Project #LDA-1404

IMPROVEMENTS TO THE WPI POWERPLANT COAL BIN

Major Qualifying Project

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Abstract

This project analyzed the current conditions of the underground coal bin used for storage on the Worcester Polytechnic Institute's (WPI) Campus, and determined effective options for rehabilitation and replacement. Each option is designed to withhold loading due to trucks and pedestrians, and withstand exposure to water runoff, snow buildup and other environmental factors. Cost and value analyses were performed for each option including a net present value and axiomatic design matrix for the consideration of WPI's decision-making process.

Acknowledgments

The project group would like to thank and acknowledge our faculty advisor, Professor Albano, whose assistance and guidance was vital to the success of the project. We would also like to thank our co-advisor, Professor Towner, for his assistance with the financial analysis of the project. Finally, we would also like to thank Chris Salter, WPI Director of Project Management and Engineering, and Bill Spratt, WPI Director of Facilities Operations, for their help and advice along the way.

Capstone Design

In this Major Qualifying Project, multiple strategies to address the issues surrounding the WPI Powerplant coal bin were designed and evaluated, including both short-term solution options for rehabilitating the area and more substantial options for replacement of the entire coal bin structure. These options range from simple waterproofing to complete demolition and renovation of the structure. The stress and loads caused by a number of different loading scenarios were analyzed to create designs that will be sustainable for the future. Upon completing the project, the requirements necessary for Capstone Design were satisfied, and the following realistic constraints were addressed: economics, sustainability, constructability, ethics, and health and safety.

Economics

A detailed cost estimate for each solution alternatives with discounted cash flows and a comprehensive axiomatic design value analysis are included in the report. This analysis compared the total costs of each solution alternative to its present value, future value, and maximum lifespan with the intention of determining the option with the highest overall lifetime value. The aim in creating this analysis is to provide WPI and its Department of Facilities the resources needed to aid them in their decision process.

Sustainability

The lifespan and sustainability of each option for improvement was considered in the design process, taking into account projected life of the plan and maintenance costs over time. The estimated durability lifespans for each portion of each option were considered in the assessment of the overall lifespan of the option.

Constructability

The constructability of each improvement option was considered throughout the design process. Each option was designed with standard sections, materials, and as much repetition as possible in order maximize the efficiency of construction. The constructability of the project was a major factor due to the restrictiveness of the coal bin location, where access issues played a part in the design. The surrounding buildings created a unique environment for this type of underground building structure, which was taken into account in the design.

Ethics

The ASCE Code of Ethics was used as a guide to ensure acceptable and ethical practices were applied. This included referencing all outside research and design material used throughout the project. Also, a confidentiality agreement was signed in accordance with the WPI Department of Facilities to ensure that no sensitive information pertaining to the structure was released in the preparation and documentation of this work.

Health and Safety

The health and safety concerns related to working in the current coal bin, including the risk of heavy loads from above, were taken into account in the design process. Alternative structural solutions were designed in accordance with the requirements of *ASCE 7*, AASHTO, ACI, *IBC*, AISC, and the *Massachusetts State Building Code* to ensure structural design safety.

Authorship

The following table summarizes the primary responsibilities of each group member. For each area of work, responsibilities included background research, execution of the work, and preparing appropriate sections of the final report.

Area of Work	Responsible Group Member(s)
Analysis of Existing Structure	**Mahoney/Mercer/Monasky**
Waterproofing Solution	**Mercer**
Reinforced Concrete Slab on Steel Frame	**Mercer/Monasky**
Composite Concrete on Steel Floor System	**Monasky**
Cost Analysis	**Mahoney**
Discounted Cash Flow	**Mahoney**
Axiomatic Design	**Mahoney**
Final Recommendations	**Mahoney/Mercer/Monasky**

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1.0 Introduction and Project Statement

The coal bin underneath the WPI Power Plant facility are in serious disrepair and in need of renovations. This Major Qualifying Project investigated the current conditions associated with the use of this area, such as water leakage and poor load bearing capabilities, and identified and designed a range of possible solutions to these problems.

In order for the WPI Powerplant to remain a sustainable structure that utilizes its functionality in an effective way, a solution must be found to repair or replace the coal bin that will transform them from an aged and unusable space into a new, safe, workable environment. As the coal bin are over a hundred years old, it is no surprise that they are in disrepair, and as such the nature of the project work encompasses the factors associated with this age in an attempt to determine the most efficient and effective way of improving the space.

Taking this into account, the project goal was to develop an in-depth plan of action for repair and restoration of the coal bin. An understanding of the existing layout and structural frame and an assessment of current structural conditions were established based on visual inspections, review of building plans obtained from the WPI Department of Facilities, and other outside research. This assessment data was used to develop multiple solutions scaling from simple waterproofing to design options for full-scale renovations. Deliverables included an outline of the process to implement each solution alternative with an associated cost analysis and breakdown, followed by an axiomatic design analysis used in the recommendation of the most sustainable and cost efficient improvement option. The completed project demonstrates fundamental knowledge of civil engineering attained from undergraduate courses at WPI and independent learning. Also included in the report is a cost and value analysis and breakdown for the proposed solutions on a level that meets the requirements for an MQP in Management Engineering.

2.0 Background

This background chapter discusses the research that contributed to in creating our final designs and recommendations. The following sections provide information on the original design of the coal bin, their purpose, and the materials of construction, as well as the resources used in developing and evaluating the solution alternatives.

2.1 Building and Location

The original purpose of this structure and where it is located is described below and provides a good understanding of the nature of the current problem. Due to the confidentiality agreement signed with the WPI Facilities Department, the specific location of the coal bin cannot be released; however, the designs of the coal bin and conditions included in the report minimize the impact of this restriction.

In the late 1800's Worcester Polytechnic Institute (WPI) was growing technologically as well as in size. With the newly built Salisbury Laboratories not providing sufficient facilities for teachers and students only four years after its opening, the Mechanical Engineering department started requesting more lab space. In 1893 a detailed plan was submitted to the Trustees in order to expand the current facilities. Sustaining the vision of a strong and growing Institute meant creating infrastructure to power and heat these new facilities, and because of this one of the expansion opportunities that was accepted was the construction of a steam powerhouse. After WPI's own professors made initial plans, Earle & Fisher, WPI's official architects, crafted them into final form. The powerhouse was built to house two 100-HP engines and vertical boilers that would allow for student experimentation and power generation. A space was excavated between the powerhouse and the laboratories in order to house the coal, ash, storage vaults and a tunnel to Washburn Shops. This construction was completed in the summer of 1895, and the powerhouse was officially put into use. The powerhouse was eventually converted to run on gas making the coal bin no longer necessary. Currently, the space is used for storage and access to an electrical conduit, and gas and steam piping are also running through the space. The coal chutes have been shut and covered by concrete and asphalt with limited road access above the underground structure.

2.2 Structural Design

The roof structure of the underground coal bin is comprised of several brick and steel arches which is commonly known as a barrel vault system. A diagram of the cross section of the roof structure can be seen below. The arches span approximately 8 feet in width and extend the length of the room. They have a rise of approximately 8 inches and are supported by 15-inch steel I-beams. In Figure 1: Structural Cross-Section, the I-beams rest on brick columns, which are approximately 20” on each side. The bottom flanges of the beams are coincident with the springing lines of the arches so that the bricks are seated on the top of the bottom flange. Between the I-beams, 3/4” diameter steel bars add additional support and resist the horizontal thrust forces from the arches. Above the brick arches there is 9” to 15” of concrete fill topped by approximately 4” of pavement. An engineering report conducted by Johnson & Seaman Engineering (2004), estimated that the approximate load bearing capacity on the pavement above is 40 lbs. /ft^2.

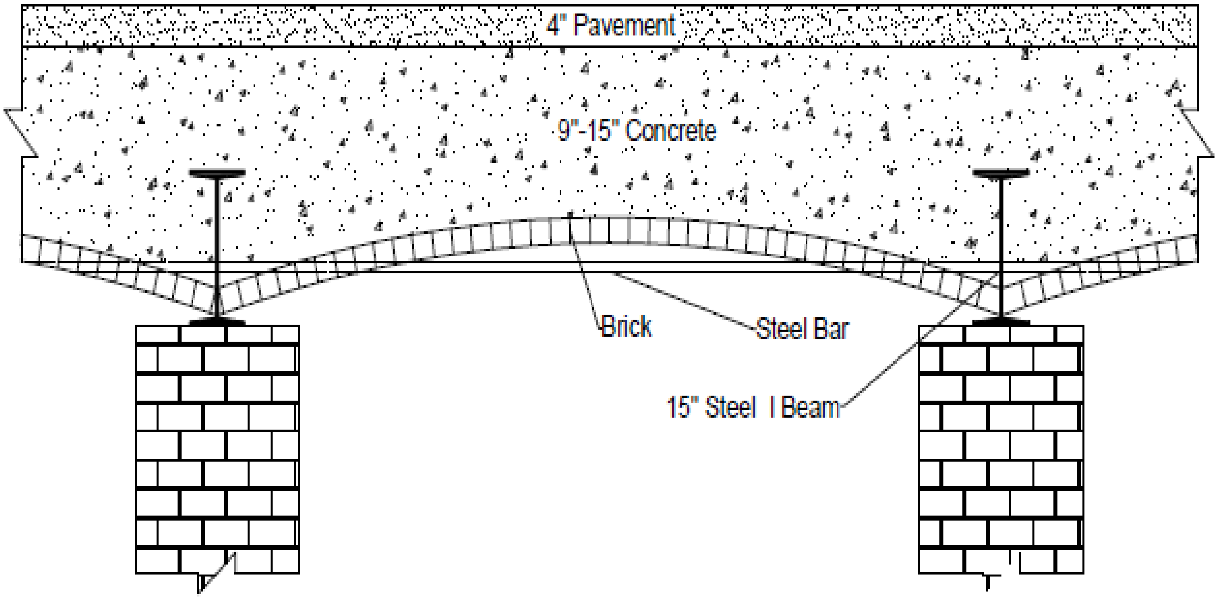

Figure 1: Structural Cross-section

2.3 Foundation Design

The foundation of the powerhouse was built from large, rough-cut stones which are held together with mortar. This foundation design was common for the time the building was constructed. The stones provide ample structural support and vertical reactions for the building above; however, their ability to prevent water seepage is quite poor due to cracks and voids in the mortar joints. Consequently, the foundation wall is one of many sources of water entering the coal bin.

2.4 Building Materials

The building materials used for the WPI Power Plant coal bin were for the most part common for the time period; however, the steel beams used for support were a fairly new technology at the time. The I-beams supporting the roof arches were originally thought to be made from wrought or cast iron, but research into the original design plans (provided by the WPI Archives) shows that they are indeed steel. At the time of construction (1895), steel was just beginning to gain popularity as a structural building material due to a newly developed method of production known as the Bessemer process. This process, named after its inventor Henry Bessemer (1813-1898), significantly reduced the cost of manufacturing steel and allowed it to be mass produced. The general standard for I-beams of that time period was a tensile strength of 60-70ksi (Bates, W.). The use of steel construction may be one of the reasons the structure has lasted so well over time; however, there is apparent rust covering the beams that may weaken their structural integrity.

Studies have found that uniform corrosion due to rust does not have a significant effect on the strength and ductility of a steel member[1]; however it can contribute to loss of effective cross-section and load capacity overall. The problem with severe rust is the decrease in bond strength between the steel and concrete. The expansion rust causes can result in cracking and separation from the steel, which increases leakage creating a detrimental cycle. Over time the increased expansion can cause cracking into the concrete sections.

Research has also shown that the brick material used in the arches is most likely the standard brick of the time. From the mid 1800’s to early 1900’s bricks were made from a combination of clay, sand, and shale; the majority of which came from the Hudson River area of New York. These molded bricks had an approximate compressive strength of 5,293±1,822psi, compared to the strength of 11,305±4,464 of a modern extruded brick (Brickmaking in the USA).

The mortar used in the coal bin construction was found through archive research to be a lime mortar combined with Portland cement, which was the most commonly used mix design in

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[1] Zahrai, S.,147

the late 1800's. The benefits of this lime mortar were high workability and a self-waterproofing capability that occurred from water reacting with the lime in potential cracks and forming calcium crystals therein, temporarily sealing the crack (History of Lime in Mortar). The observed calcium buildup on the inside of the coal bin is most likely a result of this effect taking place over the 118 years the bins have been underground, and the severe water leakage is a byproduct of these mortar cracks.

Another note on lime mortar is its lower strength than modern mortar compositions, meaning that it is recommended for used in walls of relatively low load bearing weight, not necessarily a load bearing structure such as the arches. Modern mortar property specifications run through four ranges, the strongest of which, "M" rated mortar, has a compressive strength of 2,500 psi, whereas the weakest, "O" rated, has a compressive strength of only 350 psi (Mortar Mix Designs). Although the exact compressive strength of the mortar used in the coal bin is not yet known, it is assumed based on historical data that its strength is significantly less than this, making it a weak point in the bin construction.

2.5 Resources for Analysis and Design

One main resource used for the analysis and design of the coal bin was the program Risa2D, which allows the user to analyze maximum shear, axial, and moment forces with set load combinations. Using this data in conjunction with 14th edition of the America Institute of Steel Construction (AISC) *Steel Construction Manual* allowed for the appropriate member sizes to be determined.

Other resources used in the design process include the American Concrete Institute (ACI) Manual, *Massachusetts State Building Code 8th Edition*, and the American Association of State Highway and Transportation Officials (AASHTO). The purpose of the ACI is to research and develop standards for the design and construction of concrete structures. The ACI Manuel is used to calculate the proper footings, concrete slabs, and anchor bolts that are necessary in the design and analysis of the coal bin. The American Association of State Highway and Transportation Officials (AASHTO), is a non-profit organization that serves as a guide for all modes of transportation in the United States including the District of Columbia and Puerto Rico. The AASHTO serves to guide development, operation and maintenance of all public methods of transport. This association works as a bridge between state departments and the Federal

Government to publish specifications, test protocols and guidelines for construction, design and materials. This set of specifications was chosen because the road running over the coal bin has similar loading to a bridge.

2.6 Resources for Cost and Value Analysis

In order to assist the Institute in its decisions concerning the rehabilitation or construction of the coal bin, the report includes a detailed cost analysis for each option for improvement, including a discounted cash flow for each option, as well as an axiomatic design analysis. The reason for including the cost analysis is to provide a breakdown of all costs associated with the different options and the total cost of construction that each will incur. The costs range from material and labor to future maintenance, and should be a strong consideration in the decision of which option to choose.

The purpose of the discounted cash flow breakdown included in the analysis is to provide a forecast of the predicted costs each option will incur over time, discounted to account for the time value of money. The discounted cash flow of each option is a valuation method used to estimate the attractiveness of a project, using future cash flow and expense projections to estimate the total cost associated with the project's lifespan. In a construction project such as the renovation of the coal bin, which is not associated with generating income, all of these cash flows will be negative and essentially consist of the maintenance costs associated with the continued operation of the facility. In considering these costs, and discounting them based on expected interest rates and uncertainty, an insight can be gained as to the total lifetime costs of each option for improvement. These inflation rates are used to escalate costs and the associated discount rates are used to revert those costs to present day dollar values.

The report also includes an axiomatic design analysis that compares the multiple options for complete renovation. Axiomatic design is built upon a double axiom system, defining the customer's needs and then comparing the functional requirements and design parameters of a project to judge one option against another, based on those needs. The two axioms, independence and information, are used to create an uncoupled matrix showing the various design option components that best suits the individual project parameters and needs, while remaining independent of each other. In a perfect system the matrix is completely uncoupled, meaning any one component can be changed or replaced without affecting any other components. The goal in conducting an axiomatic analysis for a project such as the coal bin renovation is to determine which option is the most feasible and best suits the needs of the Institute and the Department of Facilities.

2.7 Conclusion

The background data described above gave an insight into the history of the Coal Bin structure and offered explanation of the need for current improvement. The resources above provided a staging point from which the possible solutions to the problem were formed, with the methodology for how these solutions were created described in the next chapter of the report.

3.0 Methodology

The preceding chapter gave background information regarding the information used in the areas of study of the project. The following chapter describes in detail the methods used for solving the problems posed by the project, including analyzing the current structural conditions of the coal bin, determining options for improvement, designing full renovation options, and conducting a cost and value analysis.

3.1 Analyze Current Structural Conditions

Assessing the current structural conditions of the coal bin was the first step in design process. The strategy of going about this process consisted of gathering relevant materials available from the WPI Archives and other resources, and comparing these with first-hand observations. First, the available drawings and observations made from the field were reviewed and compared with the data from as-built configurations. The loading capacity of the coal bin was then calculated by determining dead loads, beam integrity, and major areas of water leakage. This data was vital in order to create the best design possible.

3.1.1 Beam, Columns and Tie Rod Integrity

With the amount of leakage coming through the ceiling and floors, it was necessary to calculate the effects of rust or corrosion, if any, on the integrity of the steel I-beams. This was done through outside research of similar underground structures and systems. Rust is also very prevalent on the tie rods that are used to support the arches. It was also observed in areas that the tie rods have been cut to make room for a coal chute, rendering them ineffective in resisting the horizontal thrust forces. These cuts further contribute to the poor load capacity of the structure and are taken into consideration in the design. The visual observation the extent of that rust was estimated, and the possible effects of this rust was determined based on outside research.

3.1.2 Arches

This system of construction was a common technique used during the time the coal bin were constructed. Historically, one of the first steps in construction was to analyze the load capacity of the current construction. First the capacity was calculated based on the interpolation of the as-built condition; however, this calculation does not reflect the current load bearing capacity of the structure. There are other factors that were considered such as the age of the bricks and the mortar, and the rust and pitting of the steel sections. Once the current capacity was determined, the assessment was made of whether or not the strength of the structure needs to be increased to handle the loads applied. In the past this area has been used as an access road to a loading dock on the side of Washburn shops. This type of loading scenario was considered when designing support structures.

3.1.3 Masonry

The masonry in the coal bin is the original construction, including the mortar used to keep the bricks in place. Parts of the mortar holding the bricks together are deteriorating due to water damage, as well as damage from the expansion of the rusting steel members. It is difficult to know the full extent of this mortar deterioration without conducting further test, but inferences on the effect of the conditions were made based on research of other similar structures.

3.1.4 Load Capacity

By analyzing the weight of the brick masonry, beams, rods, earth, concrete and asphalt per square foot, the dead load that is exerted on the arches and columns of the coal bin was determined. With input from the above analyses the dead load and strength assessments of the coal bin were calculated. This loading capacity was then compared to *Massachusetts State Building Code* criteria. The governing load criteria was found using superimposed loading and the self-weight of the coal bin plus additional design load requirements, such as live loads, snow loads, seismic loads and soil pressure. A major function of the coal bin in regards to live loads is the ability to carry vehicle loads. ASSHTO bridge design is referenced in order to account for tandem truck loading to adequately design the solution alternatives. In addition, load combinations from *ASCE 7* were used to determine the greatest loading combination. With the use of the program RISA, the calculated capacity for steel frames and masonry arches was compared to governing load criteria. These findings allowed us to make conclusions on the current structural condition of the coal bin and design solutions for repair and restoration.

3.1.5 Water Leakage

A major concern in the coal bin is water leakage from rainwater and especially from melting snow. The water is causing structural and property damage making the rooms unusable. Much of the exposed piping and beams have severe rust damage because of the wet environment. An assessment has been determined on whether waterproofing using a Drylok or Xypex waterproofing product will be sufficient as a long-term solution. Through investigation the determination of whether or not an application of a waterproofing compound to the ceiling and foundation will be adequate was made. This is discussed in the results and recommendations.

3.2 Determining Options for Improvement

The improvements of the coal bin structure were separated into three main categories: waterproofing, reinforcement of existing structure, and complete renovation. The main concerns associated with the area are water leakage and improving the structural integrity of the supported roof area above. In order to achieve the best long-term solution both a waterproofing solution and a structural solution will need to be selected by the WPI Department of Facilities. There are several options for both problems with varying levels of expense, longevity, and cost.

3.2.1 Waterproofing Solutions

The most basic improvement option available for the coal bin is a simple waterproofing solution. Waterproofing the interior of the coal bin, and possibly the aboveground area above, would solve the problem of water leakage in the area. The key factors considered in determining the best options for waterproofing were effectiveness, lifespan, and price. Possible options for waterproofing were identified through outside research. The results section of the report offers a breakdown of the solutions that were found.

3.2.2 Reinforcement of Existing Structural Supports

The second of the major problems the coal bin pose is the lack of load capacity for the aboveground area they support. Expected repairs would be in the form of steel reinforcements on the inside of the structure. By analyzing the loading requirements for the ground above the structure and determining what constructing a support structure underground would entail, its feasibility was determined. The constructability of such a product was considered based on feasibility of getting a support structure into the coal bin, the integrity of the masonry arches, and the rerouting of utility lines to determine whether such a project would be viable.

Loading considerations provided by the WPI Department of Facilities were used with local and state building codes to determine the required loading capacity.

3.2.3 Replacement of Roof Structure

This option is the most complete and best long-term solution; however it is also the most costly and will require the most time for WPI to implement. In order for a full renovation to take place, the existing structure must first be removed. The cost and time to do so must be taken into consideration with design alternatives. The methods for design of each three options are detailed in the next sections of the report.

3.3 Full Renovation Design

This section details the three options for full renovation that were designed.

3.3.1 Reinforced Concrete Slab on Steel Frame

The first step in the design process was to determine the design loading that the structure would need to be capable of supporting. A dead load of 1130 lbs. per linear foot was used as a starting point for loading requirements. This value represents the weight of an 8-inch reinforced concrete slab as well as 4 inches of pavement above the concrete. AASHTO[2] bridge design was then used as a reference for vehicle design loads. It was determined that the minimum design load would be for the design tandem truck as this was the most likely representative of the delivery trucks that use the space. The design tandem is a tandem axle 58,000-pound truck which is used for design purposes. The loads from the truck were idealized as an 8,000-pound point load for the front and then spaced 14ft back are two 25,000-pound point roads for the rear axles, spaced 4ft apart as seen in Figure 2.

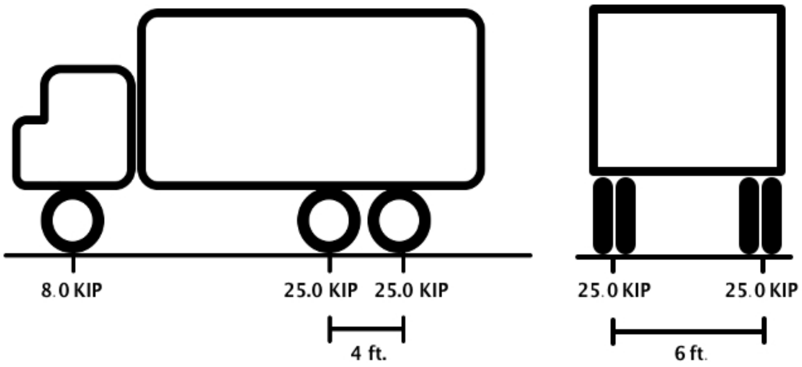

Figure 2 - ASSHTO Design Tandem Truck Loading

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[2] American Association of State Highway and Transportation Officials

Using the estimated dead loads and the loads provided by the design tandem, maximum axial, shear and moment forces were obtained for the new construction using a demo version of Risa2D. The use of Risa allowed for the application of the design tandem as a moving load, which provided an accurate understanding of how the loads from the truck will interact with the proposed structure design at any point in driving over the new roof section. With the results obtained from Risa the *AISC Steel Construction Manual* was used to establish member sizes and connection elements. In this first design no composite action was considered between the concrete slab and the supporting steel beams: therefore, the steel W section was selected that could support all of the design loads.

3.3.2 Composite Concrete on Steel Floor System

The first part of this design was similar to the previous option determining the loads on the design structure. However once the maximum loads were determined, the *AISC Steel Design Manual* was used to select a composite section that would then carry the weight of the dead loads and the design tandem. The advantage of the composite section is that, through the use of steel studs welded to the top of the steel beam, greater strength can be obtained than with concrete or steel separately. The steel studs bond the concrete to the steel, so that under loading a portion of the compression forces can be transferred into the concrete, which allows for the use of a smaller, and thus less expensive, W section.

3.3.3 Concrete Slab Design

The reinforced concrete slab was designed using the *Bridge Design Manual* published by the state of Illinois Department of Transportation. This manual uses AASHTO design specifications as well as general guidelines for good practice when designing reinforced concrete slabs. This manual was used as a guideline to design the reinforced concrete slab that will support the vehicle traffic above the coal bin. The truck traffic as well as climate and corrosion conditions are similar in our design to what is used for bridge design. The manual refers to the AASHTO LRFD code to determine design moments that the slab must support for both normal traffic and crash impact loading. Although a crash is very unlikely in our design this consideration was still included in the slab design so that in the event of a catastrophic event the roof structure doesn’t fail. AASHTO LRFD Table A4-1 uses data derived from experimental data to determine the maximum design moment of the vehicle traffic.

3.4 Cost and Value Analysis

This section discusses the methods taken to compile a cost and value analysis for each proposed option to the most accurate degree possible, which is included in the results section of the report. The goal of this analysis is to assist the WPI Department of Facilities in their decision making process. The principle resource used for this analysis was the *RSMeans* reference book series, edition 2014, which detailed the processes of each improvement. These books supplied the labor hours, units of measurement, material costs, labor costs, and equipment costs for each element of the process to produce a total cost per unit of work. The unit cost data, when combined with the calculated number of units, was used to determine the total cost and total labor time for each improvement.

Other outside resources were used for cost valuations, such as the alternative waterproofing solutions whose data was obtained from the production company's websites.

3.4.1 Waterproofing

The first waterproofing solution consists of spraying a cement-like mixture over the entire area of the walls and ceiling and effectively sealing the bins from the penetration of outside moisture. The cost data used to price this method was based off of *RSMeans Construction Cost Data (2013)*, which details the daily output, labor hours, and all costs associated per unit of work of a standard concrete waterproofing process. The square footage area of the interior of the coal bin was determined and combined with the unit value data for the *RSMeans* conversions to calculate the total cost and time (in days) for the process.

Also included in the results is data from outside sources to give a cost analysis of other waterproofing options. The two products researched were Drylok and Xypex, both waterproofing-paint type products that could be applicable to the coal bin interiors. The team determined the price per square foot of using these products and multiplied that by the total square footage of the coal bin interior to determine the final material cost. The labor costs for these two products were based off the estimated time provided by the product manufacturer combined with the hourly pay rate of the employees within the WPI Department of Facilities who will be installing it.

3.4.2 Re-Paving With Epoxy Injection

The second section of the proposed waterproofing options involved the removal of the pavement overlaying the coal bin and the use of an epoxy injection sealant to seal the cracks in the concrete below. The treated area will then be re-paved with rigid concrete paving. The costs for this option were determined by analyzing the data found in *RSMeans Sitework and Landscaping* (2014). First, the costs and labor hours necessary to remove the four to six inches of pavement above the concrete were determined. The square footage of the area was multiplied by the cost per square foot to determine price, and the total labor time required was calculated by dividing the square footage by the daily output available.

The next step in this process is the injection of the epoxy sealant. Consulting with the WPI Department of Facilities and the head engineer best estimates for the extent of the cracks in the pavement and an estimated linear footage were determined. Taking the linear footage in combination with *RSMeans* data for cost and time per unit, the total project cost and duration for sealing the cracks was found. The final step was then to determine the cost for the rigid concrete paving with an estimated depth of approximately fifteen inches (the coal bin currently have nine to eleven inches of concrete below four inches of pavement). Estimating the cost of paving the area above the coal bin was based on the square footage of the affected area multiplied by the *RSMeans* data for total per unit. The time associated with this component was determined using the square footage compared with estimated daily output.

3.4.3 Underground Support Structure

No matter which of the two previous options for waterproofing are chosen, improving the structural load capacity of the coal bin is still necessary if a complete renovation is not completed. The first proposed option is to create a support structure underground that would span that extent of the coal bin and increase their structural integrity. In order to determine the costs associated with this solution strategy, the design was compared with the labor and material costs found in *RSMeans Heavy Construction Data (2014)* to determine the material costs of the required steel beams and columns and their associated assembly and installation costs. This data was then compared to research data of similar projects to determine its accuracy, and then used with the final cost analysis as a recommendation to the WPI Department of Facilities.

3.4.4 Complete Renovation

Cost analyses were prepared for three different options for a complete renovation of the coal bin structure. Each option entailed the demolition of the existing construction, construction of the new underground steel or concrete structure, repaving the above ground area, and waterproofing the interior. The analysis of demolition costs was based on data from *RSMeans Sitework and Landscaping*. The four to six-inch pavement data was broken into a total cost per square yard multiplied by the square-yard area of pavement, whereas the seven to twenty four-inch slab concrete data had to first be converted to cubic yards. Once the cubic yardage was calculated the costs could be determined in a similar manner as for the pavement.

For the construction of the underground steel beam and concrete structures the cost data was based off of *RSMeans Heavy Construction Cost Data*, using unit cost data per linear foot of the W-shape steel sections determined with the construction and installation costs that accompany them.

Finally, the cost of re-paving the area was determined with rigid concrete paving by using unit cost data provided by *RSMeans* multiplying the square yardage of the area by the cost per square yard for the paving. The last step of this project would be to waterproof the interior of whichever structural option was chosen to prevent water leakage such as is seen in the current structure. To determine the cost for this waterproofing similar steps were taken as described in the section 3.4.1, multiplying the square footage coverage area of the interior of the coal bin with the unit cost data per square foot.

3.4.5 Discounted Cash Flow

In order to determine which option for improvement offers the maximum lifetime value, the discounted cash flow was calculated for each option. The associated maintenance and upkeep costs related to the initial building and maintenance of each option were determined, and combined with the initial cost of construction to determine the present value of each option. These costs were discounted over time to account for projected inflation rates, and then combined with a discount rate to capture the expected interest rates and uncertainty in order to provide an accurate prediction of the actual costs each option will incur.

3.4.6 Axiomatic Design

Combining the total cost analyses and discounted cash flows allowed for the creation of an axiomatic design analysis of the options for improvement. The functional requirements were set as providing adequate room for work and storage, providing a weather-sealed environment, providing structural integrity, and ease of constructability. The design parameters then used were the architectural design of the structure, the weatherproofing, and the structural design. The goal of this process is to give a perspective of the options from a solution neutral environment and to determine which option for improvement best meets the customer needs based on all of the parameters and requirements.

4.0 Results

The following chapter describes the results from the research, assessment of current condition, and proposed solutions. It is the basis for the following recommendations chapter. This chapter offers the data gathered for each improvement option, including the waterproofing methods, reinforcement of the existing structure, and complete renovation options.

4.1 Waterproofing

There were three options for waterproofing the coal bin structure considered in the report research. The first is a specialized product, Drylok, which is popular for preventing water damage caused by cracks and works completely with the existing system. The second option consists of removing the aboveground paving, sealing the cracks with an epoxy injection, and then repaving the area. Finally, the third option is to cover the entire interior of the coal bin in a cementitious waterproofing sealant spray.

The first option Drylok is used primarily as a water proofer as opposed to a sealer, and works by being spread over cracks in the wall and expanding into them when dry, thereby sealing them. For large cracks, a product such as Drylok Fast Plug can be used to seal cracks that go far into or all the way through the outside wall. Drylok Fast Plug is very good for sealing cracks in masonry but is most effective with cracks that will not experience thermal or structural movement. Drylok is relatively low in price compared to the other two options with a cost of $1,175. The problem with using Drylok is that while the product seals existing cracks, it is not designed to cover the whole interior and therefore will not cover cracks in the future.

The second option is re-paving the area above the coal bin after filling the cracks with an epoxy product. This process would seal the area and most likely prevent water leakage, especially if combined with interior waterproofing. Moreover it would cost nearly twenty times the cost incurred by interior waterproofing. The total cost of the demolition of the pavement, the epoxy injection, and re-paving the area with 15” rigid concrete paving is estimated to be approximately $26,000.

Finally, a basic cementitious waterproofing product as described in the *RSMeans Construction Cost Data* manual could be applied to the current coal bin as a temporary fix to the water leakage problems. It can also be applied after a total renovation to ensure water leakage is not a recurring problem. The estimated total cost of cementitious waterproofing, as listed by *RSMeans*, is approximately $11,752 with an installation time of less than four days. One such product with similar applications and pricing is CEM-KOTE FLEX ST, a product manufactured by the waterproofing company SealTight, which is applied by spraying the product onto walls and ceilings in two coats, with an estimated lifespan of approximately fifteen years.

A full recap of the three waterproofing option can be found in Table xx below. A full breakdown of costs associated with waterproofing is provided in section 4.4 Cost Analysis.

Product	**Cost**	**Pros**	**Cons**
Drylok	$1,175	- Easy Application - Long Installation time	- Temporary Fix - Not designed to cover entire wall
Repaving/Epoxy Injection	$26,000	- Long Term	- Expensive - Long Installation
Cementitious Waterproofing Sealant	$11,752	- Short Installation time - 15 Year Lifespan	- Temporary

4.2 Underground Support Structure

Due to the poor structural integrity of the masonry arches, the construction of a support structure underground in the existing coal bin without the removal of the overlying barrel vaults and paving would not be feasible. Analysis of the arches structures through our research and that of Johnson & Seaman Engineering Inc. has shown that it is the weakest point of the coal bin structure. The beams have retained their strength, but supporting them with more columns will not add support to the deteriorated masonry arches and concrete above which are both too thin. The overhead clearance in the bins is currently an average of six feet, and with the overhead piping and wiring reducing that in some cases by a foot or more, clearance is a major issue for workers in the area. Construction of a support structure would further limit this clearance and would also take away from the already limited open area that coal bin currently poses.

The major reason for our decision, however, is that construction of such a structure itself would be extremely difficult. The only access point to the coal bin stems from the boiler room of the power plant, with the only egress from that area being a steep set of stairs leading to a narrow door. Getting the necessary materials needed for construction of such an extensive support structure into the coal bin would be extremely difficult if not impossible. Because of this the conclusion has been made that removing the existing support structure and erecting a new structure is not feasible.

4.3 Complete Renovation

The complete renovation design will involve two major steps. The first step is the demolition and removal of the existing support structure. This would involve removing the paving, concrete and finally the steel beams and tie rods that are currently in place. This step would be the same regardless of which of the three options are chosen for the new support structure. After the demolition is complete the new structure can be constructed. The existing

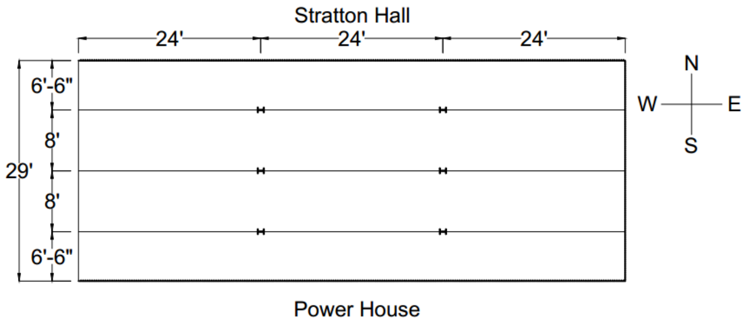

Figure 3: Basic Layout for Options 1 & 2

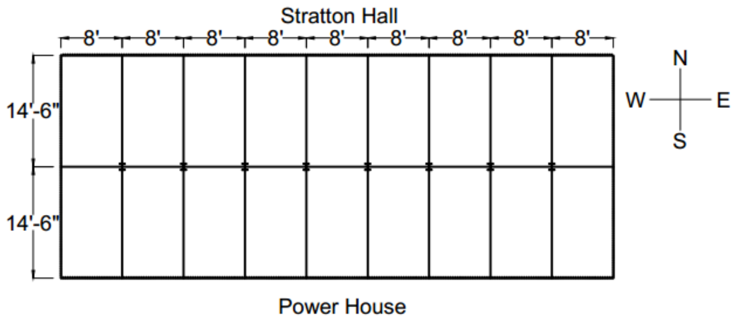

Figure 4: Basic Layout for Option 3

Table 1: Design Loads for Options 1 & 2

With Center Columns

Design Loading

Beam

Axial[k]	Shear[k]	Moment[k-ft]
36	113	465

Column

Axial[k]	Shear[k]	Moment[k-ft]
116	10	60

Without Center Columns

Design Loading

Beam

Axial[k]	Shear[k]	Moment[k-ft]
337	137	1417

foundation walls on the North and South sides of the site will be used to support the new structure. The basic layout of the area can be seen in Figure 3 and Figure 4. A summary of the design loads that were used for the design of the first two options can be seen in Table **1**, which shows the maximum loads for both a column and non-column design. Below the three options for a new structure are explained.

4.3.1 Concrete Slab

The same concrete slab is used for all of the options proposed below. It is comprised of an 8 inch deep, cast in place slab using normal weight, 3500 psi concrete. The slab features 5/8" reinforcing bars at 10 inches on center for both the positive and negative reinforcement. On the top there is 1.5 inches of concrete cover above the reinforcing steel while there is 1 inch below the bottom reinforcing steel. An 8 foot cross section of the slab can be seen in Figure 5, and the calculations that were used for slab design can be seen in Appendix B. This slab design is used for all of the following options with the reinforcing running in the in the east west direction. Above the slab will be 4 inches of asphalt paving which will help protect and extend the life of the concrete.

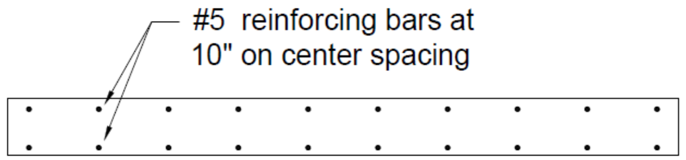

Figure 5: Reinforcement Diagram in Slab

4.3.2 Option 1: Concrete Slab on Steel Support Structure: Minimum Cost

This option will consist of a steel structure comprised of W-shape sections that make up the columns in the middle, and cross beams in the middle. The beams would span the coal bin in the longitudinal direction with a span length of 72 feet.

This option was further broken down into a design that featured a center column and one that did not. The benefits of not using a center column include greater versatility of the space and a reduced construction time. Using these design loads member sizes were selected. The selected member sizes are summarized in Table 2.

Table 2: Member Sizes for Option 1

Option 1

With Columns

Member Sizes

Beam

Member	ϕMn (kip-ft)	ϕVn (kips)
W21X55	**473**	**234**

Column

Member	ϕPn
W8X31	**348**

Without Columns

Beam

Member	ϕMn (kip-ft)	ϕVn (kips)
W33X130	**540**	**252**

Renderings of both the column and non-column designs can be seen in Figure 6 through Figure 11 which show a north elevation, east elevation and an interior view from inside the structure for both designs.

Option 1 with Columns

Figure 6: North Elevation

Figure 7: East Elevation

Figure 8: 3D Interior View

Option 1 No Columns

Figure 9: North Elevations

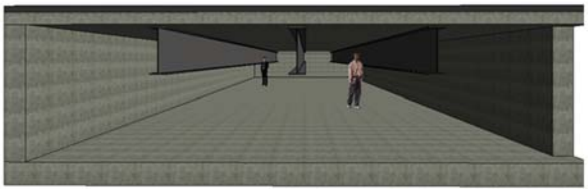

Figure 10: East Elevation

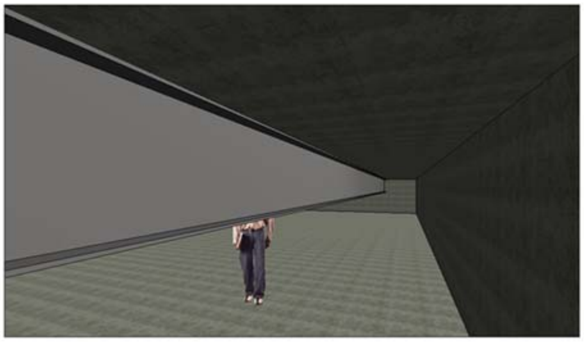

Figure 11: Interior View

4.3.3 Option 2: Concrete Slab on Steel Support Structure: Maximum Head Room

Table 3: Member Sizes for Option 2

Option 2

With Columns

Member Sizes

Beam

Member	ϕMn (kip-ft)	ϕVn (kips)
W14X74	**473**	**192**

Column

Member	ϕPn
W14X48	**572**

Without Columns

Beam

Member	ϕMn (kip-ft)	ϕVn (kips)
W21X166	**1620**	**506**

Option 2 is similar to option 1. However Option 2 is designed to optimize the head room at the expense of heaver beams. This was achieved by selecting beams with smaller depths yet thicker web and flange sections. The advantage of this option is that the versatility and usability of the spaced is increased because of the increase ceiling height. A summary of the selected members can be seen in Table 3. Renderings of this option can be seen in Figure 12 to Figure 14.

Option 2 with Columns

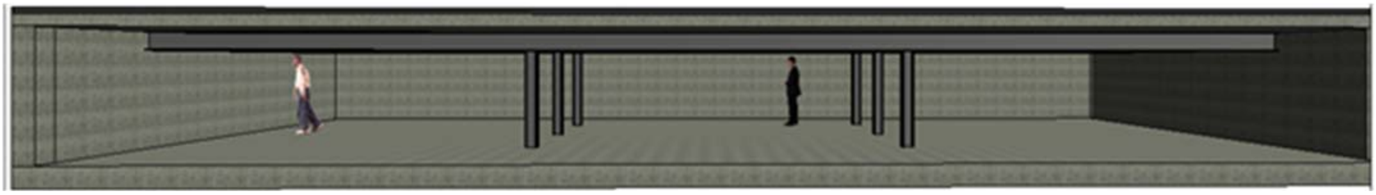

Figure 14: North Elevation

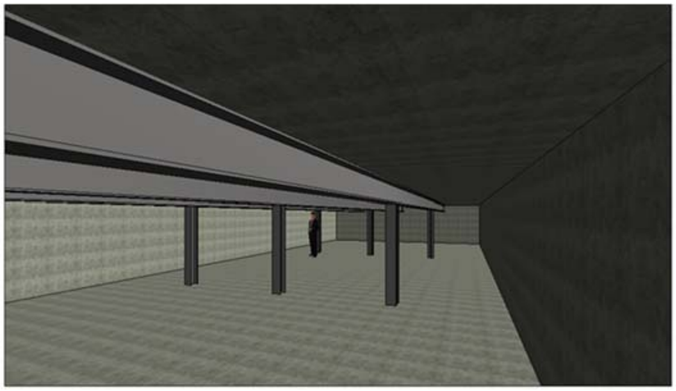

Figure 13: Interior View

Figure 12: East Elevation

4.3.4 Option 3: Composite Steel and Concrete Floor System

This option allows for a smaller steel member because it utilizes the compressive strength of the concrete. This is achieved with the use of steel shear studs welded to the beams before the concrete is placed. Again this option is broken down into a column and no column design. A summary of the full composite member size required can be seen in Table 4. Renderings of this design option can be seen in Figure 15 to Figure 20.

Table 4: Member sizes for option 3

Option 3

With Columns

Member Sizes

Beam

Member	ϕMn (kip-ft)	Studs
W12X19	**291**	**31 - 3/4 inch**

Column

Member	ϕPn
W8X31	**348**

Without Columns

Beam

Member	ϕMn (kip-ft)	Composite
W18X40	**702**	**93 - 3/4 inch**

Table 5: Design Loads for Option 3

With Center Columns

Design Loading

Beam

Axial[k]	Shear[k]	Moment[k-ft]
14	137	283

Column

Axial[k]	Shear[k]	Moment[k-ft]
166	12	54

Without Center Columns

Design Loading

Beam

Axial[k]	Shear[k]	Moment[k-ft]
95	158	687

Option 3 with Columns

Figure 17: North Elevation

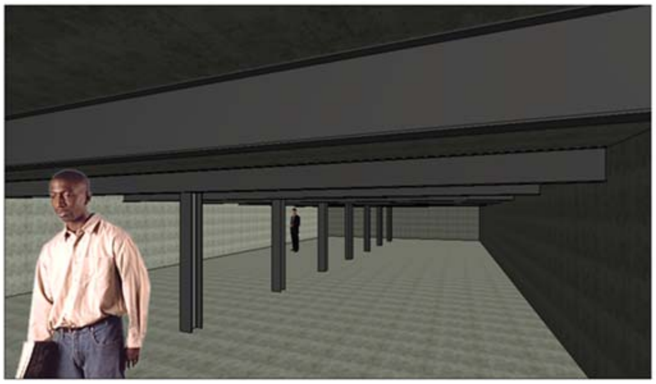

Figure 16: East Elevation

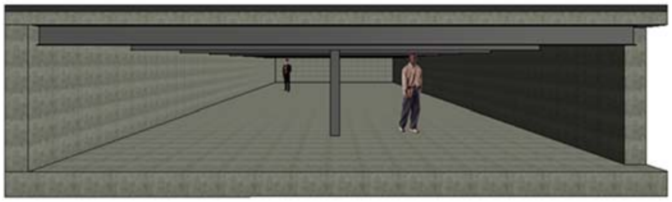

Figure 15: Interior View

Option 3 No Columns

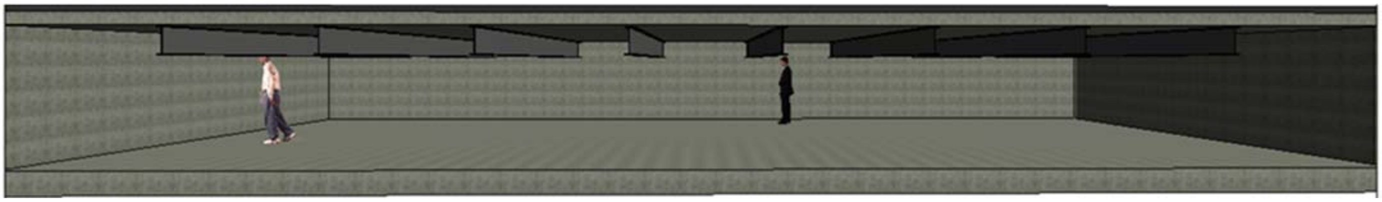

Figure 20: North Elevation

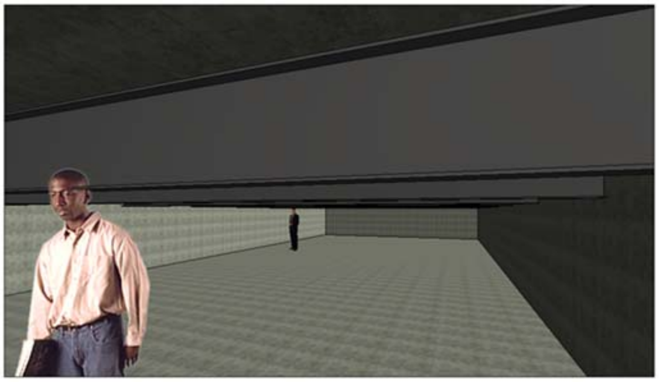

Figure 19: Interior View

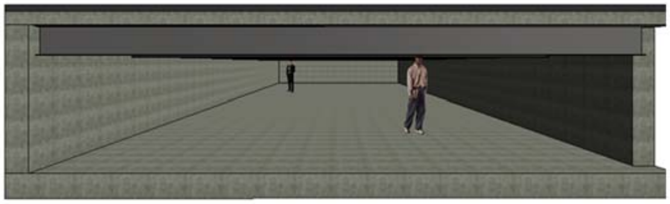

Figure 18: East Elevation

One of the design considerations that was heavily considered was the usability of the space. Part of this was the head room that each design allowed. Table 6 shows a summary of the head room for each option.

Table 6: Head Room for Each Option

Option	Head Room
1 - No Column	4' 7"
1 - With Column	5' 7"
2 - No Column	5' 7"
2 - With Column	6' 2"
3 - No Column	5' 10"
3 - With Column	6' 4"

4.4 Cost Analysis

The following table details the breakdown of the cost analysis for options of improvement for the coal bin, including the waterproofing options and the complete renovation designs.

Cost Analysis

					Costs						
Component	**Task**	**Daily Output**	**Labor-hours**	**Unit**	**Material**	**Labor**	**Equipment**	**Total Per Unit**	**# Of Units**	**Cost**	**Time (days)**
Waterproofing	Cementitious Waterproofing	1000	0.024	S.F.	2	0.78	0.59	3.37	3487.18	$11,752	3.49
Re-paving with epoxy	Pavement Demo, 4-6"	420	0.095	S.Y.		3.7	2.71	$6.41	230.88	$1,480	0.55
	Epoxy Injection repair	60	0.667	L.F.	12.7	23	3.25	$38.95	300	$11,685.00	5.00
	Rigid Concrete Paving, 15"	3000	0.029	S.Y.	53.5	1.13	1.01	$55.64	230.88	$12,846	0.08
									Total	$26,011	5.63
Complete Renovation Option 1 (No Center Columns)	Pavement Demo, 4-6"	420	0.095	S.Y.	0	3.7	2.71	$6.41	230.88	$1,480	0.55
	Structure Demolition(Reinforced Concrete/Columns)	25	2.24	C.Y.	0	88	55.5	144.5	240	$34,680	9.60
	W21x62 Beams	1036	0.077	L.F.	88.5	3.83	1.61	93.94	240	$22,546	0.23
	Steel Construction/Installation			S.F.	0	1.35	0	1.35	2160	$2,916	
	Cost of Crane	1	8	Day	0	390	980	1370	9.60	$13,152	9.60
	Rigid Concrete Paving, 8.5"	4235	0.021	S.Y.	37.985	0.8	0.71	$39.51	230.88	$9,122	0.05
	Cementitious Waterproofing	1000	0.024	S.F.	2	0.78	0.59	3.37	3487.18	$11,752	3.49
									Total	$95,647	23.52
Complete Renovation Option 1 (With Center Columns)	Pavement Demo, 4-6"	420	0.095	S.Y.	0	3.7	2.71	$6.41	230.88	$1,480	0.55
	Structure Demolition(Reinforced Concrete/Columns)	25	2.24	C.Y.	0	88	55.5	144.5	240	$34,680	9.60
	W21x62 Beams	1036	0.077	L.F.	88.5	3.83	1.61	93.94	240	$22,546	0.23
	W8x31 Column	880	0.064	L.F.	23	3.12	1.73	27.85	28	$780	0.03
	Steel Construction/Installation			S.F.	0	1.35	0	1.35	2160	$2,916	
	Cost of Crane	1	8	Day	0	390	980	1370	9.60	$13,152	9.60
	Rigid Concrete Paving, 8.5"	4235	0.021	S.Y.	37.985	0.8	0.71	$39.51	230.88	$9,122	0.05
	Cementitious Waterproofing	1000	0.024	S.F.	2	0.78	0.59	3.37	3487.18	$11,752	3.49
									Total	$96,427	23.55
Complete Renovation Option 2 (No Center Columns)	Pavement Demo, 4-6"	420	0.095	S.Y.	0	3.7	2.71	$6.41	230.88	$1,480	0.55
	Structure Demolition(Reinforced Concrete/Columns)	25	2.24	C.Y.	0	88	55.5	144.5	240	$34,680	9.60
	W21x166 Beam	1000	0.08	L.F.	174	3.96	1.67	179.63	216	$38,800	0.22
	Steel Construction/Installation			S.F.	0	1.35	0	1.35	2160	$2,916	
	Cost of Crane	1	8	Day	0	390	980	1370	9.60	$13,152	9.60
	Rigid Concrete Paving, 8.5"	4235	0.021	S.Y.	37.985	0.8	0.71	$39.51	230.88	$9,122	0.05
	Cementitious Waterproofing	1000	0.024	S.F.	2	0.78	0.59	3.37	3487.18	$11,752	3.49
									Total	$111,902	23.51
Complete Renovation Option 2 (With Center Columns)	Pavement Demo, 4-6"	420	0.095	S.Y.	0	3.7	2.71	$6.41	230.88	$1,480	0.55
	Structure Demolition(Reinforced Concrete/Columns)	25	2.24	C.Y.	0	88	55.5	144.5	240	$34,680	9.60
	W21x166 Beam	1000	0.08	L.F.	174	3.96	1.67	179.63	216	$38,800	0.22
	W14x48 Column	810	0.064	L.F.	31	3.26	1.73	35.99	28	$1,008	0.03
	Steel Construction/Installation			S.F.	0	1.35	0	1.35	2160	$2,916	
	Cost of Crane	1	8	Day	0	390	980	1370	9.60	$13,152	9.60
	Rigid Concrete Paving, 8.5"	4235	0.021	S.Y.	37.985	0.8	0.71	$39.51	230.88	$9,122	0.05
	Cementitious Waterproofing	1000	0.024	S.F.	2	0.78	0.59	3.37	3487.18	$11,752	3.49
									Total	$112,910	23.54
Complete Renovation Option 3 (No Center Columns)	Pavement Demo, 4-6"	420	0.095	S.Y.	0	3.7	2.71	$6.41	230.88	$1,480	0.55
	Structure Demolition(Reinforced Concrete/Columns)	25	2.24	C.Y.	0	88	55.5	144.5	240	$34,680	9.60
	W12x19 Beam	880	0.064	L.F.	23	3.12	1.73	27.85	216	$6,016	0.25
	Steel Construction/Installation			S.F.	0	1.86	0	1.86	2160	$4,018	
	Cost of Crane	1	8	Day	0	390	980	1370	9.60	$13,152	9.60
	Rigid Concrete Paving, 8.5"	4235	0.021	S.Y.	37.985	0.8	0.71	$39.51	230.88	$9,122	0.05
	Cementitious Waterproofing	1000	0.024	S.F.	2	0.78	0.59	3.37	3487.18	$11,752	3.49
									Total	$80,219	23.54
Complete Renovation Option 3 (With Center Columns)	Pavement Demo, 4-6"	420	0.095	S.Y.	0	3.7	2.71	$6.41	230.88	$1,480	0.55
	Structure Demolition(Reinforced Concrete/Columns)	25	2.24	C.Y.	0	88	55.5	144.5	240	$34,680	9.60
	W12x19 Beam	880	0.064	L.F.	23	3.12	1.73	27.85	216	$6,016	0.25
	W8x31 Column	880	0.064	L.F.	23	3.12	1.73	27.85	28	$780	0.03
	Steel Construction/Installation			S.F.	0	1.86	0	1.86	2160	$4,018	
	Cost of Crane	1	8	Day	0	390	980	1370	9.60	$13,152	9.60
	Rigid Concrete Paving, 8.5"	4235	0.021	S.Y.	37.985	0.8	0.71	$39.51	230.88	$9,122	0.05
	Cementitious Waterproofing	1000	0.024	S.F.	2	0.78	0.59	3.37	3487.18	$11,752	3.49
									Total	$80,999	23.57

The table above breaks the cost analysis data into its main components. The final totals of this data show the total time (in days) needed to complete each task as well as the total cost associated with that task. The elements considered in finding the total cost included material, labor, and equipment costs, which when combined with total labor hours per task determined the total cost. The subtotals under each section break the data into the individual total material, labor, and equipment costs, which are utilized in section 4.6 of the report for the axiomatic design analysis.

4.4.1 Waterproofing

The chosen waterproofing option of cementitious sealant spray offered an initial total price of approximately $11,752 and a completion time of less than four days. This time data was calculated by taking the estimated labor hours per square foot of surface, 0.024, multiplied with the total square feet of the interior of the coal bin (3487.18 s.f.). The cost data was calculated by multiplying the total cost per square foot, approximately $3.37, by the total square footage.

4.4.2 Complete Renovation #1

The first complete renovation option, demolishing the current structure and replacing it with a steel beam structure, will incur an approximate cost of $95,647 with no columns and approximately $96,427 with center columns, with an estimated construction time of 24 days for both options (based on *RS Means Construction Cost Data*). The cost data for this project, as can be seen in the table above, included material, labor, and equipment costs for the pavement and existing structure demolition, steel beams, columns, as well as re-paving and waterproofing the new structure. The total time includes the time associated with demolishing the estimated 240 cubic yards of pavement and reinforced concrete above the coal bin, construction of the steel structure including cost of crane, and re-paving.

4.4.3 Complete Renovation #2

The second complete renovation option utilizes a different type of beam in order to offer more head-room in the area. For this option the total cost will be approximately $111,902 without center columns and $112,910 with center columns, taking approximately 24 days from start. This renovation option without center columns incurs the highest price, but also offers the best utilization of space in the area.

4.4.4 Complete Renovation #3

The third renovation option, utilizing two center columns supporting the main beams, has an estimated construction cost of $80,219 without center columns and $80,999 with center columns, with similar construction times of two weeks. .

4.5 Discounted Cash Flow

The following sections are based off of the information gathered in the project cost analysis and offer a discounted cash flow for the expected life of each solution alternative, as well as the necessary investment at the time of installation needed to cover all future costs. The discounted cash flow is based on a thirty-year period. While the estimated life expectancy for similar concrete structures such as parking garages is 20 years, the coal bin renovations will be well maintained with less use, leading to an estimated 30 year life expectancy for the complete renovation options. The discounted cash flow takes into account an assumed discount rate of 3.22%[3] which was derived from US Government resources, based on rolling averages of preceding year's inflation rates as well as predictions for the future. This gives an estimation of the total cost of each improvement option over the next thirty years, or the lifetime cost-value of the project. The necessary investment WPI would need to make at the time of construction to cover initial installation as well as all future costs is also included, based on these inflation rates.

4.5.1 Waterproofing

Discounted Present Value: Waterproofing

	Cash Flow			Future Sum			Time Value		
Year	Out	In	Net	Discount Factor	Discount value	Cumulative Value	Investment	Cash Flow	Value at Year
0	-$11,752	$0	-$11,752	1.000	-$11,752	-$11,752	$24,137	-$11,752	$12,385
5	$0	$0	$0	1.161	$0	-$11,752	$0	$0	$14,358
10	$0	$0	$0	1.348	$0	-$11,752	$0	$0	$16,644
15	-$11,752	$0	-$11,752	1.565	-$18,391	-$30,143	$0	-$11,752	$7,543.43
20	$0	$0	$0	1.817	$0	-$30,143	$0	$0	$8,744.90
25	$0	$0	$0	2.109	$0	-$30,143	$0	$0	$10,138
30	-$11,752	$0	-$11,752	2.449	-$28,781	-$58,924	$0	-$11,752	$0.41

*Based on current annual USD inflation rate of 3.22%

The above data shows the discounted cash flow for the cementitious waterproofing option. Using the example product CEM-KOTE FLEX ST with an estimated installation cost of $11,752 and estimated need for re-application every fifteen years, the total investment needed to

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[3] http://inflationdata.com

cover all costs would be $24,137. If WPI chose not to invest for these future costs now, the total cost of all three applications would equal approximately $58,924 in total.

4.5.2 Epoxy Injection

Discounted Present Value: Epoxy Injection									
	Cash Flow			Future Sum			Time Value		
Year	Out	In	Net	Discount Factor	Discount value	Cumulative Value	Investment	Cash Flow	Value at Year
0	-$26,011	$0	-$26,011	1.000	-$26,011	-$26,011	$40,413	-$26,011	$14,402
5	$0	$0	$0	1.161	$0	-$26,011	$0	$0	$16,696
10	$0	$0	$0	1.348	$0	-$26,011	$0	$0	$19,355
15	$0	$0	$0	1.565	$0	-$26,011	$0	$0	$22,437.85
20	-$26,011	$0	-$26,011	1.817	-$47,259	-$73,270	$0	-$26,011	$0.61
25	$0	$0	$0	2.109	$0	-$73,270	$0	$0	$1
30	$0	$0	$0	2.449	$0	-$73,270	$0	$0	$0.83

A discounted cash flow was also conducted for the option of epoxy injection waterproofing to provide a reference against cementitious waterproofing. This data, as can be seen above, takes into account the initial installation cost of $26,011. The lifespan of this option is estimated at approximately twenty years, and as such another installation is taken into account in the year 20 data. To cover the initial and future costs, WPI would need invest $40,413 at the time of installation. If payments were rather made separately for each installation, it would cost approximately $73,270 based on the given inflation rates.

4.5.3 Complete Renovation #1

Discounted Present Value: Renovation 1 (No Columns)									
Year	Cash Flow			Future Sum			Time Value		
	Out	In	Net	Discount Factor	Discount value	Cumulative Value	Investment	Cash Flow	Value at Year
0	-$95,647	$0	-$95,647	1.000	-$95,647	-$95,647	$113,083	-$95,647	$17,436
5	$0	$0	$0	1.161	$0	-$95,647	$0	$0	$20,213
10	$0	$0	$0	1.348	$0	-$95,647	$0	$0	$23,433
15	-$11,752	$0	-$11,752	1.565	-$18,391	-$114,038	$0	-$11,752	$15,412.72
20	-$9,122	$0	-$9,122	1.817	-$16,574	-$130,612	$0	-$9,122	$8,745.57
25	$0	$0	$0	2.109	$0	-$130,612	$0	$0	$10,139
30	-$11,752	$0	-$11,752	2.449	-$28,781	-$159,393	$0	-$11,752	$1.31

Discounted Present Value: Renovation 1 (With Columns)									
Year	Cash Flow			Future Sum			Time Value		
	Out	In	Net	Discount Factor	Discount value	Cumulative Value	Investment	Cash Flow	Value at Year
0	-$96,427	$0	-$96,427	1.000	-$96,427	-$96,427	$113,863	-$96,427	$17,436
5	$0	$0	$0	1.161	$0	-$96,427	$0	$0	$20,213
10	$0	$0	$0	1.348	$0	-$96,427	$0	$0	$23,433
15	-$11,752	$0	-$11,752	1.565	-$18,391	-$114,818	$0	-$11,752	$15,412.72
20	-$9,122	$0	-$9,122	1.817	-$16,574	-$131,392	$0	-$9,122	$8,745.57
25	$0	$0	$0	2.109	$0	-$131,392	$0	$0	$10,139
30	-$11,752	$0	-$11,752	2.449	-$28,781	-$160,173	$0	-$11,752	$1.31

The data above shows the calculated discounted cash flow for the first option of complete renovation, with and without center columns. The future costs associated with this option, after the initial installation, included re-application of the cementitious waterproofing at year fifteen, re-paving the above area at year twenty, and another application of waterproofing at year thirty. In order to cover these costs as well as the cost of initial installation, an investment of $113,083 would need to be made if no center columns are included, and $113,863 if the center column design is chosen. If WPI chose to pay each maintenance payment separately at the time they occur, it would incur a total estimated cost of $159,393 and $160,173 respectively.

4.5.4 Complete Renovation #2

Discounted Present Value: Renovation 2 (No Columns)									
	Cash Flow			Future Sum			Time Value		
Year	Out	In	Net	Discount Factor	Discount value	Cumulative Value	Investment	Cash Flow	Value at Year
0	-$111,902	$0	-$111,902	1.000	-$111,902	-$111,902	$129,338	-$111,902	$17,436
5	$0	$0	$0	1.161	$0	-$111,902	$0	$0	$20,213
10	$0	$0	$0	1.348	$0	-$111,902	$0	$0	$23,433
15	-$11,752	$0	-$11,752	1.565	-$18,391	-$130,293	$0	-$11,752	$15,412.72
20	-$9,122	$0	-$9,122	1.817	-$16,574	-$146,867	$0	-$9,122	$8,745.57
25	$0	$0	$0	2.109	$0	-$146,867	$0	$0	$10,139
30	-$11,752	$0	-$11,752	2.449	-$28,781	-$175,648	$0	-$11,752	$1.31

Discounted Present Value: Renovation 2 (With Columns									
Year	Cash Flow			Future Sum			Time Value		
	Out	In	Net	Discount Factor	Discount value	Cumulative Value	Investment	Cash Flow	Value at Year
0	-$112,910	$0	-$112,910	1.000	-$112,910	-$112,910	$130,346	-$112,910	$17,436
5	$0	$0	$0	1.161	$0	-$112,910	$0	$0	$20,213
10	$0	$0	$0	1.348	$0	-$112,910	$0	$0	$23,433
15	-$11,752	$0	-$11,752	1.565	-$18,391	-$131,301	$0	-$11,752	$15,412.72
20	-$9,122	$0	-$9,122	1.817	-$16,574	-$147,875	$0	-$9,122	$8,745.57
25	$0	$0	$0	2.109	$0	-$147,875	$0	$0	$10,139
30	-$11,752	$0	-$11,752	2.449	-$28,781	-$176,656	$0	-$11,752	$1.31

The data above gives a discounted cash flow analysis for the second option of improvement (smaller beam size), which offers the most head-room and utilization of spaces. After the initial installation cost of $111,902 without center columns and $112,910 with center columns, this option would incur maintenance costs of re-paving and waterproofing re-application similar to the first option. The total investment that would need to be made at the time of construction is $129,388 and $130,346 respectively in order to cover all costs. If payments for maintenance were made separately, the estimated lifetime cost would be approximately $175,648 and $176,656.

4.5.5 Complete Renovation #3

Discounted Present Value: Renovation 3 (No Columns)									
	Cash Flow			Future Sum			Time Value		
Year	Out	In	Net	Discount Factor	Discount value	Cumulative Value	Investment	Cash Flow	Value at Year
0	-$80,219	$0	-$80,219	1.000	-$80,219	-$80,219	$97,655	-$80,219	$17,436
5	$0	$0	$0	1.161	$0	-$80,219	$0	$0	$20,213
10	$0	$0	$0	1.348	$0	-$80,219	$0	$0	$23,433
15	-$11,752	$0	-$11,752	1.565	-$18,391	-$98,610	$0	-$11,752	$15,412.72
20	-$9,122	$0	-$9,122	1.817	-$16,574	-$115,184	$0	-$9,122	$8,745.57
25	$0	$0	$0	2.109	$0	-$115,184	$0	$0	$10,139
30	-$11,752	$0	-$11,752	2.449	-$28,781	-$143,965	$0	-$11,752	$1.31

Discounted Present Value: Renovation 3 (With Columns)									
	Cash Flow			Future Sum			Time Value		
Year	Out	In	Net	Discount Factor	Discount value	Cumulative Value	Investment	Cash Flow	Value at Year
0	-$80,999	$0	-$80,999	1.000	-$80,999	-$80,999	$98,435	-$80,999	$17,436
5	$0	$0	$0	1.161	$0	-$80,999	$0	$0	$20,213
10	$0	$0	$0	1.348	$0	-$80,999	$0	$0	$23,433
15	-$11,752	$0	-$11,752	1.565	-$18,391	-$99,390	$0	-$11,752	$15,412.72
20	-$9,122	$0	-$9,122	1.817	-$16,574	-$115,964	$0	-$9,122	$8,745.57
25	$0	$0	$0	2.109	$0	-$115,964	$0	$0	$10,139
30	-$11,752	$0	-$11,752	2.449	-$28,781	-$144,745	$0	-$11,752	$1.31

This data shows the discounted cash flow for the third option of complete renovation, including the beam construction supported by the two columns, as well as all demolition and re-paving of the slab overhead. After the initial installation cost of $80,999 with center columns and $80,219 without center columns, the renovation would incur similar re-paving and re-waterproofing costs as options 1 and 2. The total investment needed at the time of construction would need to be $98,435 and $97,655 respectively in order to cover these costs. If payments for maintenance were made separately, the total estimated cost would be $144,745 and $143,965.

4.6 Axiomatic Analysis

The axiomatic design analysis of this project considers the functional requirements of the project and the design parameters that would satisfy those requirements to meet the customer needs, and determined whether or not these factors satisfy the independence and information axioms.

4.6.1 Hierarchal Breakdown

The overarching functional requirement was that of providing a design that meets the needs of the WPI Department of Facilities in the most feasible and efficient way possible. This was then broken down into three main components: providing adequate room for work and storage, providing a weather-sealed environment, and providing structural integrity. Design parameters were then determined to meet those requirements. The hierarchal breakdown of the parameters and requirements, as well as further subsections, can be seen in below.

Customer Needs:

- Structure must be:
  - Able to be used for storage and work
  - Sealed from outside environmental factors (waterproof)
  - Adequately load-bearing
  - Constructable
  - Sustainable
  - Cost efficient

Functional Requirements:

- FR0: Analyze designs meeting WPI's needs
  - FR1: Provide room for work/storage
    - FR1.1: Maximize headroom
    - FR1.2: Minimize intrusive structures
  - FR2: Provide weather sealed environment
  - FR3: Provide structural integrity
    - FR3.1: Adequate load bearing
    - FR3.2: Long-term durability
  - FR4: Ease of constructability

Design Parameters:

- DP0: Complete renovation design
  - DP1: Architectural design
    - DP1.1: Beam design arrangement
    - DP1.2: Column design arrangement
  - DP2: Weather proofing
  - DP3: Structural Design
    - DP3.1: Beam type
    - DP3.2: Slab type
  - DP4: Ease of Constructability

		Design Parameters																							
		Option 1								Option 2								Option 3							
		DP1: Architectural Design	DP1.1: Beam Design 1	DP1.2: Column Design 1	DP2: Weather proofing Design 1	DP3: Structural Design	DP3.1: Beam Design 1	DP3.2: Slab Design 1	DP4: Low cost of constructability	DP1: Architectural Design	DP1.1: Beam Design 2	DP1.2: Column Design 2	DP2: Weather proofing Design 2	DP3: Structural Design	DP3.1: Beam Design 2	DP3.2: Slab Design 2	DP4: Low cost of constructability	DP1: Architectural Design	DP1.1: Beam Design 3	DP1.2: Column Design 3	DP2: Weather proofing Design 3	DP3: Structural Design	DP3.1: Beam Design 3	DP3.2: Slab Design 3	DP4: Low cost of constructability
Functional Requirements	FR1: Provide room for work/storage	X								X								X							
	FR1.1: Maximize headroom	X	X							X	X							X	X						
	FR1.2: Minimize intrusive structures	X	X	X						X	X	X						X	X	X					
	FR2: Provide weather sealed environment				X								X								X				
	FR3: Provide structural integrity	X	X	X		X				X	X	X		X				X	X	X		X			
	FR3.1: Adequate load capacity	X	X	X		X	X			X	X	X		X	X			X	X	X		X	X		
	FR3.2: Long-term durability	X	X	X		X	X	X		X	X	X		X	X	X		X	X	X		X	X	X	
	FR4: Ease of constructability	X	X	X		X	X	X	X	X	X	X		X	X	X	X	X	X	X		X	X	X	X

4.6.2 Axiomatic Matrix

The three proposed options for complete renovation were considered against this analysis. The major design components that affected the outcome of the analysis are the type of beam/columns used (affecting structural integrity) and the design layout of the beams and columns (affecting space usage). The matrix above shows the breakdown of how each of the three design options satisfies the functional requirements and customer needs.

The data provided in the matrix shows that each option for improvement satisfies the independence axiom to the best of its ability. In terms of the information axiom, the "best solution" is dependent on WPI's specific needs at the time of construction. All three options satisfy the needs for a weatherproof, structurally sound structure, and all three have similar expected lifespans. The factors that should then be considered by the department of facilities are the cost of the project related to the usage of the space, which are directly correlated. Option 2 has the best space utilization but highest cost, followed by Option 1 with second best space utilization and second highest cost, and finally Option 3 with the worst space utilization (lower ceilings and intrusive columns) but the lowest cost.

5.0 Recommendations

This section discusses the recommendations for the renovation of the coal bin structure based on the research compiled in the report. It is important to note that this information is proposed as a solution that depends on the particular conditions and needs with which WPI and the Department of Facilities view the project, with the intention of offering differing solutions to match potentially differing needs. For consideration, all options for complete renovation solution alternatives offer an environmentally sealed structure with adequate load bearing capacity.

5.1 Waterproofing

Out of the three alternatives for waterproofing solutions, the Drylok product came with the least cost at $1,175; however, there was one main problem with using it. The Drylok product is not designed to cover the whole interior and therefore will not be viable for sealing the entire coal bin interior and preventing future cracks. Because of this it is not recommended in use as a weatherproofing option.

The second option, epoxy injection, includes the total cost of the demolition of the pavement, the epoxy injection, and re-paving the area with rigid concrete paving and is estimated to cost approximately $26,000. This option is comparably very expensive and also brings with it the same problem as the Drylok product: it does not prevent or cover future cracks. Because of this it is not recommended for use in the coal bin interior

Cementitious waterproofing as described in the *RSMeans Construction Cost Data* manual was found to be the best option for waterproofing the interior coal bin. Although it is considered a temporary fix, CEM-KOTE FLEX ST, the recommended product, has a lifespan of 15 years. The installation time, less than four days, is also relatively short since it is applied by spraying onto the walls and ceiling. This product can also be added after a full renovation to ensure water leakage will not reoccur, and will seal the entire area to prevent future cracks.

5.2 Complete Renovation Solution Alternatives

Each of the three complete renovation solution alternatives that were designed for the coal bin structures have their own pros and cons. As detailed earlier in the report, Option 1 offers the most cost effective solution. The beam design includes the least materials cost while still offering adequate storage area, although not as much overhead room as Option 2. This is the mid-ground option between cost effectiveness and space utilization. Option 2 is the most expensive solution by a significant amount; however it offers the best utilization of the interior space due to architecture of the beam design. The W21x166 beams spanning down the length of the interior offer the most overhead room due to their size and shape, and the design does not include any intrusive columns that would interfere with the space. The third option is the most cost effective of the three, but includes the least headroom and includes intrusive columns.

Choosing a single best solution alternative is not possible for this report because that choice is based off the individual needs determined by WPI and the Department of Facilities. The choice of design will be based off WPI’s needs being more focused on either space utilization or construction cost, but no matter what design is chosen the fundamental requirements of the structure will be met.

6.0 Conclusion

The work conducted in this project allowed for the completion of the planned scope of work related to the WPI Powerplant coal bin. This included the designing of multiple renovation solutions for the coal bin structure for presentation to the WPI Department of Facilities. The initial field data, calculations, and research provided a base for designing the solutions. Based on the designs, a cost analysis, discounted cash flow, and axiomatic design matrix were created. This compilation of work provided a base for the recommendations, which breaks down the possible solutions based on alternative customer needs.

There were several limiting factors that affected this project. The inability to take core samples of the structure, including the pavement and concrete above, and the brick and mortar interior, made it impossible to exactly calculate the current structural conditions. The designs created through this project were also unable to be physically built by the project team, meaning that all calculations are theoretical, and actual testing could not be conducted. This limited the ability to foresee possible conflicts with the actual construction of this project. Given the constraints, all anticipated error was noted to the best of our abilities.

This project offers several opportunities for future project work and study. Future MQP topics include issues of fire safety in the coal bin area for both the current structure and the possible renovation alternatives. There is also the issue of re-mapping the utility lines that run through the coal bins, which pose a major constraint that must be addressed if renovations are to occur. Also, the coal bin renovations could potentially connect to the project WPI is looking to implement in the IGSD, creating an elevator between Stratton and the Project Center. There is potential for this project and the coal bin renovations to be combined. Other work and research potential can stem from these topics.

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Appendix A – Project Proposal

Improvements to the WPI Power Plant Coal bin

Project Proposal

October 17, 2013

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Abstract

The purpose of this Major Qualifying Project is to assess the current structural conditions of the coal bin underneath WPI’s Power Plant and to define repair and restoration work to remove structural deficiencies. The process will include analysis and design of the current structure followed by a determination of the best possible strategies to improve the area. Included in our final report will be a summary of these options as well as an analysis and breakdown of their associated costs. Our goal is to present this report to the WPI Facilities Department to aid them in their decisions concerning future use of the structure.

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1.0 Introduction and Project Statement

The coal bins underneath the WPI Power Plant facility are in serious disrepair and in need of renovations. This Major Qualifying Project will investigate the cause of the problems associated with the area, such as water leakage, and identify possible solutions to these problems. The group will use the project to demonstrate fundamental knowledge of civil engineering attained from their undergraduate courses at WPI. We will also include a cost analysis and breakdown for the proposed solutions.

The goal is to develop an in-depth plan of action for repair and restoration of the coal bin that. The project team will establish an initial layout design and assessment of current structural conditions based on visual inspections, review of building plans obtained from the Facilities Department, and library research. We will use this assessment data to develop three solutions, detailing the steps to complete each as well as an associated cost analysis and breakdown. The final deliverable will include a written report encompassing the assessment data and proposed solution strategies, as well as digital renditions of the structure and possible renovations.

2.0 Background

This background section discusses the research needed to develop a proposal for this project. Below are sections that will provide information on the original design of the coal bin, its purpose, and the materials used to construct it.

2.1 Building and Location

The original purpose of this structure and where it is located is described below and provides a good understanding of where the problem is found today.

2.1.1 Purpose

In the late 1800's Worcester Polytechnic Institute (WPI) was growing technologically as well as in size. With the newly built Salisbury Laboratories not providing ample facilities for teachers and students only four years after its opening, the Mechanical Engineering department started requesting more lab space. In 1893 a detailed plan was submitted to the Trustees in order to expand the current facilities. One of the expansion opportunities that was accepted was the construction of a powerhouse. After WPI's own professors made initial plans, Earle & Fisher, WPI's official architects, put them into final form. The powerhouse was built to house two 100 HP engines and vertical boilers that would allow for student experimentation and power generation. A space was excavated between the powerhouse and the laboratories in order to hold the coal, ash, storage vaults and a tunnel to Washburn Shops. This construction was completed in the summer of 1895, and the powerhouse was officially put into use. The powerhouse was eventually converted to run on gas so the coal is no longer necessary. The coal bin are currently used for storage; electrical conduit as well as, gas and steam piping run through them. The coal chutes have been shut and covered by concrete and asphalt with limited road access above the underground structure.

2.1.2 Location

The powerhouse is located between Washburn Shops and Straton Hall. The coal bin are located beneath the ground between the powerhouse and Straton Hall with asphalt and concrete overhead.

2.2 Structural Design

The roof structure of the underground coal bin is comprised of several brick and steel arches which are commonly known as a barrel vault system. A diagram of the cross section of the room structure can be seen below. The arches are approximately 8 feet wide and run the length of the room. They have a depth of approximately 8 inches and are supported by 15-inch steel I-beams. The I-beams rest on brick columns, which are approximately 20” on each side. The bottom flanges of the beams are level with the bottom of the arch so that the bricks are seated on the top of the bottom flange. Between the I-beams, 3/4” steel bars add additional support and prevent the arches from kicking out at the bottom. Above the arches there is 9” to 15” of concrete and about 4” of pavement on top of that. A diagram of the cross section of the room structure can be seen below. From past engineering reports the approximate load bearing capacity on the pavement above is 40 lbs. /ft^2.

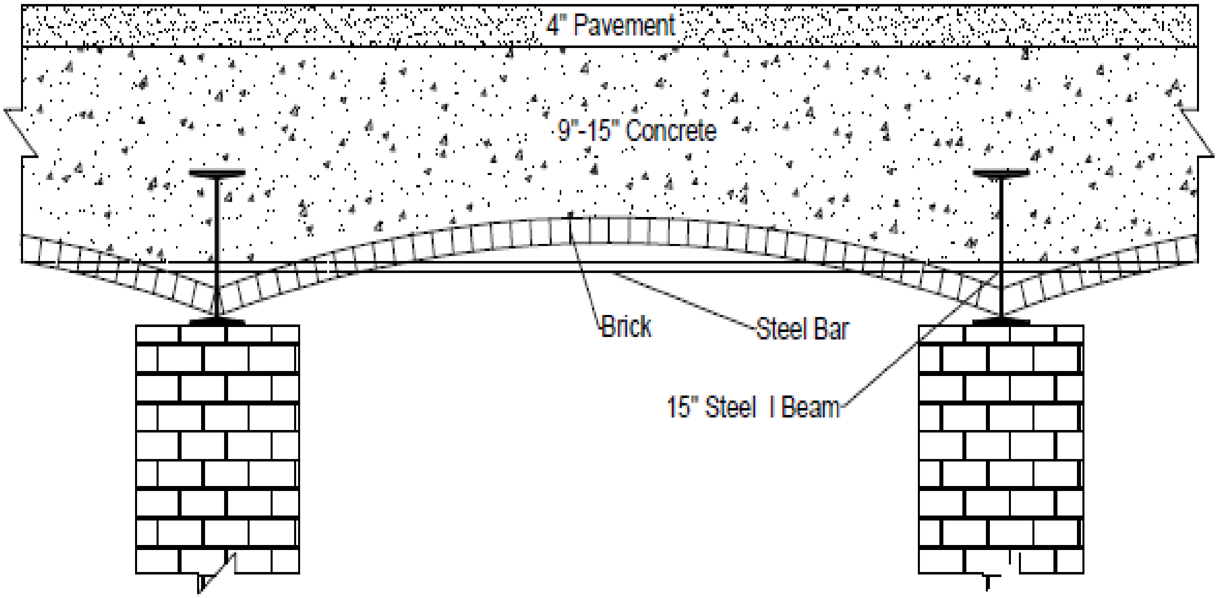

Figure 21: Structural Cross-section

2.3 Foundation Design

The foundation of the powerhouse built from large rough-cut stones which are held together with mortar. This foundation design was common for the time the building was constructed. The stones provide ample structural support for the building above; however, their ability to keep water out is quite poor. The foundation wall is one of many sources of water entering the coal bin.

2.4 Arches

The ceiling structure of the coal bin consists of brick barrel vaults that are supported by steel I-beams. This system was a common construction technique during the time the coal bin were constructed. One of the first steps for the team will be to analysis the load capacity of the current construction. To do this we will first calculate the capacity based on our interpolation of the as-built condition; however, this calculation will not reflect the current load bearing capacity of the structure. There are other factors that we must then consider such as the age of the bricks and the mortar as well as the rust and pitting of the steel sections. Once we determine the current capacity we can then assess whether or not the strength of the structure needs to be increased to handle the loads applied to it. In the past this area has been uses as an access road to a loading dock on the side of Washburn shops. We will consider this type of loading scenario when designing support structures.

2.5 Building Materials

The building materials used for the WPI Power Plant coal bin were for the most part common for the time period; however, the steel beams used for support were a fairly new technology at the time. The I-beams supporting the roof arches was originally thought to be made from wrought or cast iron, but our research shows that they are indeed steel. At the time of construction (1895) steel was just beginning to gain popularity as a structural building material due to a newly developed method of production known as the Bessemer process. This process, named after its inventor Henry Bessemer (1813-1898), significantly reduced the cost of manufacturing steel and allowed it to be mass produced. The general standard for I-beams of that time period was a tensile strength of 60-70ksi (Bates, W.). We believe that this steel construction is one of the reasons the structure has lasted so well over time.

Our research has also shown that the brick material used in the arches is most likely the standard brick of the time. From the mid 1800’s to early 1900’s bricks were made from a combination of clay, sand, and shale; the majority of which coming from the Hudson River area of New York. These molded bricks had an approximate compressive strength of 5,293±1,822psi, compared to the strength of 11,305±4,464 of a modern extruded brick (Brickmaking in the USA).

The mortar used in the coal bin construction is thought to be a lime mortar combined with Portland Cement which was the most commonly used in the late 1800’s. The benefits of this lime mortar were high workability and a self-waterproofing capability that occurred from water reacting with the lime in potential cracks and forming calcium crystals therein, temporarily sealing the crack (History of Lime in Mortar). Our thoughts on this matter is that the calcium buildup on the inside of the coal bin is a result of this effect taking place over the 118 years the bins have been underground, and that the severe water leakage is a byproduct of these mortar cracks. Through research in the WPI archives we hope to discover the exact composition of the mortar for use in replication and testing.

Another note on lime mortar is its lower strength than modern mortar compositions, meaning that it is only recommended to be used in walls of relatively low load bearing weight; not necessarily a load bearing structure such as the arches. Modern mortar property specifications run through four ranges, the strongest of which, “M” rated mortar, has a compressive strength of 2,500 psi, whereas the weakest, “O” rated, has a compressive strength of only 350 psi (Mortar Mix Designs). Although we do not yet know the exact compressive strength of the mortar used in the coal bin we assume based on historical data that its strength is significantly less than this, making it a weak point in the bin construction.

3.0 Scope of Work

In order to better structure our project our team has detailed the scope of our work below. This information is broken into the key major areas of study we will cover, and further separated into subsections for each major area. These subsections detail the individual tasks and areas of study needed to complete the project objective: compiling a final deliverable report to present to the WPI Department of Facilities detailing plans for future improvement. Finally, we have listed the references we will utilize in order to complete these tasks.

Major Areas of Study	**Subsections**	**References**
Current Status	• **Room Dimensions**	• **Team's Measurements** • **Archive Plans of the Structure**
	• **Exterior Roof/Road Materials**	• **Archive Research and Plans of Structure** • **Facilities Staff**
	• **Arch Design & Load Capacity**	• **Arch Construction Reference**

		· **Archive Plans of the Structure**
Options for Improvement	· **Complete Renovation**	· ***Massachusetts State Building Code*** · ***ASCE-7 Reference*** · ***ACI Standards Reference***
	· **Waterproofing**	· ***Massachusetts State Building Code*** · ***ASCE-7 Reference*** · ***ACI Standards Reference***
	· **Re-paving**	· ***Massachusetts State Building Code*** · ***ASCE-7 Reference*** · ***ACI Standards Reference***
	· **Structural Support**	· ***Massachusetts State Building Code*** · ***ASCE-7 Reference*** · ***ACI Standards Reference***
Cost Analysis and Evaluation	· **Complete Renovation**	· **Excavation Cost References** · **New Structure Material Cost Analysis (Concrete, Steel, Pavement, etc.)**

		- **Labor Cost Assessment**
	- **Waterproofing**	- **Waterproofing Options Cost References** - **Labor Cost Assessment**
	- **Re-Paving**	- **Concrete Cost References** - **Pavement Cost References** - **Labor Cost Assessment**
	- **Structural Support**	- **Steel Beam or Column Analysis** - **Steel Cost References** - **Labor Cost References**

4.0 Methodology

This methodology section will provide a breakdown of the steps we will take to propose the best solution to the problem. We will begin by assessing the current structural conditions of the coal bin. Based on this analysis we will determine possible solutions and perform a cost analysis. Any designs our team develops will take into account all health and safety concerns, including the compliance of building safety codes, fire safety codes, and fire protection methods.

4.1 Analyze Current Structural Conditions

As a group, we will assess the current structural conditions of the coal bin. We will first review the available drawings and observations made from the field and compare with as-built configurations. We will then calculate its loading capacity by determining dead loads, beam integrity, and major areas of water leakage. This data will be vital in order to come to the best design possible.

4.1.1 Beam, Columns and Tie Rod Integrity

With the amount of leakage coming through the ceiling and floors, it will be necessary to calculate the effects the rust, if any, on the integrity of beams. Rust is also very prevalent on the tie rods that are used to support the arches. Studies have found that uniform corrosion due to rust does not have a significant effect on the strength and ductility of a steel member[4]. However it can contribute to loss of effective cross-section and load capacity overall. The problem with severe rust is with the decrease in bond strength between the steel and concrete.[5] The expansion rust causes can result in cracking and separation from the steel, which increases leakage creating a cyclical cycle. Over time the increased expansion can cause cracking into the concrete sections. An assessment on the damage the rust has caused on the concrete and masonry structures will be made by the group. If damage is not severe, a solution will be created in order to strip away the rust from the steel and methods for rust prevention will be evaluated and used. If the internal concrete, masonry arches and brick piers have been severely damaged, resulting in significant losses in effective cross sections, then a complete restructure of the roof may be necessary.

It is also observed in areas that the tie rods have been cut to make room for a coal chute, rendering them useless. The group will assess the effect the cut tie rods have on the arches carrying capacity. If the load capacity of the arches is severely decreased then restructure of the roof will be necessary.

4.1.2 Masonry

The masonry in the coal bin is still all original architecture including the mortar used to keep the bricks in place. Parts of the mortar holding the bricks together are eroding due to water damage and rust from the steel beams and support rods. Taking into account the water damage, mortar integrity, and rust expansion on steel members our group will do an assessment of the current strength of the masonry arches and brick piers. This will include observations made in

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[4] Zahrai, S.,147

[5] Fu, X., Chung, D.

the field. If the masonry arches have been severely damaged, resulting in a significant loss of compression strength, a restructure of the arches and brick columns will be necessary.

4.1.3 Load Capacity

By analyzing the weight of the brick masonry, beams, rods, earth, concrete and asphalt per square foot we will be able to determine the dead load that is being put on the arches and columns of the coal bin. With input from the above analyses our group will calculate the current load carrying capacity of the coal bin. The calculated loading capacity will be compared to Massachusetts State loading criteria. The governing load criteria will be found using superimposed loading and the self-weight of the coal bin structure plus additional design load requirements, such as live loads, snow loads, seismic loads and soil pressure. Load combinations from *ASCE 7* will be used to determine the greatest loading combination. The calculated capacity should be compared to governing load criteria. These findings will allow us to make conclusions on the current structural condition of the coal bin and design solutions for repair and restoration.

4.1.4 Water Leakage

A major concern in the coal bin is water leaking in when it is raining and especially from melting snow. The water is causing structural and property damage making the rooms unusable. Much of the exposed piping and beams have severe rust damage because of this. The group will locate major areas of concerns where leaks occur. An assessment will be determined on whether waterproofing using a Drylok or Xypex waterproofing product will be sufficient as a long-term solution. If it is determined that the application of a waterproofing compound to the ceiling and foundation will not be adequate, then alternate solutions including repaving or complete roof removal will be assessed.

4.2 Determine Options for Improvement

We will investigate three options for improving the current structure. The main concerns are water leaking into the area as well as the structural integrity of the supported roof area above. In order to achieve the best long term solution both a waterproofing solution and a structural solution will need to be selected by the Facilities Department. There are several options for both problems with varying levels of expense, longevity, and cost.

4.2.1 Waterproofing Solutions

There are three options for waterproofing the structure. The first two- Drylok and Xypex- are popular products used for preventing water damage caused by cracks and work completely with the existing system. The third is requires removal and replacement of the pavement layer.

Drylok is used primarily as a water proofer not a sealer, and works by expanding when it dries and becoming part of the wall. Xypex is a much stronger brand that applies to walls like a waterproof concrete that will bond with the moisture to create its waterproof crystalline structure and become part of the wall. Because of this curing process small areas of water leakage will seal themselves. The down side to using this product is that it is 2 to 4 times as expensive as Drylok. For large cracks, since these products are not suitable, a product such as Drylok Fast Plug can be used to seal cracks that go far into or all the way through the outside wall. Drylok Fast Plug is very good for sealing cracks in masonry but is most effective with cracks that will not experience thermal or structural movement. Another alternative to Fast Plug is using a construction grade epoxy that penetrates the crack fully by injection.

The third option will be a little more costly but will offer a more long-term solution. Instead of waterproofing the as is, we will recommend stripping off the current layer of pavement. This will allow access to the concrete below and allow for the insertion of additional mortar or injection of epoxy. After this process has been finished a thin layer of waterproofing concrete will be applied as well as fresh pavement. This option would also require additional supports on the underside to accommodate the added weight of paving equipment.

4.2.2 Reinforcement of Existing Structural Supports

The second of the major problems is the support structure. Expected repairs would be in the form of steel reinforcements on the inside of the structure. Once we analyze the loading requirements for the ground above the structure we will design the interior steel support.

We will use the loading considerations provided by the WPI Facilities Department as well as local and state building codes to determine the required loading capacity.

4.2.3 Replacement of Roof Structure

This option is the most complete and best long-term solution; however it is also the most costly and will require the most time for WPI to implement. We will begin by analyzing the cost and time for removing the entire existing roof structure. We can then design a new roof system to accommodate the required loading. A new system of steel columns and girders would then be designed to replace the current system of barrel vaults. Reinforced or pre-stressed concrete slabs would be placed on top of the new framework and then covered with pavement. In this option the existing foundation would still need to be waterproofed but this is only as small portion of the water entering the facility, with the majority entering through the roof. We will also analyze the existing foundation structure to determine if it is capable of supporting the new framework.

4.3 Cost and Value Analysis

Our team will do a cost analysis of each of our proposed options for improvement. We will consider the cost breakdowns associated with each option and compile overall estimates for labor and materials. We will also include value propositions for estimating the potential value of each option to the Facilities Department based on an axiomatic analysis, comparing potential costs associated with construction to potential value to the customer.

4.3.1 Waterproofing

For a recommendation of waterproofing of the area we will need to determine the cost of multiple options to do so. We have identified Drylok and Xypex as two popular and potentially viable options and will use their price references to determine an accurate recommendation of costs. This recommendation will include the cost of the materials themselves as well as cost of installation, along with the potential value based on sustainability of the options.

4.3.2 Re-Paving

Included in our recommendation for re-paving and waterproofing the area we will include a cost breakdown of removing the pavement, sealing the area, and re-paving based on references from past projects and potential quotes from contractors. We will include an estimate for the materials and labor costs associated herein as well as a similar value proposition.

4.3.3 Structural Support

For a recommendation of the additional structural supports needed to increase the load capacity of the structure to a desired level we will analyze the cost of materials and labor associated with the project. This will include any material costs, such as steel beams or reinforcing plates, as well as labor cost for installation. Once these have been determined we will create a value proposition based on overall cost of construction compared to sustainability and overall value.

4.3.4 Complete Renovation

For a recommendation of complete excavation and renovation of the area we will first consider the cost of excavating and removing the existing pavement, cement, and brick above the coal bin based on cost references associated with similar excavation projects. We will then analyze the cost of materials needed for a new structure based on our designs thereof, and determine an estimate of total material cost for the project. Finally we will determine the estimated labor cost associated with the project.

5.0 Capstone Design

This Major Qualifying Project will analyze the WPI Power Plant coal bin and assess their current status, as well as possible solutions for improvements. Upon completing the project the group will have satisfied the requirements necessary for WPI's Civil Engineering Capstone Design. The project team will analyze the structural design of the facility and will investigate the design and construction techniques used in its construction. We will then determine possible solutions for improvements in accordance with the *Massachusetts State Building Codes 7th Edition* which we will submit to the WPI Department of Facilities. The challenges the group will face during this project include economic, political, social, sustainability, constructability, ethical, and health and safety factors. The following sections discuss these challenges.

5.1 Economics

Our team will provide a cost estimate for each element of proposed options for improvement and design. This will include overall material costs associated with each option as well as the labor costs that they necessitate. This material will then be submitted to the WPI Facilities Department for use in deciding plans for the future related to budgeting for the project and possible funding options.

5.2 Social

Our team will determine the social factors related to each possible solution for renovation of the coal bin. This will most likely be based on the affect the construction would have on the campus and all those involved. We will submit this data to the Department of Facilities for consideration in their decision.

5.3 Sustainability

Our team will analyze the sustainability and life span of each proposed option. We will take into account historical life spans of similar projects and will research ways to improve on these. We will then include this data in our recommendation to Facilities for use in comparison to the respective cost estimates of each option.

5.4 Constructability

After analysis of current status of the coal bin, the group will come up with multiple designs in order come to a solution to the problem at hand. These different scenarios will include various beam configuration, beam and girder sizes, column size and placement, possible excavation of asphalt and soil above the bins. The coal bin may be filled if deemed necessary which would require re-routing of steam piping, and gas lines. All designs will be done in accordance with national and local building codes, *ASCE-7*, and ACI standards.

5.5 Ethics

In compliance with WPI confidentiality, the group has signed the WPI Student/Facilities Department Non-Disclosure Agreement. The compliance agreement is presented below.

To ensure integrity, protection, and security of WPI Facilities-related material, data and information, any floor plans, drawings, square footage, utilities, financial, or other information that the WPI Facilities Office provides must be considered confidential and maintained as proprietary information and the sole property of WPI. It cannot be shared with others inside or outside of the WPI community, nor distributed or displayed as part of any collective work. The material, data, and information provided are intended to support a student's research, data collection and/or analysis for academic project work. This confidential and proprietary material, data, and information cannot be directly included, attached or displayed electronically, on-line or hardcopy as a portion of the finished document, appendix, or presentation without prior written consent. Any material, data and information provided is expected to be returned, deleted or destroyed at the completion of the research presentation, unless specifically excused by the Facilities Department.

After signing this agreement the group is very limited to the information that we can provide as evidence to our findings without written consent from the facilities department. We will maintain a workbook containing this evidence for use under the permission of the University.

During this project the group will also refer to the Engineering Code of Ethics in order to make sure our project is applying acceptable practices.

5.6 Health and Safety

Since the structural integrity of the coal bin are currently in question, the group will make sure that all designs will not result in collapse of the structure due to loading above. The designs will also be under the compliance of building safety codes, fire safety codes, and fire protection methods.

6.0 Conclusion

In conclusion, our team will follow the methodology found earlier in this proposal to create a final written report deliverable. This report will compile our data for the Coal Bin structure and will detail the current status of the structure followed by a breakdown of the process for each method of improvement. This will also include a cost and value estimate for each method to assist the Facilities Department in their decisions.

Finally, we will include in the final deliverable a visual representation of our recommendations for improvement. These representations will provide a detailed picture of every aspect of the recommendation. Our team will create multiple cross section designs of the structure using AutoCAD to include in the final report. These designs will be used throughout the project as a basis for our calculations. We will also include in the final deliverable 3D computer models for use in the design process. This visual aid will assist us in our research and design as well as provide the Facilities Department with a visual representation of the current status.

To complete this project we will utilize the knowledge and real-world problem solving skills gained through the undergraduate program at WPI. The project will fulfill the requirements of a capstone design and provide valuable experience for our team to reference in the future.

7.0 Schedule of Objectives

		B-Term						
Objective	**Area**	**Week 1**	**Week 2**	**Week 3**	**Week 4**	**Week 5**	**Week 6**	**Week 7**
1. Analyze Current Structural Conditions	Beam, Column, and Tie Rod Integrity	🟩	🟩					
	Masonry	🟩	🟩					
	Water Leakage		🟩	🟩				
	Load Capacity		🟩	🟩	🟩			
2. Determine Options for Improvement	Waterproofing Solutions			🟨	🟨			
	Reinforcement of Existing Structural Supports				🟨	🟨	🟨	
	Replacement of Roof Structure						🟨	🟨
3. Cost and Value Analysis	Waterproofing Solutions						🟦	🟦
	Re-paving							🟦
	Structural Support							
	Complete Renovation							
4. Final Report Writing	Report Compilation							

		C-Term						
Objective	**Area**	**Week 1**	**Week 2**	**Week 3**	**Week 4**	**Week 5**	**Week 6**	**Week 7**
1. Analyze Current Structural Conditions	Beam, Column, and Tie Rod Integrity							
	Masonry							
	Water Leakage							
	Load Capacity							
2. Determine Options for Improvement	Waterproofing Solutions							
	Reinforcement of Existing Structural Supports							
	Replacement of Roof Structure	🟨	🟨					
3. Cost and Value Analysis	Waterproofing Solutions	🟦						
	Re-paving	🟦	🟦					
	Structural Support	🟦	🟦	🟦				
	Complete Renovation		🟦	🟦	🟦			
4. Final Report Writing	Report Compilation					🟥	🟥	🟥

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Appendix B

Concrete Slab Design - Negative Moment Reinforcement

$f'c := 3.5$ ksi

$f_y := 60$ ksi

Assume $d := 8$ in

$L := 7.5$ ft <--Center to center beam spacing - half top flange width

Unfactored Loads and Moments

$w_{DC1} := .150\left(\frac{d}{12}\right) = 0.1 \quad \frac{k}{ft}$

$w_{DW} := .125\left(\frac{4}{12}\right) = 0.042 \quad \frac{k}{ft}$ <--Assume 4" Depth of Asphalt at 125 pcf

$$M_{DC1} := \left[\frac{\left(w_{DC1} \cdot L^2\right)}{10}\right] = 0.562 \quad \text{k-ft}$$

$$M_{DW} := \frac{\left(w_{DW} \cdot L^2\right)}{10} = 0.234 \quad \text{k-ft}$$

$M_{LL.IM} := 5.65$ <--k-ft from AASHTO Table A4-1

Factored Moments

$\eta_D := 1$

$\eta_R := 1$

$\eta_I := 1$

$\eta_i := \eta_D \cdot \eta_R \cdot \eta_I > 0.95$

$\eta_i = 1$ <--For Typical Bridge Design

$$M_{Strength1} := \eta_i \cdot \left(1.25 M_{DC1} + 1.5 M_{DW} + 1.75 M_{LL.IM}\right) \cdot 12 = 131.306 \quad \text{k-in}$$

$$M_{Service1} := \eta_i \cdot \left(M_{DC1} + M_{DW} + M_{LL.IM}\right) \cdot 12 = 77.363 \quad \text{k-in}$$

Design for Ultimate Moment Capacity

$d_s := d - (2.25 + .25) - \left[.5 \cdot \left(\frac{5}{8}\right)\right] = 5.188$ in   <--Slab depth   cover

$b := 12$ in   <--Width of design strip

$\Phi M_n := \left[A_s \cdot f_y \cdot \left[d_s - \left(\frac{1}{2}\right) \cdot \left(\frac{A_s \cdot f_y}{0.85 f'c \cdot b}\right)\right]\right]$ ▮ $\geq M_{strength1}$

$\Phi M_n \rightarrow 60 \cdot A_s \cdot (-0.8403361344537815126 A_s + 5.1875)$

$A_{s.calc} := 1$ <--Guess

Given

$123.81 = 60 \cdot A_{s.calc} \cdot (-0.8403361344537815126 A_{s.calc} + 5.1875)$

$\mathrm{Find}(A_{s.calc}) = 0.427$

Try $A_s := .53$ in^2 #5 bars at 7" center to center spacing

$\Phi M_n := \left[A_s \cdot f_y \cdot \left[d_s - \left(\frac{1}{2}\right) \cdot \left(\frac{A_s \cdot f_y}{0.85 f'c \cdot b}\right)\right]\right]$

$\Phi M_n = 150.799$ k-in

$\beta_1 := .85$ <--for concrete less then 4000psi

Assume fs = fy=60 ksi

$c := \frac{A_s \cdot f_y}{.85 \beta_1 \cdot f'c \cdot b} = 1.048$

$d_s = 5.188$ in

$\frac{c}{d_s} = 0.202$ $.202 \leq 0.$ Assumption of fs = fy = 60 ksi is valid

Check Control of Cracking

$d_c := (2.25 + .25) + .5\cdot\left(\frac{5}{8}\right) = 2.813$ 2.5" clear + half bar diameter

$h := 8$ in

$$\beta_s := 1 + \frac{d_c}{.7(h - d_c)} = 1.775$$

$\gamma_e := .75$

$A_s = 0.53$

$n := 9$

$$\rho := \frac{A_s}{b\cdot d_s} = 0.00851$$

$$k := \sqrt{(\rho\cdot n)^2 + 2\rho\cdot n} - \rho\cdot n$$

$k = 0.322$

$$j := 1 - \frac{k}{3} = 0.893$$

$$f_s := \frac{M_{Service1}}{A_s\cdot j\cdot d_s} = 31.525 \quad \text{ksi}$$

$$s := \left(\frac{700\gamma_e}{\beta_s\cdot f_s}\right) - 2\cdot d_c = 3.76$$

10 in < 12.67 in

use #5 bars at 10 in center to center spacing

Check Maximum Reinforcement

$c = 1.048$

$d_t := d_s = 5.188$

$$\varepsilon_t := \frac{\left[.003\left(d_t - c\right)\right]}{c} = 0.012$$

0.012 > 0.005 no reduction in resistance factors is required and Ultimate Moment Capacity calculations are valid

Check Minimum Reinforcement

$M_r > M_{cr}$

$S := \left(\frac{1}{6}\right)\cdot b\cdot h^2 = 128$ $\quad in^3$

$f_r := .24\sqrt{fc} = 0.449$ $\quad ksi$

$\gamma_3 := .75$ for A706, Grade 60 reinforcement

$\gamma_1 := 1.6$ for non-segmentally constructed bridges

$M_{cr} := \gamma_3 \cdot \gamma_1 \cdot S \cdot f_r = 68.966$ k-in

Mr = $\Phi M_n = 150.799$

150.799> 68.966 k-in PASSES CHECK

Concrete Slab Design - Positive Moment Reinforcement

$f'c := 3.5$ ksi

$f_y := 60$ ksi

Assume $d := 8$ in

$L := 8$ ft <--Center to center beam spacing

Unfactored Loads and Moments

$w_{DC1} := .150\cdot\left(\frac{d}{12}\right) = 0.1$ $\frac{k}{ft}$

$w_{DW} := .125\left(\frac{4}{12}\right) = 0.042$ $\frac{k}{ft}$ <--Assume 4" Depth of Asphalt at 125 pcf

$$M_{DC1} := \left[\frac{\left(w_{DC1}\cdot L^2\right)}{10}\right] = 0.64 \quad \text{k-ft}$$

$$M_{DW} := \frac{\left(w_{DW}\cdot L^2\right)}{10} = 0.267 \quad \text{k-ft}$$

$M_{LL.IM} := 5.21$ <--k-ft from AASHTO Table A4-1

Factored Moments

$\eta_D := 1$

$\eta_R := 1$

$\eta_I := 1$

$\eta_i := \eta_D\cdot\eta_R\cdot\eta_I > 0.95$

$\eta_i = 1$ <--For Typical Bridge Design

$$M_{Strength1} := \eta_i\cdot\left(1.25M_{DC1} + 1.5M_{DW} + 1.75M_{LL.IM}\right)\cdot 12 = 123.81 \quad \text{k-in}$$

$$M_{Service1} := \eta_i\cdot\left(M_{DC1} + M_{DW} + M_{LL.IM}\right)\cdot 12 = 73.4 \quad \text{k-in}$$

Design for Ultimate Moment Capacity

$d_s := d - 1 - \left[.5\cdot\left(\frac{5}{8}\right)\right] = 6.688$ in <--Slab depth - 1" cover

$b := 12$ in <--Width of design strip

$\Phi M_n := \left[A_s\cdot f_y\cdot\left[d_s - \left(\frac{1}{2}\right)\cdot\left(\frac{A_s\cdot f_y}{0.85\cdot f'c\cdot b}\right)\right]\right] \geq M_{strength1}$

$\Phi M_n \rightarrow 60\cdot A_s\cdot(-0.84033613445378151261\cdot A_s + 6.6875)$

$A_{s.calc} := 1$ <--Guess

Given

$123.81 = 60\cdot A_{s.calc}\cdot(-0.84033613445378151261\cdot A_{s.calc} + 6.6875)$

$\text{Find}(A_{s.calc}) = 0.322$

Try $A_s := .37$ in #5 bars at 10" center to center spacing

$\Phi M_n := \left[A_s\cdot f_y\cdot\left[d_s - \left(\frac{1}{2}\right)\cdot\left(\frac{A_s\cdot f_y}{0.85\cdot f'c\cdot b}\right)\right]\right]$

$\Phi M_n = 141.56$ k-in

$\beta_1 := .85$ <--for concrete less then 4000psi

Assume fs = fy=60 ksi

$c := \frac{A_s\cdot f_y}{.85\cdot\beta_1\cdot f'c\cdot b} = 0.732$

$d_s = 6.688$ in

$\frac{c}{d_s} = 0.109$ $.109 \leq 0.6$ Assumption of fs = fy = 60 ksi is valid

Check Control of Cracking

$d_c := 1 + .5 \cdot \left(\frac{5}{8}\right) = 1.313$ 1" clear + half bar diameter

$h := 8$ in

$\beta_s := 1 + \frac{d_c}{.7(h - d_c)} = 1.28$

$\gamma_e := .75$

$A_s = 0.37$

$n := 9$

$\rho := \frac{A_s}{b \cdot d_s} = 0.00461$

$k := \sqrt{(\rho \cdot n)^2 + 2\rho \cdot n} - \rho \cdot n$

$k = 0.25$

$j := 1 - \frac{k}{3} = 0.917$

$f_s := \frac{M_{Service1}}{A_s \cdot j \cdot d_s} = 32.356$ ksi

$s := \frac{700\gamma_e}{\beta_s \cdot f_s} = 12.673$

10 in < 12.67 in

use #5 bars at 10 in center to center spacing

Check Maximum Reinforcement

$c = 0.732$

$d_t := d_s = 6.688$

$$\varepsilon_t := \frac{\left[.003\left(d_t - c\right)\right]}{c} = 0.024$$

0.024 > 0.005 no reduction in resistance factors is required and Ultimate Moment Capacity calculations are valid

Check Minimum Reinforcement

$M_r > M_{cr}$

$S := \left(\frac{1}{6}\right)\cdot b\cdot h^2 = 128$ in^3

$f_r := .24\sqrt{f'c} = 0.449$ ksi

$\gamma_3 := .75$ for A706, Grade 60 reinforcement

$\gamma_1 := 1.6$ for non-segmentally constructed bridges

$M_{cr} := \gamma_3 \cdot \gamma_1 \cdot S \cdot f_r = 68.966$ k-in

Mr = $\Phi M_n = 141.56$

141.56 > 68.966 k-in PASSES CHECK

Appendix C

East West Loads - With Center Column

used for design option 3

		Column	
Live Load (1.6 load factor):	Design Tandon Rear (two 50k loads 6ft apart)	Max Axial	166.058
Dead Load (1.2 load factor):	1130 plf (800 plf for 8" slab + 330plf for 4" asphalt)	Beam	
		Max Moment	283.224
		Max Shear	136.742
		Max Axial	14.146

Member	Sec	Axial[k]	LC	Shear[k]	LC	Moment[k-ft]	LC
Foundation Wall South	1 max	127.468	1	2.41	1	0	1
	min	-5.038	1	-14.146	1	0	1
	2 max	127.468	1	2.41	1	21.219	1
	min	-5.038	1	-14.146	1	-3.616	1
	3 max	127.468	1	2.41	1	42.439	1
	min	-5.038	1	-14.146	1	-7.231	1
	4 max	127.468	1	2.41	1	63.658	1
	min	-5.038	1	-14.146	1	-10.847	1
	5 max	127.468	1	2.41	1	84.877	1
	min	-5.038	1	-14.146	1	-14.463	1
Foundation Wall North	1 max	127.468	1	14.146	1	84.877	1
	min	-5.038	1	-2.41	1	-14.463	1
	2 max	127.468	1	14.146	1	63.658	1
	min	-5.038	1	-2.41	1	-10.847	1
	3 max	127.468	1	14.146	1	42.439	1
	min	-5.038	1	-2.41	1	-7.231	1
	4 max	127.468	1	14.146	1	21.219	1
	min	-5.038	1	-2.41	1	-3.616	1
	5 max	127.468	1	14.146	1	0	1
	min	-5.038	1	-2.41	1	0	1
Beam	1 max	14.146	1	114.537	1	84.877	1
	min	-2.41	1	-5.038	1	-14.463	1
	2 max	14.146	1	33.089	1	82.559	1
	min	-2.41	1	-55.294	1	-283.224	1
	3 max	14.146	1	136.742	1	215.602	1
	min	-2.41	1	-136.742	1	37.237	1
	4 max	14.146	1	55.294	1	82.559	1
	min	-2.41	1	-33.089	1	-283.224	1
	5 max	14.146	1	5.038	1	84.877	1
	min	-2.41	1	-114.537	1	-14.463	1
Center Column	1 max	166.058	1	11.892	1	71.351	1
	min	23.896	1	-11.892	1	-71.351	1
	2 max	166.058	1	11.892	1	53.513	1
	min	23.896	1	-11.892	1	-53.513	1
	3 max	166.058	1	11.892	1	35.675	1
	min	23.896	1	-11.892	1	-35.675	1
	4 max	166.058	1	11.892	1	17.838	1
	min	23.896	1	-11.892	1	-17.838	1
	5 max	166.058	1	11.892	1	0	1
	min	23.896	1	-11.892	1	0	1

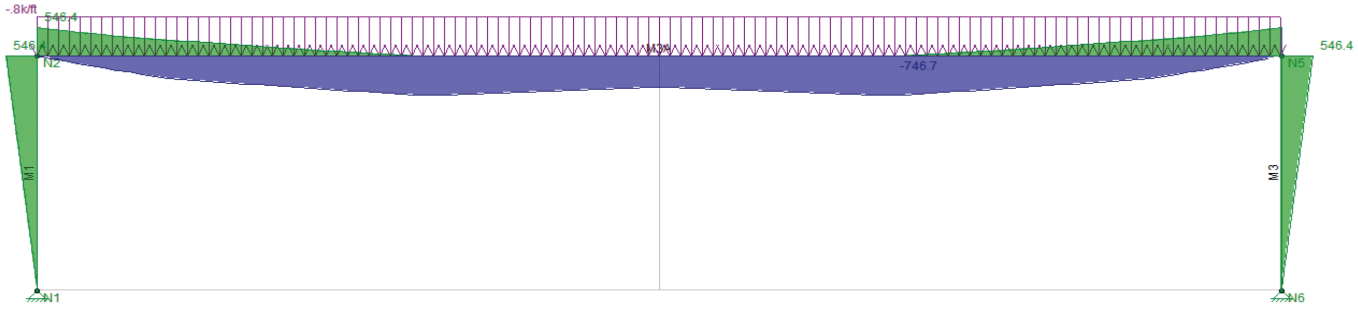
East West Loads - No Center Column

used for design option 3

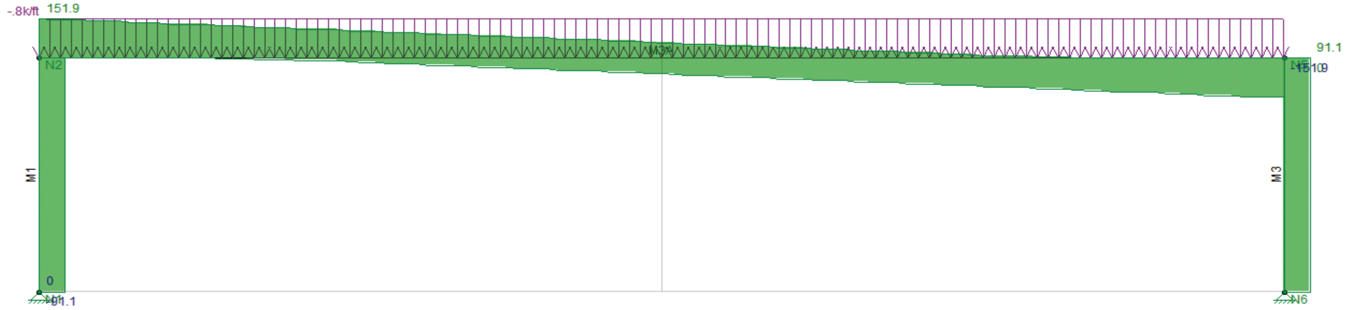
		Column	
Live Load (1.6 load factor):	Design Tandon Rear (two 50k loads 6ft apart)	Max Axial	163.11
Dead Load (1.2 load factor):	1130 plf (800 plf for 8" slab + 330plf for 4" asphalt)	Beam	
		Max Moment	686.847
		Max Shear	157.593
		Max Axial	95.131

Member	Sec	Axial[k]	LC	Shear[k]	LC	Moment[k-ft]	LC
Foundation Wall South	1 max	163.11	1	-0.002	1	0	1
	min	19.662	1	-95.131	1	0	1
	2 max	163.11	1	-0.002	1	142.697	1
	min	19.662	1	-95.131	1	0.003	1
	3 max	163.11	1	-0.002	1	285.393	1
	min	19.662	1	-95.131	1	0.007	1
	4 max	163.11	1	-0.002	1	428.09	1
	min	19.662	1	-95.131	1	0.01	1
	5 max	163.11	1	-0.002	1	570.787	1
	min	19.662	1	-95.131	1	0.014	1
Foundation Wall North	1 max	163.11	1	95.131	1	570.787	1
	min	19.662	1	0.002	1	0.014	1
	2 max	163.11	1	95.131	1	428.09	1
	min	19.662	1	0.002	1	0.01	1
	3 max	163.11	1	95.131	1	285.393	1
	min	19.662	1	0.002	1	0.007	1
	4 max	163.11	1	95.131	1	142.697	1
	min	19.662	1	0.002	1	0.003	1
	5 max	163.11	1	95.131	1	0	1
	min	19.662	1	0.002	1	0	1
Beam	1 max	95.131	1	157.593	1	570.787	1
	min	0.002	1	19.662	1	0.014	1
	2 max	95.131	1	109.141	1	76.183	1
	min	0.002	1	-12.238	1	-686.847	1
	3 max	95.131	1	60.69	1	-142.536	1
	min	0.002	1	-60.69	1	-622.484	1
	4 max	95.131	1	12.238	1	76.183	1
	min	0.002	1	-109.141	1	-686.847	1
	5 max	95.131	1	-19.662	1	570.787	1
	min	0.002	1	-157.593	1	0.014	1

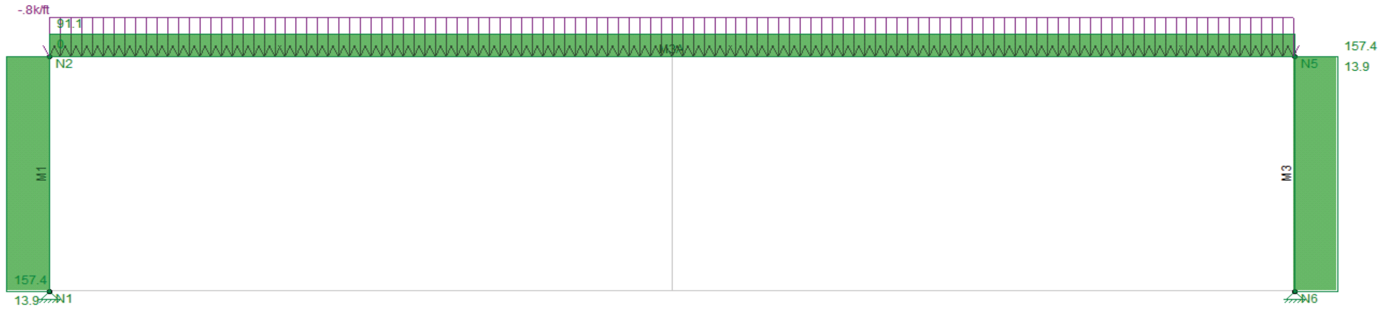
Moment



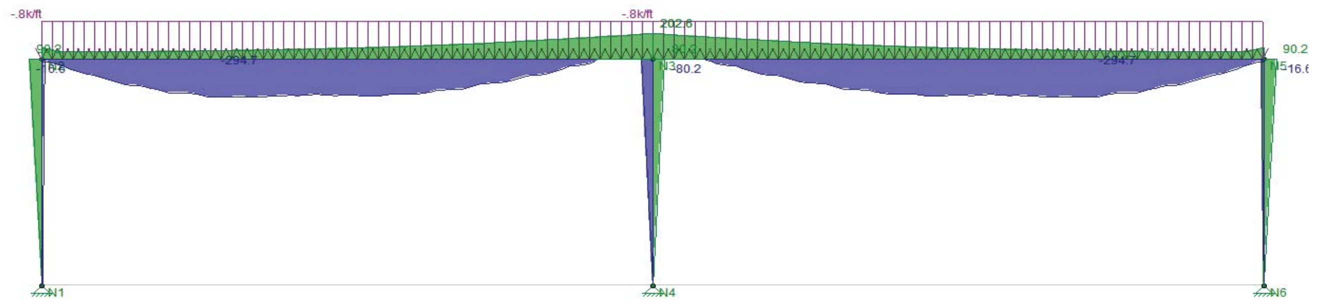
Shear



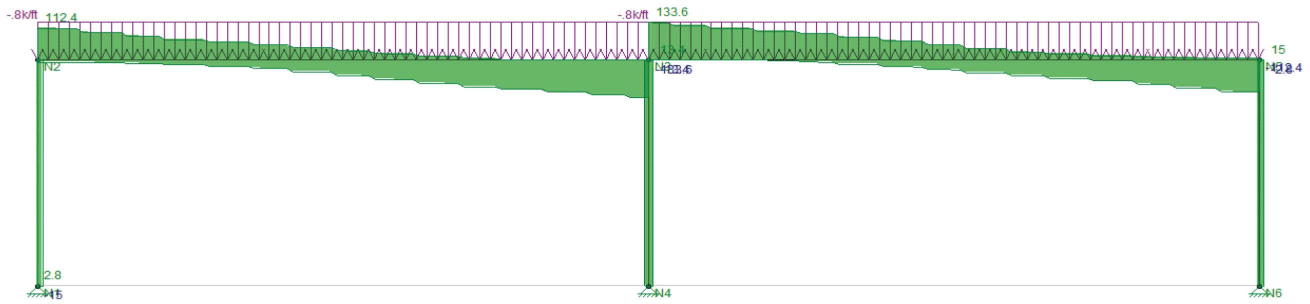
Axial



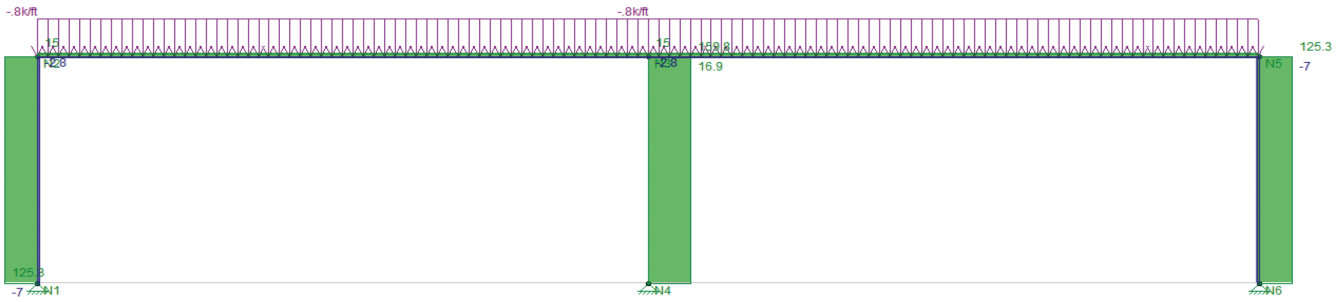
Moment



Shear



Axial



North - South Loads - No Columns

used for design option 1 & 2

Live Load (1.6 load factor): Design Tandon Side (8k load and two 25K loads)

Dead Load (1.2 load factor): 1130 plf (800 plf for 8" slab + 330plf for 4" asphalt)

	Beam
Max Moment	1416.507
Max Shear	137.348
Max Axial	337.006

Member	Sec	Axial[k]	LC	Shear[k]	LC	Moment[k-ft]	LC
Beam	1 max	337.006	1	137.348	1	1416.507	1
	min	135.183	1	47.877	1	540.732	1
	2 max	337.006	1	91.777	1	-12.31	1
	min	135.183	1	12.039	1	-507.539	1
	3 max	337.006	1	37.783	1	-292.897	1
	min	135.183	1	-39.446	1	-1036.328	1
	4 max	337.006	1	-13.196	1	-12.31	1
	min	135.183	1	-93.286	1	-507.539	1
	5 max	337.006	1	-47.877	1	1416.507	1
	min	135.183	1	-137.348	1	540.732	1
Foundation Wall West	1 max	137.884	1	-135.183	1	-540.732	1
	min	48.816	1	-337.006	1	-1416.507	1
	2 max	137.884	1	-135.183	1	-318.411	1
	min	48.816	1	-337.006	1	-938.17	1
	3 max	137.884	1	-135.183	1	96.691	1
	min	48.816	1	-337.006	1	-479.251	1
	4 max	137.884	1	-135.183	1	580.498	1
	min	48.816	1	-337.006	1	-46.907	1
	5 max	137.884	1	-135.183	1	1083.192	1
	min	48.816	1	-337.006	1	202.776	1
Foundation Wall East	1 max	137.884	1	337.006	1	1416.507	1
	min	48.816	1	135.183	1	540.732	1
	2 max	137.884	1	337.006	1	938.17	1
	min	48.816	1	135.183	1	318.411	1
	3 max	137.884	1	337.006	1	479.251	1
	min	48.816	1	135.183	1	-96.691	1
	4 max	137.884	1	337.006	1	46.907	1
	min	48.816	1	135.183	1	-580.498	1
	5 max	137.884	1	337.006	1	-202.776	1
	min	48.816	1	135.183	1	-1083.192	1

North - South Loads - With Columns

used for design option 1 & 2

Live Load (1.6 load factor): Design Tandon Side (8k load and two 25K loads)

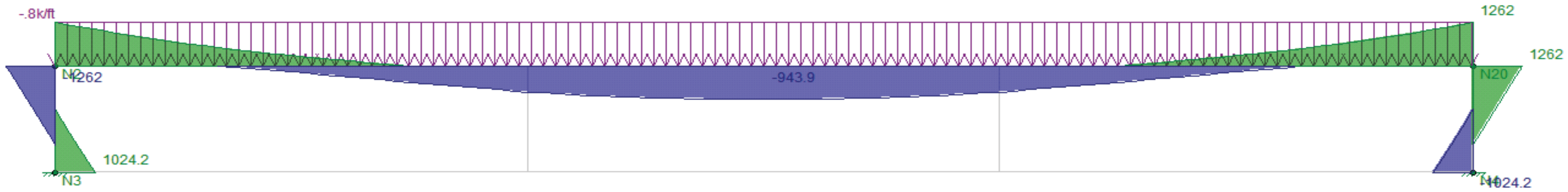
Dead Load (1.2 load factor): 1130 plf (800 plf for 8" slab + 330plf for 4" asphalt)

	Column
Max Axial	116.435

	Beam
Max Moment	278.406
Max Shear	45.531
Max Axial	45.531

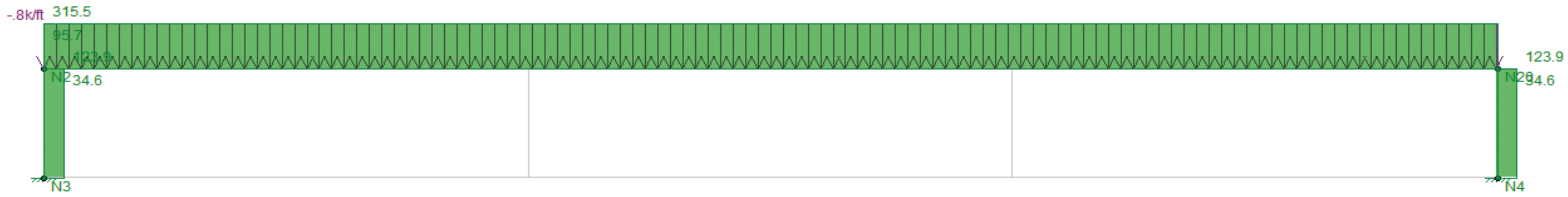
Member	Sec	Axial[k]	LC	Shear[k]	LC	Moment[k-ft]	LC
Beam	1 max	45.531	1	81.607	1	230.267	1
	min	-2.01	1	6.39	1	-9.957	1
	2 max	45.531	1	-1.23	1	94.696	1
	min	-2.01	1	-63.726	1	-183.093	1
	3 max	45.53	1	28.737	1	19.152	1
	min	-10.607	1	-32.818	1	-278.406	1
	4 max	45.531	1	59.875	1	94.696	1
	min	-2.01	1	-1.865	1	-183.093	1
	5 max	45.531	1	-6.39	1	230.267	1
	min	-2.01	1	-81.607	1	-9.957	1
Foundation Wall West	1 max	85.411	1	2.01	1	9.957	1
	min	6.39	1	-45.531	1	-230.267	1
	2 max	85.411	1	2.01	1	8.596	1
	min	6.39	1	-45.531	1	-161.97	1
	3 max	85.411	1	2.01	1	26.352	1
	min	6.39	1	-45.531	1	-99.489	1
	4 max	85.411	1	2.01	1	92.488	1
	min	6.39	1	-45.531	1	-43.302	1
	5 max	85.411	1	2.01	1	158.625	1
	min	6.39	1	-45.531	1	-41.077	1
Foundation Wall East	1 max	85.411	1	45.531	1	230.267	1
	min	6.39	1	-2.01	1	-9.957	1
	2 max	85.411	1	45.531	1	161.97	1
	min	6.39	1	-2.01	1	-8.596	1
	3 max	85.411	1	45.531	1	99.489	1
	min	6.39	1	-2.01	1	-26.352	1
	4 max	85.411	1	45.531	1	43.302	1
	min	6.39	1	-2.01	1	-92.488	1
	5 max	85.411	1	45.531	1	41.077	1
	min	6.39	1	-2.01	1	-158.625	1
West Column	1 max	116.435	1	10.61	1	63.661	1
	min	20.724	1	-10.059	1	-60.355	1
	2 max	116.435	1	10.61	1	47.746	1
	min	20.724	1	-10.059	1	-45.266	1
	3 max	116.435	1	10.61	1	31.83	1
	min	20.724	1	-10.059	1	-30.177	1
	4 max	116.435	1	10.61	1	15.915	1
	min	20.724	1	-10.059	1	-15.089	1
	5 max	116.435	1	10.61	1	0	1
	min	20.724	1	-10.059	1	0	1
East Column	1 max	116.435	1	10.059	1	60.355	1
	min	20.724	1	-10.61	1	-63.661	1
	2 max	116.435	1	10.059	1	45.266	1
	min	20.724	1	-10.61	1	-47.746	1
	3 max	116.435	1	10.059	1	30.177	1
	min	20.724	1	-10.61	1	-31.83	1
	4 max	116.435	1	10.059	1	15.089	1
	min	20.724	1	-10.61	1	-15.915	1
	5 max	116.435	1	10.059	1	0	1
	min	20.724	1	-10.61	1	0	1

Moment

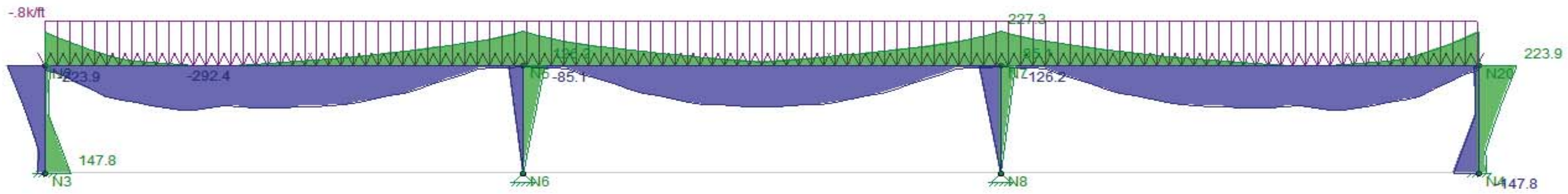


Shear

Axial



Moment



Shear

Axial