was utilized for structural analyses of the alternative design. *Autodesk Revit Structures (Revit)* was used as a platform for Building Information Modeling (BIM). BIM is a technology-based collaborative approach that allows design and construction professionals to visualize and share information about the project through a 3D digital model. This study created a 3-D representation of the alternative design integrated in the Recreation Center utilizing BIM.

This report fully details the work that was done to accompany it. Chapter 2 includes the research that was completed on the topics of structural analysis, project management, and the different software programs used. This research was used to help understand the scope of work that had to be completed. When the research was completed, the project took way by benchmarking the existing design to analyze the system that is currently in the Recreation Center; Chapter 3 details the benchmarking work that was completed. Following the benchmarking work, Chapter 4 details how the alternative design was created through its structural design as well as how the cost and schedule was created for the alternative design. Finally, Chapters 5 and 6 detail the comparative analysis of the two designs and sum up the findings from the analysis. Much classroom and work experience was used to complete this report, but the learning experience that was gained was immense. The connectedness of different concentrations within Civil Engineering was a highlight of this project, as well as the integration of new technologies into engineering and construction settings.

Chapter 2 - Background

The background section discusses WPI's need for a new Recreation Center and explains the structural, project management, and the uses of technology in construction. The background section further covers the current state of the WPI Recreation Center and the specific technologies that were used throughout this project as an aid. The structural portion elaborates on the potential alternative designs for the suspended track. The project management section explains how the schedule and costs are used in the field of construction. Last, new advancements in technology provide aid for both the structural and project management fields.

2.1 Recreation Center

Worcester Polytechnic Institute has a need for a new Recreation Center to serve the needs of the general community on campus as well as the varsity sport teams. WPI is an active community, and the current facilities do not meet the needs of the population they serve. WPI's current recreation facilities consist of Harrington Auditorium and Alumni Gym. WPI primarily uses Harrington Auditorium, built in 1968, for varsity basketball games, and other gatherings such as career fairs, guest speakers, Robotics competitions, and varsity practices. Due to the large amount of space in Harrington Auditorium it is usually occupied by large events as described above, thus there is little to no free time for the general community to use it for recreation. Alumni Gym was built in 1916, and is currently out of date, but is used frequently by the WPI community. Alumni Gym has a small basketball court with a suspended wooden track around the upper level of the court. There is also a small swimming pool only 20 yards long and a weight room that does not meet the needs of the WPI community. These spaces have been over used for many years and with the increasing population of students, and employees at WPI, the need to expand is highly overdue. The overlap of activities and competition for space reservations, along with the increasing student population have become large issues, and to relieve some of the difficulty, the university has decided to construct a new Recreation Center. Its main attractions are an Olympic-size pool, personal fitness area, and a multipurpose gymnasium which includes four basketball courts, track and field accommodations, a suspended track, and robotics pit.

This project specifically looks into levels four and five of the Recreation Center which house the multipurpose basketball courts, the suspended track, and a long-span roofing system. Each of these aspects has its own unique purpose which contributes a distinct and important function to the center. The multipurpose basketball courts consist of two wood courts, with an overlapping third, and two "Mondo" basketball courts that can accommodate practices for varsity team sports including softball, baseball, and track. The suspended track is a three-lane jogging track which is intended for indoor track practices and faculty and employee enjoyment.

2.2 Structural Evaluation

The design of constructed facilities involves many components and disciplines, and structural engineering is one of the primary disciplines. Structural engineers strategically determine the correct configurations, members, and members sizes of the structure to resist the required loads while minimizing project costs. Their main objective is ensuring the structural integrity of the building to withstand varying live and dead loads. These professional engineers put their stamp of approval on the final design before it is built, assuming full responsibility for structural performance and the accuracy of the structural drawings and specifications that guide construction.

2.2.1 Suspended Track System

The suspended track is located on the fifth level of the Recreation Center and the current plans are represented in Figure 2 below. It is supported by vertical hangers that attach from the roof truss to the outside edges of the track. The track surface is made up of a material called "Mondo". Mondo is a type of rubber flooring used for multipurpose athletic flooring (Harmon, 2011). The suspended track is designed for walking and jogging purposes only. Dana Harmon, WPI's Director of Physical Education, Recreation, and Athletics, clarified that the track was not made for excessive running but more for the lifestyle of the WPI community (Harmon, 2011). The intent of the track was geared towards general recreation use which had an impact on its design including the structural support system.

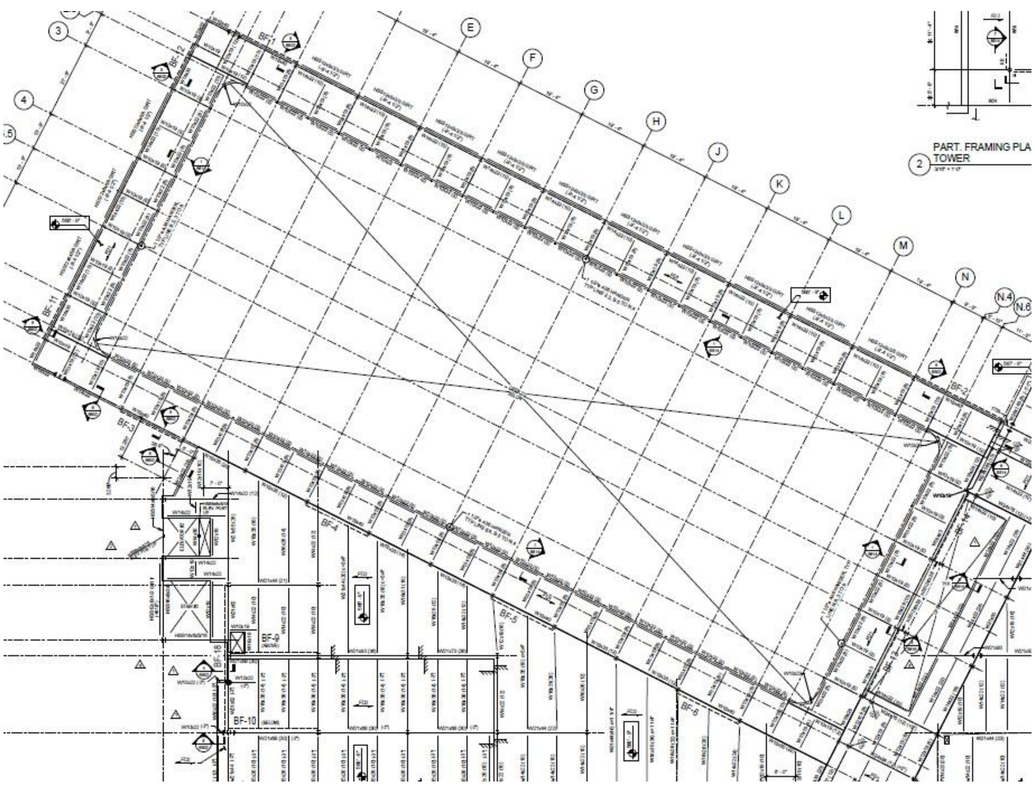

Figure 2: Current Suspended Track

Support Systems

There are many different support systems that could be implemented into the Recreation Center as an alternative design to the suspended track, and each alternative has unique qualities that contribute to the reason for its installation. The building was designed to be visually pleasing as well as functional. Various restrictions within the building apply when altering the suspended track. Support systems can range from simple column supports as a sort of simple post-and-beam system to complex trusses to cantilever beams.

Column Supports

Columns are commonly used support systems that can be beautifully decorated to match the décor of a building. Structurally, columns are one of the most effective compression members that can range in height, shape and width (ASDIP, 2011). Column members are defined as vertical elements whose length is nominally larger than their width and are usually composed of steel or concrete. Examining an efficient use of materials to reduce steel costs is normally used in larger buildings because the larger loads associated with larger buildings and the strength advantages associated with steel. If the columns are composed of steel, their shape can range from W-shape to HSS-rectangular and even C-shape which can also be encased in concrete for added strength and fire resistance (AISC, 2010).

Some advantages to using columns are their simplicity and the minimal amount of labor required for their installation. Also, the various design shapes mentioned above make this support system versatile and effective. Columns can also be easily hidden in walls or kept in the open to maintain an ambiance. One major disadvantage to columns is the unavoidable obstructions they present in large open spaces. They can obstruct viewing and/or pose a hazard to the flow of people when constructed in large areas such as swimming pools and basketball courts.

Trusses

Trusses are an assortment of members strategically composed into a structurally sound geometry to withstand a large amount of force. There are many different configurations that can be used when designing a truss, and each arrangement has advantages for different loading types. Also, when considering each configuration, the member geometry can be altered to compensate for project-specific cases. Just like a column, a truss can be aesthetically constructed to match the décor of a building, or it can be concealed behind ceilings or walls.

Some advantages to a truss are the large functional spaces, the use of small and lighter members when constructed, and the ability to span long distances without intermediate support. In some cases, the aesthetic appeal of a metal truss system can create a certain environment in a building. The Recreation Center has a height restriction from the court floor to the ceiling beneath the track and one major disadvantage of a truss is height of the structure. If the truss is too large then the ceiling height beneath the track may not pass the required standards. Additionally, the amount of labor associated with the construction of each individual truss can be very costly especially when associated with a large project like WPI's Recreation Center. The investigation of a cantilever system, discussed below, has some of the same advantages of as truss system, without introducing the disadvantages of a truss system, making it one of the most reasonable alternatives.

Cantilever Beams

A cantilever beam is singular structural member that is anchored at only one end, and extended outward to support a lateral or transverse force. Cantilevers can be composed of various sized beams chosen to be large and strong enough to support the track, yet small enough to limit cost. They can also range in shape, from W-shape to HSS-rectangular, and even C-shape similar to a column support. Cantilever beams can also be constructed with trusses and slabs, but in this particular scenario we referenced simpler cantilever systems. Cantilever beams are fabricated by a steel fabricator with specific measurements defined by a structural engineer so as to support the specified area with the most strategic beam size.

The main advantage to implementing a cantilever system is its simplicity of design and installation, and its ability to be concealed easily by walls and ceilings. Since this system is mainly composed of a series of relatively large, thick beams, the cost of these beams may be a large disadvantage. Another disadvantage of this system is the need to accommodate for fixed-end moments in the supporting elements of the structure.

Knowing all the components of the possible alternative solutions for a problem such as this is very beneficial. The best solution can be found when each choice is analyzed and compared to the needs of the project. Table 1 below summarizes the attributes of each proposed support system for the track. Other components to consider for the track other than the structural design are the materials that make up the track which can increase the overall weight in design load as well as alter the material cost.

Table 1: Track Support System Feasibility

Support System	Utilizes Space	Easily Concealed	Easily Installed	Cost Effective	Feasible
Suspension	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Columns	No	No	Yes	Yes	No
Trusses	Yes	No	No	No	No
Cantilever	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

Materials

One major component of our project and construction management in general, is the cost analysis of all methods and materials used. When selecting materials it is crucial for the designers to use the lowest costing materials without compromising structural integrity while complying with all specifications. The current proposed track is composed of W10x19 girders and W10x22 joists with three lanes of Mondo flooring, a railing to prevent users from injury, and other basic materials used to encase the unit. The materials that are used in the current track design could be carried over to the new proposed track, but an investigation into structural design configuration as well as structural materials could provide some cost savings to the owner.

2.2.2 Long-Span Roofing System

The Recreation Center's current roofing system involves a series of thirteen trusses designed to support the suspended track, the roof deck, all the equipment on the roof, and all variable live loads normally associated with building roofs such as snow load and wind load. The existing design, which has been created by Cannon, the Architect on Record for WPI's Recreation Center Project, is presented in Figure 3. The current roofing system has been designed by professionally licensed structural engineers to safely support all of the components mentioned above, but if our project alters one component it may be necessary to reanalyze the existing truss design to assess its adequacy. By altering the existing support system, the long-span roofing system may become too heavy for the structural columns to support due to the changes of the track design. It will be necessary to reanalyze these components to insure the safety and integrity of the building.

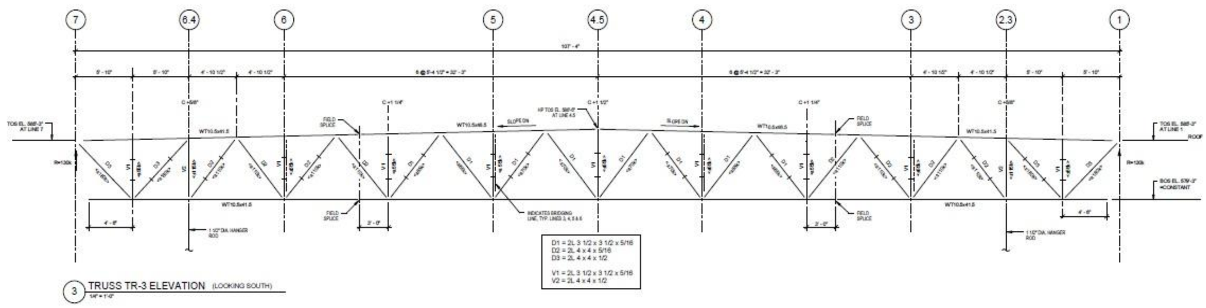

Figure 3: Cannon’s Structural Truss

2.2.3 Massachusetts Building Code

For every construction project and structural design there are a set of standards in place and enforced by the Authority-Having-Jurisdiction to ensure safety. For the Commonwealth Massachusetts, there is a state building code which is supplemented with the provisions from *International Building Code* (IBC) (Mass.gov, 2011). The purpose of the *IBC* is to ensure safety of buildings by setting limits on design values for the structure design (IBC, 2009). For this project the code of record is the 7th Edition of the *Massachusetts State Building Code* (780 CMR), which is consistent with the actual project documents.

2.3 Project Management

Project Management is defined as the art and science of coordinating people, equipment, materials, money and schedules to successfully complete a project (Oberlender, 2000). Many owners find it difficult to manage construction projects because they don’t have the expertise, or they don’t have the time to successfully oversee the entire construction process. For this reason, owners seek help in construction management (CM) firms. CM firms specialize in project management for all construction processes. CM firms can provide pre-construction services as well as coordinate construction activities throughout the duration of the project. These firms provide experience and knowledge that an owner may be lacking. The CM uses their expertise to help the owner throughout the design and construction of their building. Hiring a CM allows the owner to be involved, but maintain their responsibilities outside of the project. The owner remains involved through attending weekly project meetings and staying in contact with the Project Manager from the CM firm. This allows them to stay in the loop and have the say that they need for the end product to be favorable for them.

One type of CM that is chosen regularly is a CM-at-Risk. This is the case for the Recreation Center. The term CM-at-Risk identifies that the CM is taking on the project at a financial risk to them. If the CM-at-Risk approach is chosen, the profit for the CM is "at-risk" if the final cost of the project is over budget. This aspect of the CM-at-Risk approach is discussed further in a later section, Cost, that details a GMP contract. With a CM-at-Risk, all of the subcontracts on the job have a contract that exists between the CM and the sub. If there was no "at-risk" the contracts would be made between the owner and the subcontractors, placing the risk on the owner not the CM. When there is not risk for the CM, they are simply working for a fee and not assuming any risk in the project (Oberlender, 2000).

For the WPI Recreation Center, WPI, as the owner enlisted the help of Project Manager, or PM in Cardinal Construction. They represent WPI as the liaison between the architect (Cannon Design) and the chosen CM-at-Risk (Gilbane). WPI does not always choose to use a CM-at-Risk for construction projects, but they chose to execute the Recreation Center in this manner for many reasons. One of which was that Cardinal has expertise in construction that very few, if any, WPI employees have. Also, there is no one on the WPI staff that has the necessary time to devote to fully managing a construction project. If an employee were to take on this responsibility, they would have to drop all other responsibilities that they normally have. WPI has appointed a representative within its staff in the Department of Facilities to oversee the project. For the Recreation Center, WPI chose Mr. Alfredo DiMauro to be the contact point for the Department of Facilities. He works with other operations managers to add their input and oversee the construction on behalf of the campus. All of these professionals come together to successfully bring the product that the campus is expecting at the end of construction. In order to create a successful product, project meetings are held weekly to keep all parties on the same page and guarantee that every party is updated on the progress of the project. These meetings are crucial for communication between parties during the pre-construction and construction processes. These meetings were attended by members of the group throughout the MQP and gave insight to how the schedule and cost aspects of project management are integrated into a project.

2.3.1 Schedule

Scheduling is one of the most important functions related to project management. When a project is contracted to a CM firm, a completion date is set. For a CM-at-Risk, this completion date is a contracted date that corresponds with the "at-risk" responsibilities. Maintaining a schedule through constant updates ensures that the completion date is always in sight for the CM. A schedule ensures the completion date is achievable from the first schedule that is made on the job. The initial schedule created on the job is important for setting goals and placing realistic guidelines on the schedule as a whole.

Gilbane completes what is called a "card trick" to make an initial project schedule with the input of all or most of the subcontractors. In this method of creating an overall schedule, a representative from each subcontractor is present so that every party can create the schedule together. Most subcontractors will send a representative to speak on behalf of their scope of work. This allows for everyone to be in the same room and visually see how the schedule is going together. It gives each construction trade an opportunity to have an input. This helps to avoid coordination problems in the future because many potential problems and conflicts are recognized and handled at the very beginning. This also helps all parties to be involved very early in the project and "buy into" creating a successful project because they are putting their own feedback into the process.

Most CM firms, including Gilbane, have an employee who is dedicated solely to keeping track of the schedule to ensure it is up to date during the construction process. It is that person's job to make sure that the schedule constantly reflects what has already happened in the field, as well as portray an accurate projection of what is going to happen in the immediate and distant future, based on the information they have been given. Each subcontractor submits their own schedule, and it is the job of the CM to input that individual schedule into the master schedule. Subcontractors and CMs also have regular meetings during the progress of the project to discuss what is happening in the field and what they expect to happen; this also helps to keep the schedule up to date. It is the job of the scheduler to sort through the schedule to ensure that the precedence of different activities is properly entered in the software. When the project gets moving, the scheduler continuously updates the schedule and reviews its logic to help guide the project to successful completion. In the case of the Recreation Center, Gilbane's scheduler updates the schedule monthly. He gathers information from the members of the project team that are on-site every day and updates the schedule based on the information he receives from them (Salazar, 2011).

There are many different software programs that can be used to create a schedule, but *Primavera* is one of the most commonly used to create a Critical Path Method based schedule (The Bright Hub, 2011). *Primavera* is capable of tracking all the important aspects of a schedule mentioned above, such as duration to each activity, a cost, as well as the relationships between two or more activities. *Primavera* can track different aspects of the project besides schedule, such as cost, contracts, risk management and document control items. It can do all of these tasks own its own, but also through the integration with other programs such as *E-business Suite* and *JD Edwards Enterprise One* (Oracle, 2011). For contracts, it can track the contract summary to date, change orders, and payment processing rates. Pertaining to risk management, the software can calculate confidence levels based on pitfalls commonly associated with the activities within the schedule and predefined risk factors that are incorporated in the software. For document control, it can help monitor communication processes such as RFI and submittal turnaround rates, the number of issues resolved and unresolved, and different actions that must be taken to keep the schedule on time (Oracle, 2011). Because of all the benefits that *Primavera* has to offer, it is widely used.

An example of a *Primavera* schedule can be seen below in Figure 4 (Gilbane, 2011). It is only one portion of a larger schedule. Also, it should be noted that past activities are not shown on this schedule because Gilbane shows only current and future activities when they present a schedule. On the left side of this figure is the list of activities. The activities are broken down by different scopes of work (Design and Engineering, Procurement, Sitework, etc.). On the right side of the figure, the duration of each activity is displayed by a horizontal bar that relates to the date the work will be starting on the top of the screen. Red activities are critical path items and green bars denote all other activities. One more item that can be identified in the figure is the vertical blue line that is running through the right side of the figure. This vertical blue line represents the current date. The presence of this vertical blue line helps each person who views the schedule to comprehend where the project currently stands.

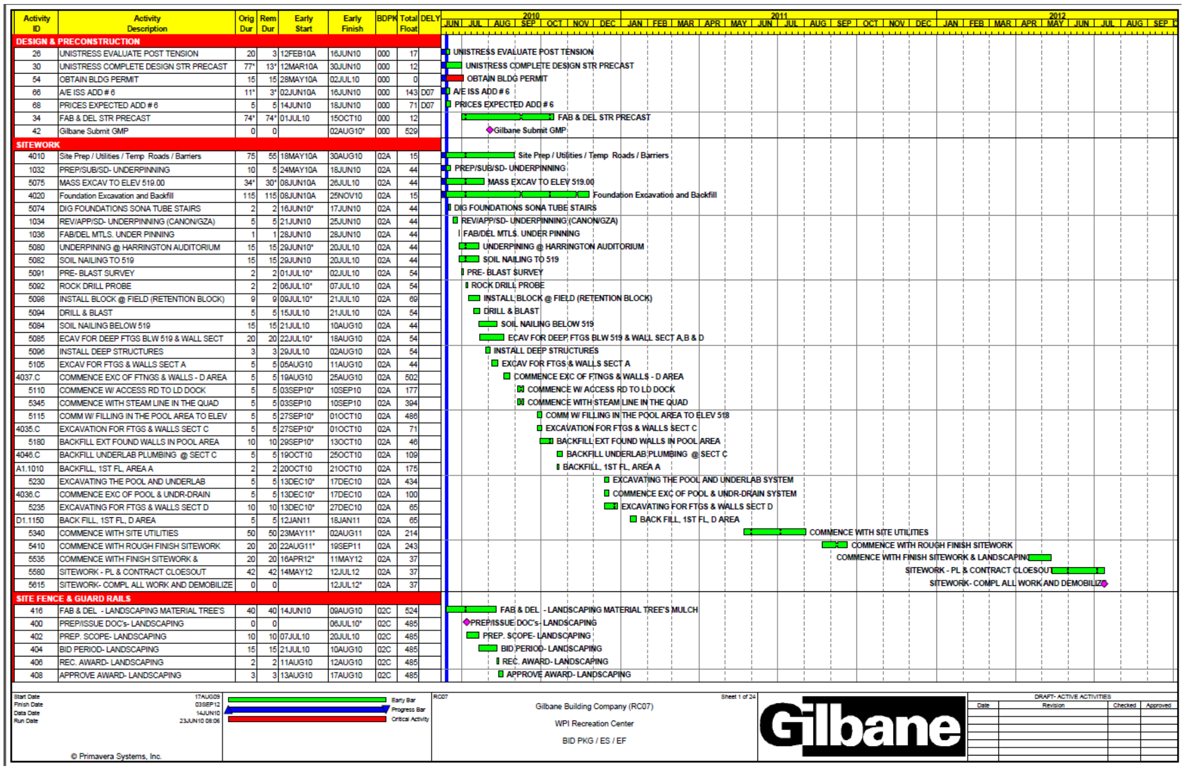

Figure 4: Primavera Schedule for Recreation Center (Gilbane, 2011)

Many schedules are created using the Critical Path Method (CPM). The CPM identifies a chain of connected activities within a schedule that have zero float time. Two float definitions are important for the scope of this project: total float and zero float. Total float is number of days that an individual activity can be delayed without affecting the final completion date of a project. When the total float of an activity is exceeded, the activity has the potential to become a critical activity and affect the overall schedule because it will have zero float (Oberlender, 2000). Quantifying and monitoring float values are important to avoid creating unnecessary critical items, especially total float.

In order for the project to complete on time, the critical activities must finish on time. If these activities do not get completed on time, the completion date will be pushed out (Oberlender, 2000). An example of this can be found in the figures below. Figure 5 displays a schedule that was created in November 2010. In this figure, it is clear that the mobilization for the squash and racquetball courts, activity 2346 "Fab/Del – Squash Racquetball Courts" is set for November/December 2010. In this schedule, the mobilization and the succeeding activities are not critical. Activity 2346 is a green bar, which is called an Early Bar. This indicates that the dates shown in Figure 5 are the earliest that these activities will begin. In reality, they could begin later, due to their float time, and still finish without impacting the overall schedule. Also, this schedule displays the precedence relationships that have been established between the activities. In the column labeled "Successors," numbers are displayed for each activity in the respective row, these numbers represent other activities in the schedule that are going to succeed the activity whose row they are in.

Activity ID	Activity Description	Orig Dur	Rem Dur	Early Start	Early Finish	BDPK	DELY	AREA	Successors
INDOOR ROWING TANK									
2303	WPI FINALIZE SCOPE INDOOR ROWING TANK	10	10	30SEP10A	29NOV10	13B			2304*
2304	RE-PRICE PERIOD- INDOOR ROWING TANK	10	10	30NOV10	13DEC10	13B			2306*
2306	REC. AWARD- INDOOR ROWING TANK	5	5	14DEC10	20DEC10	13B			2308*
2308	APPROVE AWARD- INDOOR ROWING TANK	5	5	21DEC10	28DEC10	13B			2310*
2310	AWARD CONTRACT- INDOOR ROWING TANK	3	3	29DEC10	03JAN11	13B			2312*, 2318*
2318	MOBILIZE ON SITE-FLAG POLES	0	0	04JAN11		13B			A1.1112
2312	PREP/SUB/SD- INDOOR ROWING TANK	30	30	04JAN11	14FEB11	13B			2314*
2314	REV/APP/SD- INDOOR ROWING TANK	10	10	15FEB11	28FEB11	13B			2316*
2316	FAB/DEL- ROWING TANK	70	70	01MAR11	07JUN11	13B			A1.1112*
A1.1112	INSTALL ROWING TANK, 1ST FL, AREA A	20	20	08JUN11	06JUL11	13B		A	A1.1110, A1.1144*
SQUASH / RACQUETBALL COURTS									
2340	AWARD CONTRACT- SQUASH RACQUETBALL	17*	6*	28OCT10A	22NOV10	13C			2342*, 2348*
2348	MOBILIZE ON SITE- SQUASH RACQUETBALL	0	0	23NOV10		13C			A1.1085
2342	PREP/SUB/SD- SQUASH RACQUETBALL	30	30	23NOV10	06JAN11	13C			2344*
2344	REV/APP/SD- SQUASH RACQUETBALL COURTS	10	10	07JAN11	20JAN11	13C			2346*
2346	FAB/DEL- SQUASH RACQUETBALL COURTS	70	70	21JAN11	28APR11	13C			A1.1085*
ELEVATORS									
2612.WC	PREP/SUB/SD- WHEEL CHAIR LIFT	20	10	13SEP10A	29NOV10	14A			2614.WC*
2625	WPI CONFIRM BUTTONS	10	5	06OCT10A	19NOV10	14A	D15		2616*, 2616-2*
2616	FAB/DEL-ELEVATOR # 1	80	80	22NOV10	16MAR11	14A			5395, 5425
2616-2	FAB/DEL-ELEVATOR # 2	80	80	22NOV10	16MAR11	14A			5395
2614.WC	REV/APP/SD- WHEEL CHAIR LIFT	10	10	30NOV10	13DEC10	14A			2616.WC*
2616.WC	FAB/DEL- WHEEL CHAIR LIFT	60	60	14DEC10	09MAR11	14A			5425, 5480
5395	COMMENCE W/ ELEVATOR # 2	50	50	05JUL11*	13SEP11	14A		A	5420
5420	STATE TEST FOR PREL USE OF ELEV # 2	5	5	26SEP11*	30SEP11	14A		A	5425*, 5570
5425	COMMENCE W/ ELEV # 1	50	50	03OCT11*	14DEC11	14A		D	5575
5480	COMMENCE W/ WHEEL CHAIR LIFT	5	5	03JAN12*	09JAN12	14A			5565
5565	STATE TEST FOR ELEVATOR # 1	1	1	01MAR12*	01MAR12	14A		D	5570*, 5585*
5570	STATE TEST FOR ELEVATOR # 2	1	1	02MAR12	02MAR12	14A		A	5575, 5590*
5585	FINAL CLEAN ELEVATOR # 1	1	1	02MAR12	02MAR12	14A		D	5590*
5590	FINAL CLEAN ELEVATOR # 2	1	1	05MAR12	05MAR12	14A		A	5595
5575	STATE TEST FOR WHEEL CHAIR LIFT	1	1	06JUN12*	06JUN12	14A			5595
5595	FINAL CLEAN WHEEL CHAIR LIFT	1	1	21JUN12*	21JUN12	14A			
5600	FINAL CLEAN WHEEL CHAIR LIFT	1	1	21JUN12*	21JUN12	14A			
FIRE PROTECTION									
2716.5	FAB/DEL- SPRINKLER HANGERS & SEISMIC	5	5	15OCT10A	19NOV10	15A			A1.1055

Start Date 17AUG09
Finish Date 17AUG12
Data Date 15NOV10
Run Date 22NOV10 15:23

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Early Bar
Progress Bar
Critical Activity

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Gilbane Building Company (RC15)
WPI Recreation Center
BID PKG / ES / EF

Gilbane

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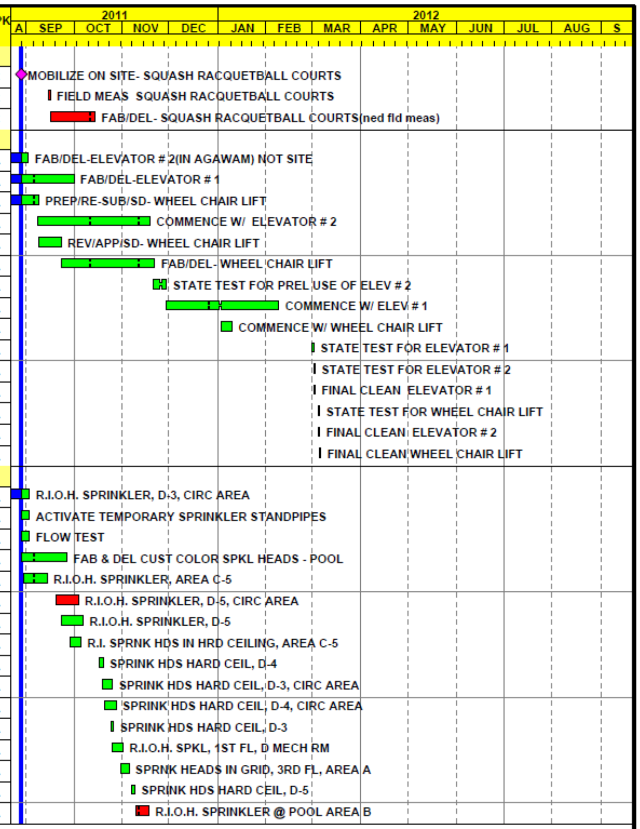
Figure 5: November 2010 Schedule (Gilbane, 2011)

Figure 6 displays a schedule that was created in August 2011. At the top of this figure, the schedules regarding the squash and racquetball courts are displayed. These activities were pushed until August 2011, and this made activity 2346, as well as the other activities regarding the courts critical path activities. Critical path items are displayed in red; both "Fabrication/Delivery – Squash/Racquetball Courts" (2346) and "Field Measurements of Squash/Racquetball courts" (2345) are critical activities.

Activity ID	Activity Description	Rem Dur	Early Start	Early Finish	BDPK
SQUASH / RACQUETBALL COURTS					
2348	MOBILIZE ON SITE- SQUASH RACQUETBALL	0	29AUG11		13C
2345	FIELD MEAS SQUASH RACQUETBALL COURTS	1	15SEP11	15SEP11	13C
2346	FAB/DEL- SQUASH RACQUETBALL COURTS(ned	20	16SEP11	14OCT11	13C
ELEVATORS					
2616-2	FAB/DEL-ELEVATOR # 2(IN AGAWAM) NOT SITE	4	26MAY11A	01SEP11	14A
2616	FAB/DEL-ELEVATOR # 1	24*	26MAY11A	30SEP11	14A
2612.WC1	PREP/RE-SUB/SD- WHEEL CHAIR LIFT	8	18JUL11A	08SEP11	14A
5395	COMMENCE W/ ELEVATOR # 2	50	08SEP11	18NOV11	14A
2614.WC1	REV/APP/SD- WHEEL CHAIR LIFT	10	09SEP11	22SEP11	14A
2616.WC	FAB/DEL- WHEEL CHAIR LIFT	40	23SEP11	21NOV11	14A
5420	STATE TEST FOR PREL USE OF ELEV # 2	5	21NOV11*	28NOV11	14A
5425	COMMENCE W/ ELEV # 1	50	29NOV11*	08FEB12	14A
5480	COMMENCE W/ WHEEL CHAIR LIFT	5	03JAN12*	09JAN12	14A
5565	STATE TEST FOR ELEVATOR # 1	1	01MAR12*	01MAR12	14A
5570	STATE TEST FOR ELEVATOR # 2	1	02MAR12	02MAR12	14A
5585	FINAL CLEAN ELEVATOR # 1	1	02MAR12	02MAR12	14A
5575	STATE TEST FOR WHEEL CHAIR LIFT	1	05MAR12	05MAR12	14A
5590	FINAL CLEAN ELEVATOR # 2	1	05MAR12	05MAR12	14A
5595	FINAL CLEAN WHEEL CHAIR LIFT	1	06MAR12	06MAR12	14A
FIRE PROTECTION					
D3.4020	R.I.O.H. SPRINKLER, D-3, CIRC AREA	5	16AUG11A	02SEP11	15A
5385	ACTIVATE TEMPORARY SPRINKLER	5	29AUG11*	02SEP11	15A
5390	FLOW TEST	5	29AUG11*	02SEP11	15A
2724	FAB & DEL CUST COLOR SPKL HEADS - POOL	20	29AUG11	26SEP11	15A
C.5010	R.I.O.H. SPRINKLER, AREA C-5	10	30AUG11	13SEP11	15A
D5.4020	R.I.O.H. SPRINKLER, D-5, CIRC AREA	10	20SEP11	03OCT11	15A
D5.5010	R.I.O.H. SPRINKLER, D-5	10	23SEP11	06OCT11	15A
C5.5062	R.I. SPRNK HDS IN HRD CEILING, AREA C-5	5	29SEP11	05OCT11	15A
D4.4245	SPRINK HDS HARD CEIL, D-4	2	18OCT11	19OCT11	15A
D3.4075	SPRINK HDS HARD CEIL, D-3, CIRC AREA	5	19OCT11	25OCT11	15A
D4.4075	SPRINK HDS HARD CEIL, D-4, CIRC AREA	5	21OCT11	27OCT11	15A
D3.3300	SPRINK HDS HARD CEIL, D-3	2	25OCT11	26OCT11	15A
D1M.4025	R.I.O.H. SPKL, 1ST FL, D MECH RM	5	26OCT11	01NOV11	15A
A3.3135	SPRNK HEADS IN GRID, 3RD FL, AREA A	5	31OCT11	04NOV11	15A
D5.5065	SPRINK HDS HARD CEIL, D-5	2	07NOV11	08NOV11	15A
5288.P	R.I.O.H. SPRINKLER @ POOL AREA B	5	10NOV11	17NOV11	15A



Start Date 17AUG09
Finish Date 20AUG12
Data Date 29AUG11
Run Date 31AUG11 11:20

Early Bar
Progress Bar
Critical Activity

R27R
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WPI Recreation Center
BID PKG ES EF

Date	Revision	Checked	Approved

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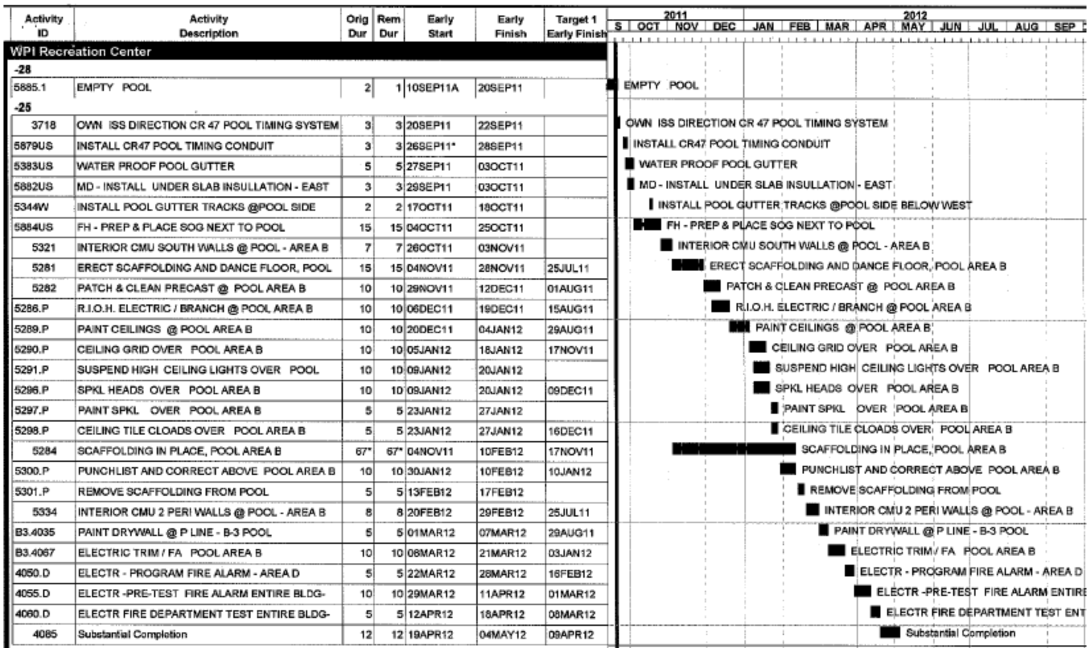
Figure 6: August 2011 Schedule (Gilbane, 2011)

In Figure 7 below, the critical path for the Recreation Center can be seen. This is the critical path for the completion of the pool only. The complete critical path schedule shows a much longer critical path for the entirety of the project. The length of the project is about two years (May 2010 – April 2012), therefore only one portion of the critical path could be captured in Figure 7. The schedule is consistently updated to reflect the current construction that is occuring in the field. This ensures the CM and the owner that the critical path is still on track for the final completion date.



Activity ID	Activity Description	Orig Dur	Rem Dur	Early Start	Early Finish	Target 1 Early Finish
WPI Recreation Center						
-28						
5885.1	EMPTY POOL	2	1	10SEP11A	20SEP11	
-25						
3718	OWN ISS DIRECTION CR 47 POOL TIMING SYSTEM	3	3	20SEP11	22SEP11	
5879US	INSTALL CR47 POOL TIMING CONDUIT	3	3	26SEP11*	28SEP11	
5383US	WATER PROOF POOL GUTTER	5	5	27SEP11	03OCT11	
5882US	MD - INSTALL UNDER SLAB INSULLATION - EAST	3	3	29SEP11	03OCT11	
5344W	INSTALL POOL GUTTER TRACKS @POOL SIDE	2	2	17OCT11	18OCT11	
5884US	FH - PREP & PLACE SOG NEXT TO POOL	15	15	04OCT11	25OCT11	
5321	INTERIOR CMU SOUTH WALLS @ POOL - AREA B	7	7	26OCT11	03NOV11	
5281	ERECT SCAFFOLDING AND DANCE FLOOR, POOL	15	15	04NOV11	28NOV11	25JUL11
5282	PATCH & CLEAN PRECAST @ POOL AREA B	10	10	29NOV11	12DEC11	01AUG11
5286.P	R.I.O.H. ELECTRIC / BRANCH @ POOL AREA B	10	10	06DEC11	19DEC11	15AUG11
5289.P	PAINT CEILINGS @ POOL AREA B	10	10	20DEC11	04JAN12	29AUG11
5290.P	CEILING GRID OVER POOL AREA B	10	10	05JAN12	18JAN12	17NOV11
5291.P	SUSPEND HIGH CEILING LIGHTS OVER POOL	10	10	09JAN12	20JAN12	
5296.P	SPKL HEADS OVER POOL AREA B	10	10	09JAN12	20JAN12	09DEC11
5297.P	PAINT SPKL OVER POOL AREA B	5	5	23JAN12	27JAN12	
5298.P	CEILING TILE CLOADS OVER POOL AREA B	5	5	23JAN12	27JAN12	16DEC11
5284	SCAFFOLDING IN PLACE, POOL AREA B	67*	67*	04NOV11	10FEB12	17NOV11
5300.P	PUNCHLIST AND CORRECT ABOVE POOL AREA B	10	10	30JAN12	10FEB12	10JAN12
5301.P	REMOVE SCAFFOLDING FROM POOL	5	5	13FEB12	17FEB12	
5334	INTERIOR CMU 2 PERI WALLS @ POOL - AREA B	8	8	20FEB12	29FEB12	25JUL11
B3.4035	PAINT DRYWALL @ P LINE - B-3 POOL	5	5	01MAR12	07MAR12	29AUG11
B3.4067	ELECTRIC TRIM / FA POOL AREA B	10	10	08MAR12	21MAR12	03JAN12
4050.D	ELECTR - PROGRAM FIRE ALARM - AREA D	5	5	22MAR12	28MAR12	16FEB12
4055.D	ELECTR -PRE-TEST FIRE ALARM ENTIRE BLDG-	10	10	29MAR12	11APR12	01MAR12
4060.D	ELECTR FIRE DEPARTMENT TEST ENTIRE BLDG-	5	5	12APR12	18APR12	08MAR12
4085	Substantial Completion	12	12	19APR12	04MAY12	09APR12

Figure 7: Critical Path for the Pool (Gilbane, 2011)

In the case of the Recreation Center, the Critical Path, as well as the completion date are both very important items. Because this is a WPI project, it must be completed in a timely manner for many reasons. First, the school has promised its faculty, staff, and students that the facility would be done by a certain time, Fall 2012. Not only is the community waiting for the building, but they are also awaiting the restoration of the Quad. The Quad is the heart of many student activites, as well as a space for Commencement, one of the most important activities every year on the campus. Another reason, is that the Recreation Center is intended to be a major selling point for the Admissions Office. As soon as it is completed, the actual building and its amenitites can be displayed to incoming students. There is also the added benefit that when the Quad is restored this area of the campus will be more asthetically pleasing than the current conditions. Once the importance of scheduling in project management and for the Recreation

Center specifically was researched, it was important to understand how cost impacts project management.

2.3.2 Cost

The initial construction cost of a project is determined by the bid that is submitted by the Construction Manager. For the Recreation Center, a Guaranteed Maximum Price (GMP) contract is in place. In this type of contract, a CM-at-risk agrees to a fixed completion date, as well as a maximum price for the completed project. As previously mentioned, the CM will not make a profit if they go over the contracted budget; they will pay the extra expenses out of pocket (Oberlender, 2000).

In many situations, to guarantee that the contracted completion date is kept, an owner will have liquidated damages written into the contract. Liquidated damages are the price that the CM must pay for every day the project does not meet a milestone on time or the specified completion date. This is another way for the CM-at-Risk to assume risk for the project (Allen, 1995). For the Recreation Center, liquidated damages are not involved even though Gilbane is contracted as a CM-at-Risk (Salazar, 2011).

A GMP can be created prior to receiving subcontractor bids or after. For the Recreation Center, Gilbane chose to establish the GMP after awarding the subcontractor bids (Salazar, 2012). With this choice, the GMP is more accurate because the contractor has the advantage of knowing specific pricing on each of the trade packages. Because of the accuracy of the GMP, less contingency will be added to the overall cost because there should be very few imperfections because the pricing for all of the subcontractor packages is known (Oberlender, 2000). For the Recreation Center, as of winter 2011, there were 36 awarded packages in place. With a project of this magnitude, most packages are awarded as early as possible, but some are not awarded until later in the process. This can be because they are not critical to award immediately, or additional scopes of work were deemed necessary by the owner later in the project.

2.4 Computer-Aided Engineering

Computer-aided engineering is a practice dependent on using a computer to build, design, model, simulate and analyze engineering projects. Computer-aided engineering has been around since the 1950's, but is still gaining popularity as an application in the construction and design fields. Over the years, the technology has been developed for many different types of fields and specially designed programs that tailor to a specific trade. A major leader in the development of these programs is Autodesk (Autodesk Inc., 2011). Autodesk is a company that makes over 50 programs that manufacturing, architecture, building, construction, and media and entertainment industries use (Autodesk, 2011). Autodesk's programs are very popular today due to the open application programming interface (API), which allows easy file sharing between Autodesk products; file share is great for the construction field where many different people are involved in one project.

2.4.1 Robot Structural Analysis

Among the many types of programs Autodesk offers, *Autodesk Robot Structural Analysis* is used by structural engineers to aid in the analysis of buildings. "*Autodesk Robot Structural Analysis* (*Robot*) is a single integrated program used for modeling, analyzing and designing various types of structures. The program allows users to create structural models, to carry out structural analysis, to verify obtained results, to perform code check calculations of structural members and to prepare documentation for a calculated and designed structure" (*Autodesk Robot Structural Analysis* - Getting Started Guide, 2010). *Robot* uses an open API which allows the files created in *Robot* to be transferred to other programs such as Autodesk *Revit* Structures, another open API program. Autodesk *Revit* Structures is a part of the *Revit* platform for Building Information Modeling.

2.4.2 Building Information Modeling (BIM)

Building Information Modeling, more commonly known as BIM, is "an electronic representation of a facility for the purpose of design, analysis, construction and operation" (Klancnik, 2009). Companies use 3D modeling software such as Autodesk *Revit* and *Navisworks*, to create and/or review their BIM models. Some companies create the models themselves using Autodesk *Revit*, others may receive a model made by another company and they use *Navisworks* to review and coordinate the building. The 3D geometric models are combined with additional information, such as time or money, to create the most unique applications of BIM. The idea of trying to use computer-generated isometric objects in construction is not new. The first three-axis computer models were constructed in the 1950s (Klancnik, 2009). At this time there was no practical software for these models to have any sort of everyday value. Today, BIM is the most popular construction management and design tool on the rise. In the 2009, SmartMarket reported the percentage of projects using an aspect of BIM in construction went from 28% in 2007 to 48% in 2009 (Klancnik, 2009). The same report concluded that the number of U.S. contractors using BIM has almost quadrupled over that same time period.

BIM continues to grow because its greatest asset is that it can be used within all phases of construction. It is not another program that is specialized just for contractors, or just for architects, or engineers. Figure 8 shows how BIM can be used by the owners, the architects, engineers, contractors, and sub-contractors, all putting in their own information and detail into the model so that it becomes an overarching work environment that can lead to improved accuracy of information and increased construction efficiency.

Figure 8: BIM Contribution Breakdown (Partridge, 2011)

BIM does not change the roles of the players within the project team, but it plays a significant role in coordinating the different trades to avoid any conflicts found in the proposed design ahead of time. Initially, it takes a lot of work to set up the BIM model with all the different information, but when done correctly it gets everyone on the same page so that coordination problems can be solved ahead of time.

When issues are found in a project and an alternate design may be needed, BIM helps cut down on the time it takes to propose and evaluate options. Designers can more easily propose an alternative design and instantly see how it fits into the construction and assess its impact on the rest of the building. The builders can quickly look at the proposed change and takeoff quantities for the materials and the man power required to build the new detail. Then the contractor can quickly access all the information provided and generate a cost estimate for the proposed change, and investigate how it will affect the schedule of the project. In the case of the WPI Recreation Center, the BIM model is used mostly for visualizations of how the building will come together. In our project, the team will use the model for structural, cost, and schedule analysis.

Uses in Project Management

Because BIM is still relatively new, not all companies are fully functional with BIM. Its usage is still growing and on most jobs in 2011, it can be found that the BIM model is used as a tool mostly by the construction managers (Klancnik, 2009). As of now the major uses of BIM for general contractors are visualization, coordination, 4D models, and 5D models (Klancnik, 2009). It is not yet to a point where the structural and mechanical engineers update their portion of the model, and the sub-contractors update their portions so that the model works as a tool to integrate the work of everyone. As its usage continues, BIM is expected to reach that potential in the coming years.

Visualizations are one of the main uses for BIM because they provide an easy way for everyone to get on the same page on a conflict or concern. Sometimes the 2D drawings do not depict or show an issue that may be in the field, or maybe the owner is not as familiar with the drawings as everyone else. When the issue is investigated using BIM, anyone who was looking at the building for the first time would easily be able to understand what they were looking at and what the issue maybe. This type of clarity can cut down on the amount of time that an issue may be debated; thereby, cutting down on meeting times significantly.

Coordination is another major use of BIM by general contractors. Coordination can be between trades, or even the coordination of the job site. At the beginning of a project, coordinating how the job site will be set up is always a big concern. This is because there are property lines to deal with, along with making sure material deliveries are possible, and many other coordination issues that the owner will have questions about. With BIM the site plan can be clearly demonstrated to everyone, including the location of the trailers, materials storage, and how material deliveries will be made, etc. It is a great way to clarify the set-up of the site, or how the building should be orientated on the property. For example, Figure 9 shows a site plan that lays out the locations for the cranes, trailers, dumpsters, gates, etc.

Figure 9: BIM Site Plan (Knutson, 2011)

Coordination between the different subcontractors is another current use of BIM by general contractors. A report can be run within BIM that detects any and all interferences between the geometric shapes. A perfect example is laid out in the *Contractor's Guide to BIM* where there might be an interference with the way the plumbing and HVAC equipment is supposed to be installed (Klancnik, 2009). With BIM, the plumbing and HVAC sub-contractors can be shown the issue through the model and use the model to propose a new design on how to install the equipment. Figure 10 shows the conflict between the proposed location of the purple pipe, and that of the grey hangars for the red conduit. Any type of interference like this can be found early on in the project with the use of BIM.

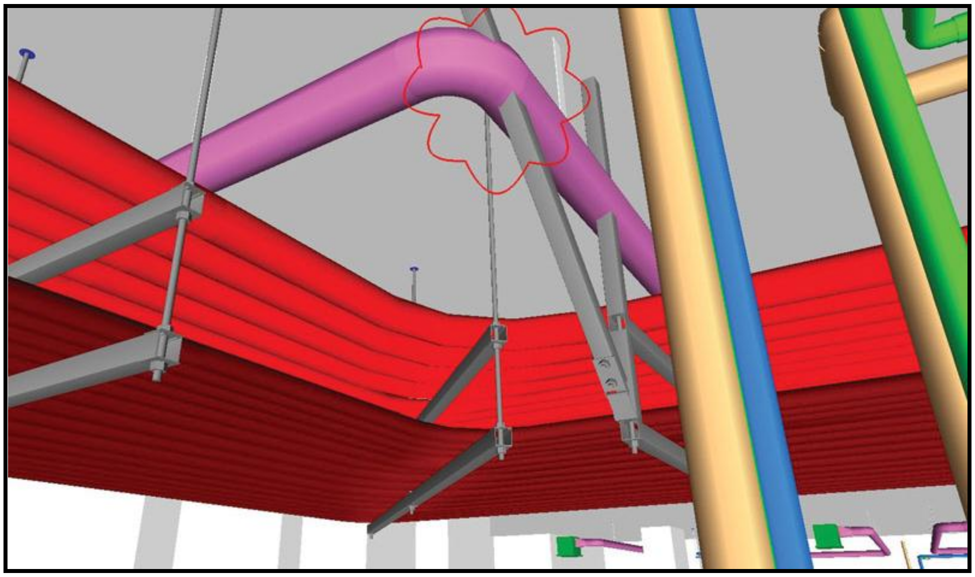


Figure 10: Interface Detections (Hope, 2010)

Without BIM, this issue may not have been discovered until the materials were on site and ready to be installed; therefore, causing a delay in the project as well as a potential change order. For the Recreation Center, BIM is not a contractual requirement. Cannon provided a BIM model with no contractual ties in it to Gilbane. Gilbane then refined the model so that they could use it as clash detection for the mechanical, electrical, and fire protection trades.

4D and 5D models are the most current uses for BIM by general contractors. The most popular and practical model is the 4D model. The 4D model consists of taking the 3D model and adding in the element of time. The 4D model works by importing the project schedule into the 3D model. Combining the schedule and the model, causes the sequence of activities from the schedule to be linked to corresponding portions of the 3D model. This is a good tool for visualizing the progress of a building over time, as well as, exploring the effect on the schedule when a certain area of work is delayed or changed. A 5D model is created by expanding the 4D model by adding the element of cost. Currently, this method is not used as frequently because the types of estimating software that are used are not compatible with BIM. The advantages of this method in the future will be the ability to quickly assess the impact to the schedule and cost when an area of work is changed. This will help to more accurately project the end date and final cost of each project. In the project, our team will be using the WPI Recreation Center model and schedule to create a 4D model that shows the existing and new design. The group will also look into the feasibility of creating a 5D model by adding the costs of the new and existing track designs.

Uses in Structural Engineering

Although BIM is primary used by construction managers, structural engineers are quickly realizing its potential as well. BIM is enticing for engineers because it uses an object-oriented programming paradigm (Nelson and Schinler, 2008). This means that the 3D model of the structure possesses all the information and functionality of each of its members. For example it contains information pertaining to its material, section properties, location in the building etc. From a structural point of view BIM is used for coordination, documentation, analysis and design.

Similar to project management, coordination of all the aspects of the project assists the structural engineer as well. Coordination amongst the architects, structural, and mechanical engineers results in better decision making based on actual and current designs. This coordination also allows for better updating and changing between programs and designs. This results in reducing time and conflicts because everyone is using the same model.

Documentation is the only aspect that the structural engineers have complete control over because it is based on their work and analyses (Nelson and Schinler, 2008). Since the BIM model can hold all the information and functionality of each member in the structure, it can easily be found all in one place. This makes documentation much easier because everything is in one file. This kind of documentation is also good because if changes are made later in the project, the changes are consistently applied to the entire design and documentation. However documentation does have its flaws in BIM. Repeating members in a structure will be documented individually, when traditionally usually a single drawing would have sufficed. Also, many structural engineering firms take pride in the way they present their drawings, and BIM has limits for the presentation of the drawings.

Chapter 3 - Benchmarking the Current Design

A critical part of progressing forward to alternative design is to first understand the existing design, and then modify from there. This chapter focuses on the uses of *Revit* to create a model unique to this project's needs, a baseline cost estimate both on the given information and *RS Means*, a schedule of the existing design and a 4-D creation of the existing design through BIM. All of these aspects give this project a fair understanding of the different dimensions of the existing design which all start with the *Revit* Model.

3.1 *Revit* Model Creation of Existing Design

Revit was used to gain an understanding of the track structure and its relationship to the Recreation Center, as well as provide a base for modeling and analyzing the alternative design. *Revit* was initially used as a visual aid to assist the group during 2-D visual restriction. The lengths and beam sizes that are mentioned in the structural plans were translated into *Revit* for a 3-D full visual aid. It was altered into an interactive representation that could be analyzed from both structural and project management perspectives. The structural component of Revit allows the structure to be transformed into an analytical model which can be analyzed in *Robot.* Additionally, *Revit* has many components that supplement project management such as scheduling and cost.

3.2 Creation of Baseline Cost Estimate Based on Given Information

In benchmarking the current design through a cost analysis, the ease of integration between *Revit* and *RS Means* cost data was displayed. *Revit* readily provided the information that was necessary to utilize the cost data provided by the *RS Means* book.

Revit easily exported the existing track steel information into three different schedule spreadsheets (steel framing, columns, and trusses). *Revit* was able to give the type of beam, length in linear feet, and volume of each steel member. This information was used, in congruence with the cost of the steel package provided by Gilbane to create a unit cost for the steel (Gilbane, 2012). Complete Tables with all of this information can be seen in Appendix B: Exported Information from *Revit*. Below, Figure 11 displays a step-by-step flowchart on the process behind exporting the quantities from *Revit.* A more detailed document for extracting information from *Revit* and placing it into an *Excel* spreadsheet for analysis can be seen in Appendix C: How to Export Quantity "Schedules" From *Revit*.

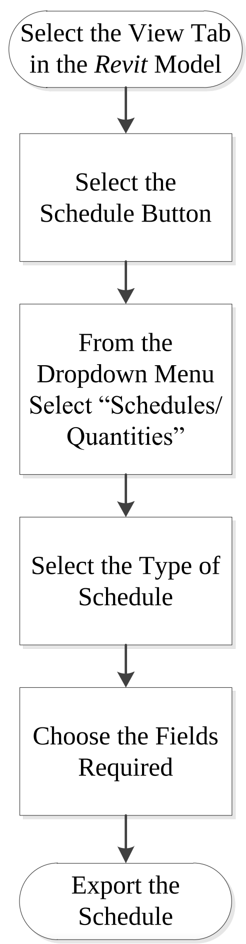


Figure 11: Flowchart for Exporting Schedules

First, a baseline price was created from cost data for the actual project. Table 2 below provides a breakdown of the total tonnage of steel as allocated to the columns, the framing, and the roof trusses. Knowledge of the total steel package cost, obtained from a Gilbane project meeting, and the total tonnage of steel allowed for the unit cost ($/ton) of steel to be determined. This calculation is also summarized in Table 2. The tables with individual calculations to determine the total quantities of steel columns, framing, and trusses, as referenced before, can be found in Appendix B: Exported Information from Revit.

Table 2: Unit Cost Breakdown of Total Structural Steel

Quantities of Total Rec. Center		
	CF	**TONS**
Structural Steel Columns	795.26	194.84
Structural Steel Framing	3,367.10	824.94
Structural Steel Trusses	610.00	149.45
TOTAL	4,772.36	1,169.23
Cost		
Structural Steel Contract ($)	$ 3,497,809.00	(includes labor)
Cost/Ton	$ 2,991.55	(includes labor)

After the unit cost of steel in $/ton was calculated for the entire building, information on only the track steel was exported from *Revit*. In order to extract only the track information, a separate *Revit* model was saved from the Cannon model by deleting all other steel elements in the building except for the track steel. An estimate for the cost of the track steel was determined by multiplying the tonnage of steel supporting the track by the unit cost of steel in $/ton. The breakdown for this analysis can be seen in Table 3 below.

Table 3: Unit Cost Breakdown of Track Steel

Quantities of Existing Track and Roof Design		
	CF	**TONS**
Structural Steel Columns	201.16	49.28
Structural Steel Framing	300.57	73.64
Structural Steel Trusses	602.58	147.63
TOTAL	1,104.31	270.56
Cost		
Cost/Ton	$ 2,991.55	(includes labor)
Cost of Existing Track and Roof	$ 809,381.65	(includes labor)

After determining the cost of the track steel based on the actual total cost of the steel package, the amount of steel exported had to be adjusted for to add welding to the trusses and connections. These percentages were assumptions made from instructions from *RS Means*. *RS Means* is fully discussed in the next section. Table 4 is a summary table of the adjusted estimate with the additions of welded trusses and connections. The total cost of the existing track was found to be approximately $922, 700.

Table 4: Complete Estimate for Existing Design with Adjustments from RS Means

	CF	TONS
Structural Steel Columns	201.16	49.28
Structural Steel Framing	300.57	73.64
Structural Steel Trusses	602.58	147.63
TOTAL	1,104.31	270.56
	10% for connections	27.06
	4% for welded trusses	10.82
TOTAL	(tons of steel)	308.43
	Cost/Ton	$ 2,991.55
	Cost of Existing Track and Roof	$ 922,695.08

When the original estimate was completed, a second estimate was prepared using a quantity take-off and discrete cost data from *RS Means* (RS Means, 2009). Both estimates were based on the model provided by Cannon.

3.3 Creation of Baseline Estimate Based on *RS Means*

For creating the cost estimates in this project, Gilbane provided baseline information that was very useful because it provided the means to create unit costs for steel that were described in the previous section. To complement the information given by Gilbane, *RS Means* was used as a main resource used in creating the cost estimates for this project. The book provides up-to-date cost data information. It also provides adjustments for different areas of the country if necessary. It is a widely used estimating tool due to its diversity. It offers information in many different sectors: home improvement, commercial construction, residential construction, facility management, green construction, and educational construction (RS Means, 2012).

In the research process, *RS Means* was found to be a resource in many educational papers: *Why is Manhattan So Expensive? and Review of Current Estimating Capabilities of the*

3D BIM. It was also found as a reference in a U.S. Government document, *Appendix B: Energy and Construction Cost Estimates.* The use of *RS Means* by many reliable sources made it a good option for the cost estimate created in this project.

3.3.1 Estimate Process Based on Cost Data

The difference between *RS Means* and using the steel package price was that estimates for line items such as steel connections, welding, and overhead and profit had to be made. Instructions for all of these items were provided by first pages of *RS Means*, called "How to Use the Unit Price Pages", that fully detailed how to use the information provided in the book. Steel Connections were added by applying 10% to the overall cost and welded trusses were accounted for by applying 4% to the overall cost. Overhead and profit percentages had to be added individually to each aspect of the project that was available to us (Material, Labor, and Equipment). If an estimate for a real construction job were created, a much more detailed overhead and profit adjustment would be made. Contractors can add overhead and profit to many different areas individually. These areas include shop labor, field labor, engineering, office support, material, and equipment (Turgeon, 2012). The estimate presented for this project did not get this detailed given the scope of the project. A basic flowchart describing how the *RS Means* cost data was used can be seen in Figure 12 below. A more detailed description of how the *RS Means* text was interpreted can be seen in the step-by-step methodological description in Appendix D: Example Using *RS Means*.

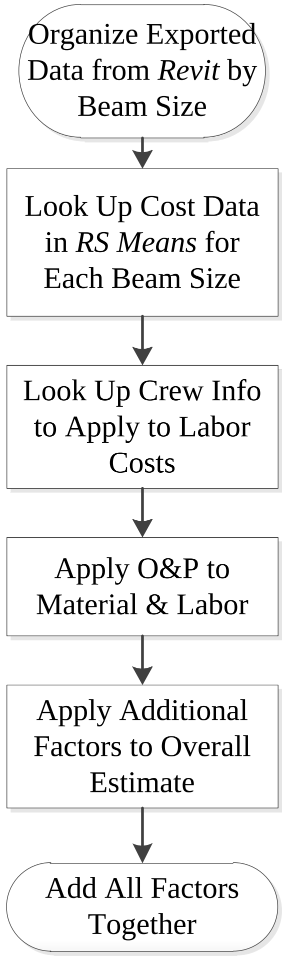


Figure 12: Flowchart for the Use of *RS Means*

A numerical example showing how the latter part of the flow chart can be put in place can be seen in Table 5 below. This table displays how each column member was accounted for, as well as the addition for overhead and profit. The 10% is added for the material and equipment is for overhead and profit only.

Table 5: Estimate for Steel Columns Including Overhead and Profit

COLUMN COST BREAKDOWN				
	Labor Cost/Unit	Total Labor Cost	Material Cost	Equipment Cost
HSS1.900x0.120	$ 7.82	$ 6,176.92	$ 4,817.48	$ 1,761.14
W12x120	$ 6.30	$ 266.72	$ 8,382.00	$ 76.62
W12x152	$ 1.74	$ 73.58	$ 13,335.00	$ 80.86
W12x40	$ 5.87	$ 345.12	$ 4,853.75	$ 99.43
W12x53	$ 5.87	$ 1,231.86	$ 17,325.00	$ 354.90
W12x58	$ 5.87	$ 165.20	$ 2,323.32	$ 47.59
W12x65	$ 5.87	$ 2,850.40	$ 40,088.12	$ 821.20
W12x72	$ 5.87	$ 2,441.73	$ 34,340.62	$ 703.46
W12x87	$ 6.19	$ 262.12	$ 6,096.00	$ 74.93
W12x96	$ 6.19	$ 418.99	$ 9,744.00	$ 119.77
Total		$ 14,232.64	$ 141,305.30	$ 4,139.91
O&P	Add 10%	Already Adjusted	$ 155,435.82	$ 4,553.90
		Total Cost of Columns		$ 174,222.36

Another add-on to the *RS Means* base estimate was inflation. This was added to the estimate because the *RS Means* book that was used was 2009 based and the steel was erected in 2011; the two year difference had to be accounted for through inflation rates. Using the ENR-CCI (Engineering News Record - Construction Cost Index), it was determined that the equivalent inflation rate from 2009-2010 was 3.15%. This number has remained approximately constant for the past 10 years (ENR, 2011). When taking the mentioned factors into account estimates for the three individual categories of the steel were created and combined to create the total estimate.

Using the cost of the columns, steel framing, and trusses we determined our final steel estimate to be $1,060, 400. This was a difference of 15% in comparison to the original estimate of $922,700 that was based on the steel package submitted to Gilbane. The cause of variance in the estimate could be due to many reasons. As stated before, many estimates on items such as connections and for welded trusses were assumed based on RS Means and are not exact. Also, the adjustment for inflation may not be exact. The value of 3.15% was based on information from ENR and is an equivalent value, not a value directly from 2009 to 2010 (ENR, 2012). To adjust the cost for the two years from 2009 to 2011, we added $(1.0315)^2$. The breakdown of our final estimate can be seen in Table 6 below.

Table 6: Estimate of Existing Design Using RS Means

OUR ESTIMATE OF EXISTING		
Our Estimate (no O&P)	$	905,526.37
10% for connections	$	90,552.64
4% for welded trusses	$	36,221.05
Total w/o Inflation	$	1,032,300.07
Total Cost of Our Estimate for Existing w/ Inflation	$	1,064,881.52
Error		15%

3.4 Schedule Investigation of Current Design

In order to help analyze the existing design and the alternative design two schedules of the steel work were developed. One schedule was a baseline of the existing design and the other was a schedule created to put a time frame to the alternative design. The first step was to develop a schedule that involved only the track-area steel pertinent to the project. Because the project only involves the columns, framing, and trusses that make up the track area of the Recreation Center the entire Gilbane steel schedule involves more activities than are needed for the investigation.

To develop the project-specific construction schedule the group started with the master schedule of the entire project from August 2010 which was one of the project's early projected schedules. This schedule included anything that had not been completed from the current date until the end of the project. Activities ranged from site work, and concrete, to pool installation, and floor finishes. Then, all the steel-specific activities were broken down to create an all-steel *Primavera* schedule based on the August 2010 start and finish dates. To make the schedule more accurate for the project, any steel activities that did not pertain to the columns, framing, or trusses around the track were eliminated. This schedule illustrated roughly how long Gilbane had originally estimated the track steel would take to be installed. Of course, as a project progresses there can be changes to the schedule due to fabrication delays, weather delays, and slow production, etc. The next step was to compare the actual time duration for erection of the track steel to the August 2010 projection, to see if the installation took longer or went faster than they originally suspected. WPI has used four webcams at four different locations around the Recreation Center to monitor the progress. With access to these images a spreadsheet was created involving four photos from each day that steel for the track area was being installed. A screenshot of the assembled time lapse photo spreadsheet can be seen below in Figure 13.

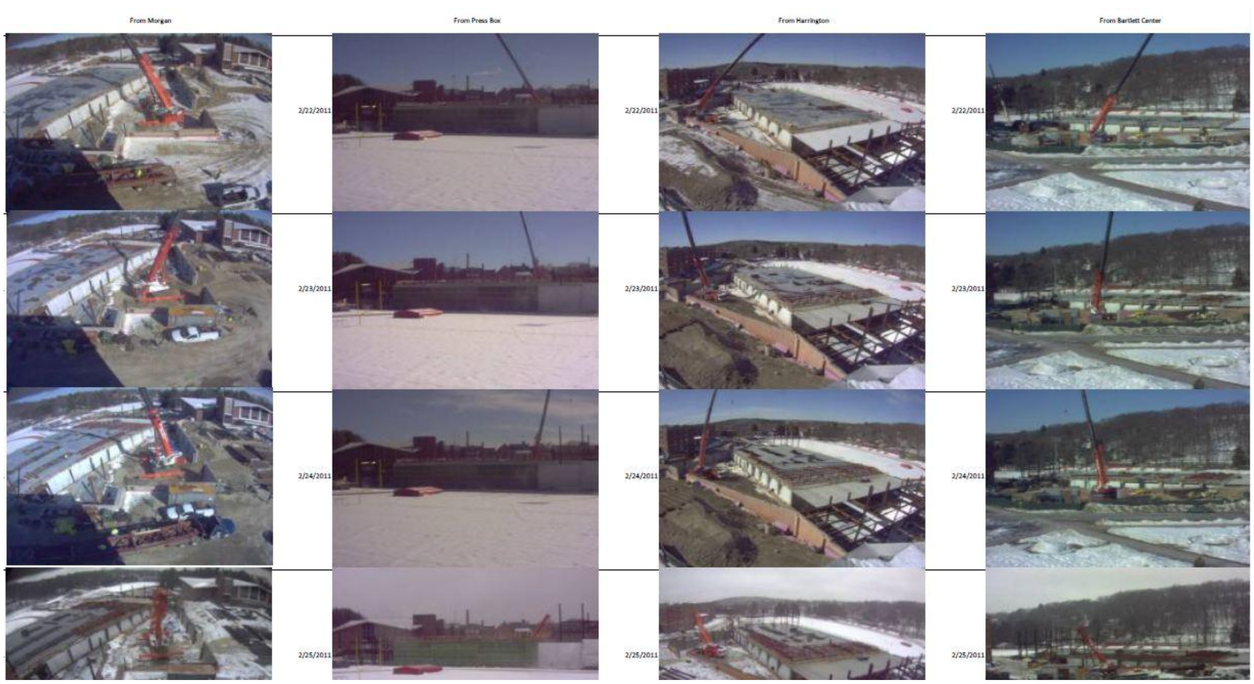


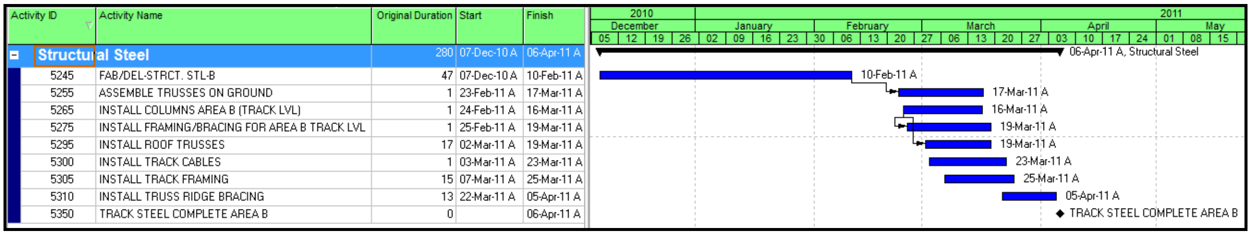
Figure 13: Time-lapse Photos Spreadsheet

These photos aided in determining when the steel actually started to be erected and when it was finished. It also revealed the production rates per day of the columns, framing, and trusses which was very beneficial for developing the schedule of the alternative design. On a second spreadsheet the steel activities were broken down into five major activities and the quantity of each type of steel installed on a given day was estimated and recorded. The five major activities were trusses, bracing/framing, columns, track framing, and track cables (Table 7).

Table 7: Existing Production Breakdown

		5 workers	7 workers	7 workers	7 workers		
		25 trusses	68 beams	36 columns	34 bays (inbetween columns)		
	Trusses on ground	Trusses	Bracing/Framing	Columns	Track Framing	Track Cables	Truss Bracing
23-Feb	2 trusses assembled on ground						
24-Feb	2 trusses assembled on ground			12 columns installed			
25-Feb	2 trusses assembled on ground		16 braces installed				
26-Feb							
27-Feb							
28-Feb							
1-Mar							
2-Mar	2 trusses assembled on ground	3 trusses installed	6 braces installed	2 columns installed			
3-Mar				1 column installed	7 bays track framing installed	Start cable install	
4-Mar		3 trusses installed	4 braces installed	1 column installed	2 bays track framing installed 1 each side		
5-Mar							
6-Mar							
7-Mar	3 trusses assembled on ground				2 bays track framing installed 1 each side		
8-Mar	2 trusses assembled on ground	3 trusses installed	4 braces installed	2 columns installed	2 bays track framing installed 1 each side		
9-Mar	2 trusses assembled on ground	2 trusses installed	4 braces installed	2 columns installed	2 bays track framing installed 1 each side		
10-Mar	2 trusses assembled on ground	2 trusses installed	4 braces installed	2 columns installed	2 bays track framing installed 1 each side		
11-Mar	2 trusses assembled on ground	3 trusses installed	4 braces installed	2 columns installed			
12-Mar							
13-Mar							
14-Mar	2 trusses assembled on ground						
15-Mar		3 trusses installed	4 braces installed	3 columns installed			
16-Mar	2 trusses assembled on ground		13 braces installed	9 column installed	2 bays track framing installed 1 each side		
17-Mar	2 trusses assembled on ground	2 trusses installed	2 braces installed				
18-Mar		2 trusses installed	5 braces installed		2 bays track framing installed 1 each side		
19-Mar		2 trusses installed	2 braces installed				
20-Mar							
21-Mar							
22-Mar					2 bays track framing installed 1 each side		Start Bracing Install
23-Mar					11 bays track framing installed	Finish cable install	
24-Mar							
25-Mar							
26-Mar							
27-Mar							
28-Mar							
29-Mar							
30-Mar							
31-Mar							
1-Apr							
2-Apr							
3-Apr							
4-Apr							
5-Apr							
6-Apr							Finish Bracing Install
7-Apr							

This breakdown facilitated the creation of a project-specific *Primavera* schedule of the elapsed time for the installation of the existing track steel (Figure 14).



Activity ID	Activity Name	Original Duration	Start	Finish
Structural Steel		280	07-Dec-10 A	06-Apr-11 A
5245	FAB/DEL-STRCT. STL-B	47	07-Dec-10 A	10-Feb-11 A
5255	ASSEMBLE TRUSSES ON GROUND	1	23-Feb-11 A	17-Mar-11 A
5265	INSTALL COLUMNS AREA B (TRACK LVL)	1	24-Feb-11 A	16-Mar-11 A
5275	INSTALL FRAMING/BRACING FOR AREA B TRACK LVL	1	25-Feb-11 A	19-Mar-11 A
5295	INSTALL ROOF TRUSSES	17	02-Mar-11 A	19-Mar-11 A
5300	INSTALL TRACK CABLES	1	03-Mar-11 A	23-Mar-11 A
5305	INSTALL TRACK FRAMING	15	07-Mar-11 A	25-Mar-11 A
5310	INSTALL TRUSS RIDGE BRACING	13	22-Mar-11 A	05-Apr-11 A
5350	TRACK STEEL COMPLETE AREA B	0		06-Apr-11 A

Figure 14: Existing Design Primavera Screenshot

The actual time it took to erect the steel for the track and the projected time were quite similar. The difference between the two schedules was about one week's time, the added length was due to a couple lost days because of the amount of snow Worcester received in the early months of 2011. Using the time lapse photos to compare the actual and projected construction schedules helped to understand the process for installing the steel. Each truss was delivered in two sections and assembled on the ground. The steel erectors started at one end by installing the columns and bracing for two column bays. Once they erected and braced the two column bays, they installed the trusses for one of the bays which included three trusses. They repeated this process from one end to the other, making sure to have installed one more bay of columns and bracing than trusses. Figure 15 shows the steel installation proceeding from the left to the right by installing the columns and bracing first, then the trusses, and finally the track framing and cables.

Figure 15: Progress Photos

These photos were also beneficial because they provided a means to estimate the average production per day for each piece of the steel structure. The most important production rate was for the installation of the trusses. Trusses were the most important because they are the largest steel members and none of the other steel in the track area could be installed until the trusses for a bay were installed. The workers were able to install on average two trusses, four columns, and six pieces of bracing per day. The workers could install up to eleven bays of lighter weight track framing in a day. But because the rest of the construction could only complete one bay each day, the workers only installed one bay of track framing and cables each day for consistency. In all, the installation of the track area steel took six weeks, while the projected installation time obtained from Gilbane's schedule was five weeks.

3.5 Creation of 4-D BIM

Integrating the schedule into the BIM was necessary to create a 4-D model. This was completed through "Phasing" within the *Revit* model. The process was learned from an MQP completed in the previous academic year by Fournier et. al. We created four phases for the existing design based on the percentage completed for the track area. Because the overall schedule was six weeks, screen shots were taken at one and a half weeks, three weeks, four and a half weeks into the process, and final construction. The phases referred to 25%, 50%, 75% and 100% completion time-wise. Below, Table 8 breaks down each phase through different components. It displays the phase, the date the phase is depicted on, and the completion percentage of steel based on the tonnage that has been erected.

Table 8: Phase Breakdown Information

Breakdown by Phase			
Phase	Date	Steel	
% Complete		Tonnage	% Complete
25%	3/7/2011	20.49	7.50%
50%	3/17/2011	109.44	40%
75%	3/27/2011	179.82	66%
100%	4/6/2011	270.56	100%

Figure 16 shown below is the track at 25% completion. The percentages were based on the timing of the schedule. This figure is shown on 3/7/2011, 25% complete schedule wise. At this 25% schedule mark, there was 20.49 tons of steel completed. That is only 7.5% complete in terms of steel tonnage. This could be due to many things: weather, holds on certain parts of the steel, among other reasons. Figure 16 depicts the beginning stages of the track construction on the Morgan side of the building.

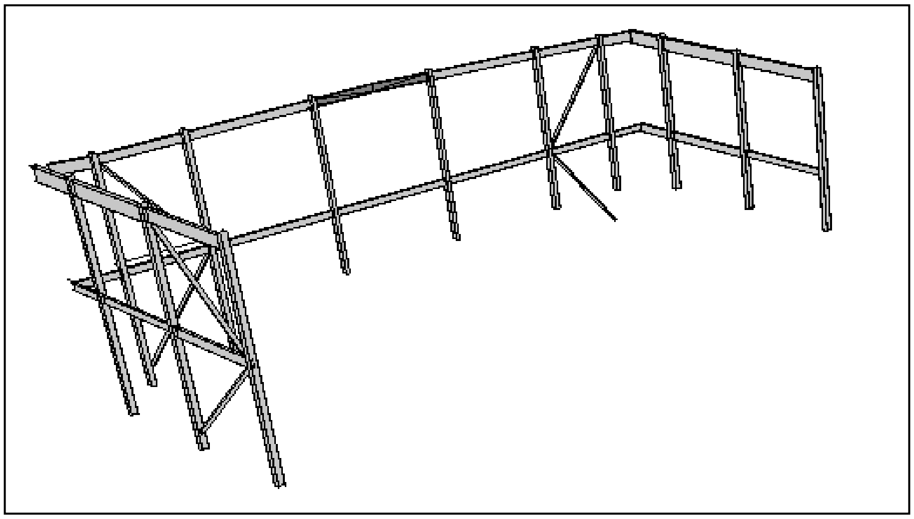


Figure 16: Phase 1 - 25% of Track Complete

When the schedule is 50% complete, there is much more steel up. Figure 17 below shows the progression at 50% complete. There are many more trusses erected, as well as 3 complete column spans. At 50% done, this Phase has 109.44 tons erected. That is about 37% more steel erected than Phase I and 40.44% of the total track steel, work-wise. Phase II is depicted on 3/17/2011.

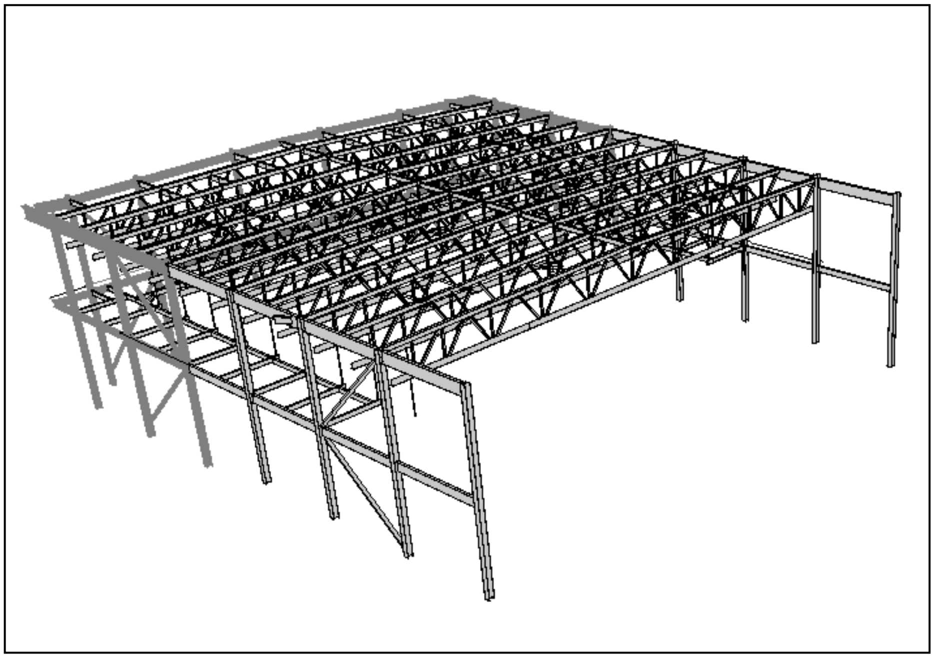


Figure 17: Phase 2 - 50% of Track Complete

Figure 18 is Phase 3 – 75% complete. At 75% complete, it is visible that the track is very close to completion. At this point in time, there are 179.82 tons of steel erected. This is only 34% from completion in terms of work.

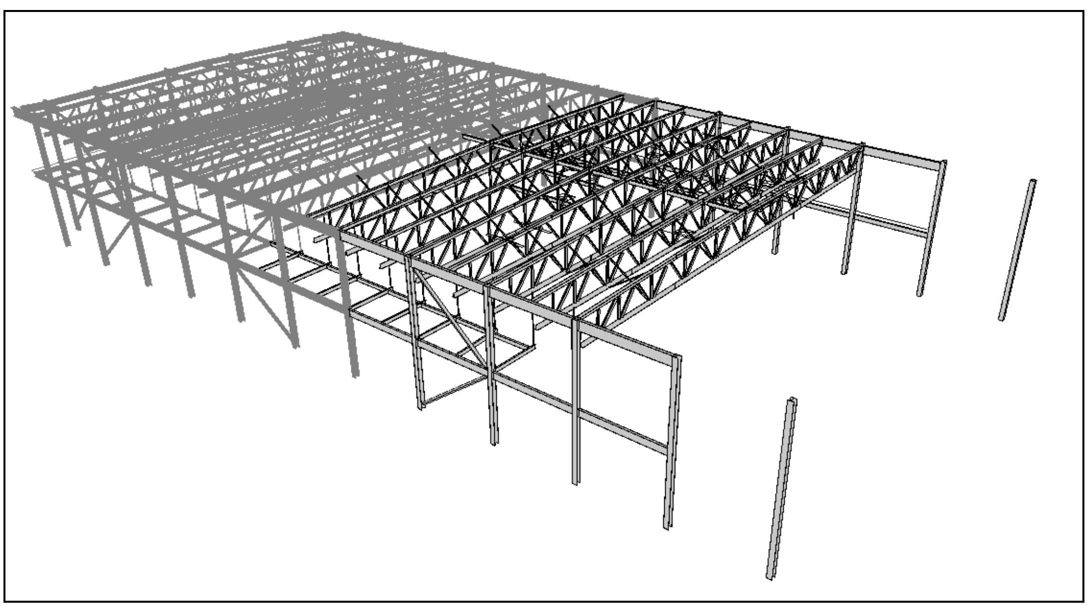


Figure 18: Phase 3 - 75% of Track Complete

The final phase is named “New Construction.” For the steel work, this phase includes the remaining 33% of steel erected. It is in this time period that the remaining columns and track framing are completed. This can be seen in Figure 19 below.

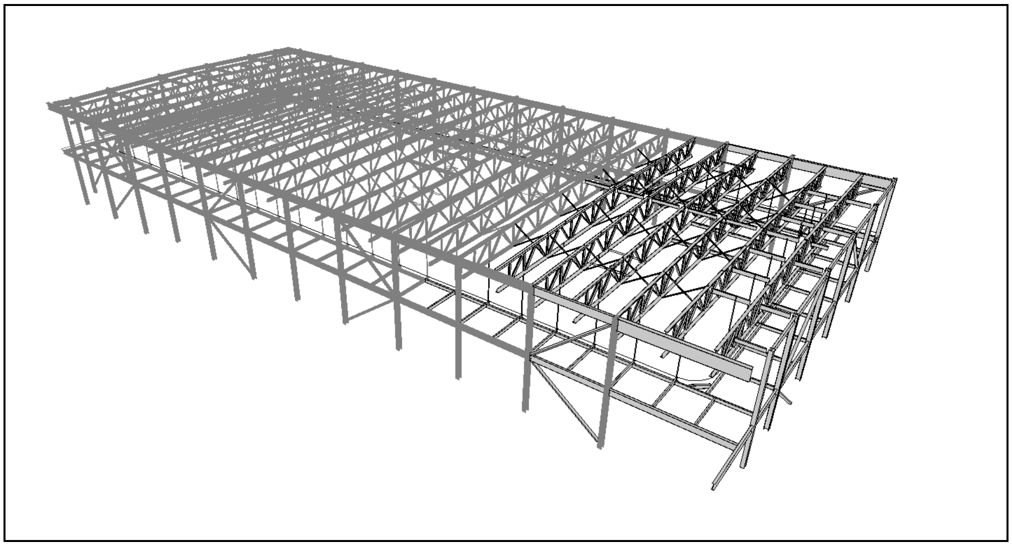


Figure 19: Final Construction Phase of Existing Track

The tonnage of the steel from each phase was determined by filtering the schedule information. This included a few additional steps in *Revit.* The steps for this process are also included in Appendix C: How to Export Quantity “Schedules” From *Revit*. Creating the 4-D model was the last step in the benchmarking of the existing design. At this point, the next step of the MQP, to create and analyze the alternative design could begin.

Chapter 4 - Alternate Designs

Once the existing track had been investigated thoroughly, and alternative track design can be proposed. The following chapter goes into the detail of how the alternative track was created through the structural evaluation, the cost development, and schedule formation. There were two alternatives attempted through this project; the cantilever approach and simple beam approach. Both of these designs were based off of the existing design with the elimination of the hanging supports.

4.1 Structural Evaluation

The structural evaluation of the alternative design tested two different approaches. Each approach eliminated the hanging supports on the inner side of the track. The first approach considered using cantilever beams that spanned perpendicular to the outer wall beams and inner beams of the track. This method did not work because in order for the cantilevers to have enough moment resistance, they exceeded the height restriction of 44", which then became an issue for head clearance on the fourth level (gym floor). This inspired our second approach of changing every other perpendicular cantilever beam to a simply supported beam. To facilitate this change, the lengths of the inner beams were extended to span the same length as the outer beams or girders. This approach did not eliminate the cantilever beams all together, it merely reduced their number because substituting simple beam configurations for cantilever configurations dispersed the loading across the track and allowed the cantilevers to have a smaller member size. These two approaches were investigated through the use of spreadsheets and hand calculations. However another component of each analysis used *Robot* as a computer-aided design resource to solve indeterminate equations and gauge approximate results for the hand calculations.

4.1.1 Existing Design Criteria & Adjustments

During the calculation phase of the alternative design some alterations were made to the member design process such as the loading scheme, change to the construction load, and minor alterations to the beam lengths and design. In addition to these design alterations, there is a labeling system to the orientation of the project. Through the remainder of this project, the Recreation Center is broken down to different components and each section has certain labels. Instead of referencing the direction of each building, this project labels each side by the major landmarks associated with each direction. For example, the West side of the building is next to Football field, so throughout this project, the West side is also known as the Football side. Additional references associated with the directions of the Recreation Center are the Softball side (North), Quad side (East) and Morgan side (South).

As previously stated, the track system consists of steel beams that support metal decking, a concrete slab, and various sections of conduit piping for MEP (Mechanical, Electrical, Plumbing) systems. All of these loads must be incorporated into the factored design loads for the beam which determine the beam's required strength and resulting size. In order to insure that the dead and live loads were properly accounted for, a conservative approach was used. A design strategy was adopted that if one beam were to fail, then the loads would still be supported by the other beams within the area of the failure. This was achieved by creating loading schemes for each section of the track. For example, Figure 20 below shows the loading scheme for the straight away section of track along the wall of the Recreation Center facing the football field. The end beams were designed to support half the tributary area of the various loads applied, and these beams were designed first.

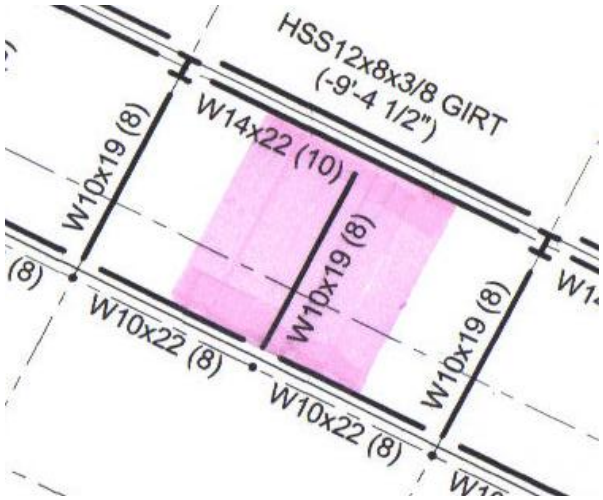


Figure 20: Girder loading scheme across tributary width (Football Side)

Next the middle beams were designed to support the tributary area on either side of the beam. The middle beams not only support the various dead and live loads across their tributary width, but also the pick up the loading from the end beam. Figure 21 is an example of the loading scheme of the one of the girders located between the columns on the Football side of the track. When the loading of the girders were calculated, they were designed to support half the tributary area of the track floor, as well as the middle beam's reaction and the reactions from the beams on the other side of the track, if any where present.

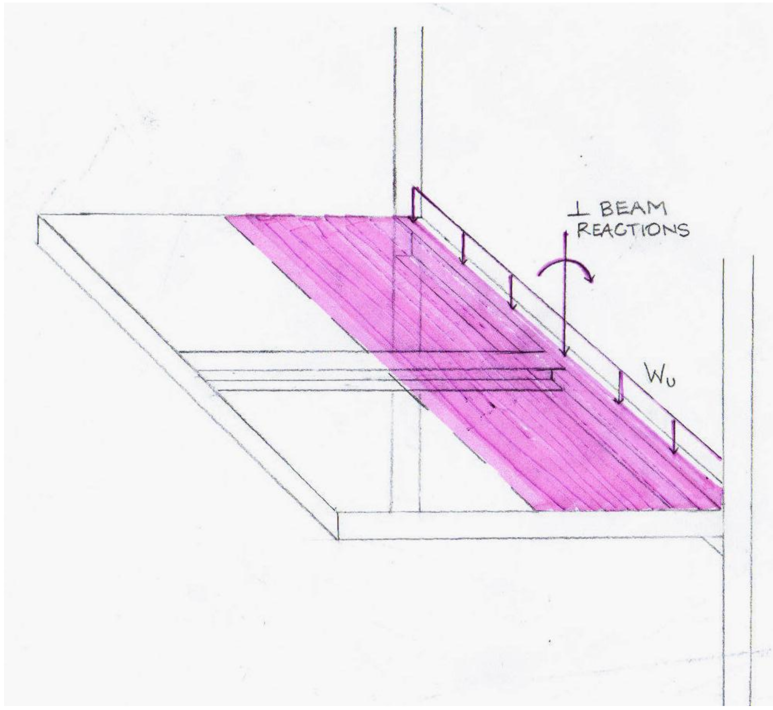


Figure 21: Girder Loading on Football Side of Track

The Quad side of the track is similar to Figure 21, but had beams attached to both sides of the girder. In this scenario, the reactions due to the beams on the other side of the track were calculated using factored loads to ensure that the girder would not only sustain the track loadings but also the other side if needed. The rest of the loading schemes can be seen in Appendix E: Loading Schemes.

The track framing was designed for different deflections including strength and deflection performance during construction. Typically the construction load is assumed to be 20 psf due to the workers and equipment, but because the track is a limited area, the construction load was decreased to 10 psf. It is a safe assumption because it was not possible to accommodate a large number of workers and equipment within the allotted space.

These design criteria and adjustments created a foundation for the track design for the alternative approach. Due to the fact that the alternative design does not have the hanging supports, some alterations to the beam lengths and layout geometry were necessary. The first attempt at an alternative design was a cantilever based model with strengthened beams perpendicular to the track.

4.1.2 Alternative Design – Cantilever Approach

The first attempt at an alternative design was a cantilever method with the same configuration as the existing design, but without the hanging supports. Figure 22 represents a 3 dimensional view of the design and Figure 23 represents the framing plans of the cantilever method. In order to compensate for the lack of hanging supports, recalculations of the supporting beams were made to sustain the new added weight.

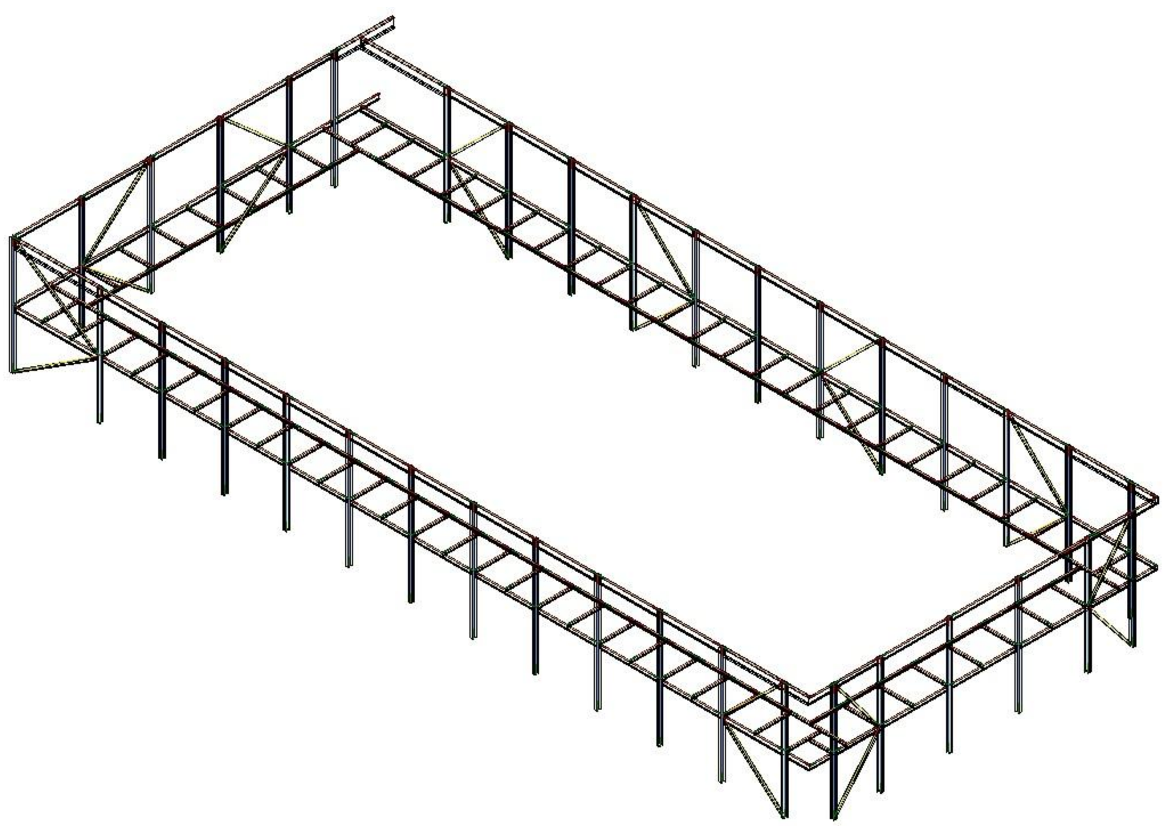


Figure 22: Cantilever Approach (Trusses Omitted)

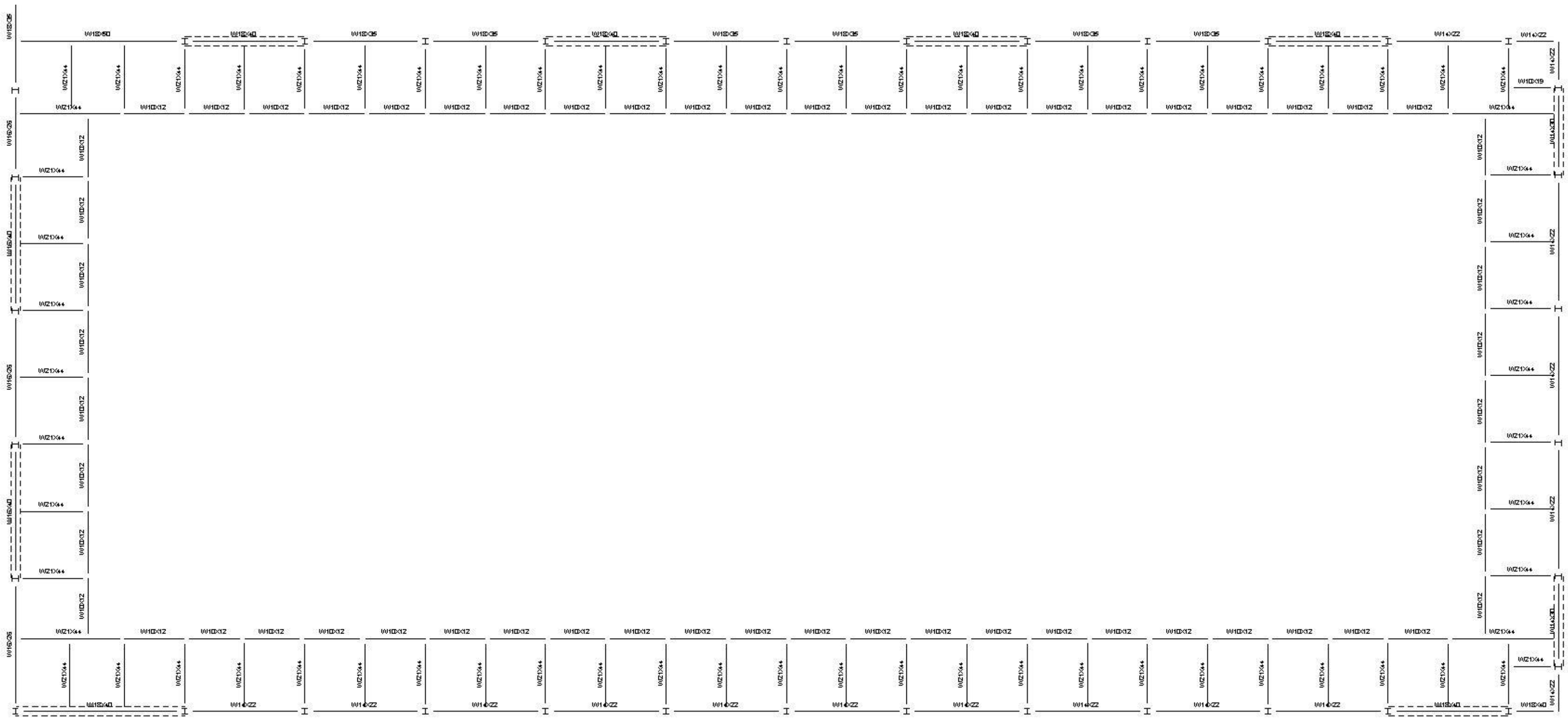


Figure 23: Framing Plans of Cantilever Method

This new alternative created 11'8" cantilevers spaced every 9' 8" in which each cantilever took on a large moment force from the various forces acting on the member. It was soon discovered that these cantilevers created too much moment and their respective depths would be a hazard to head clearance on the basketball courts. Table 9 below shows some of the member sizes of the various beams of the first attempt. The calculations for this method can be found in Appendix G: Cantilever Method Calculations.

Table 9: Cantilever Approach Member Sizes and Forces for Football Side

Member Sizes (Football Side)			
Beam Type	**Beam Size**	**Force (k)**	**Moment (ft.k)**
End	W10x12	0.012	0.14
Cantilever	W21x44	10.32	482.51
Girder	W18x40	22.96	268.37

There were not any W-shaped beams that could withstand its specified moment as well as fall within the 44" height restriction, which meant a rounded HSS beam would have to be used. The substitution of a rounded beam would also not work in this scenario because that type of beam could not support the various vertical live and dead loads associated with the track. All of these findings pointed in one direction, to reconfigure the alternative design by minimizing our cantilevers and moment reactions.

4.1.3 Alternative Design – Simple Beam Approach

The second design that was attempted was a modified version of the Cantilever Approach. It was modified by alternating the cantilevers to a simply supported beam. Figure 24 represents the framing plans of the Beam approach and Figure 25 represents a 3D *Revit* model of the framing plans. The simply supported beams were located at the mid-span of each girder and end beams. The end beams were combined to form a longer beam, the same length as the girder it is parallel to. This eliminated the moment on the girders from the original cantilever design.

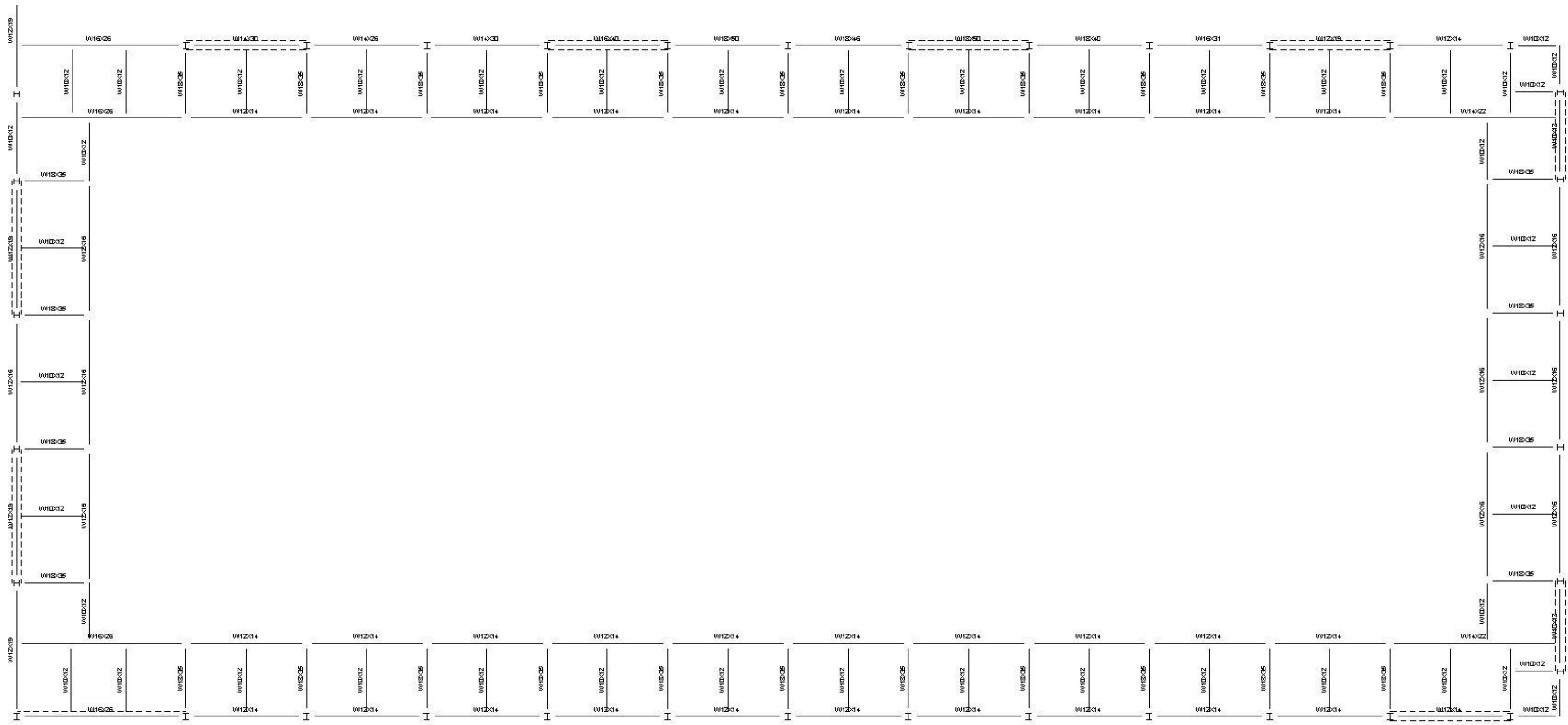


Figure 24: Framing Plans of Beam Approach Alternative Design

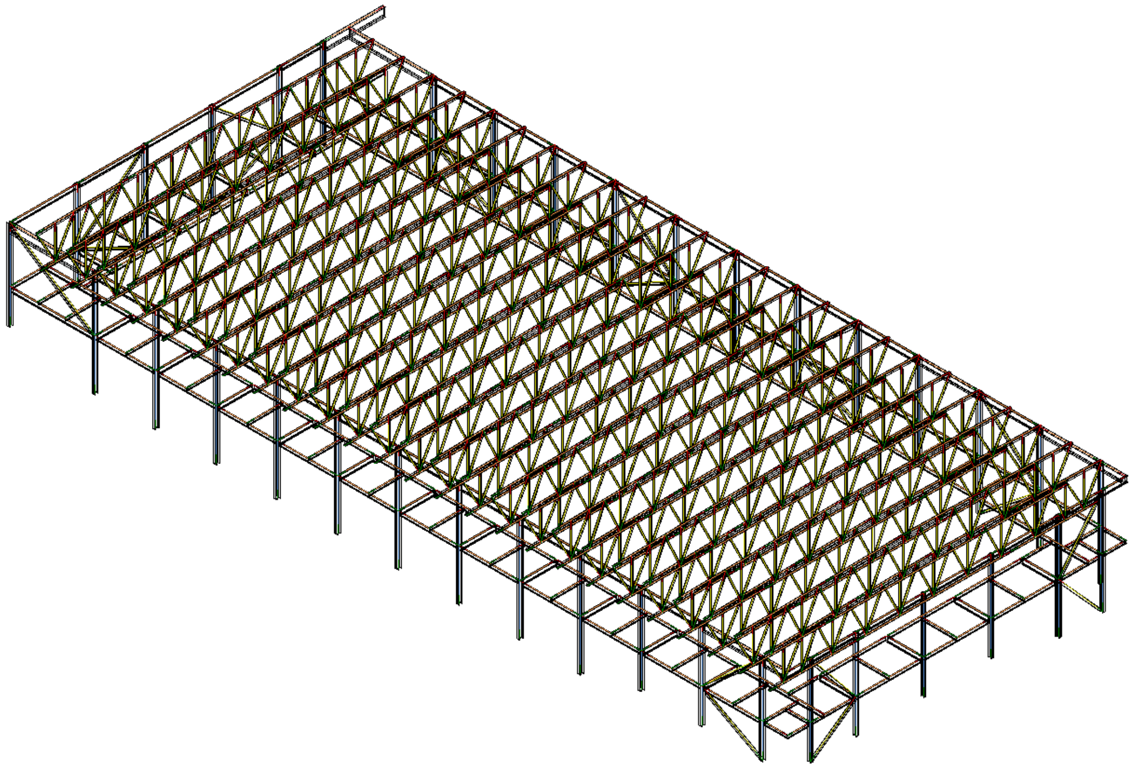


Figure 25: *Revit* Model of Beam Approach Alternative

The calculations for the process were done through hand calculations, spreadsheets, and Robot Structural Analysis. The hand calculations, located in Appendix H: Simple Beam Approach Hand Calculations were used to show an example of each type of beam calculated with the spreadsheets. The spreadsheets were used to simplify the timely process of writing out the procedure used to design the beams. The spreadsheets also allowed for quicker checks of member selection and calculations, these can be seen in Appendix I: Simple Beam Approach Spreadsheet Calculations. Robot was used to calculate reactions for fixed end beams, as well as member verification of selected beams. These specific uses of *Robot* are detailed in the next section. Each *Robot* function used was checked with hand calculations or spreadsheets to verify the accuracy of the operation.

4.1.4 *Robot*, Structural Analysis Program

Robot was used as a computer-aided engineering tool throughout this project. Prior to the start of the project, no group member had ever used this program before, and so the scope of work included gaining familiarity with the use of *Robot* for structural modeling and analysis. This learning process involved reading the user guide, watching videos online, and working with the help function within the program. These initial resources were a good starting point but did not provide the in-depth instructions of what the group felt was necessary to use the program for their project. These established resources gave more of a general overview of individual functions but didn't relate the functions together. Instead a trial and error process or "playing around" with the program was relied upon to gain insight into the relationships and interactions between two or more functions. This interactive learning method proved to be more effective than searching for guidance from established resources. The outcomes of the process are detailed in the below paragraphs and shown in the Appendix M: Creating a Simply Supported Beam in Robot, through Appendix O: Steel Design as tutorials.

After gaining a general understanding of some specific functions the group was able to use *Robot* throughout the project. Some of the main functions the group used were solving indeterminate structures, verifying that an appropriate steel member was being used for non-composite beams, and modeling structural members in 2-D or 3-D.

Originally it was thought to transfer the *Revit* model for the alternative track design that was created by the group, into *Robot*; however this translation of information proved to be problematic. Due to the limited knowledge about *Robot*, the group was unable to make sense of how to make use of the transferred structure in *Robot*. The interoperability with *Revit Structures* and *Robot* worked correctly, however once in Robot, it was confusing of how to proceed with the model. Because the design was complex, it was difficult to accomplish the desired tasks through a trial and error process. In order to make use of the program, the group decided to explore some specific uses *Robot* as a learning tool.

The simplest model to use in *Robot* was when only one beam was transferred. This was tested by transferring beams, a combination of beams, and larger combinations of beams from the *Revit* model to *Robot.* Once in *Robot*, one beam was easier to work with due to the simplicity of having only one beam. From this point the group only used one beam at a time in the program. By only using one beam, the group could control the unknown variables of the program better. A disadvantage of only using a one beam model, the group had to create much more models than if all the members were combined into a frame design. Future users should experiment using a frame design with multiple members, to reduce the amount of models needed. *Robot* also has a function to allow the user to build and create beams in Robot itself. This proved to be easier when using Robot because the program only allows transfers from Revit if the programs are linked together. The group found it easier to create the model in Robot to ensure it was the right dimensions and maintained the correct properties. An example of how to build a beam and control the properties can be seen in Appendix M: Creating a Simply Supported Beam in Robot.

After learning how to build a beam in Robot, different loading schemes were applied to solve for the reactions, deflections, displacements, stresses, and forces. These features were useful when solving for the reactions of the girders. The girders were fixed at both ends making them indeterminate structures, which if solved by hand would be timely and complex. With the use of *Robot* it was simply a matter of applying the correct loading schemes and clicking a few buttons. Appendix N: Loading Schemes and Results illustrates the application of applying different loading schemes to a beam. This function was used for solving the indeterminate structures for the alternative design, for example the girders. To make sure Robot was correctly determining the reactions and that the group understood how to apply the loads correctly, a simple model was tested both with hand calculations and *Robot*. This can be seen Appendix K: Comparison of Girder Reactions in Robot and by Hand Calculations. All the girder reactions can be seen in Appendix L: Girder Reactions.

Once the loads were applied to a beam it was analyzed as a non-composite beam to check for an appropriate beam size. This was done using the Steel Design layout. Steel Design is a function in *Robot,* which can be used to check appropriate beam sizes. This function offers two different calculation methods LRFD and ASD that can be combined with alternative verification methods, like flexure, compression, and shear. For this project LRFD was chosen as the verification method for all beams. Originally the group wanted to use *Robot* to use the Steel Design function for all the beams in the structure; however based off the research and literature available this idea proved to be unsuccessful because the group was unable to find the process to model this type of beam necessary for composite action. The Steel Design function was only used for the cantilever middle beams because they are non-composite beams. An example of how to use the Steel Design function in *Robot* can be seen in Appendix O. To make sure the group understood how to interpret the Results of the Steel Design function, they compared the *Robot* results to hand calculations. This also helped to understand how the Results are portrayed, by comparing the different sets of calculations. This comparison can be seen in Appendix J: Comparison of Steel Design in Robot and by Hand Calculations.

The comparison of the *Robot* analyses and hand calculations in Appendix K: Comparison of Girder Reactions in Robot and by Hand Calculations and Appendix J: Comparison of Steel Design in Robot and by Hand Calculations may show some small discrepancies. These discrepancies are caused by rounding numbers at different stages of the calculation process. In

Robot, the load table only displays loads and lengths up to two decimal places. If three or more decimal places are entered, the table will automatically round to display only two decimal places. Versus when calculating by hand the decimal places could be more causing the resulting numbers to differ.

Using the specific functions mentioned in the above paragraphs, *Robot* has demonstrated some of its powerful capabilities and why it would be a favorable tool for engineers. The first comparison can be made with time. The time it takes *Robot* to analysis loads or steel design is much shorter than human calculations. This is favorable because when working with large structures, this could save the engineer countless hours of "crunching numbers". It also decreases the amount of human error possible. Also because Robot has standard sections of members and properties stored in its database, it also saves time by limiting the need to look up values in the AISC Manual. If a specific property of a beam was needed, the right panel displays all the section properties information, making it more convenient. Robot also increases the modes of communication between group members because of its ability to model in 2-D and 3-D.

4.1.5 Column Design

The columns in the alternative design were grouped into two different categories. One category was all the columns surrounding the track that were part of the braced frame and resist lateral and gravity loads. The other category was the remaining columns around the track that only resist gravity loads. Each category was designed to support both axial and bending forces. This investigation studied the existing columns sizes for the effects of the alternative design of the track system. The columns were found be sufficient for the alternative design.

The columns resisting lateral and gravity were considered braced frames consisting of two columns with a diagonal bracing connecting them, shown in Figure 26.

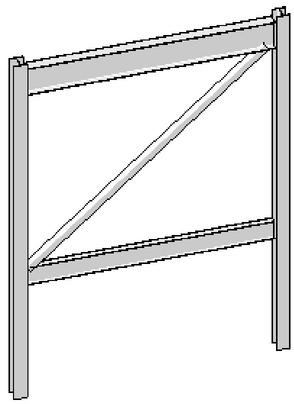


Figure 26: Braced Frame

There were ten total braced frame systems for the track level sides. The football, Morgan, and softball sides all contained two frames, while the Quad side has four braced frames along the track. These frames were designed using an approximation method for second-order P-Δ effects because of the lateral transition due to the wind and earthquake forces. The method used was the Effective Length Method. This method takes into consideration magnification effects for sway and no sway conditions by using modifiers B1 and B2. Table 10 below shows some of the key findings from the braced frame analysis. This analysis also referenced Chapter H in the AISC Specification because the columns are subjected to combined flexure and axial compression. The governing equations from ASIC Chapter H used for each member can be seen below in Table 10.

Table 10: Lateral and Gravity Column Results

Side		Football	Morgan	Quad	Softball
Frame		FB-SB	both	M2	both
Columns		W12x72*	W12x53*	W12x65*	W12x65*
K2		1	1	1	1
Pnt	kips	227.62	31.19	251.60	35.27
Plt	kips	15.25	40.66	34.92	25.89
Mnt	k-ft	189.35	41.86	118.57	13.12
Mlt	k-ft	18.76	14.94	12.66	11.84
B2		1.06	1.04	1.09	1.03
K1		1.00	1.00	1.00	1.00
B1 Calculated		0.54	0.53	0.44	0.50
B1 used		1.00	1.00	1.00	1.00
Governing Equation		H1-1a	H1-1b	H1-1a	H1-1b
1>		0.40	0.10	0.50	0.06

The columns in the unbraced category were analyzed individually for both axial and bending forces. Although these columns were not part of the braced framing there was still a bending force applied due to the cantilever middle beams and the girders between each column. The unbraced columns were only designed to carry gravity loads and moments. The Effective Length Method was used again, however only the B1 multiplier was used because there was no lateral force applied. Each column consisted of a 2-D analysis. This resulted in analyzing the column in one plane, then analyzing the column in another plane to account for both the girder and cantilever moments. Then, each analysis was combined through superposition and substituted into the governing equation (Equation H1-1a or H1-1b) in Chapter H of the AISC Specification. An example of some of the key findings of this analysis is presented below in Table 11.

Table 11: Gravity Load Column Results

Side		Quad side	
Frame		MQ 2	
Columns		W12x65	
		Girder Plane	Cantilever Plane
Pnt	kips	109.18	130.24
Mnt	k-ft	72.30	113.50
K1		1.00	1.00
B1		0.62	0.62
ΦPn		428.00	428.00
H1-1a			
1>		0.27	0.33
		Combined	
H1-1a			
< 1		0.57	
x reaction (k)			5.53

Part of the column investigation was to examine the reaction at the top and bottom of the column to engage diaphragm action at the roof and gym floor level. These pins helped to stabilize the columns. The horizontal or x-directional reaction due to the pin was deemed not to be of any significance for the structural integrity of the design. It was not investigated further because when compared to the total force acting on the column it was much smaller. All the results from the column design can be seen in Appendix P: Column Design.

4.1.6 *Revit* Model

Once the beam-and-girder framing for the alternative design was defined, a 3D model was created in *Revit* to assist the group in visualizing the alternative model completely. This also was an interactive drawing that could be analyzed from various perspectives, such as structural design as well as project management cost and scheduling. Figure 27 below is a representation of the alternative designed created in *Revit*.

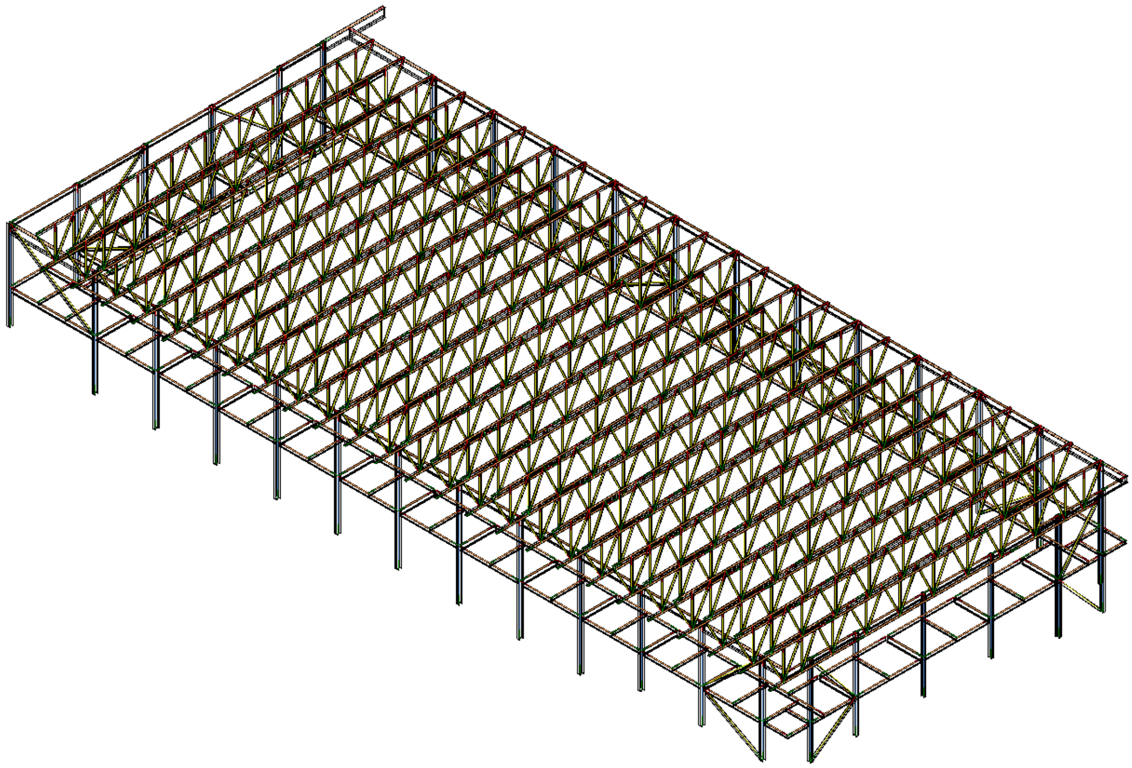


Figure 27: Revit Model of Alternative Design

4.2 Cost Development for Alternative Design

Once the design of the structural framing on the alternate design was completed, this includes the beams and girders; the cost estimate for the alternative design was able to begin. The estimate was completed using RS Means in the same way the existing design estimate was created, as described in Section 3.3: Creation of Baseline Estimate Based on *RS Means*. Table 12 below shows the breakdown for the structural framing in the alternative design.

Table 12: Structural Framing for Alternative Design

FRAMING COST BREAKDOWN							
	Total LF	Labor Cost/LF	Total Labor Cost	Material Cost/ LF	Material Cost	Equipment Cost/ LF	Equipment Cost
HSS7X7X1/2	20	$ 112.65	$ 2,252.99	$ 515.00	$ 10,300.00	$ 32.00	$ 640.00
W10x12	482.920	$ 10.10	$ 4,878.75	$ 19.80	$ 9,561.82	$ 2.90	$ 1,400.47
W12X14	580.000	$ 6.95	$ 4,032.35	$ 26.50	$ 15,370.00	$ 1.98	$ 1,148.40
W12x16	215.000	$ 6.95	$ 1,494.75	$ 26.50	$ 5,697.50	$ 1.98	$ 425.70
W12x19	238.000	$ 6.95	$ 1,654.65	$ 36.50	$ 8,687.01	$ 1.98	$ 471.24
W14X26	19.333	$ 6.19	$ 119.71	$ 43.00	$ 831.33	$ 1.76	$ 34.03
W14x30	136.250	$ 6.74	$ 917.65	$ 49.50	$ 6,744.39	$ 1.93	$ 262.96
W16X26	128.917	$ 6.08	$ 784.24	$ 43.00	$ 5,543.42	$ 1.74	$ 224.32
W16x31	19.333	$ 6.74	$ 130.21	$ 51.00	$ 986.00	$ 1.93	$ 37.31
W16X36	83.333	$ 6.74	$ 561.26	$ 51.00	$ 4,250.00	$ 1.93	$ 160.83
W16X40	19.333	$ 7.60	$ 147.01	$ 66.00	$ 1,276.00	$ 2.18	$ 42.15
W18X35	350.000	$ 9.02	$ 3,155.70	$ 58.00	$ 20,300.00	$ 1.95	$ 682.50
W18x40	19.333	$ 9.02	$ 174.31	$ 66.00	$ 1,276.00	$ 1.95	$ 37.70
W18X46	19.333	$ 9.02	$ 174.31	$ 76.00	$ 1,469.33	$ 1.95	$ 37.70
W18X50	38.667	$ 9.56	$ 369.63	$ 82.50	$ 3,190.00	$ 2.06	$ 79.65
W21X44	14.750	$ 8.15	$ 120.17	$ 72.50	$ 1,069.38	$ 1.76	$ 25.96
W24X55	212.667	$ 7.82	$ 1,663.34	$ 91.00	$ 19,352.67	$ 1.69	$ 359.41
W24X62	154.667	$ 7.82	$ 1,209.70	$ 102.00	$ 15,776.00	$ 1.69	$ 261.39
W24X76	19.333	$ 7.82	$ 151.21	$ 125.00	$ 2,416.67	$ 1.69	$ 32.67
W27X84	74.000	$ 7.28	$ 538.59	$ 139.00	$ 10,285.95	$ 1.58	$ 116.92
W33X118	62.167	$ 7.39	$ 459.22	$ 195.00	$ 12,122.57	$ 1.59	$ 98.85
Total			$ 22,736.77		$146,206.04		$ 5,940.15
Inc. O&P		Add 10%	Already Added		$160,826.64		$ 6,534.17
			Total Cost of Framing				$ 190,097.58

After the framing was designed, the columns were analyzed to see if they could sustain the load that the beams and girders would put on them. The columns analyzed were the same as the existing design and they were all found to be of sufficient strength. Due to this, the column and truss sizes remained the same, keeping the costs for both the same as the existing design.

4.3 Schedule Development for Alternative Design

After developing the schedule for the existing design as discussed above in Section 3.4, the schedule for erection of the alternative design was developed. The information learned from developing the schedule for the existing design helped tremendously in creating a schedule for the alternative design. The average production rates for erecting each type of steel, determined from the time lapse photos, were the base line for estimating the alternative schedule. In the new design of the track the suspended cables were eliminated, and the track framing was redesigned to support the design loads accordingly. Therefore, the sequence of construction and the production rates are judged to be very similar to that for the existing design. The track framing does include some larger and smaller members with different connection details so it was thought that it may take longer to install each bay. But because the steel erectors will not have to install and connect to the system of suspended cables, the working height of the crane will be less, and the work will be much more repetitive.

From analysis of the existing design, it was observed that the production rates for erection of the columns, bracing, and track framing increased dramatically when the ends of the track steel were being installed. Initially the workers were able to install twelve columns and sixteen brace in two days. Near the end of the construction, in order to close up the other end, nine columns were installed in a day. During the majority of the construction the average daily production rates for each type of steel were: two to three trusses, two columns, four braces, and two bays of track framing. The average rates are significantly less than the rates of installing the ends of the track because the columns, braces, and track framing can only be put up as fast as the trusses are put up.

The average production rates were used to base the calculations to estimate how long the alternative design would take. Table 13 was a table used to develop an estimated time based on production rate and days of delay time.

Table 13: Estimated Alternative Schedule Durations

	average 2.5 trusses per day	average 4 braces per day	average 2 columns per day	average 2 bays of track a day	average 4 cables per day
Estimated Install Days	10	17	18	17	no cables
Days Start to Finish	14	17	15	15	no cables
Actual Install Days	10	12	10	10	no cables
Delay Days	4	5	5	5	no cables
Time for Alternative Design	14	19.5	19	18.5	no cables

The first row shows estimated install days. This was determined by dividing the quantities of that specific type of steel by the average daily install rate. For example, there are twenty five trusses and the installation rate is two and a half trusses per day. The result equals ten days to install the trusses. The next row is days start to finish. This value is the number of days it took from the first truss installed until the last truss was installed. The third row is the number of actual install days, this is the number of days where trusses were being installed and progress was made. The fourth row is delay days. The delay days are the second row less the third row. There are days where no progress was made due to weather, delivery delays, or maybe the workers were needed elsewhere to help catch up. These delay days were determined by looking at the time lapse photos and recording what days no steel was installed. The final row is the estimated number of days used to develop the alternative schedule. This number was derived by first taking the average of the estimated install days and the actual install days and then adding the number of delay days. These numbers are good estimates of the time it should take for installation. The numbers take into account the higher production rates at the beginning and end of construction and an average number of extra days due to delays. The calculated durations above (Table 13) were used to make a first draft of the schedule similar to the spreadsheet created for the existing design (Table 7). Instead of using the quantity of each type of steel installed each day, the durations were shaded-in with different colors (Table 14). Developing this spreadsheet helped to show all the activities in relation to one another. Seeing the activities in relation to each other helped to determine the start and finish dates of each activity.

Table 14: Alternative Durations Spreadsheet

		5 workers	7 workers	7 workers	7 workers	
		25 trusses	68 beams	36 columns	34 bays	
	Trusses on ground	Trusses	Bracing/Framing	Columns	Track Framing	Truss Bracing
23-Feb						
24-Feb						
25-Feb						
26-Feb						
27-Feb						
28-Feb						
1-Mar						
2-Mar						
3-Mar						
4-Mar						
5-Mar						
6-Mar						
7-Mar						
8-Mar						
9-Mar						
10-Mar						
11-Mar						
12-Mar						
13-Mar						
14-Mar						
15-Mar						
16-Mar						
17-Mar						
18-Mar						
19-Mar						
20-Mar						
21-Mar						
22-Mar						
23-Mar						
24-Mar						
25-Mar						
26-Mar						
27-Mar						
28-Mar						
29-Mar						
30-Mar						
31-Mar						
1-Apr						

A *Primavera* schedule was then established using the durations developed from the start and finish dates determined from Table 14. As seen in Figure 28 below, the alternative design is projected to take about five and a half weeks starting on February 23rd and completing on April 1st. It was assumed when making the *Primavera* schedule that the alternative design and the existing design have the same starting construction date (February 23rd). Including delay days the schedule predicts construction to be completed on April 1st; the construction may proceed faster due to better weather or more favorable production rates.

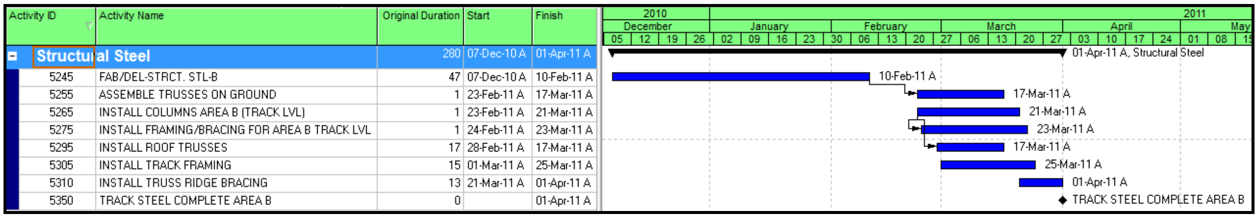


Figure 28: Alternative Schedule Primavera Screenshot

4.4 Creation of 4-D BIM for Alternate Design

The creation of the 4-D model followed the same "phasing" process that was followed in Section 3.5: Creation of 4-D BIM. We again created four phases for the alternative design based on the alternative schedule. The phases were created out of the model made by members of the group, not based from the Cannon model as it was no longer the same design. We took the phase snap-shots on the same dates as existing design, except for the last phase. Based on the schedule analysis, it was projected that the alternative design could be completed about a week before the existing if there are no delays. Even though this is unlikely, the last phase is shown on April 1st in the assumption that everything would be perfect. We kept all other phases on the same date for ease of comparison in the next chapter.

Table 15: Breakdown by Phase for Alternative Design

Breakdown by Phase				
Phase #	Date	%Complete	Steel	
			Tonnage	%Complete
1	3/7/2011	25%	21.05	11%
2	3/17/2011	50%	85.15	45%
3	3/27/2011	75%	146.4	77%
4	4/1/2011	100%	191.26	100%

Phase 1 is shown below for the alternative design on 3/7/2011. In Phase 1, one column bay has been completed, along with some of the track framing on the Morgan side of the building. In this Phase, 21.05 tons have been erected; that is 11% of the total steel.

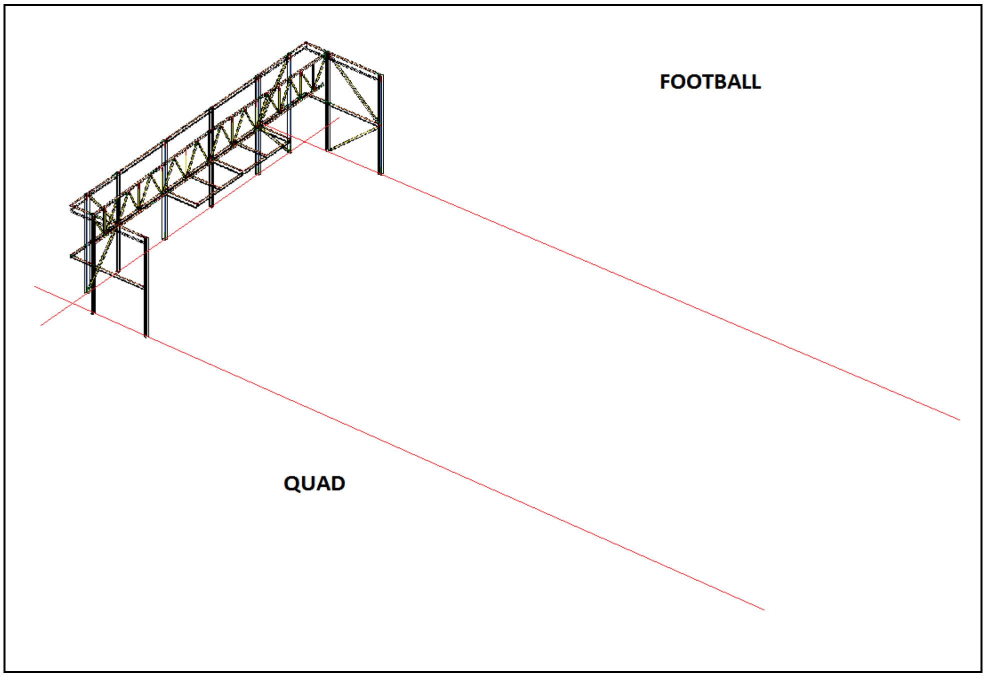


Figure 29: Phase 1 Alternative Design

Below, Figure 30 shows Phase 2 on 3/17/2011. This phase shows significant progress from the first phase. There is a total of 85.15 tons of steel erected; that is 45% of the total tonnage of steel and 34% more steel erected than was in Phase 1.

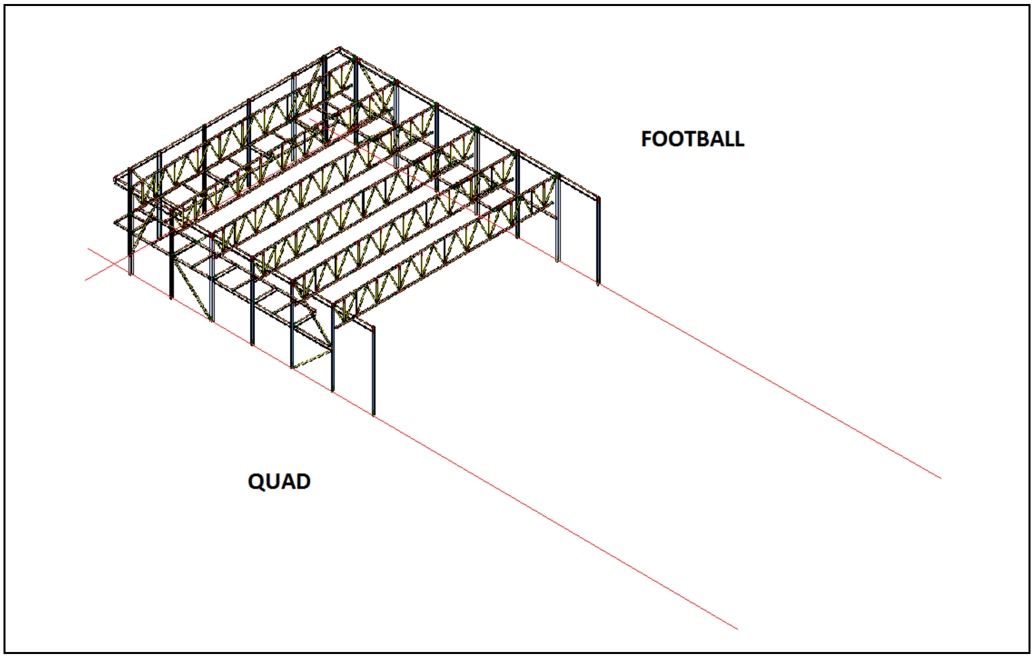


Figure 30: Phase 2 of Alternative Design

Phase 3 for the alternative design is right on track work-wise with the schedule. Phase 3 shows the track at 75% complete schedule-wise and work-wise it is 77% complete. Figure 31 shows Phase 3 as it is seen in the *Revit* model.

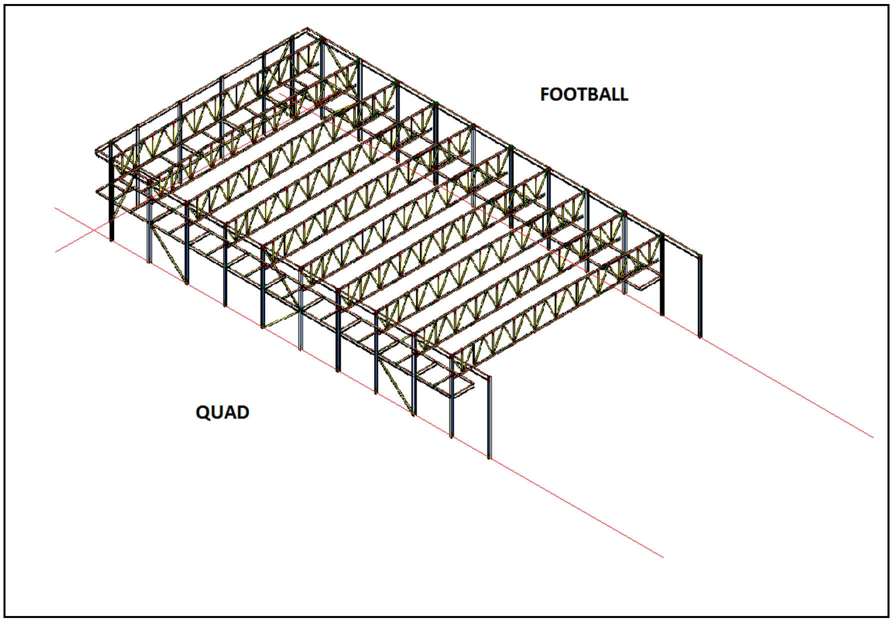


Figure 31: Phase 3 of Alternative Design

The last phase or “New Construction” is the alternate track at completed. This phase shows the final 27% of steel that had to be erected from Phase 3. The entire 191 tons of steel is erected and shown in Figure 32.

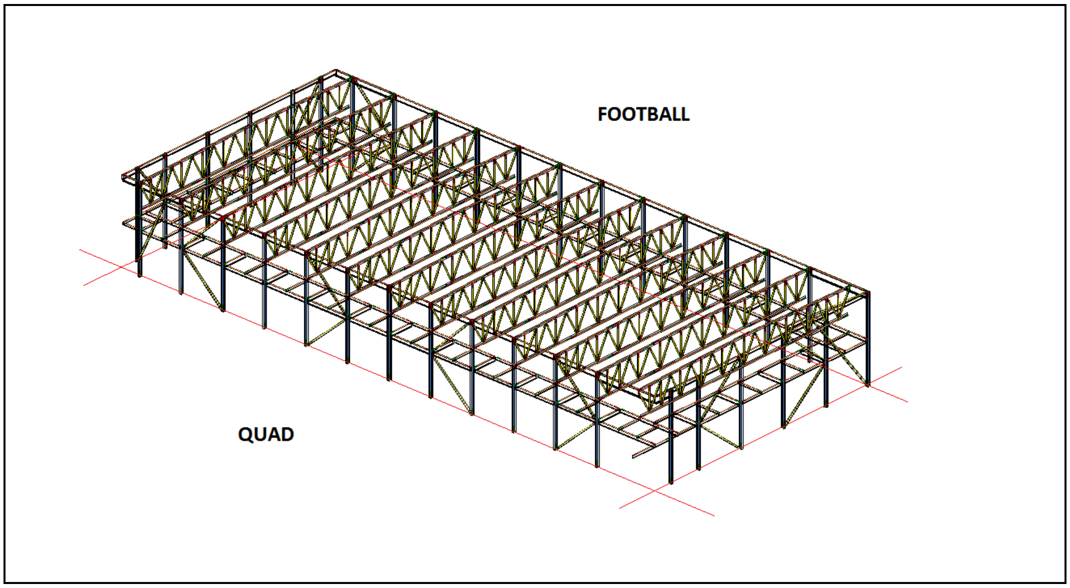


Figure 32: Completed Alternate Track Design

This phase is shown on 4/1/2011. As previously mentioned, if no delays occur the alternate design could take a total of five weeks to complete.

Chapter 5 - Evaluation/Analysis of Designs

Both designs were compared based on the evaluation and analysis of this project. This chapter will compare the designs based on the structural design, the cost differences, the schedule differences, and the differences found through the use of BIM.

5.1 Design Comparison

The main design differential between the two designs is the configuration of the structural supports for the track due to the elimination of the hanging supports. Eliminating the hanging supports caused an increase of weight on all portions of the track. Each component that was altered by the removal of the hanging supports was accommodated for the additional weight.

The main differences in the straight portions of the track were the lengths of the end beams to accommodate the revised framing, the creation of the cantilevers, and strengthening of girders between the columns. Figure 33 represents Cannon's configuration of the Football Side's straight portions which consists of hanging supports, end beams (which connect to the hanging supports at each set of end beams, parallel to the columns), perpendicular girders and supporting beams between each set of columns. The hanging supports were determined from the drawings to be HSS7x7x0.5 vertical supports which run parallel to the columns. The end beams were designed as simple beams and were configured to be W10x22 sections. Between each set of hanging supports, there are two W10x22 end beams supporting the track. The perpendicular girders span across each straight away and connect, connect each end beam to the columns or column beams; they were specified to be W10x19 sections. A series of W14x22 beams span between the columns and support the W10x19 girders.

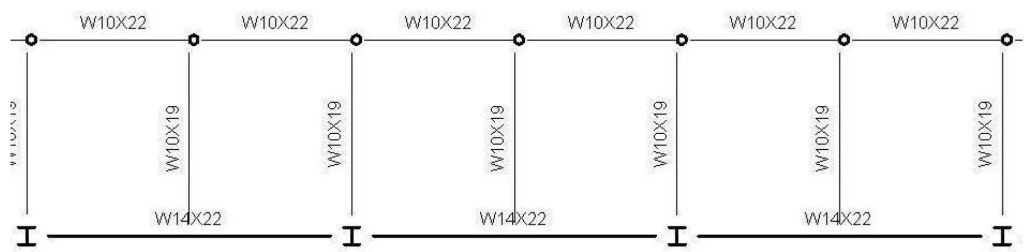


Figure 33: Existing *Revit* Design Football Side

As previously stated throughout the project, the main alteration to the design was the removal of the vertical hanging supports. A section of the alternative design is portrayed in Figure 34 which represents the straight portions of the track along the Football Side of the building; it is a revised version of Figure 33 for was of comparison. Most of the configuration is the same from the previous design except for the lengthening of the end beams from 9’8” to 19’4”. This minimized the number of cantilevers in the design and the overall moment on the columns. Since the end beams were lengthened, they pick up more dead and live load, and consequently the member size increased from W10x22 to W12x14 sections. The perpendicular girders that span the width of the track (the W10x19 sections in Figure 33) were converted into a system of cantilevers (at the column lines) and simple beams (between the columns). The cantilevers develop moments at the column faces from the various design loads for the track, and so the member sizes were increased from the existing W10x19 to W18x35. The perpendicular middle beams that were treated as simple beams did not carry much of a load because of the new design, so they were calculated to be W10x22s. Finally, a small decrease in loading occurred in the girders that span between the columns, and so their member size was reduced from W14x22 to W12x14. The section of the track along the football field is simplest portion because of the limited factors associated with the design. The other sides, such as the Quad side, have additional loadings which cause the scheme to be more complex. For example, the beams and columns along the Quad side of the track must also support an adjacent floor slab. Investigation into these other areas of the track can be referenced in Appendix H: Simple Beam Approach Hand Calculations.

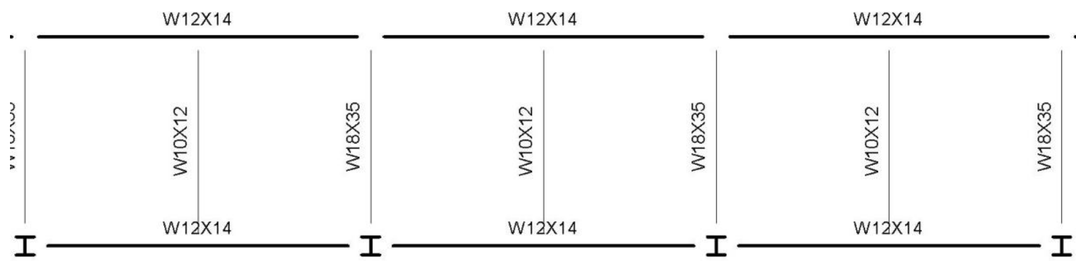


Figure 34: Alternative *Revit* Design Football Side

The four corners of the track can be classified into three sections: the Morgan side, the Football/ Softball side, and Quad/ Softball side. The Morgan corners of the track are mirror reflections of each other because they do not have additional factors affecting their design. Figure 35 presents the existing design from the Morgan side of the track which includes hanging supports.

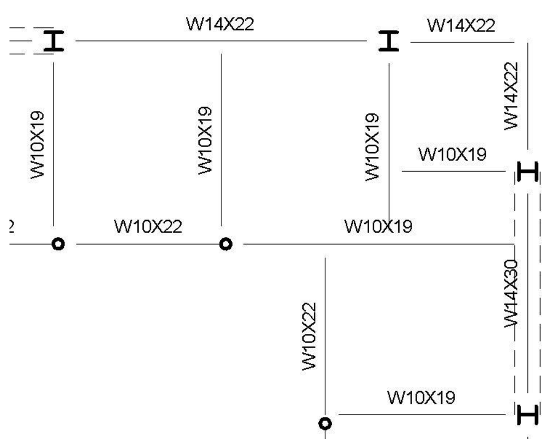


Figure 35: Morgan Corner of Existing Design

Figure 36 represents the alternative design configuration of the Morgan side of the track. Some of the aspects that have been altered from the existing design were the beam lengths of the long middle beam and the member sizes of all of the beams. Specifically, the middle beam was lengthened to minimize the cantilevers in the corner scenario, and the member sizes were all changed because the loading scheme had changed due to the elimination of the hanging supports. As mentioned before, Figure 36 is the simplest example of one of the four corners. The Football/ Softball corner and the Quad/ Softball have different configurations and can be reference in Appendix F: Corner Calculations.

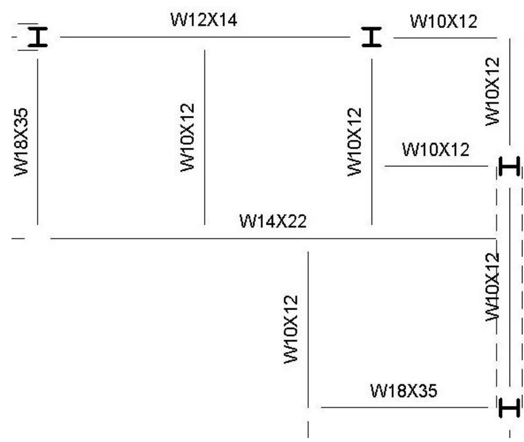


Figure 36: Morgan Corner of Alternative Design

The columns supporting the track remained the same size for every column surrounding the track. This was the one structural element that was not changed between the existing design and the alternative design. The existing column capacities were analyzed, and they were found to be sufficient to support the alternative track, including the moment effects from the cantilever beams.

These alterations to the design are only one component to the overall analysis of the track. Aspects such as the project cost and schedule still need to be analyzed and incorporated to understand which design has better components.

5.2 Cost Comparison

The two designs were compared based on the beam and girders, columns, and trusses. The alternative design proved to be 0.67% more expensive than the existing design that was created in this project. The beam and girders for the alternative design are about $6,000 more expensive. This slight increase in price is due to the cantilever members in the alternative design. Many of the beam sizes for the simple span beams decreased, but the cantilever member sizes increased greatly in many cases versus their counterparts in the existing design, causing an increase in price for the framing aspect of the design.

When the columns were analyzed, it was found that all of the columns in the existing building could remain the same because they have sufficient capacity to support the new design, including the combined effects of flexure and axial compression. A consideration of constructability was also a part of the motivation to keep the columns the same size as for the existing design. It was assumed that the existing column sizes were established to be convenient to fabricate and erect: many of the columns throughout the affected area are the same or similar in size. The trusses were also assumed to be adequate in strength because the hanger supports were removed from the loading on the trusses. For this reason, the costs of both the columns and the trusses remained the same. Below, Table 16 shows the comparison for the costs between each aspect of the alternative and existing designs. The boxes highlighted in yellow show the totals for each individual design.

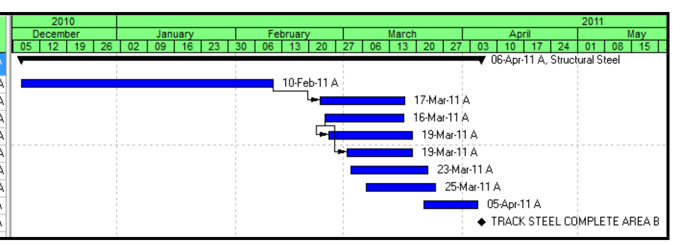
Table 16: Cost Comparison of Existing and Alternative Design

Existing Design			Alternative Design		
Cost Per Group			Cost Per Group		
Framing	Columns	Trusses	Framing	Columns	Trusses
$184,100	$174,200	$547,200	$190,000	$174,200	$547,200
Total		$905,526.37	Total		$911,513.83

As noted before, it can be seen that the difference in price is simply from the beams and girders. It is a difference of $5,987.46. Overall, that makes the alternative design .67% more expensive. In the overall scheme of the project, this difference of about $6000 is practically negligible as the total cost of the project is approaching $46.5 Million.

5.3 Schedule Comparison

While the manner in which the structural framing for the track supports the applied loads and its physical appearance have changed dramatically, the expected process for installation of the track and its supporting steel has not. Schedules of the existing and alternative design were developed to reflect estimated durations and the sequence of completion. Below, in Figure 37 and Figure 38, are the *Primavera* schedules which compare the two different designs. The designs followed similar sequences of installing approximately one column bay per day.



Activity ID	Activity Name	Original Duration	Start	Finish
Structural Steel		280	07-Dec-10 A	06-Apr-11 A
5245	FAB/DEL-STRCT. STL-B	47	07-Dec-10 A	10-Feb-11 A
5255	ASSEMBLE TRUSSES ON GROUND	1	23-Feb-11 A	17-Mar-11 A
5265	INSTALL COLUMNS AREA B (TRACK LVL)	1	24-Feb-11 A	16-Mar-11 A
5275	INSTALL FRAMING/BRACING FOR AREA B TRACK LVL	1	25-Feb-11 A	19-Mar-11 A
5295	INSTALL ROOF TRUSSES	17	02-Mar-11 A	19-Mar-11 A
5300	INSTALL TRACK CABLES	1	03-Mar-11 A	23-Mar-11 A
5305	INSTALL TRACK FRAMING	15	07-Mar-11 A	25-Mar-11 A
5310	INSTALL TRUSS RIDGE BRACING	13	22-Mar-11 A	05-Apr-11 A
5350	TRACK STEEL COMPLETE AREA B	0		06-Apr-11 A

Figure 37: Existing Design Schedule

Activity ID	Activity Name	Original Duration	Start	Finish
Structural Steel		280	07-Dec-10 A	01-Apr-11 A
5245	FAB/DEL-STRCT. STL-B	47	07-Dec-10 A	10-Feb-11 A
5255	ASSEMBLE TRUSSES ON GROUND	1	23-Feb-11 A	17-Mar-11 A
5265	INSTALL COLUMNS AREA B (TRACK LVL)	1	23-Feb-11 A	21-Mar-11 A
5275	INSTALL FRAMING/BRACING FOR AREA B TRACK LVL	1	24-Feb-11 A	23-Mar-11 A
5295	INSTALL ROOF TRUSSES	17	28-Feb-11 A	17-Mar-11 A
5305	INSTALL TRACK FRAMING	15	01-Mar-11 A	25-Mar-11 A
5310	INSTALL TRUSS RIDGE BRACING	13	21-Mar-11 A	01-Apr-11 A
5350	TRACK STEEL COMPLETE AREA B	0		01-Apr-11 A

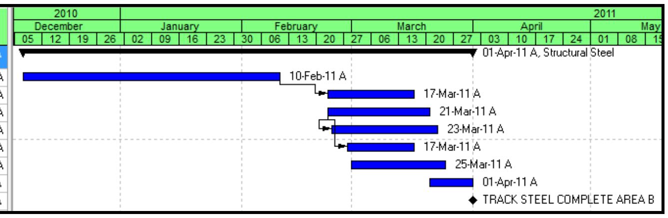


Figure 38: Alternative Design Schedule

Both constructions start out by installing the columns and bracing at the end closer to the Morgan dormitory. As the construction proceeded towards Harrington Auditorium, the sequence was to stay one bay of columns and bracing ahead of the erection of the trusses, and the installation of the track framing was assumed to follow a bay or two behind the trusses. The sequences for the existing and alternative designs are about the same because the design of the major structural steel members (columns and trusses) did not change dramatically. The difference between the two designs will principally emerge from the installation of the track framing itself. Figure 39 depicts the construction process by each phase. The left hand side shows how the existing design was constructed and the right hand side shows the alternative design. For each design, Phase 1 is on the top with all other Phases below it sequentially. The main thing to note in these figures is the difference in Phase 1. As mentioned before, the lack of suspension cables allowed for the track framing to be erected earlier and this is clearly shown in Phase 1 of the alternative design. Beyond Phase 1, the sequencing of the construction is very similar.

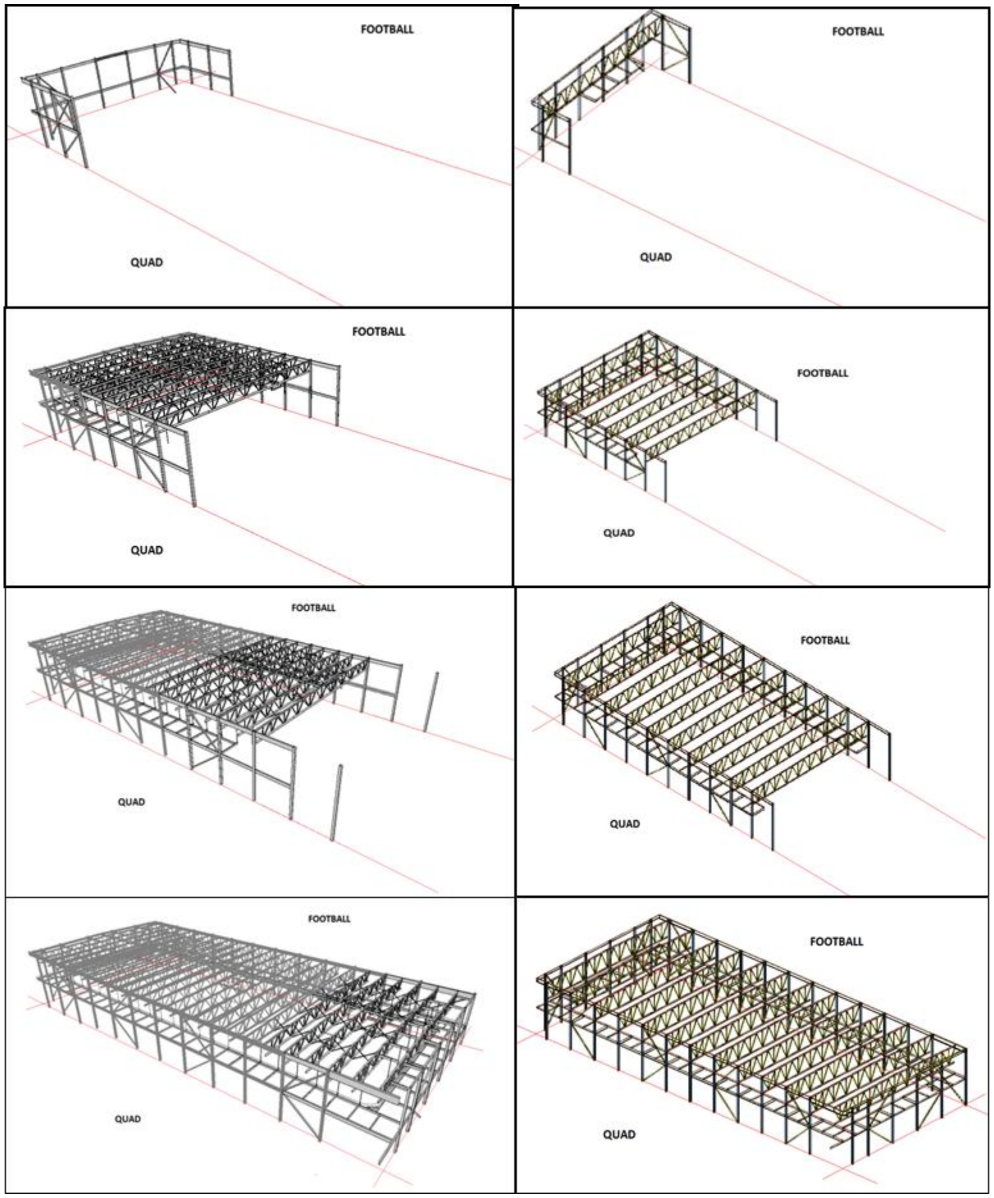


Figure 39: Phase Comparisons from Revit

Because the suspended cables are being eliminated from the existing design, the erection of the proposed alternative design should be a little faster for two or more reasons. First, the alternative should be faster to erect because the workers will not need to take a lift up to the level of the roof trusses to attach the cables. The second reason is because eliminating the cables will make the design more uniform and repetitious. Without the cables, erecting the track framing becomes the repetitive installation of beams, allowing the workers production to increase as they do more. With these anticipated changes in the erection process it would be expected that the alternative design would take a lot less time to install, but it does not. The reason it does not is because the track framing cannot be installed until the columns, bracing, and trusses are installed. For coordination purposes the track framing erection follows one or two column bays behind the erection of the columns, bracing and trusses. This sequence of erection assures the safety of the workers erecting the track framing so that no trusses are being flown in and erected directly above where they are working. Therefore, the track framing cannot be installed any faster than the trusses.

Both schedules were created with the same start date of February 23, 2011, and both ended near the beginning of April. The alternative design's completion date was projected at April 1, 2011. The actual existing design's completion date was April 6, 2011, which was estimated to have been delayed a few days due to snow, and a couple other days due to reasons not clear from looking at the time lapse photos. Because of the method used to project the durations of the alternative design the estimated time intervals allow for several delays due to unforeseen events. If the construction runs smoothly the alternative design could possibly be installed a week or two faster than the existing design. But, because the new design does not speed up the overall installation of the track significantly, the benefits of choosing the alternative design because of schedule are not overwhelming. With the track being installed earlier there is a chance that other trades such as plumbers and electricians could install there pipes and conduits underneath the track earlier. This could in turn allow them to start earlier on other projects, potentially shortening the entire project.

5.3.1 Phase Comparison through *Revit*

The other aspect of the schedule that could be compared through the *Revit* model was the percent completed in each phase. Table 17 below shows the information for the existing design on the left side and the alternative design on the right side of the table. The table shows the percent complete for Phase 1 as slightly greater because of the additional erected steel that was shown in Figure 39 of the previous section Table 17. Also, a final note to be made is that the final phase in the alternative design was also assumed to be completed under perfect conditions on 4/1/2011.

Table 17: % Complete by Tonnage and Schedule for Both Designs

Breakdown by Phase							
Existing Design						Alternate Design	
Steel		Date	Phase#	%Complete	Date	Steel	
Tonnage	%Complete					Tonnage	%Complete
20.49	7.50%	3/7/2011	1	25%	3/7/2011	21.05	11.00%
109.44	40%	3/17/2011	2	50%	3/17/2011	85.15	45%
179.82	66%	3/27/2011	3	75%	3/27/2011	146.4	77%
270.56	100%	4/6/2011	4	100%	4/1/2011	191.26	100%

The differences in the percentage complete for the other phases can be explained through looking at the difference in total tonnage for the existing and alternate design. Because the total tonnage is different, it causes the percentage complete of steel to be misleading. The percent complete by phase appears to vary significantly between the two designs, even though the figures and schedule show them to be more similar. The difference in these values can be accounted for by many things. First, it could be caused by human error. The original phases were made in the *Revit* model provided by Cannon. When creating these phases, the track construction was isolated from the rest of the building by deleting those members and analytical lines that were not considered relevant. Some of the analytical lines may have been missed, and consequently were added to our schedule quantities. Another variance is due to including the truss bracing in the schedules exported from the Cannon model. These brace members were not addressed in the scope of the project and were not included when the alternative design was modeled in *Revit.*

Overall, the *Revit* model supports the previous findings through the design, cost, and schedule in determining that the alternative design does not have any significant advantages or disadvantages in comparison to the existing design.

Chapter 6 – Conclusions & Recommendations

The focus of our results in this MQP was the comparative analysis between the existing and alternative designs. The design, cost, and schedule were analyzed to make determinations about each design against the other. The comparative analysis in this project was heavily dependent on different software programs such as *Revit, Robot,* and *Primavera.* These three programs were intended to help us create the design, cost estimate, and schedule for the alternate track support structure. The main focus was on *Revit* and *Robot*, and the integration of these programs into structural engineering and project management in a realistic project setting allowed for the potential uses in these technologies to be realized. The heavy reliance on software also put some constraints and difficulties on the project as well.

6.1 Recommendations Based on Comparisons

In creating an alternate design, the goal was to propose a structural solution that would still meet the same needs that the original track design was intended to meet. The alternate design was analyzed based on its structural capability, its cost, and its schedule. It was found that the alternate design was almost equivalent to the existing design in every way.

Structurally, the alternate option was designed to hold the same loads as the existing and serve the same purpose as an indoor walking/jogging track. Through the cost analysis, the alternate design was 0.67% more expensive than the system currently in place. Schedule-wise, the alternate design has the potential to finish 5 days sooner; this includes weather delays likely during the winter months and other unexpected happenings. By accounting for unexpected delays in the alternative schedule it allows for a chance that the construction could finish a few days earlier in the case of no delays.

Based on these findings, it can be determined that the final decision for the design could be based on the look, or aesthetic aspects as that is the main difference between the two systems designed. The suspended track provides a visible support system and the alternate design makes the track area more open to the space in Level 4 of the building. This is because the cables have been removed, removing the additional barrier should allow for a more open feeling. Below is a depiction of the track designs side-by-side. Although, Figure 40 does not show the railings for the track, it successfully shows the difference in the designs. With the cables removed in the alternative design the obstruction to the view of the courts below is eliminated.

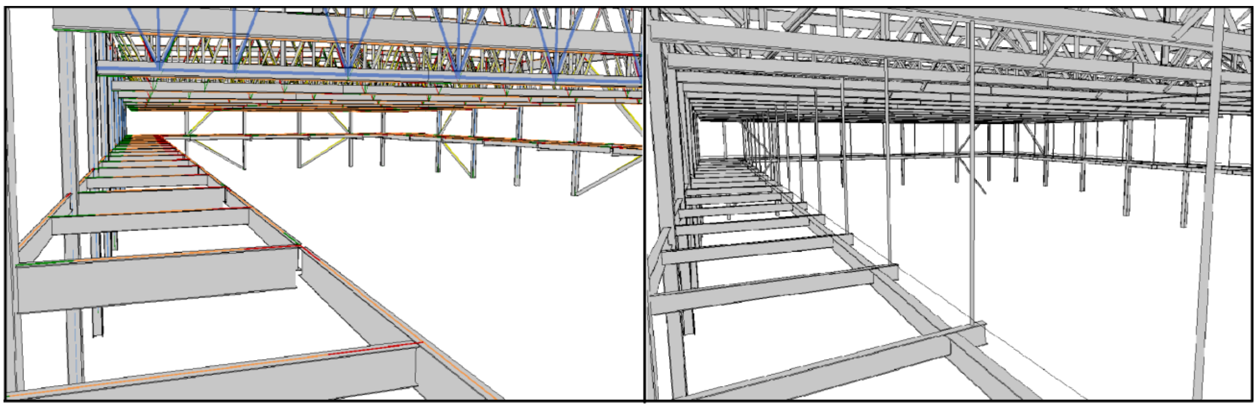


Figure 40: View Comparison

6.2 Utilization of Technology

Robot was originally intended to assist in the design of the alternate approach and help determine if the met strength requirements, as well as eliminate extensive calculations by hand and through *Excel*. *Robot* is a relatively new program for the WPI community and the MQP groups that used it this year were pioneering its use, which was a learning process. One of the constraints we found was that as a program, *Robot* was not very intuitive for a new user. The complexity of the program and the limited time frame for the MQP created a steep learning curve. Consequently the full intentions for use of the program were not realized, and alternative strategies were adopted to complete the structural design effort. For example, a separate plan utilizing hand calculations and *Excel* was put into place.

Revit was used as a means of creating a 4-D model for the project and researching the potential uses of Building Information Modeling (BIM). In the scope of this MQP, *Revit* was able to create a 4-D model by incorporating schedule items through the use of phasing in the program. In the future, BIM could be used to create a 5-D model by also incorporating cost into the model. This would allow for even more information to be available to the building users in the model. A 5-D model is not as common in construction as 4-D, but has potential to gain significant popularity.

In the process of creating and comparing the designs, cost estimates, and schedules, it was easy to see the potential for technology to play an even larger role in engineering and construction. In future MQP's the use of *Robot* can be built upon and used more effectively to take advantage of the great possibilities that the program has. Also, the exploration of creating a 5-D model would be interesting to study and to explore how that advancing technology can be integrated better decision making into the engineering and construction areas of a project.

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Appendix A: Project Proposal

GFS-1201
LDA-1201

WPI Recreation Center:
Track Alternative Design and Construction Management Software

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

Submitted By:
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Date: December 12, 2011

Abstract

The WPI Recreation Center has given students the opportunity to research alternative construction methods with a crossover of the new technologies in the construction and project management fields. This MQP investigates alternative support systems for the recreation center's suspended track and the effect it might impose on the roof structure with an emphasis on the integration of new software tools such as *Robot* and BIM (Building Information Modeling). The procedures show that a new support system for the track may impact and require a change to the entire roofing system, affecting the roof trusses and even cantilever canopies. As a result, all aspects of the alternative design must be investigated for structural integrity, but notably the programs, *Robot* and BIM, could be a valuable learning tool to use in academic settings and professional practices as well.

1 Introduction

Construction is an everyday activity that to a varying extend is part of our lives. The construction industry is continuously growing with new projects and the development of new infrastructures. Construction, especially in large-scale construction, is accomplished through multiple inter-disciplinary fields of work coming together to complete one project. Architects, structural engineers, project managers, and contractors are just a few of the many parties that can be involved in any project at one time. These parties come together and must work efficiently and collaboratively to design and build a facility based on the clients or owner's vision and that meets his/her needs.

Two major parties involved in construction projects are the design and project management teams. The design team usually includes architects and structural engineers, as well as other specialty engineers and design professionals. The architect works to take the owner's vision and provide a realistic design to meet the owner's demands. Structural engineers are responsible for the structural integrity of the project. Project managers are usually involved in construction, coordinating the involvement of supplies and trades, tracking the development of the project and assisting the owner throughout the entire project development process.

Worcester Polytechnic Institute has recently decided to undertake the construction of a new Recreation Center for its community. WPI has a great need for a new recreation center because its community of students, faculty, and staff has grown so much in the past five years the current facilities are no longer sufficient. The new Recreation Center is comprised of six levels including the roof. Some of the features that will be available in the new facility include an olympic-sized swimming pool, a four-court gymnasium, a suspended jogging track, a 14,000 square foot fitness center, multi-purpose spaces, a Robotics pit and new athletic personnel offices. This study investigates the structural implications for an alternative design of the fourth and fifth floors of the new Recreation Center.

The main functional uses of the fourth and fifth floors of the design contain the four-court gymnasium and the suspended track. The suspended track is supported by vertical supports hanging down from the roof trusses and attaching to the sides of track. This study will also investigate the alternative design to the current suspended track using project management principles as well. An evaluation of the loading changes of the alternative design affecting the roofing system and cantilever canopies will also be completed, as well as a cost analysis and schedule comparison of the alternative design compared to the current model.

To facilitate integration of the structural and project management aspects of the project, computer-aided engineering tools will be utilized. *Autodesk Robot Structural Analysis (Robot) and Autodesk Revit Structures (Revit)* are the computer-aided tools that will be used. *Robot* will be utilized for structural analyses of the alternative design and *Revit* will be used as a platform for Building Information Modeling (BIM). BIM is a technology-based collaborative approach that many project managers have implemented to track schedules, costs and provide a 3-D model of the proposed project. This study will create a 3-D representation of the alternation design integrated in the Recreation Center utilizing BIM.

2 Background

The background section discusses WPI's need for a new Recreation Center and explains the structural, project management, and technological roles in construction. The background section further covers the current state of the WPI Recreation Center and the specific technologies that will be used throughout this project as an aid. The structural portion elaborates on the potential alternative designs for the suspended track. The project management section explains how the schedule and costs are used in the field of construction. Lastly, new advancements in technology provide aid for both the structural and project management fields.

2.1 Recreation Center

Worcester Polytechnic Institute has a need for a new recreation center to serve the needs of the general community on campus as well as the varsity sport teams. WPI is an active community, and the current facilities do not meet the needs of the population they serve. WPI's current recreation facilities consist of Harrington Auditorium and Alumni Gym. WPI primarily uses Harrington Auditorium, built in 1968, for varsity basketball games, and other gatherings such as career fairs, guest speakers, Robotics competitions, and varsity practices. Due to the large amount of space in Harrington Auditorium it is usually occupied by large events as described above, thus there is little to no free time for the general community to use it for recreation. Alumni Gym was built in 1916, and is currently out of date, but is used frequently by the WPI community. Alumni Gym has a small basketball court with a suspended wooden track around the upper level of the court. There is also a small swimming pool only 20 yards long and a weight room that does not meet the needs of the WPI community. These spaces have been over used for many years and with the increasing population of students, and employees at WPI, the need to expand is highly overdue. The overlap of activities and competition for space reservations, along with the increasing student population has become a large issue, and to relieve some of the difficulty, the university has decided to construct a new recreation center. Its main attractions will be an Olympic-size pool, personal fitness area, and a multipurpose gymnasium which includes four basketball courts, track and field accommodations, a suspended track, and robotics pit.

This project will specifically look into levels four and five of the recreation center which houses the multipurpose basketball courts, the suspended track, roofing system, and cantilever canopies. Each of these aspects has its own unique purpose which contributes a distinct and important function to the center. The multipurpose basketball courts consist of two wood courts, with an overlapping third, and two "Mondo" basketball courts that can accommodate practices for varsity team sports including softball, baseball, and track. The suspended track is a three-lane jogging track which is intended for indoor track practices and faculty and employee enjoyment. The track is connected to the roof trusses which support the track and all components of the roof, including the HVAC equipment, wind loads, snow loads, and cantilever canopies.

2.2 Structural Evaluation

The design of constructed facilities has many components, and structural engineering is one of the primary disciplines. Structural engineers strategically determine the correct configurations, members, and members sizes to minimize costs. Their main objective is ensuring the structural integrity of the building to withstand varying live and dead loads. They are professional engineers who put their stamp of approval on the final design before it is built, assuming full responsibility for structural performance and the accuracy of the structural drawings and specifications.

2.2.1 Suspended Track System

The current suspended track is located on the fifth level of the recreation center. It is supported by vertical hangers that attach from the roof truss to the outside edges of the track. The track surface is made up of a material called “Mondo”. Mondo is a type of rubber flooring used for multipurpose athletic flooring. The suspended track was designed for walking and jogging purposes only. Dana Harmon, WPI’s athletic director, clarified that the track was not made for excessive running but more for the lifestyle of the WPI community (Harmon, 2011). The intent of the track was geared towards general recreation use which had an impact on the design including the structural support system.

2.2.1.1 Support Systems

There are many different support systems that could be implemented into the Recreation Center as an alternative design to the suspended track, and each alternative has unique qualities that contribute to the reason for its installation. The building was designed to be visually pleasing as well as functional. Various restrictions with the building may apply when altering the suspended track. Support systems can range from simple column supports as a sort of simple post-and-beam system to complex trusses to cantilever beams.

2.2.1.1.1 Column Supports

Columns are commonly used support systems that can be beautifully decorated to match the décor of a building. Structurally, columns are one of the most effective compression members that can range in height, shape and width (ASDIP, 2011). Column members are defined as vertical elements whose length is nominally larger than their width and are usually composed of steel or concrete. Looking at an efficient use of materials to reduce costs steel is normally used in larger buildings because of the various shapes and sizes options. If the columns are composed of steel, their shape can range from W-shape to HSS-rectangular and even C-shape which can also be encased in concrete for added strength and fire resistance (AISC, 2010).

Some advantages to using columns are their simplicity and the minimal amount of labor they require to install. Also, the various design shapes mentioned above make this support system versatile and effective. Columns can also be easily hidden in walls or kept in the open to maintain an ambiance. One major disadvantage to columns is their unavoidable obstructionist presence in large open spaces. They can obstruct viewing and/or pose as a hazard to the flow of people when constructed in large areas such as swimming pools and basketball courts.

2.2.1.1.2 Trusses

Trusses are an assortment of members strategically composed into a structurally sound shape to withstand a large amount of force. There are many different configurations that can be used when designing a truss and each arrangement has advantages for different loading types. Also, when considering each configuration, the member size and shape can be altered to compensate for each specific case. Just like a column, a truss can be aesthetically constructed to match the décor of a building or it can be concealed behind ceilings or walls.

Some advantages to a truss are the optimization of space, the use of small and lighter members when constructed, and ability to span long distances without intermediate support. In some cases, the aesthetic appeal of a metal truss system can create a certain environment in a building. One major disadvantage of a truss is the inability to be concealed without reducing the space of a room especially when they are relatively large. Additionally, the amount of labor associated with the construction of each individual truss can be very costly especially when associated with a large project like WPI’s Recreation Center. The investigation of a cantilever system has some of the same advantages of the truss system, while also minimizes its disadvantages making it one of the most reasonable alternatives.

2.2.1.1.3 Cantilever Beams

A cantilever beam is singular piece of steel that is anchored at only one end, but extended outward to support a downward force. Cantilevers can be composed of various sized beams chosen to be large and strong enough to support the track, yet small enough to conserve money. They can also range in shape, from W-shape to HSS-rectangular, and even C-shape similar to a column support. Cantilever beams can also be constructed with trusses and slabs, but in this particular scenario we will be referencing simpler cantilever systems. Cantilever beams are fabricated by a steel fabricator with specific measurements defined by a structural engineer that support the specified area with the most strategic beam size.

The main advantage to implementing a cantilever system is its simplicity of design and installation, and its ability to be concealed easily by walls and ceilings. Since this system is mainly composed of a series of relatively large, thick beams, the price of these beams may be a large disadvantage. Another disadvantage of these beams is accommodating for fixed-end moments in the supporting elements of the structure.

Knowing all the components of every possible alternative for a problem such as this is very beneficial. The best solution can be found when each choice is analyzed and compared to the need of the project. Other components to consider for the track other than the structural design are the materials that make up the track. Table 1 below summarizes the attributes of each proposed support system.

Table 1: Track Support System Feasibility

Support System	Utilizes Space	Easily Concealed	Easily Installed	Cost Effective	Feasible
Suspension	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Columns	No	No	Yes	Yes	No
Trusses	Yes	No	No	No	No

Cantilever	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

2.2.1.2 Materials

One major component of our project and construction management in general, is the cost analysis of all methods and materials used. When selecting materials it is crucial for the designers to use the lowest costing materials without compromising structural integrity while complying with all specifications. The current proposed track is composed of W10x19 girders and W10x22 joists with three lanes of Mondo flooring, a railing to prevent users from injury, and other basic materials used to encase the unit. The materials that are used in the current track design could be carried over to the new proposed track, but an investigation into structural design configuration as well as structural materials could save the owner extra money.

2.2.1.3 Track Activity Accommodation

Another component to analyze when creating the jogging track is to consider the various activities that track will endure. This pertains not only to the live and dead load of the track, which is associated with its construction, but with the maximum load that the track can be expected to sustain with certain activities. As mentioned previously Harrington Auditorium holds large events such as the career fair and Colleges Against Cancer's *Relay for Life*. Extreme loading cases should be considered because of the potential for a large number of people to walk around the track. One must investigate topics such as these to identify the maximum capacity of the current and proposed system to insure the safety of all users. The in-depth study of the construction and materials leads into the next important aspect of the Recreation Center, the roof system.

2.2.2 Roofing System & Cantilever Canopies

The Recreation Center's current roofing system is a series of thirteen trusses designed to support the suspended track, all the equipment on the roof, a portion of the cantilever canopies, and all variable live loads normally associated with building roofs such as snow load and wind load. The current roofing system has been designed by professionally licensed structural engineers to safely support all components mentioned above, but if our project alters one component it may be necessary to reanalyze the proposed truss. This design, which has been created by Cannon, the Architect on Record for WPI's Recreation Center Project, is presented in Figure 1. This project's new proposed support system for the track may impact all structural supports at the fourth and fifth level, and it will be necessary to reanalyze these components to insure the safety and integrity of the building. One unique aspect of the Recreation Center's roofing system is the cantilever canopies that extend from the edge of the roof. These distinctive components not only need to be reanalyzed if a new system is implemented, but their many uses will be researched further throughout our project.

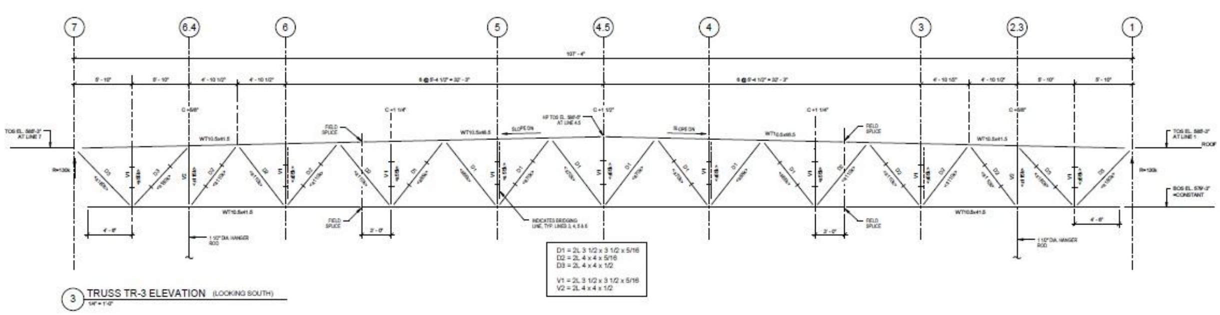


Figure 1: Cannon's Structural Truss

The canopies are awning-like structures that extend 8'-3" from the edge of the roof and are attached to the spandrel beams and roof trusses to create an aesthetic appeal for the building. Because the building is a giant box shape the cantilever canopies create a more vibrant look. After talking to a representative from Cannon, the canopies are intended to lure the viewer into thinking the building is more dynamic (Cannon, 2011). With the installment of the canopies, the viewer looks at the whole building, making the building seem much more animated. The representative also mentioned that the canopies will help to reflect more sunlight into the building during the day, and at night the lights will reflect off the canopies making the building light up more. The canopies are angled upward to help keep everything sloping into the building for safety purposes. As mentioned previously, the roof trusses may change and an investigation into the effects of the canopies on the supporting structural members will be conducted throughout the methodology sections. Figure 2 below shows the current plans for the suspended track.

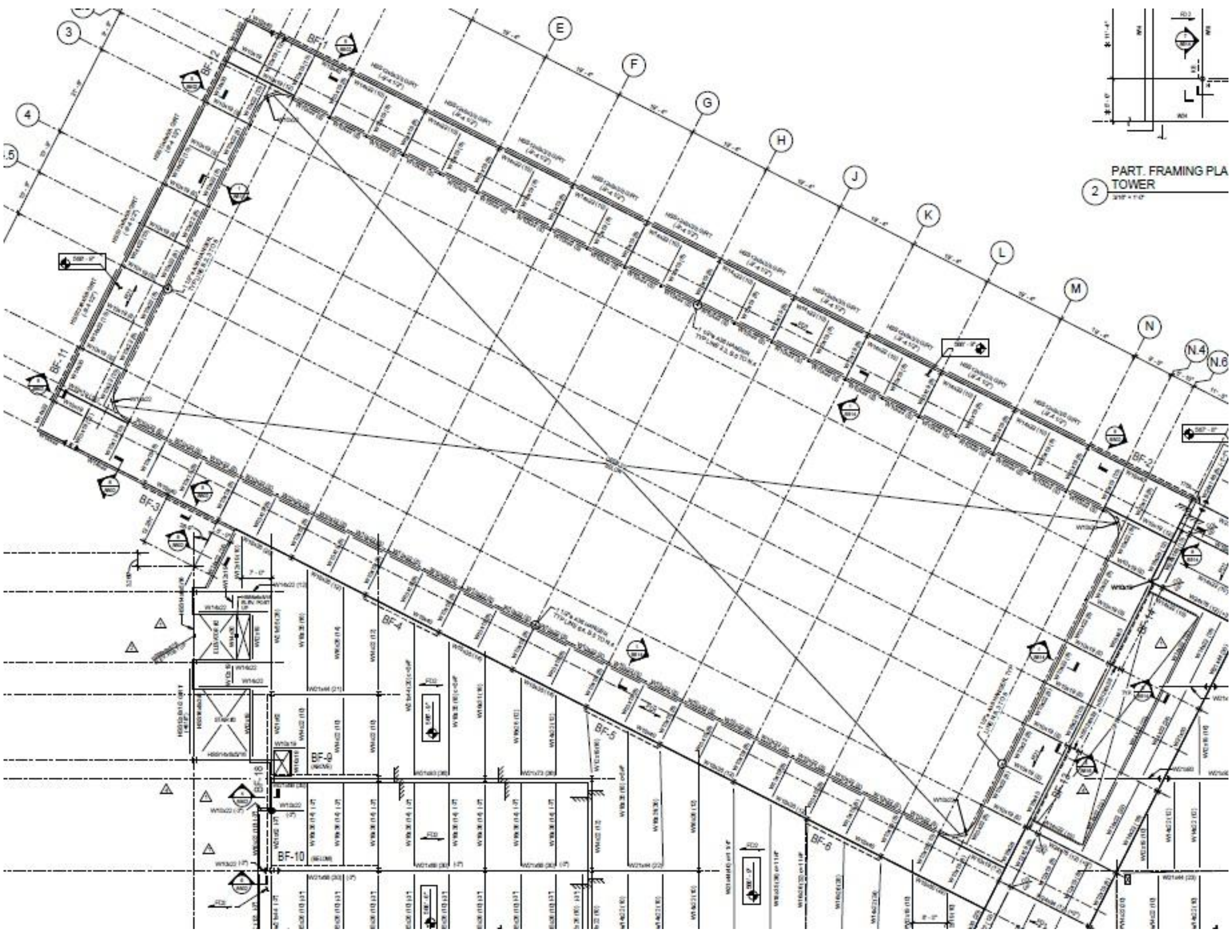


Figure 2: Current Suspended Track

2.2.3 Massachusetts Building Code

For every construction project and structure design there are a set of standards in place by the state to ensure safety. For the state of Massachusetts, there is a state building code which is supplemented with the *International Building Code* (IBC) provisions. The purpose of the IBC is to ensure safety of buildings by setting limits on design values for the structure design (IBC, 2009). Our project code will be consistent with the state of Massachusetts Building Codes (Mass.gov, 2011).

2.3 Project Management

Project Management is defined as the art and science of coordinating people, equipment, materials, money and schedules to successfully complete a project (Oberlender, 2000). Many owners find it difficult to manage construction projects because they don't have the expertise, or they don't have the time to successfully oversee the entire construction process. For this reason, owners seek help in construction management (CM) firms. CM firms typically provide pre-construction services as well as coordinating construction throughout the duration of the project. In the state of Massachusetts, it is necessary that public projects are advertised and bid on. This ensures that these projects are obtaining the proper supervision that they need (Sullivan, 2011). These firms provide experience and knowledge that an owner may be lacking. The CM uses their expertise to help the owner throughout the design and construction of their building. Hiring a CM allows the owner to be involved, but maintain their responsibilities outside of the project, as well as ensuring that the project is properly overseen by the CM.

In the case of the WPI Rec Center, WPI, as the owner enlisted the help of an Owner's (WPI) representative in Cardinal Construction. They represent WPI as the liaison between the architect (Cannon Design) and the CM at Risk (Gilbane). WPI sought help for many reasons. One of which was that Cardinal has expertise in construction that very few, if any, WPI employees have. Also, there is no one on the WPI staff that has the necessary time to devote to fully managing a construction project. If an employee were to take on this responsibility, they would have to drop all other responsibilities that they normally have. WPI has appointed a project manager within the staff at WPI to oversee the whole project. For the Rec Center, WPI has chosen Alfredo DiMauro to be the project manager and he works with other operations managers to add their input and oversee the construction on behalf of the campus. All of these teams of people come together to successfully bring a product that the campus will be happy with.

2.3.1 Schedule

Scheduling is one of the most important functions related to project management. When a project is contracted to a Construction Management firm, a completion date is set. Maintaining a schedule that is constantly updated ensures that the completion date is always in sight for the CM. A schedule not only ensures the completion date is achievable but it has many other valuable attributes for a project.

In order to make an accurate schedule and keep it up to date, most CM firms have an employee who is dedicated solely to keeping track of the schedule. It is that person's job to make sure that the schedule constantly reflects what has already happened in the field, as well as to create an accurate projection of what is going to happen in the immediate and distant future. When beginning a project, the scheduler creates a base schedule, but as more details are learned and subcontractors for each trade are on board, the schedule can become much more accurate. Each subcontractor submits their own schedule, and it is the job of the CM to input that individual schedule into the master schedule. Gilbane completes what is called a "card trick." In this method of creating an overall schedule, a CM brings in a representative from each subcontractor so that everyone can create the schedule together. This allows for everyone to be in the same room and visually see how the schedule is going together and it gives each person a chance to have an input. This helps to avoid coordination problems in the future because they are handled those problems at the very beginning. It is also the job of the scheduler to sort through the schedule to ensure that the logic behind the sequence of activities continues to make sense. When the project gets moving, the scheduler continuously updates the schedule and reviews its logic to guide the project to successful completion. In the case of the Recreation Center, Gilbane has a scheduler that generally comes in monthly to update the schedule. He gathers information from the members of the project team that are on-site every day and updates the schedule based on the information he receives from them.

There are many different software programs that can be used to create a schedule, but *Primavera* is one of the most commonly used (The Bright Hub, 2011). *Primavera* is capable of tracking all the important aspects to a schedule that were mentioned above, such as duration to each activity, a cost, as well as the relationships between each activity. *Primavera* also is capable of tracking different aspects of the project besides schedule, such as cost, contracts, risk management and document control items. It can do all of these tasks because the software is capable of integrating with other programs such as *E-business* suite and *JD Edwards Enterprise One* (Oracle, 2011). For contracts, it can track the contract summary to date, change orders, and payment processing rates. Pertaining to risk management, the software can calculate confidence levels based on pitfalls commonly associated with the activities within the schedule and predefined risk factors that are incorporated in the software. For document control, it can help monitor communication processes such as RFI and submittal turnaround rates, the number of issues resolved and unresolved, and different actions that must be taken to keep the schedule on time (Oracle, 2011). Because of all the benefits that *Primavera* has to offer, it is of great use for many projects.

Below, an example of a *Primavera* schedule can be seen in Figure 3 (Gilbane, 2011). On the left side of this figure is the list of activities. The activities are broken down by different scopes of work (Design and Engineering, Procurement, Sitework, etc.). On the right side of the figure, the duration of each activity is displayed by a horizontal bar that relates to the date the work will be starting on the top of the screen. Red activities are critical path items and green bars are all other activities. One more thing that can be identified in the figure is the vertical blue line that is running through the right side of the figure. This vertical blue line represents the current date. The presence of this vertical blue line helps each person who views the schedule to comprehend where the project currently stands.

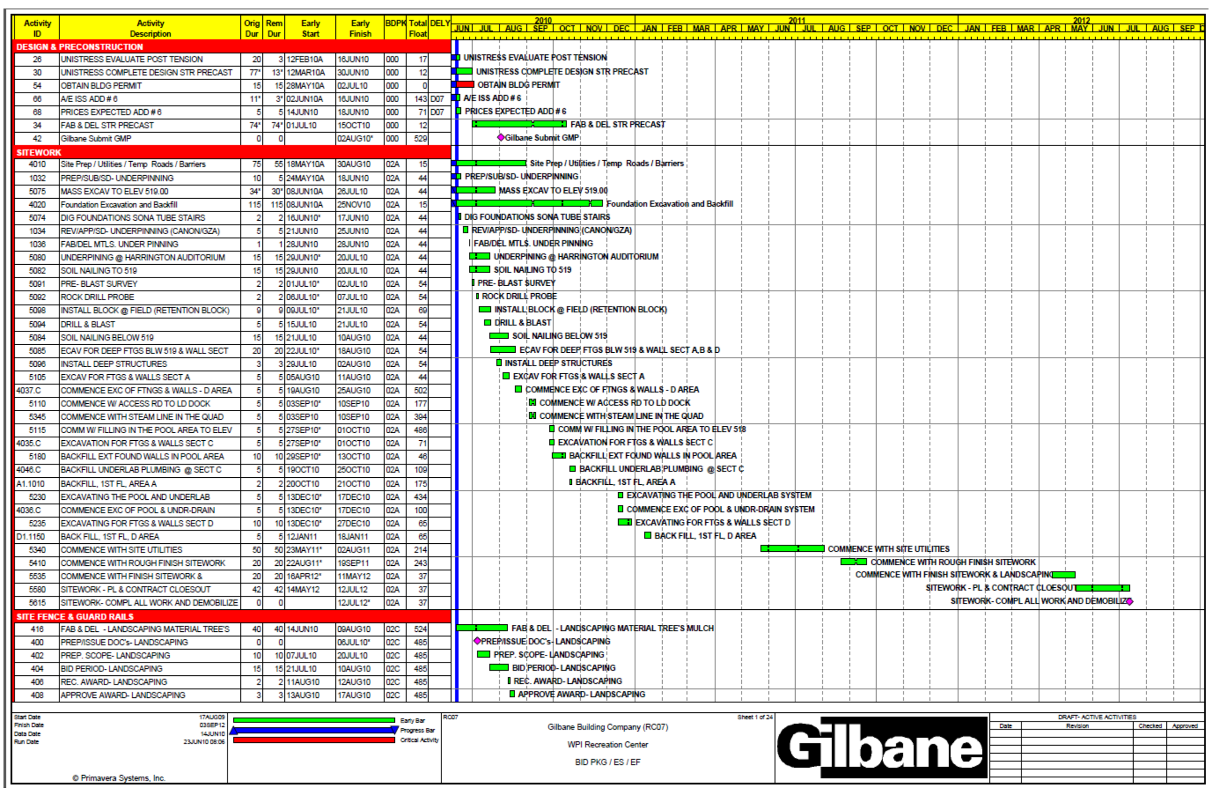
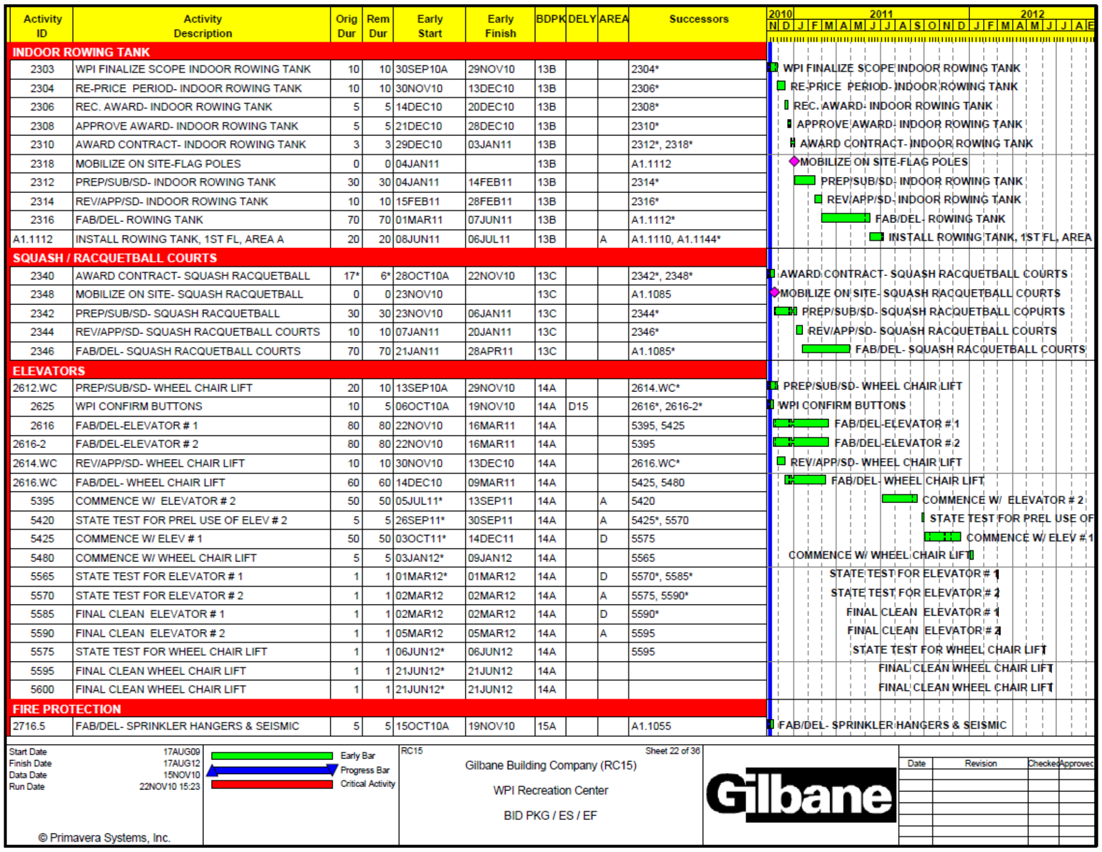


Figure 3: Primavera Schedule for Recreation Center (Gilbane, 2011)

Many schedules implement the Critical Path Method (CPM). The CPM identifies a chain of connected activities within a schedule that have zero float time. In order for the project to complete on time, the critical activities must finish on time. If these activities do not get completed on time, the completion date will be pushed out (Oberlender, 2000). Float is another important aspect of a schedule. Float can be defined in two different ways: total float and free float. Total float is number of days that an individual activity can be delayed without affecting the final completion date of a project. Free float is the number of days that an activity can be delayed without affecting the earliest start time of the activity linked immediately after it in the schedule. Quantifying and monitoring both of these float values are important, especially total float. When the total float of an activity is exceeded, the activity has the potential to become a critical activity and affect the overall schedule. An example of this can be found in the figures below. Figure 4 displays a schedule that was created in November 2010. In this figure, it is clear that the mobilization for the squash and racquetball courts, activity 2346 "Fab/Del – Squash Racquetball Courts" is set for November/December 2010. In this schedule, the mobilization and the succeeding activities are not critical. Activity 2346 is a green bar, which is called an Early Bar. This indicates that the dates shown in Figure 4 are the earliest that these activities will begin. In reality, they could begin later, due to their float time, and still finish without impacting the overall schedule. Also, a schedule displays the relationships that have been established between the activities. In the column labeled "Successors," numbers are displayed for each activity in the respective row, these numbers represent other activities in the schedule that are going to succeed the activity whose row they are in.

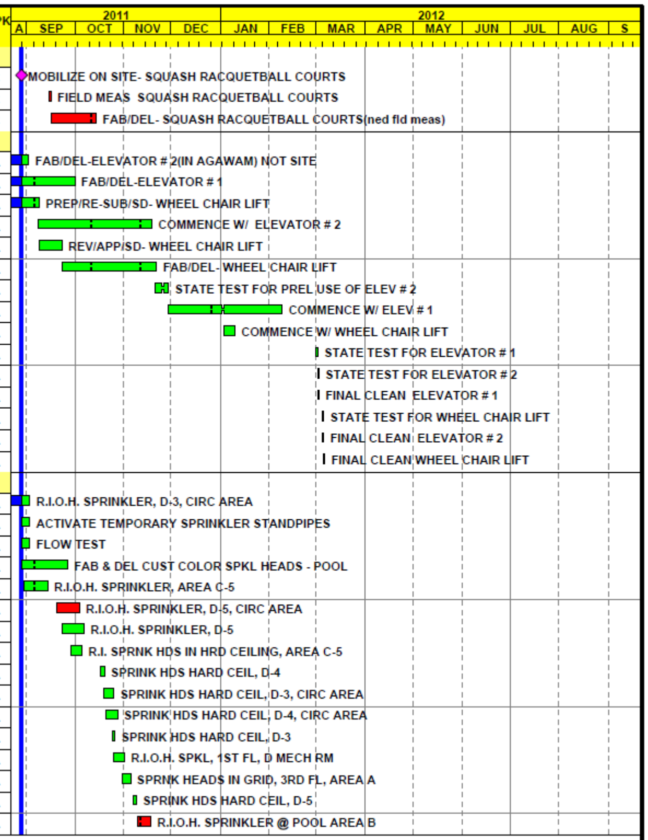


Activity ID	Activity Description	Orig Dur	Rem Dur	Early Start	Early Finish	BDPK	DELY	AREA	Successors
INDOOR ROWING TANK									
2303	WPI FINALIZE SCOPE INDOOR ROWING TANK	10	10	30SEP10A	29NOV10	13B			2304*
2304	RE-PRICE PERIOD- INDOOR ROWING TANK	10	10	30NOV10	13DEC10	13B			2306*
2306	REC. AWARD- INDOOR ROWING TANK	5	5	14DEC10	20DEC10	13B			2308*
2308	APPROVE AWARD- INDOOR ROWING TANK	5	5	21DEC10	28DEC10	13B			2310*
2310	AWARD CONTRACT- INDOOR ROWING TANK	3	3	29DEC10	03JAN11	13B			2312*, 2318*
2318	MOBILIZE ON SITE-FLAG POLES	0	0	04JAN11		13B			A1.1112
2312	PREP/SUB/SD- INDOOR ROWING TANK	30	30	04JAN11	14FEB11	13B			2314*
2314	REV/APP/SD- INDOOR ROWING TANK	10	10	15FEB11	28FEB11	13B			2316*
2316	FAB/DEL- ROWING TANK	70	70	01MAR11	07JUN11	13B			A1.1112*
A1.1112	INSTALL ROWING TANK, 1ST FL, AREA A	20	20	08JUN11	06JUL11	13B		A	A1.1110, A1.1144*
SQUASH / RACQUETBALL COURTS									
2340	AWARD CONTRACT- SQUASH RACQUETBALL	17*	6*	28OCT10A	22NOV10	13C			2342*, 2348*
2348	MOBILIZE ON SITE- SQUASH RACQUETBALL	0	0	23NOV10		13C			A1.1085
2342	PREP/SUB/SD- SQUASH RACQUETBALL	30	30	23NOV10	06JAN11	13C			2344*
2344	REV/APP/SD- SQUASH RACQUETBALL COURTS	10	10	07JAN11	20JAN11	13C			2346*
2346	FAB/DEL- SQUASH RACQUETBALL COURTS	70	70	21JAN11	28APR11	13C			A1.1085*
ELEVATORS									
2612.WC	PREP/SUB/SD- WHEEL CHAIR LIFT	20	10	13SEP10A	29NOV10	14A			2614.WC*
2625	WPI CONFIRM BUTTONS	10	5	06OCT10A	19NOV10	14A	D15		2616*, 2616-2*
2616	FAB/DEL-ELEVATOR # 1	80	80	22NOV10	16MAR11	14A			5395, 5425
2616-2	FAB/DEL-ELEVATOR # 2	80	80	22NOV10	16MAR11	14A			5395
2614.WC	REV/APP/SD- WHEEL CHAIR LIFT	10	10	30NOV10	13DEC10	14A			2616.WC*
2616.WC	FAB/DEL- WHEEL CHAIR LIFT	60	60	14DEC10	09MAR11	14A			5425, 5480
5395	COMMENCE W/ ELEVATOR # 2	50	50	05JUL11*	13SEP11	14A		A	5420
5420	STATE TEST FOR PREL USE OF ELEV # 2	5	5	26SEP11*	30SEP11	14A		A	5425*, 5570
5425	COMMENCE W/ ELEV # 1	50	50	03OCT11*	14DEC11	14A		D	5575
5480	COMMENCE W/ WHEEL CHAIR LIFT	5	5	03JAN12*	09JAN12	14A			5565
5565	STATE TEST FOR ELEVATOR # 1	1	1	01MAR12*	01MAR12	14A		D	5570*, 5585*
5570	STATE TEST FOR ELEVATOR # 2	1	1	02MAR12	02MAR12	14A		A	5575, 5590*
5585	FINAL CLEAN ELEVATOR # 1	1	1	02MAR12	02MAR12	14A		D	5590*
5590	FINAL CLEAN ELEVATOR # 2	1	1	05MAR12	05MAR12	14A		A	5595
5575	STATE TEST FOR WHEEL CHAIR LIFT	1	1	06JUN12*	06JUN12	14A			5595
5595	FINAL CLEAN WHEEL CHAIR LIFT	1	1	21JUN12*	21JUN12	14A			
5600	FINAL CLEAN WHEEL CHAIR LIFT	1	1	21JUN12*	21JUN12	14A			
FIRE PROTECTION									
2716.5	FAB/DEL- SPRINKLER HANGERS & SEISMIC	5	5	15OCT10A	19NOV10	15A			A1.1055

Figure 4: November 2010 Schedule (Gilbane, 2011)

Figure 5 displays a schedule that was created in August 2011 is shown. CM firms often update their schedules monthly to ensure that it is accurate and is reflecting what is happening in the field. At the top of this figure, the schedules regarding the squash and racquetball courts are displayed. These activities were pushed until August 2011, and this made activity 2346, as well as the other activities regarding the courts critical path activities. Critical path items are displayed in red; both “Fabrication/Delivery – Squash/Racquetball Courts” (2346) and “Field Measurements of Squash/Racquetball courts” (2345) are critical activities.

Activity ID	Activity Description	Rem Dur	Early Start	Early Finish	BDPK
SQUASH / RACQUETBALL COURTS					
2348	MOBILIZE ON SITE- SQUASH RACQUETBALL	0	29AUG11		13C
2345	FIELD MEAS SQUASH RACQUETBALL COURTS	1	15SEP11	15SEP11	13C
2346	FAB/DEL- SQUASH RACQUETBALL COURTS(ned	20	16SEP11	14OCT11	13C
ELEVATORS					
2616-2	FAB/DEL-ELEVATOR # 2(IN AGAWAM) NOT SITE	4	26MAY11A	01SEP11	14A
2616	FAB/DEL-ELEVATOR # 1	24*	26MAY11A	30SEP11	14A
2612.WC1	PREP/RE-SUB/SD- WHEEL CHAIR LIFT	8	18JUL11A	08SEP11	14A
5395	COMMENCE W/ ELEVATOR # 2	50	08SEP11	18NOV11	14A
2614.WC1	REV/APP/SD- WHEEL CHAIR LIFT	10	09SEP11	22SEP11	14A
2616.WC	FAB/DEL- WHEEL CHAIR LIFT	40	23SEP11	21NOV11	14A
5420	STATE TEST FOR PREL USE OF ELEV # 2	5	21NOV11*	28NOV11	14A
5425	COMMENCE W/ ELEV # 1	50	29NOV11*	08FEB12	14A
5480	COMMENCE W/ WHEEL CHAIR LIFT	5	03JAN12*	09JAN12	14A
5565	STATE TEST FOR ELEVATOR # 1	1	01MAR12*	01MAR12	14A
5570	STATE TEST FOR ELEVATOR # 2	1	02MAR12	02MAR12	14A
5585	FINAL CLEAN ELEVATOR # 1	1	02MAR12	02MAR12	14A
5575	STATE TEST FOR WHEEL CHAIR LIFT	1	05MAR12	05MAR12	14A
5590	FINAL CLEAN ELEVATOR # 2	1	05MAR12	05MAR12	14A
5595	FINAL CLEAN WHEEL CHAIR LIFT	1	06MAR12	06MAR12	14A
FIRE PROTECTION					
D3.4020	R.I.O.H. SPRINKLER, D-3, CIRC AREA	5	16AUG11A	02SEP11	15A
5385	ACTIVATE TEMPORARY SPRINKLER	5	29AUG11*	02SEP11	15A
5390	FLOW TEST	5	29AUG11*	02SEP11	15A
2724	FAB & DEL CUST COLOR SPKL HEADS - POOL	20	29AUG11	26SEP11	15A
C.5010	R.I.O.H. SPRINKLER, AREA C-5	10	30AUG11	13SEP11	15A
D5.4020	R.I.O.H. SPRINKLER, D-5, CIRC AREA	10	20SEP11	03OCT11	15A
D5.5010	R.I.O.H. SPRINKLER, D-5	10	23SEP11	06OCT11	15A
C5.5062	R.I. SPRNK HDS IN HRD CEILING, AREA C-5	5	29SEP11	05OCT11	15A
D4.4245	SPRINK HDS HARD CEIL, D-4	2	18OCT11	19OCT11	15A
D3.4075	SPRINK HDS HARD CEIL, D-3, CIRC AREA	5	19OCT11	25OCT11	15A
D4.4075	SPRINK HDS HARD CEIL, D-4, CIRC AREA	5	21OCT11	27OCT11	15A
D3.3300	SPRINK HDS HARD CEIL, D-3	2	25OCT11	26OCT11	15A
D1M.4025	R.I.O.H. SPKL, 1ST FL, D MECH RM	5	26OCT11	01NOV11	15A
A3.3135	SPRNK HEADS IN GRID, 3RD FL, AREA A	5	31OCT11	04NOV11	15A
D5.5065	SPRINK HDS HARD CEIL, D-5	2	07NOV11	08NOV11	15A
5288.P	R.I.O.H. SPRINKLER @ POOL AREA B	5	10NOV11	17NOV11	15A



Start Date	17AUG09
Finish Date	20AUG12
Data Date	29AUG11
Run Date	31AUG11 11:20

Early Bar
Progress Bar
Critical Activity

R27R

Sheet 16 of 27

Gilbane Building Company (R27R)

WPI Recreation Center

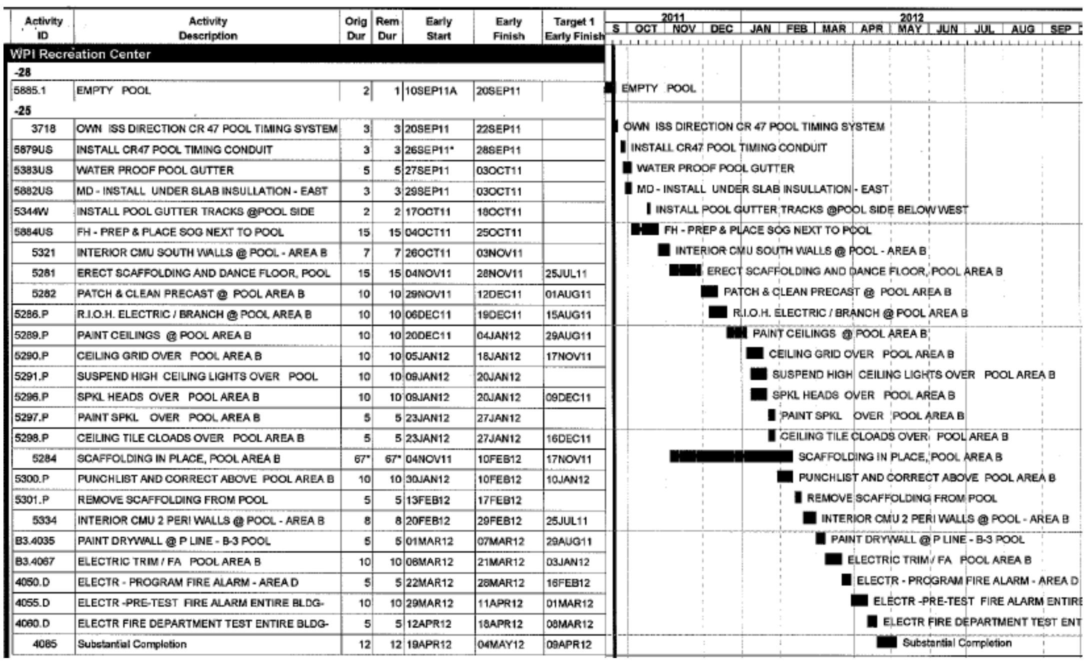
BID PKG ES EF

Date	Revision	Checked	Approved

Figure 5: August 2011 Schedule (Gilbane, 2011)

In the case of the Recreation Center, the Critical Path, as well as the completion date are both very important items. Because this is a University project, it must be completed in a timely manner for many reasons. First, the school has promised its faculty, staff, and students that the facility would be done by a certain time, Fall 2012. Not only is the community waiting for the building, but they are also awaiting the restoration of the Quad. The Quad is the heart of many student activites, as well as a space for a little more parking when it is restored. Another reason, is that the Recreation Center is a major selling point for the Admissions Office. As soon as it is completed, the actual building be a selling point to incoming students, but the Quad will also be restored and will be more asthetically pleasing than the construction that is overtaking half of the

Quad currently. In Figure 6 below, the critical path for the Recreation Center can be seen. This is the critical path for the completion of the pool. This figure is only one section of the critical path document. The complete schedule shows a much longer critical path for the entirety of the project. The length of the project is about two years (May 2010 – April 2012), therefore only one portion of the critical path could be captured in Figure 6. The schedule is consistently updated to reflect the current construction that is occuring in the field. This ensures the CM and the owner that the critical path is still on track for the final completion date.



Activity ID	Activity Description	Orig Dur	Rem Dur	Early Start	Early Finish	Target 1 Early Finish
WPI Recreation Center						
-28						
5885.1	EMPTY POOL	2	1	10SEP11A	20SEP11	
-25						
3718	OWN ISS DIRECTION CR 47 POOL TIMING SYSTEM	3	3	20SEP11	22SEP11	
5879US	INSTALL CR47 POOL TIMING CONDUIT	3	3	26SEP11*	28SEP11	
5383US	WATER PROOF POOL GUTTER	5	5	27SEP11	03OCT11	
5882US	MD - INSTALL UNDER SLAB INSULLATION - EAST	3	3	29SEP11	03OCT11	
5344W	INSTALL POOL GUTTER TRACKS @POOL SIDE	2	2	17OCT11	18OCT11	
5884US	FH - PREP & PLACE SOG NEXT TO POOL	15	15	04OCT11	25OCT11	
5321	INTERIOR CMU SOUTH WALLS @ POOL - AREA B	7	7	26OCT11	03NOV11	
5281	ERECT SCAFFOLDING AND DANCE FLOOR, POOL	15	15	04NOV11	28NOV11	25JUL11
5282	PATCH & CLEAN PRECAST @ POOL AREA B	10	10	29NOV11	12DEC11	01AUG11
5286.P	R.I.O.H. ELECTRIC / BRANCH @ POOL AREA B	10	10	06DEC11	19DEC11	15AUG11
5289.P	PAINT CEILINGS @ POOL AREA B	10	10	20DEC11	04JAN12	29AUG11
5290.P	CEILING GRID OVER POOL AREA B	10	10	05JAN12	18JAN12	17NOV11
5291.P	SUSPEND HIGH CEILING LIGHTS OVER POOL	10	10	09JAN12	20JAN12	
5296.P	SPKL HEADS OVER POOL AREA B	10	10	09JAN12	20JAN12	09DEC11
5297.P	PAINT SPKL OVER POOL AREA B	5	5	23JAN12	27JAN12	
5298.P	CEILING TILE CLOADS OVER POOL AREA B	5	5	23JAN12	27JAN12	16DEC11
5284	SCAFFOLDING IN PLACE, POOL AREA B	67*	67*	04NOV11	10FEB12	17NOV11
5300.P	PUNCHLIST AND CORRECT ABOVE POOL AREA B	10	10	30JAN12	10FEB12	10JAN12
5301.P	REMOVE SCAFFOLDING FROM POOL	5	5	13FEB12	17FEB12	
5334	INTERIOR CMU 2 PERI WALLS @ POOL - AREA B	8	8	20FEB12	29FEB12	25JUL11
B3.4035	PAINT DRYWALL @ P LINE - B-3 POOL	5	5	01MAR12	07MAR12	29AUG11
B3.4067	ELECTRIC TRIM / FA POOL AREA B	10	10	08MAR12	21MAR12	03JAN12
4050.D	ELECTR - PROGRAM FIRE ALARM - AREA D	5	5	22MAR12	28MAR12	16FEB12
4055.D	ELECTR -PRE-TEST FIRE ALARM ENTIRE BLDG-	10	10	29MAR12	11APR12	01MAR12
4060.D	ELECTR FIRE DEPARTMENT TEST ENTIRE BLDG-	5	5	12APR12	18APR12	08MAR12
4085	Substantial Completion	12	12	19APR12	04MAY12	09APR12

Figure 6: Critical Path for the Pool (Gilbane, 2011)

One final valuable aspect of a schedule is the capability to aid in the computation of an Earned Value Analysis of a project. An earned value analysis is the comparison of the cost of the projected work at a certain point in time and the actual units of cost of the work that have been completed. Using an updated schedule, the quantity of work that has been completed can be determined and compared to the projected work that was previously planned. This type of analysis is used as both a cost and schedule analysis (Oberlender, 2000). Gilbane does not use the Earned Value Analysis exactly as a type of project controls; they track manpower to track the progress of the project.

2.3.2 Cost

The original cost of a project is determined by the bid that is submitted by the Construction Manager. Once a CM is chosen, the CM will create bid packages with individual scopes of work for different parts of the project that must be done by different contractors. Once the packages are complete with drawings and contract documents, they are sent to subcontractors. When these packages are awarded, the actual cost of the project can be determined. With complex projects, the actual cost associated with the project often cannot be determined for months due to the complexity of the work. With the Recreation Center, as of Fall 2011, there are 36 awarded packages in place to date. With a project of this magnitude, most packages are awarded as early as possible, but some are not awarded until later in the process. This can be because they are not critical to award immediately, or additional scopes of work were deemed necessary by the owner later in the project.

At the Recreation Center, a Guaranteed Maximum Price (GMP) contract is in place. In this type of contract, the CM agrees to a fixed completion date, as well as a maximum price that the project will be completed in without exceeding. In many situations, to guarantee that this date is kept, an owner will have liquidated damages written into the contract. Liquidated damages are the price that the CM must pay for every day the project exceeds the specified completion date. In the Recreation Center, liquidated damages are not involved.

A GMP can be created prior to receiving subcontractor bids or after. For the Rec. Center, Gilbane chose to make the GMP after receiving the subcontractor bids. With this choice, the GMP is more accurate because the contractor has the advantage of knowing specific pricing on each of the trade packages. This allows for a more accurate price and a smaller chance for change orders.

2.4 Computer-Aided Engineering

Computer-aided engineering is using a computer to build, design, model, simulate and analyze engineering projects. Computer-aided engineering has been around since the 1950's, but is still gaining popularity as an application in the construction and design fields. Over the years, the technology has been developed for many different types of fields and specially designed programs that tailor to a specific trade. A major leader in the development of these programs is Autodesk (Autodesk Inc., 2011). Autodesk is a company that makes over 50 programs that manufacturing, architecture, building, construction, and media and entertainment industries use (Autodesk, 2011). Autodesk's programs are very popular today due to the open application programming interface (API), which allows easy file sharing between Autodesk products; file share is great for the construction field where many different people are involved in one project.

2.4.1 *Robot* Structural Analysis

Among the many types of programs Autodesk offers, *Autodesk Robot Structural Analysis* is used by structural engineers to aid in the analysis of buildings. "Autodesk *Robot* Structural Analysis (*Robot*) is a single integrated program used for modeling, analyzing and designing various types of structures. The program allows users to create structural models, to carry out structural analysis, to verify obtained results, to perform code check calculations of structural members and to prepare documentation for a calculated and designed structure" (Autodesk *Robot* Structural Analysis - Getting Started Guide, 2010). *Robot* uses an open API which allows the files created in *Robot* to be transferred to other programs such as Autodesk *Revit* Structures, another open API program. Autodesk *Revit* Structures is a part of the *Revit* platform for Building Information Modeling.

2.4.2 Building Information Modeling (BIM)

Building Information Modeling, more commonly known as BIM, is a three-dimensional electronic demonstration of a building or construction site. Companies use 3D modeling software such as Autodesk Revit and Navisworks, to create and/or review their BIM models. The 3D geometric models are combined with additional information, such as time or money, to create the most unique applications of BIM. The idea of trying to use computer-generated isometric objects in construction is not new. The first three-axis computer models were constructed in the 1950s (Klancnik, 2009). At this time there was no practical software for these models to have any sort of everyday value. Today, BIM is the most popular construction management tool on the rise. In the 2009, SmartMarket reported the percentage of companies using BIM in construction went from 28% in 2007 to 48% in 2009 (Klancnik, 2009). The same report concluded that the number of U.S. contractors using BIM has almost quadrupled over that same time period.

BIM continues to grow because its greatest asset is that it can be used by all aspects of construction. It is not another program that is specialized just for contractors, or just for architects, or engineers. Figure 7 shows how BIM can be used by the owners, the architects, engineers, contractors, and sub-contractors, all putting in their own information and detail into the model so that it becomes an overarching work environment that can lead to an increased construction efficiency.

Figure 7: BIM Contribution Breakdown (Partridge, 2011)

BIM does not change the roles of the players within the project team, but it plays a significant role in coordinating the different trades to avoid any conflicts found in the proposed design ahead of time. In the beginning, it takes a lot of work to set up the BIM model with all the different information, but when done correctly it gets everyone on the same page so that coordination problems can be solved ahead of time.

When issues are found in a project and an alternate design may be needed, BIM helps cut down on the time it takes to resolve these issues. Designers can more easily propose an alternative design and instantly see how it fits into the construction and assess its impact on the rest of the building. The builders can quickly look at the proposed change and takeoff quantities for the materials and the man power required to build the new detail. Then the contractor can quickly access all the information provided and generate a cost estimate for the proposed change, and investigate how it will affect the schedule of the project. In the case of the WPI Rec Center, the BIM model is used mostly for visualizations of how the building will come together. In our project, the team will use the model for structural, cost, and schedule analysis.

2.4.2.1 Uses in Project Management

Because BIM is still relatively new, not all companies are fully functional with BIM. Its usage is still growing and on most jobs in 2011, it can be found that the BIM model is used as a tool mostly by the construction managers (Klancnik, 2009). As of now the major uses of BIM for general contractors are visualization, coordination, 4D models, and 5D models (Klancnik, 2009). It is not yet to a point where the structural and mechanical engineers update their portion of the model, and the sub-contractors update their portions so that the model works as a tool to integrate the work of everyone. As its usage continues, BIM is expected to reach that potential in the coming years.

Visualizations are one of the main uses for BIM because they provide an easy way for everyone to get on the same page on an issue. Sometimes the 2D drawings do not depict or show an issue that may be in the field, or maybe the owner is not as familiar with the drawings as everyone else. When the issue is investigated using BIM, anyone who was looking at the building for the first time would easily be able to understand what they were looking at and what the issue may be. This type of clarity can cut down on the amount of time that an issue may be debated; therefore, cutting down on meeting times significantly.

Coordination is another major use of BIM by general contractors. Coordination can be between trades, or even the coordination of the job site. At the beginning of a project, coordinating how the job site will be set up is always a big concern. This is because there are property lines to deal with, along with making sure material deliveries are possible, and many other coordination issues that the owner will have questions about. With BIM the site plan can be clearly demonstrated to everyone, including where the trailers will be located, where materials storage will be located, and how material deliveries will be made, etc. It is a great way to clarify the set up of the site, or how the building should be oriented on the property. For example, Figure 8 shows a site plan that lays out the locations for the cranes, trailers, dumpsters, gates, etc.

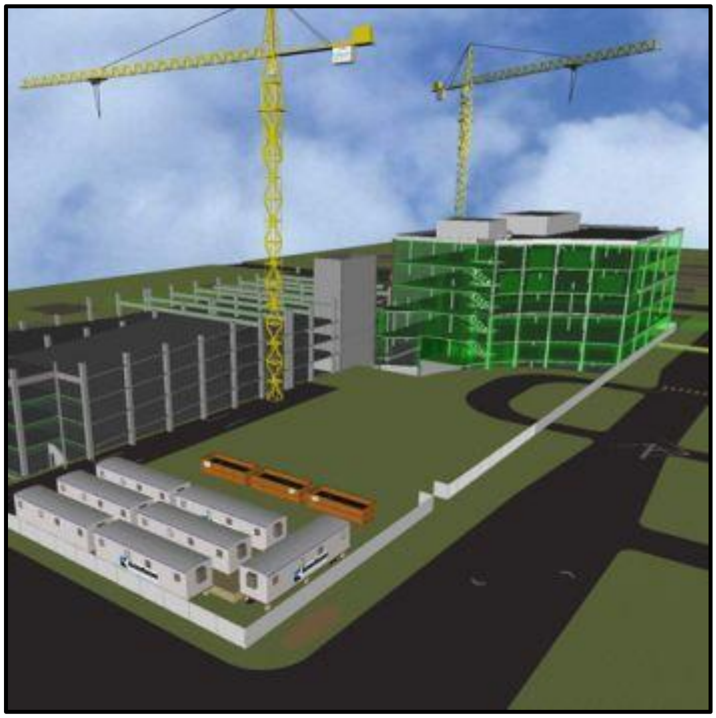


Figure 8: BIM Site Plan (Knutson, 2011)

Coordination between the different subcontractors is another current use of BIM by general contractors. A report can be run within BIM that detects any and all interferences between the geometric shapes. A perfect example is laid out in the *Contractor's Guide to BIM* where there might be an interference with the way the plumbing and HVAC equipment is supposed to be installed (Klancnik, 2009). With BIM, the plumbing and HVAC sub-contractors can be shown the issue through the model and use the model to propose a new design on how to install the equipment. Figure 9 shows the conflict between the proposed location of the purple pipe, and that of the grey hangars for the red conduit. Any type of interference like this can be found early on in the project with the use of BIM.

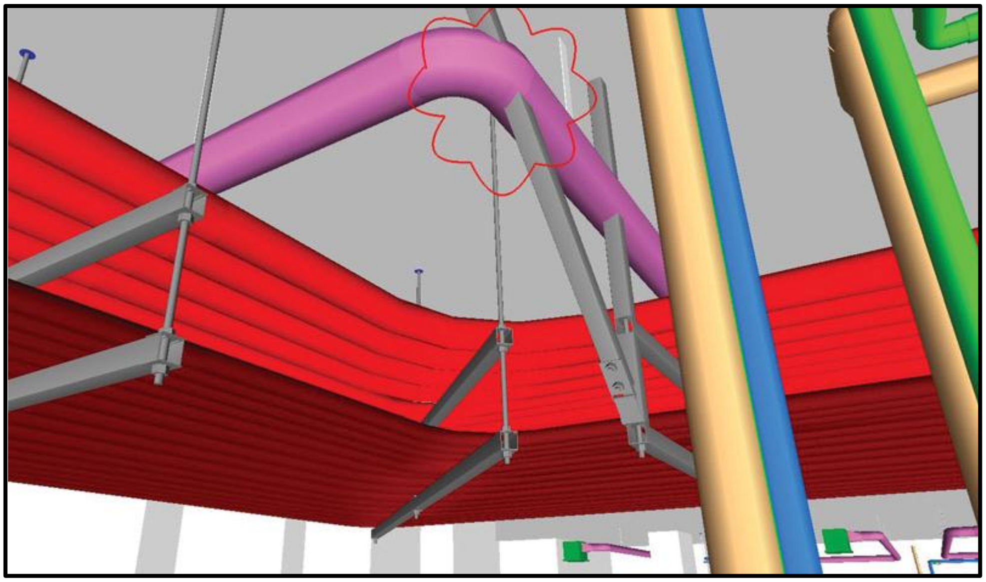


Figure 9: Interface Detections (Hope, 2010)

Without BIM, this issue may not have been discovered until the materials were on site and ready to be installed; therefore, causing a delay in the project as well as a potential change order. For the Rec Center, BIM is not a contractual requirement. Cannon provided a BIM model with no contractual ties in it to Gilbane. Gilbane then refined the model so that they could use it as clash detection for the mechanical, electrical, and fire protection trades.

4D and 5D models are the most current uses for BIM by general contractors. The most popular and practical model is the 4D model. The 4D model consists of taking the 3D model and adding in the element of time. This works by importing the project schedule into the 3D model, causing the different portions of the building to be linked to a certain duration and order. This is a good tool for visualizing the progress of a building over time; as well as, exploring the effect on the schedule when a certain area of work is delayed or changed. 5D models include expanding the 4D model by adding the element of cost. Currently, this method is not used as frequently because the types of estimating software that are used are not compatible with BIM. The advantages of this method in the future will be the ability to quickly assess the impact to the schedule and cost when an area of work is changed. This will help to more accurately project the end date and final cost of each project. In the project, our team will be using the WPI Rec Center model and schedule to create a 4D model that shows the existing and new design. The group will also look into the feasibility of creating a 5D model by adding the costs of the new and existing track designs.

2.4.2.2 Uses in Structural Engineering

Although BIM is primary used by construction managers, structural engineers and firms are quickly realizing its potential as well. BIM is enticing for engineers because it uses object-oriented programming paradigm (Nelson and Schinler, 2008). This means that the 3D model of the structure possesses all the information and functionality of each of its members. For example it knows the material, section properties, location in the building etc. From a structural point of view BIM is used for coordination, documentation, analysis and design.

Similar to project management, coordination of all the aspects of the project assists the structural engineer as well. Coordination between the architects, structural, and mechanical engineers results in better decision making based on actual and current designs. This coordination also allows for better updating and changing between programs and designs. This results in reducing time and conflicts because everyone is using the same model.

Documentation is the only aspect that the structural engineers have complete control over because it is based on their work and analyses (Nelson and Schinler, 2008). Since the BIM model can hold all the information and functionality of each member in the structure, it can easily be found all in one place. This makes documentation much easier because everything is in one file. This kind of documentation is also good because if changes are made later in the project, changes are applied to the entire design and documentation. However documentation does have its flaws in BIM. Repeating members in a structure will be documented individually, when traditionally usually a single drawing would have sufficed. Also, many structural companies take pride in the way they present their drawings, and BIM has limits for the presentation of the drawings.

3 Methodology

The methodology section explains how our group plans to use structural computations and programs to implement an alternative design for WPI's suspended track. The section on project management clarifies how we will conduct a schedule and cost analysis of the new alternative design to compare with the existing design. It also describes how we plan to use computer programs such as *Revit* to visually display the comparison between the current design and new design, as well as use *Robot* to analyze the structure to insure its structural integrity.

3.1 Structural Evaluation

The structural evaluation portion of our methodology highlights the various processes that we must accomplish to implement our alternative suspended track design. The various types of alternative solutions are evaluated based on the application of mechanics and an understanding of structural systems, then cross referenced and filtered down to the most viable system: the cantilever method. We further investigate the cantilever method and describe the necessary procedures associated with implementation of this system such as the calculation of new beam sizes, and the analysis of the effect that the change will have on the rest of the building.

3.1.1 Alternative Suspended Track System

The fourth level of the WPI Recreation Center has a large multipurpose area available for the student body. The suspended track on the upper portion of the fourth level is currently supported by underneath beams and vertical suspension supports which are connected to most of the roof trusses. The design of these components is intertwined, and changing one component will likely have an impact on and require a change to all the rest. Our project will investigate an alternative support system for the suspended track which will unite various concepts of the structural and project management fields. The beginning of our project starts with identifying feasible solutions for the support system of the suspended track.

The three proposed alternative support systems previously mentioned in the Background section are all considered for our substitution. The first system mentioned is column supports. When looking at the need of WPI's Recreation Center, one of the main restrictions is size. The building was limited to a certain lateral area thus restricting the fourth and fifth levels of the building. The current design of the fourth level has the suspended track overhanging the outer area of the basketball courts. Since the current system is supported from overhead, recreational users of the gymnasium have the ability to move freely underneath the track. If column supports were implemented, it would pose a great danger to people utilizing the basketball courts and Mondo floor. They could possibly hurt themselves during recreational use of the courts or by merely not paying enough attention. For this one crucial reason, the column support system is not the best alternative for the suspended track. All floor mounted methods pose this potential danger, and other overhead methods should be implemented instead.

A common support system associated with bridging is trusses. This alternative would definitely eliminate the previous danger of possible injury to the people utilizing the facilities. Some aspects to consider when implementing a truss system are the large amount of labor associated with the fabrication and assembly. A major expense for the construction of a building is the amount of time and money associated with labor. Putting a lot of time and money into a simple support system of a minor component may not be worth the effort. Another disadvantage to consider is the amount of space that the truss will occupy under the track. If the trusses take up a lot of space, and become a hazard for people walking underneath them, then the overall height of the building will be extended to compensate for the depth of the truss. Additionally, if the overall height of the building is increased, the ancillary costs would increase. Also, having these trusses exposed may be acceptable to the owner and architect, but if it is not, then one must consider the options for concealing the units. Hiding a truss unit is viable, but one must also consider the costs of all the materials and labor needed to complete such a task.

Another overhead system that can be concealed easily and is simple to install is a cantilever system. One of the most crucial aspects of the cantilever system is the beam shape and size implemented. When purchasing steel, a large beam means more costs and because each individual beam will be supporting the majority of the loading it is important to choose the smallest beam possible without compromising the structural integrity of the track. Also, one of the most important structural loadings that must be considered when implementing a cantilever system is the fixed-end moment acting on the supporting structure.

An analysis of the previous alternative methods brings us to the conclusion that a cantilever system is probably the most effective system when compared to the current suspended track. Now that we have established which system should be analyzed and implemented, we must look further into the effects that this system will have on the fourth and fifth levels of the building.

3.1.1.1 Cantilever Alternative

The new cantilever system will be relatively simple to implement because it closely resembles the proposed suspended track system. The cantilever system will take the current suspended track system, remove the vertical suspension components and strengthen the beams underneath to compensate for the additional loading and revised load path.

Figure 10 presents an enlarged section of the suspended track including structural elements for both the straight-aways and complex corners. The current floor beams that are located underneath the track are perpendicular to the wall and are the primary supports for the loading on the track. According to the proposed design, these floor beams are estimated to be W10x19 sections. The joists that connect each of these perpendicular beams limit rotation, movement, and estimated at W10x22 sections. Our plan is to determine the loads associated with the track and properly calculate for new joists and girders. The larger cantilever beams will connect to both the columns and the spandrel girders of level four. They will be attached in a similar bolt and welding fashion, but of course will be strengthened where necessary. The track will be connected to the cantilever in the same technique as the suspended track.

The corners of the track are the most complicated area because of all the intricacies, but it will be assessed and revised similar to the straight-aways. Finally, the diagonal W10x22 beam will probably be changed because of the different type of forces applied to the track.

The cantilever system will be encased in the same manner as the suspended track beams. It is necessary that these beams will be larger than the previous joists and girders, resulting in an increased cost in steel. This is one of the main factors of our new implementation that we will analyze further in the project management portion of our project.

One main component of our project is to utilize *Robot* and *Revit* to minimize human error and find simple solutions to complicated problems, quickly and correctly. Since our working knowledge of these new programs is limited, we will breakdown the complex 3D structure into multiple 2D systems to simplify the structural analysis. We will create an "analytical model" of the suspended track in *Revit* which will establish a model that can be analyzed freely in two dimensions. Different sectional views of the track will give us planar frames that will be analyzed and translated through the entire project. Also, breaking the structure into 2D components will eliminate any complicated boundary conditions necessary to avoid global and local instabilities in a 3D model.

A final obstacle that we must solve is the topic of dynamic loading of the track. The track will be a very popular feature of the new recreation center and events like Relay for Life could pose an extreme loading case. These extreme cases should be examined due to the large number of people walking around the track.

These alterations to the suspended track system will inevitably have an impact and require a change to all components connected to it. The first dimension that will be affected by the new support system is the roof trusses.

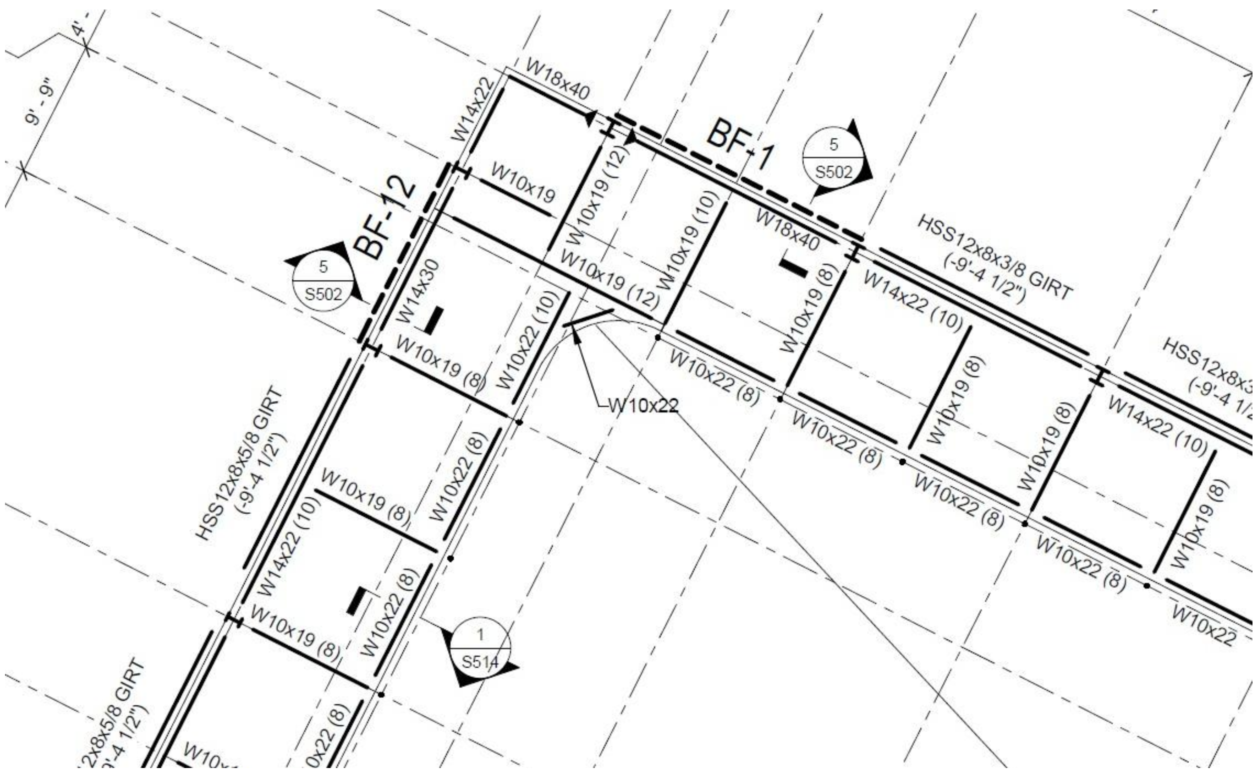


Figure 10: Suspended Track Section

3.1.1.2 Roofing System & Cantilever Canopies

The proposed roofing system accommodates for a suspended track, but with our alternative design, a reanalysis of the roof trusses will be in order. The truss configuration designed by Canon (the Architect on Record) was specifically designed, but now that there is less loading associated with the roof, it may be necessary to investigate the elements of the roof truss to potentially minimize steel and labor costs. If the load change is minimal, a redesign of the roof truss would be unnecessary. There are many factors to consider when analyzing the roof such as the variable live loads (snow, wind etc.) and the dead loads (building materials and HVAC units).

The cantilever canopies represented in Figure 11 are supported by some of the same components as the track. The cantilever canopies are an additional component added to the building to increase aesthetic appeal and increase the lighting of the building. To maintain the aesthetic component added by the owner and architect, we must insure that cantilever canopies' supports are not compromised by the new alternative track system.

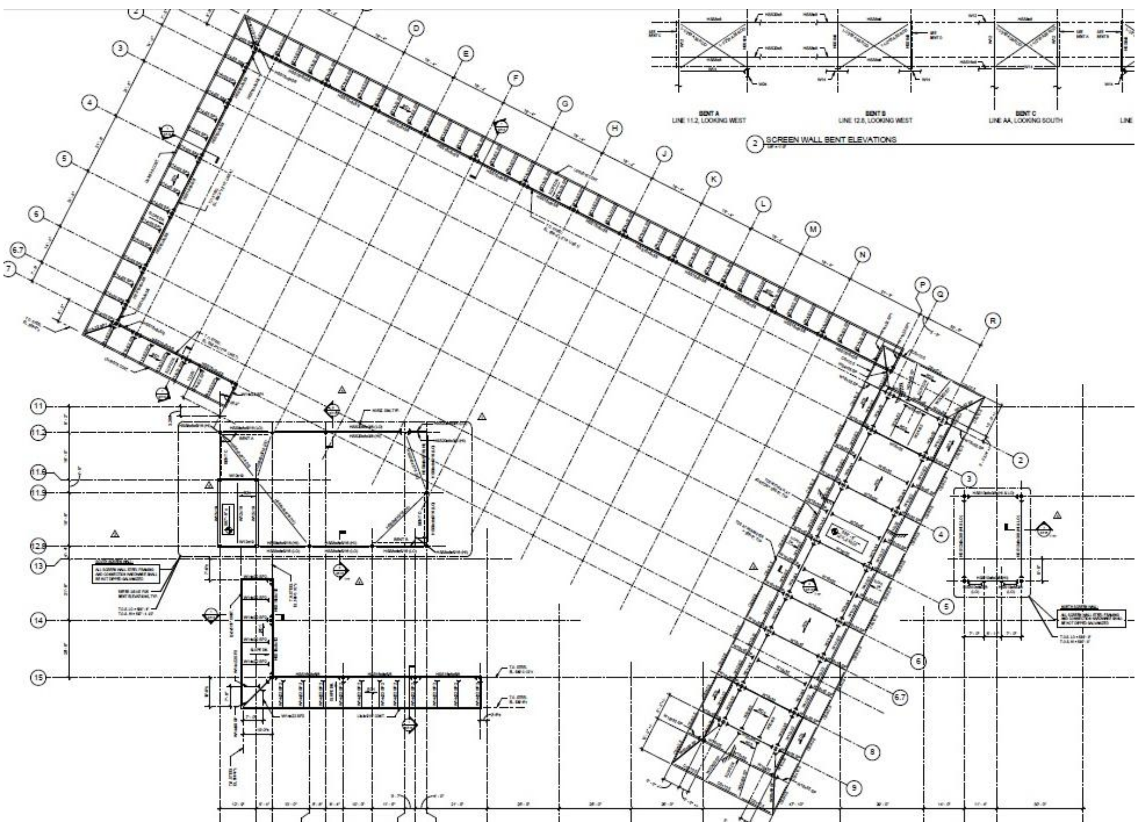


Figure 11: Cantilever Canopies

3.1.1.3 Robot and Structural Analysis and BIM

The BIM model from a previous MQP, WPI Recreation Center: *Construction Management and Alternative Design Analysis* will be used as a starting point for our model. Using this *Revit* file, we will select sections of the current design to be transferred to *Robot* for a structural analysis. The alternative design will be built in *Revit* then selected sections will be transferred to *Robot* for structural analysis and design evaluations. The two designs will be in separate files but undergo the same analysis and procedure detailed below. Using *Robot* all of the code-specified design loads and load combinations will be applied to both models and analyzed. *Robot* then will produce a member report based on code and specification compliance and identify members that are over stressed for each design. These members will be redesign to fit all codes and specifications for structural integrity. Additionally, this process of correcting over stressed members will be repeated until the entire alternative design has been successfully created. We will then compare the two reports to each other. After the structural analysis the *Robot* files will then be transferred back into their respected *Revit* or BIM files, the current design and the alternative design. This will update the Revit files with the new structural analysis information which will be useful to reference when needed because all the information about any member can be located if that member is selected. This will help keep the project organized and controlled.

Before we can start with this process, we will take a measured approach to using *Robot*, because the group is unfamiliar with it. Our group will do a test of the software to ensure the models can be moved back and forth between *Revit* and *Robot*. To test out the software, we will create a simple 2D design, with columns and girders in *Revit*, and then transfer it to *Robot*. We will analyze it in *Robot* and transfer it back to *Revit*. This small step will help us to see the challenges we will face when working with the bigger model.

3.2 Project Management

After the alternate design is created, our group will evaluate the differences in cost and schedule between the current and proposed design to determine which approach is more beneficial to the project. In order to evaluate the cost differentials, we will first obtain the actual cost of this portion of the building as designed by Cannon. Our group only has access to the total fabrication and erection contract for the structural steel throughout the entire building, but we only want to consider the cost to fabricate and erect the steel pieces that are being used for the track section. We will find the cost per volume of steel for the whole building; we will then apply those unit prices to the volume of steel for the track portion. For the alternate design, we will analyze information from cost data books that have costs for each step of the process of fabricating and erecting the steel on site. As a check to our estimate on the alternative design, we are going to use our methods of cost estimating for the existing design to make sure it is comparable to the cost of the actual design. After establishing an estimate for our design, we will compare the costs to see if the new design was more or less expensive than the actual design.

We will then compare the schedule differences. We will obtain the actual schedule from Gilbane as a base schedule. To create a new schedule based on the alternate design, we will analyze the existing schedule, as well as watch the footage from the video cameras that are taping the site to determine durations for different activities. We will also look at the productivity notes from Gilbane to help us create a more precise schedule. This will allow us to determine if our design will take more or less time than required for the actual construction. We will use *Primavera* to create our schedule.

Based on the new schedule, our group will also be able to determine if the new design will affect any other aspects of construction. If the new design has any effect on other trades and the way they are constructing their part of the project, it may change the critical path of the overall project. These will all be things that we will look at through the analysis of the schedule.

3.2.1 Project Management and BIM

Once a new alternate design has been proposed for the suspended track and roof, our group will use Autodesk *Revit* and BIM to show a visual of our cost and schedule analysis. Using the BIM model of the recreation center our team will import the *Primavera* project schedule to create a 4D model displaying the construction of the recreation center over time. Using the 4D model the group will show the construction of the suspended track and roof in different stages as it was originally proposed and built. The team will then compare the sequence and time for erecting the original design with those for the proposed alternate design. This comparison will be shown by taking a screenshot of each BIM model at a consistent time interval.

The group will also perform a cost analysis of the original track and roof compared to our alternate design. Creating a 5D model to show the cost of the two projects at different stages is something that our team will investigate to see if it is plausible with the technology that is available. As mentioned in the *Contractor's Guide to BIM* creating a true 5D model with the available technologies is not as beneficial as a 4D model. It is usually not beneficial to create a whole 5D model for a project because of how much more effort it takes than a 4D, without that much more of a reward. But because our team is only looking at a portion of a project it may be beneficial to create a 5D model for the construction of the suspended track and roof.

3.3 Group Responsibilities and Term Schedules

Our group consists of four members, all majoring in Civil Engineering. Two of our members are concentrating on the Structural aspects of Civil Engineering and the other two are focused on the Construction Management aspects. Table 2, below, illustrates how our project will be broken down amongst the four members.

Table 2: Responsibility Breakdown Chart

Topic	Responsibility
STRUCTURAL	
Existing Design Analysis	Sean Minor, Suzanne Najem
New Design Analysis	Sean Minor, Suzanne Najem
CONSTRUCTION MANAGEMENT	
Cost Analysis of Existing	John Flynn, Kathryne Kulzer
Cost Analysis of New	John Flynn, Kathryne Kulzer
4D of Existing	John Flynn, Kathryne Kulzer
4D of New	John Flynn, Kathryne Kulzer

Also below, are our planned schedules for A through C terms. The term schedules sequence of the scope of work, which includes collecting data, analyzing the existing solution, developing and evaluating alternative solutions, and writing the report.

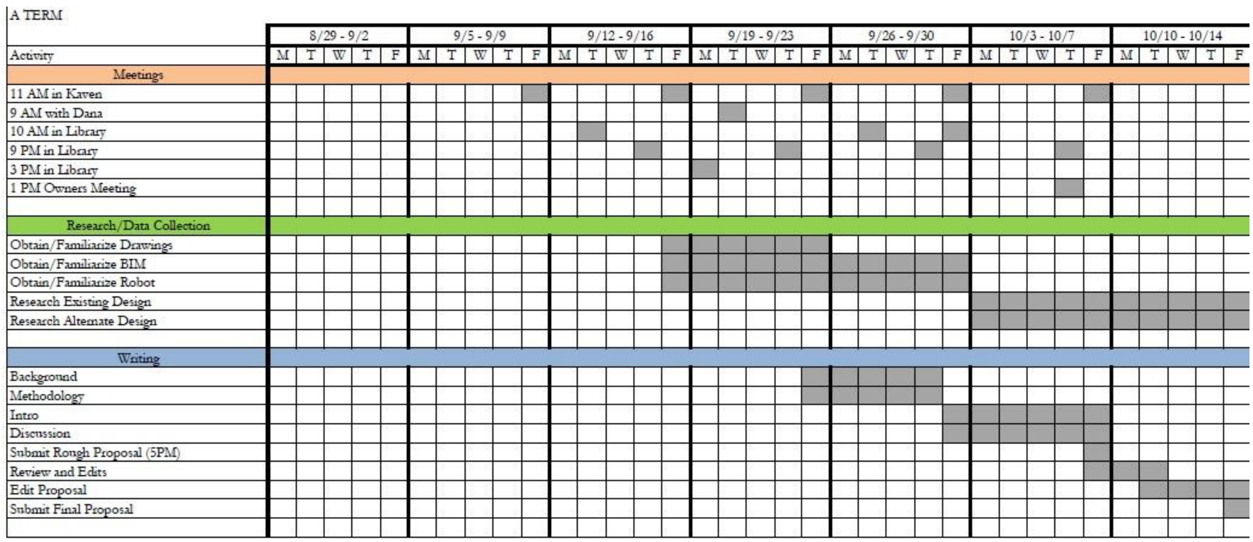


Figure 12: A Term Schedule

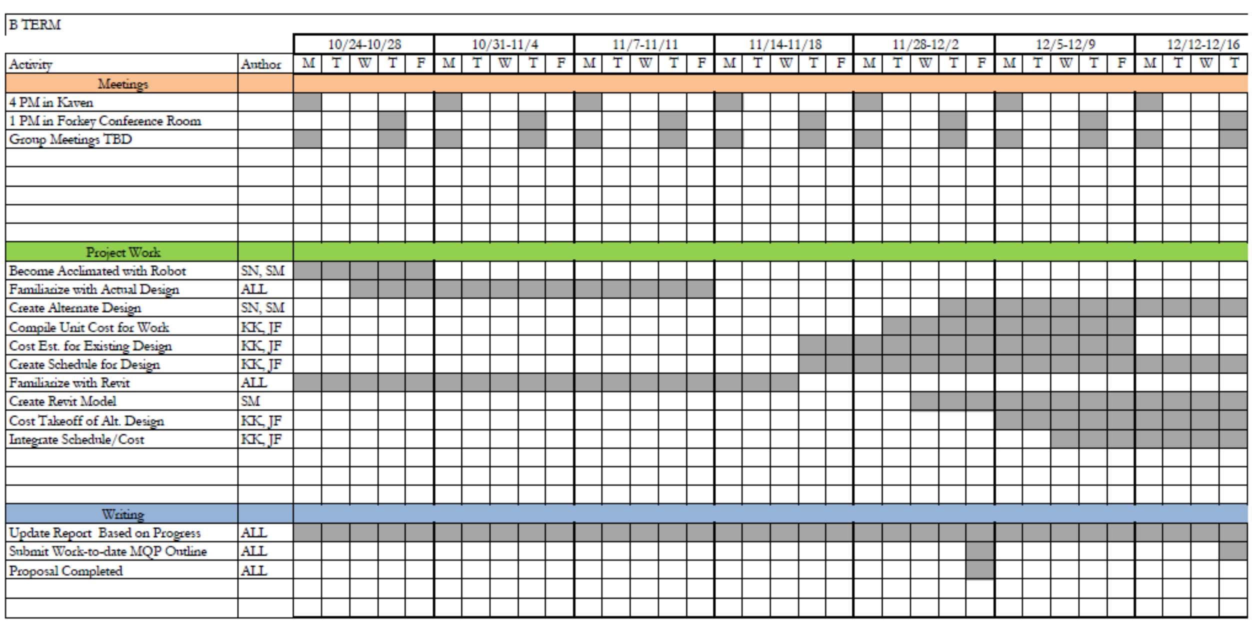


Figure 13: B Term Schedule

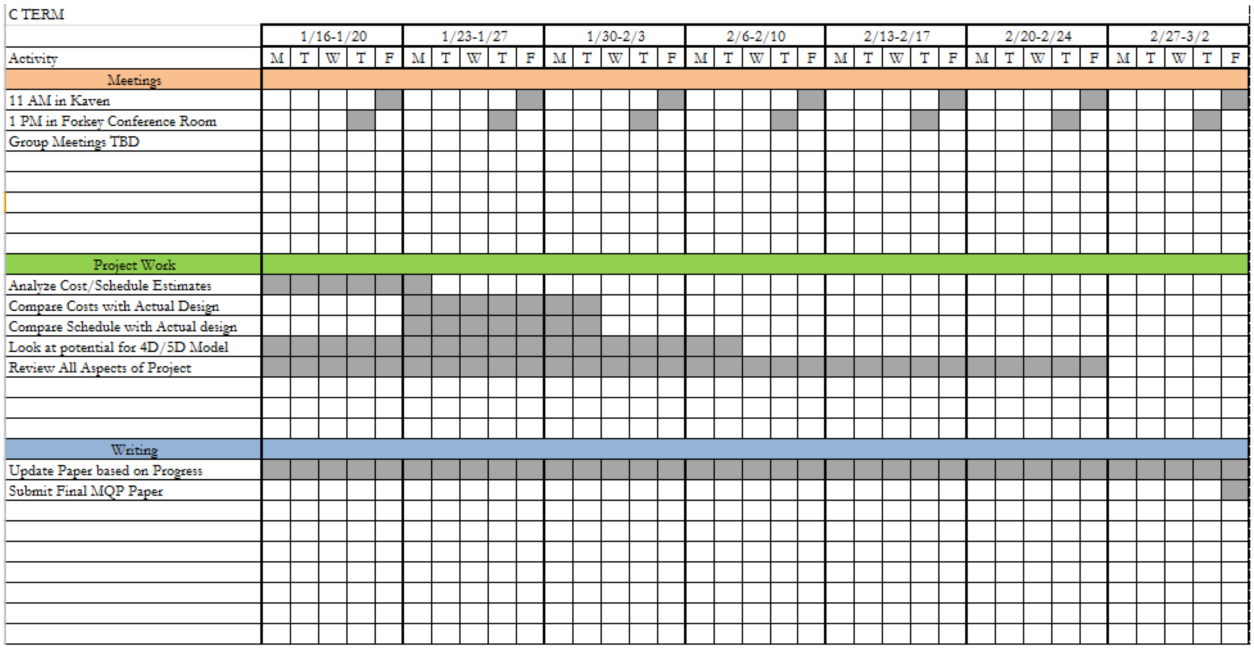


Figure 14: C Term Schedule

4 Discussion

The discussion section explains the guidelines that WPI Department of Civil and Environmental Engineering lays out so the students can meet their capstone requirement through their Major Qualifying Project. This section explains how we plan to meet our capstone requirements. It also touches upon the constraints that we will face throughout the duration of our project.

4.1 Capstone Design

Worcester Polytechnic Institute is known for its project-based learning system. There are three major projects that each student must complete in order to graduate. The Major Qualifying Project (MQP) is usually the final year or senior year project that each student completes. The MQP should demonstrate application of the skills, methods, and knowledge of discipline to the solution of a problem that would be representative of the type to be encountered in one's career. (WPI, 2011).

Our group consists of four members with two members' concentration in structural design and two members' concentration in project management. Half of the project will cover aspects that are related to structural engineering, such as evaluation of loading types and design. The other half of the project will cover project management topics, including cost analysis, scheduling, and considerations for the constructability of the design. The halves are intertwined through the general field of construction. Each half will demonstrate the knowledge learned from previous classes but will build off that knowledge to foster a capstone experience needed to complete this specific project.

4.2 Constraints

Another potion of completing the MQP is addressing the eight realistic constraints given by the Civil Department adopted out of the ASCE commentary. **Error! Not a valid bookmark self-reference.** outlines the constraints we will specifically address in our project.

Table 3: Project Constraints

Constraint	Description
Economic	We will look at the economic constraint through our cost analysis of the current design verses our design.
Sustainability	The current construction process of the New Recreation Center is incorporating LEED aspects. We will do the same in our design.
Manufacturability/Constructability	This applies to how we design the supporting frame work for the track and the material we select for it. We will demonstrate the constructability by using standard member sizes.
Health and Safety	This applies to our design and making sure we follow building codes to ensure safety and structural integrity of the track.
Social	This applies to the uses of the track and how it will be used in a social setting. For this constraint we will look into extreme loading cases that could potentially happen on the track itself.

4.3 References

We are going to use the following sources as references for our project:

Table 4: Sources Utilized for the Project

Source	Description of Use
Dana Harmon	Dana Harmon is the Athletic director at WPI and can gave information about the needs for the project through WPI's perspective and other general information relating to the start up of the building.
Cannon	This company is the Architect of Record for the WPI Recreation Center and they can provide various structural details about the project that are relevant and are also not shown in the drawings.
Gilbane	This company is the Construction Manager for the Recreation Center, and they also can provide with relevant information about the building as well as periodic tours through the building process.

Western New England College	This college's recreation center is similar to WPI's. We will use their suspended track as a visual aid and a reference to absorb the environment and compare it to our own.
Primavera	This program will be used in the Project Management portion of our project. It generates a schedule of all the tasks needed to complete the project with appropriate time and job overlap.
Revit	This program is the foundation for BIM. There are also many *Revit* files from Gilbane and Cannon illustrating the structural design of the Recreation Center.
Robot	This is a new program that analyzes the various structural aspects of constructing a new building. Its cross over to *Revit* could lead to a advancement in BIM and construction management.

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Appendix B: Exported Information from Revit

Column Information					
Quantity	Length	Type	Volume		Tot. Vol.
46	11.125	HSS1.900x0.120	0.05	CF	2.3
16	17.375	HSS1.900x0.120	0.07	CF	1.12
	42.333	W12x120	10.3	CF	10.3
	42.333	W12x152	13.07	CF	13.07
2	29.417	W12x40	2.35	CF	4.7
	20.833	W12x53	2.21	CF	2.21
	21.333	W12x53	2.26	CF	2.26
	28.583	W12x53	3.03	CF	3.03
	28.958	W12x53	3.07	CF	3.07
	36.583	W12x53	3.87	CF	3.87
	36.667	W12x53	3.88	CF	3.88
	37.042	W12x53	3.92	CF	3.92
	28.161	W12x58	3.27	CF	3.27
2	28.500	W12x65	3.72	CF	7.44
2	29.000	W12x65	3.78	CF	7.56
9	33.083	W12x65	4.32	CF	38.88
2	33.583	W12x65	4.77	CF	9.54
4	28.500	W12x72	4.12	CF	16.48
9	33.583	W12x72	4.86	CF	43.74
	42.333	W12x87	7.4	CF	7.4
2	33.833	W12x96	6.56	CF	13.12
		Volume in CF			201.16
		Volume in Tons			49.28

STRUCTURAL FRAMING SCHEDULE						
Quantity	Length	Type	Volume		Tot. Vol	
1	0.333	W18x40	0.01	CF	0.01	CF
1	1.667	W10x12	0.03	CF	0.03	CF
11	1.667	W12x19	0.05	CF	0.55	CF
2	1.000	W18x40	0.06	CF	0.12	CF
1	1.000	W18x40	0.07	CF	0.07	CF
12	4.583	W12x19 SP	0.14	CF	1.68	CF
1	5.833	W10x22	0.16	CF	0.16	CF

4	5.661	W10x22	0.2	CF	0.8	CF
89	11.630	2L2-1/2x2-1/2x5/16	0.22	CF	19.58	CF
5	5.833	W10x19	0.22	CF	1.1	CF
87	11.630	2L2-1/2x2-1/2x5/16	0.23	CF	20.01	CF
3	5.917	W10x19	0.23	CF	0.69	CF
1	6.000	W10x22	0.24	CF	0.24	CF
1	5.833	W12x19	0.24	CF	0.24	CF
3	7.667	W10x19	0.25	CF	0.75	CF
12	7.667	W12x19	0.25	CF	3	CF
3	7.417	W14x22	0.29	CF	0.87	CF
2	7.833	W12x19	0.3	CF	0.6	CF
1	7.417	W14x22	0.3	CF	0.3	CF
22	7.667	W10x22	0.32	CF	7.04	CF
1	8.000	W14x22	0.34	CF	0.34	CF
1	7.667	W12x26	0.37	CF	0.37	CF
3	10.651	W10x19	0.38	CF	1.14	CF
10	10.667	W10x19	0.39	CF	3.9	CF
1	10.667	W10x19	0.4	CF	0.4	CF
33	9.667	W10x22	0.41	CF	13.53	CF
2	10.667	W10x19	0.42	CF	0.84	CF
11	9.667	W10x22	0.43	CF	4.73	CF
27	11.667	W10x19	0.44	CF	11.88	CF
29	11.651	W10x19	0.45	CF	13.05	CF
2	10.750	W10x22	0.45	CF	0.9	CF
2	11.682	W10x19	0.46	CF	0.92	CF
9	10.750	W10x22	0.46	CF	4.14	CF
5	10.750	W10x22	0.48	CF	2.4	CF
2	10.755	W16x26	0.53	CF	1.06	CF
2	10.750	W16x26	0.54	CF	1.08	CF
1	7.422	W21x44	0.54	CF	0.54	CF
1	7.464	W21x44	0.57	CF	0.57	CF
2	8.000	W18x40	0.62	CF	1.24	CF
2	17.490	W10x19	0.65	CF	1.3	CF
2	17.667	W10x19	0.66	CF	1.32	CF
2	13.969	W16x26	0.68	CF	1.36	CF
1	8.000	W18x50	0.73	CF	0.73	CF
2	14.000	W14x30	0.79	CF	1.58	CF
11	19.047	W14x22	0.81	CF	8.91	CF
2	21.500	W14x22	0.91	CF	1.82	CF
1	21.500	W14x22	0.92	CF	0.92	CF

2	13.995	W16x36	0.95	CF	1.9	CF
1	21.214	HSS6x6x3/8	1.05	CF	1.05	CF
3	22.693	HSS6x6x3/8	1.06	CF	3.18	CF
2	22.255	HSS6x6x3/8	1.07	CF	2.14	CF
4	21.495	W16x26	1.08	CF	4.32	CF
1	14.000	W14x43	1.1	CF	1.1	CF
1	21.859	HSS6x6x3/8	1.11	CF	1.11	CF
1	17.083	W18x35	1.2	CF	1.2	CF
1	11.292	W24x55	1.2	CF	1.2	CF
1	17.089	HSS7x7x1/2	1.25	CF	1.25	CF
6	19.047	W18x35	1.29	CF	7.74	CF
1	8.000	W27x84	1.32	CF	1.32	CF
1	19.333	W18x35	1.36	CF	1.36	CF
1	19.766	W18x35	1.39	CF	1.39	CF
6	19.333	W18x40	1.47	CF	8.82	CF
2	21.500	W16x36	1.48	CF	2.96	CF
1	20.151	HSS7x7x1/2	1.52	CF	1.52	CF
1	224.120	HSS7x7x1/2	1.64	CF	1.64	CF
2	21.500	W16x40	1.65	CF	3.3	CF
1	24.458	HSS7x7x1/2	1.68	CF	1.68	CF
1	24.401	HSS7x7x1/2	1.69	CF	1.69	CF
1	8.000	W27x84	1.75	CF	1.75	CF
1	24.057	HSS7x7x1/2	1.81	CF	1.81	CF
1	24.104	HSS7x7x1/2	1.82	CF	1.82	CF
1	19.333	W18x50	1.84	CF	1.84	CF
1	25.672	HSS7x7x1/2	1.88	CF	1.88	CF
1	24.130	HSS7x7x1/2	1.89	CF	1.89	CF
1	25.667	HSS7x7x1/2	1.98	CF	1.98	CF
2	25.042	HSS7x7x1/2	2.01	CF	4.02	CF
1	27.755	HSS7x7x1/2	2.02	CF	2.02	CF
11	19.333	W24x55	2.03	CF	22.33	CF
1	25.359	HSS7x7x1/2	2.04	CF	2.04	CF
1	27.167	W18x40	2.11	CF	2.11	CF
2	28.094	HSS7x7x1/2	2.21	CF	4.42	CF
8	19.333	W24x62	2.28	CF	18.24	CF
1	29.474	HSS8x8x1/2	2.6	CF	2.6	CF
1	27.167	W18x50	2.66	CF	2.66	CF
1	19.333	W24x76	2.81	CF	2.81	CF
1	19.333	W27x84	3.11	CF	3.11	CF
1	19.333	W27x84	3.12	CF	3.12	CF
1	18.667	W33x118	4.37	CF	4.37	CF

1	21.500	W33x118	5.11	CF	5.11	CF
1	21.250	W36x135	5.61	CF	5.61	CF
1	26.333	W33x118	6.14	CF	6.14	CF
1	27.167	W33x118	6.21	CF	6.21	CF
		Volume in Tons			73.64	
		Volume in CF			300.57	

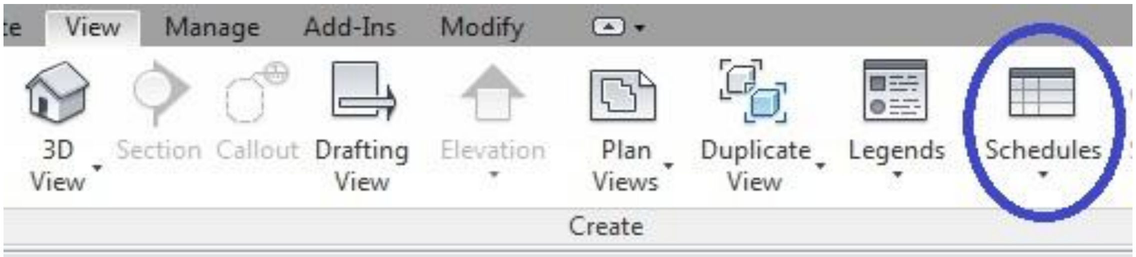
STRUCTURAL TRUSSES SCHEDULE						
Quantity	Length	Type	Volume		Tot. Vol.	
49	6.125	2L3-1/2x3-1/2x5/16	0.12	CF	5.88	CF
50	6.464	2L3-1/2x3-1/2x5/16	0.13	CF	6.5	CF
48	6.698	2L3-1/2x3-1/2x5/16	0.14	CF	6.72	CF
47	6.932	2L3-1/2x3-1/2x5/16	0.15	CF	7.05	CF
24	7.167	2L3-1/2x3-1/2x5/16	0.15	CF	3.6	CF
50	6.255	2L4x4x3/8	0.17	CF	8.5	CF
1	6.125	2L4x4x3/8x3/8	0.17	CF	0.17	CF
196	8.682	2L3-1/2x3-1/2x5/16	0.18	CF	35.28	CF
100	8.016	2L4x4x5/16	0.18	CF	18	CF
4	6.698	2L3-1/2x3-1/2x5/16	0.19	CF	0.76	CF
49	8.500	2L4x4x5/16	0.19	CF	9.31	CF
1	7.167	2L3-1/2x3-1/2x5/16	0.2	CF	0.2	CF
1	6.932	2L4x4x3/8x3/8	0.2	CF	0.2	CF
50	8.500	2L4x4x5/16	0.2	CF	10	CF
4	8.682	2L3-1/2x3-1/2x5/16	0.22	CF	0.88	CF
28	8.370	2L4x4x3/8	0.22	CF	6.16	CF
50	8.552	2L4x4x3/8	0.23	CF	11.5	CF
1	8.370	2L4x4x3/8	0.24	CF	0.24	CF
5	8.370	2L4x4x3/8	0.25	CF	1.25	CF
17	8.370	2L4x4x3/8	0.26	CF	4.42	CF

1	24.505	WT10.5x46.5	2.27	CF	2.27	CF
3	24.505	WT10.5x46.5	2.28	CF	6.84	CF
25	24.505	WT10.5x46.5	2.29	CF	57.25	CF
21	24.505	WT10.5x46.5	2.3	CF	48.3	CF
50	27.833	WT10.5x41.5	2.33	CF	116.5	CF
11	29.172	WT10.5x41.5	2.34	CF	25.74	CF
25	29.172	WT10.5x41.5	2.4	CF	60	CF
10	29.172	WT10.5x41.5	2.41	CF	24.1	CF
4	29.172	WT10.5x41.5	2.44	CF	9.76	CF
25	49.000	WT10.5x46.5	4.6	CF	115	CF
		Volume in Tons			147.58	
		Volume in CF			602.38	

Appendix C: How to Export Quantity "Schedules" From Revit

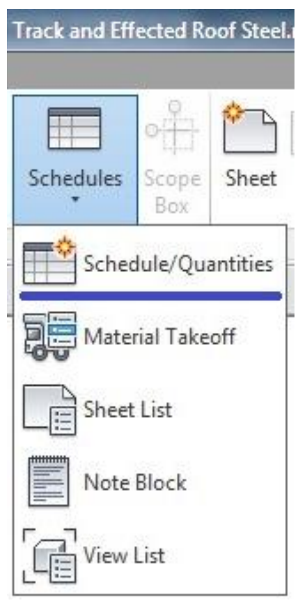
Step 1: Choose the View Tab in Revit.

The Schedules button will be on the right side of the task bar.



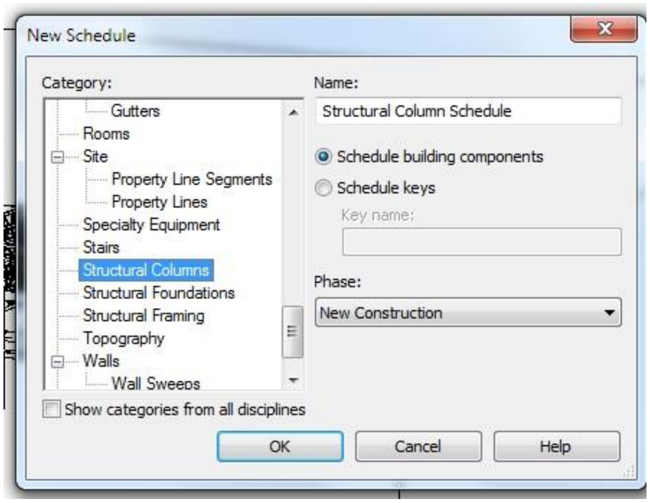
Step 2: Choose the Schedules button and when it drops down, select "Schedules/Quantities."

It is underlined in blue.



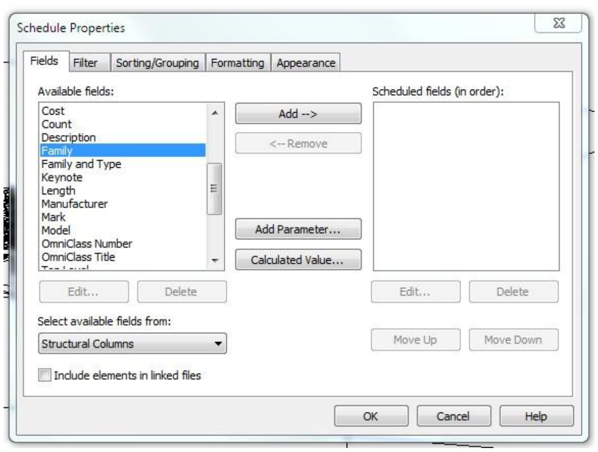
Step 3: Choose which type of schedule you would like.

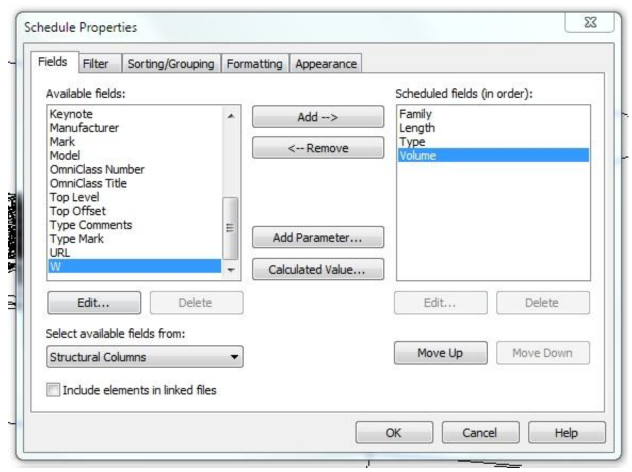
A small window will pop up and it is possible to scroll and choose from many types of schedules to take quantities of. As seen below, Structural Columns were chosen.



Step 4: Choose the categories to be exported.

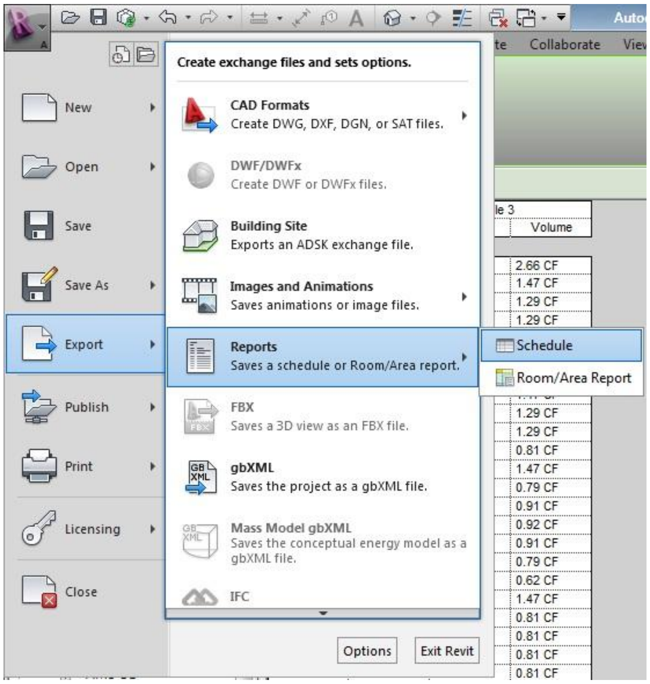
These options will pop up in another window. The figure below on the left is the initial window that will pop up. The figure on the right shows how it looks after different properties have been added using the "Add" button.





Step 5: Export the schedule shown out of *Revit*.

By clicking the large R that represents the main menu in *Revit*. The picture shown below has all of the necessary items highlighted in blue. In the background, what the schedule of the columns will look like can be seen when it appears. Once the "Schedule" button is selected to export, a window will appear asking where the document should be saved.



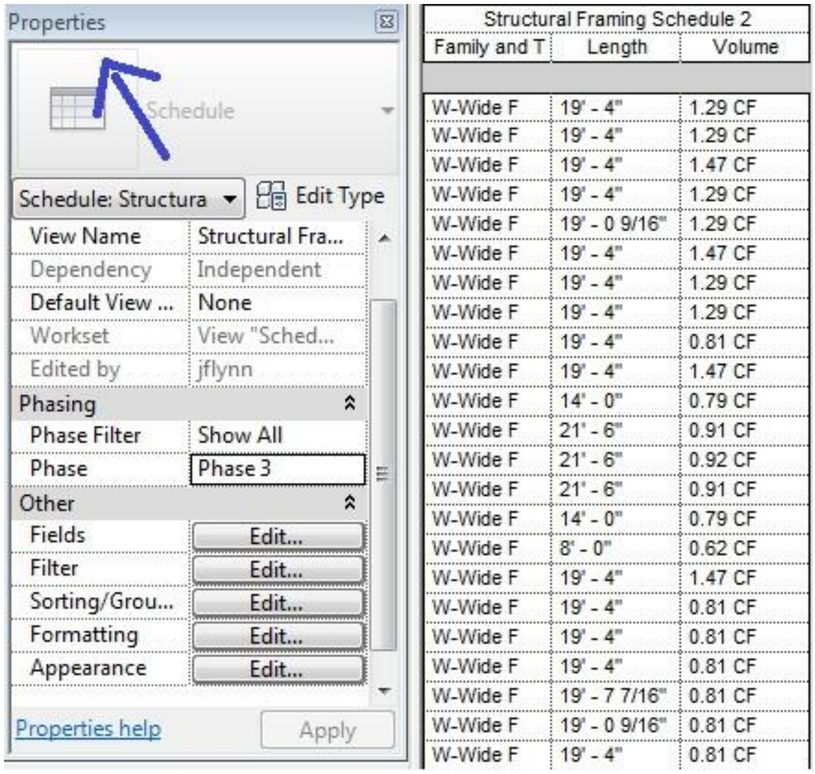
Step 6: Putting the schedule information into Microsoft Excel.

The information will export as a .txt document. If you highlight all of the information exported and paste it into Excel, Excel will organize the information into different rows and columns. From this point, the information can be organized and used as it wanted by the user.

If only certain Phase information is wanted follow the next instructions.

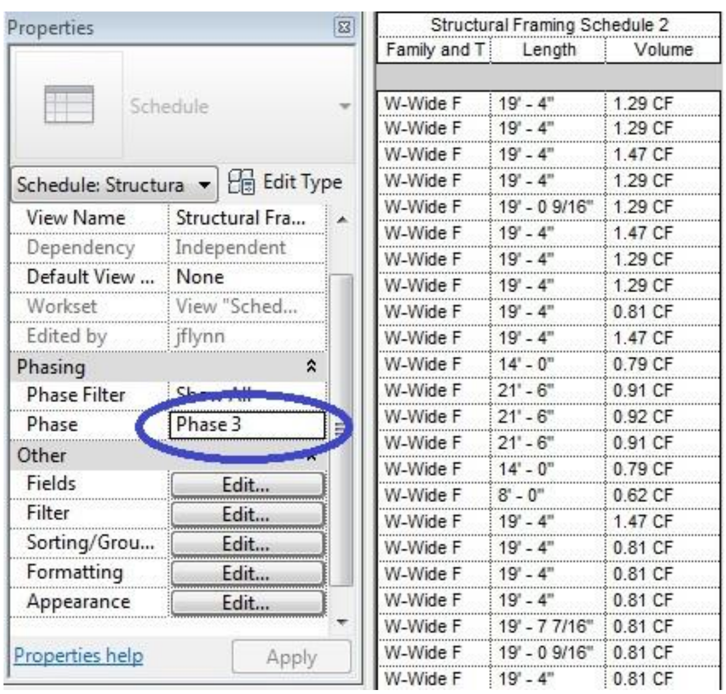
Step 7: Go to the properties toolbar on the left side of the screen.

After producing the schedule look to the left side of the screen in the properties toolbar.



Step 8: Choose the Phase that you want the information from.

There should be a dropdown menu where the blue circle is on the following figure. From the dropdown, any phase can be selected.



Family and T	Length	Volume
W-Wide F	19' - 4"	1.29 CF
W-Wide F	19' - 4"	1.29 CF
W-Wide F	19' - 4"	1.47 CF
W-Wide F	19' - 4"	1.29 CF
W-Wide F	19' - 0 9/16"	1.29 CF
W-Wide F	19' - 4"	1.47 CF
W-Wide F	19' - 4"	1.29 CF
W-Wide F	19' - 4"	1.29 CF
W-Wide F	19' - 4"	0.81 CF
W-Wide F	19' - 4"	1.47 CF
W-Wide F	14' - 0"	0.79 CF
W-Wide F	21' - 6"	0.91 CF
W-Wide F	21' - 6"	0.92 CF
W-Wide F	21' - 6"	0.91 CF
W-Wide F	14' - 0"	0.79 CF
W-Wide F	8' - 0"	0.62 CF
W-Wide F	19' - 4"	1.47 CF
W-Wide F	19' - 4"	0.81 CF
W-Wide F	19' - 4"	0.81 CF
W-Wide F	19' - 4"	0.81 CF
W-Wide F	19' - 7 7/16"	0.81 CF
W-Wide F	19' - 0 9/16"	0.81 CF
W-Wide F	19' - 4"	0.81 CF

Step 9: Click Apply

Step 10: Put information into Excel as described in Step 6.

Following Steps 5 and 6 from above, the information can be put into an excel file.

Appendix D: Example Using RS Means

This appendix is meant to show how RS Means was used for our use in applying it to the schedules exported out of *Revit.*

Step 1: Creating a spreadsheet that has all the basic details of each beam used in the model. Below is our table that details the Structural Column Members. Total LF was used as the unit of measure for many of the items in RS Means so we documented it in the table to make spreadsheet calculations more convenient.

COLUMN BREAKDOWN		
TYPE OF COLUMN	COUNT	TOTAL LF
HSS1.900x0.120	62	789.750
W12x120	1	42.333
W12x152	1	42.333
W12x40	2	58.833
W12x53	7	210.000
W12x58	1	28.161
W12x65	15	485.917
W12x72	13	416.250
W12x87	1	42.333
W12x96	2	67.667

Step 2: Find cost multipliers in RS Means and apply to Material and Equipment categories. Using the data above, we copied the corresponding information from the *RS Means 2009: Heavy Construction* book. An example of what we copied down can be seen in the table below. The two rows seen are for HSS1.900X0.120 and W12x120.

RS MEANS COST MULTIPLIERS								
CREW	DAILY OUTPUT	LABOR-HOURS	UNIT	MATERIAL	LABOR	EQUIPMENT	TOTAL	PAGE
E-2	780	0.072	LF	6.1	3.13	2.23	11.46	PG. 102
E-2	960	0.058	LF	198	2.54	1.81	202.35	PG. 103

This table shows the cost multipliers that were necessary to complete the estimate. These numbers can be found on the page listed in the last column. For material and equipment, the cost multiplier could be directly multiplied by the Total LF for that beam. This will give the cost regarding that beam. The steps taken for the Labor was different.

Step 3: Find Crew Info and Apply to Labor Hours.

The crew information is found in one of the reference sections of the book and must be used to find the labor costs for each member. This step is different for labor than it is for the others because O & P is included. A data table for the crew can be seen below. The number that is highlighted in red is multiplied by the factors highlighted in red in the RS Means Cost Multiplier table (found in the previous step).

RS MEANS CREW DETAILS			
	Bare Costs		Cost Per Labor Hour
Crew E-2	Hr ($)	Daily ($)	Incl. O&P
1 Struc. Steel Foreman	46.70	373.60	74.44
4 Struc. Steel Workers	44.70	1430.40	
1 Equip Oper. (crane)	42.55	340.40	
1 Equip Oper. Oiler	36.80	294.40	
1 Lattice Boom Crane, 90 Ton		1741.00	34.20
56 L.H., Daily Totals		4179.80	108.63

By multiplying these two red numbers, the unit cost to do the labor can be determined. Once the unit cost is determined, it can be multiplied by the total linear feet. Because O&P is included here, it does not need to be added on at the end.

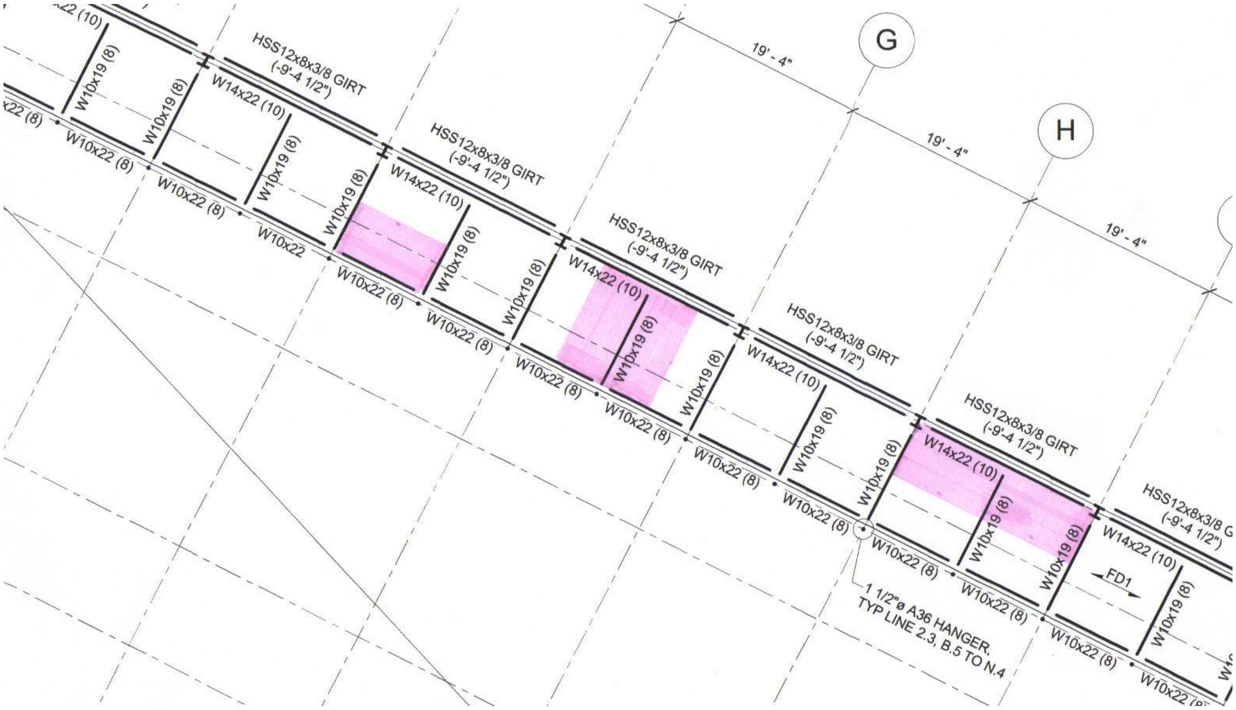
Step 4: Apply O & P to Material and Equipment

After summing the individual costs for each element, RS Means gave instructions to apply O&P to Material and Equipment by adding 10% to their totals. After this step, they can be summed to find the total cost for the structural columns.

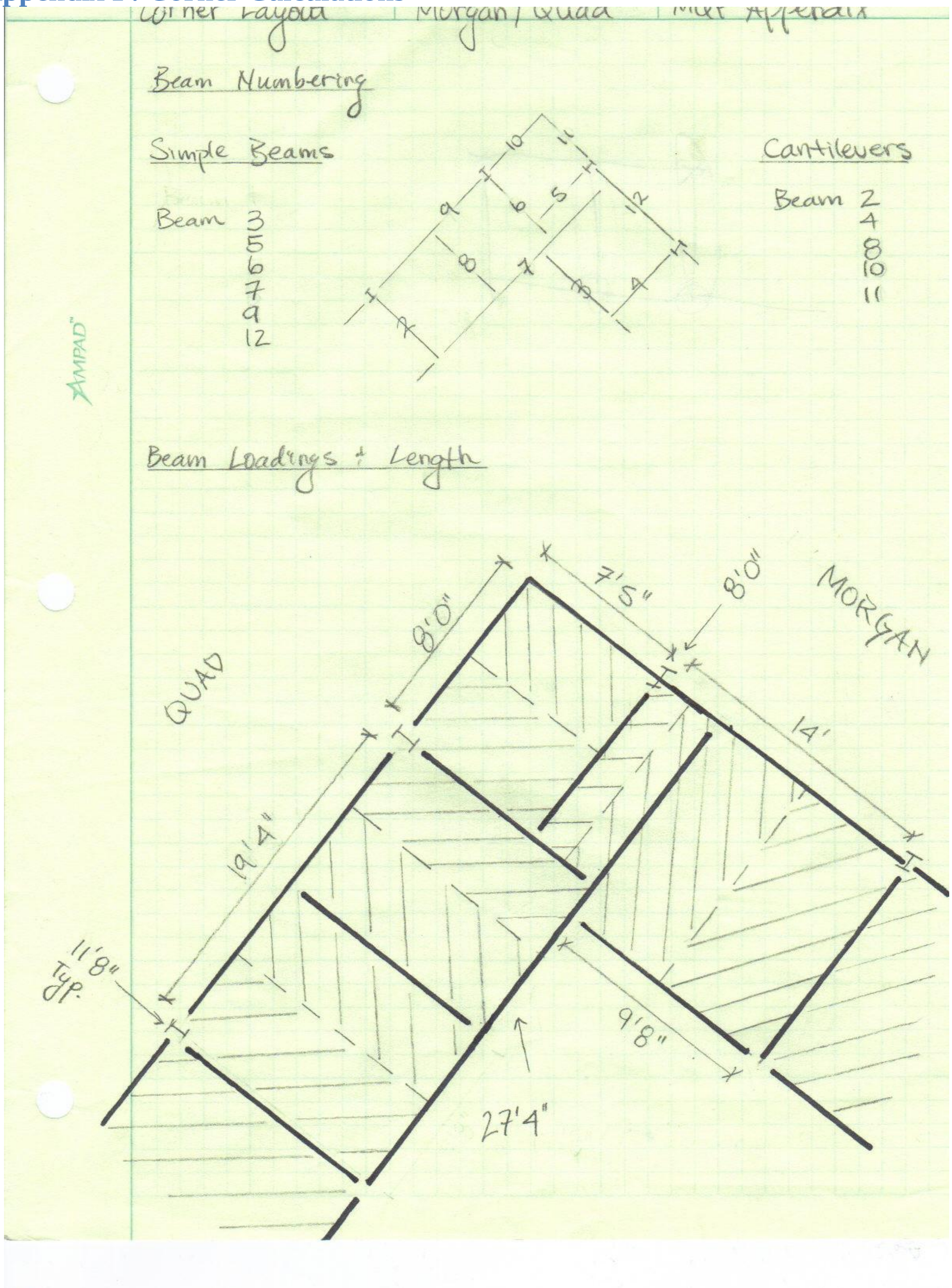
Step 5: Add Additional Factors to Overall Estimate

Once the structural columns, framing, and trusses were summed other factors had to be added. These included inflation (3.15%), connections (10%), and a welded truss percentage (4%). Once these factors were added, our estimate was complete.

Appendix E: Loading Schemes



Appendix F: Corner Calculations



Corner Design | M/Q Beam 3 | MQP Appendix

SIMPLE BEAM EXAMPLE

Beam 3 – 10x12
concrete slab = 4.5" thickness

steel decking = 3" @ 18 gague (parallel)

design load = 100psf

beam length = 9.67'

beam spacing = 5.83'

Loads

$LL = (100psf)(5.83') = 0.583\ k/ft$

DL = concrete + decking + ceiling

$= 331.4\ lb/ft + 15.7\ lb/ft + 29.2\ lb/ft = 0.376\ k/ft$

$w_u = 1.2D + 1.6L$

$= 1.2(.376) + 1.6(.583) = 1.38\ k/ft$

$M_u = \frac{w_u L^2}{8} = \frac{(1.38)(9.67)^2}{8} = 16.2\ ft \cdot k$

Assume $a = 2$; $y_{con} = 4.5"$

$y_2 = y_{con} - a/2 = 4.5" - 2/2 = 3.5"$

Try 10x12 => y_1 @ PNA = 7 (partial composite) = 1.31" (T3.19)

$\phi_b M_n = 71.5\ ft \cdot k$ (T3.19) @ $y_2 = 3.5"$, PNA = 7

$A = 3.54"$, $d = 9.87"$, $t_w = 0.190"$ (T1.1)

Check Critical Moment

$LL = 0.583\ k/ft$; $DL = 0.376 + 0.012 = 0.388$

$w_u = 1.2D + 1.6L = 1.2(.388) + 1.6(.583) = 1.40\ k \cdot ft$

$M_u = \frac{w_u L^2}{8} = \frac{(1.4)(9.67')^2}{8} = 16.35\ ft \cdot k < 71.5\ ft \cdot k = \phi_b M_n$

OK

Corner Design | M/Q Beam 3 | MQP Appendix

Composite Compacity

$\Sigma Q_n = 44.2$ (T3.19) $f'_c = 4000$ psi, 4 ksi

Effective Width

$b_E = 1/4(L) = 1/4(9.67')(12''/1') = 29.01''$

$a = \frac{\Sigma Q_n}{0.85 f'_c b_E} = \frac{44.2}{0.85(4)(29)} = 0.448''$

$y_2 = 4.5'' - 0.448/2 = 4.28''$

$y_{2\,low} = 4'' \Rightarrow 73.2$ ft·k $\frac{4.28'' - 4.5''}{4.0'' - 4.5''}(73.2 - 74.8) + 74.8$

$y_{2\,high} = 4.5'' \Rightarrow 74.8$ ft·k $\phi_b M_n = 74.1$ k·ft > 16.35 k·ft $= M_u$ OK

Studs ⇒ 3/4" φ studs

$Q_n = 21.5''$ (parallel deck - Table 3.21) GOVERNS

Check: $R_g R_p A_{sc} F_u = (1.0)(1.0)(.422)(65) = 28.72$

$\#\text{studs} = \frac{\Sigma Q_n}{Q_n} = \frac{44.2}{21.5} = 2.06 \Rightarrow 3\ \text{studs} \times 2 = 6$ studs

Deflection During Service

Live

$LL = 0.583$; $E = 29000$ ksi

$y_{2\,low} = 4.0 \rightarrow I_{LB} = 110''$

$y_{2\,hi} = 4.5 \Rightarrow I_{LB} = 117'' \Rightarrow y_2 = 4.28 \Rightarrow I_{LB} = 113.9''$

$\Delta = \frac{5wL^4}{384EI} = \frac{5(.583)(9.67')}{384(29000)(113.9)} = 0.034'' < 0.322'' = \frac{9.67'}{360} \times \frac{12''}{1'} = \frac{L}{360}$ OK

Dead+Live

$DL + LL = 0.388 + 0.583 = 0.971$ k/ft ; $I_{LB} = 113.9''$

$\Delta = \frac{5wL^4}{384EI} = \frac{5(.971)(9.67)^4}{384(29000)(113.9)} = 0.053'' < 0.484'' = \frac{9.67}{240} \times \frac{12''}{1'} = \frac{L}{360}$

OK

Corner Design | M/Q Beam 3 | MQP Appendix

During Construction

DL = Beam wt + decking = 12 lb/ft + (2.7)(9.67') = 27.7 lb/ft

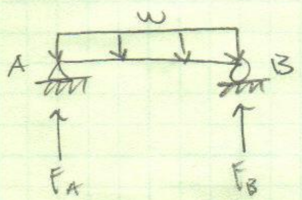
LL = conc wet = 389.69 lb/ft ; I_x = 53.8

$w_u = 1.2(D) + 1.6(L) = 1.2(27.7) + 1.6(389.69) = 417.43$ lb/ft

$M_u = \frac{wL^2}{8} = \frac{(417.43)(9.67)^2}{8} = 4.88$ k·ft < 71.5 k·ft

OK

$\Delta = \frac{5wL^4}{384EI} = \frac{5(417.43)(9.67')^2}{384(29000)(53.8)} = 0.0526" < 0.3223" = \frac{9.67'}{360} \times \frac{12"}{1} = \ldots$



w = factored loads = 0.012 k/ft

P = 0.012 × 9.67' = 0.116 k

$\circlearrowleft M = -(.116)(5.83') + (F_B)(9.67')$

F_B = 0.058 k

$\Sigma F_y = F_A - .116 + .058$

F_A = 0.058 k

Corner Design | M/Q Beam 4 | MQP Appendix

CANTILEVER EXAMPLE

concrete slab = 4.5" Beam4 - 18x35

steel decking = 3" @ 18 gague (parallel)

design load = 100psf

beam length = 11.67'

beam spacing = 9.67'

AMPAD

Loads

$LL = (100psf)(9.67') = 0.967\ k/ft$

DL = concrete + decking + ceiling + piping + Quad Track + Beam 3

$= 331.4\ lb/ft + 15.7\ lb/ft + 29.2\ lb/ft + 96.70\ lb/ft + 9.94 + 29.4$

$0.760\ k/ft$

$W_U = 1.2D + 1.6L = 1.2(.760) + 1.6(.967) = 2.461\ k/ft$

$M_U = \frac{W_U L^2}{2} = \frac{(2.46)(11.67)^2}{2} = 167.50\ ft \cdot k$

$Z_x > \frac{M_U}{\phi F_y}$; $\phi = 0.9$, $F_y = 50\ ksi$ TRY 18x35

$Z_x = \frac{(167.50)}{(0.9)(50)}\left(\frac{12''}{1'}\right) = 44.66\ in^3 < 65\ in^3$

OK

Updated W_U

New $DL = 0.760 + 0.035 = 0.795$

$W_U = 1.2D + 1.6L = 1.2(.795) + 1.6(.967) = 2.501$

$M_U = \frac{WL^2}{2} = \frac{(2.50)(11.67')}{2} = 170.34\ k\,ft$

New $Z_x \geq \frac{(170.34)}{(0.90)(50)}\left(\frac{12''}{1'}\right) = 45.42\ in^3 < 66.5\ in^3$

OK

Corner Design | M/Q Beam 4 | MQP Appendix

FLB

$\frac{b_f}{2t_f} < 0.38\sqrt{\frac{E}{F_y}}$; E=29000 ksi Fy=50ksi

$\frac{b_f}{2t_f} = 7.06"$ (T1.1)

$7.06" < .38\sqrt{\frac{29000}{50}}$

7.06 < 9.15 OK

WLB

$\frac{h}{t_w} < 3.76\sqrt{\frac{E}{F_y}}$ $\frac{h}{t_w} = 53.5$ (T1.1)

$53.5 < 3.76\sqrt{\frac{29000}{50}}$

53.5 < 90.55 OK

Deflection - Service

LL= 0.967 k/ft

$\Delta = \frac{wL^4}{8EI} = \frac{(.967)(11.67^4)}{8(29000)(510)} = 0.262" < 0.389" = \frac{11.67'}{360}\left(\frac{12"}{1'}\right) = \frac{L}{360}$ OK

DL+LL = 0.967 + 0.795 = 1.762 k/ft

$\Delta = \frac{wL^4}{8EI} = \frac{(1.76)(11.67)^4}{8(29000)(510)} = 0.477" < 0.584" = \frac{11.67'}{240}\left(\frac{12"}{1'}\right) = \frac{L}{240}$ OK

During Construction

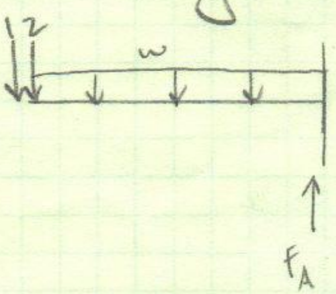
DL= 61.1 lb/ft ; LL= 646.37 lb/ft

W = DL+LL = 61.1 + 646.37 = 0.707 k/ft

$M_o = \frac{wL^2}{2} = \frac{.707(11.67)^2}{2} = 48.17 < 169.37$ k-ft OK

$\Delta = \frac{wL^4}{8EI} = \frac{(.707)(11.67)^4}{8(29000)(510)} = .192" < .389 = \frac{L}{360}$ OK

Corner Design | M/Q Beam 4 | MQP Appendix



1 = Beam wt from Morgan Track = 16 lb/ft

=> converted to w => 0.029 k/ft

2 = Beam wt from Beam 3 = 12 lb/ft

=> converted to w => 0.010 k/ft

DL = concrete + decking + piping + ceiling + beam wt

= 549.7 lb/ft + 26.11 lb/ft + 96.70 lb/ft + 48.35 + 35

= 0.795 k/ft

LL = (100 psf)(9.67') = 0.967 k/ft

Total W_u = 1.2D + 1.6L = 1.2(.795) + 1.6(.967)

= 2.501

conc load = (2.501)(9.67') = 24.192k (2) = 48.384k

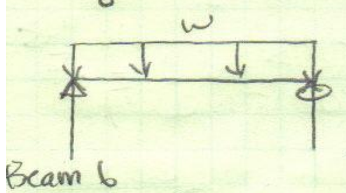
@ column

Corner Design | M/Q Beam | MQP Appendix

Beam 5

Simple Beam Example

Try 10x12



length = 8 ft

spacing = 1.67'

DL = conc + deck + ceiling + piping + beam wt

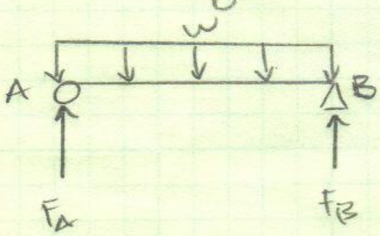
= 94.9 + 4.5 + 8.4 + 16.7 + 12

= .135 k/ft

LL = (100 psf)(1.67') = 0.167 k/ft

$W_u = 1.2D + 1.6L = 1.2(.135) + 1.6(.167) = 0.429 \text{ k/ft}$

$M_u = \frac{wL^2}{8} = \frac{(.429)(8')^2}{8} = 3.43 \text{ ft}\cdot\text{k} < 71.5 = \phi_b M_n$ OK



w = uniform load = .429 k/ft (8) = 3.432k = w_p

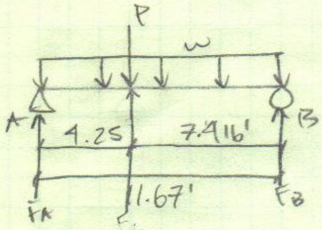
$F_A = F_B = 1.716^k$

Beam 6 (simple beam) 10x12

length = 11.67'

$\text{span} = \frac{(4.83)(11.67') + (4.83')(7.416)}{11.67'} = 7.90'$

Corner Design | M/Q Beam 6/7 | MQP Appendix [8?]



$P = 1.716^k$

$w_u = 1.2D + 1.6L = 1.2(.537) + 1.6(.790)$

$= 1.908^{k}/ft$

$w_{u_P} = 1.908(11.67') = 22.27^k$

$\circlearrowleft + M_A = (-1.716)(4.25) - (22.27)(5.83') + (F_B)(11.67')$

$F_B = 10.51^k$

$\Sigma F_y = F_A - 1.716^k - 22.27 + 10.51$

$F_A = 13.475^k$

DL = conc deck + ceiling + piping + beam wt

$= 449.1 + 21.3 + 39.5 + 77 + 12$

$= 0.537^k$

$LL = (100psf)(7.90) = .790^{k}/ft$

$w_u = 1.2(DL) + 1.6(LL) = 1.2(.537) + 1.6(.790) = 1.908^{k}/ft$

$M_u = \frac{wL^2}{8} = \frac{(1.908)(11.67)^2}{8} = 32.49$ ft·k

$M_{u\,point} = \frac{Pab}{l} = \frac{(1.716)(4.25)(7.416)}{11.67} = 4.63$ ft·k

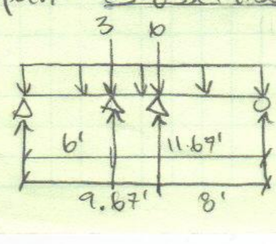
$M_{u\,tot} = 32.49 + 4.63 = 37.12 < 71.5$ ft·k $= \phi_b M_n$ 10x12

OK

Beam 7 (simple beam) 14x22

length = 27'4" or 27.33'

span = $\frac{(5.83)(19.33') + (4.83)(11.67) + (8)(2.125)}{27.33'} = 6.67'$



$3 = 0.058^k$

$6 = 13.475^k$

Corner Design | M/Q Beam 7 | MQP Appendix 9

DL = conc + deck + ceiling + piping + beam wt

= 387 + 18.4 + 34 + 68.10 + 19 = .473 k/ft

LL = 100psf (6.67') = .667 k/ft

$W_u = 1.2D + 1.6L = 1.2(.473) + 1.6(.667) = 1.657$ k/ft

$M_u = \frac{W_u L^2}{8} = \frac{(1.657)(17.67')^2}{8} = 64.68$ ft·k

Mom

$P_{L3} = \frac{Pab}{L} = \frac{(0.058)(6)(11.67)}{17.67} = 0.23$ ft·k

$P_{L6} = \frac{Pab}{L} = \frac{(13.475)(8)(9.67)}{17.67} = 59.0$ ft·k

Total M = 63.45 + 0.23 + 59 = 123.91 ft·k < 135 ft·k = $\phi_b M_n$

OK

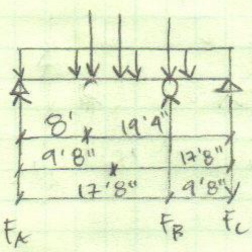
12x19

Transfer Span $= \frac{(1.125)(8) + (11.67)(4.83')}{21.67'} = 3.386'$

DL = conc + deck + ceiling + piping + beam wt

= (145)(4.5/12) − 2.7)(1.1)(3.22) + (2.7)(3.22)
+ (15)(3.22) + 19

= 0.262 k/ft



LL = ((100psf)(3.22) = .322 k/ft

$W_u = 1.2D + 1.6L = 1.2(.250) + 1.6(.322) = 0.856$ k/ft

Indeterminate ⇒ RISA

F_A = 5.82k (Beam 12)

F_B = 10.60k (Beam 8)

F_C = 2.88k (downward) (Beam 2)

Beam 8 (Simple Beam)

DL = conc + deck + ceiling + piping + beam wt

= 549.7 + 26.11 + 48.35 + 96.90

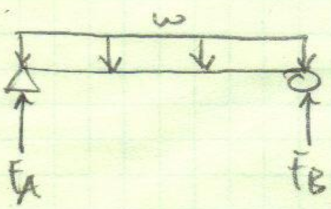
= 0.639

Corner Design | Beam 8 | MQP Appendix | 1(

$LL = (100\,psf)(9.67') = 0.967\ ^k/ft$

$W_u = 1.2(.639) + 1.6(.967) = 2.31^k$

$M_u = \frac{wL^2}{8} = \frac{(2.31)(11.67^2)}{8} + 10.60 = 50.0\ ft\cdot k$



$w = 2.31^k(11.67) = 27.17^k$

$F_A = F_B = 13.58^k$

Beam 9 fixed beam (12x14)

DL = conc + deck + ceiling + beam wt

$= 331.4 + 15.7 + 29.2 + 16 = .392\ ^k/ft$

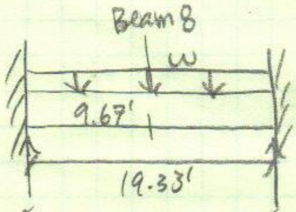
$LL = 100\,psf(5.83') = .583\ ^k/ft$

$W_u = 1.2D + 1.6L$

$= 1.2(.392) + 1.6(.583) = 1.40 + (13.58/19.33) = 2.10\ ^k/ft$

$M_u = \frac{wL^2}{8} = \frac{(2.10)(19.33^2)}{8} = 98.4\ ft\cdot k < 111\ ft\cdot k$

OK



$(+ M_A = (9.67')(13.58^k) + (-2.10^k/ft)(19.33')(9.67) + F_B(19.33)$

$F_B = 13.572^k$

$\Sigma F_y = -13.58 - 40.72 + 13.572 + F_A$

$F_A = 13.572^k$

Corner Design | Beam 2/10 | MQP Appendix

Beam 2 (cantilever)

DL = conc + deck + ceiling + piping + Quad straight + beam wt

$= 549.7 + 26.11 + 48.35 + 96.70 + 23.19 + 35$

$= 0.779\ ^k/ft$

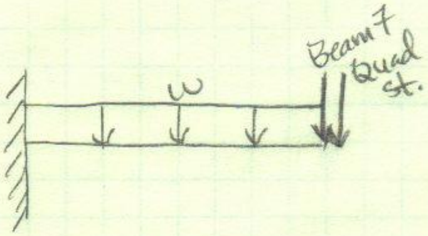
LL = 100psf(9.67') = 0.967 $^k/ft$

$W_u = 1.2(.779) + 1.6(.967) - .494\ ^k/ft$ ← Beam 7

$= 1.988\ ^k/ft$

$M_u = 135.36^k \cdot ft \Rightarrow Z_x = \frac{M_u}{\Phi F_y} = \frac{(135.36)}{(0.9)(50)} = 36.10\ in$ < 66.5 in³

OK 18x35



$W_u = 1.988\ ^k/ft\ (11.67') = 23.198^k (2) = 46.396^k$ @ column

Beam 10 (cantilever) 10x12

DL = conc + deck + ceiling + beam wt

$= 210.8 + 10.01 + 18.54 + 12$

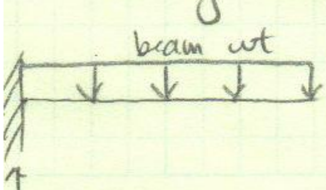
$= 0.251\ ^k/ft$

LL = 100psf(3.708) = 0.3708 $^k/ft$

$W_u = 1.2(.251) + 1.6(.3708) = 0.895\ ^k/ft$

$M_u = \frac{wL^2}{2} = \frac{(.895)(8')}{2} = 28.64\ k \cdot ft$

$Z_x = \frac{M_u}{\Phi F_y} = \frac{28.64}{(0.9)(50)} = 7.64\ in^3 < 12.6\ in^3$ OK



(12 lb/ft)(8') = 96 lb (2) = 0.192 k @ column

Corner Design | Beam 11/12 | MQP Appendix

Beam 11 (cantilever) 10x12

DL = conc + deck + ceiling + beam wt

= 227.4 + 10.80 + 20 + 40

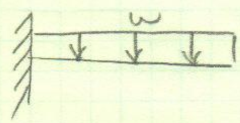
= .298 k/ft

LL = (100 psf)(4) = 0.4 k/ft

$w_u = 1.2(.298) + 1.6(.4) = 1.0$ k/ft

$M_u = \frac{w_u L^2}{2} = \frac{(1)(7.5)^2}{2} = 28.1$ k·ft

$Z_x = \frac{M_u}{(\phi)(F_y)} = \frac{28.1}{(.9)(50)} = 7.48 \text{ in}^3 < 12.6 \text{ in}^3$ OK



w = 1.0 k/ft (7.5') = 7.5k (2) = 15k @ column

Beam 12 (simple beam) 10x12

DL = conc + deck + ceiling + beam wt

= 99.5 + 4.7 + 8.8 + 12 = 0.125k

LL = 100 psf (1.75') = 0.175k

$w_u = 1.2D + 1.6L = 1.2(.125) + 1.6(.175)$

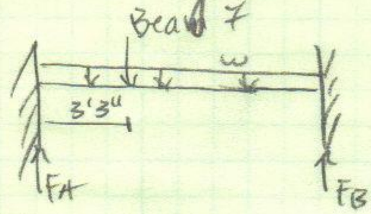
= 0.420 k/ft

$M_u = \frac{wL^2}{8} = \frac{(.420)(14)^2}{8} = 10.2$ k·ft

$M_{u_7} = \frac{Pab^2}{L^2} = \frac{(5.8)(4.75)(9.67)^2}{14^2} = 11.80$ k·ft

$M_{Tot} = 10.2 + 11.80 = 21.98$ k·ft < 71.5 k·ft OK

Corner Layout | Morgan/Quad | MQP Appendix



$w = 0.42^k/ft\,(14) = 5.82^k$ @ $7'$

Beam $7 = 5.82^k$ @ $3'3"$

$\circlearrowleft + M = (5.82)(3'3") + (-5.82)(7') + (F_B)(14)$

$F_B = 4.30^k$

$\Sigma F_y = -5.82 - 5.82 + 4.30 + F_A$

$F_A = 7.340^k$

Appendix G: Cantilever Method Calculations

Alt Track Design | End Beams | MQP Appendix

concrete slab = 4.5" slab thickness

steel decking ≟ 3" 18 gauge   length = 9'8" or 9.67'

design load = 100 psf   span = 5'10" or 5.83'

<u>Loads</u>

LL = (100 psf)(5.83') = 0.583 k/ft

DL ⇒ concrete = [(145 pcf)(4.5"/12") − 2.7 psf](1.1)(5.83')
  = 331.6 lb/ft   (1.1 ↑ ponding)

decking = (2.7 psf)(5.83')
  = 15.7 lb/ft

Total DL = 331.6 lb/ft + 15.7 lb/ft = 0.347 k/ft

<u>Load Combination</u>

$\omega_u = 1.2D + 1.6L \Rightarrow 1.2(.347\ k/ft) + 1.6(.583\ k/ft)$
$= 1.35\ k/ft$

<u>Critical Moment</u>

$M_u = \frac{W_u L^2}{8} = \frac{(1.35\ k/ft)(9.67)^2}{8} = 15.8\ ft \cdot k$

Assume $a = 2$

$y_{con} = 4.5"$

$y_2 = y_{con} - a/2 = 4.5" - 2/2 = 3.5"$

Try 10×12 → y_1 @ PNA = 7 (partial composite) = 2.61"

$\phi_b M_n = 71.5\ k \cdot ft$ (Table 3.19) @ $y_2 = 3.5"$, PNA = 7

$A = 3.54\ in^2$ (Table 1.1)

$d = 9.87\ in$

$t_w = .190\ in$

Alt Track Design | End Beams | MQP Appendix | 2

Composite capacity

$\Sigma Q_n = 44.2$ (T3.19) $f'_c = 4000$ psi, 4 ksi

Effective Width

$b_E = 1/4(L) = 1/4(9.67')(12''/1') = 29.01''$

$a = \frac{\Sigma Q_n}{0.85 f'_c b_E} = \frac{44.2}{0.85(4)(29)} = 0.448''$

$y_2 = 4.5'' - 0.448/2 = 4.28''$

$y_{2\,low} = 4'' \Rightarrow 73.2$ ft·k $\frac{4.28''-4.5''}{4.0''-4.5''}(73.2-74.8)+74.8$

$y_{2\,high} = 4.5'' \Rightarrow 74.8$ ft·k $\phi_b M_n = 74.1$ k·ft > 16.35 k·ft $= M_u$ OK

Studs ⇒ 3/4" ϕ studs

$Q_n = 21.5''$ (parallel deck - Table 3.21) GOVERNS

Check: $R_g R_p A_{sc} F_u = (1.0)(1.0)(.422)(65) = 28.72$

$\#\text{studs} = \frac{\Sigma Q_n}{Q_n} = \frac{44.2}{21.5} = 2.06 \Rightarrow 3 \text{ studs} \times 2 = 6$ studs

Deflection During Service

Live

$LL = 0.583$; $E = 29000$ ksi

$y_{2\,low} = 4.0 \rightarrow I_{LB} = 110''$

$y_{2\,hi} = 4.5 \Rightarrow I_{LB} = 117'' \Rightarrow y_2 = 4.28 \Rightarrow I_{LB} = 113.9''$

$\Delta = \frac{5wL^4}{384EI} = \frac{5(.583)(9.67')}{384(29000)(113.9)} = 0.034'' < 0.322'' = \frac{9.67'}{360} \times \frac{12''}{1'} = \frac{L}{360}$ OK

Dead + Live

$DL + LL = 0.388 + 0.583 = 0.971$ k/ft ; $I_{LB} = 113.9''$

$\Delta = \frac{5wL^4}{384EI} = \frac{5(.971)(9.67)^4}{384(29000)(113.9)} = 0.053'' < 0.484'' = \frac{9.67}{240} \times \frac{12''}{1'} = \frac{L}{360}$

OK

1st

Alt Track Design | End Beams | MQP Appendix

$Q_n = 21.5^k$ (parallel deck - Table 3.21)

Check: $R_g R_p A_{sc} F_u = (1.0)(0.6)(0.442)(65) = 28.72$

Deflection - During Service

$LL = 100 psf \rightarrow w_L = 100 psf (5.83') = 0.583 ^k/ft$

$M_L = \frac{(0.583^k/ft)(9.67')^2}{8} = 6.82 \; k \cdot ft$

AISC Table 3-20 (W10x2; PNA-7)

$y_2 = 4.5''$ $I_{LB} = 117$ $\frac{4.15'' - 4.5''}{4.0'' - 4.5''}(267-280)+280$

$y_2 = 4.0''$ $I_{LB} = 110$

$274.6 \; in^4$ = Actual I_{LB}

$\Delta L = \frac{M_L L^2}{CI} = \frac{(6.82)(9.67')^2}{(161)(274.6)} = 0.014''$

$\wedge$

$\frac{L}{360} = \left(\frac{9.67'}{360}\right)\left(\frac{12''}{1'}\right) = 0.322''$ OK

During Construction

DL = weight of beam: 19 lb/ft

LL = 331.06 lb/ft + (20 psf × 5.83') = 448.22

wet concrete   workers + equipment

$w = DL + LL = 19 + 448.12 = 467.22 \; lb/ft$

$M_u = \frac{wL^2}{8} = \frac{(467.22)(9.67')}{8} = 5.46 \; k \cdot ft < 138.6$

$\Delta = \frac{M_u L^2}{CI_x} = \frac{(5.46)(9.67)^2}{(161)(130)} = 0.024''$

$\wedge$

$\frac{L}{360} = \frac{(9.67')}{360}\left(\frac{12''}{1'}\right) = 0.322''$ OK

Alt Track Design & Cantilevers | MQP Appendix

concrete decking = 4.5" slab thickness
steel decking = 3" 18 gague   length = 11'8" or 11.67'
floor length   span = 9'8" or 9.67'
girder design – partial composite

Loads

LL ⇒ (100 psf)(9.67 ft) = 967 p/f or 0.967 k/ft

DL ⇒ concrete = [(145 pcf)(4.5"/12") − 2.7 psf](1.1)(9.67') ← ponding
= 549.7 p/f

decking = (2.7 psf)(9.67')
= 26.1 p/f

Total DL = 549.7 p/f + 26.1 p/f + 19 p/f (end beam wt) = 0.595 k/ft

Load Combination ⇒

$W_u = 1.2D + 1.6L \Rightarrow 1.2(0.595) + 1.6(0.967)$
$= 2.26$ k/ft

Critical Moment

$M_u = \frac{W_u L^2}{2} = \frac{(2.26)(11.67)^2}{2} = 154.2$ ft·k

$Z_x \geq \frac{M_u}{\phi F_y}$; $\phi = 0.9$, $F_y = 50$ ksi

$Z_x \geq \frac{(154.2'k)}{(0.9)(50ksi)}\left(\frac{12"}{1'}\right) = 41.12 \text{ in}^3$

Table 3-2 ⇒ Try 18×35 w/ $Z_x = 66.5 \text{ in}^3$

Updated W_u

New DL = 595 lb/f + 26 lb/ft = 630 lb/ft

1st

Alt Track Design | ⊥ Cantilevers | MQP Appendix

$w_u = 1.2(.630) + 1.6(.467)$

$= 2.30$ k/ft

$M_u = \frac{(2.30 \text{ k/ft})(11.67 \text{ ft})^2}{2} = 156.82$ ft·k

$Z_x \geq \frac{156.82 \text{ ft·k}}{(0.9)(50 \text{ ksi})} \left(\frac{12''}{1'}\right)$

$Z_x \geq 41.82 \text{ in}^3$

$66.5 \geq 41.82 \text{ in}^3$ ✓ OK W18x35

Check FLB

$\frac{b_f}{2t_f} \leq 0.38\sqrt{\frac{E}{F_y}}$; $E = 29000$ ksi $F_y = 50$ ksi
$b_f/2t_f = 7.06''$ (T1-1)

$7.06'' \leq .38\sqrt{\frac{29000}{50}}$

$7.06'' \leq 9.15$ ✓ OK

Check WLB

$\frac{h}{t_w} \leq 3.76\sqrt{\frac{E}{F_y}}$; $E = 29000$ ksi, $F_y = 50$ ksi
$\frac{h}{t_w} = 53.5$ (T1-1)

$53.5 \leq 3.76\sqrt{\frac{29000}{50}}$

$53.5 \leq 90.55$ ✓ OK

Deflection LL = 0.967 k/ft DL = 0.626 k/ft ; $I_x = 510$ (T1.1

$\Delta_{LL} = \frac{WL^2}{8EI} = \frac{(.967)(11.67')}{8(29000)(510)}(1728) = 0.262$

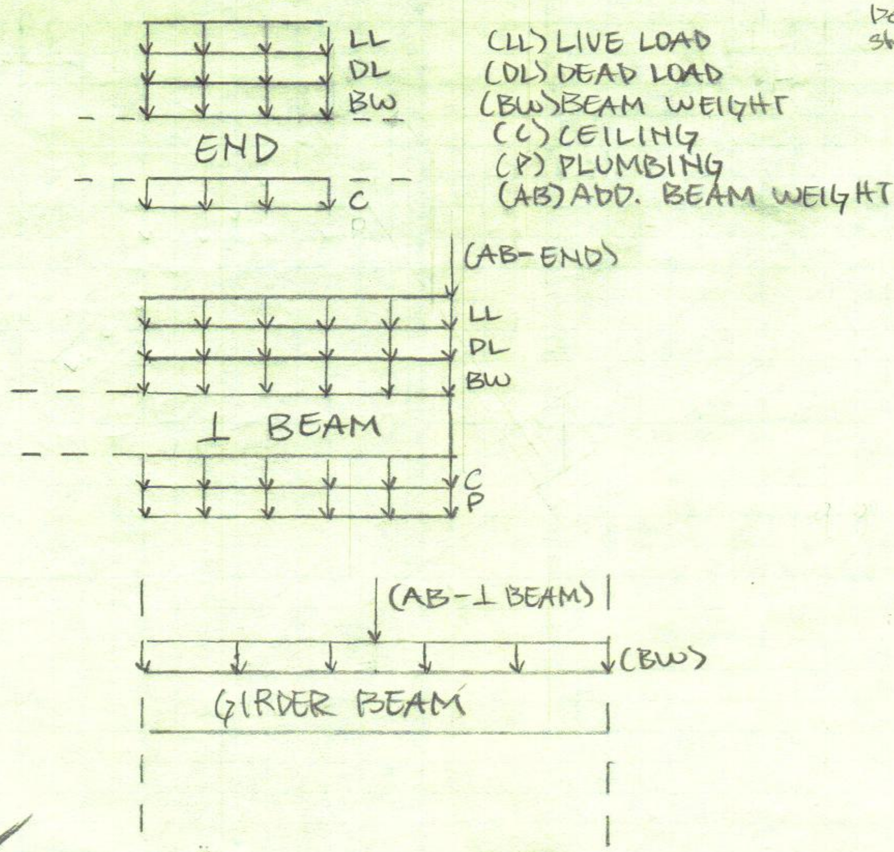
$\frac{L}{360} = \frac{11.67'}{360}\left(\frac{12''}{1'}\right) = 0.389$ OK

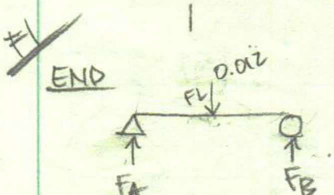
$\Delta_{TL} = \frac{WL^2}{8EI} = \frac{(1.593)(11.67')}{8(29000)(510)}(1728) = 0.433''$

$\frac{L}{240} = \frac{11.67'}{240}\left(\frac{12''}{1'}\right) = 0.584''$ OK

Alt Track Design | Beam Loading | MQP Appendix

Beam overlap
shear studs girder





DL = beam wt = 12 lb/ft = 0.012 k/ft

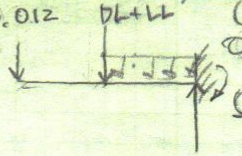
$\circlearrowleft + M_A = (-0.012)(5.83') + (F_B)(9.67')$

$F_B = 0.006^k$

$\Sigma F_y = -0.012 + 0.006 + F_A$

$F_A = 0.006^k \Rightarrow$ to cantilever

Alt Track Design | Beam Loading | MQP Appendix



$0.012 @ 11.67' = 0.024^k @ 5.83'$

$\frac{0.024^k}{11.67'} = 0.002^k/ft$

DL = concrete + decking + ceiling + piping + beam wt + (end beam)

= 549.7 lb/ft + 26.1 lb/ft + 48.4 lb/ft + 48.4 lb/ft + 44 lb/ft

= 0.668 k/ft

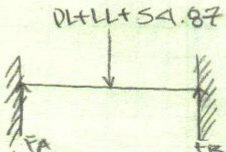
LL = 0.967 k/ft

FL = 1.2(0.668) + 1.6(0.967) + 0.002 k/ft

= 2.35 k/ft × (11.67')

Conc. L = 27.43^k (2) = 54.87

M_u =



$\frac{54.87^k}{19.33'} = 2.84^k/ft$

DL = concrete + decking + beam wt.

= 1098.8 lb/ft + 52.2 lb/ft + 50 lb/ft

= 1.201 k/ft

LL = 0.583 k/ft

FL = 1.2(1.201) + 1.6(0.583)

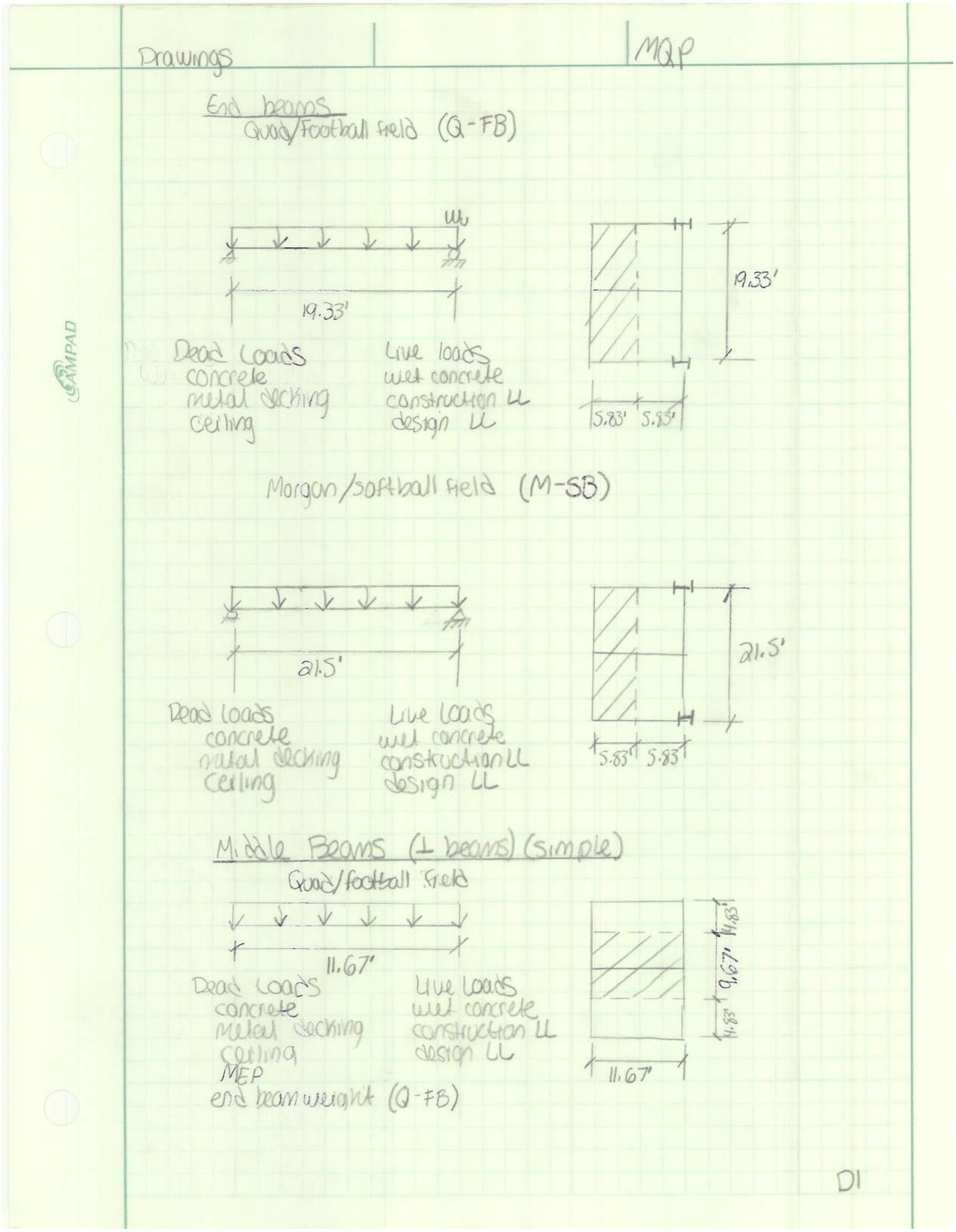
= 2.374 k/ft (19.33')

Conc. L = 45.89^k

$+M_A = (45.89^k)(9.67') - (F_y)(19.33')$

$F_A = F_B = 22.96^k$

Appendix H: Simple Beam Approach Hand Calculations



Drawings | MQP

End beams

Quad/Football field (Q-FB)

w_u

19.33'

19.33'

5.83' 5.83'

Dead Loads
- concrete
- metal decking
- ceiling

Live loads
- wet concrete
- construction LL
- design LL

Morgan/softball field (M-SB)

21.5'

21.5'

5.83' 5.83'

Dead loads
- concrete
- metal decking
- ceiling

Live loads
- wet concrete
- construction LL
- design LL

Middle Beams (⊥ beams) (simple)

Quad/football field

11.67'

11.67'

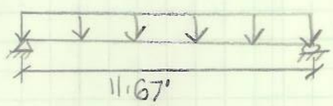
4.83' 9.67' 4.83'

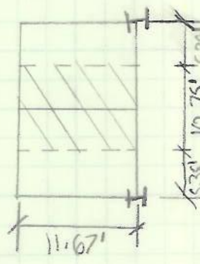
Dead Loads
- concrete
- metal decking
- ceiling
- MEP
- end beam weight (Q-FB)

Live Loads
- wet concrete
- construction LL
- design LL

D1

Morgan - Softball Field



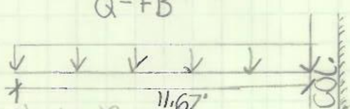


Dead Loads
concrete
metal decking
ceiling
MEP
end beam (M-SB)

Live Loads
wet concrete
construction LL
design LL

Middle Beam (⊥ beams) (cantilever)

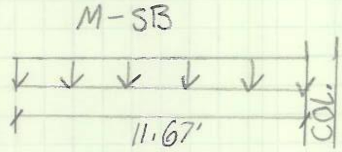
Q-FB

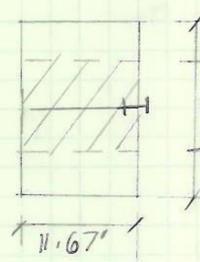


Dead Loads
concrete
metal decking
ceiling
MEP
end beam (Q-FB)

Live Loads
wet concrete
construction LL
design LL

M-SB

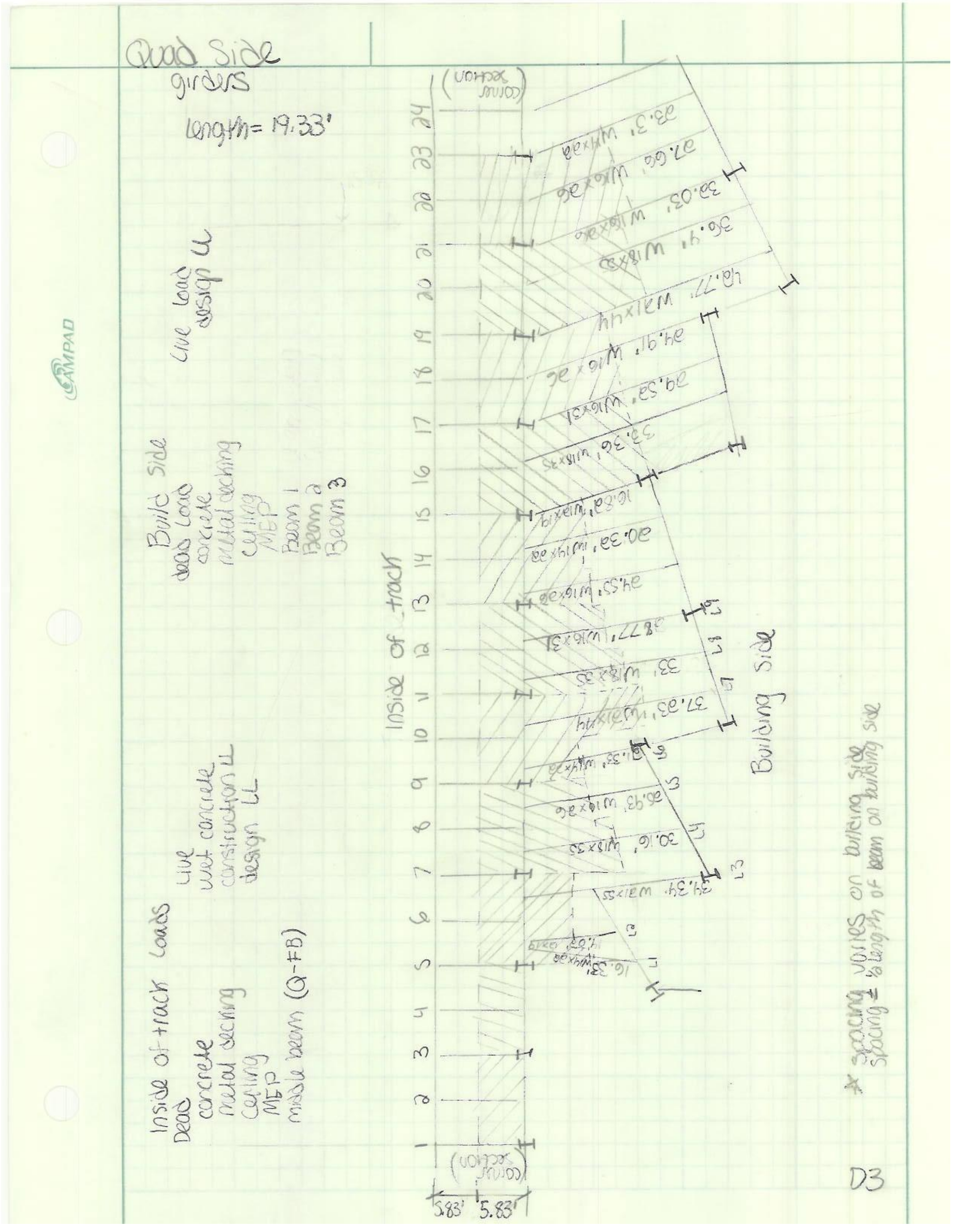




Dead Load
concrete
metal decking
ceiling
MEP
end beam (M-SB)

Live Loads
wet concrete
construction LL
design LL

D2


Quad Side
girders
length= 19.33'
Inside of track
Building Side
D3

Alt design track 2 | end beams (Quad/Ft) | MAP

Concrete Slab = 4.5"
Steel decking = 3"
Span = 19.33'
Spacing = 5.83'

F_y = 50 KSI
E = 29000 KSI

dead load
concrete = 145 pcf (4.5"/12) = (54.375 psf − 2.7 psf)(1.1)(5.83') = 331.39 lb/ft
metal decking = 2.7 psf (5.83') = 15.74 lb/ft
ceiling = 5 psf (5.83') = 29.15 lb/ft

DL total = 376.28 lb/ft

Live load
design = 100 psf (5.83') = 583 lb/ft

W_u = 1.2(376.28 lb/ft) + 1.6(583 lb/ft)
W_u = 1384.34 lb/ft
$M_u = \frac{1384.34 \text{ lb/ft} (19.33')^2}{8}$ = 64.66 k·ft

assume a = 2"
Y_2 = 4.5" − 2"/2 = 3.5"

try 12 x 14 $\phi_b M_n$ = 123 k·ft @ PNA = BFL, Y_2 = 3.5"
(table 3-19 AISC manual)

recheck M_u
W_u = 1.2(376.28 lb/ft + 14 lb/ft) + 1.6(583 lb/ft)
W_u = 1401.14 lb/ft
$M_u = \frac{1401.14 \text{ lb/ft} (19.33')}{8}$ = 65.44 k·ft

ΣQ_n = 119.0 kips (table T-3-19 AISC manual)
f'c = 4 KSI
be = 2(1/8)(19.33' x 12) = 29.00 in

$a = \frac{119 K}{0.85(4 KSI)(29.00 in)}$ = 1.21 in

Y_2 = 4.5" − 1.21"/2 = 3.90 in

Y_{2h} = 4" $\phi_b M_{nh}$ = 128 k·ft
Y_{2L} = 3.5" $\phi_b M_{nL}$ = 123 k·ft

1

end beams (quad/ft)

$\phi_b M_n = 123\,k\cdot ft + \left(\frac{3.5''-3.9''}{3.5''-4''}\right)(128-123) = 126.96\,k\cdot ft$

$\phi_b M_n = 126.96\,k\cdot ft > 65.44\,ft\cdot k = M_U$ ✓

deflection

$LL = 583\,lb/ft$

$Y2_n = 4''$ $I_{LB_n} = 238\,in^4$
$Y2_L = 3.5''$ $I_{LB_L} = 224\,in^4$

$I_{LB} = 224\,in^4 + \left(\frac{3.5''-3.9''}{3.5''-4''}\right)(238\,in^4 - 224\,in^4) = 235.1\,in^4$

$\Delta_{LL} = \frac{5(583\,lb/ft)(19.33')^4}{384(29000\,ksi)(235.1\,in^4)} \times \frac{1728\,in^3}{1\,ft^3} \times \frac{1k}{1000\,lb} = 0.269\,in$

$\Delta_{max} = L/360 = \frac{19.33' \times 12''}{360} = 0.644\,in$

$\Delta_{max} = 0.644\,in > 0.269\,in = \Delta_{LL}$ ✓

Total load $= 583\,lb/ft + 376.28\,lb/ft + 14\,lb/ft = 973.28\,lb/ft$

$\Delta_T = \frac{5(973.28\,lb/ft)(19.33')^4}{384(29000\,ksi)(235.1\,in^4)} \times \frac{1728\,in^3}{1\,ft^3} \times \frac{1k}{1000\,lb} = 0.448\,in$

$\Delta_{max} = L/240 = \frac{19.33' \times 12''}{240} = 0.967\,in$

$\Delta_{max} = 0.967\,in > 0.448\,in = \Delta_T$

Construction Loading construction $LL = 10\,psf$

$DL = 14\,lb/ft + 2.7\,psf(5.83') = 29.74\,lb/ft$
$LL = 331.39\,lb/ft + 10\,psf(5.83') = 389.69\,lb/ft$

$W_U = 1.2(29.74\,lb/ft) + 1.6(389.69\,lb/ft) = 659.20\,lb/ft$
$M_U = \frac{659.20\,lb/ft(19.33')^2}{8} = 30.79\,k\cdot ft$

$\phi_b M_n = 129.59\,k\cdot ft > 30.79\,k\cdot ft = M_U$

deflection
$I_x = 88.6\,in^4$ (table 1-1 AISC manual)

$\Delta_C = \frac{5(29.74\,lb/ft + 389.69\,lb/ft)(19.33')^4}{384(29000\,ksi)(88.6\,in)} \times \frac{1728\,in^3}{ft^3} \times \frac{1k}{1000\,lb}$

$\Delta_C = 0.51\,in$
$\Delta_{max} = L/360 = 0.644\,in$

$\Delta_{max} = 0.644\,in > 0.51\,in = \Delta_C$ ✓

2

end beams (Quad/ft)

Studs

Note: Cannon drawings
Max spacing = 24in
min spacing = 5.5in

$d = 3/4''$

$A = \frac{\pi(3/4'')^2}{4} = 0.44 in^2$

$R_p = 1.0$ parallel decking

$R_g = 1.0$

$F_u = 65 ksi$

$Q_n = 21.5 k$ (table 3.21 AISC manual) ← governs

$Q_n = 1.0(1.0)(65 ksi)(0.44) = 28.72 kips$

$n = \frac{119 k}{21.5 k} = 5.53 \rightarrow 6$ studs

total = 12 studs

$Spacing = \frac{19.33' \times 12''}{(12+1)} = 17.84 in$

$min = 5.5 in < 17.84 in < 24 in$ ✓

So use 12x14

3

End beams (Morgan-Softball)

concrete slab = 4.5"
steel decking = 3"
span = 21.50'
spacing = 5.83'

E = 29000 ksi
F_y = 50 ksi

Dead load
concrete = 145 pcf (4.5/12) = (54.38 − 2.7 psf)(1.1)(5.83')
= 331.39 lb/ft
metal decking = 2.7 psf (5.83') = 15.74 lb/ft
ceiling = (5 psf)(5.83') = 29.15 lb/ft

DL total = 376.28 lb/ft

Live Load
design load = 100 psf (5.83') = 583 lb/ft

$w_u = 1.2(376.28) + 1.6(583) = 1384.34$ lb/ft
$M_u = \frac{1384.34 \text{ lb/ft } (21')^2}{8} = 79.99$ k·ft

assume a = 2"
$Y2 = 4.5" - 2"/2 = 3.5"$

try W12 x 16
$\phi_b M_n = 127$ k·ft @ PNA Pos. 6 in web
(Table 3-19 AISC manual)

recheck Mu
$w_u = 1.2(376.28 + 16 \text{ lb/ft}) + 1.6(583 \text{ lb/ft})$
= 1403.54 lb/ft

$M_u = \frac{(1403.54)(21)^2}{8} = 81.10$ k·ft ✓

$\Sigma Q_n = 94.30$ k (Table 3-19)
$f'_c = 4$ ksi
$b_e = (1/8)(21' \times 12") = 32.25$ in

$a = \frac{94.30 \text{ k}}{.85(4)(32.25")} = 0.86$ in

$Y2 = 4.5" - 0.86"/2 = 4.07"$

$Y2_n = 4.5"$ $\phi_b M_n = 134$ k·ft
$Y2_L = 4.0"$ $\phi_b M_n = 131$ k·ft

4

end beams (morgan-softball)

$\Phi_b M_n = 131\ k\cdot ft + \left(\frac{4" - 4.28"}{4" - 4.5"}\right)(134 - 131)$

$= 132.71\ k\cdot ft > 81.10\ k\cdot ft = M_u$ ✓

Deflection

$LL = 583\ lb/ft$

$Y2_n = 4.5"$ $\quad I_{LBh} = 251\ in^4$

$Y2_L = 4"$ $\quad I_{LBL} = 238\ in^4$

$I_{LB} = 238\ in^4 + \left(\frac{4" - 4.28"}{4.5" - 4"}\right)(251 - 238)$

$= 254.4\ in^4$

$\Delta_{LL} = \frac{5(583\ lb/ft)(21')^4}{384(29000)(254.4)} = 0.403\ in.$

$L/360 = \Delta max = \frac{21' \times 12"}{360} = .717\ in > 0.403\ in$ ✓

Total load = 583 lb/ft + 376.28 lb/ft + 16 lb/ft

= 975.28 lb/ft

$\Delta_T = \frac{5(683.78\ lb/ft)(21)^4}{384(29000)(254.4)} = 0.674\ in$

$\Delta max = L/240 = \frac{21' \times 12"}{240} = 1.075\ in > 0.674\ in$ ✓

Construction Loading Cons. LL = 10 psf

DL = 16 lb/ft + 2.7 psf (5.83') = 31.74 lb/ft

LL = 331.39 lb/ft + 10 psf (5.83) = 389.69 lb/ft

$w_u = 1.2(31.74\ lb/ft) + 1.6(389.69\ lb/ft)$

$= 661.60\ lb/ft$

$M_u = \frac{(661.60\ lb/ft)(21')^2}{8} = 38.23\ k\cdot ft$

$\Phi_b M_n = 132.71\ k\cdot ft > 38.23\ k\cdot ft$ ✓

deflection

$I_x = 103.00\ in^4$ (Table 1-1 AISC manual)

5

$$\Delta_c = \frac{5(31.74\ lb/ft + 389.69\ lb/ft)(21)^4}{384(29000)(103\ in^4)}$$

$= 0.68$ in

$$\Delta_{max} = \frac{L}{360} = \frac{21' \times 12''}{360} = 0.72'' > 0.68'' \checkmark$$

studs

$d = 3/4''$

$A = \frac{\pi (3/4'')^2}{4} = .44\ in^2$

$F_u = 65$ ksi
$R_p = 1.0$
$R_g = 1.0$

Note from cannon drawings
max spacing = 24"
min spacing = 5.5"

$Q_n = 21.5$ k Table 3-21 parallel decking

$Q_n = (1.0)(1.0)(65\ ksi)(.44\ in^2)$
$= 28.72$ k

$n = \frac{94.30\ k\ (\Sigma Q_n)}{21.5\ k}$
$= 4.39$ studs use 5 studs

total = 10 studs

spacing $= \frac{21' \times 12''}{10+1} = 23.45''$

$5.5'' < 23.45'' < 25''$ ✓

use W12×16

6

Alt track design 2 | ⊥ beams simple (Quad-FB) MQP

Concrete Slab = 4.5in   Span = 11.67ft
Steel decking = 3.0in   Spacing = 9.67ft

F_y = 50KSI   ponding = 1.1
E = 29000 KSI

dead Loads
concrete = 145pcf(4.5"/12') = (54.375 psf − 2.7psf)(1.1)(9.67') = 549.67 lb/ft
metal decking = 2.7psf(9.67') = 26.11 lb/ft
ceiling = 5 psf(9.67') = 48.35 lb/ft
MEP, etc = 10psf(9.67') = 96.7 lb/ft
end beam = 14 lb/ft(19.33')(2)(1/2)(2)/11.67' = 46.38 lb/ft

Live Loads
design = 100 psf(9.67') = 967 lb/ft

DL = 767.21 lb/ft
LL = 967 lb/ft

$W_u = 1.2(767.21\text{ lb/ft}) + 1.6(967\text{ lb/ft}) = 2467.85\text{ lb/ft}$

$M_u = \frac{2467.85\text{ lb/ft}(11.67')^2}{8} = 42.01\text{ k·ft}$

assume a = 2in
$Y2 = 4.5" - 2"/2 = 3.5"$

try W10×12 $\phi_b M_n = 71.5\text{ k·ft}$ (table 3-19 AISC Manual)
PNA at 7

recheck Mu
DL = 767.21 lb/ft + 12 lb/ft = 779.21 lb/ft
LL = 967 lb/ft

$W_u = 1.2(779.21\text{ lb/ft}) + 1.6(967\text{ lb/ft}) = 2482.25\text{ lb/ft}$

$M_u = \frac{2482.25\text{ lb/ft}(11.67')^2}{8} = 42.26\text{ k·ft}$

$\Sigma Q_n = 44.3\text{ kips}$ (table 3-19 AISC Manual)
$f'c = 4\text{ KSI}$
$b_e = 2(1/8)(11.67' \times 12"/1') = 35.01in$

$a = \frac{44.3K}{0.85(4KSI)(35.01in)} = 0.37in$

$Y2 = 4.5" - 0.37"/2 = 4.31"$

7

1 beams simple (quad-FB)

$Y2_{hi} = 4.5''$ $\phi_b M_{n_L} = 73.2$ k·ft
$Y2_{low} = 4.0''$ $\phi_b M_{n_h} = 74.9$ k·ft

$\phi_b M_n = 73.2 + \left(\frac{4.0''-4.31''}{4.0''-4.5''}\right)(74.9-73.2) = 74.25$ k·ft
$\phi_b M_n = 74.25$ k·ft > 42.26 k·ft $= M_u$

deflection

$LL = 967$ lb/ft

$I_{LB_L} = 110\,in^4$ $Y2_h = 4.5''$
$I_{LB_h} = 117\,in^4$ $Y2_L = 4.0''$

$I_{LB} = 110\,in^4 + \left(\frac{4.0''-4.31''}{4.0''-4.5''}\right)(117\,in^4 - 110\,in^4) = 114.34\,in^4$

$\Delta_{LL} = \frac{5(967\text{ lb/ft})(11.67')^4}{384(29000\text{ ksi})(114.34\,in^4)} \times \frac{1728\,in^3}{ft^3} \times \frac{1k}{1000\,lb} = 0.122\,in$

$\Delta_{max} = \frac{L}{360} = \frac{11.67' \times 12}{360} = 0.389\,in$

$\Delta_{max} = 0.389\,in > 0.122 = \Delta_{LL}$ ✓

Total load $= 779.21$ lb/ft $+ 967$ lb/ft $= 1746.20$ lb/ft

$\Delta_T = \frac{5(1262.71\text{ lb/ft})(11.67')^4}{384(29000\text{ ksi})(114.34\,in^4)} \times \frac{1728\,in^3}{ft^3} \times \frac{1k}{1000\,lb} = 0.220\,in$

$\Delta_{max} = \frac{L}{240} = \frac{11.67' \times 12}{240} = 0.584\,in$

$\Delta_{max} = 0.584'' > 0.22\,in = \Delta_T$

Construction loading

dead load
metal decking + beam $= 26.11$ lb/ft $+ 12$ lb/ft $= 38.11$ lb/ft

Live load
wet concrete + construction LL $= 549.67$ lb/ft $+ 10\,psf(9.67')$
$LL = 646.37$ lb/ft

$W_U = 1.2(38.11\text{ lb/ft}) + 1.6(646.37\text{ lb/ft}) = 1079.92$ lb/ft

$M_U = \frac{1079.92\text{ lb/ft}(11.67')^2}{8} = 18.38$ k·ft

$\phi_b M_n = 74.25$ k·ft > 18.38 k·ft ✓

deflection

$I_x = 53.8\,in^4$ (table 1-1 AISC manual)

8

⊥ beams simple (quad-FB)

$$\Delta_c = \frac{5(38.11^{lb}/ft + 646.37^{lb}/ft)(11.67')^4}{384(29000\ ksi)(53.8in^4)} \times \frac{1728in^3}{ft^3} \times \frac{1k}{1000\ lb} = 0.18in$$

$$\Delta_{max} = \frac{L}{360} = \frac{11.67' \times 12}{360} = 0.39in$$

$$\Delta_{max} = 0.39in > 0.18in = \Delta_c \checkmark$$

Studs

Note: from campus drawing
max spacing = 24"
min spacing = 5.5"

$d = 3/4"\ \varnothing$

$A = \frac{\pi(3/4")^2}{4} = 0.44in^2$

$F_u = 65\ ksi$

$R_p = 1.0$ parallel decking

$R_g = 1.0$

$Q_n = 21.50\ k$ (table 3.21 AISC manual)

$Q_n = (1.0)(1.0)(65ksi)(0.44in^2) = 28.6\ k$

$n = \frac{44.3k}{21.50k} = 2.06$ studs => 3 studs

total 6 studs

$$\text{spacing} = \frac{11.67'(12"/1')}{(6+1)} = 20.0"$$

$$min = 5.5" < 20.0" < 24" = max \checkmark$$

so use 10x12

$$\text{Reactions} = \frac{wl}{2} = \frac{(767.20^{lb}/ft + 967^{lb}/ft)\ 11.67ft}{2} = 10119.08\ lb$$

9

Middle Beam Simple (Morgan-SB)

This was calculated similar to middle beam simple (Quad-FB). The following numbers were changed.
See attached spreadsheet for detail calculations.
spacing = 10.75 ft
end beam weight = 16 lb/ft

So use W10x12
PNA 7
Total shear studs = 6 studs
Stud spacing = 20.01 in

$$Reaction = \frac{[(860.29\ lb/ft)+(1075.00\ lb/ft)](11.67\ ft)}{2} = 11292.40\ lbs$$

10

Alt track design 2 | ⊥ beam cantilever | (quad-FB)

concrete slab = 4.5in
steel decking = 3.0in
span = 11.67ft
spacing = 9.67ft

F_y = 50 KSI
E = 29000 KSI
ponding = 1.1

same loading as ⊥ beam simple

$DL = 767.21$ lb/ft
$LL = 967$ lb/ft

$W_u = 1.2(767.21 \text{ lb/ft}) + 1.6(967 \text{ lb/ft}) = 2467.85 \text{ lb/ft}$

$M_u = \frac{2467.85 \text{ lb/ft}(11.67ft)^2}{2} = 168.05 \text{ k-ft}$

$Z_x \geq \frac{168.05 \text{ k-ft}(12")}{0.9(50KSI)} = 44.81 \text{ in}^3$

try W18x35 $Z_x = 66.5in^3$ (table 3-2 AISC Manual)

$DL = 767.21 \text{ lb/ft} + 35 \text{ lb/ft} = 802.21 \text{ lb/ft}$
$LL = 967$ lb/ft

$W_u = 1.2(802.21 \text{ lb/ft}) + 1.6(967 \text{ lb/ft}) = 2509.85 \text{ lb/ft}$

$M_u = \frac{2509.85 \text{ lb/ft}(11.67')^2}{2} = 170.91 \text{ k-ft}$

$\phi M_p = \frac{0.9(66.5in^3)(50KSI)}{12} = 249.38 \text{ k-ft}$

$\phi M_p = 249.38 \text{k-ft} > 170.91 \text{ k-ft} = M_u$ ✓

FLB

$\frac{b_f}{2t_f} = 7.06in$ (table 1-1 AISC manual)

$\text{Limit} = 0.38\sqrt{\frac{29000}{50}} = 9.15in$ ✓

WLB

$\frac{h}{t_w} = 53.5in$ (table 1-1 AISC manual)

$\text{Limit} = 3.76\sqrt{\frac{29000}{50}} = 90.6in$ ✓

Deflection

$I_x = 510 \text{ in}^4$ (table 1-1 AISC Manual)

11

Alt track design 2 | ⊥ beam cantilever | (quad-FB)

Concrete slab = 4.5 in
Steel decking = 3.0 in
Span = 11.67 ft
Spacing = 9.67 ft

$F_y = 50$ KSI
$E = 29000$ KSI
ponding = 1.1

Same loading as ⊥ beam simple

$DL = 767.21$ lb/ft
$LL = 967$ lb/ft

$W_u = 1.2(767.21 \text{ lb/ft}) + 1.6(967 \text{ lb/ft}) = 2467.85 \text{ lb/ft}$
$M_u = \frac{2467.85 \text{ lb/ft}(11.67 \text{ ft})^2}{2} = 168.05 \text{ k·ft}$

$Z_x \geq \frac{168.05 \text{ k·ft}(12")}{0.9(50 \text{ KSI})} = 44.81 \text{ in}^3$

try W18x35 $Z_x = 66.5 \text{ in}^3$ (table 3-2 AISC Manual)

$DL = 767.21 \text{ lb/ft} + 35 \text{ lb/ft} = 802.21 \text{ lb/ft}$
$LL = 967 \text{ lb/ft}$

$W_u = 1.2(802.21 \text{ lb/ft}) + 1.6(967 \text{ lb/ft}) = 2509.85 \text{ lb/ft}$
$M_u = \frac{2509.85 \text{ lb/ft}(11.67')^2}{2} = 170.91 \text{ k·ft}$

$\phi M_p = \frac{0.9(66.5 \text{ in}^3)(50 \text{ KSI})}{12} = 249.38 \text{ k·ft}$

$\phi M_p = 249.38 \text{ k·ft} > 170.91 \text{ k·ft} = M_u$ ✓

FLB

$\frac{b_f}{2t_f} = 7.06 \text{ in}$ (table 1-1 AISC manual)

$\text{Limit} = 0.38\sqrt{\frac{29000}{50}} = 9.15 \text{ in}$ ✓

WLB

$\frac{h}{t_w} = 53.5 \text{ in}$ (table 1-1 AISC manual)

$\text{Limit} = 3.76\sqrt{\frac{29000}{50}} = 90.6 \text{ in}$ ✓

Deflection

$I_x = 510 \text{ in}^4$ (table 1-1 AISC Manual)

11

| I beams cantilever | (quad-FB) |

$LL = 967 \text{ lb/ft}$

$\Delta_{LL} = \frac{967 \text{ lb/ft}(11.67)^4}{8(29000\text{ksi})(510\text{in}^4)} \times \frac{1728\text{in}^3}{\text{ft}^3} \times \frac{1\text{k}}{1000\text{lb}} = 0.262\text{in}$

$\Delta_{max} = L/360 = \frac{11.67' \times 12}{360} = 0.39\text{in}$

$\Delta_{max} = 0.39\text{in} > 0.262\text{in} = \Delta_{LL}$

Total load

$TL = 967 \text{ lb/ft} + 798.21 \text{ lb/ft} = 1769.20 \text{ lb/ft}$

$\Delta_T = \frac{1281.71 \text{ lb/ft}(11.67')^4}{8(29000\text{ksi})(375\text{in}^4)} \times \frac{1728\text{in}^3}{\text{ft}^3} \times \frac{1\text{k}}{1000\text{lb}} = 0.48\text{in}$

$\Delta_{max} = L/240 = \frac{11.67' \times 12''}{240} = 0.58\text{in}$

$\Delta_{max} = 0.58'' > 0.48'' = \Delta_T$ ✓

construction $LL = 10\text{psf}$

$\text{load} = 31 \text{ lb/ft} + 26.11 \text{ lb/ft} + 549.67 \text{ lb/ft} + 10\text{psf}(9.67')$

$\text{load} = 703.48 \text{ lb/ft}$

$\Delta_C = \frac{703.48 \text{ lb/ft}(11.67')^4}{8(29000\text{ksi})(510\text{in}^4)} \times \frac{1728\text{in}^3}{\text{ft}^3} \times \frac{1\text{kip}}{1000\text{lb}} = 0.19\text{in}$

$\Delta_{max} = L/360 = 0.39\text{in}$

$\Delta_{max} = 0.39\text{in} > 0.19\text{in} = \Delta_C$ ✓

so use W18×35

$\text{Reaction} = wL = (767.21 + 967)(11.67) = 20238.17\text{lb}$

12

Middle Beam Cantilever (Morgan-SB)

- Calculated similarily to Middle Beam Cantilever (quad-FB)
- The following numbers were changed. See spreadsheet for detailed calculations.

Spacing = 10.75 ft
End beam = 16 ft/lb

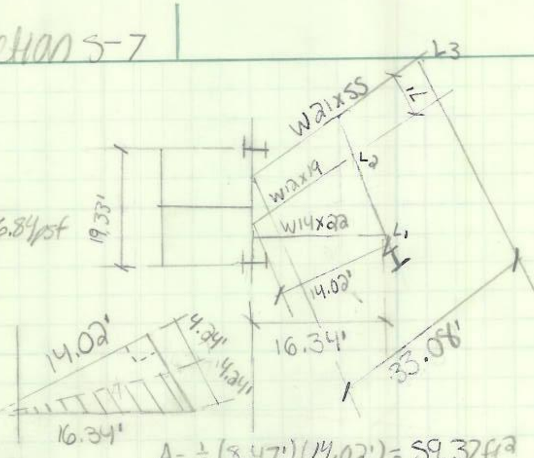
W18X35

Reaction = (860.29 lb/ft + 1075.0 lb/ft)(11.67') = 22584.79 lbs

14

Quad section S-7

Beam L1



W14x22

weight = 22 lb/ft

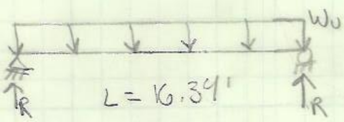
concrete = (54.38 psf - 2.7 psf)1.1 = 56.84 psf

metal decking = 2.7 psf

MEP = 10 psf

ceiling = 5 psf

design LL = 100 psf



$A = \frac{1}{2}(8.47')(14.02') = 59.37 ft^2$

$\frac{1}{2}A = 29.69 ft^2$

- assume triangular shape

$(56.84psf + 2.7psf + 10psf + 5psf)(29.69ft^2) = 2213.09 lb$

$22 lb/ft(16.34') = 359.48 lb$

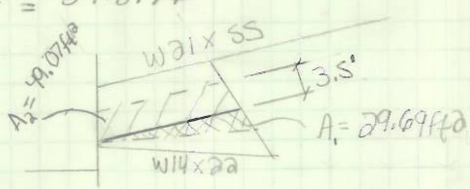
$DL_T = 2213.09 lb + 359.48 lb = 2572.57 lb$

$LL_T = 100psf(29.69ft^2) = 2969 lbs$

$P_u = 1.2(2572.57 lb) + 1.6(2969 lbs) = 7837.48 lb$

$R = \frac{P_u}{2} = \frac{7837.48 lb}{2} = 3918.74 lb$

Beam L2



W12x19

weight = 19 lb/ft

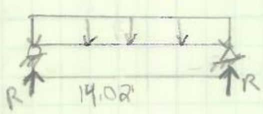
concrete = 56.84 psf

metal decking = 2.7 psf

MEP = 10 psf

ceiling = 5 psf

design LL = 100 psf



triangular section

- same as L1, change beam size

$P_{u1} = 1.2(2213.09 lb + (19 lb/ft)(14.02')) + 1.6(2969 lbs) = 7725.76 lb$

other side, spacing = 3.5'

$DL_T = 74.54 psf(3.5')(14.02') = 3657.68 lb$

$LL_T = 100 psf(3.5')(14.02') = 4907 lb$

$P_{u2} = 1.2(3657.68 lb) + 1.6(4907 lb) = 12240.41 lb$

$P_{uT} = 7725.76 lb + 12240.41 lb = 19966.18 lb$

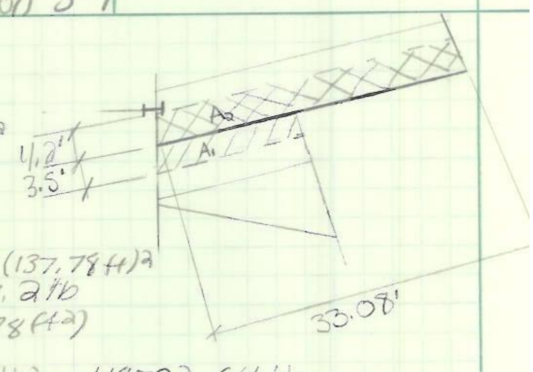
$R = \frac{19966.18 lb}{2} = 9983.09 lb$

15

Quad Section S-7

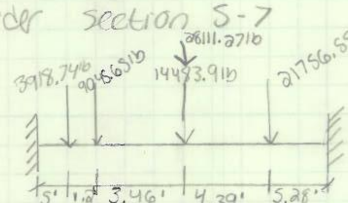
Beam L3
W21x55

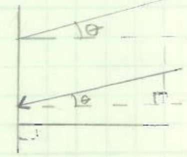
Same loading as previous beam L2
- change beam weight



$A_1 = 3.5'(14.02') = 49.07 ft^2$
$A_2 = 4.2'(33.08') = 137.78 ft^2$
$DL_T = 74.54 psf(49.07ft^2) + 74.54 psf(137.78 ft)^2 + 55 lb/ft(33.08') = 15747.2 lb$
$LL = 100 psf(49.07 ft^2) + 100 psf(137.78 ft^2) = 18685 lb$
$P_u = 1.2(15747.2 lb) + 1.6(18685 lb) = 48792.64 lb$
$R = \frac{48792.64}{2} = 24396.32$

Girder section S-7





$\theta = 26.9°$

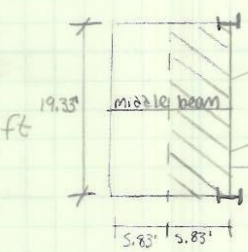
change forces to be ⊥ to beam

beam L2 $9983.09 lb \cos 26.9° = 8902.89 lb$
beam L3 $24396.32 lb \cos 26.9° = 21756.58 lb$

$M_{L_1} = \frac{3918.74(5')(14.33')}{19.33'} = 14.53 k \cdot ft$

$M_{L_2} = \frac{8902.89 lb(6.2')(13.13')}{19.33'} = 37.49 k \cdot ft$

$M_{L_3} = \frac{21756.58 lb(14.05')(5.28')}{19.33'} = 83.5 k \cdot ft$



over conservative

P_u of beam $= 1.2(74.54 psf(19.33')(5.83')) + 1.6(100 psf(19.33' \times 5.83')) = 28111.27 lbs$
- acts at ½L

P_u due to middle beam $= 14483.91 lb$
- acts at ½L

$P_{u_T @ \frac{1}{2}L} = 14483.91 lb + 28111.27 lb = 42595.17 lb$

$M_U = \frac{42595.17 lb(19.33)}{8} = 102.92 k \cdot ft$

$M_T = 14.53 k \cdot ft + 37.49 k \cdot ft + 83.5 k \cdot ft + 102.92 k \cdot ft = 238.44 k \cdot ft$

16

Quad section S-7

assume $a = 2in$

$Y2 = 4.5'' - 2''/2 = 3.5''$

try W16x31

$\phi_b M_n = 283.0$ k·ft @ $Y2 = 3.5''$ PNA @ 7 table 3-19 AISC manual

recheck M_T

P_u of beam $= 1.2(8400.20 lb + 31 \frac{lb}{ft}(19.33')) + 1.6(100(19.33)(5.83)) = 30407.67 lb$

$P_{uT} = 14483.90 lb + 30407.67 lb = 44891.57 lb$

$M_u = \frac{44891.57 lb (19.33 ft)}{8} = 104.66$ k·ft

$M_T = 104.66 + 14.53 + 37.49 + 83.5 = 240.18$ k·ft

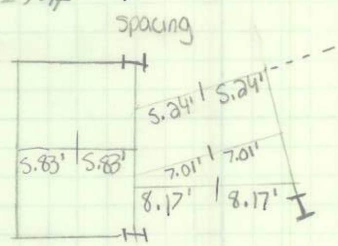
$\phi_b M_n = 283$ k·ft > 240.18 k·ft $= M_T$ ✓

$\Sigma Q_n = 114$ k (table 3-19 AISC manual)

$f'c = 4 ksi$

$b_e = \frac{1}{8}(19.33')(12''/1')(2) = 57.99 in$ ← governs

$b_e = \frac{1}{2}(6.56')(12''/1')(2) = 78.72 in$



$a = \frac{114 k}{0.85(4 ksi)(57.99 in)} = 0.58 in$

$Y2 = 4.5'' - 1.84''/2 = 4.21 in$

ave spacing

spacing $= (5.83' + 8.17' + 7.01' + 5.24')/4$
$= 6.56' = 78.75''$

$\phi_b M_{nL} = 287$ k·ft $Y2_L = 4''$

$\phi_b M_{nh} = 292$ k·ft $Y2_h = 4.5''$

$\phi_b M_n = 287$ k·ft $\left(\frac{4 - 4.21}{4 - 4.5}\right)(292 k·ft - 287 k·ft) = 289.11$ k·ft

$\phi_b M_n = 289.11$ k·ft > 240.18 k·ft $= M_T$ ✓

LL only $= 100 psf(5.83') = 583 lb/ft$

-use full load

$I_{LB\,L} = 636 in^4$ $Y2_L = 4''$

$I_{LB\,h} = 658 in^4$ $Y2_h = 4.5''$

$I_{LB} = 636 in^4 + \left(\frac{4'' - 4.21''}{4'' - 4.5''}\right)(658 in^4 - 636 in^4) = 645.28$

$\Delta_{LL} = \frac{583 lb/ft (19.33 in)^4}{384(29000 ksi)(645.28 in^4)} \times \frac{1728 in^3}{ft^3} \times \frac{1k}{1000 lb} = 0.02 in$

$\Delta_{max} = L/360 = \frac{19.33' \times 12}{360} = 0.644 in$

$\Delta_{max} = 0.64 in > 0.02 in = \Delta_{LL}$ ✓

17

Quad section S-7

Total Load = $\frac{8999.72 lb}{19.33'}$ + 583 lb/ft = 1048.58 lb/ft

$\Delta_T = \frac{1048.58 lb/ft (19.33 ft)^4}{384(29000 ksi)(645.28 in^4)} \times \frac{1728 in^3}{ft^3} \times \frac{1k}{1000 lb} = 0.035 in$

$\Delta_{max} = L/240 = \frac{19.33' \times 12''/1'}{240} = 0.967 in$

$\Delta_{max} = 0.97 in > 0.035 in = \Delta_T$ ✓

construction LL = 10 psf

DL = 31 lb/ft + 2.7 psf(5.83') = 46.74 lb/ft
LL = 56.84 lb/ft (5.83') + 10 psf (5.83') = 389.68 lb/ft
T = 46.74 lb/ft + 389.68 lb/ft = 436.43 lb/ft (unfactored)
W_U = 1.2(46.74 lb/ft) + 1.6(389.68 lb/ft) = 679.60 lb/ft (factored)

$M_U = \frac{679.6 lb/ft (19.33')^2}{12} = 21.16$ k·ft

$\phi_b M_n$ = 1573.18 k·ft > 21.16 k·ft = M_U ✓

$I_x = 375 in^4$ table 1-1, AISC manual

$\Delta_c = \frac{436.43 lb/ft (19.33')^4}{384(29000 ksi)(375 in^4)} \times \frac{1728 in^3}{ft^3} \times \frac{1k}{1000 lb} = 0.025 in$

Δ_{max} = L/360 = 0.64 in

$\Delta_{max} = 0.64 in > 0.025 in = \Delta_c$ ✓

Studs

Note: from Cannon Drawings
Max spacing = 24"
Min spacing = 5.5"

d = 3/4"
$A = \frac{(3/4'')^2 \pi}{4} = 0.44 in^2$

$R_p = 1.0$ parallel decking
$R_g = 1.0$
F_u = 65 ksi

Q_n = 21.5 k table 3.21 AISC manual ← governs
Q_n = 1.0(1.0)(65 ksi)(0.44 in²) = 28.72 kips

$n = \frac{114 k}{21.5 k} = 5.30 \Rightarrow$ 6 studs

So use 12 studs

18

Girders Softball field-side

Sections 1-3, 5-7

These sections were calculated similar to the Quad section 5-7 Girder. They following numbers were changed. For a full set of calculations see the spreadsheets in Appendix

Span = 21.50ft
Beam 1 Reaction = 3874.46 lb
Middle Beam Reaction = 11292.40 lb

W12 x 19

Sections 3-5

This girder was calculated similarly to the football side girders. A full set of calculations can be seen in the Appendix

Span = 21.50ft
Middle Beam Reaction = 11292.40 lb

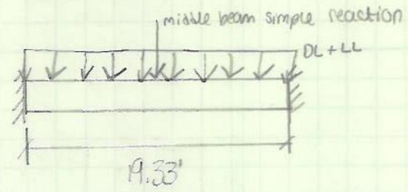
W 10 x 19

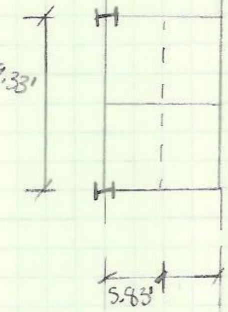
19

Girders Football field side

concrete slab = 4.5"
metal decking = 3"
span = 19.33'
Spacing = 5.83'

F_y = 50 ksi
E = 29000 ksi





Dead load
concrete = 145 pcf (4.5"/12) = 54.38 psf   ponding = 1.1
decking = 2.7 psf
MEP = 10 psf
Ceiling = 5 psf
middle beam simple reaction = 10119.08 lbs

Live loads
design = 100 psf
LL = 10 psf

$DL = [(54.38 - 2.7)(1.1)(5.83')] + (2.7 + 10 + 5)(5.83') = 434.58$ lb/ft
$LL = 100\,psf(5.83') = 583$ lb/ft

=> translated to a point load
$DL = 434.58$ lb/ft $(19.33') = 8400.4$ lbs
$LL = 583$ lb/ft $(19.33') = 11269.39$ lbs
$P_u = 1.2(8400.4) + 1.6(11269.39) = 28111.5$ lb
P_u + Reaction = 28111.5 lbs + 10119.08 lbs = 38230.58 lb

$$M_u = \frac{38230.58\,lb\,(19.33')}{8} = 92.37\ k\cdot ft$$

assume
a = 2"
$Y_2 = 4.5" - 2"/2 = 3.5"$

W12x14
$\phi_b M_n = 123.0$ k-ft for $Y_2 = 3.5"$ PNA = BFL

DL = 8400.4 lbs + 14 lb/ft (19.33') = 8671.02 lbs
New P_u + Reaction = 1.2(8671.02) + 1.6(11269.39) + 10119.08
= 38555.33 lbs

$$M_u = \frac{38555.33\,lb\,(19.33')}{8} = 93.16\ k\cdot ft$$

20

Girders football field side

$\phi_b M_n = 123$ k·ft > 93.16 k·ft $= M_u$ ✓

$\Sigma Q_n = 119.00$ kips table 3-19 AISC manual
$f'_c = 4$ ksi
$b_e = \frac{1}{8}(19.33') = 29.00$ in

$a = \frac{119k}{0.85(4ksi)(29in)} = 1.21$ in

$y_2 = 4.5'' - \frac{1.21''}{2} = 3.90''$

$\phi_b M_{n_L} = 123$ ft·k $Y2_L = 3.5''$ (table 3-19 AISC Manual)
$\phi_b M_{n_h} = 128$ ft·k $Y2_h = 4.0''$

$\phi_b M_n = 123 + \left(\frac{3.5-3.9}{3.5-4}\right)(128-123) = 126.96$ k·ft

$\phi_b M_n = 126.96$ k·ft > 93.16 k·ft $= M_u$ ✓

$w_L = 583.00$ lb/ft
$I_{LB_h} = 238$ in^4 $Y2_h = 4''$
$I_{LB_L} = 224$ in^4 $Y2_L = 3.5''$

$I_{LB} = 224 + \left(\frac{3.5-3.9}{3.5-4}\right)(238-224) = 235.1$ in^4

$\Delta_L = \frac{5(583 \text{ lb/ft})(19.33 ft)^4}{384(29000 ksi)(235.1 in^4)} \times \frac{1728 in^3}{ft^3} \times \frac{1k}{1000 lb} = 0.054$ in

$\Delta_{max} = L/360 = 19.33'/360 = 0.64''$

$\Delta_{max} = 0.64'' > 0.054''$ ✓

Total Load $= \frac{8671.02 \text{ lb}}{19.33 ft} + 583.0$ lb/ft $= 1031.58$ lb/ft

$\Delta_T = \frac{1031.58 \text{ lb/ft}(19.33ft)^4}{384(29000 ksi)(235.1 in^4)} \times \frac{1728 in^3}{ft^3} \times \frac{1k}{1000 lb} = 0.095$ in

$\Delta_{max} = L/240 = 19.33'/240 = 0.967$ in
$\Delta_{max} = 0.967$ in > 0.095 in $= \Delta_T$ ✓

construction

$DL = 2.7(5.83) + 14 = 29.74$ lb/ft
$LL = (54.38 - 2.7)(1.1)(5.83) + 10$ psf$(5.83') = 389.69$ lb/ft

$W_u = 1.2(29.74) + 1.6(389.69) = 659.2$ lb/ft

21

Girders football field side

$M_u = \frac{659.21 lb/ft (19.33')^2}{12} = 20.53$ k·ft

$\phi_b M_n = 126.96$ k·ft > 20.53 k·ft $= M_u$

$I_x = 88.6$ in table 1-1 AISC Manual

$\Delta_c = \frac{(29.74 lb/ft + 389.69 lb/ft)(19.33')^4}{384(29000 ksi)(88.6 in)} \times \frac{1728 in^3}{ft^3} \times \frac{1k}{1000 lb}$

$\Delta_c = 0.1026$ in

$\Delta_{max} = l/360 = 0.64$ in

$\Delta_{max} = 0.64$ in > 0.103 in $= \Delta_c$ ✓

Studs

$d = 3/4''$

$R_p = 1.0$ parallel decking

$R_g = 1.0$

$F_u = 65.00$ ksi

$A_{sa} = \frac{(3/4'')^2 \pi}{4} = 0.44 in^2$

$Q_n = 21.5$ kips table 3.21 AISC manual

$Q_n = 0.44(65)(1)(1) = 28.72$ kips

$n = \frac{119 kips}{21.5 kips} = 5.53 \Rightarrow 6$ studs

so use 12 studs total

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Girders Morgan Side

These girders were calculated similarly to the football side girders. The following numbers were changed. A full set of calculations can be seen in Appendix

Span = 21.50ft
Middle beam reaction = 11292.4lb

W 12x16

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Appendix I: Simple Beam Approach Spreadsheet Calculations

		End Beams		Middle Beam (Simple)	
		Quad/FB Side	Morgan/SB Side	Quad/FB Side	Morgan/SB Side
		W12x14	W12x16	W10x12	W10x12
Length	ft	19.33	21.50	11.67	11.67
Concrete Slab	in	4.50	4.50	4.50	4.50
Steel Decking	in	3.00	3.00	3.00	3.00
Fy	KSI	50	50	50	50
E	KSI	29000	29000	29000	29000
Spacing	ft	5.83	5.83	9.67	10.75
Dead Loads					
Concrete	PSF	54.38	54.38	54.38	54.38
Decking	PSF	2.70	2.70	2.70	2.70
MEP (piping)	PSF	0.00	0.00	10.00	10.00
Ceiling	PSF	5.00	5.00	5.00	5.00
Other Beam Weight	lb/ft	0.00	0.00	14.00	16.00
Live Loads					
Design Load	PSF	100.00	100.00	100.00	100.00

Construction LL	PSF	10.00	10.00		10.00	10.00
unfactored DL		376.28	376.28		11.67	11.67
unfactored LL		583.00	583.00		9.67	10.75
Total Loading						
DL	lb/ft	376.28	376.28		767.20	860.29
LL	lb/ft	583.00	583.00		967.00	1075.00
						4.41
Wu	lb/ft	1384.34	1384.34		2467.85	2752.34
Mu	K-FT	64.66	79.99		42.01	46.85
Assume a	in	2.00	2.00		2.00	2.00
Y2	in	3.50	3.50		3.50	3.50
try		W12x14	W12x16		W10x12	W10x12
ΦbMn	K-FT	123.00	127.00		71.50	71.50
PNA		bfl	6.00		7.00	7.00
Beam Weight	lb/ft	14.00	16.00		12.00	12.00
Check Critical Moment						
DL	lb/ft	390.28	392.28		779.20	872.29

LL	lb/ft	583.00	583.00		967.00	1075.00
Wu	lb/ft	1401.14	1403.54		2482.25	2766.74
Mu	K-FT	65.44	81.10		42.26	47.10
ΦbMn > Mu		OKAY	OKAY		OKAY	OKAY
Composite Capacity						
ΣQn	Kips	119.00	94.30		44.30	44.30
f'c	KSI	4.00	4.00		4.00	4.00
be	in	29.00	32.25		35.01	35.01
a	in	1.21	0.86		0.37	0.37
Y2	in	3.90	4.07		4.31	4.31
ΦbMn	K-FT	126.96	131.42		74.27	74.27
ΦbMn>Mu		OKAY	OKAY		OKAY	OKAY
LL	lb/ft	583.00	583.00		967.00	1075.00
I_{LB}	in4	235.10	239.82		114.39	114.39
ΔLL	in	0.27	0.40		0.12	0.14
L/360	in	0.64	0.72		0.39	0.39
L/360 > ΔLL		OKAY	OKAY		OKAY	OKAY
Total Load	lb/ft	973.28	975.28		1746.20	1947.29

ΔT	in	0.45	0.67		0.22	0.24
L/240	in	0.97	1.08		0.58	0.58
L/240 > ΔT		OKAY	OKAY		OKAY	OKAY
DL	lb/ft	29.74	31.74		38.11	41.03
LL	lb/ft	389.69	389.69		646.37	718.56
unfactored Total	lb/ft	419.43	421.43		684.48	759.58
factored	lb/ft	659.20	661.60		1079.92	1198.92
Mu	K-FT	30.79	38.23		18.38	20.41
ΦbMn>Mu		OKAY	OKAY		OKAY	OKAY
Deflection						
Ix	in	88.60	103.00		53.80	53.80
ΔC	in	0.51	0.68		0.18	0.20
L/360	in	0.64	0.72		0.39	0.39
L/360 > ΔC		OKAY	OKAY		OKAY	OKAY
Studs						
diameter	in	0.75	0.75		0.75	0.75
max spacing	in	24.00	24.00		24.00	24.00
min spacing	in	5.50	5.50		5.50	5.50
Rp		1.00	1.00		1.00	1.00

Rg		1.00	1.00	1.00	1.00
Fu	KSI	65.00	65.00	65.00	65.00
Asa	in2	0.44	0.44	0.44	0.44
Qn	Kips	21.50	21.50	21.50	21.50
Qn	Kips	28.72	28.72	28.72	28.72
n	Studs	5.53	4.39	2.06	2.06
use	studs	6.00	5.00	3.00	3.00
total	studs	12.00	10.00	6.00	6.00
spacing	in	17.84	23.45	20.01	20.01
max		OKAY	OKAY	OKAY	OKAY
min		OKAY	OKAY	OKAY	OKAY
Reaction	lb	N/A	N/A	10119.08	11292.40
Reaction	kips	N/A	N/A	10.12	11.29

		Middle Beam (Cantilever)	
		Quad/FB Side	Morgan/SB Side
		W18x35	W18x35
Length	ft	11.67	11.67
Concrete Slab	in	0.00	0.00
Steel Decking	in	0.00	0.00

Fy	KSI	50	50
E	KSI	29000	29000
Spacing	ft	9.67	10.75
Dead Loads			
Concrete	PSF	54.38	54.38
Decking	PSF	2.70	2.70
MEP (piping)	PSF	10.00	10.00
Ceiling	PSF	5.00	5.00
End Beam	lb/ft	14.00	16.00
Live Loads			
Design Load	PSF	100.00	100.00
Construction LL	PSF	10.00	10.00
unfactored DL	lb/ft	767.20	860.29
unfactored LL	lb/ft	967.00	1075.00
Wu	lb/ft	2467.85	2752.34
Mu	K-FT	168.05	187.42
		0.00	

Zx	in4	44.81	49.98
Table Zx	in4	66.50	66.50
try		W18x35	W18x35
Beam Weight	lb/ft	35.00	35.00
DL	lb/ft	802.20	895.29
LL	lb/ft	967.00	1075.00
Wu	lb/ft	2509.85	2794.34
Mu	K-ft	170.91	190.28
Check Critical Moment			
ΦMp	K-FT	249.38	249.38
ΦMp > Mu		OKAY	OKAY
FLB	in	7.06	6.28
Limit	in	9.15	9.15
Check		OKAY	OKAY
WLB	in	53.50	51.60

Limit	in	90.55	90.55
Check		OKAY	OKAY
Deflection			
LL	lb/ft	967.00	1075.00
Ix	in4	510.00	510.00
∆LL	in4	0.26	0.29
L/360	in	0.39	0.39
or 1" MAX	in	1.00	1.00
L/360 > ∆LL		OKAY	OKAY
Total Load	lb/ft	1769.20	1970.29
∆T	in	0.48	0.53
L/240	in	0.58	0.58
L/240 > ∆T		OKAY	OKAY
Deflection			
C-Load	lb/ft	707.48	782.58
∆C	in	0.19	0.21
L/360	in	0.39	0.39
L/360 > ∆C		OKAY	OKAY
Reaction	lbs	20238.17	22584.79

Reaction	kips	20.24	22.58

		Girders (Fixed)	
		Football Side	Morgan Side
		W12x14	W12x16
Length	ft	19.33	21.50
Concrete Slab	in	4.50	4.50
Steel Decking	in	3.00	3.00
Fy	KSI	50	50
E	KSI	29000	29000
Spacing	ft	5.83	5.83
Dead Loads			
Concrete	PSF	54.38	54.38
Decking	PSF	2.70	2.70
MEP (piping)	PSF	10.00	10.00
Ceiling	PSF	5.00	5.00
Middle Beam Simple	PSF	12.00	12.00
Length	lb/ft	11.67	11.67
Reaction	lb	10119.08	11292.40

Live Loads			
Design Load	PSF	100.00	100.00
Construction LL	PSF	10.00	10.00
unfactored DL	lb/ft	434.58	434.58
unfactored LL	lb/ft	583.00	583.00
Mu	K-FT	92.37	114.38
Assume a	in	2.00	2.00
Y2	in	3.50	3.50
try		W12x14	W12x16
ΦbMn	K-FT	123.00	139.00
PNA		bfl	bfl
Beam Weight	lb/ft	14.00	16.00
Check Critical Moment			
Pu	lb	28436.35	31680.24
Mu	K-FT	93.16	115.49
ΦbMn > Mu		OKAY	OKAY

Composite Capacity			
ΣQn	Kips	119.00	130.00
f'c	KSI	4.00	4.00
be=(1/8)L	in	29.00	32.25
a	in	1.21	1.19
Y2	in	3.90	3.91
ΦbMn	K-FT	126.96	143.07
ΦbMn>Mu		OKAY	OKAY
LL ONLY	lb/ft	583.00	583.00
I_{LB}	in4	235.10	267.84
ΔLL	in	0.05	0.07
L/360	in	0.64	0.72
L/360 > ΔLL		OKAY	OKAY
Total Load	lb/ft	1031.58	1033.58
ΔT	in	0.10	0.13
L/240	in	0.97	1.08
L/240 > ΔT		OKAY	OKAY
DL	lb/ft	29.74	31.74
LL	lb/ft	389.69	389.69

unfactored Total	lb/ft	419.43	421.43
factored	lb/ft	659.20	661.60
Mu	K-FT	20.53	25.49
ΦbMn>Mu		OKAY	OKAY
Deflection			
Ix	in	88.6	103
ΔC	in	0.10	0.14
L/360	in	0.64	0.72
L/360 > ΔC		OKAY	OKAY
Studs			
diameter	in	0.75	0.75
max spacing	in	24.00	24.00
min spacing	in	5.50	5.50
Rp		1.00	1.00
Rg		1.00	1.00
Fu	KSI	65.00	65.00
Asa	in2	0.44	0.44
Qn	Kips	21.50	21.50
Qn	Kips	28.72	28.72

n	Studs	5.53	6.05
use	studs	6.00	7.00
total	studs	12.00	14.00
spacing	in	17.84	17.20
max		OKAY	OKAY
min		OKAY	OKAY
Calculated Reaction	kips	14.89	16585.21
Robot			
Reaction left side	kips	14.88	16.59
Reaction right side	kips	14.91	16.59
Moment left	k-ft	-56.11	-69.55
moment right	k-ft	-56.12	69.55

		Girders (Fixed)		
		Quad Side 1-3	Quad Side 3-5	Quad Side 5-7
		W12x16	W12x16	W16x26
Length	ft	19.33	19.33	19.33
Concrete Slab	in	4.50	4.50	4.50
Steel Decking	in	3.00	3.00	3.00
Fy	KSI	50.00	50.00	50.00
E	KSI	29000.00	29000.00	29000.00

Track Side Spacing	ft	5.83	5.83	5.83
Dead Loads				
Concrete	PSF	54.38	54.38	54.38
Decking	PSF	2.70	2.70	2.70
MEP (piping)	PSF	10.00	10.00	10.00
Ceiling	PSF	5.00	5.00	5.00
Middle Beam Simple	PSF	14.00	14.00	14.00
Length	lb/ft	11.67	11.67	11.67
Reaction	lb	10119.08	10119.08	10119.08
Live Loads				
Design Load	PSF	100.00	100.00	100.00
Construction LL	PSF	10.00	10.00	10.00
unfactored DL	lb/ft	434.58	434.58	434.58
unfactored LL	lb/ft	583.00	583.00	583.00
Beam 1				
weight	lb/ft			22.00
length	ft			16.34
Reaction of Beam 1	lb			3918.79

Mu of Beam 1	K-FT			14.53
Beam 2				
weight	lb/ft			19.00
length	ft			14.02
Reaction of Beam 2	lb			8903.00
Mu of Beam 2	K-FT			37.49
Beam 3				
weight	lb/ft			55.00
length	ft			33.08
Reaction of Beam 3	lb			21756.83
Mu of Beam 3	K-FT			83.50
Pu of Girder	lb	28111.61	28111.61	28111.61
Pu of Middle Beam	lb	10119.08	10119.08	10119.08
Mu of Girder and Middle Beam	K-FT	92.37	92.37	92.37
Total Mu	K-FT	92.37	92.37	227.89
Assume a	in	2.00	2.00	2.00
Y2	in	3.50	3.50	3.50

try		W12x16	W12x16	W16x26
ΦbMn	K-FT	127.00	127.00	234.00
PNA		6.00	6.00	7.00
Beam Weight	lb/ft	16.00	16.00	26.00
Check Critical Moment				
New Pu of beam	lb	16918.84	16918.84	28714.70
Mu	K-FT	19.70	19.70	93.83
Mt	K-FT	112.08	112.08	229.35
ΦbMn > Mu		OKAY	OKAY	OKAY
Composite Capacity				
ΣQn	Kips	94.30	94.30	96.00
f'c	KSI	4.00	4.00	4.00
be=(1/8)L	in	29.00	29.00	57.99
a	in	0.96	0.96	0.49
Y2	in	2.52	2.52	4.26
ΦbMn	K-FT	120.17	124.17	239.05
ΦbMn>Mu		OKAY	OKAY	OKAY

LL ONLY	lb/ft	583.00	583.00	583.00
I_{LB}	in4	200.52	216.87	526.24
ΔLL	in	0.06	0.06	0.02
L/360	in	0.64	0.64	0.64
L/360 > ΔLL		OKAY	OKAY	OKAY
Total Load	lb/ft	1111.32	1111.32	1043.58
ΔT	in	0.12	0.11	0.04
L/240	in	0.97	0.97	0.97
L/240 > ΔT		OKAY	OKAY	OKAY
DL	lb/ft	31.74	31.74	41.74
LL	lb/ft	389.69	389.69	389.69
unfactored Total	lb/ft	421.43	421.43	431.43
factored	lb/ft	661.60	661.60	673.60
Mu	K-FT	20.60	20.60	20.97
ΦbMn>Mu		OKAY	OKAY	OKAY
Deflection				
Ix	in	103.00	103.00	301.00

ΔC	in	0.09	0.09	0.03
L/360	in	0.64	0.64	0.64
L/360 > ΔC		OKAY	OKAY	OKAY
Studs				
diameter	in	0.75	0.75	0.75
max spacing	in	24.00	24.00	24.00
min spacing	in	5.50	5.50	5.50
Rp		1.00	1.00	1.00
Rg		1.00	1.00	1.00
Fu	KSI	65.00	65.00	65.00
Asa	in2	0.44	0.44	0.44
Qn	Kips	21.50	21.50	21.50
Qn	Kips	28.72	28.72	28.72
		0.00	0.00	0.00
n	Studs	4.39	4.39	4.47
use	studs	5.00	5.00	5.00
total	studs	10.00	10.00	10.00
spacing	in	21.09	21.09	21.09
max		OKAY	OKAY	OKAY
min		OKAY	OKAY	OKAY
Reaction left side	kips	14.88	14.88	28.88

Reaction right side	kips	14.91	14.91	35.49
Moment left	k-ft	-71.94	-71.94	-130.98
moment right	k-ft	72.01	72.01	148.48

		Girders (Fixed)		
		Quad Side 7-9	Quad Side 9-11	Quad Side 11-13
		W18x40	W18x50	W18x46
Length	ft	19.33	19.33	19.33
Concrete Slab	in	4.50	4.50	4.50
Steel Decking	in	3.00	3.00	3.00
Fy	KSI	50.00	50.00	50.00
E	KSI	29000.00	29000.00	29000.00
Track Side Spacing	ft	5.83	5.83	5.83
Dead Loads				
Concrete	PSF	54.38	54.38	54.38
Decking	PSF	2.70	2.70	2.70
MEP (piping)	PSF	10.00	10.00	10.00
Ceiling	PSF	5.00	5.00	5.00
Middle Beam Simple	PSF	14.00	14.00	14.00

Length	lb/ft	11.67	11.67	11.67
Reaction	lb	10119.08	10119.08	10119.08
Live Loads				
Design Load	PSF	100.00	100.00	100.00
Construction LL	PSF	10.00	10.00	10.00
unfactored DL	lb/ft	434.58	434.58	434.58
unfactored LL	lb/ft	583.00	583.00	583.00
Beam 1				
weight	lb/ft	35.00	22.00	35.00
length	ft	30.14	21.33	33.00
Reaction of Beam 1	lb	56364.04	39635.37	61549.75
Mu of Beam 1	K-FT	180.77	117.10	133.52
Beam 2				
weight	lb/ft	36.00	44.00	31.00
length	ft	25.93	309.01	28.77
Reaction of Beam 2	lb	33900.71	61802.00	53598.39
Mu of Beam 2	K-FT	139.23	301.71	245.90
Beam 3				
weight	lb/ft			

length	ft			
Reaction of Beam 3	lb			
Mu of Beam 3	K-FT			
Pu of Girder	lb	28111.61	28111.61	28111.61
Pu of Middle Beam	lb	10119.08	10119.08	10119.08
Mu of Girder and Middle Beam	K-FT	92.37	92.37	92.37
Total Mu	K-FT	412.38	511.19	471.79
Assume a	in	2.00	2.00	2.00
Y2	in	3.50	3.50	3.50
try		W18x40	W18x50	W18x46
ΦbMn	K-FT	439.00	516.00	505.00
PNA		6.00	7.00	6.00
Beam Weight	lb/ft	40.00	50.00	46.00
Check Critical Moment				
New Pu of beam	lb	29039.45	29271.41	29178.62
Mu	K-FT	94.62	95.18	94.95

Mt	K-FT	414.62	513.99	474.37
ΦbMn > Mu		OKAY	OKAY	OKAY
Composite Capacity				
ΣQn	Kips	211.00	184.00	239.00
f'c	KSI	4.00	4.00	4.00
be=(1/8)L	in	57.99	57.99	57.99
a	in	1.07	0.93	1.21
Y2	in	3.96	4.03	3.89
ΦbMn	K-FT	446.44	523.47	512.09
ΦbMn>Mu		OKAY	OKAY	OKAY
LL ONLY	lb/ft	583.00	583.00	583.00
I_{LB}	in4	1127.19	1302.67	1301.51
ΔLL	in	0.01	0.01	0.01
L/360	in	0.64	0.64	0.64
L/360 > ΔLL		OKAY	OKAY	OKAY
Total Load	lb/ft	1057.58	1067.58	1063.58
ΔT	in	0.02	0.02	0.02

L/240	in	0.97	0.97	0.97
L/240 > ΔT		OKAY	OKAY	OKAY
DL	lb/ft	55.74	65.74	61.74
LL	lb/ft	389.69	389.69	389.69
				0.00
unfactored Total	lb/ft	445.43	455.43	451.43
factored	lb/ft	690.40	702.40	697.60
Mu	K-FT	21.50	21.87	21.72
ΦbMn>Mu		OKAY	OKAY	OKAY
Deflection				
Ix	in	612.00	800.00	712.00
ΔC	in	0.02	0.01	0.01
L/360	in	0.64	0.64	0.64
L/360 > ΔC		OKAY	OKAY	OKAY
Studs				
diameter	in	0.75	0.75	0.75
max spacing	in	24.00	24.00	24.00
min spacing	in	5.50	5.50	5.50
Rp		1.00	1.00	1.00

Rg		1.00	1.00	1.00
Fu	KSI	65.00	65.00	65.00
Asa	in2	0.44	0.44	0.44
Qn	Kips	21.50	21.50	21.50
Qn	Kips	28.72	28.72	28.72
		0.00	0.00	0.00
n	Studs	9.81	8.56	11.12
use	studs	10.00	9.00	12.00
total	studs	20.00	18.00	24.00
spacing	in	11.05	12.21	9.28
max		OKAY	OKAY	OKAY
min		OKAY	OKAY	OKAY
Reaction left side	kips	72.42	69.44	91.54
Reaction right side	kips	47.63	69.60	53.40
Moment left	k-ft	-257.38	-269.38	-283.54
moment right	k-ft	206.57	293.38	239.83

		Girders (Fixed)		
		Quad Side 13-15	Quad Side 15-17	Quad Side 17-19
		W16x40	W14x30	W14x26
Length	ft	19.33	19.33	19.33

Concrete Slab	in	4.50	4.50	4.50
Steel Decking	in	3.00	3.00	3.00
Fy	KSI	50.00	50.00	50.00
E	KSI	29000.00	29000.00	29000.00
Track Side Spacing	ft	5.83	5.83	5.83
Dead Loads				
Concrete	PSF	54.38	54.38	54.38
Decking	PSF	2.70	2.70	2.70
MEP (piping)	PSF	10.00	10.00	10.00
Ceiling	PSF	5.00	5.00	5.00
Middle Beam Simple	PSF	14.00	14.00	14.00
Length	lb/ft	11.67	11.67	11.67
Reaction	lb	10119.08	10119.08	10119.08
Live Loads				
Design Load	PSF	100.00	100.00	100.00
Construction LL	PSF	10.00	10.00	10.00
unfactored DL	lb/ft	434.58	434.58	434.58
unfactored LL	lb/ft	583.00	583.00	583.00

Beam 1				
weight	lb/ft	26.00	35.00	26.00
length	ft	24.55	33.36	24.91
Reaction of Beam 1	lb	45672.17	29175.25	24237.62
Mu of Beam 1	K-FT	99.07	138.91	116.89
Beam 2				
weight	lb/ft	22.00		
length	ft	20.32		
Reaction of Beam 2	lb	40435.46		
Mu of Beam 2	K-FT	188.51		
Beam 3				
weight	lb/ft			
length	ft			
Reaction of Beam 3	lb			
Mu of Beam 3	K-FT			
Pu of Girder	lb	28111.61	28111.61	28111.61
Pu of Middle Beam	lb	10119.08	10119.08	10119.08
Mu of Girder and Middle Beam	K-FT	92.37	92.37	92.37

Total Mu	K-FT	379.96	231.28	209.27
Assume a	in	2.00	2.00	2.00
Y2	in	3.50	3.50	3.50
try		W16x40	W14x30	W14x26
ΦbMn	K-FT	394.00	246.00	213.00
PNA		6.00	7.00	7.00
Beam Weight	lb/ft	40.00	30.00	26.00
Check Critical Moment				
New Pu of beam	lb	29039.45	28807.49	28714.70
Mu	K-FT	94.62	94.06	93.83
Mt	K-FT	382.20	232.96	210.72
ΦbMn > Mu		OKAY	OKAY	OKAY
Composite Capacity				
ΣQn	Kips	192.00	111.00	96.10
f'c	KSI	4.00	4.00	4.00
be=(1/8)L	in	57.99	57.99	57.99
a	in	0.97	0.56	0.49
Y2	in	4.01	4.22	4.26

ΦbMn	K-FT	401.21	252.19	218.05
ΦbMn>Mu		OKAY	OKAY	OKAY
LL ONLY	lb/ft	583.00	583.00	583.00
I_{LB}	in4	935.94	510.74	456.23
ΔLL	in	0.01	0.02	0.03
L/360	in	0.64	0.64	0.64
L/360 > ΔLL		OKAY	OKAY	OKAY
Total Load	lb/ft	1057.58	1047.58	1043.58
ΔT	in	0.02	0.04	0.05
L/240	in	0.97	0.97	0.97
L/240 > ΔT		OKAY	OKAY	OKAY
DL	lb/ft	55.74	45.74	41.74
LL	lb/ft	389.69	389.69	389.69
		0.00	0.00	0.00
unfactored Total	lb/ft	445.43	435.43	431.43
factored	lb/ft	690.40	678.40	673.60

Mu	K-FT	21.50	21.12	20.97
ΦbMn>Mu		OKAY	OKAY	OKAY
Deflection				
Ix	in	518.00	291.00	245.00
ΔC	in	0.02	0.03	0.04
L/360	in	0.64	0.64	0.64
L/360 > ΔC		OKAY	OKAY	OKAY
Studs				
diameter	in	0.75	0.75	0.75
max spacing	in	24.00	24.00	24.00
min spacing	in	5.50	5.50	5.50
Rp		1.00	1.00	1.00
Rg		1.00	1.00	1.00
Fu	KSI	65.00	65.00	65.00
Asa	in2	0.44	0.44	0.44
Qn	Kips	21.50	21.50	21.50
Qn	Kips	28.72	28.72	28.72
		0.00	0.00	0.00
n	Studs	8.93	5.16	4.47
use	studs	9.00	6.00	5.00
total	studs	18.00	12.00	10.00

spacing	in	12.21	17.84	21.09
max		OKAY	OKAY	OKAY
min		OKAY	OKAY	OKAY
Reaction left side	kips	71.98	26.82	26.18
Reaction right side	kips	43.91	32.14	27.84
Moment left	k-ft	-230.13	-132.95	-127.75
moment right	k-ft	198.40	149.91	133.09

		Girders (Fixed)
		Quad Side 19-21
		W14x30
Length	ft	19.33
Concrete Slab	in	4.50
Steel Decking	in	3.00
Fy	KSI	50.00
E	KSI	29000.00
Track Side Spacing	ft	5.83
Dead Loads		

Concrete	PSF	54.38
Decking	PSF	2.70
MEP (piping)	PSF	10.00
Ceiling	PSF	5.00
Middle Beam Simple	PSF	14.00
Length	lb/ft	11.67
Reaction	lb	10119.08
Live Loads		
Design Load	PSF	100.00
Construction LL	PSF	10.00
unfactored DL	lb/ft	434.58
unfactored LL	lb/ft	583.00
Beam 1		
weight	lb/ft	35.00
length	ft	36.40
Reaction of Beam 1	lb	35570.06
Mu of Beam 1	K-FT	171.89
Beam 2		
weight	lb/ft	
length	ft	

Reaction of Beam 2	lb	
Mu of Beam 2	K-FT	
Beam 3		
weight	lb/ft	
length	ft	
Reaction of Beam 3	lb	
Mu of Beam 3	K-FT	
Pu of Girder	lb	28111.61
Pu of Middle Beam	lb	10119.08
Mu of Girder and Middle Beam	K-FT	92.37
Total Mu	K-FT	223.75
Assume a	in	2.00
Y2	in	3.50
try		W14x30
ΦbMn	K-FT	246.00
PNA		7.00
Beam Weight	lb/ft	30.00

Check Critical Moment		
New Pu of beam	lb	28807.49
Mu	K-FT	94.06
Mt	K-FT	225.43
ΦbMn > Mu		OKAY
Composite Capacity		
ΣQn	Kips	111.00
f'c	KSI	4.00
be=(1/8)L	in	57.99
a	in	0.56
Y2	in	4.22
ΦbMn	K-FT	252.19
ΦbMn>Mu		OKAY
LL ONLY	lb/ft	583.00
I_{LB}	in4	510.74
ΔLL	in	0.02
L/360	in	0.64

L/360 > ΔLL		OKAY
Total Load	lb/ft	1047.58
ΔT	in	0.04
L/240	in	0.97
L/240 > ΔT		OKAY
DL	lb/ft	45.74
LL	lb/ft	389.69
		0.00
unfactored Total	lb/ft	435.43
factored	lb/ft	678.40
Mu	K-FT	21.12
ΦbMn>Mu		OKAY
Deflection		
Ix	in	291.00
ΔC	in	0.03
L/360	in	0.64
L/360 > ΔC		OKAY
Studs		

diameter	in	0.75
max spacing	in	24.00
min spacing	in	5.50
Rp		1.00
Rg		1.00
Fu	KSI	65.00
Asa	in2	0.44
Qn	Kips	21.50
Qn	Kips	28.72
		0.00
n	Studs	5.16
use	studs	6.00
total	studs	12.00
spacing	in	17.84
max		OKAY
min		OKAY
Reaction left side	kips	32.81
Reaction right side	kips	32.86
Moment left	k-ft	-158.60
moment right	k-ft	158.77

Girders (Fixed)

		Softball 1-3	Softball 3-5	Softball 5-7
		W12x19	W10x19	W12x19
Length	ft	21.50	21.50	21.50
Concrete Slab	in	4.50	4.50	4.50
Steel Decking	in	3.00	3.00	3.00
Fy	KSI	50.00	50.00	50.00
E	KSI	29000.00	29000.00	29000.00
Track Side Spacing	ft	5.83	5.83	5.83
Dead Loads				
Concrete	PSF	54.38	54.38	54.38
Decking	PSF	2.70	2.70	2.70
MEP (piping)	PSF	10.00	10.00	10.00
Ceiling	PSF	5.00	5.00	5.00
Middle Beam Simple	PSF	12.00	12.00	12.00
Length	lb/ft	11.67	11.67	11.67
Reaction	lb	11292.40	11292.40	11292.40
Live Loads				
Design Load	PSF	100.00	100.00	100.00
Construction LL	PSF	10.00	10.00	10.00

unfactored DL	lb/ft	434.58	434.58	434.58
unfactored LL	lb/ft	583.00	583.00	583.00
Beam 1				
weight	lb/ft	22.00		22.00
length	ft	14.21		14.21
Reaction of Beam 1	lb	3874.46		3926.84
Mu of Beam 1	K-FT	7.28		7.47
Beam 2				
weight	lb/ft			
length	ft			
Reaction of Beam 2	lb			
Mu of Beam 2	K-FT			
Beam 3				
weight	lb/ft			
length	ft			
Reaction of Beam 3	lb			
Mu of Beam 3	K-FT			
Pu of Girder	lb	31267.44	31267.44	31267.44

Pu of Middle Beam	lb	11292.40	11292.40	11292.40
Mu of Girder and Middle Beam	K-FT	114.38	114.38	114.38
Total Mu	K-FT	121.66	114.38	121.85
Assume a	in	2.00	2.00	2.00
Y2	in	3.50	3.50	3.50
try		W12x19	W10x19	W12x19
ΦbMn	K-FT	150.00	129.00	150.00
PNA		6.00	6.00	6.00
Beam Weight	lb/ft	19.00	19.00	19.00
Check Critical Moment				
New Pu of beam	lb	31757.64	31757.64	31757.64
Mu	K-FT	115.70	115.70	115.70
Mt	K-FT	122.98	115.70	123.17
ΦbMn > Mu		OKAY	OKAY	OKAY
Composite Capacity				
ΣQn	Kips	104.00	96.20	104.00
f'c	KSI	4.00	4.00	4.00

be=(1/8)L	in	64.50	32.25	64.50
a	in	0.47	0.88	0.47
Y2	in	4.26	4.06	4.26
ΦbMn	K-FT	156.10	132.49	156.10
ΦbMn>Mu		OKAY	OKAY	OKAY
LL ONLY	lb/ft	583.00	583.00	583.00
I_{LB}	in4	292.41	216.59	292.41
ΔLL	in	0.07	0.09	0.07
L/360	in	0.72	0.72	0.72
L/360 > ΔLL		OKAY	OKAY	OKAY
Total Load	lb/ft	1036.58	1036.58	1036.58
ΔT	in	0.12	0.16	0.12
L/240	in	1.08	1.08	1.08
L/240 > ΔT		OKAY	OKAY	OKAY
DL	lb/ft	34.74	34.74	34.74
LL	lb/ft	389.69	389.69	389.69

		0.00	0.00	0.00
unfactored Total	lb/ft	424.43	424.43	424.43
factored	lb/ft	665.20	665.20	665.20
Mu	K-FT	25.62	25.62	25.62
ΦbMn>Mu		OKAY	OKAY	OKAY
Deflection				
Ix	in	130.00	96.30	130.00
ΔC	in	0.11	0.15	0.11
L/360	in	0.72	0.72	0.72
L/360 > ΔC		OKAY	OKAY	OKAY
Studs				
diameter	in	0.75	0.75	0.75
max spacing	in	24.00	24.00	24.00
min spacing	in	5.50	5.50	5.50
Rp		1.00	1.00	1.00
Rg		1.00	1.00	1.00
Fu	KSI	65.00	65.00	65.00
Asa	in2	0.44	0.44	0.44
Qn	Kips	21.50	21.50	21.50
Qn	Kips	28.72	28.72	28.72
		0.00	0.00	0.00

n	Studs	4.84	4.47	4.84
use	studs	5.00	7.00	5.00
total	studs	10.00	14.00	10.00
spacing	in	23.45	17.20	23.45
max		OKAY	OKAY	OKAY
min		OKAY	OKAY	OKAY
Reaction left side	kips	20.36	16.59	16.69
Reaction right side	kips	16.69	16.59	20.40
Moment left	k-ft	-95.72	-89.14	-89.88
moment right	k-ft	89.85	89.14	95.88

Appendix J: Comparison of Steel Design in Robot and by Hand Calculations

Cantilever Middle Beams
Quad – Football Side
Robot Analysis

Autodesk Robot Structural Analysis Professional 2012
Author:
Address:

File: **Quad-FB Cantilever.rtd**
Project: Quad-FB Cantilever

Symbol	Values	Unit	Symbol description	Section
			MEMBER: 1 ; COORDINATE: x = 0.00 L = 0.00 ft	
			Cross-section properties: W 18x35	
Ax	10.300	in2	Cross-section area	
Ay	5.100	in2	Shear area - Y-axis	
Az	5.310	in2	Shear area - Z-axis	
J	0.506	in4	Torsional constant	
Iy	510.000	in4	Moment of inertia of a section about the Y-axis	
Iz	15.300	in4	Moment of inertia of a section about the Z-axis	
Zy	66.500	in3	Plastic section modulus about the Y (major) axis	
Sy	57.627	in3	Elastic section modulus about the Y-axis	
Zz	8.060	in3	Plastic section modulus about the Z (minor) axis	
Sz	5.100	in3	Elastic section modulus about the Z-axis	
d	17.70	in	Height of cross-section	
b	6.00	in	Width of cross-section	
tf	0.42	in	Flange thickness	
tw	0.30	in	Web thickness	
ry	7.04	in	Radius of gyration - Y-axis	
rz	1.22	in	Radius of gyration - Z-axis	
			Material:	
Name			STEEL A992-50	
Fy	50.00	ksi	Specified minimum yield strength of material	
Fu	65.00	ksi	Specified minimum tensile strength	
E	29000.00	ksi	Longitudinal elasticity coefficient	
			Partial factor method LRFD	
Fib	0.90		Resistance factor for flexure	[F1.(1)]
Fiv	0.90		Resistance factor for shear	[G1]
			Local buckling	
x	7.06		Width-thickness ratio for a flange	[Table B4.1]
y	53.50		Width-thickness ratio for a web	[Table B4.1]
Section class for simple bending (My moment)				
Xp_My	9.15		Maximum slenderness of a compact flange	[Table B4.1]
Xr_My	24.08		Maximum slenderness of a non-compact flange	[Table B4.1]
UNS_My	Compact		Flexibility of a flange in local buckling	[Table B4.1]
Yp_My	90.55		Maximum slenderness of a compact web	[Table B4.1]
Yr_My	137.27		Maximum slenderness of a non-compact web	[Table B4.1]
STI_My	Compact		Flexibility of a web for local buckling	[Table B4.1]
			Parameters of lateral buckling analysis:	
Rm	1.00		Cross-section monosymmetry parameter	[F1.(2)]
Cb	1.00		Lateral-torsional buckling modification factor	[F1.(2)]
Lb	11.67	ft	Laterally unbraced length of a member (lateral-torsional buckling)	[F2.2]
Lpy	4.30	ft	Limiting laterally unbraced length for the limit state of yielding	[F2.2]

Autodesk Robot Structural Analysis Professional 2012
Author:
Address:

File: **Quad-FB Cantilever.rtd**
Project: Quad-FB Cantilever

Symbol	Values	Unit	Symbol description	Section
Lry	12.38	ft	Limiting laterally unbraced length for the limit state of inelastic lateral-torsional buckling	[F2.2]
			Other:	
Cw	1141.48	in6	Warping constant	[E,F]
Cvz	1.00		Ratio for critical web stress calculations	[G2.1]
kvz	1.20		Shear buckling coefficient	[G2.1]
			Internal forces	
Mry	-65.85	kip*ft	Required flexural strength	
Vrz	11.28	kip	Required shear strength	
			Nominal strength:	
About the Y axis of cross-section				
Mpy	277.08	kip*ft	Plastic bending moment	[F]
Mny[YD]	277.08	kip*ft	Flexural strength in the limit state of yielding	[F2.1]
Mny[LTB]	177.67	kip*ft	Lateral-torsional buckling strength	[F2.2]
Mny	177.67	kip*ft	Design flexural strength	[F2]
Vnz	159.30	kip	Design shear strength	[G2.1]
			Verification formulas:	
UF(H1_1b)	0.41		Mry/(Fib*Mny)	Verified
UF(G2_1)	0.07		Vrz/(Fiv*Vnz)	Verified
			Ratio:	
RAT	0.41		Efficiency ratio	Section OK

Hand Calculations

Alt track design 2 | ⊥ beam cantilever | (quad-FB)

Concrete slab = 4.5 in
Steel decking = 3.0 in
Span = 11.67 ft
Spacing = 9.67 ft

$F_y = 50$ KSI
$E = 29000$ KSI
ponding = 1.1

Same loading as ⊥ beam simple

$DL = 767.21$ lb/ft
$LL = 967$ lb/ft

$W_U = 1.2(767.21\ \text{lb/ft}) + 1.6(967\ \text{lb/ft}) = 2467.85\ \text{lb/ft}$

$M_U = \frac{2467.85\ \text{lb/ft}\,(11.67\ \text{ft})^2}{2} = 168.05\ \text{k·ft}$

$Z_x \geq \frac{168.05\ \text{k·ft}\,(12'')}{0.9(50\ \text{KSI})} = 44.81\ \text{in}^3$

try W18x35 $Z_x = 66.5\ \text{in}^3$ (table 3-2 AISC Manual)

$DL = 767.21\ \text{lb/ft} + 35\ \text{lb/ft} = 802.21\ \text{lb/ft}$
$LL = 967\ \text{lb/ft}$

$W_U = 1.2(802.21\ \text{lb/ft}) + 1.6(967\ \text{lb/ft}) = 2509.85\ \text{lb/ft}$

$M_U = \frac{2509.85\ \text{lb/ft}\,(11.67')^2}{2} = 170.91\ \text{k·ft}$

$\phi M_p = \frac{0.9(66.5\ \text{in}^3)(50\ \text{KSI})}{12} = 249.38\ \text{k·ft}$

$\phi M_p = 249.38\ \text{k·ft} > 170.91\ \text{k·ft} = M_U$ ✓

FLB

$\frac{b_f}{2t_f} = 7.06\ \text{in}$ (table 1-1 AISC manual)

$\text{Limit} = 0.38\sqrt{\frac{29000}{50}} = 9.15\ \text{in}$ ✓

WLB

$\frac{h}{t_w} = 53.5\ \text{in}$ (table 1-1 AISC manual)

$\text{Limit} = 3.76\sqrt{\frac{29000}{50}} = 90.6\ \text{in}$ ✓

Deflection

$I_x = 510\ \text{in}^4$ (table 1-1 AISC Manual)

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⊥ beams cantilever | (quad - FB)

$LL = 967\ lb/ft$

$\Delta_{LL} = \frac{967\ lb/ft\,(11.67)^4}{8(29000\,ksi)(510\,in^4)} \times \frac{1728\,in^3}{ft^3} \times \frac{1k}{1000\,lb} = 0.262\,in$

$\Delta_{max} = L/360 = \frac{11.67' \times 12}{360} = 0.39\,in$

$\Delta_{max} = 0.39\,in > 0.262\,in = \Delta_{LL}$

Total load

$TL = 967\ lb/ft + 798.21\ lb/ft = 1769.20\ lb/ft$

$\Delta_T = \frac{1281.71\ lb/ft\,(11.67')^4}{8(29000\,ksi)(375\,in^4)} \times \frac{1728\,in^3}{ft^3} \times \frac{1k}{1000\,lb} = 0.48\,in$

$\Delta_{max} = L/240 = \frac{11.67' \times 12''}{240} = 0.58\,in$

$\Delta_{max} = 0.58'' > 0.48'' = \Delta_T$ ✓

construction $LL = 10\,psf$

$load = 31\ lb/ft + 26.11\ lb/ft + 549.67\ lb/ft + 10\,psf\,(9.67')$
$load = 703.48\ lb/ft$

$\Delta_C = \frac{703.48\ lb/ft\,(11.67')^4}{8(29000\,ksi)(510\,in^4)} \times \frac{1728\,in^3}{ft^3} \times \frac{1\,kip}{1000\,lb} = 0.19\,in$

$\Delta_{max} = L/360 = 0.39\,in$

$\Delta_{max} = 0.39\,in > 0.19\,in = \Delta_C$ ✓

so use W18×35

$Reaction = wL = (767.21 + 967)(11.67) = 20238.17\,lb$

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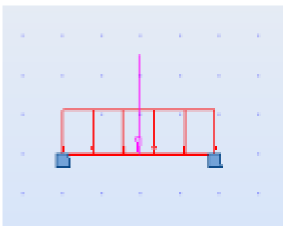
Appendix K: Comparison of Girder Reactions in Robot and by Hand Calculations

Football Side Girders

Robot Analysis Hand

Calculations

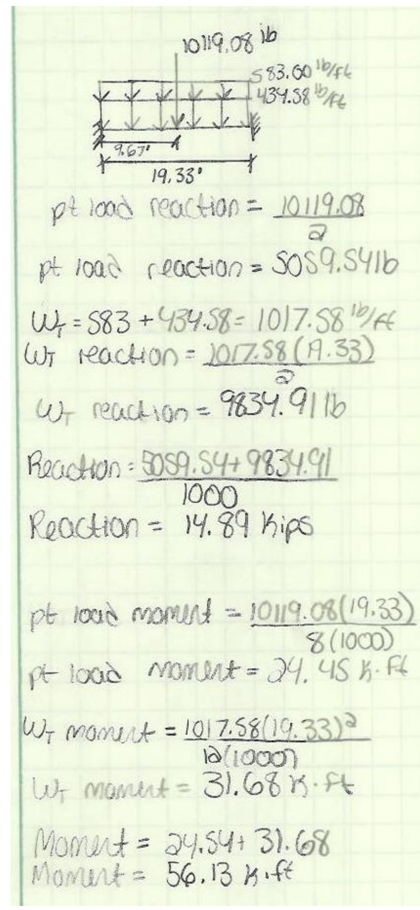


Loads

Case	Load type	List					
1:DL	uniform load	1	PX=0.0	PZ=-0.43	global	not project.	absolute
2:LL1	uniform load	1	PX=0.0	PZ=-0.58	global	not project.	absolute
1:DL	bar force	1	FX=0.0	FZ=-10.12	CY=0.0	X=9.67	global

Reactions

Node/Case		FX (kip)	FZ (kip)	MY (kip-ft)
1/	1	0.0	9.25	-37.96
1/	2	0.0	5.63	-18.15
2/	1	0.0	9.26	37.97
2/	2	0.0	5.63	18.15



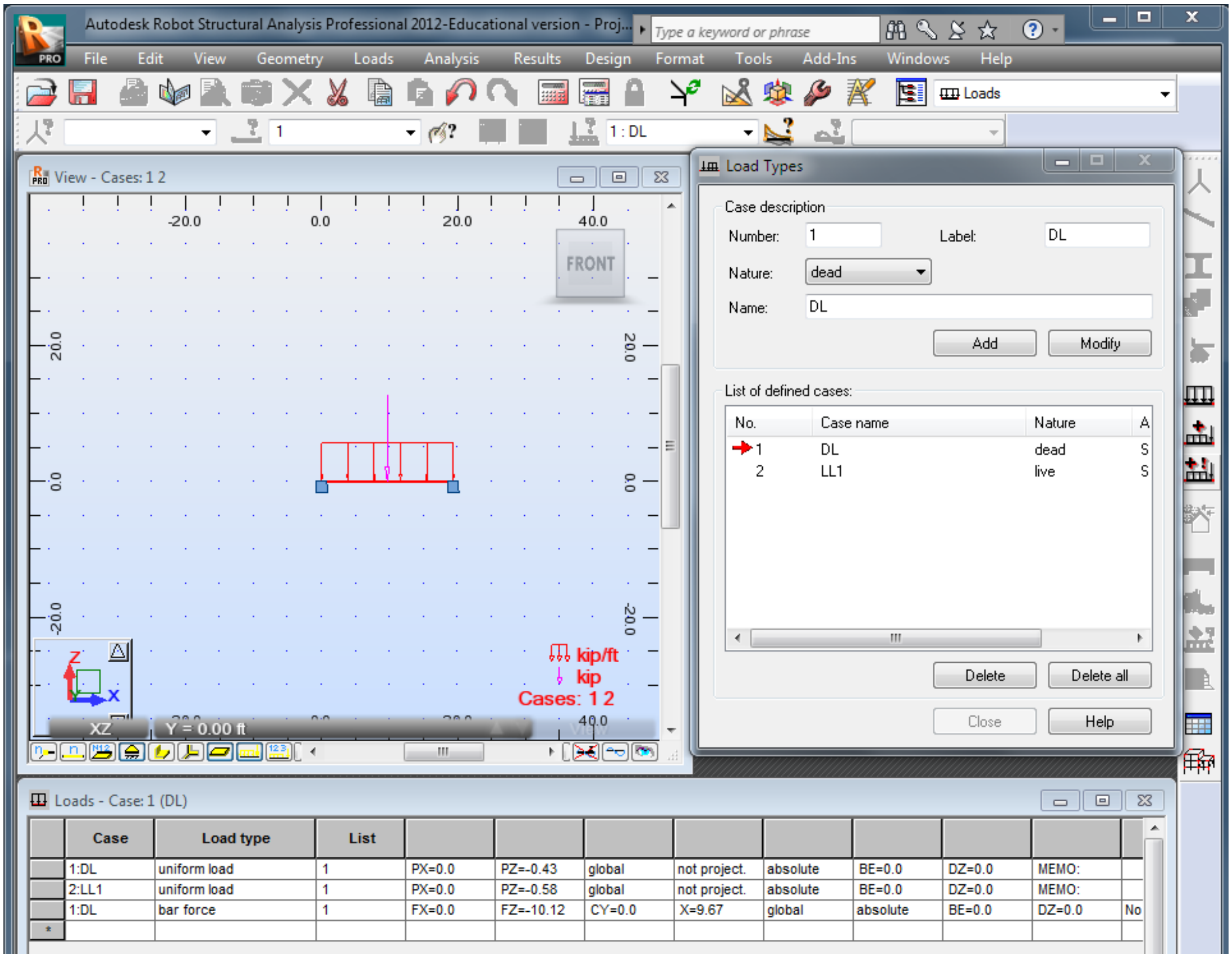
10119.08 lb
583.60 lb/ft
434.58 lb/ft
9.67'
19.33'

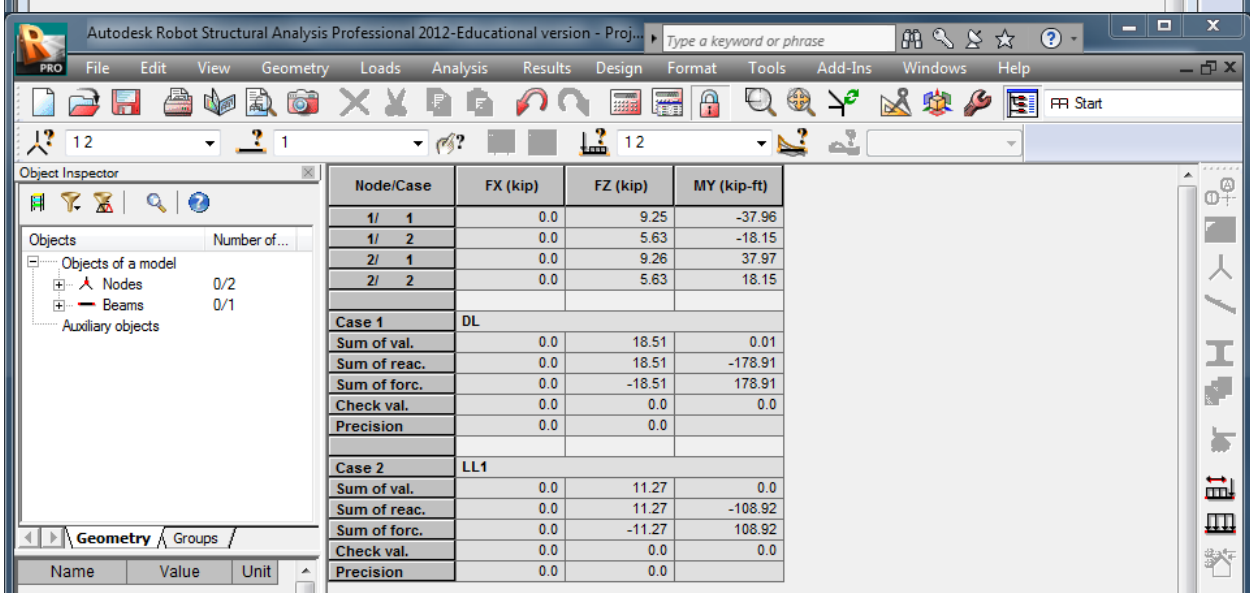
pt load reaction = 10119.08 / 2
pt load reaction = 5059.54 lb
W_T = 583 + 434.58 = 1017.58 lb/ft
W_T reaction = 1017.58 (19.33) / 2
W_T reaction = 9834.91 lb
Reaction = 5059.54 + 9834.91 / 1000
Reaction = 14.89 kips

pt load moment = 10119.08 (19.33) / 8 (1000)
pt load moment = 24.45 k·ft
W_T moment = 1017.58 (19.33)^2 / 12 (1000)
W_T moment = 31.68 k·ft
Moment = 24.54 + 31.68
Moment = 56.13 k·ft

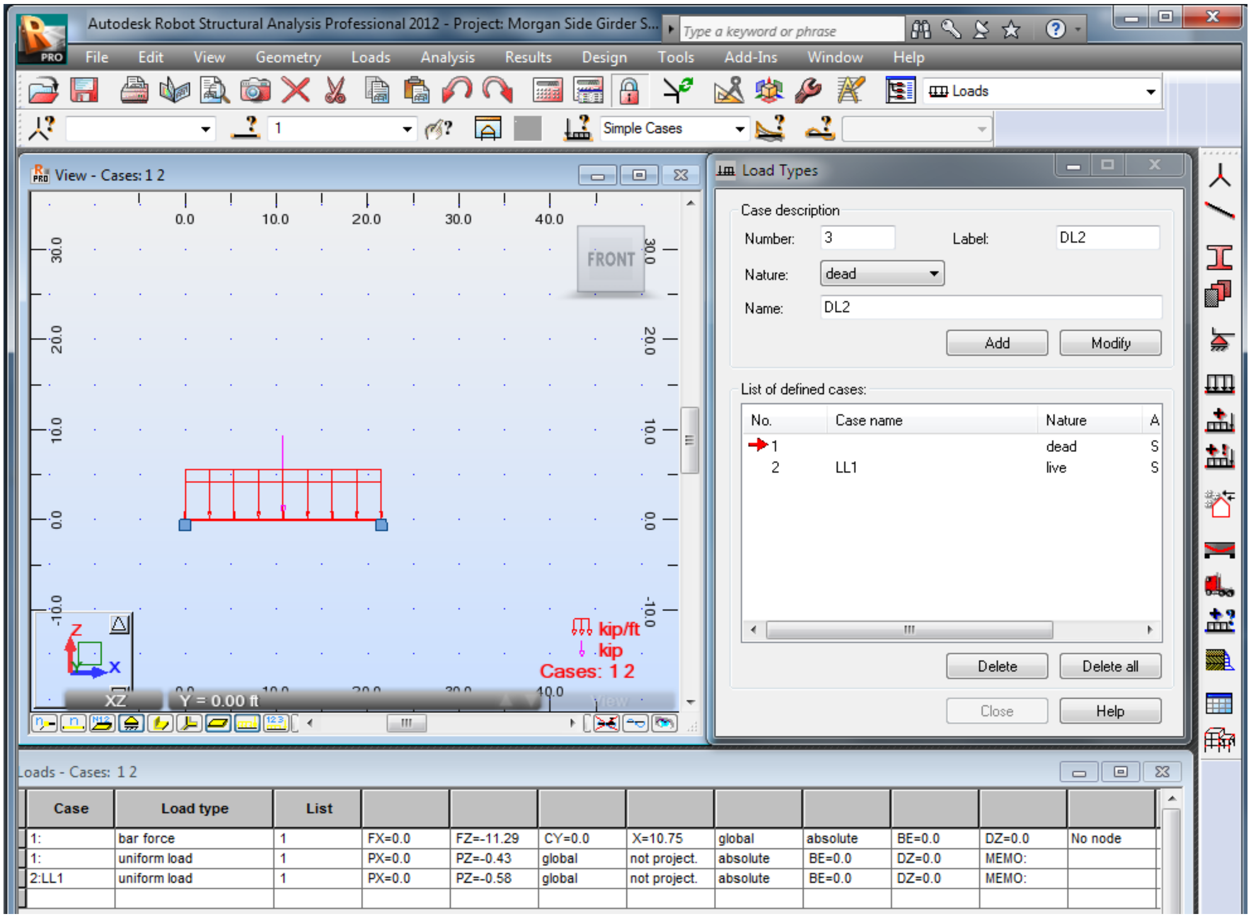
Appendix L: Girder Reactions

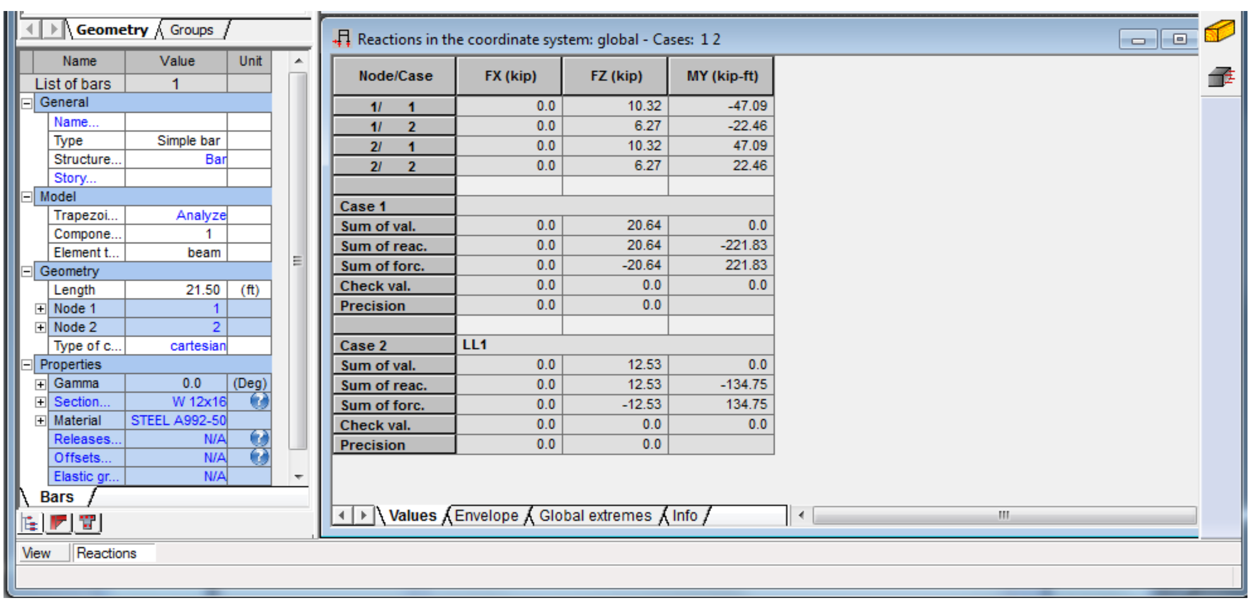
Football Field Side





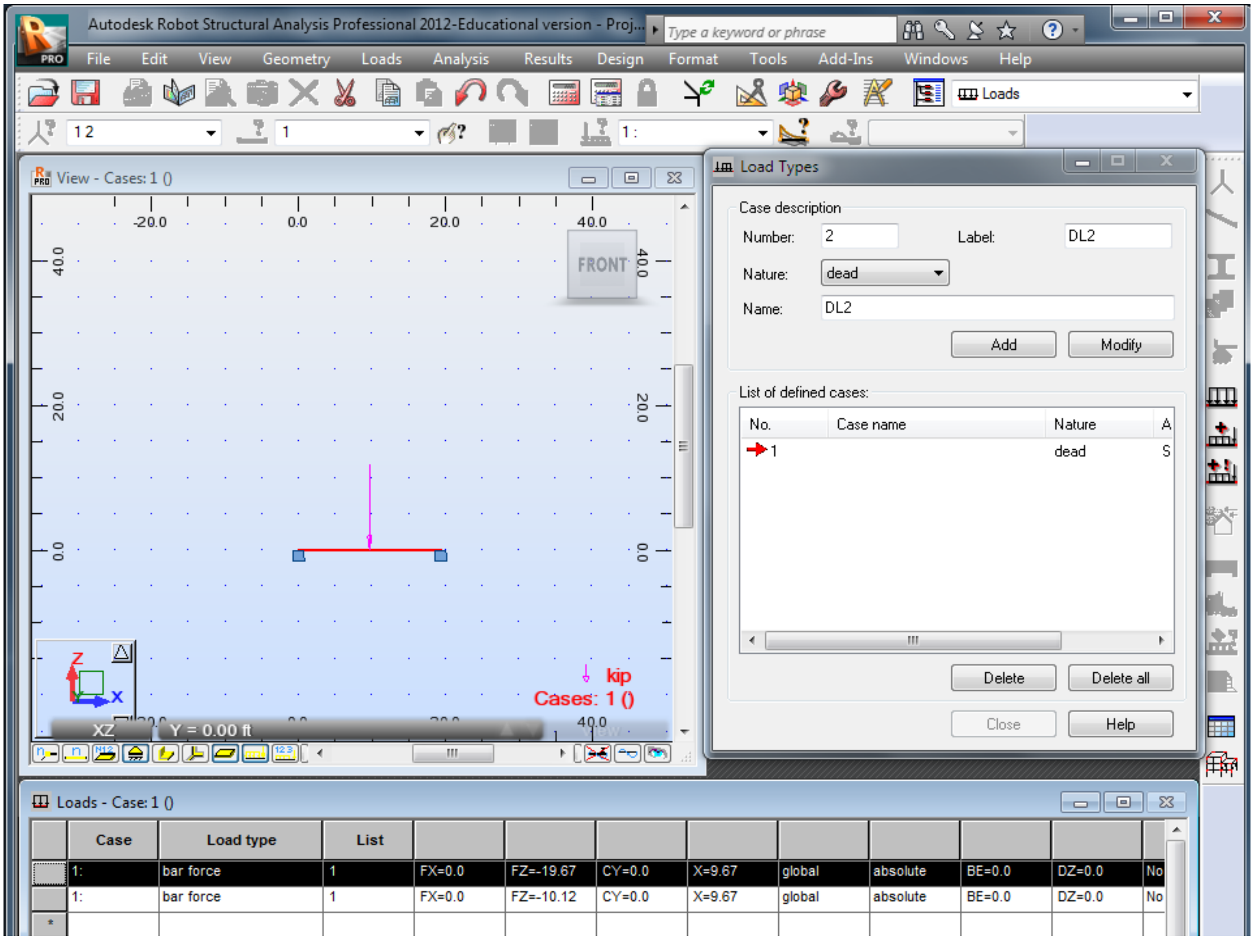
Morgan Side

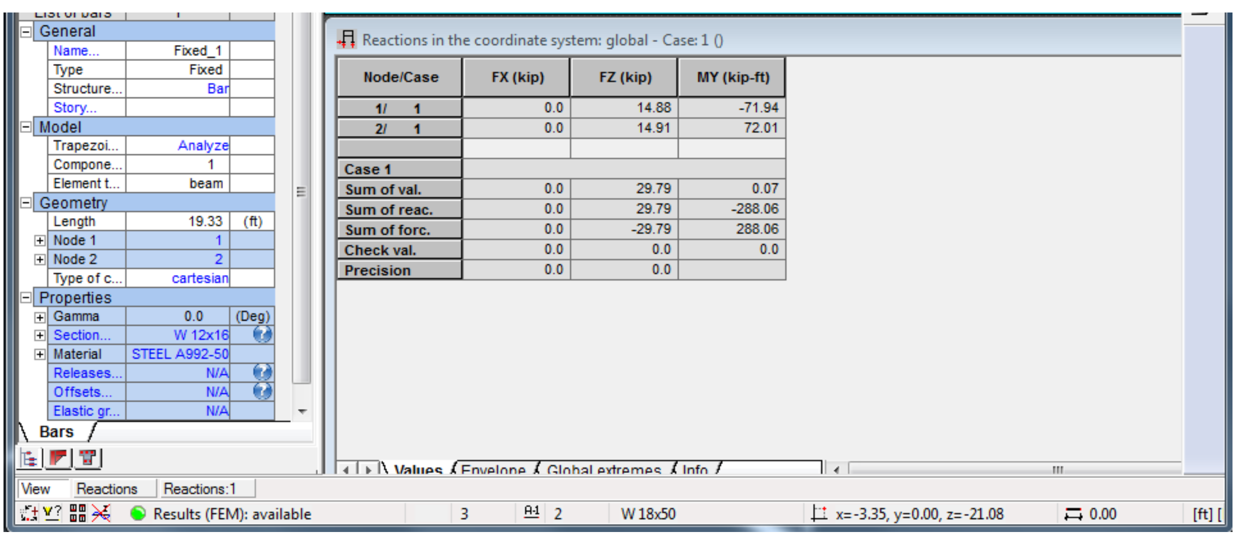




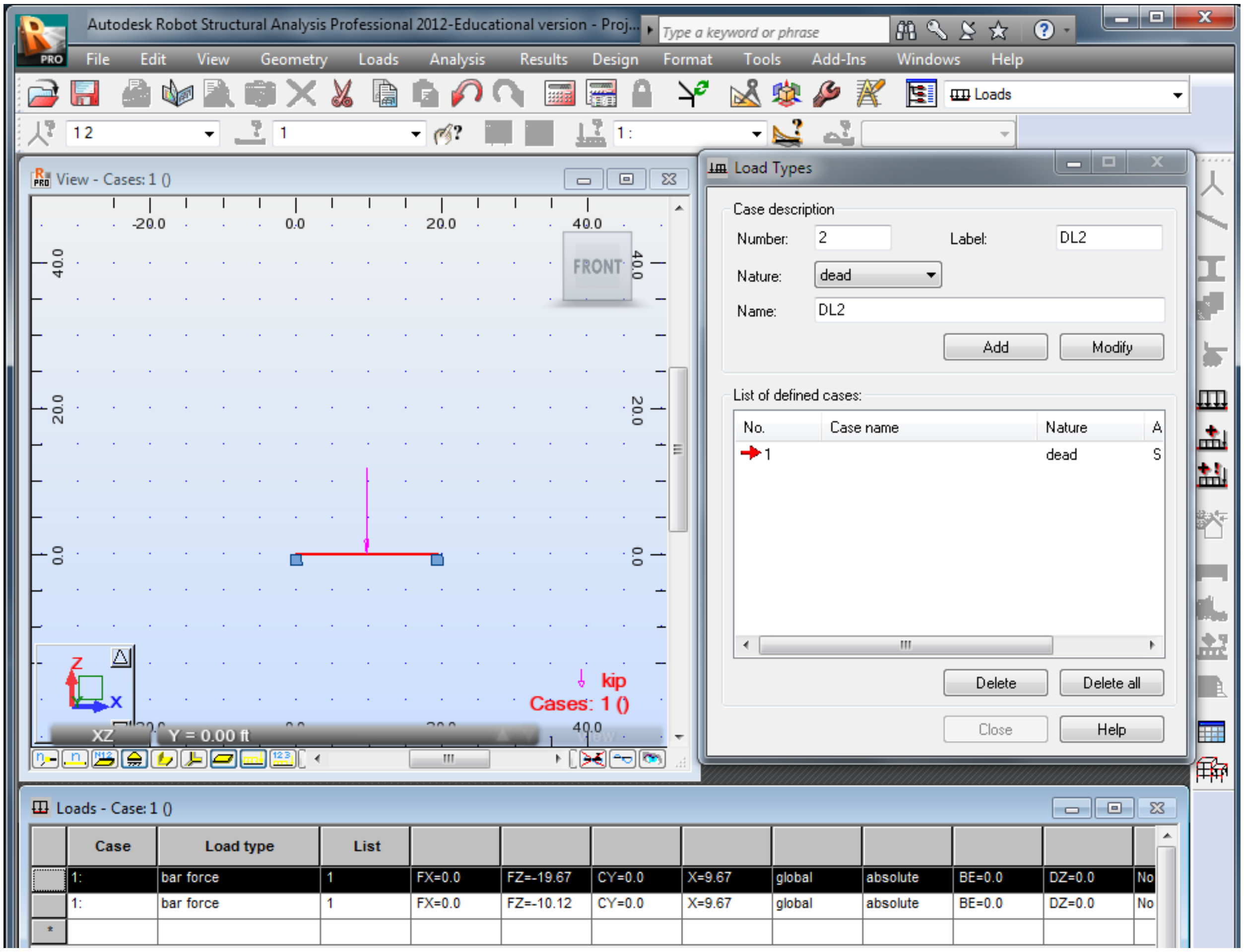
Quad Side

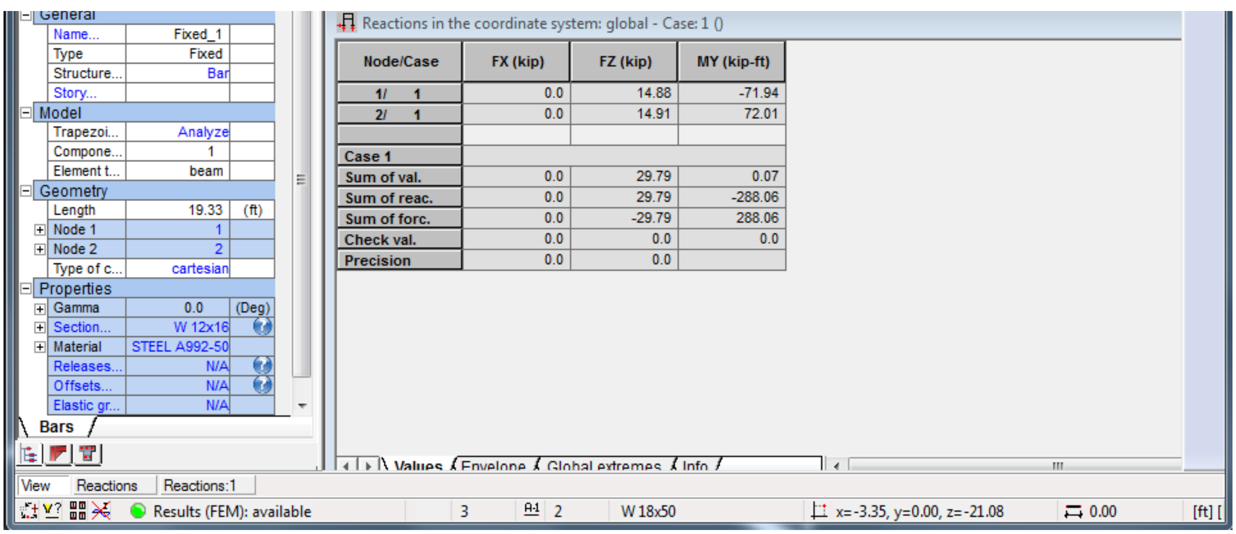
Section 1-3


Autodesk Robot Structural Analysis Professional 2012-Educational version
View - Cases: 1 ()
Load Types
Case description
Number: 2
Label: DL2
Nature: dead
Name: DL2
Add
Modify
List of defined cases:
No. Case name Nature
1 dead
Delete
Delete all
Close
Help
Loads - Case: 1 ()
Case Load type List
1: bar force 1 FX=0.0 FZ=-19.67 CY=0.0 X=9.67 global absolute BE=0.0 DZ=0.0
1: bar force 1 FX=0.0 FZ=-10.12 CY=0.0 X=9.67 global absolute BE=0.0 DZ=0.0
kip
Cases: 1 ()

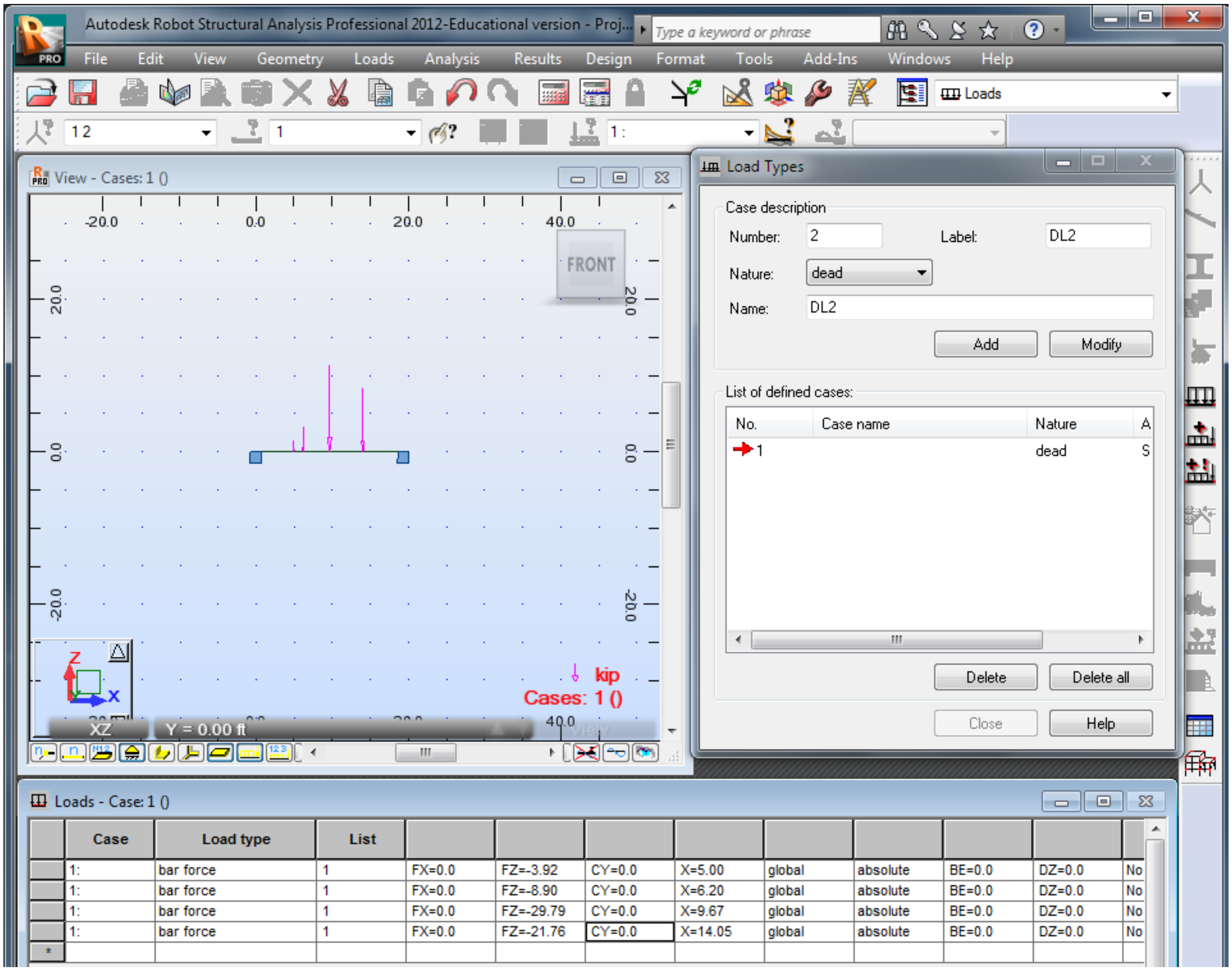

General
Name... Fixed_1
Type Fixed
Structure... Bar
Model
Trapezoi... Analyze
Compone... 1
Element t... beam
Geometry
Length 19.33 (ft)
Node 1 1
Node 2 2
Type of c... cartesian
Properties
Gamma 0.0 (Deg)
Section... W 12x16
Material STEEL A992-50
Releases... N/A
Offsets... N/A
Elastic gr... N/A
Bars
Reactions in the coordinate system: global - Case: 1 ()
Node/Case FX (kip) FZ (kip) MY (kip-ft)
1/ 1 0.0 14.88 -71.94
2/ 1 0.0 14.91 72.01
Case 1
Sum of val. 0.0 29.79 0.07
Sum of reac. 0.0 29.79 -288.06
Sum of forc. 0.0 -29.79 288.06
Check val. 0.0 0.0 0.0
Precision 0.0 0.0
Results (FEM): available
W 18x50
x=-3.35, y=0.00, z=-21.08

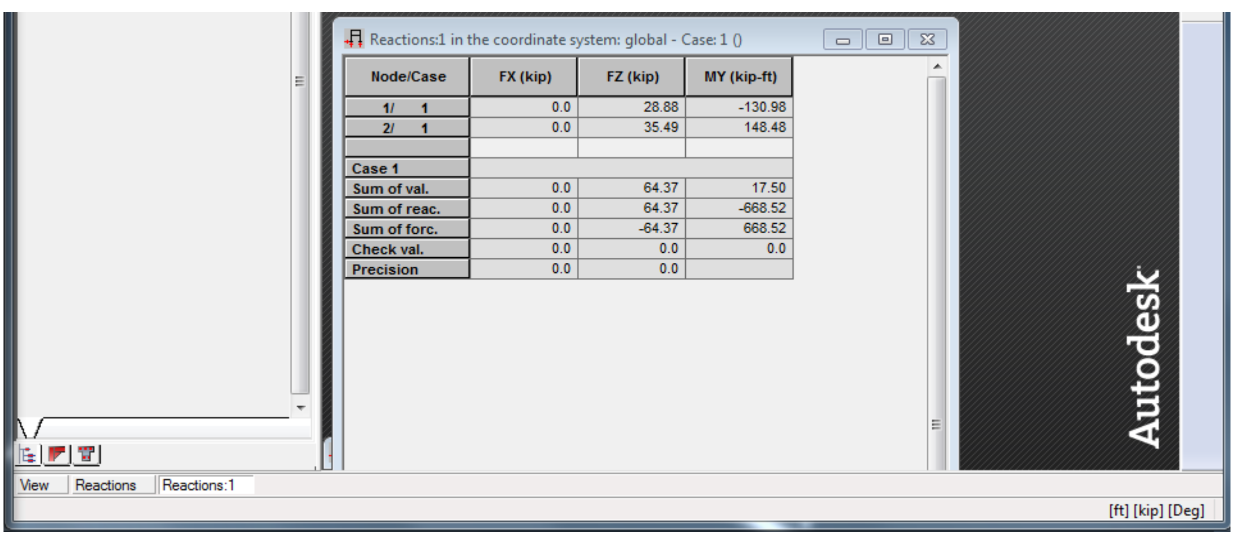
Section 3-5



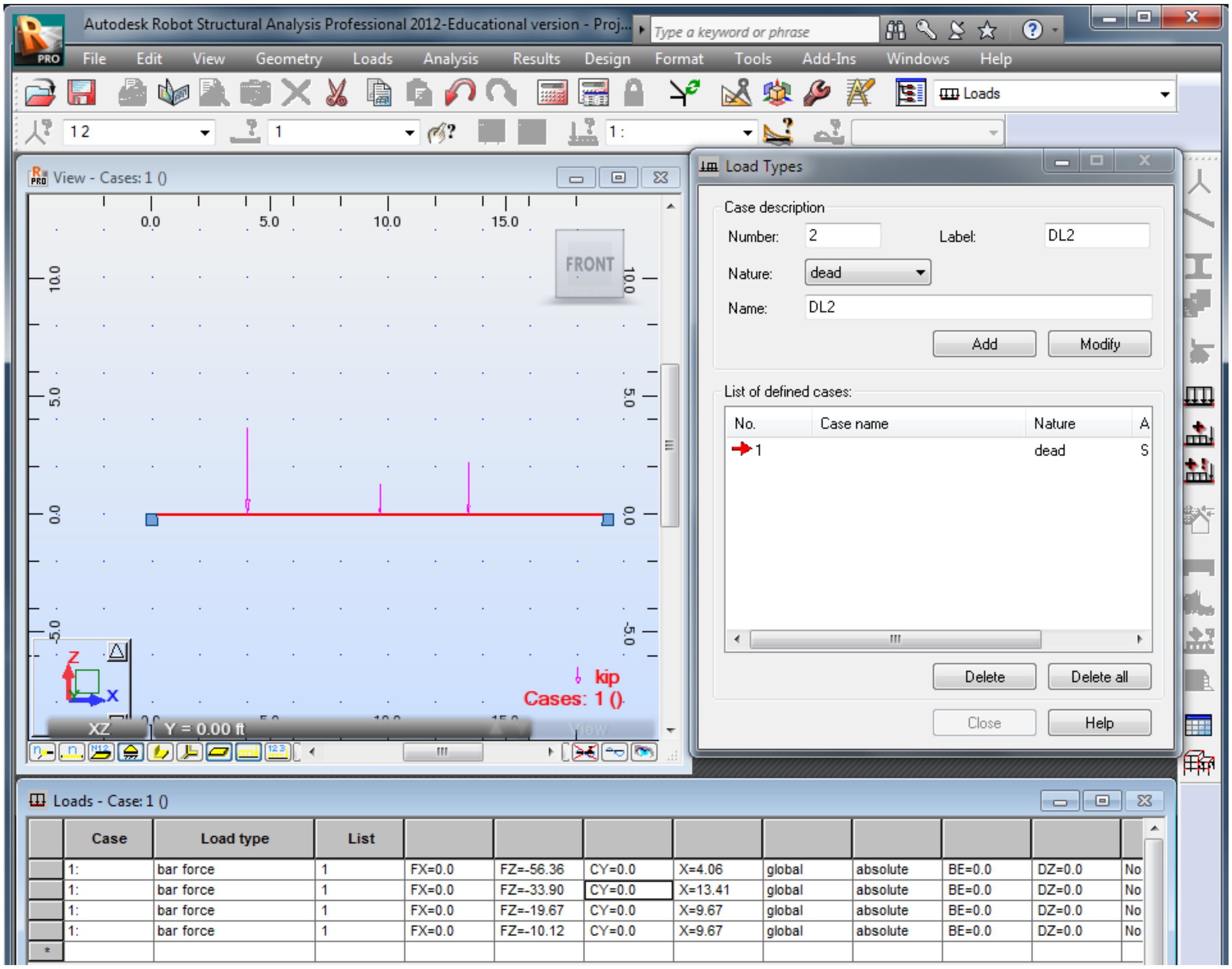


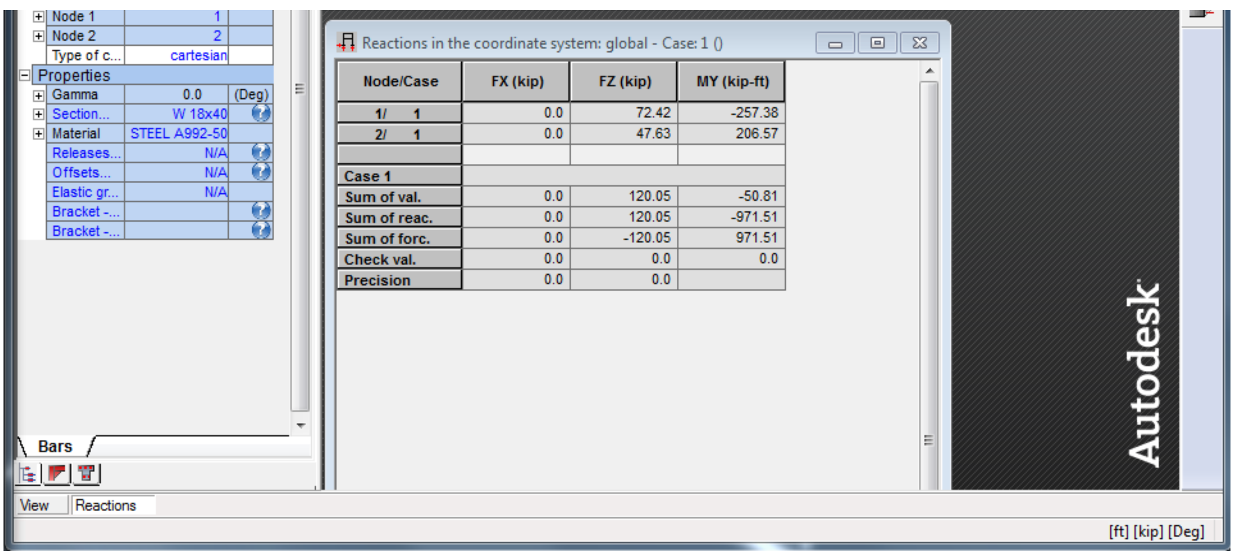
Section 5-7


Autodesk Robot Structural Analysis Professional 2012-Educational version - Proj...
File Edit View Geometry Loads Analysis Results Design Format Tools Add-Ins Windows Help
View - Cases: 1 ()
FRONT
kip
Cases: 1 ()
Load Types
Case description
Number: 2
Label: DL2
Nature: dead
Name: DL2
Add Modify
List of defined cases:
No. Case name Nature
1 dead
Delete Delete all
Close Help
Loads - Case: 1 ()
Case | Load type | List
1: | bar force | 1 | FX=0.0 | FZ=-3.92 | CY=0.0 | X=5.00 | global | absolute | BE=0.0 | DZ=0.0 | No
1: | bar force | 1 | FX=0.0 | FZ=-8.90 | CY=0.0 | X=6.20 | global | absolute | BE=0.0 | DZ=0.0 | No
1: | bar force | 1 | FX=0.0 | FZ=-29.79 | CY=0.0 | X=9.67 | global | absolute | BE=0.0 | DZ=0.0 | No
1: | bar force | 1 | FX=0.0 | FZ=-21.76 | CY=0.0 | X=14.05 | global | absolute | BE=0.0 | DZ=0.0 | No

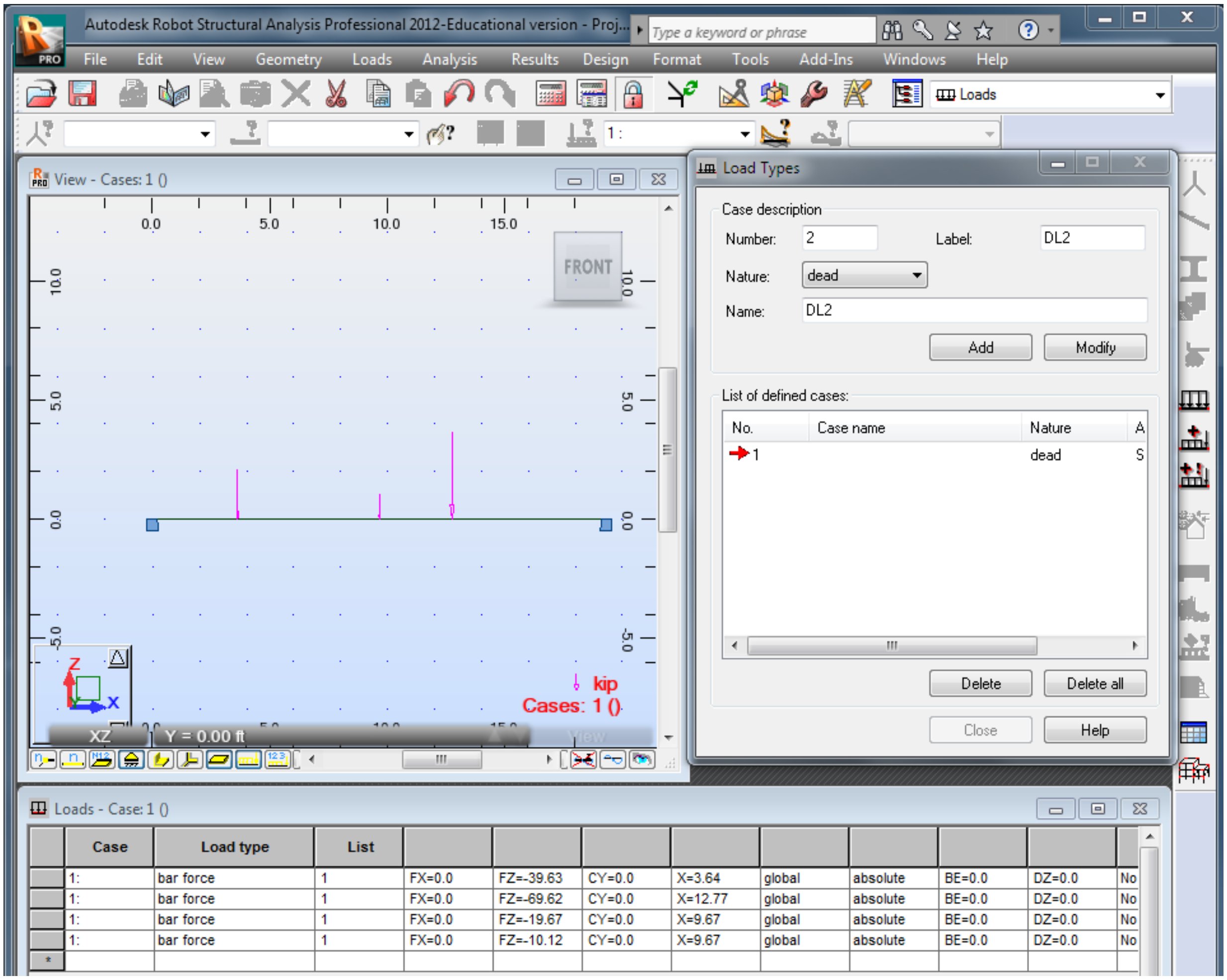

Reactions:1 in the coordinate system: global - Case: 1 ()
Node/Case | FX (kip) | FZ (kip) | MY (kip-ft)
1/ 1 | 0.0 | 28.88 | -130.98
2/ 1 | 0.0 | 35.49 | 148.48
Case 1
Sum of val. | 0.0 | 64.37 | 17.50
Sum of reac. | 0.0 | 64.37 | -668.52
Sum of forc. | 0.0 | -64.37 | 668.52
Check val. | 0.0 | 0.0 | 0.0
Precision | 0.0 | 0.0
View Reactions Reactions:1
[ft] [kip] [Deg]
Autodesk

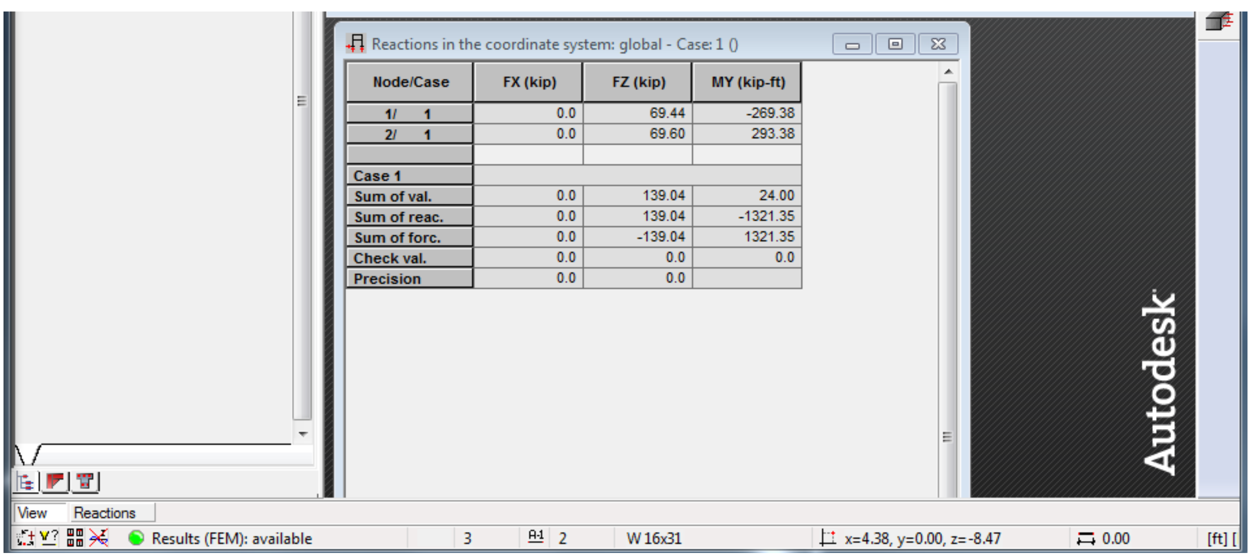
Section 7-9


Autodesk Robot Structural Analysis Professional 2012-Educational version
View - Cases: 1 ()
FRONT
kip
Cases: 1 ()
Load Types
Case description
Number: 2
Label: DL2
Nature: dead
Name: DL2
Add
Modify
List of defined cases:
No. Case name Nature
1 dead
Delete
Delete all
Close
Help
Loads - Case: 1 ()
Case Load type List
1: bar force 1 FX=0.0 FZ=-56.36 CY=0.0 X=4.06 global absolute BE=0.0 DZ=0.0 No
1: bar force 1 FX=0.0 FZ=-33.90 CY=0.0 X=13.41 global absolute BE=0.0 DZ=0.0 No
1: bar force 1 FX=0.0 FZ=-19.67 CY=0.0 X=9.67 global absolute BE=0.0 DZ=0.0 No
1: bar force 1 FX=0.0 FZ=-10.12 CY=0.0 X=9.67 global absolute BE=0.0 DZ=0.0 No

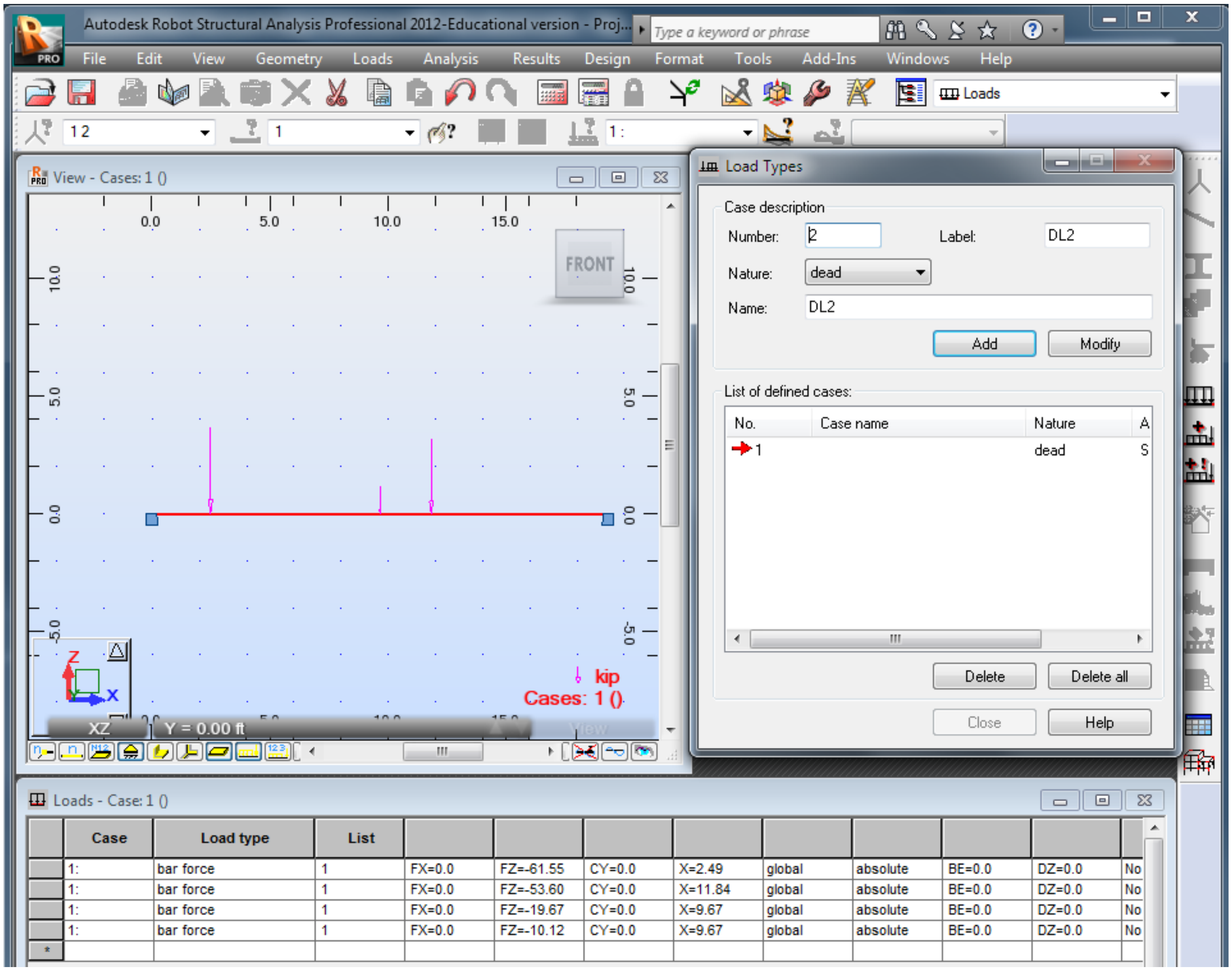

Node 1 1
Node 2 2
Type of c... cartesian
Properties
Gamma 0.0 (Deg)
Section... W 18x40
Material STEEL A992-50
Releases... N/A
Offsets... N/A
Elastic gr... N/A
Bracket -...
Bracket -...
Bars
View
Reactions
Reactions in the coordinate system: global - Case: 1 ()
Node/Case FX (kip) FZ (kip) MY (kip-ft)
1/ 1 0.0 72.42 -257.38
2/ 1 0.0 47.63 206.57
Case 1
Sum of val. 0.0 120.05 -50.81
Sum of reac. 0.0 120.05 -971.51
Sum of forc. 0.0 -120.05 971.51
Check val. 0.0 0.0 0.0
Precision 0.0 0.0
Autodesk
[ft] [kip] [Deg]

Section 9-11

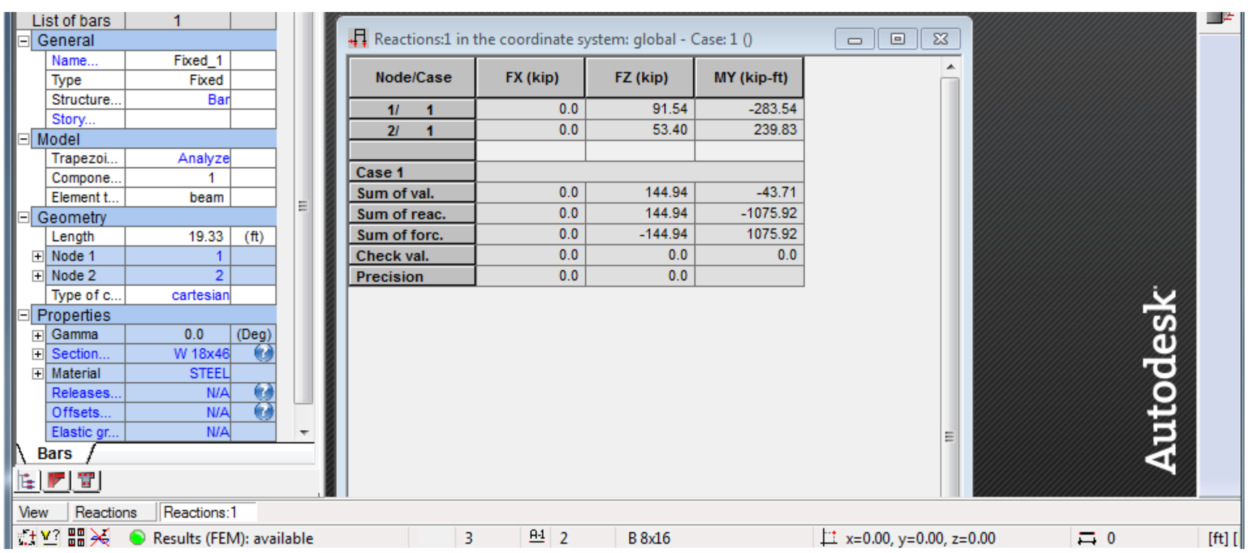

Autodesk Robot Structural Analysis Professional 2012-Educational version - Proj...
File Edit View Geometry Loads Analysis Results Design Format Tools Add-Ins Windows Help
View - Cases: 1 ()
FRONT
kip
Cases: 1 ()
Y = 0.00 ft
Load Types
Case description
Number: 2
Label: DL2
Nature: dead
Name: DL2
Add
Modify
List of defined cases:
No. Case name Nature
1 dead
Delete
Delete all
Close
Help
Loads - Case: 1 ()
Case | Load type | List
1: bar force 1 FX=0.0 FZ=-39.63 CY=0.0 X=3.64 global absolute BE=0.0 DZ=0.0 No
1: bar force 1 FX=0.0 FZ=-69.62 CY=0.0 X=12.77 global absolute BE=0.0 DZ=0.0 No
1: bar force 1 FX=0.0 FZ=-19.67 CY=0.0 X=9.67 global absolute BE=0.0 DZ=0.0 No
1: bar force 1 FX=0.0 FZ=-10.12 CY=0.0 X=9.67 global absolute BE=0.0 DZ=0.0 No


Reactions in the coordinate system: global - Case: 1 ()
Node/Case | FX (kip) | FZ (kip) | MY (kip-ft)
1/ 1 | 0.0 | 69.44 | -269.38
2/ 1 | 0.0 | 69.60 | 293.38
Case 1
Sum of val. | 0.0 | 139.04 | 24.00
Sum of reac. | 0.0 | 139.04 | -1321.35
Sum of forc. | 0.0 | -139.04 | 1321.35
Check val. | 0.0 | 0.0 | 0.0
Precision | 0.0 | 0.0
Autodesk
View Reactions
Results (FEM): available 3 2 W 16x31 x=4.38, y=0.00, z=-8.47 0.00 [ft]

Section 11-13

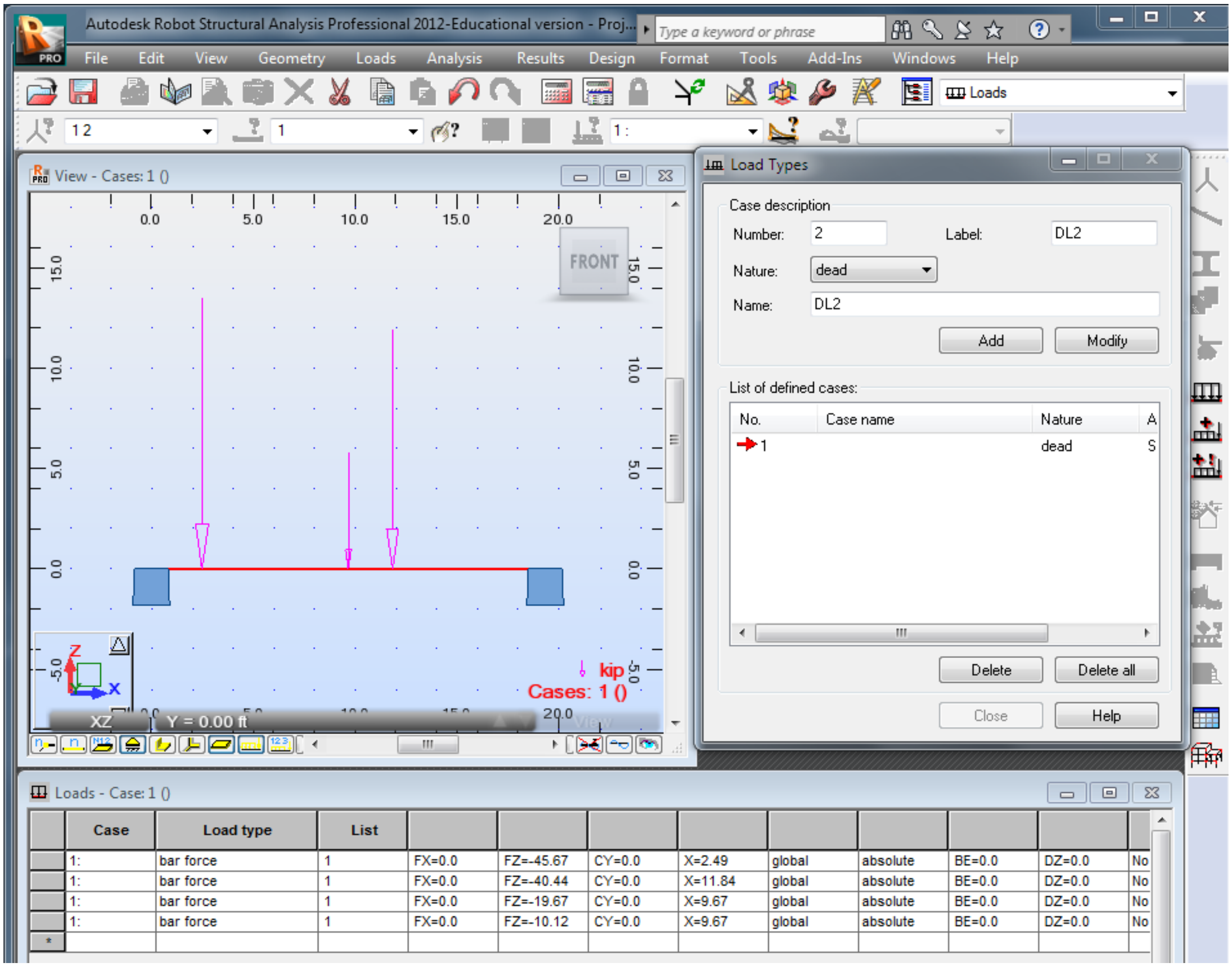


Case	Load type	List									
1:	bar force	1	FX=0.0	FZ=-61.55	CY=0.0	X=2.49	global	absolute	BE=0.0	DZ=0.0	No
1:	bar force	1	FX=0.0	FZ=-53.60	CY=0.0	X=11.84	global	absolute	BE=0.0	DZ=0.0	No
1:	bar force	1	FX=0.0	FZ=-19.67	CY=0.0	X=9.67	global	absolute	BE=0.0	DZ=0.0	No
1:	bar force	1	FX=0.0	FZ=-10.12	CY=0.0	X=9.67	global	absolute	BE=0.0	DZ=0.0	No

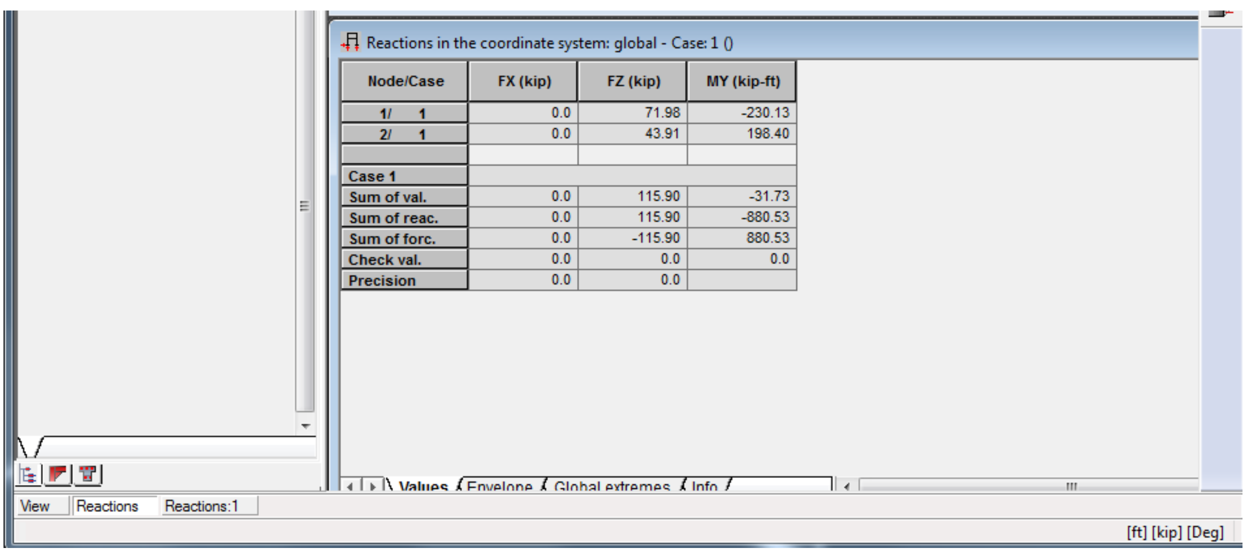


Node/Case	FX (kip)	FZ (kip)	MY (kip-ft)
1/ 1	0.0	91.54	-283.54
2/ 1	0.0	53.40	239.83
Case 1			
Sum of val.	0.0	144.94	-43.71
Sum of reac.	0.0	144.94	-1075.92
Sum of forc.	0.0	-144.94	1075.92
Check val.	0.0	0.0	0.0
Precision	0.0	0.0	

Section 13-15

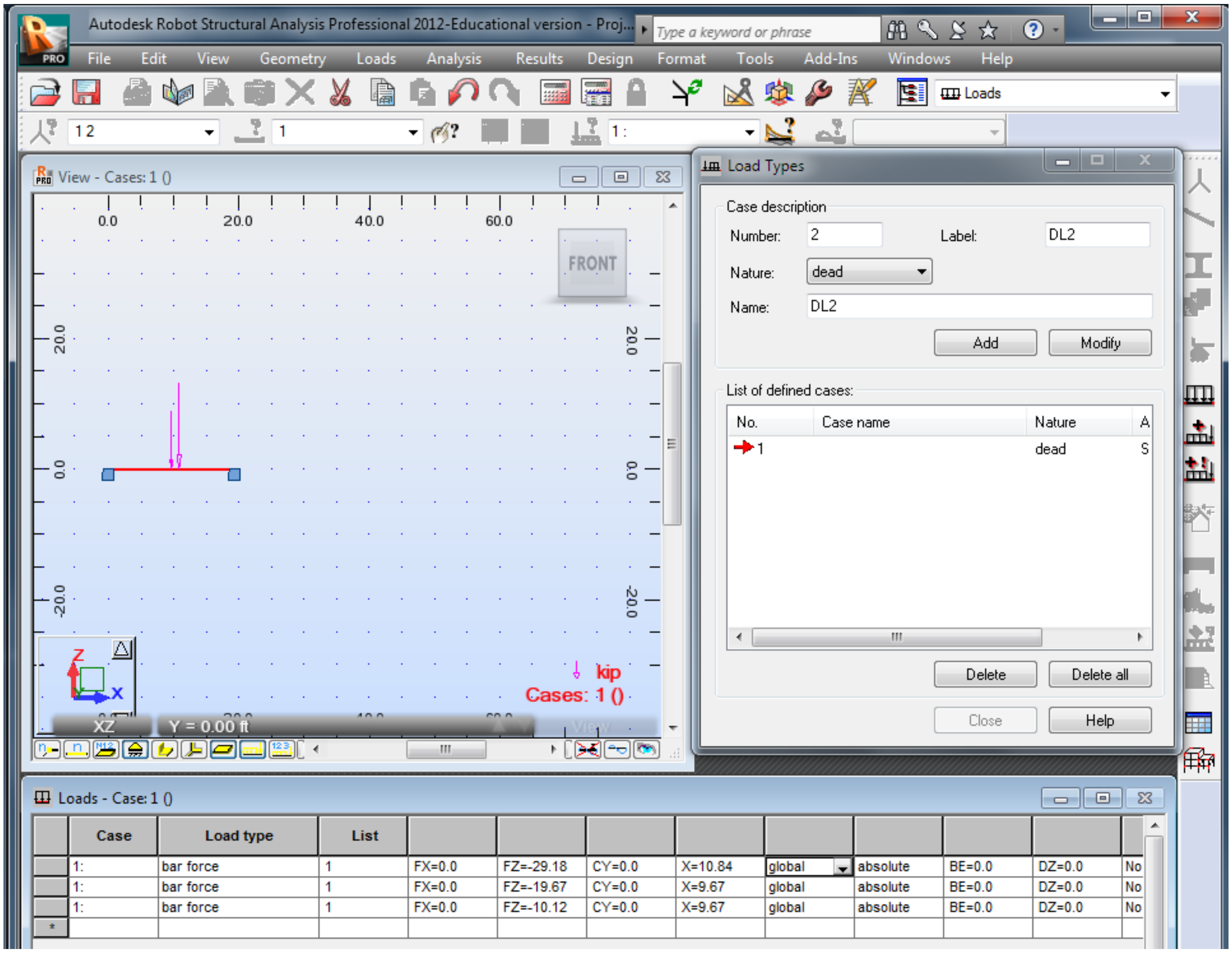


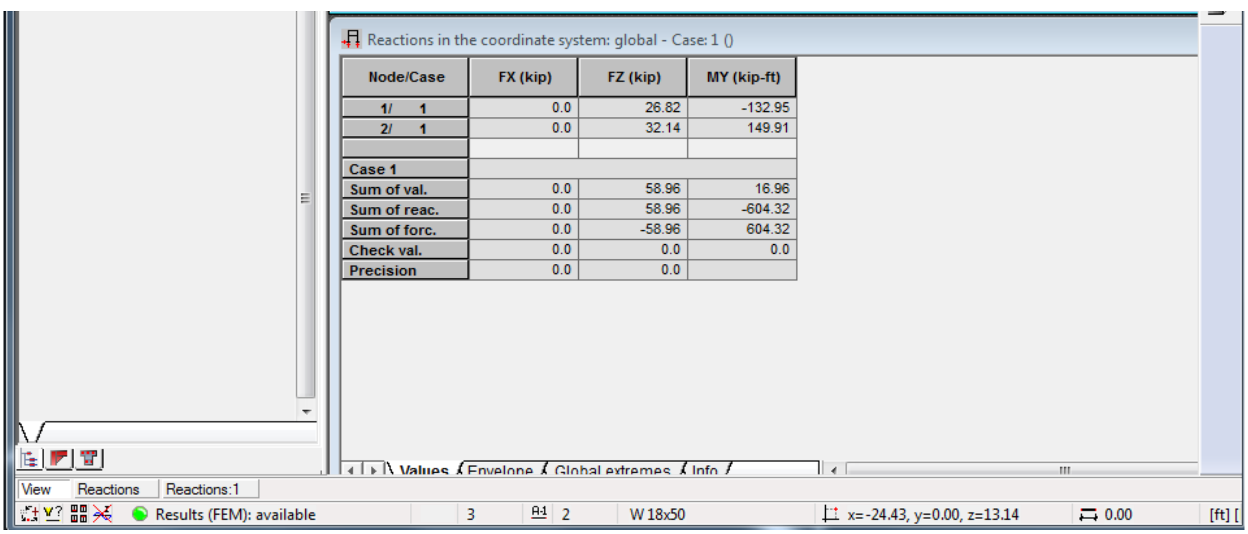
Case	Load type	List									
1:	bar force	1	FX=0.0	FZ=-45.67	CY=0.0	X=2.49	global	absolute	BE=0.0	DZ=0.0	No
1:	bar force	1	FX=0.0	FZ=-40.44	CY=0.0	X=11.84	global	absolute	BE=0.0	DZ=0.0	No
1:	bar force	1	FX=0.0	FZ=-19.67	CY=0.0	X=9.67	global	absolute	BE=0.0	DZ=0.0	No
1:	bar force	1	FX=0.0	FZ=-10.12	CY=0.0	X=9.67	global	absolute	BE=0.0	DZ=0.0	No



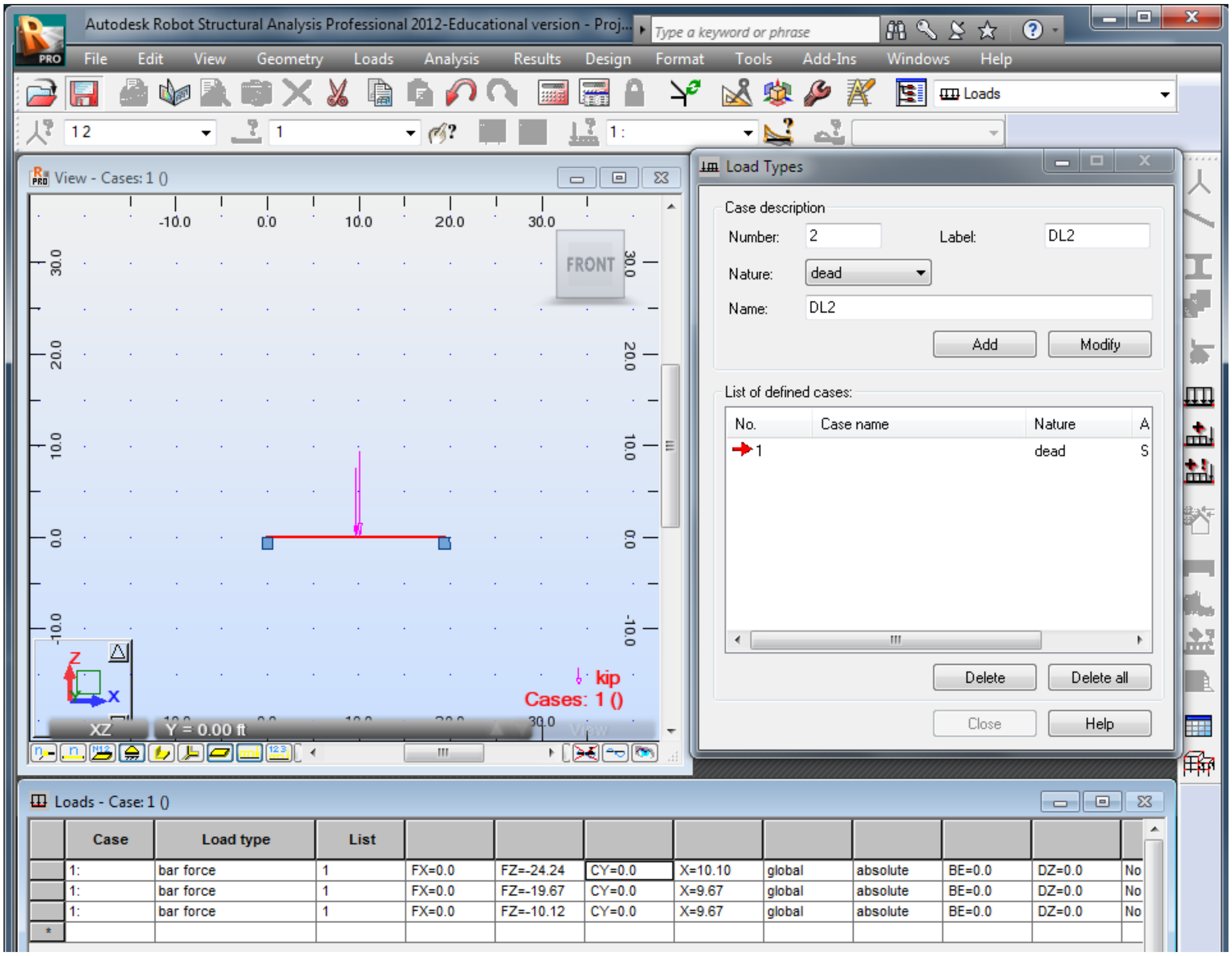
Node/Case	FX (kip)	FZ (kip)	MY (kip-ft)
1/ 1	0.0	71.98	-230.13
2/ 1	0.0	43.91	198.40
Case 1			
Sum of val.	0.0	115.90	-31.73
Sum of reac.	0.0	115.90	-880.53
Sum of forc.	0.0	-115.90	880.53
Check val.	0.0	0.0	0.0
Precision	0.0	0.0	

Section 15-17

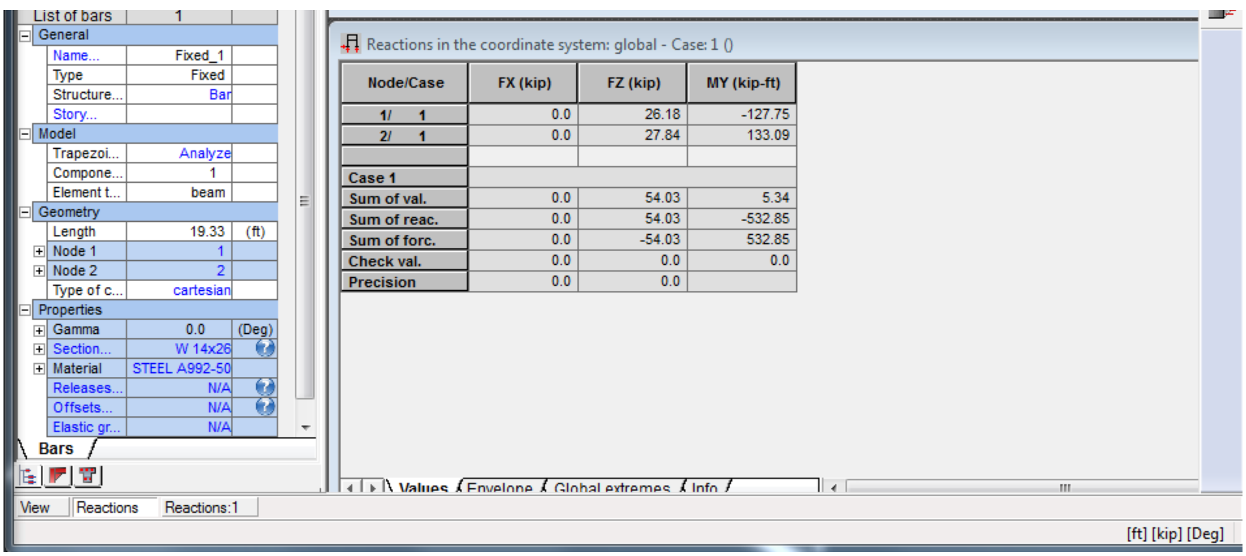




Section 17-19



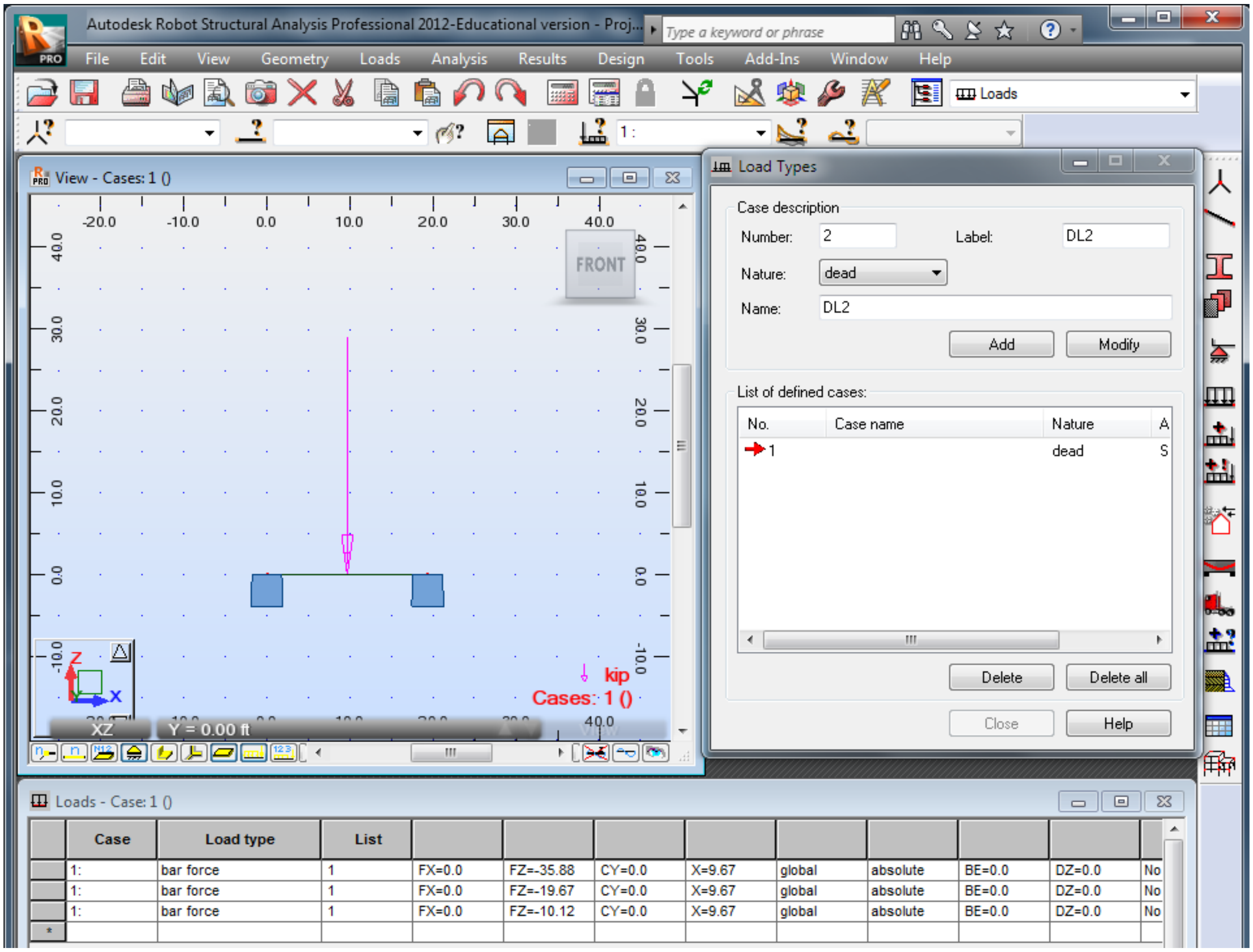
Case	Load type	List									
1:	bar force	1	FX=0.0	FZ=-24.24	CY=0.0	X=10.10	global	absolute	BE=0.0	DZ=0.0	No
1:	bar force	1	FX=0.0	FZ=-19.67	CY=0.0	X=9.67	global	absolute	BE=0.0	DZ=0.0	No
1:	bar force	1	FX=0.0	FZ=-10.12	CY=0.0	X=9.67	global	absolute	BE=0.0	DZ=0.0	No

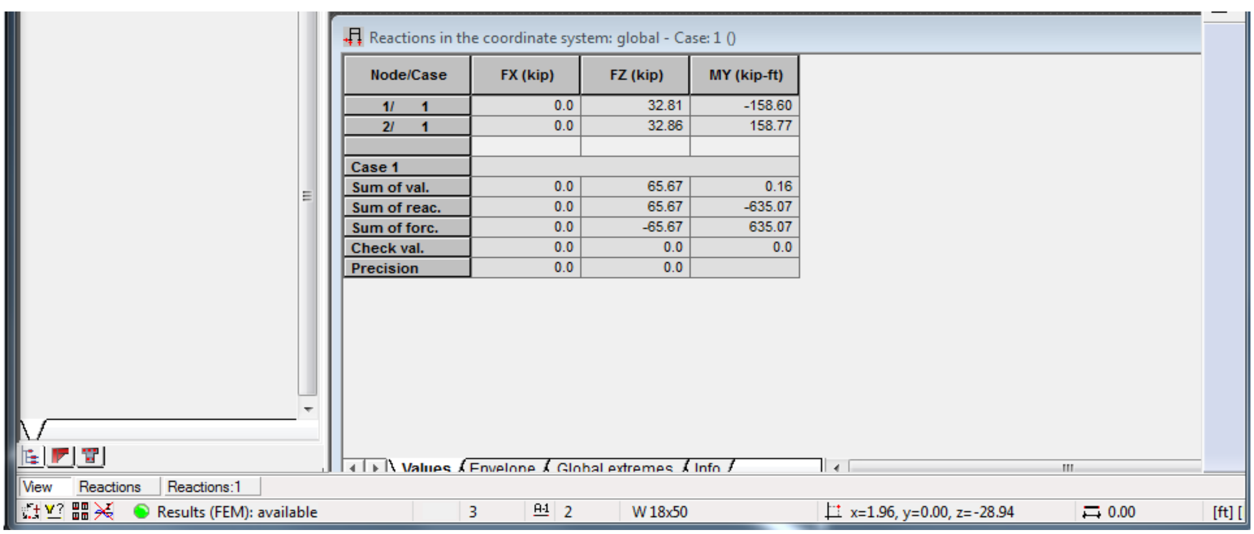


Reactions in the coordinate system: global - Case: 1 ()

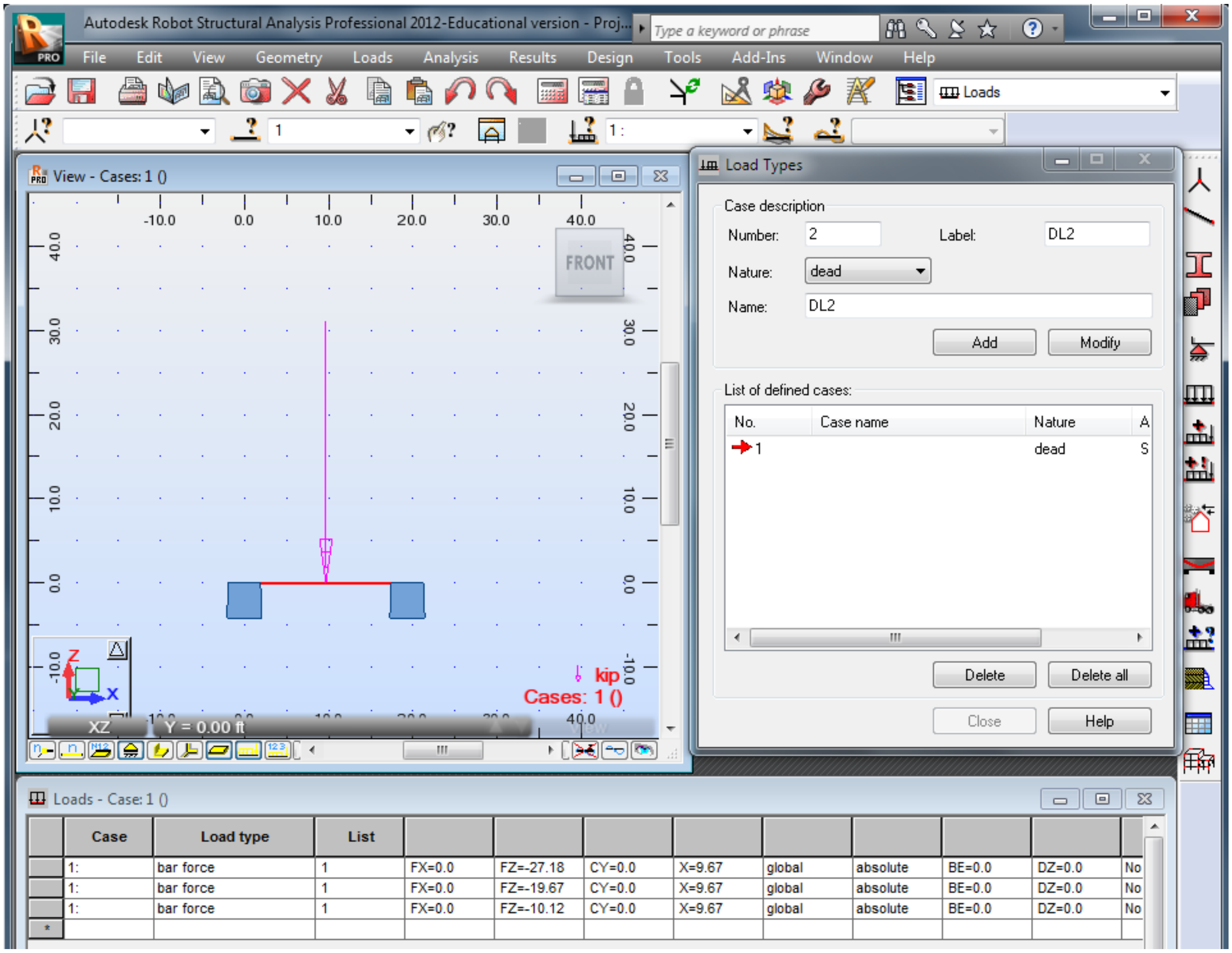
Node/Case	FX (kip)	FZ (kip)	MY (kip-ft)
1/ 1	0.0	26.18	-127.75
2/ 1	0.0	27.84	133.09
Case 1			
Sum of val.	0.0	54.03	5.34
Sum of reac.	0.0	54.03	-532.85
Sum of forc.	0.0	-54.03	532.85
Check val.	0.0	0.0	0.0
Precision	0.0	0.0	

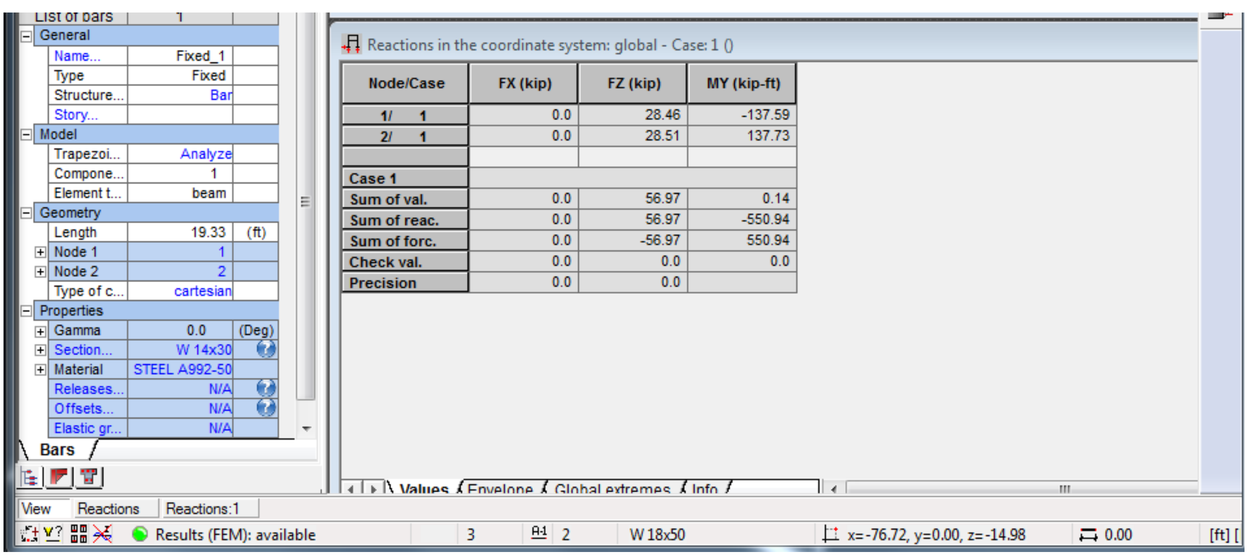
Section 19-21





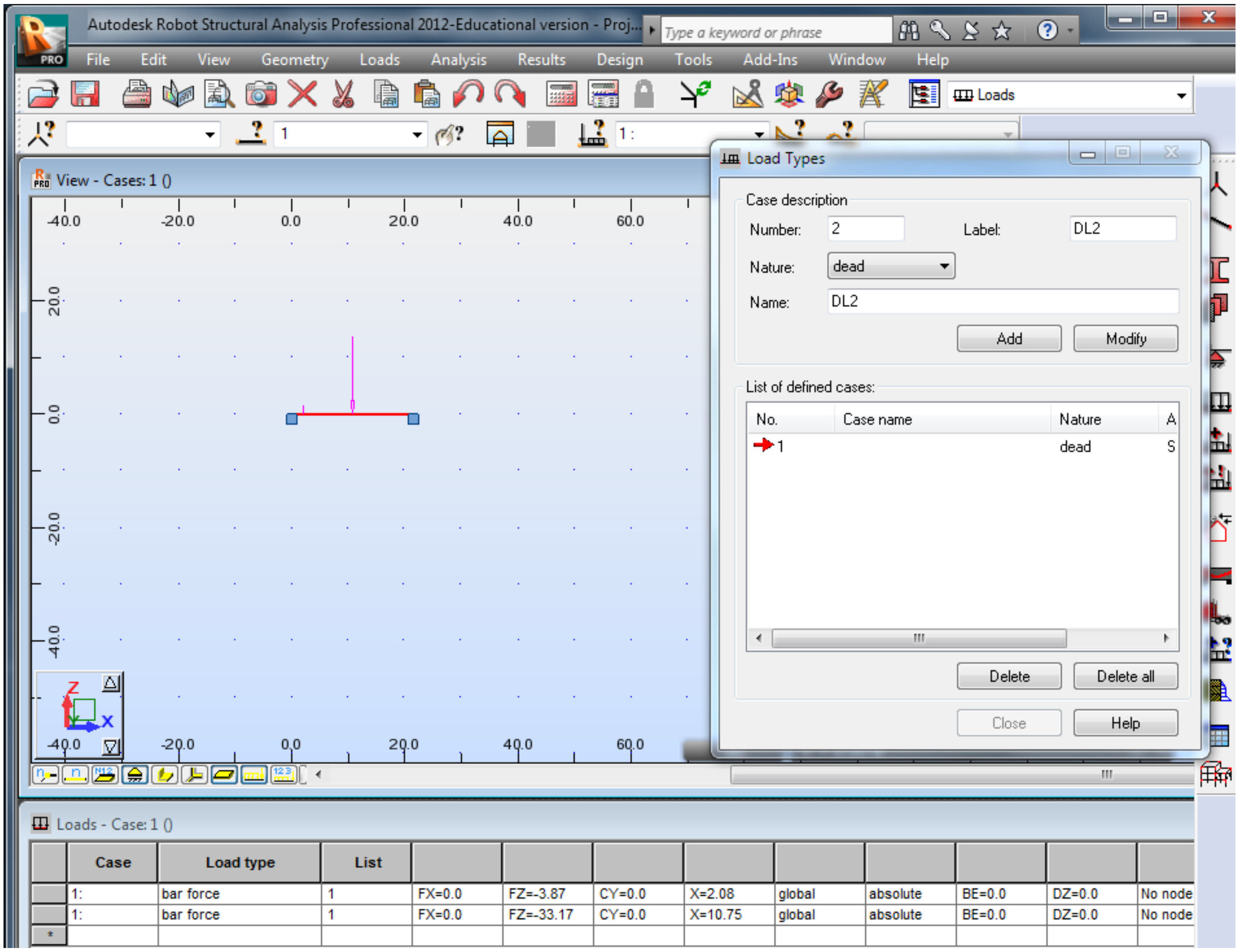
Section 21-23

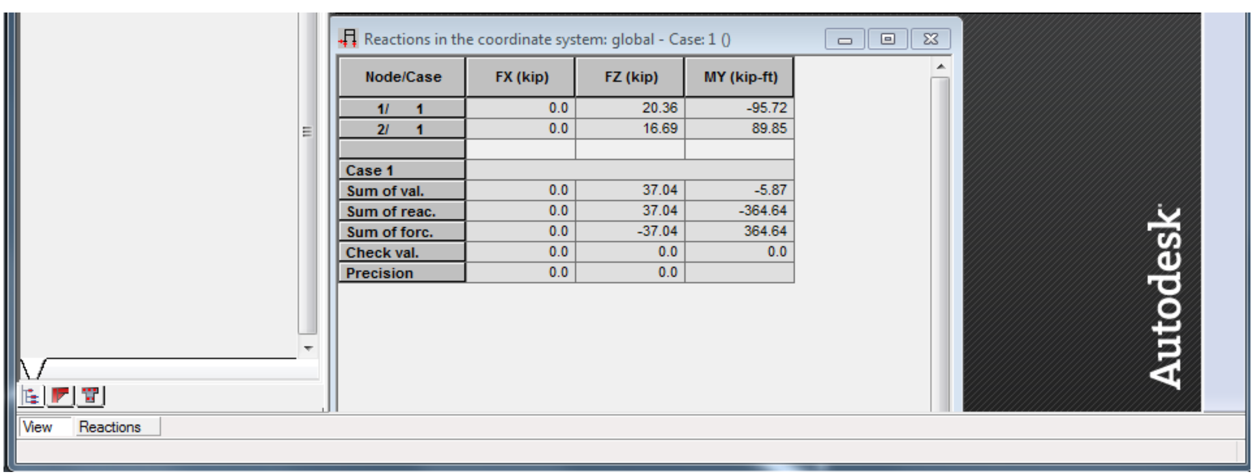




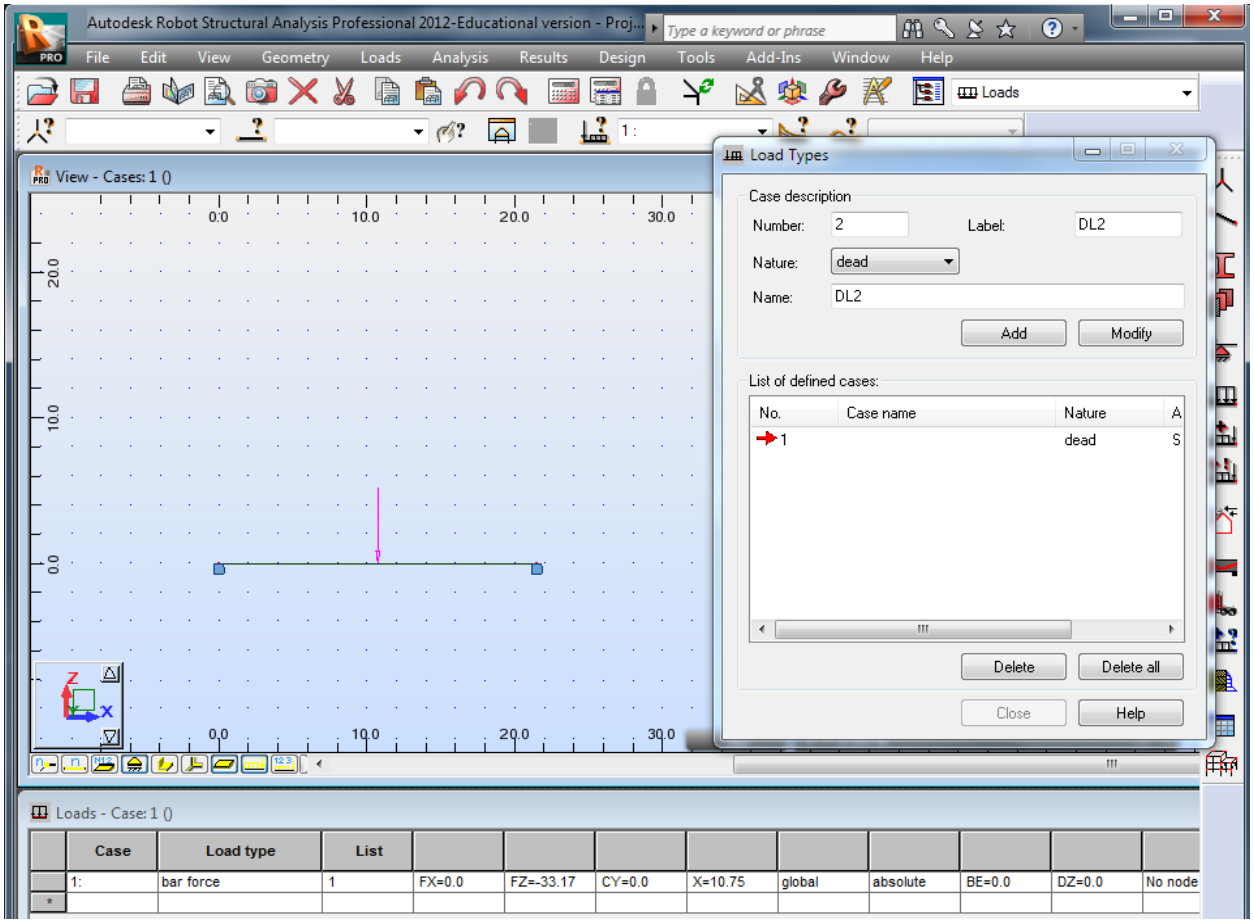
Softball Side

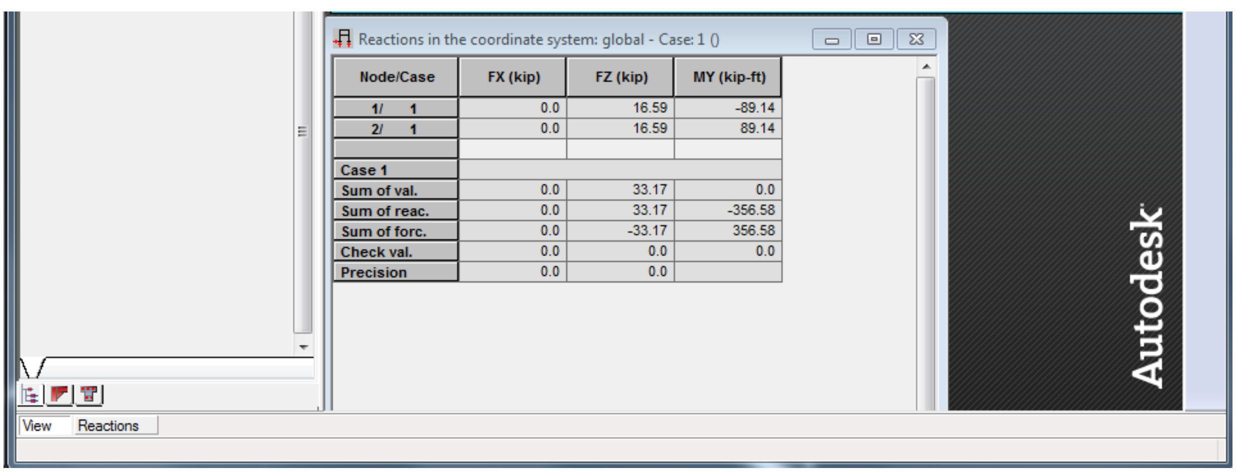
Section 1-3





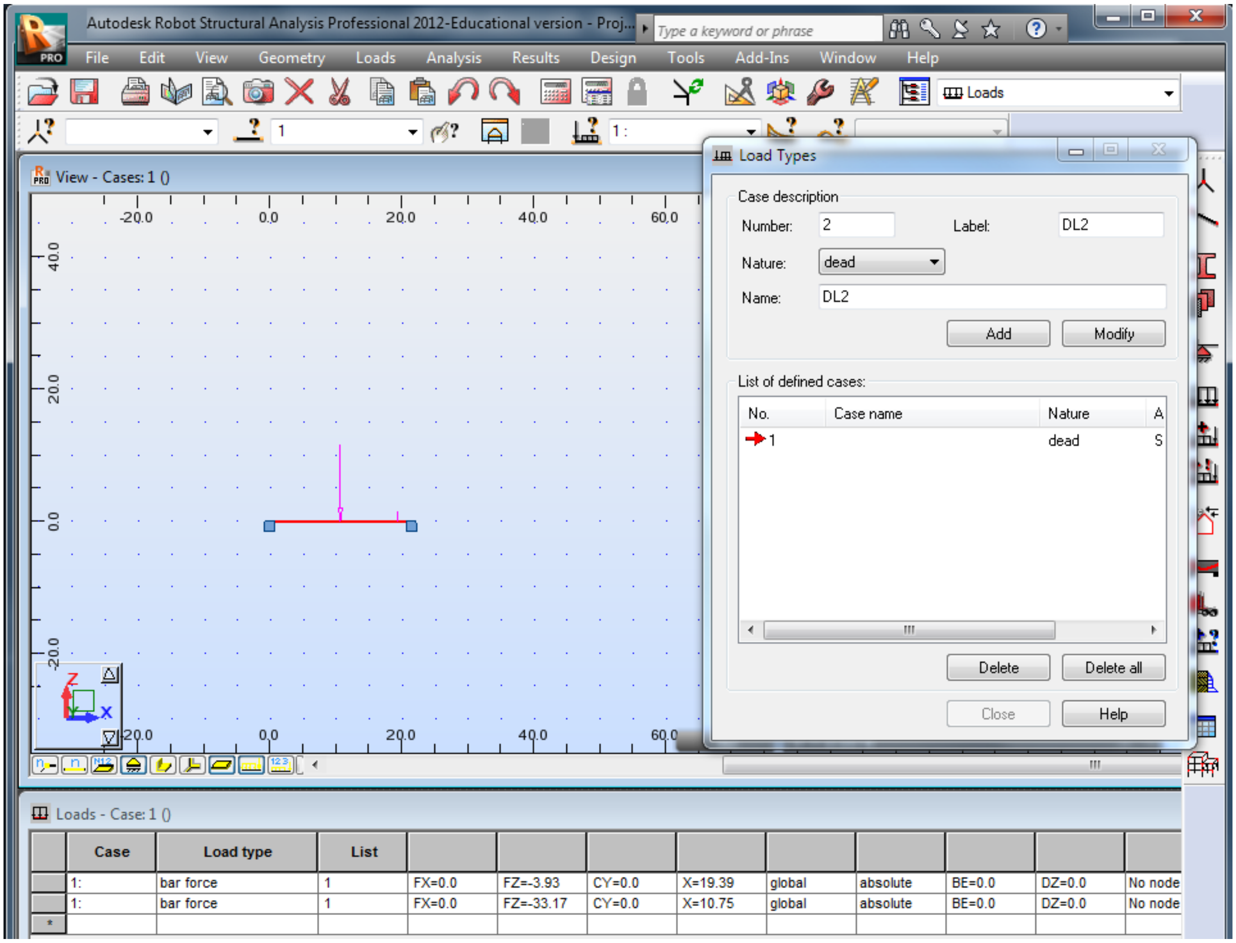
Section 3-5

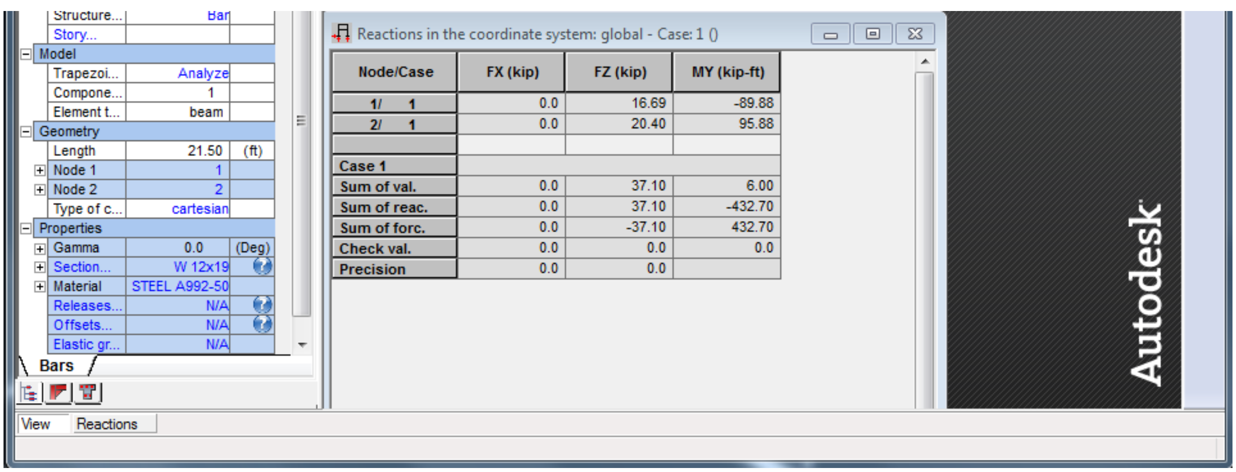




Node/Case	FX (kip)	FZ (kip)	MY (kip-ft)
1/ 1	0.0	16.59	-89.14
2/ 1	0.0	16.59	89.14
Case 1			
Sum of val.	0.0	33.17	0.0
Sum of reac.	0.0	33.17	-356.58
Sum of forc.	0.0	-33.17	356.58
Check val.	0.0	0.0	0.0
Precision	0.0	0.0	

Section 5-7

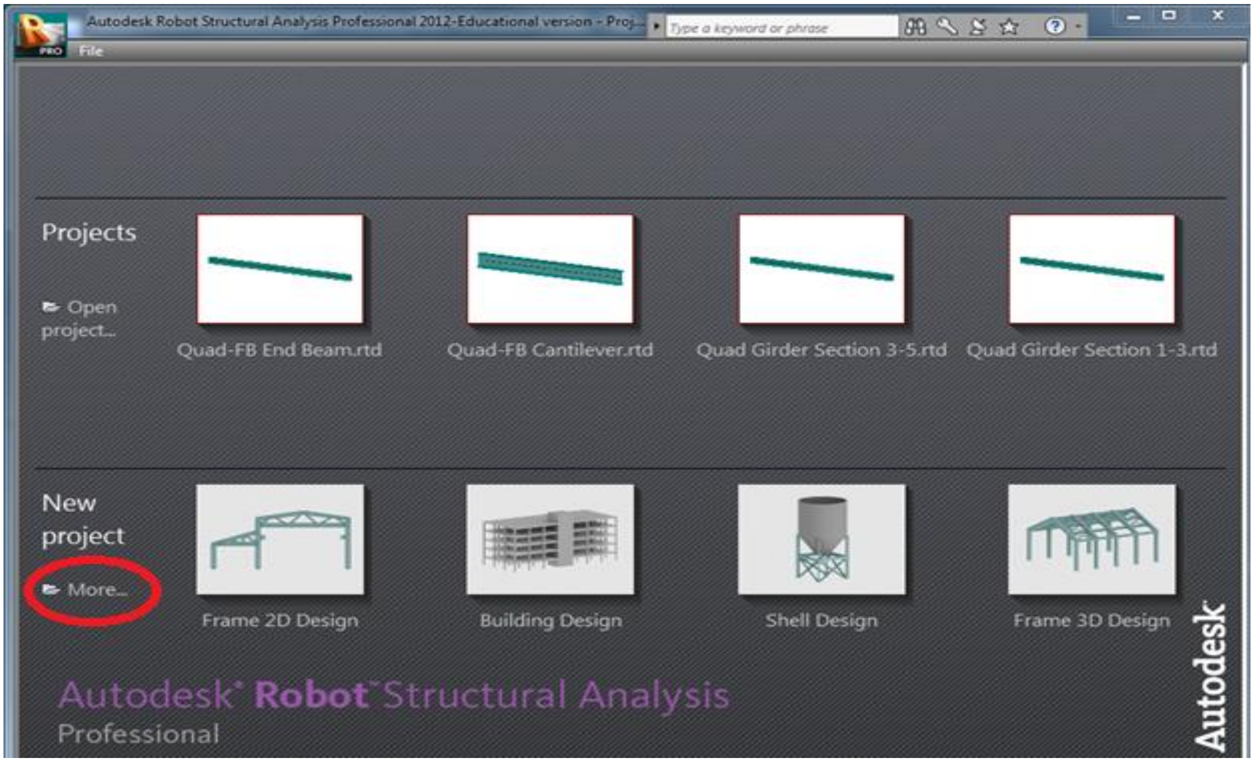

Autodesk Robot Structural Analysis Professional 2012-Educational version - Proj...
File Edit View Geometry Loads Analysis Results Design Tools Add-Ins Window Help
View - Cases: 1 ()
Load Types
Case description
Number: 2
Label: DL2
Nature: dead
Name: DL2
Add
Modify
List of defined cases:
No. Case name Nature
1 dead
Delete
Delete all
Close
Help
Loads - Case: 1 ()
Case Load type List
1: bar force 1 FX=0.0 FZ=-3.93 CY=0.0 X=19.39 global absolute BE=0.0 DZ=0.0 No node
1: bar force 1 FX=0.0 FZ=-33.17 CY=0.0 X=10.75 global absolute BE=0.0 DZ=0.0 No node


Model
Trapezoi... Analyze
Compone... 1
Element t... beam
Geometry
Length 21.50 (ft)
Node 1 1
Node 2 2
Type of c... cartesian
Properties
Gamma 0.0 (Deg)
Section... W 12x19
Material STEEL A992-50
Releases... N/A
Offsets... N/A
Elastic gr... N/A
Bars
Reactions in the coordinate system: global - Case: 1 ()
Node/Case FX (kip) FZ (kip) MY (kip-ft)
1/ 1 0.0 16.69 -89.88
2/ 1 0.0 20.40 95.88
Case 1
Sum of val. 0.0 37.10 6.00
Sum of reac. 0.0 37.10 -432.70
Sum of forc. 0.0 -37.10 432.70
Check val. 0.0 0.0 0.0
Precision 0.0 0.0
Autodesk
View Reactions

Appendix M: Creating a Simply Supported Beam in Robot

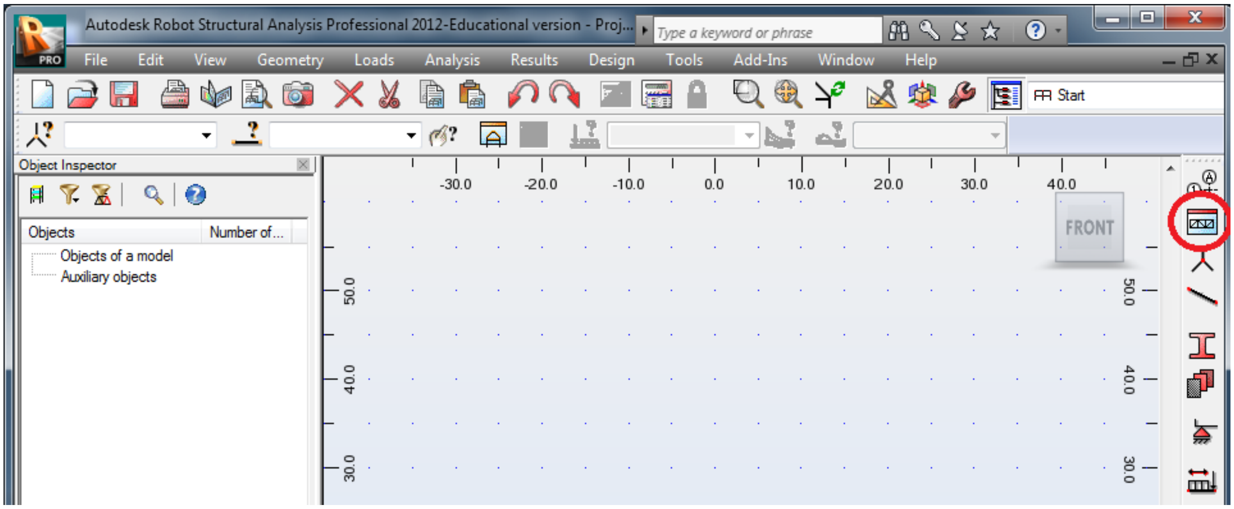
Step 1: Open a New Project.

To see all the different kinds of projects Robot offers, click the word More (circled in red) under New project. For this example a Frame 2D Design was chosen because it can be used to model a simply support beam.



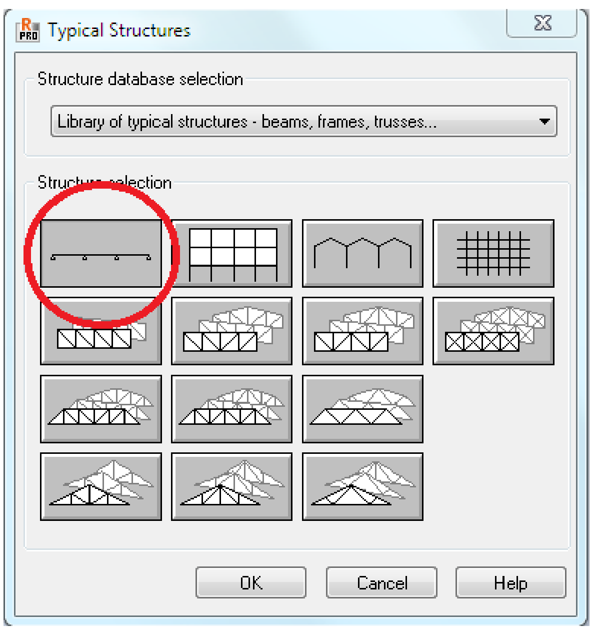
Step 2: Locate the Library Structure.

This is usually located on tool bar on left side near the top. It is circled in red. Also moving the cursor over the icon will display its name.



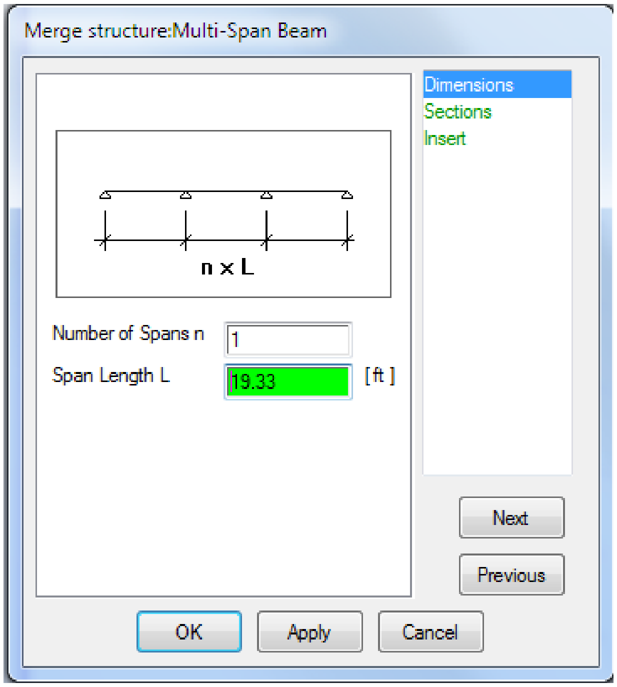
Step 3: Choose the picture that looks like a multi-span beam.

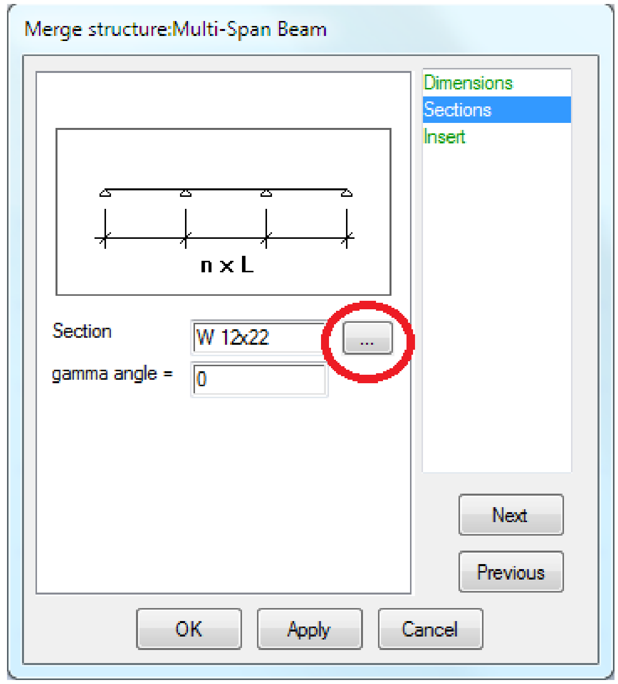
The multi-span beam is circled in red below. Make sure to click OK or double click the picture to proceed forward. If unsure about what the different pictures mean, clicking the help button will pop-up a window explain what each picture represents.



Step 4: Define the beam.

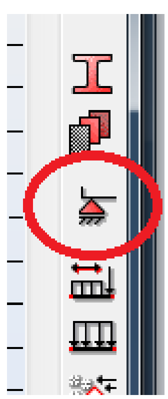
In this window enter the desire number of spans and span length need. Hit Apply, then the Next button. This will allow you to pick the size of the beam. By clicking the … button (circled in red) next to the section bow, a new window will open containing the database of all the shapes Robot has stored. From here select the member you want. Hit Apply. Then click OK.

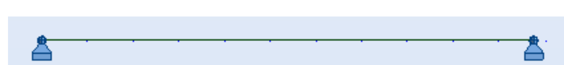




Step 5: Change the Supports.

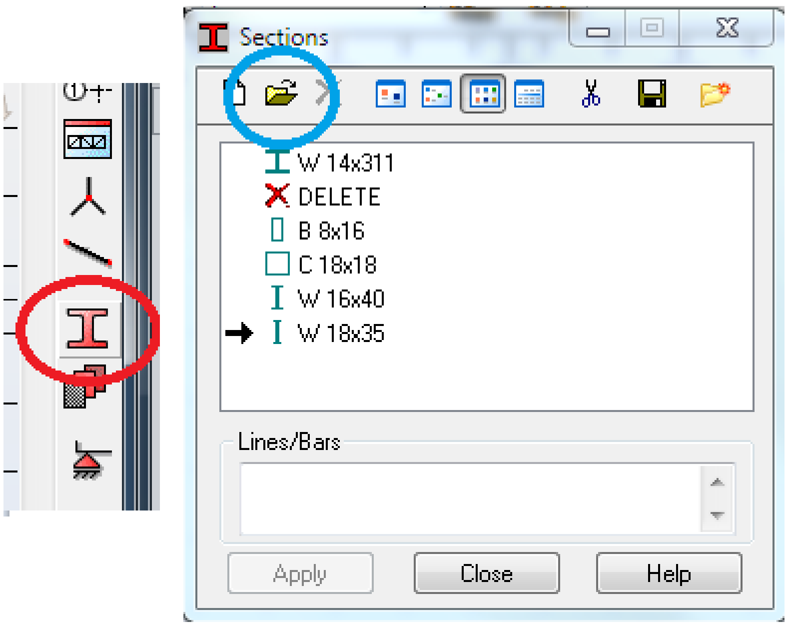
The default supports are fixed which can be seen by the blocks at either end of the beam. To change to Pins click on the Support Icon (circled in red) on the left side tool bar. Click on the desire support need and then click on the ends of the beam. For pins the model should now show triangular shapes at either end of the beam.





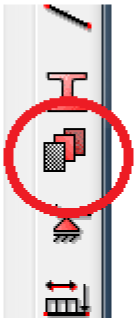
Step 6: Changing properties.

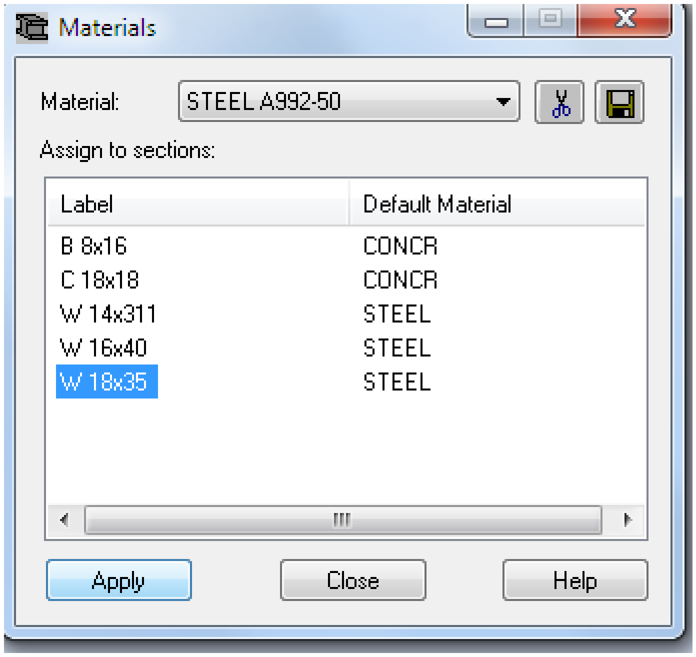
To change the beam size click on the Sections Icon (circled in red) on the left side tool bar. If the desired beam size is not present click on the folder at the top of the box (circled in blue). From here select the proper size needed and hit Add. Then close out of the Section Properties Box. Reselect the beam desired by clicking on it in the Section window. Click apply.



Step 7: Change the material.

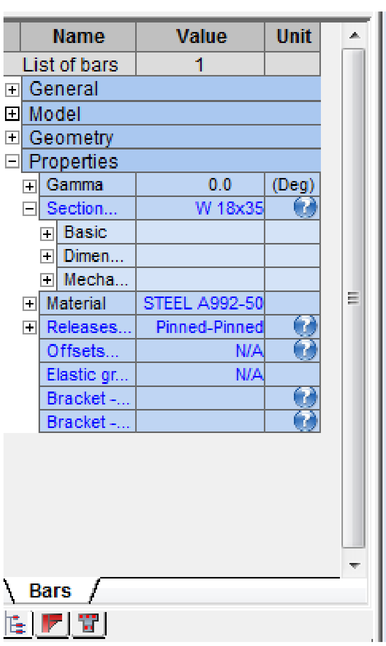
To change the material of the beam, select the Materials icon (circled in red) on the left side tool bar. Use the drop down menu to select the desired material need. Steel A992-50 is used for Fy = 50KSI steel. Click the beam you are using and hit Apply.





Step 8: Alternative methods.

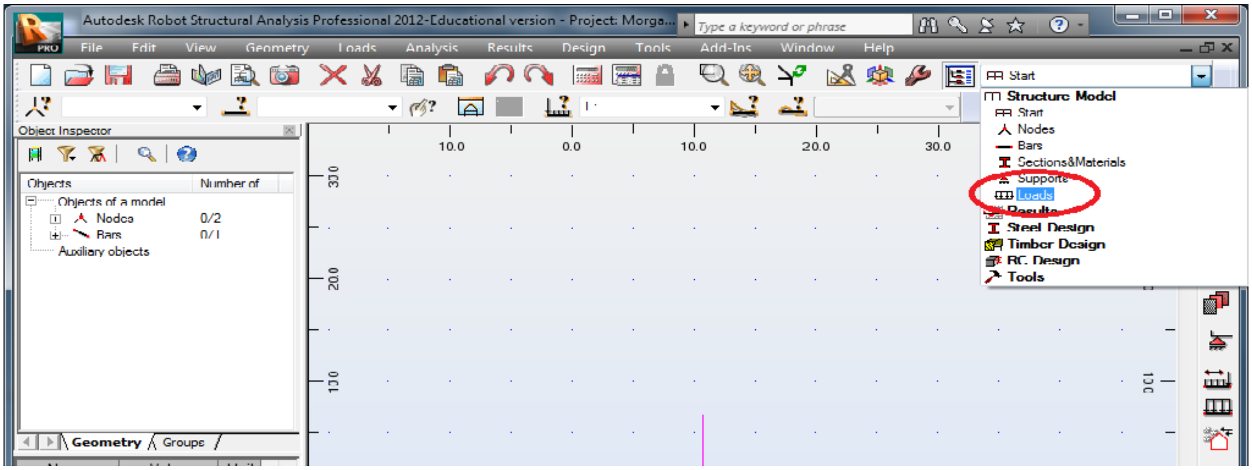
Another way to change to the beam size, material and supports is using the right side panel. Select the beam you wish to change. Anything in blue on the right side panel can be changed by clicking on it. Under the Properties section, the beam size, material, and releases can all be altered by clicking on the cell under the value column.



Appendix N: Loading Schemes and Results

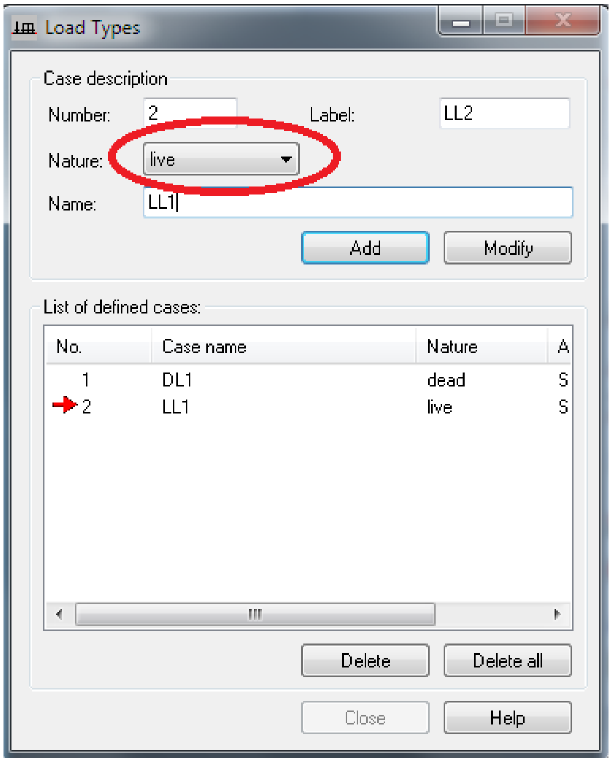
Step 1: Change Layout.

Using the drop down menu located on the upper tool start select Loads.



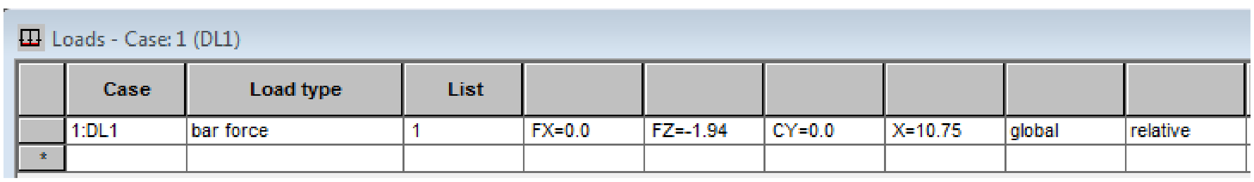
Step 2: Define Load Types.

In the Load Types Box, Add the type of loads that are desired. Robot allows user to define six different load types by changing the drop down menu (circled in red) next to nature.



Step 3: Apply Loads.

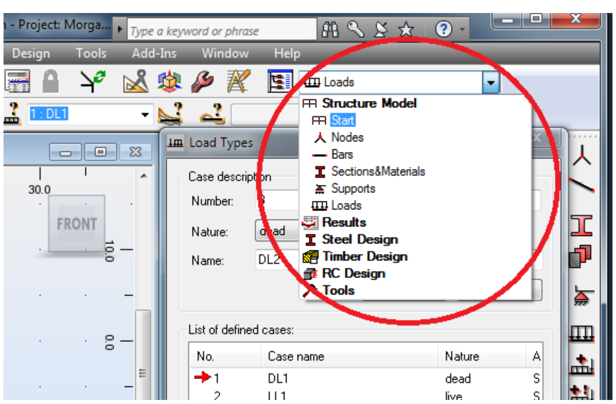
In the Loads – Cases window, each box can be modified. Under cases, select the correct case that is associated with the type of load that is being applied. Moving from left to right across the spreadsheet, define the correct load type that is needed. Depending on what is selected the right most cells will change. For a uniform load, the PZ box will be used for a downward load applied across the whole beam. A Bar Force can be applied as point load anywhere along the beam. To use this type change the FZ to equal the numerical number in kips. For a downward force make FZ negative. Also change "relative" to be "absolute". This will allow you to enter the length in term of feet and not a ratio. Next change X to equal the location of the load across the beam. See the picture below for the Load-Case window of a bar force. To apply a second load, repeat this step by clicking the next blank row under the Cases column.

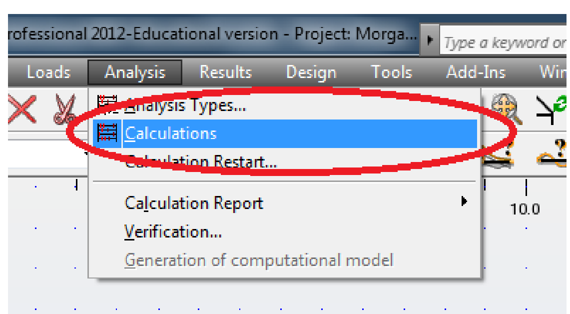

Loads - Case: 1 (DL1)

	Case	Load type	List						
	1:DL1	bar force	1	FX=0.0	FZ=-1.94	CY=0.0	X=10.75	global	relative
*									

Step 4: Run Calculations.

Change the layout back to Start by using the drop down menu located on the top menu bar. Using the upper most toolbar click on the Analysis Tab, then click Calculations.





Step 5: Results.

Click on the Results button, located next to Analysis, then click on desire results wanted. An example of the Reaction Results is shown below.

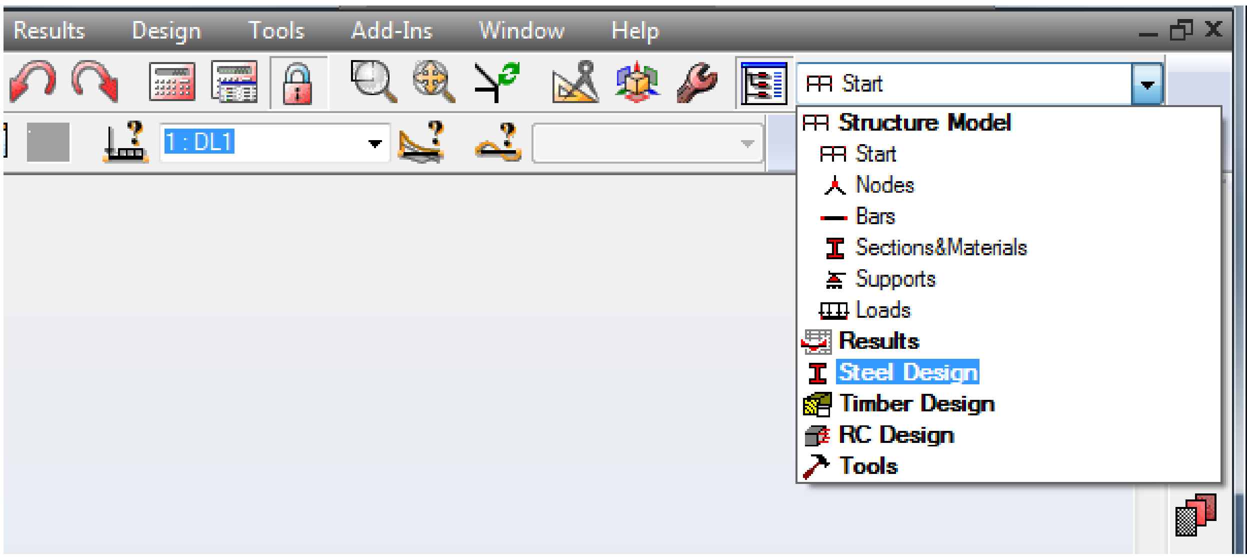
Reactions in the coordinate system: global - Cases: 1 2

Node/Case	FX (kip)	FZ (kip)	MY (kip-ft)
1/ 1	0.0	0.43	0.00
1/ 2	0.0	0.54	0.0
2/ 1	0.0	0.43	0.00
2/ 2	0.0	0.54	0.0
Case 1	DL1		
Sum of val.	0.0	0.86	0.00
Sum of reac.	0.0	0.86	-5.02
Sum of forc.	0.0	-0.86	5.02
Check val.	0.0	0.0	-0.00
Precision	2.67065e-016	1.78309e-032	
Case 2	LL1		
Sum of val.	0.0	1.08	0.0
Sum of reac.	0.0	1.08	-6.28
Sum of forc.	0.0	-1.08	6.28
Check val.	0.0	0.0	0.0
Precision	0.0	0.0	

Appendix O: Steel Design

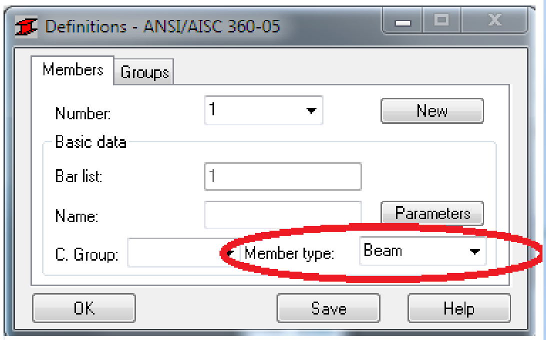
Step 1: Change Layout.

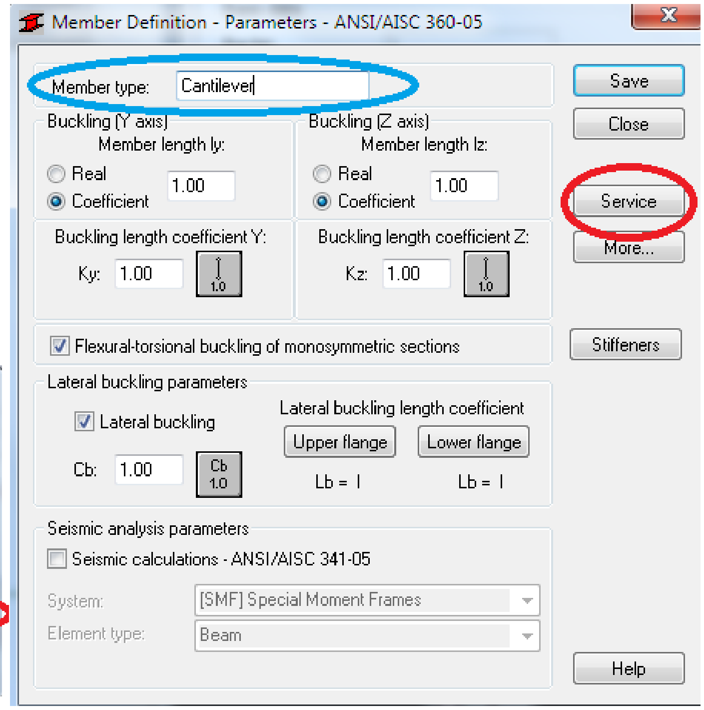
Change the layout view by using the drop menu at the top located on the toolbar to Steel Design, then click Steel/Aluminum Design.

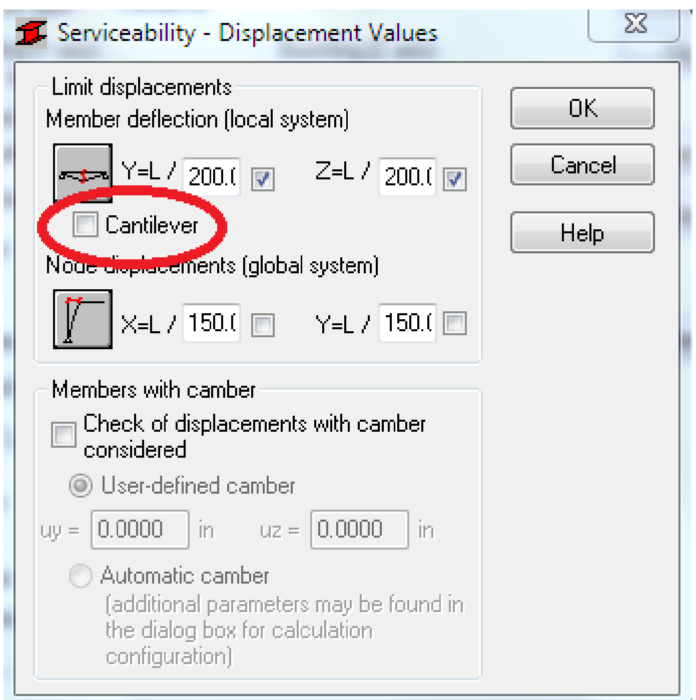


Step 2: Define the member.

Using the Definitions Window, define the beam you want to do the analysis on. If there is only one beam in your file, then it will automatically detect it as the member. Notice the Member type box located near the bottom (circled in red). Make sure it is the correct type is selected. To change it to a Cantilever click on Parameters. In the Member Definition – Parameters window, Change the Member type name to Cantilever (shown in blue) and click on the service button on the right side of the box (circled in red). In the Serviceability window check the box next to Cantilever (circled in red). Click Save in the Member Definition Box to save the changes.



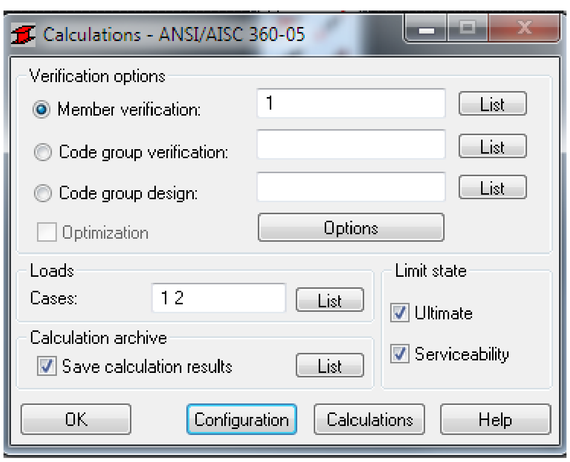


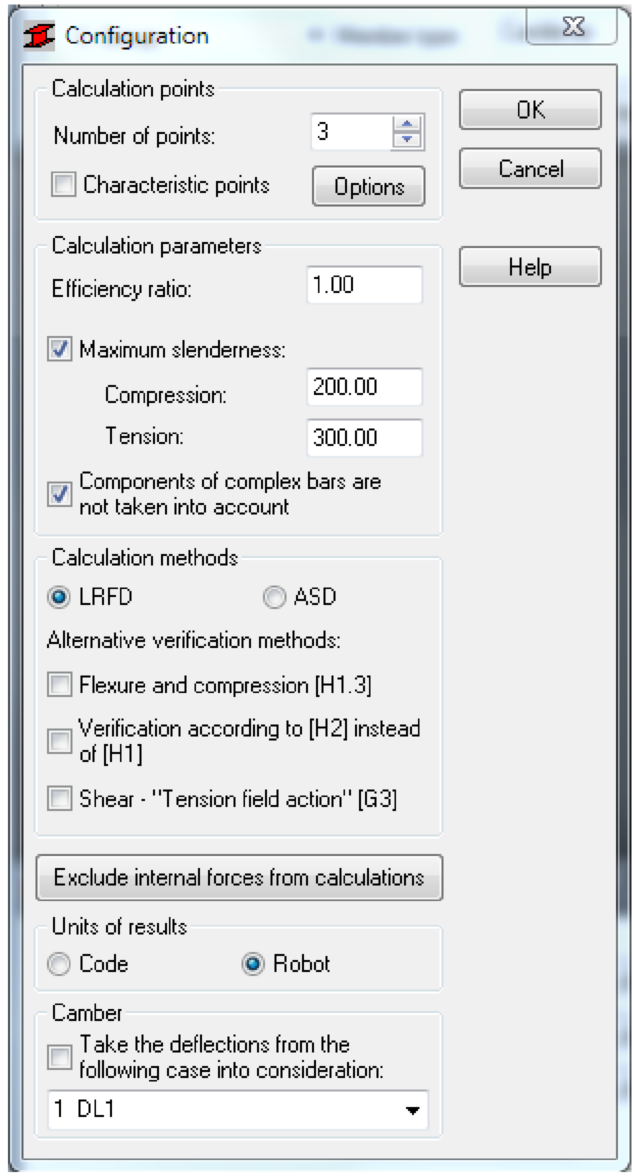


Step 3: Calculations.

In the Calculations window, make sure the correct member is being verified and the correct load cases applied are show in the load cases cell. The Configuration button allows the user to pick

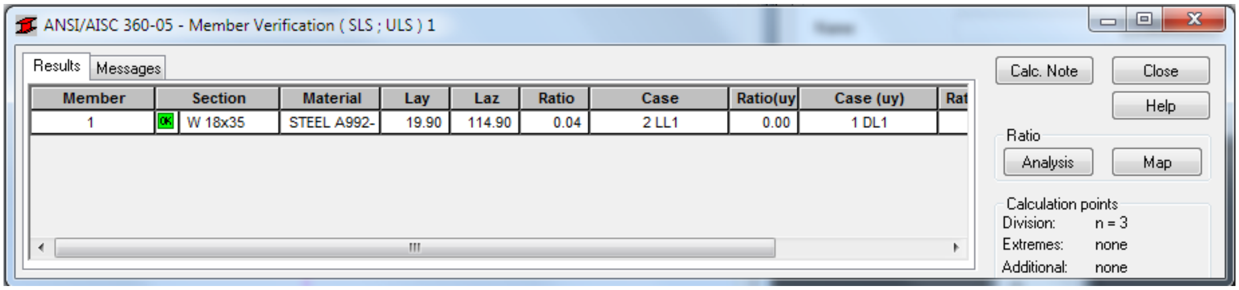
LRFD or ASD, and other calculation parameters. Then hit Calculations at the bottom of the Calculations window to run the verification.

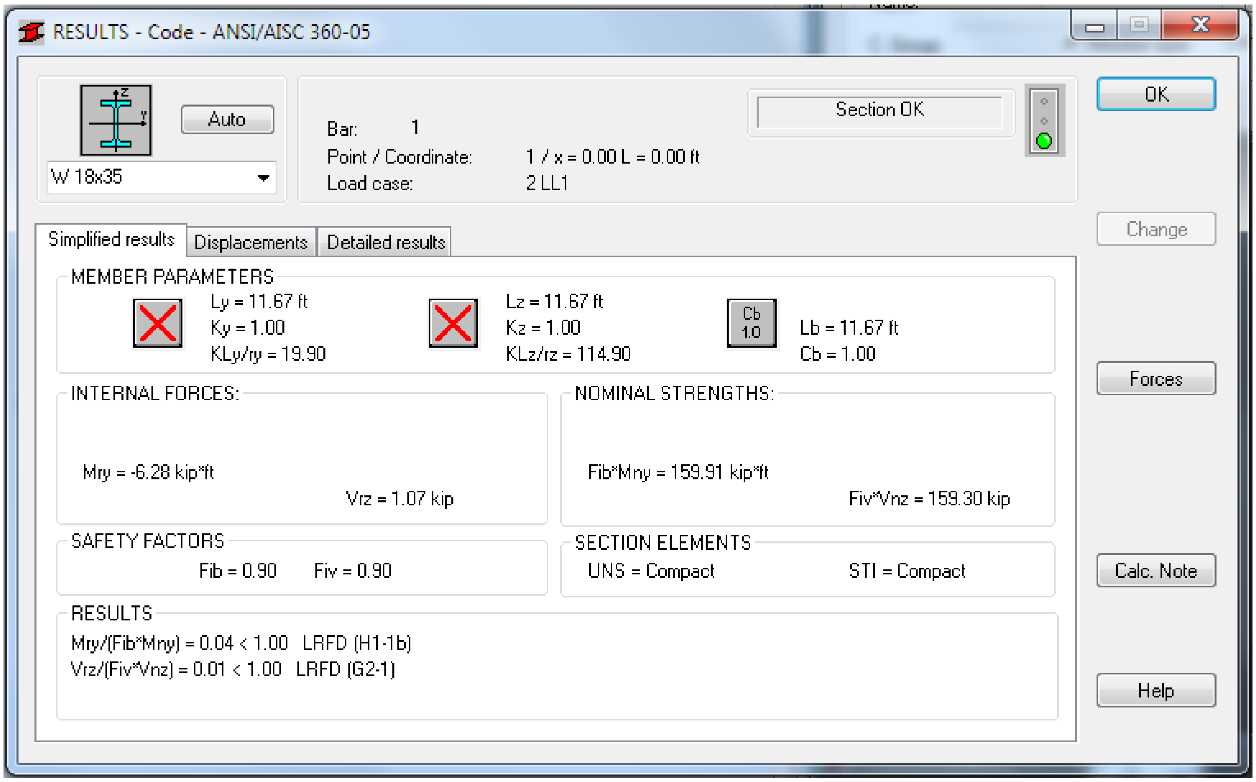




Step 4: Interpreting the Member Verification.

The results box will pop up and will either have a green OK symbol or red X symbol. For our example it has a green OK which means it passed, or the member is large enough to support the loading applied. By clicking any cell, the RESULTS – Code window will open. From here you can see any information that pertained to the analysis.


ANSI/AISC 360-05 - Member Verification (SLS ; ULS) 1
Results
Messages
Member | Section | Material | Lay | Laz | Ratio | Case | Ratio(uy) | Case (uy) | Rat
1 | OK W 18x35 | STEEL A992- | 19.90 | 114.90 | 0.04 | 2 LL1 | 0.00 | 1 DL1
Calc. Note
Close
Help
Ratio
Analysis
Map
Calculation points
Division: n = 3
Extremes: none
Additional: none


RESULTS - Code - ANSI/AISC 360-05
Auto
W 18x35
Bar: 1
Point / Coordinate: 1 / x = 0.00 L = 0.00 ft
Load case: 2 LL1
Section OK
OK
Change
Simplified results
Displacements
Detailed results
MEMBER PARAMETERS
Ly = 11.67 ft
Ky = 1.00
KLy/ry = 19.90
Lz = 11.67 ft
Kz = 1.00
KLz/rz = 114.90
Cb 1.0
Lb = 11.67 ft
Cb = 1.00
INTERNAL FORCES:
Mry = -6.28 kip*ft
Vrz = 1.07 kip
NOMINAL STRENGTHS:
Fib*Mny = 159.91 kip*ft
Fiv*Vnz = 159.30 kip
Forces
SAFETY FACTORS
Fib = 0.90 Fiv = 0.90
SECTION ELEMENTS
UNS = Compact STI = Compact
Calc. Note
RESULTS
Mry/(Fib*Mny) = 0.04 < 1.00 LRFD (H1-1b)
Vrz/(Fiv*Vnz) = 0.01 < 1.00 LRFD (G2-1)
Help

Appendix P: Column Design

Braced

Side		Football Side		Morgan	Softball
Frame		FB-SB	FB-M	both	both
Columns		W12x72*	W12x72*	W12x53*	W12x65*
L	ft2	16.89	16.89	16.89	16.89
E	ksi	29000.00	29000.00	29000.00	29000.00
I	in4	597.00	597.00	425.00	533.00
top girder		W16x26	W27x84	W16x36	W16x36
K2		1.00	1.00	1.00	1.00
girder	kips	30.84	0.85	7.34	10.95
truss m	kips	160.00	110.00	0.00	0.00
truss m	kips	130.00	130.00	0.00	0.00
truss e	kips	100.00	100.00	0.00	0.00
bracing	kips	197.00	197.00	197.00	197.00
cantilever	kips	20.24	20.24	22.58	22.58
Pnt	kips	227.62	225.20	31.19	35.27
Wind	kips	0.88	0.88	0.10	0.22
Earthquake	kips	40.44	40.44	53.92	53.92
Plt	kips	15.25	22.09	40.66	25.89
girder moment	k-ft	56.12	56.12	69.55	23.30
Mnt	k-ft	189.35	104.64	41.86	13.12
Mlt	k-ft	18.76	16.75	14.94	11.84
Sum Pe2	kips	8319.18	8319.18	5922.36	7427.34
Sum Pnt	kips	492.98	557.24	226.92	230.54
B2		1.06	1.07	1.04	1.03
M1		41.21	59.21	8.94	3.67
M2	ft-k	189.35	104.64	41.86	13.12
reverse					
Cm		0.51	0.37	0.51	0.49
Pr	kips	243.83	248.87	73.46	61.99
K1	assumed	1.00	1.00	1.00	1.00
Pel	kips	4159.59	4159.59	2961.18	3713.67
B1 Calculated		0.54	0.40	0.53	0.50
B1 used		1.00	1.00	1.00	1.00

Mr	ft-k	209.29	122.60	57.40	25.34
ϕPn	table 4-1 aisc	683.00	683.00	428.00	616.00
pr/pc		0.36	0.36	0.17	0.10
Fy	ksi	50.00	50.00	50.00	50.00
Zx	in3	108.00	108.00	77.90	96.80
Mcx	k-ft	4860.00	4860.00	3505.50	4356.00
Governing Equation		H1-1a	H1-1a	H1-1b	H1-1a
1>		0.40	0.39	0.10	0.06

Braced					
Side		Quad			
Frame		M	M2	M3	S
Columns		W12x65*	W12x65*	W12x65*	W12x65*
L	ft2	16.89	16.89	16.89	16.89
E	ksi	29000.00	29000.00	29000.00	29000.00
I	in4	533.00	533.00	533.00	533.00
top girder		W24x55	W24x62	W24x55	W24x55
K2		1.00	1.00	1.00	1.00
girder	kips	14.91	72.42	71.98	0.00
truss m	kips	100.00	110.00	100.00	110.00
truss m	kips	100.00	110.00	100.00	110.00
truss e	kips	100.00	110.00	100.00	110.00
bracing	kips	197.00	197.00	197.00	197.00
cantilever	kips	20.24	20.24	20.24	20.24
Pnt	kips	195.30	251.60	224.54	204.04
Wind	kips	0.68	0.92	0.86	1.17
Earthquake	kips	40.44	40.44	40.44	40.44
Plt	kips	34.36	34.92	34.86	35.00
girder moment	k-ft	72.01	-257.38	-230.13	0.00
Mnt	k-ft	128.27	118.57	136.20	138.97
Mlt	k-ft	14.37	12.66	12.29	12.17
Sum Pe2	kips	7427.34	7427.34	7427.34	7427.34
Sum Pnt	kips	532.15	619.66	589.22	547.24
B2		1.08	1.09	1.09	1.08

M1		66.06	57.81	111.30	93.47
M2	ft-k	128.27	118.57	136.20	138.97
reverse					
Cm		0.39	0.40	0.27	0.33
Pr	kips	232.32	289.69	262.40	241.82
K1	assumed	1.00	1.00	1.00	1.00
Pel	kips	3713.67	3713.67	3713.67	3713.67
B1 Calculated		0.42	0.44	0.29	0.35
B1 used		1.00	1.00	1.00	1.00
Mr	ft-k	143.76	132.38	149.55	152.10
ϕPn	table 4-1 aisc	616.00	616.00	616.00	616.00
pr/pc		0.38	0.47	0.43	0.39
Fy	ksi	50.00	50.00	50.00	50.00
Zx	in3	96.80	96.80	96.80	96.80
Mcx	k-ft	4356.00	4356.00	4356.00	4356.00
Governing Equation		H1-1a	H1-1a	H1-1a	H1-1a
1>		0.41	0.50	0.46	0.42

Unbraced						
Side	Football					
Frame	Middle 9					
Columns	W12x72*					
L	16.89	ft2				
E	29000	ksi				
I	597	in4				
A	21.10	in2				
K2	1.00					
Girder Plane				Cantilever Plane		
girder	29.76	kips		truss m	130.00	kips
top beam	1.198	kips		cantilever	20.24	kips
Pu	30.958	kips		Pu	150.24	kips
Pnt	30.958	kips		Pnt	150.24	kips
girder moment	-56.12	k-ft		cantilever moment	170.91	k-ft
girder moment	56.12					
Mnt	0	k-ft		Mnt	113.47	k-ft
Sum Pnt	30.958	kips		Sum Pnt	150.24	kips

				M1	0.00	k-ft
				M2	113.47	ft-k
				Single		
				Cm	0.60	
pr	30.958	kips		Pr	150.24	kips
				K1	1.00	
				Pel	4159.59	kips
				B1 Calculated	0.62	
				B1 Used	1.00	
Mr	0	ft-k		Mr	113.47	ft-k
			Table 4-1 AISC	ϕPn	683.00	kips
				pr/pc	0.22	
				Fy	50.00	ksi
				Zx	108.00	in3
				Mcx	4860.00	ft-k
				H1-1a		
combined				1>	0.24	
ϕPn	683	kips				
pr/pc	0.27					
Fy	50	ksi				
Zx	108	in3				
Mcx	4860	ft-k				
Governing Equation	H1-1a					
1>	0.27					

X reaction at top of column - cantilever (k)	3.379
X reaction at top of column - girder (k)	0
x reaction (k)	3.379

Unbraced	
Side	Morgan

	side					
Frame	Middle 2					
Columns	W12x40					
L	16.89	ft2				
E	29000.00	ksi				
I	307.00	in4				
A	11.70	in2				
K2	1.00					
Girder Plane				Cantilever Plane		
girder	33.18	kips		truss m	0.00	kips
top beam	0.56	kips		cantilever	22.58	kips
Pu	33.74	kips		Pu	22.58	kips
Pnt	33.74	kips		Pnt	22.58	kips
girder moment	69.55	k-ft		cantilever moment	190.28	k-ft
girder moment	-69.55	k-ft				
Mnt	0.00	k-ft		Mnt	126.30	k-ft
Sum Pnt	33.74	kips		Sum Pnt	22.58	kips
				M1	0.00	k-ft
				M2	126.30	ft-k
				Single	0.00	
				Cm	0.60	
pr	33.74	kips		Pr	22.58	kips
				K1	1.00	
				Pel	2139.02	kips
				B1 Calculated	0.61	
				B1 Used	1.00	
Mr	0.00	ft-k		Mr	126.30	ft-k
			Table 4-1 AISC	ϕPn	235.00	kips
				pr/pc	0.10	
				Fy	50.00	ksi
				Zx	57.00	in3
				Mcx	2565.00	ft-k
				H1-1a		
				1>	0.14	

combined		
ϕPn	235.00	kips
pr/pc	0.24	
Fy	50.00	ksi
Zx	57.00	in3
Mcx	2565.00	
H1-1a		
1>	0.24	
X reaction at top of column - cantilever (k)	3.762	
X reaction at top of column - girder (k)	0	
x reaction (k)	3.76	

Unbraced						
Side	Quad side					
Frame	MQ 1					
Columns	W12x53					
L	16.89	ft2				
E	29000.00	ksi				
I	425.00	in4				
A	15.60	in2				
K2	1.00					
Girder Plane				Cantilever Plane		
girder	13.76	kips		truss m	110.00	kips
top beam	1.15	kips		cantilever	20.24	kips
Pu	14.91	kips		Pu	130.24	kips
Pnt	14.91	kips		Pnt	130.24	kips
girder moment	64.99	k-ft		cantilever moment	170.91	k-ft
girder moment	-64.99	k-ft				
Mnt	0.00	k-ft		Mnt	113.50	k-ft
Sum Pnt	14.91	kips		Sum Pnt	130.24	kips
				M1	0.00	k-ft
				M2	113.50	ft-k

				Single		
				Cm	0.60	
pr	14.91	kips		Pr	130.24	kips
				K1	1.00	
				Pel	2961.18	kips
				B1 Calculated	0.63	
				B1 Used	1.00	
Mr	0.00	ft-k		Mr	113.50	ft-k
			Table 4-1 AISC	ϕPn	428.00	kips
				pr/pc	0.30	
				Fy	50.00	ksi
				Zx	77.90	in3
				Mcx	3505.50	ft-k
				H1-1a		
				1>	0.33	
combined						
ϕPn	428.00	kips				
pr/pc	0.34					
Fy	50.00	ksi				
Zx	77.90	in3				
Mcx	3505.50					
H1-1a						
1>	0.34					
X reaction at top of column - cantilever (k)				3.379		
X reaction at top of column - girder (k)				0		
x reaction (k)				3.379		

Unbraced		
Side	Quad side	
Frame	MQ 2	
Columns	W12x65	
L	16.89	ft2
E	29000.00	ksi
I	533.00	in4

A	19.10	in2				
K2	1.00					
Girder Plane				Cantilever Plane		
girder	107.91	kips		truss m	110.00	kips
top beam	1.27	kips		cantilever	20.24	kips
Pu	109.18	kips		Pu	130.24	kips
Pnt	109.18	kips		Pnt	130.24	kips
girder moment	148.48	k-ft		cantilever moment	170.91	k-ft
girder moment	-257.38	k-ft				
Mnt	72.09	k-ft		Mnt	113.50	k-ft
Sum Pnt	109.18	kips		Sum Pnt	130.24	kips
M1	0.00	k-ft		M1	0.00	k-ft
M2	72.09	ft-k		M2	113.50	ft-k
Single				Single		
Cm	0.60			Cm	0.60	
pr	109.18	kips		Pr	130.24	kips
K1	1.00			K1	1.00	
Pel	3713.67	kips		Pel	3713.67	kips
B1 Calculated	0.62			B1 Calculated	0.62	
B1 Used	1.00			B1 Used	1.00	
Mr	72.09	ft-k		Mr	113.50	ft-k
ϕPn	428.00	kips	Table 4-1 AISC	ϕPn	428.00	kips
pr/pc	0.26			pr/pc	0.30	
Fy	50.00	ksi		Fy	50.00	ksi
Zx	96.80	in3		Zx	96.80	in3
Mcx	4356.00	ft-k		Mcx	4356.00	ft-k
H1-1a				H1-1a		
1>	0.27			1>	0.33	
combined						
ϕPn	428.00	kips				
pr/pc	0.56					

Fy	50.00	ksi
Zx	96.80	in3
Mcx	4356.00	
H1-1a	0.00	
1>	0.57	< 1

X reaction at top of column - cantilever (k)	3.379
X reaction at top of column - girder (k)	2.179
x reaction (k)	5.558

Unbraced						
Side	Quad side					
Frame	MQ 3					
Columns	W12x65					
L	16.89	ft2				
E	29000.00	ksi				
I	533.00	in4				
A	19.10	in2				
K2	1.00					
Girder Plane				Cantilever Plane		
girder	125.38	kips		truss m	110.00	kips
top beam	1.13	kips		cantilever	20.24	kips
Pu	126.51	kips		Pu	130.24	kips
Pnt	126.51	kips		Pnt	130.24	kips
girder moment	239.83	k-ft		cantilever moment	170.91	k-ft
girder moment	-230.13	k-ft				
Mnt	6.42	k-ft		Mnt	113.50	k-ft
Sum Pnt	126.51	kips		Sum Pnt	130.24	kips
M1	0.00	k-ft		M1	0.00	k-ft
M2	6.42	ft-k		M2	113.50	ft-k
Single				Single		
Cm	0.60			Cm	0.60	
pr	126.51	kips		Pr	130.24	kips
K1	1.00			K1	1.00	
Pel	3713.67	kips		Pel	3713.67	kips

B1 Calculated	0.62		B1 Calculated	0.62	
B1 Used	1.00		B1 Used	1.00	
Mr	6.42	ft-k	Mr	113.50	ft-k
ϕPn	428.00	kips	ϕPn	428.00	kips
pr/pc	0.30		pr/pc	0.30	
Fy	50.00	ksi	Fy	50.00	ksi
Zx	96.80	in3	Zx	96.80	in3
Mcx	4356.00	ft-k	Mcx	4356.00	ft-k
H1-1a			H1-1a		
1>	0.30		1>	0.33	
combined	0.00				
ϕPn	428.00	kips			
pr/pc	0.60				
Fy	50.00	ksi			
Zx	96.80	in3			
Mcx	4356.00	ft-k			
H1-1a					
1>	0.60				

X reaction at top of column - cantilever (k)	3.379
X reaction at top of column - girder (k)	0.194
x reaction (k)	3.573

Unbraced					
Side	Quad side				
Frame	MQ 4				
Columns	W12x65				
L	16.89	ft2			
E	29000.00	ksi			
I	533.00	in4			
A	19.10	in2			
K2	1.00				
Girder Plane			Cantilever Plane		
girder	60.65	kips	truss m	110.00	kips
top beam	1.06	kips	cantilever	20.24	kips

Pu	61.71	kips		Pu	130.24	kips
Pnt	61.71	kips		Pnt	130.24	kips
girder moment	133.09	k-ft		cantilever moment	170.91	k-ft
girder moment	-158.60	k-ft				
Mnt	193.10	k-ft		Mnt	113.50	k-ft
Sum Pnt	61.71	kips		Sum Pnt	130.24	kips
M1	0.00	k-ft		M1	0.00	k-ft
M2	193.10	ft-k		M2	113.50	ft-k
Single				Single		
Cm	0.60			Cm	0.60	
pr	61.71	kips		Pr	130.24	kips
K1	1.00			K1	1.00	
Pel	3713.67	kips		Pel	3713.67	kips
B1 Calculated	0.61			B1	0.62	
B1 Used	1.00			so use	1.00	
Mr	193.10	ft-k		Mr	113.50	ft-k
ϕPn	428	kips	Table 4-1 AISC	ϕPn	428.00	kips
pr/pc	0.144189252			pr/pc	0.30	
Fy	50	ksi		Fy	50.00	ksi
Zx	96.8	in3		Zx	96.80	in3
Mcx	4356	ft-k		Mcx	4356.00	ft-k
H1-1a				H1-1a		
1>	0.183594211			1>	0.33	
combined						
ϕPn	428.00	kips				
pr/pc	0.45					
Fy	50.00	ksi				
Zx	96.80	in3				
Mcx	4356.00	ft-k				
H1-1a						

1>	0.49	
X reaction at top of column - cantilever (k)	3.379	
X reaction at top of column - girder (k)	5.837	
x reaction (k)	9.22	

Unbraced						
Side	Softball side					
Frame	1					
Columns	W12x58					
L	16.89	ft2				
E	29000.00	ksi				
I	475.00	in4				
A	17.00	in2				
K2	1.00					
Girder Plane				Cantilever Plane		
girder	25.59	kips		truss m	0.00	kips
top beam	1.28	kips		cantilever	22.58	kips
Pu	26.87	kips		Pu	22.58	kips
Pnt	26.87	kips		Pnt	22.58	kips
girder moment	36.66	k-ft		cantilever moment	170.91	k-ft
girder moment	0.00	k-ft				
Mnt	36.66	k-ft		Mnt	107.31	k-ft
Sum Pnt	26.87	kips		Sum Pnt	22.58	kips
M1	0.00	k-ft		M1	0.00	k-ft
M2	36.66	ft-k		M2	107.31	ft-k
Single				Single		
Cm	0.60			Cm	0.60	
pr	26.87	kips		Pr	22.58	kips
K1	1.00			K1	1.00	
Pel	3309.55	kips		Pel	3309.55	kips
B1 Calculated	0.60			B1	0.60	
B1 Used	1.00			so use	1.00	
Mr	36.66	ft-k		Mr	107.31	ft-k

ϕPn	428.00	kips	Table 4-1 AISC	ϕPn	428.00	kips
pr/pc	0.06			pr/pc	0.05	
Fy	50.00	ksi		Fy	50.00	ksi
Zx	96.80	in3		Zx	86.40	in3
Mcx	4356.00	ft-k		Mcx	3888.00	ft-k
H1-1a				H1-1a		
1>	0.07			1>	0.08	
combined						
ϕPn	428.00	kips				
pr/pc	0.12					
Fy	50.00	ksi				
Zx	86.40	in3				
Mcx	3888.00	ft-k				
H1-1a						
1>	0.12					
X reaction at top of column - cantilever (k)				3.765		
X reaction at top of column - girder (k)				0.513		
x reaction (k)				4.278		

Calculations for Lateral Loadings

Wind Loads			
Method 2			
Elevation at foundation	519.50	ft	cannon
Elevation at roof	585.50	ft	cannon
Elevation	66.00	ft	cannon
Gf			
Cp			
Cf			
alpha	7.00		table 6-2
Kd	0.85		table 6-4
V	100.00	MPH	cannon
I	1.15		cannon
Zg	1200.00	ft	table 6-2

Kz	0.88	note 2	Table 6-3
Kzt	1.00	assumed	section 6.5.7
G	0.85	assumed	section
Gcpi	0.18		cannon
Gcpi	-0.18		
qz	21.96	psf	
q	21.96	psf	section 6.5.3
Cp			
qi	21.96	psf	section 6.5.3
b	107.33	ft	cannon
l	249.13	ft	cannon
l/b	2.32		
b/l	0.43		
wall Cp	l/b	b/l	
windward	0.80		
leeward	-0.29	-0.5	interpolation
sidewall	-0.70		
Roof Cp		Flat Roof	
h/l	2.35		
0 to H	-0.90		
H to 2H	-0.50		
> 2H	-0.30		
Second Cp	-0.18		
MWFRS Pressures			
Windward wall p+	11.57	psf	
Windward wall p-	18.29	psf	
Leeward wall p+	-9.27	psf	l/b
Leeward wall p-	-1.37	psf	l/b
Leeward wall p+	-13.29	psf	b/l
Leeward wall p-	-5.38	psf	b/l
Roof			
p +	-20.75	psf	
p -	-12.85	psf	

used p + roof because it is the biggest			
N-S braced frames	24		
p	-0.86472	psf	
E-W braced frames	32		
p	-0.64854	psf	

Earthquake Loads			
I	1.25		cannon
Ss	0.24		cannon
S1	0.067		cannon
SDS	0.192		cannon
SD1	0.076		cannon
R	3.25		cannon
Ω o	2		cannon
Cd	3.25		cannon
Cs	0.055		cannon
V	1294	kips	cannon
Ip	1.5		cannon
Fa	1.2		table 11.4-1
Fv	1.7		table 11.4-2
Sms	0.288		
Sm1	0.1139		
Ct	0.028		table 12.8-2
x	0.8		table 12.8-3
T	0.799453	sec	
Ts	0.395833	sec	
To	0.079167	sec	
Sa	1.240131		
TL	6		Figure 22-15
W	23527.27	kips	12.8-1
Number of braced frames			
North-South	24		
East-West	32		
weight is comparable			
N-S			

Shear per frame	53.92	k	
E-W			
Shear per frame	40.44	k	