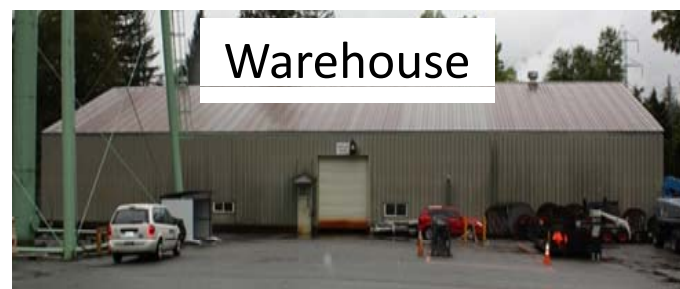


# Structural Evaluation and Retrofit of a Warehouse

## Project Background

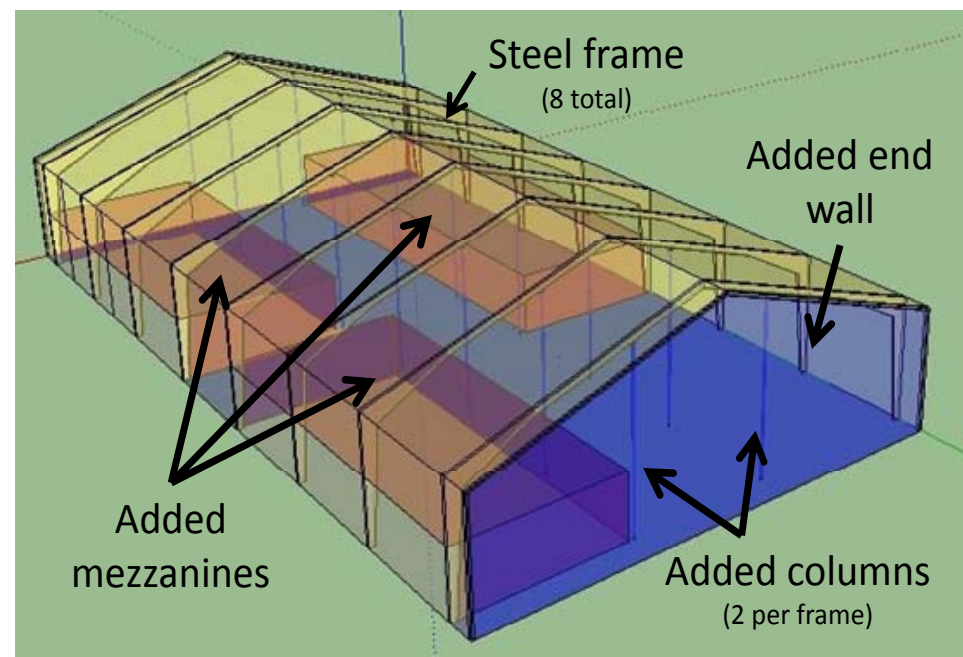
### Introduction



Local utility uses warehouse as office, gymnasium and storage facility for \$3-5 million powerhouse and dam replacement parts

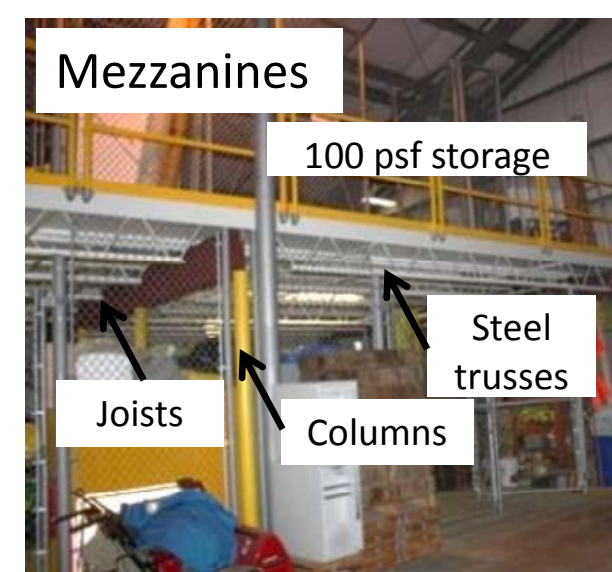
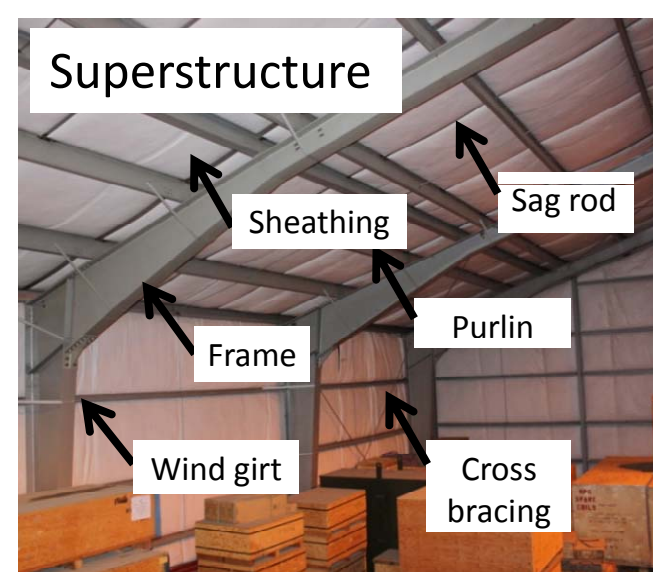
### Background:

- Warehouse originally constructed on one side of state and moved 300 miles to current location
- Reconstructed and modified *without structural analysis*

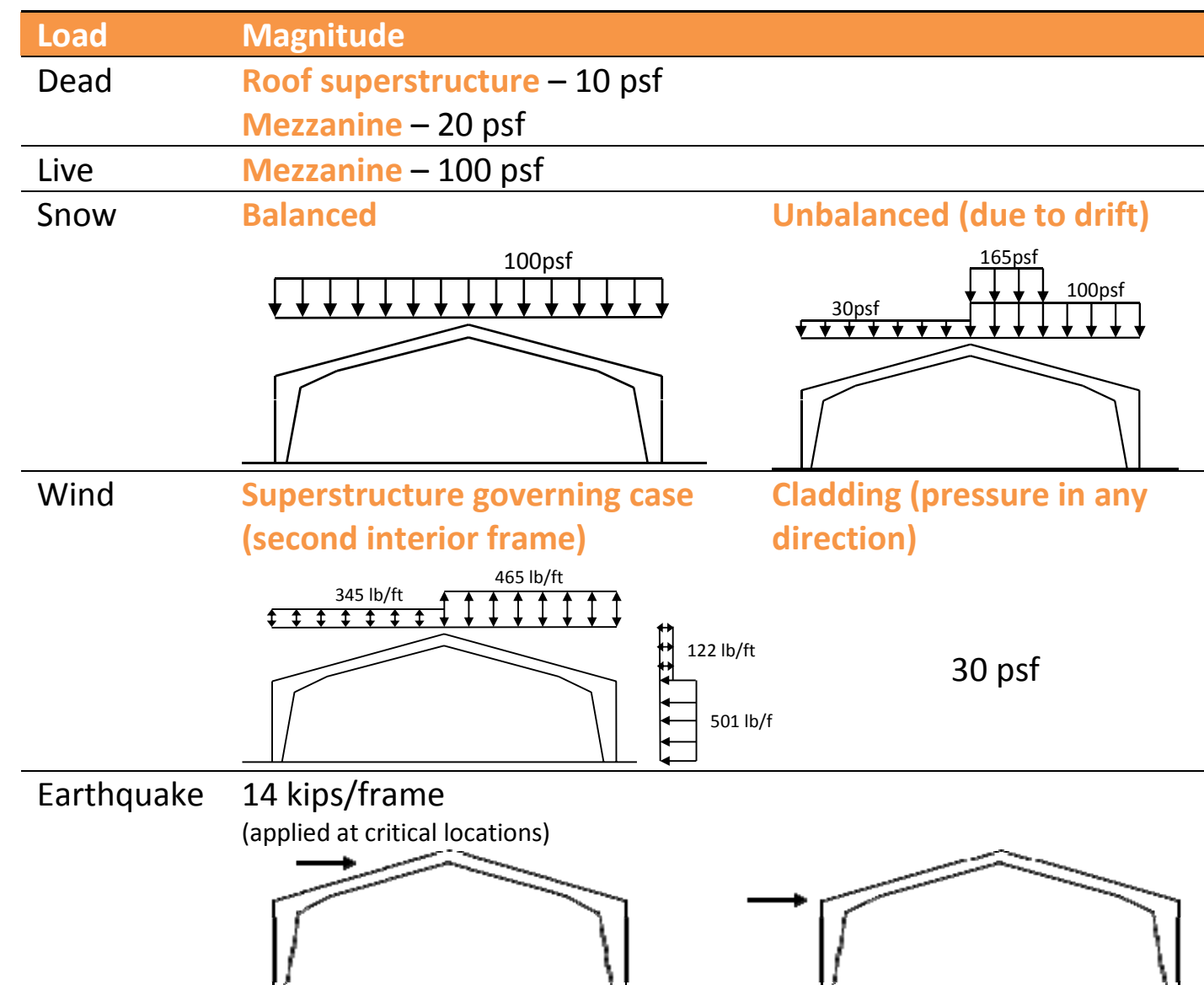


### Project Scope:

- Create as-built drawings
- Determine loads (demand)
- Analyze capacity of superstructure and mezzanines
- Foundation analysis omitted due to time constraints



### Design Loads



Loads in new location up to **4 times** larger than original design

**Immediate Life-Safety Issue**

## Student Collaboration with Faculty, Licensed Engineers and Allied Professionals

- A four-student team worked with **faculty advisor** and three company liaisons (**two licensed Structural Engineers** and **project manager**)

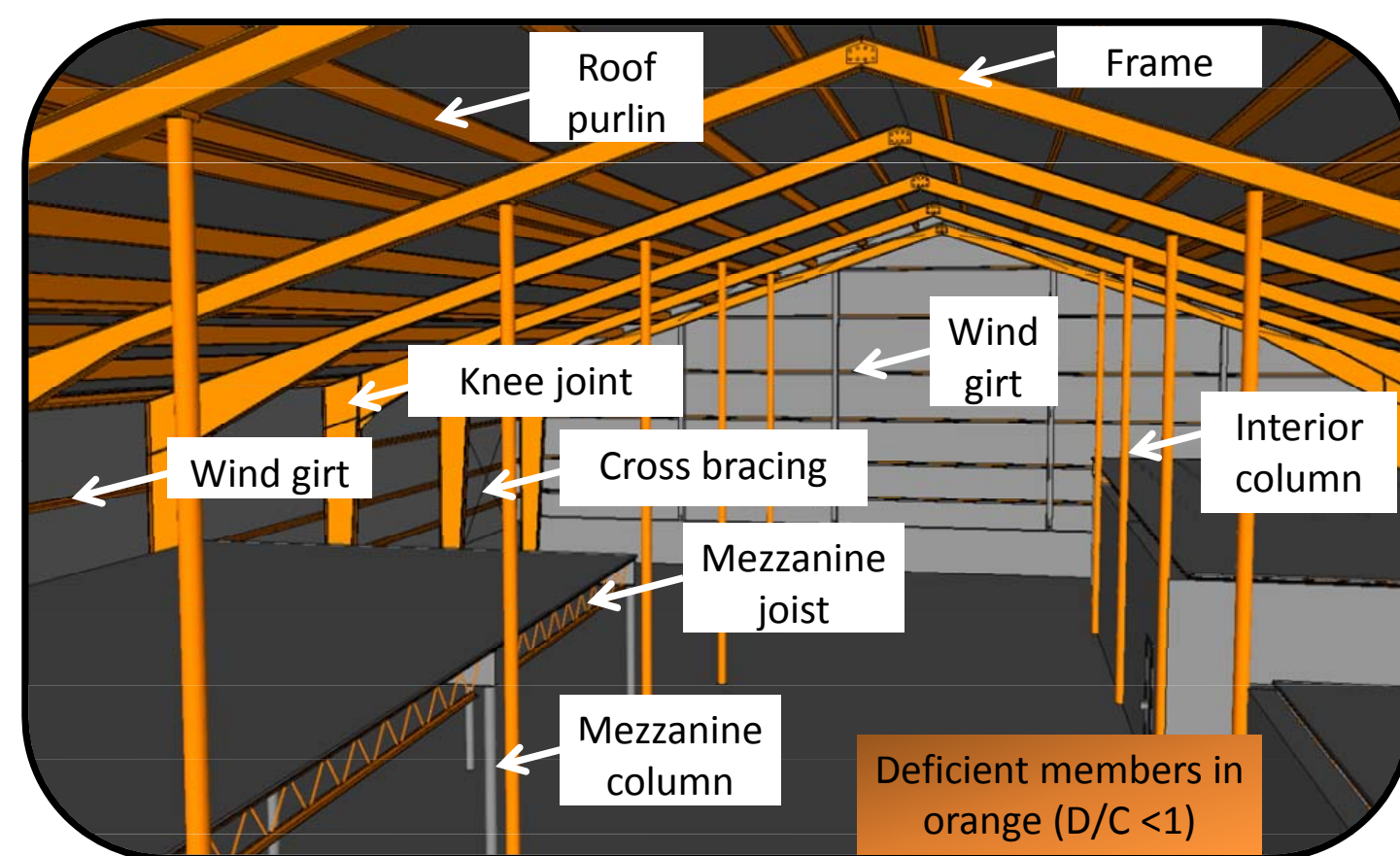
### Major Milestones:

Fall	Winter	Spring
Site Visit Written Proposal	Analysis and Design	Final Report, Presentation

- Proposal/Report reviewed by five civil engineering faculty (three **licensed engineers**, multiple sub-disciplines) and two **licensed Structural Engineers** (external to the project)
- Team presented to **civil engineering capstone class** (multiple sub-disciplines) and to **utility agency** (attended by individuals from multiple disciplines) and to **university's industrial advisory board** (consisting of ten **licensed engineers**)
- Client Interaction** – Extensive interaction with **utility workers at warehouse location** to understand facility use
- Material Testing** – Consulted with laboratory manager (**licensed engineer**) from local cement company to evaluate compressive strength of existing concrete

## Structural Evaluation

- Demand/Capacity** ratios determined for all members
  - Demand** according to governing loads
  - Capacity** based on steel and concrete specifications (AISC 14<sup>th</sup> ed and ACI 318-11)
- If **Demand/Capacity (D/C) < 1** → **mitigations designed**

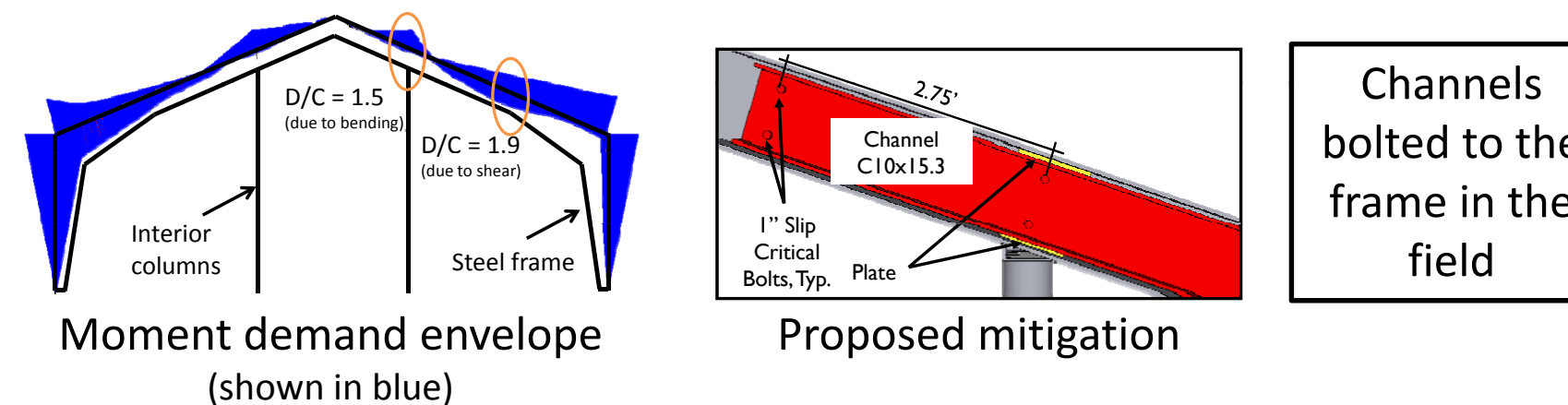


Member	Governing D/C		Retrofit Design Recommendations
	Initial	Final	
<b>Frame</b>			
Beam above	1.5	0.9	20' C10x15.3
Beam at transition	1.5	0.9	20' C10x15.3
Peak connection	0.4	-	-
Frame column	0.2	-	-
<b>Knee Joint</b>			
Top connection	1.2	<1	Remove existing plate, weld wider plate and replace
Bottom connection	1.3	<1	Remove existing plate, weld wider plate and replace
Web	1.3	<1	Add angle with bolts 3" on center
Stiffener Plate	3.2	<1	Additional stiffener plate
<b>Interior Columns</b>			
Angle above	2.3	0.6	Add 25' collar of (XS) 8" pipe welded to existing
	6.6	<1	3/8x9.5x4.5 added to each side of angle
<b>End wall columns</b>			
W10x22	0.6	-	-
W10x12	0.5	-	-
<b>Strut Purlins</b>			
	2.5	0.8	C6x6.5 extending 4' on either side of frame
<b>Roof Purlins</b>			
	3.5	0.9	C9x13.4 extending 6' on either side of the frame
<b>Wind Girts</b>			
South end wall	1.8	0.7	15' C3x6 in center of girt
North end wall	1.8	0.9	15' C3x6 in center of girt
East-West walls	2.1	0.9	C3x6 extending 4' on either side of the frame
<b>Sheathing</b>			
	0.9	-	-
<b>Cross Bracing</b>			
	0.9	-	-
<b>Mezzanine</b>			
Columns	0.32	-	-
Beams	0.85	-	-
Joists	2.25	0.94	Reduce storage capacity from 100 psf to 35 psf

Note: C represents a channel cross section with the nominal depth and weight specified. For example, a C3x6 has a nominal depth of 3" and weight of 6 lb/ft.

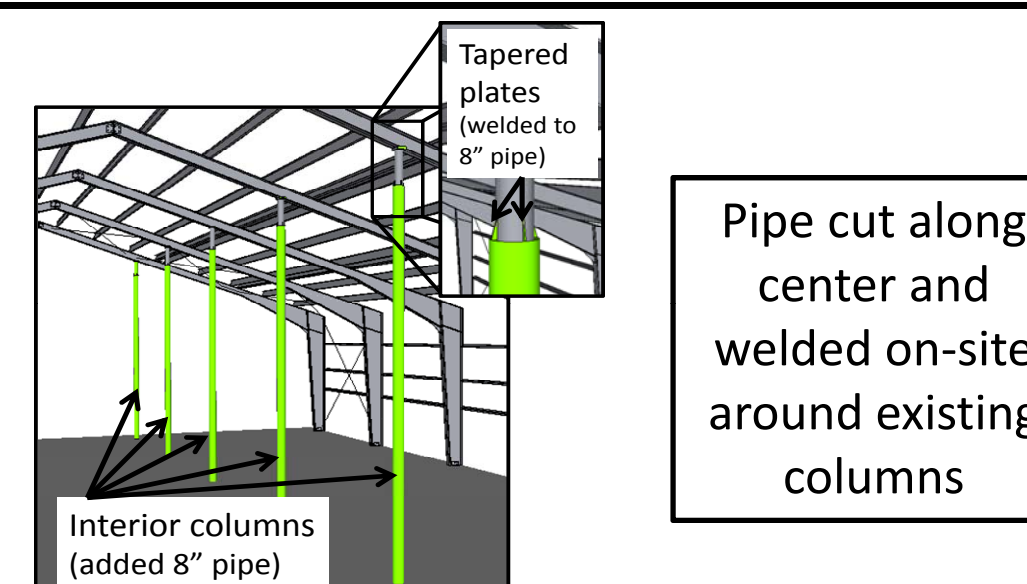
## Retrofit Designs

### Frame:

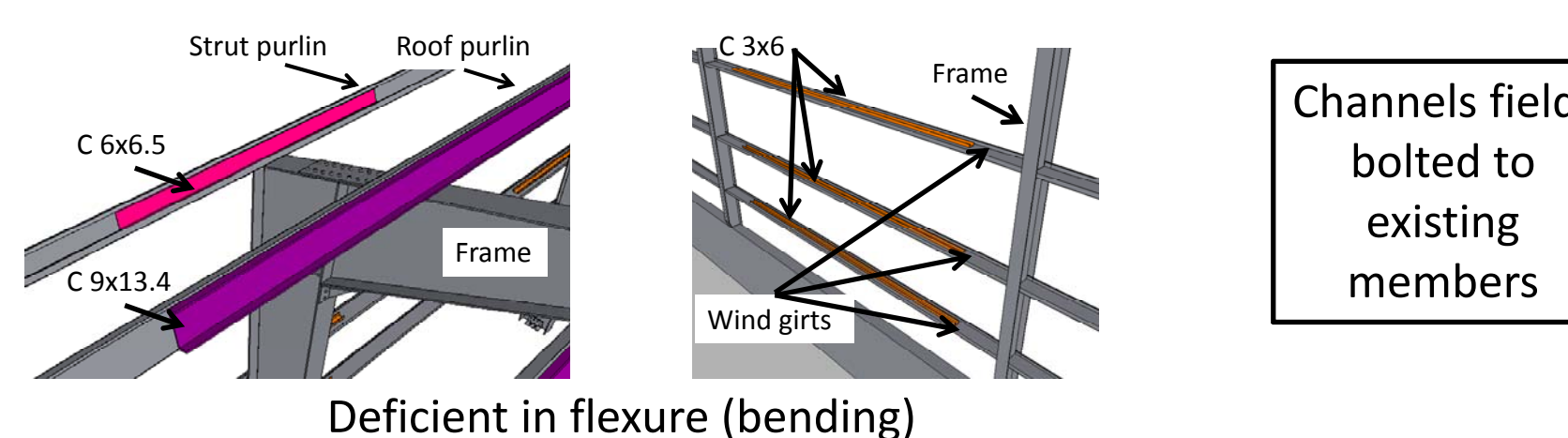


### Interior Columns:

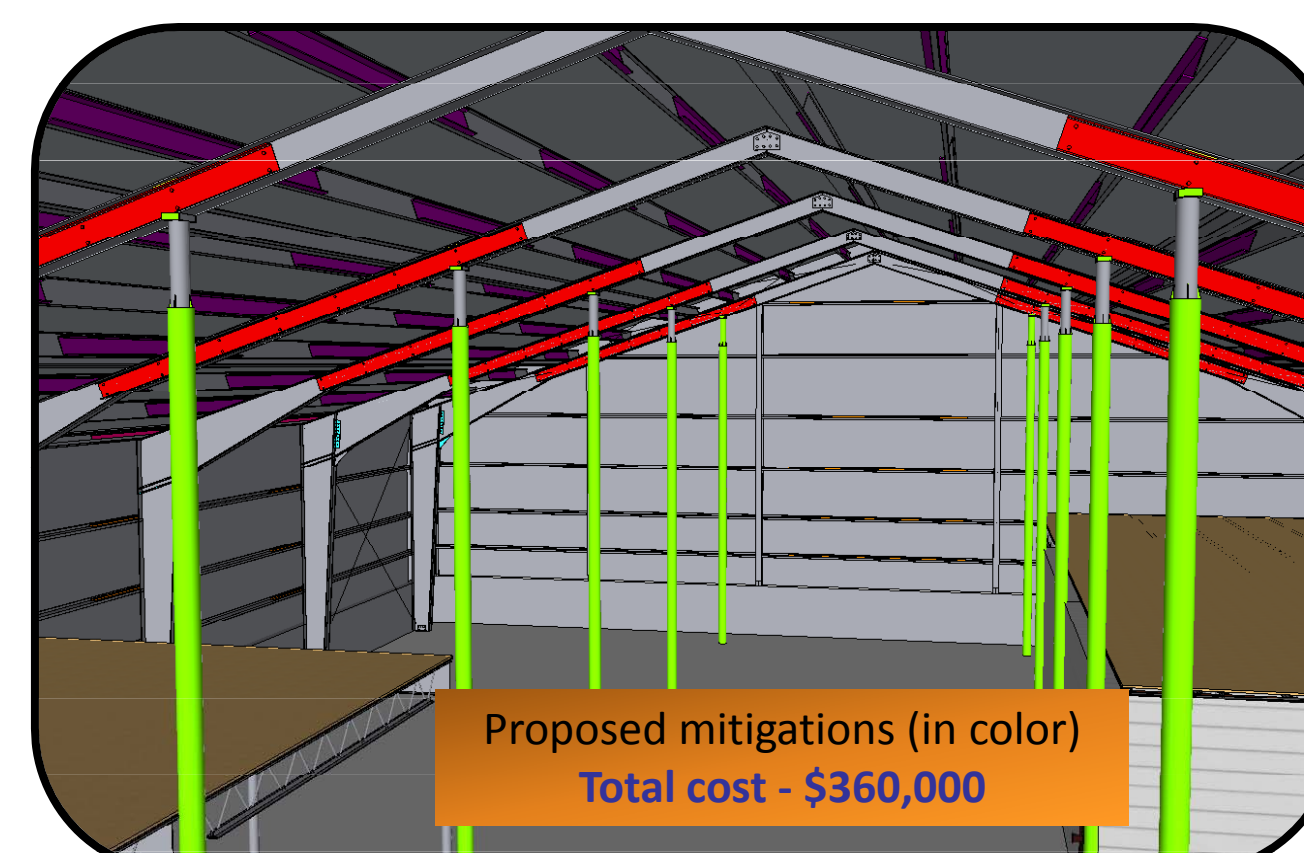
- Insufficient in compression
- Collar of extra strong (XS) 8" pipe added to a height of 25 feet
- Tapered plates transfer load from 6" to 8" pipe



### Purlins and Girts:



## Final Recommendation



Proposed mitigations (in color)  
Total cost - \$360,000

## Benefit to Public Health, Safety and Welfare

### Worker Life Safety

- Initial analysis indicated warehouse posed **immediate life-safety threat**
- Team advised employees that if more than 1 foot of snow accumulated, the building must be evacuated
- Final design recommendations **considered worker safety** (such as bolted connections for frames to avoid more dangerous field welding at significant heights)

### Public Health and Safety

- Warehouse stores expensive and unique equipment
- Damage to equipment would **significantly impact the power supply**, including **critical operations** such as hospitals

## Skills Gained

### Technical

- Learned to analyze and make **recommendations for existing structure**
- Worked with **building codes, design specifications, structural analysis software, design and presentation aids**
- Unique exposure to **constructability and connection design**

### Communication

- Written** – proposal, calculations, final report, professional emails
- Oral** – Effective presentations to senior design class, sponsor, local chapter of engineering society, including use of Google-SketchUp to effectively communicate mitigation concepts to the client and non-engineers

### Project Management and Leadership

- Weekly meetings** organized by team
- Rotating **project manager responsibilities**
- Working as a team and conflict resolution**
- Time management skills**

- Cost Estimating** - Prepared detailed cost estimate of design option to retrofit structure or demolish and build a prefabricated warehouse



# Structural Evaluation and Retrofit of a Warehouse

## Abstract

A local utility company requested our university's capstone program to perform the structural evaluation and retrofit designs of a warehouse that is not up to current codes and poses a life-safety threat to its employees. Working closely with two licensed structural engineers (SEs) from the company and a faculty advisor, a four-member student team analyzed the building based on current design codes and found multiple structural deficiencies. The final project deliverable was a report detailing these deficiencies, retrofit designs and a comprehensive cost analysis.

The warehouse functions as an office, gymnasium, and storage facility of key replacement parts for the utility company's powerhouses and dams. It was originally constructed 300 miles from its current location and later moved and reconstructed at the project site. During reconstruction, multiple modifications were made without adequate structural analysis. As a result, at the beginning of the project there were no as-built drawings of the structure and much was unknown about the building's structural stability, strength, and stiffness. At its current location, the loads are considerably higher (up to four times greater) than those for which the building was designed.

The project began with a site visit and creation of as-built drawings. Next, the design loads were determined according to current building codes. Finally, a structural analysis was performed and retrofits were designed. Many deficiencies were identified, including the frames, interior columns, flexural beams (girt and purlins) and the mezzanines. Retrofit designs considered numerous constructability issues, such as the remote site location, severe winter weather and the impact of construction on day-to-day operations at the warehouse.

The team performed a cost analysis that considered two design options: (1) to retrofit the existing warehouse based on the retrofit design concepts and (2) to demolish the building and purchase a new, prefabricated structure to replace it. The total estimated costs of the two options were \$360,000 and \$1.2 million, respectively. Based on these data, the team recommended that the utility retrofit the warehouse.

Students met weekly with their faculty advisor and the sponsoring company liaisons. The team's design calculations were reviewed by the faculty advisor, company liaisons, and two other licensed structural engineers. Project highlights included exposure to constructability issues and professional presentations to their peers, the utility company (including licensed engineers from various disciplines) and a local chapter of a professional society. The team also learned to use Google SketchUp to effectively communicate their mitigation concepts to the client and non-engineers. The project culminated in a final report to the utility company and a poster presentation to the local university and engineering community. Throughout the year, students developed important technical, communication, project management and cost estimating skills to help prepare them for their future careers as practicing engineers.

# Structural Evaluation and Retrofit of a Warehouse

## I. Project Description

### Introduction

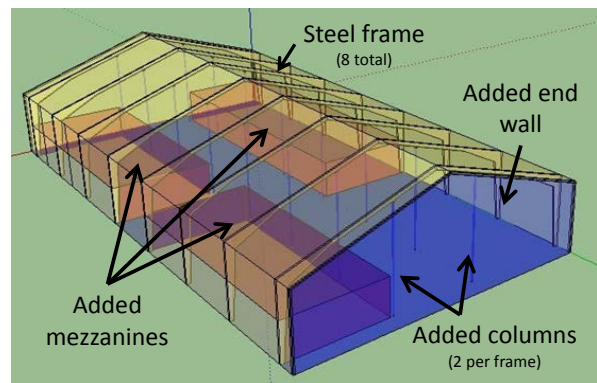
A local utility company requested our university's capstone program to perform the structural evaluation and retrofit designs of a warehouse that is not up to current codes and poses a life-safety threat to its employees. Working closely with two licensed structural engineers from the company and a faculty advisor, a four-member student team analyzed the building based on current design codes and found multiple structural deficiencies. The final project deliverable was a report detailing these deficiencies, retrofit designs and a comprehensive cost analysis.

### Background

Figure 1 presents the warehouse, which functions as an office, gymnasium, and storage facility of key replacement parts for the utility company's powerhouses and dams. Originally constructed on one side of the state, the building was later moved over 300 miles and reconstructed at its current location. During reconstruction, multiple modifications (Figure 1b) were made without adequate structural analysis. As a result, at the beginning of the project there were no as-built drawings of the structure and much was unknown about the building's structural stability, strength, and stiffness. At its current location, the loads are considerably higher (up to four times greater) than those for which the building was designed due to its new location which sees greater snow loads and updated seismic and wind loading codes.



(a)



(b)

Figure 1. Steel warehouse: (a) photo and (b) schematic of original portion (yellow), the elements added during reassembly (blue), and the subsequent modifications (orange)

The current warehouse is 350 feet by 80 feet wide and consists of three parts (Figure 1b): the original portion, the end wall and columns added during reassembly, and the subsequent construction of three mezzanines. Figure 2 presents the interior structure of the warehouse showing the superstructure (Figure 2a) and one of the mezzanines (Figure 2b).

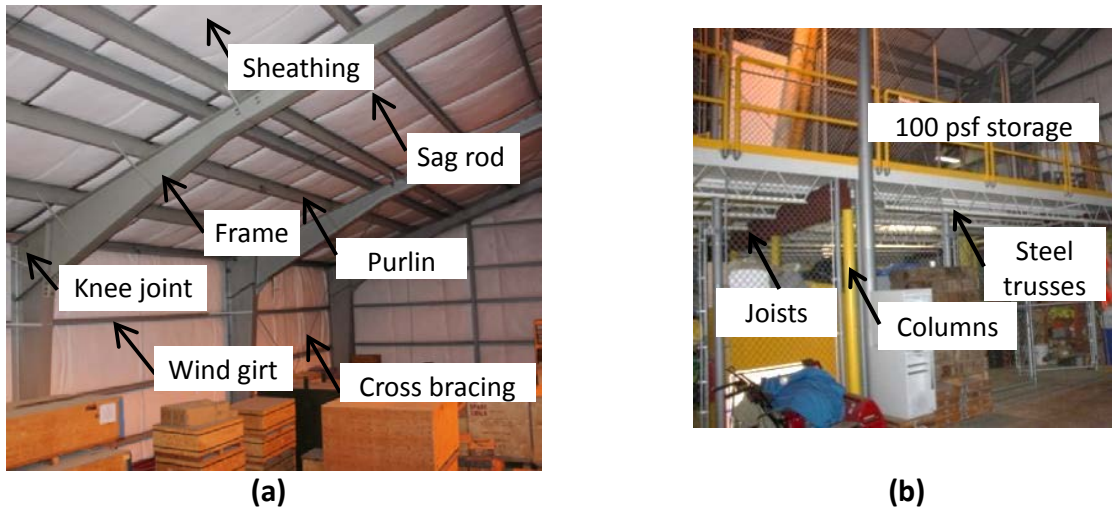


Figure 2. Warehouse structural members (a) superstructure and (b) mezzanine

### Capstone Project Scope

The project began with a site visit and creation of as-built drawings. Next, the design loads were determined according to current building codes. Finally, a structural analysis was performed and retrofits were designed for any deficient members.

### Determination of Loads

The dead, live, snow, wind and earthquake loads to which the building will be exposed were determined according to the local county building codes, the *American Society of Civil Engineers (ASCE) 7-10 Minimum Design Loads for Structures and Other Buildings* and the *International Building Code (IBC 2012)*. The dead load for the roof superstructure and the mezzanine are 10 and 20 psf, respectively. Based on the posted signs, the mezzanine live load is 100 psf. Snow and wind loads vary by location on the frame and are shown in Figure 3. Snow loads consider uniform snow fall (balanced condition) and the effects of drift (unbalanced). The seismic load is 14 kips/frame. The warehouse was classified as Risk Category II, which is used for typical buildings. The utility, however, requested the more stringent Risk Category IV, which is for “essential facilities.”

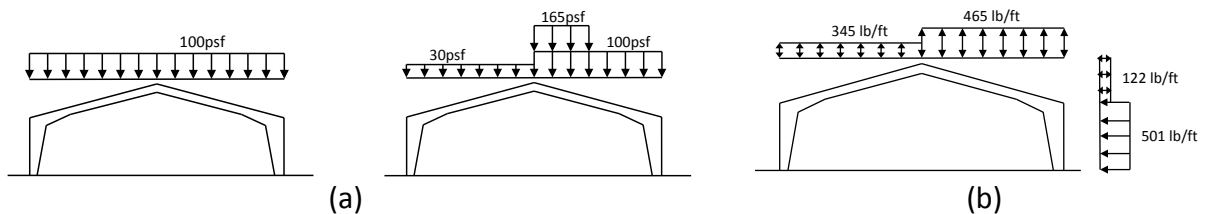


Figure 3. Design loads for: (a) balanced and unbalanced snow loads and (b) wind loads

### Structural Analysis and Retrofit Recommendations

Each structural member was analyzed by determining its demand/capacity ratio. When the demand/capacity was greater than 1, retrofits were designed to mitigate the deficiency.

The demands were determined based on the design loads. Capacities were calculated according to the *American Institute of Steel Construction (AISC) Steel Construction* and American Concrete Institute's (ACI) *ACI: 318-11 Building Code Requirements for Structural Concrete and Commentary*.

Table 1 presents a summary of all of the structural members that the team analyzed. Each of the structural members was analyzed in detail. The analysis and mitigation designs for some of the more critical members follow. Due to project time constraints and the limited information available, the foundation of the structure was not analyzed.

Table 1. Demand/Capacity (D/C) of Structural Members Before and After the Retrofit

Member	Governing D/C		Retrofit Design Recommendations
	Initial	Final	
<b>Frame</b>			
Beam	1.5	0.9	Add 20' of channel (C10x15.3)
Peak connection	0.4	-	
Frame column	0.2	-	
<b>Knee Joint</b>			
Connections	1.3	<1	Weld wider plate and replace bolts
Web	1.3	<1	Add angle with bolts 3" on center
Stiffener Plate	3.2	<1	Add stiffener plate
<b>Interior Columns</b>	2.3	0.6	Add 25' collar of (XS) 8" pipe welded to existing column with four tapered plates
<b>End Wall Columns</b>	0.6	-	
<b>Strut and Roof Purlins</b>	2.5-3.5	0.8-0.9	Add channels either side of frame (C6x6.5 and C9x13.4 for strut and roof, respectively)
<b>Roof Purlins</b>	3.5	0.9	Add 6' of channel either side of frame
<b>Wind Girts</b>	1.80-	0.7-0.9	Add 15' of channel (C3x6)
<b>Sheathing</b>	0.9	-	
<b>Cross Bracing</b>	0.9	-	
<b>Mezzanine</b>			
Beams and Joists	0.32-	-	
	2.25	0.94	Reduce posted storage capacity from 100 psf

Note: C represents a channel cross sections with the nominal depth and weight specified. For example, a C3x6 has a nominal depth of 3" and weight of 6 lb/ft.

Figure 4 shows the steel frame analysis and proposed mitigation. Due to the complex geometry, and statically indeterminate nature of the frame, a structural engineering software program (SAP) was used to determine the governing demands (Figure 4a). The frame fails at the location of the interior column and at the joint where the beam-frame tapers to the column-frame (as

shown by the orange ellipses in Figure 4a). Figure 4b presents the mitigation design which includes bolting a channel inside the frame member to increase the moment and shear capacity and plates to transfer the shear load to the interior column.

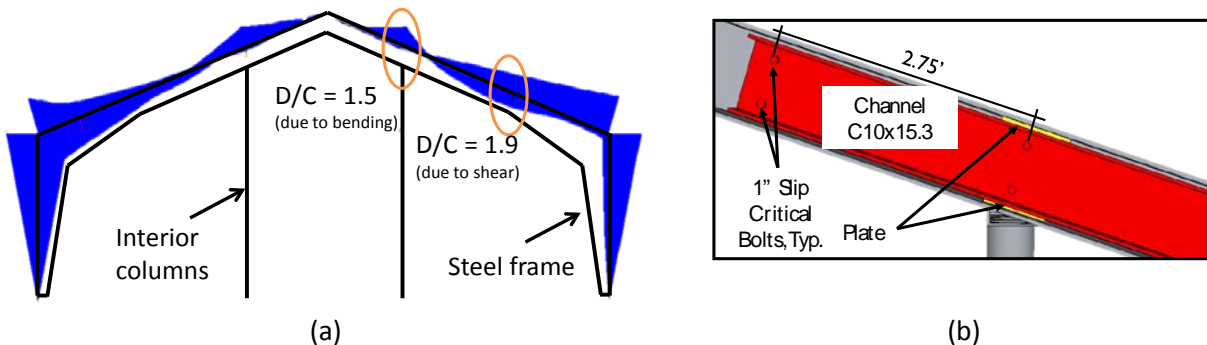


Figure 4. Steel frame: (a) analysis showing moment demand envelope (blue) based on SAP output and points of deficiencies based on demand/capacity (D/C) and (b) mitigation design

The interior columns were found to be insufficient in compression. To increase the capacity, a collar of extra strong (XS) 8 inch nominal diameter pipe will be constructed around the column to a height of 25 feet, as shown in Figure 5. To construct the collars, the 8 inch pipe will be cut along the center, and then welded on-site around the existing columns. To transfer the load from the 6 inch pipe columns to the 8 inch pipe, the connection at the top of the collar will consist of four tapered plates that are welded to the collar (Figure 5).

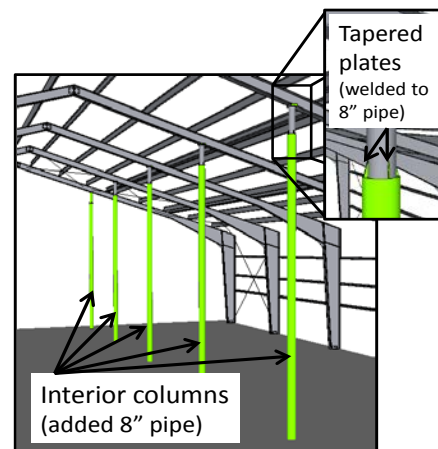


Figure 5. Interior Column Mitigation

Many flexural (bending) members (purlins and wind girts) were found to be extremely deficient, with demand/capacity as high as 3.5. To increase the capacity of these purlins and wind girts, channels were bolted to the insides of the members, as shown in Figure 6. The team sized these channels and detailed the bolt connections.

The mezzanines were found to be deficient at the posted storage rating of 100 psf. Rather than reinforcing these members, the team recommended changing the storage limits to 35 psf. The staff indicated that this change would not affect building operations.

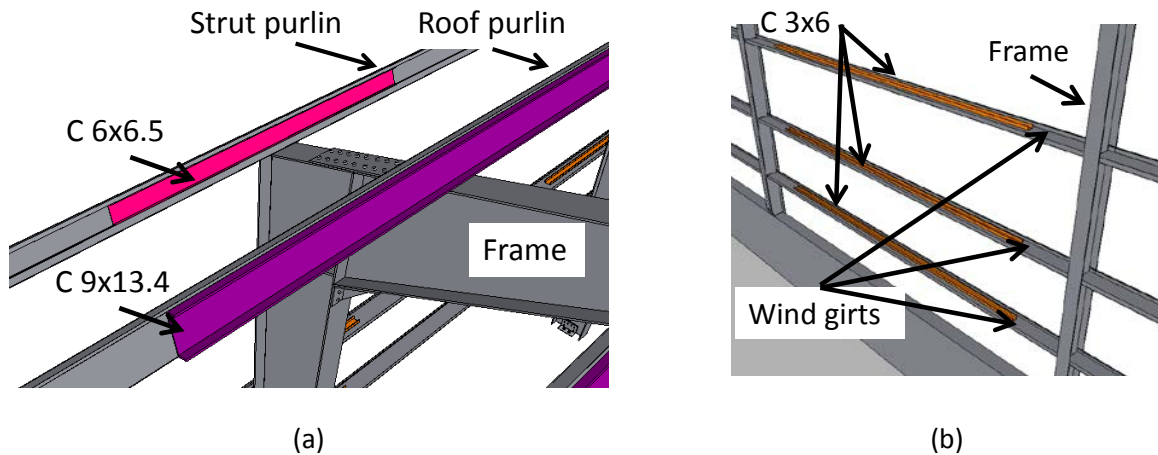


Figure 6. Design mitigations: (a) strut and roof purlins and (b) wind girts

### Final Recommendations Based on Cost Analysis

The team performed a cost analysis that considered two options: (1) to retrofit the existing warehouse based on the retrofit designs and (2) to demolish the building and purchase a new, prefabricated structure to replace it. The total estimated costs of the two options were \$360,000 and \$1.2 million, respectively. After a consideration of the benefits and disadvantages of both options, including the impact on utility operations, the team recommended that the retrofit of the building be pursued.

## II. Collaboration of Faculty, Students and Licensed Professional Engineers

At our institution, senior Civil and Environmental Engineering students are required to complete a year-long, real-world, capstone design project. A diverse team of four students was assigned to this project, working under the guidance of a faculty advisor and three company sponsor liaisons, two of whom were licensed structural engineers and the other a project manager.

As part of the capstone course, students completed: (1) a project proposal during the fall quarter, (2) the major analysis and design work during the winter, and (3) a final report and presentation in the spring quarter. The student team held weekly meeting with their faculty advisor and company liaisons. They gave two presentations to the sponsor – one in the fall detailing the proposal and one in the spring explaining the final design. These presentations were attended by other licensed professional engineers (PEs) and project managers from the sponsoring company.

The team also interacted with licensed professional engineers outside of the sponsoring company. The team's proposal and final report were reviewed by two external licensed structural engineers. They also gave a presentation at the local ASCE chapter in the spring.

### **III. Benefit to Public Health, Safety and Welfare**

Worker Life-Safety - The warehouse poses life-safety concerns for utility workers. Preliminary analysis indicated that the structure would be in danger of collapse if subjected to excessive snow loads. The team immediately contacted the workers using the facility and advised that if snow in excess of 1 foot accumulated on the building, it must be evacuated. All designs considered worker safety. For example, bolted connections were designed for the frames since field welding at significant heights is difficult to accomplish on ladders.

Public Health and Welfare – The warehouse is used to store \$3 to \$5 million worth of utility owned equipment for the maintenance of dams critical to the power supply of a large city. Some of the equipment stored is unique and, if damaged, cannot be replaced for many months. Therefore, damage to the equipment would significantly impact the power supply to a large city, including critical operations such as hospitals.

### **IV. Multidiscipline and Allied Profession Participation**

Client Interaction – In addition to working with liaisons engineers from the project sponsor, the team had extensive interaction with the utility workers at the warehouse location. During site visits they learned about dam operations and the use of the building. In the spring, the team revisited the site to present their findings to the warehouse users. An important topic was the feasibility of the proposed mitigations based on how they would impact day-to-day operations.

Material testing – Although the foundation analysis was not part of the scope, the team evaluated the condition and tested the existing concrete for its compressive strength to (1) analyze anchorage connections and (2) provide the sponsor with data for its future use. The team consulted with a laboratory manager (licensed professional engineer) from a local cement company about the relevant American Society for Testing and Materials (ASTM) standards and ACI provisions.

### **V. Knowledge and Skills Gained**

The senior design experience is unique in that it helps students to develop a variety of important skills needed for practicing engineers.

Technical - The students learned how to assess and analyze an existing structure and then prepare design recommendations to remedy structural deficiencies. This process included using:

- **Building codes** - 2012 IBC, ASCE 7-10, local county code
- **Design specifications** - AISC Steel Construction Manual, ACI: 318-11, ASTM
- **Structural software** - SAP2000
- **Design aid** - Hilti PROFIS Anchor 2 (for foundation anchorage analyses)
- **Presentation aid** - Google SketchUp



Additionally, the students had to take into account **constructability** issues in their design and perform **detailed connection design**, topics not covered in traditional course work. Their final designs addressed **site-specific constructability issues** (such as severe winter weather and issues related to construction in a remote location).

Communication - During the year students developed both writing and speaking skills. They submitted a written proposal and a final report to the sponsor. Students provided detailed engineering calculations to the liaison throughout the year and received feedback. They were also responsible for sending professional emails to the project liaisons. The team presented their project to their peers, the sponsor and a professional engineering society (ASCE). For their final presentation, the team developed a detailed Google SketchUp model of the warehouse, including an animated walk-through of the structure. This model was a powerful way to present their final design mitigations, particularly to more general audiences.

Project Management and Leadership - The team organized weekly meetings with the faculty advisor and sponsor liaisons. Throughout the year, students took turns serving as the project manager. The project manager was responsible for preparing the agenda, leading meetings, assigning tasks, and tracking overall progress.

Cost Estimating - The students prepared cost estimates for two options: retrofitting the structure and replacing the warehouse with a prefabricated building. In addition to material costs, estimates included transportation costs to the remote location. They also considered the effects that each option had on utility operations.

## **VI. Summary**

A four-member student team performed a structural analysis and designed retrofits for a warehouse that poses a life safety threat. The building was originally constructed on one side of the state and later moved and reconstructed at its current location. During reconstruction, multiple modifications were made without adequate structural analysis. The team worked closely with two licensed structural engineers from the sponsoring company, as well as a faculty advisor, to perform a structural analysis of the warehouse. They identified multiple deficiencies and proposed mitigations to address the vulnerabilities. Their final designs considered many constructability issues as well as the overall cost. The students developed technical, communication, project management and cost estimating skills for their future careers as practicing engineers.