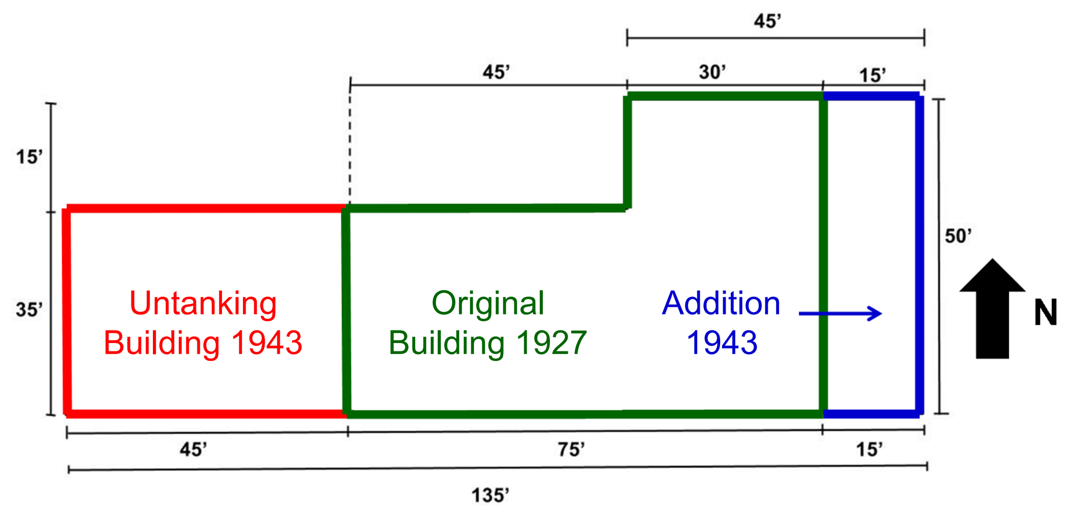
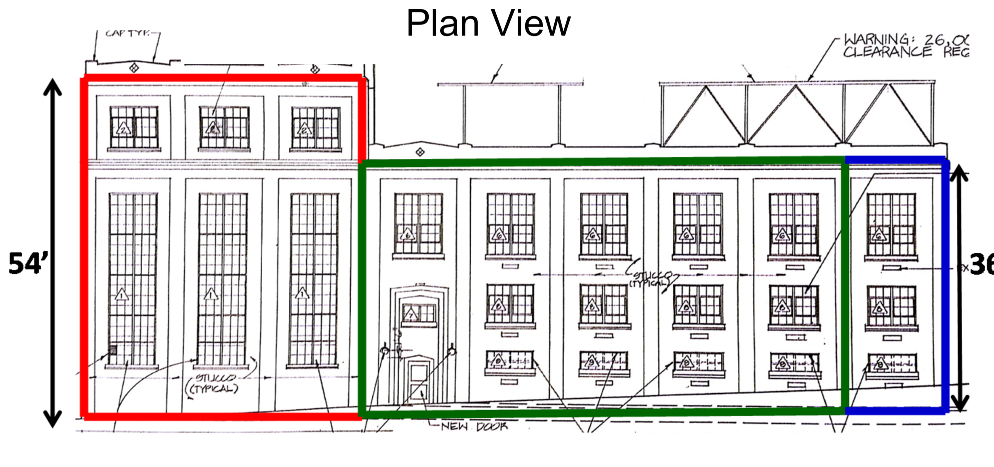
Seismic Analysis and Retrofit Design of a Historic Substation Control Building

Project Description

A local utility company issued a Request for Proposal to our university's capstone program for the structural evaluation and seismic retrofit of one of their control substation buildings. The historic substation was built before official seismic design provisions existed. Due to the importance of the structure for supplying power to a large city, the company needs the facility to be operational after a significant earthquake.



Plan View



South Elevation View

Design Constraints

- **Historic Building** – The building is on the Register of Historic Places. Any proposed modification must preserve historic aesthetics.
- **Constructability** – Proposed mitigations must allow continued use and contain dust, so as to not harm workers or the equipment.

Structural Deficiencies

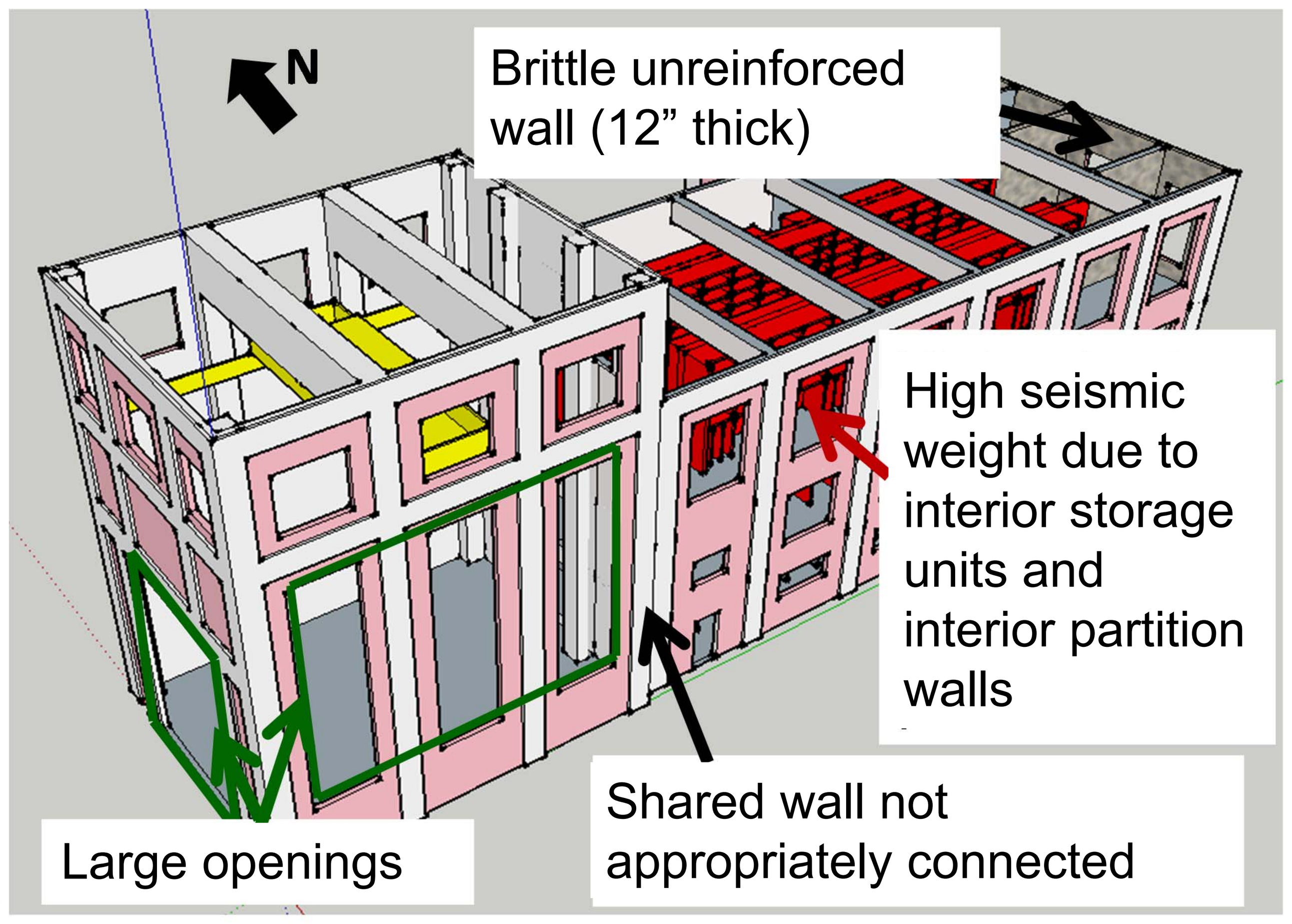
Using seismic standard ASCE 31-03, the students analyzed the building and found seismic deficiencies:

Heavy Interior Shelves – heavy interior concrete storage units and partition walls significantly increase earthquake induced forces

Large Openings – large window openings significantly reduce ability to carry lateral loads induced by earthquake

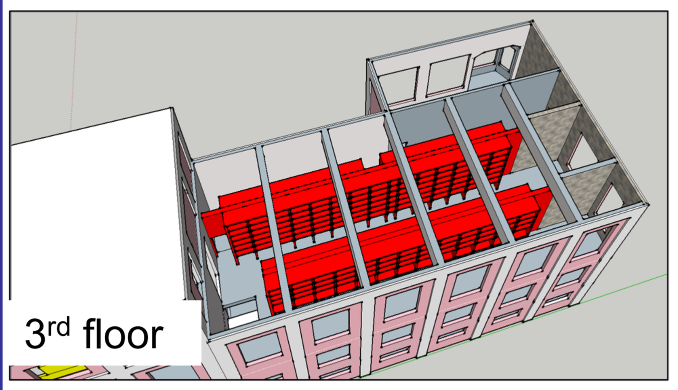
Unreinforced Masonry Wall – east wall prone to brittle failure (without warning) under earthquake forces

Shared Wall Not Properly Connected – wall between original building and addition not properly connected to the two structures. During a major earthquake, buildings may act independently and collide into each other.



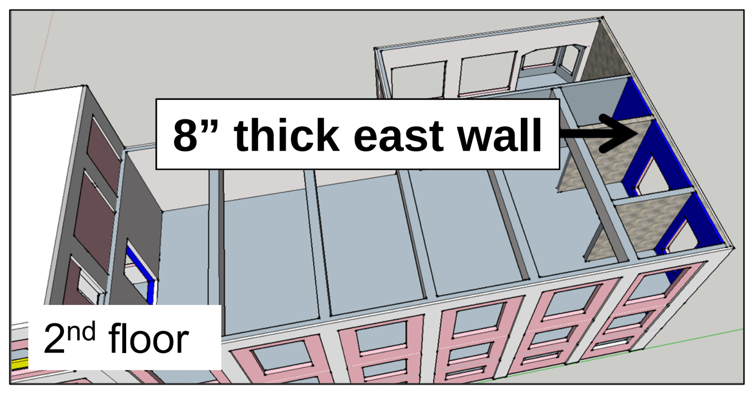
Proposed Mitigations

(1)Remove heavy shelves (red) on 2nd and 3rd floor → reduce seismic weight by 20%



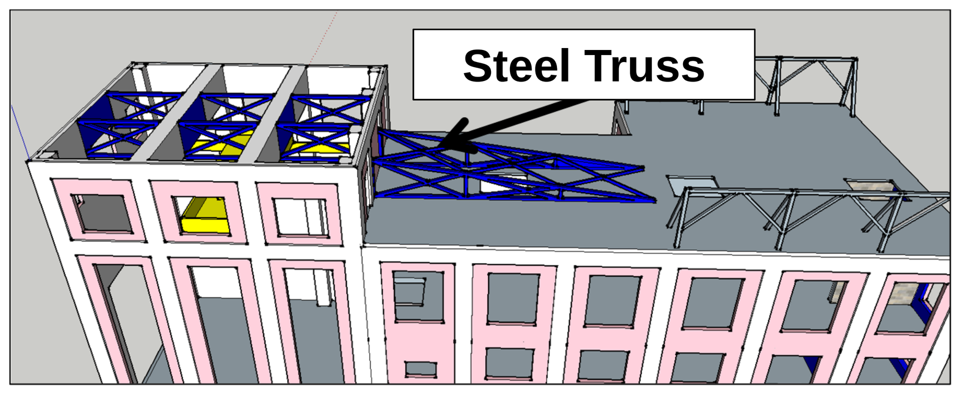
Projected Cost: **$53,000**

(2) Add concrete (shear) walls (blue) on all floors → increase shear wall strength



$130,000

(3) Connect buildings with truss (blue) → buildings will act together in earthquake



$60,000

Student Collaboration with Faculty, Licensed Engineers and Allied Professionals

- Four-student team worked with faculty advisor ***(PE)*** and company liaison (***PE and Structural Engineer (SE)***)

Fall Quarter
- Site visit
- Checking as-built drawings
- Checking old and new code requirements
- Sessions on PM, team dynamics

Deliverables
- Proposal to client
- Presentations to class

→

Winter Quarter
- Seismic tutorials with faculty advisors
- Analysis (using hand calculations and spreadsheets)
- Computer modeling

Deliverables
- Technical memoranda
- Presentations to client/ professional society

→

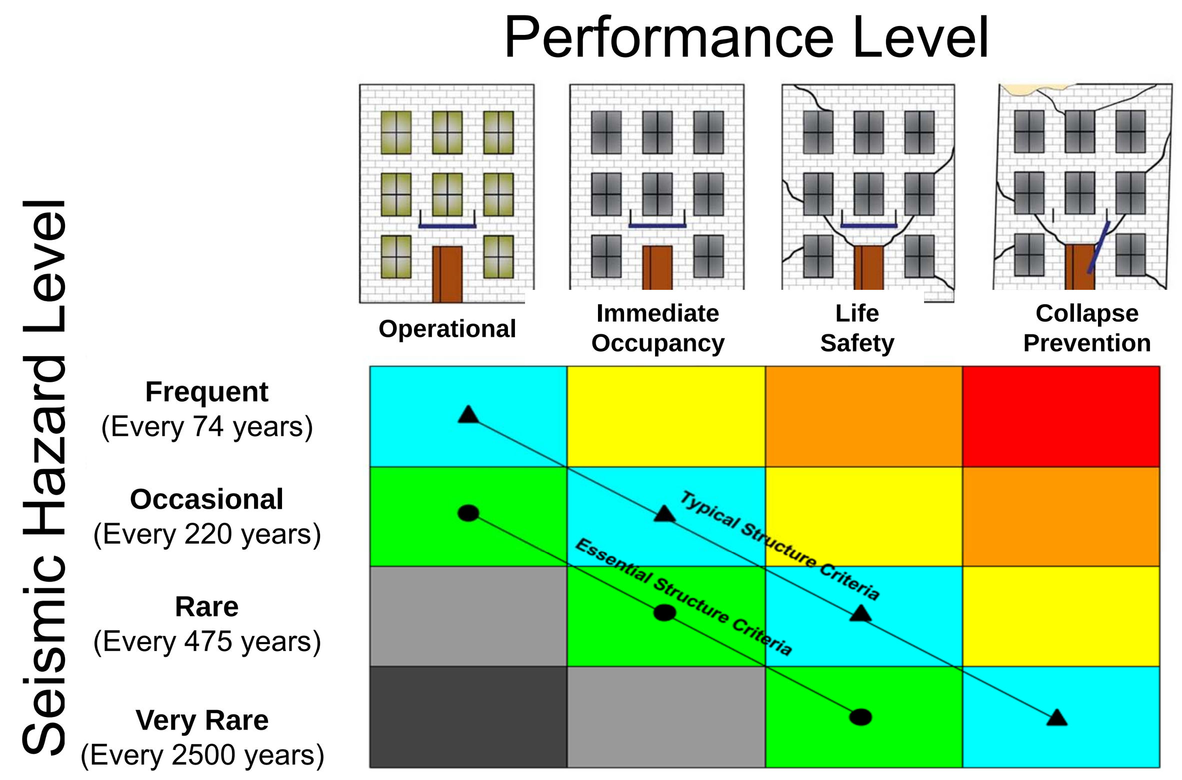
Spring Quarter
- Site visit to verify feasibility of retrofit concepts
- Refine mitigation designs

Deliverables
- Final Report
- Presentations to client/ class/community

- Team presented project to civil engineering capstone class and faculty (multiple sub-disciplines, most faculty with **PE**), power company (attended by individuals from multiple disciplines, many **PEs**) and professional society
- Interacted with allied professions: power company employees, historical specialist and electrical engineer; learned the role art plays in public works projects

Health, Safety and Welfare of the Public

- Substation supplies power to large city → designs ensured it can be occupied after design level earthquake
- Team considered relationship between seismic risk, performance level and cost → gained better perspective on **engineers' responsibility towards the health, safety and welfare of the public**



Based on "FEMA 356: "PRESTANDARD AND COMMENTARY FOR THE SEISMIC REHABILITATION OF BUILDINGS"

Skills Gained

Technical

- Developed understanding of seismic design/analysis
- Learned to analyze existing structure and make appropriate mitigation measures
- Worked with building codes, design specifications, structural analysis software, and presentation aids
- Accounted for historical restraints in their designs
- Gained working knowledge of constructability and connection design

Communication

- **Written** – proposal, presenting calculations, technical memoranda, final report, composing professional emails
- **Oral** – effective presentations to senior design class, sponsor, local chapter of engineering society, use of Trimble-SketchUp® to effectively communicate mitigation concepts to the client and non-engineers

Project Management/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 mitigation options

Seismic Analysis and Retrofit Design of a Historic Substation Control Building

Abstract

A local utility company issued a Request for Proposal to our university's capstone program for the structural evaluation and seismic retrofit of one of their substation control buildings (hereafter referred to as the "Building") which was built before official seismic design provisions existed. Due to the importance of the structure for supplying power to a large city, the company needs the facility to be operational after a major earthquake.

The original Building was constructed in 1927 with major structural additions made in 1943. It is a three-story reinforced concrete structure with a square footage of approximately 13,000 ft^2. The utility company imposed following design constraints: the Building must remain functional in the event of a major earthquake; due to the operational importance of the structure, any proposed mitigations must allow continued use and contain dust, so as to not harm workers or the equipment; because the Building is a historic landmark, any proposed changes need to preserve the aethetics of the original builidng.

Based on the design constraints, the team determined the performance level of the building to be "immediate occupancy" per design code which ensures employee safety and uninterrupted power supply to the city following an earthquake. Considering the relationship between seismic risk, performance level and cost helped the students gain a better perspective on engineers' responsibility to consider the health, safety and welfare of the public in this project.

The team used a two-tiered process specified by the *American Society of Civil Engineers Standard for Seismic Evaluation for Existing Buildings* (*ASCE 31-03*) to perform the seismic assessment of the substation control building. Site visit by the team followed by analysis revealed that, a) the building has a high seismic weight due to interior storage concrete shelves and partition walls, b) the building has unreinforced walls which may fail in a brittle manner without warning, c) the original building and the addition lack appropriate connections enabling the two structures to act independently during a major earthquake.

The team recommended three mitigations: (1) removing the interior shelves and partition walls to reduce the weight and, therefore, the inertial forces caused by an earthquake, (2) adding reinforced concrete walls (referred to as shear walls) to strengthen the building and (3) connecting the original building and the addition with a steel truss at the roof level so that both the structures act together in an earthquake. The projected costs for these mitigations were $53,000, $130,000 and $60,000, respectively.

Four students were assigned to this project and worked under the guidance of a faculty advisor who is a licensed professional engineer (PE) and a licensed professional and structural engineer (PE and SE) from the sponsoring company. As part of the capstone course, students completed: (1) a written 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. Project highlights included site visits, professional presentations to their class, the project sponsor and an outside professional chapter, working with a historical specialist and electrical engineers from the utility company and learning about the role art plays in public works projects. The team also learned to use Trimble SketchUp® to effectively convey their mitigation concepts to the client and non-engineers. The project culminated in an oral and poster presentation event to the university and local 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.

Seismic Analysis and Retrofit Design of a Historic Substation Control Building

I. Project Description

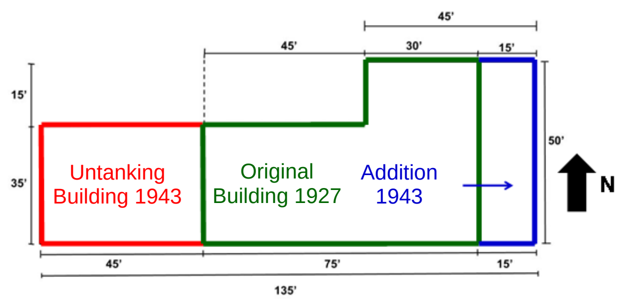
Introduction

A local utility company issued a Request for Proposal to our university's capstone program for the structural evaluation and seismic retrofit of one of their substation control buildings. The historic substation was built before official seismic design provisions existed. Due to the importance of the structure for supplying power to a large city, the company needs the facility to be operational after a significant earthquake.

Background

The substation control building is a three-story reinforced concrete structure with a square footage of approximately 13,000 ft^2. The lowest story of the building is partially below grade. Lateral loads, such as those induced by earthquakes and wind, are resisted by a system of reinforced concrete walls referred to as shear walls.

Figure 1 shows the plan and front elevation views of the control building. The original building was constructed in 1927 with major additions made in 1943. A wing was constructed on the east side and the untanking building against the west side. The untanking building is a single 54 ft-tall story that hosts a crane for handling transformers and other heavy substation components. The second and third floors of the original building contain many concrete shelving units intended for storage and non-load bearing partition walls.



Plan View

(a)

South Elevation View

(b)

Figure 1. Control Building: (a) Plan and (b) South Elevation View

The building is located in a high seismic region. Construction before standard seismic design requirements existed bring into question whether the building can remain functional in the event of a major earthquake. Because the substation provides critical power to a large city, damage to the control building could cause extensive power outages to these areas and inhibit disaster response.

Seismic Assessment Process

The team used a two-tiered process specified by the *American Society of Civil Engineers Standard for Seismic Evaluation for Existing Buildings* (*ASCE 31-03*) to perform the seismic assessment of the substation control building. The first tier consists of a screening phase to identify critical areas of the structural system and establish compliance or non-compliance based on the seismic criteria set forth by *ASCE 31-03*. The second tier involves a more detailed analysis of components identified as noncompliant during the screening phase.

Tier 1 (Screening Phase)

The team began the Tier 1 analysis by conducting a site visit and reviewing the as-built drawings to understand the operations and usage of the facility, identify design constraints, and observe the general condition of the building. They then investigated/researched the standard classification of the building, established the target level of performance under an earthquake, and determined the site seismicity risk using United States Geologic Survey (USGS) Seismic Design Maps. This investigation revealed that the building could be classified as a reinforced concrete structure with shear walls (denoted as Type 2 in *ASCE 31-03*) and that the client wanted to be able to occupy the facility immediately after the occurrence of the design earthquake (referred to as immediate occupancy performance level in *ASCE 31-03*). The team also determined that the building is located in a high seismic region. For clarification, in this building, the perimeter walls of the building serve as shear walls.

At the end of the Tier 1 analysis the team produced a list of non-compliant components within the structure. The major areas of concern they found are shown in Figure 2 and include:

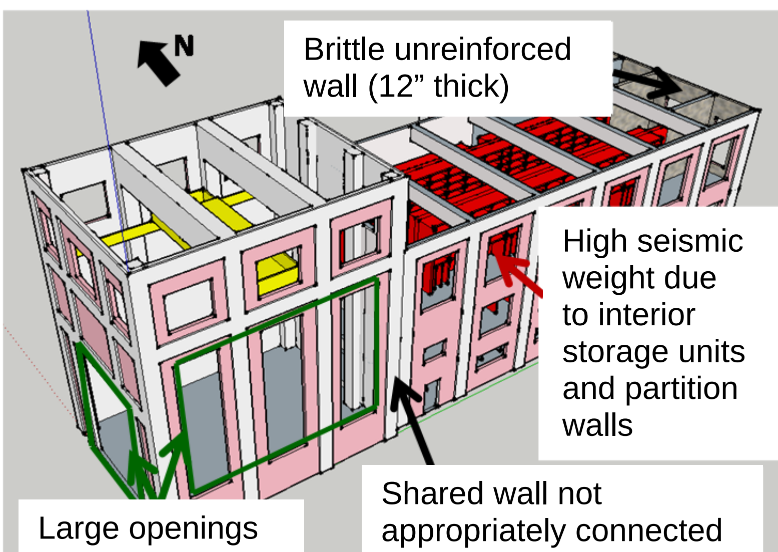


Figure 2. Major Areas of Concern Identified in Tier 1 (Screening) Analysis

- Large openings – untanking building window openings significantly reduce the ability of the structure to carry lateral loads such as those induced during a major earthquake.
- Unreinforced masonry wall – east wall is made of unreinforced masonry which makes it prone to failure in a brittle manner (without warning) during an earthquake.

- Large seismic weight - heavy interior concrete storage units significantly increase inertial forces induced by earthquakes (since inertial forces are proportional to mass).
- Shared wall not properly connected – wall between untanking building and original building is not properly connected to the two structures. In the event of an earthquake, the buildings would act independently and collide into each other.

Tier 2 (Evaluation Phase)

In the Tier 2 evaluation, the team carried out structural calculations to further analyze non-compliant components found through the Tier 1 screening. This phase involved more in depth calculations of the structural demand and capacity of the non-compliant components. For cases in which the demand/capacity ratio was found to be greater than one, the member under evaluation was considered inadequate or non-compliant.

Shear Wall Analysis

In the Tier 1 screening phase, the team found that many of the deficiencies were related to weaknesses in the lateral force resisting system of the building and particularly high shear stresses in the concrete walls. Figure 3 illustrates the calculated vertical distribution of earthquake-induced inertial forces on the control building as dictated by standard building codes. Shear walls must be able to resist these forces. Figure 4 presents the demand/capacity for all the shear walls in the three-story building (original and addition) and shows that the majority of walls did not have enough capacity to support the shear demand from the design level earthquake (demand/capacity > 1). Due to the large openings and significant height of the untanking building this portion of the structure resists little shear and was therefore, neglected in this analysis.

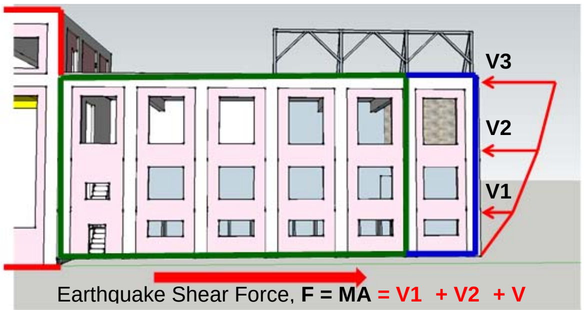
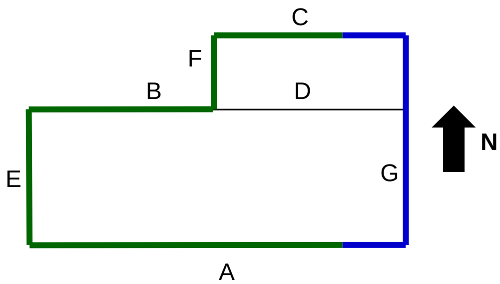


Figure 3. Vertical Distribution of Shear Forces due to Earthquake



Wall	Demand/Capacity Floor 1	Floor 2	Floor 3
A	5.1	4.4	1.2
B	1.5	1.8	0.8
C	1.6	1.5	1.1
D	1.5	1.7	0.8
E	2.1	4.1	0.5
F	0.1	1.1	0.1
G	1.2	1.9	0.6

Grayed out cells show walls that are inadequate (D/C > 1)

(a) (b)

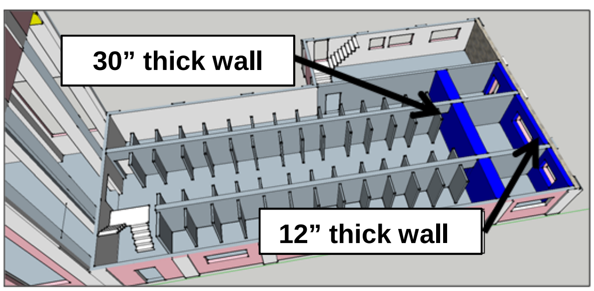
Figure 4. Earthquake Performance Analysis: (a) Building Plan View Indicating Walls Analyzed and (b) Demand/Capacity Ratios of Walls for Earthquake-Induced Forces

Roof and Floor Analysis
The team also evaluated the ability of the roof and floors to transfer forces to supporting concrete walls. The analysis was done by modeling the roof and floors as deep beams supported by the concrete (shear) walls. Calculations similar to the one presented in Figure 4 were done for the roof floors but are not presented here due to space constraint. The team's analysis showed that all floors were deficient for the design earthquake (demand/capacity > 1).

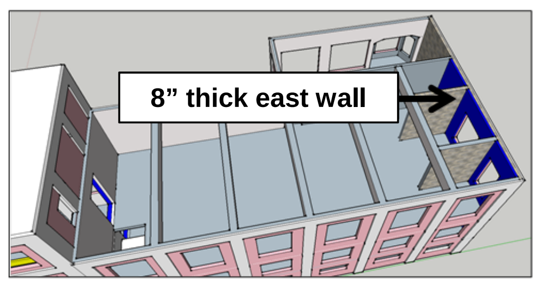
Mitigation Recommendations
To address the deficiencies identified in the Tier 2 analysis, the team proposed a number of mitigation measures.

Removal of Interior Walls
Heavy concrete cabinets on the third floor of the building, shown in Figure 2, were originally constructed for storage of equipment but they are rarely used. Because these cabinets are not connected to the floors, they do not provide vertical or lateral load resistance to the building. Additional interior concrete walls on the second floor are used as partitions but they do not extend the entire height of the floor and they do not contribute to the load resisting system of the building. Demolishing these cabinets and partition walls will reduce the seismic mass of the building by approximately 20 percent, which leads to similar reductions in the lateral force induced by earthquakes.

New Shear Walls
The team proposed adding new shear walls to reduce the stress demand on walls induced by earthquake loads. They provided reinforced concrete walls against the existing masonry walls on the east side walls to provide extra stiffness/strength and, thus, better performance in the case of an earthquake. Figure 5 shows the proposed shear walls for the first and second stories of the building.



(a)



(b)

Figure 5. Retrofit of Reinforced Concrete Shear Walls for (a) First and (b) Second Floor

New Steel Roof Truss
Figure 6 depicts the steel roof truss designed by the team to connect the roof of the untanking building to the roof of the original building so that both structures act as a single unit in the event of an earthquake. The proposed roof truss is to be constructed with double angles (2L6x6x5/16) throughout to facilitate constructability.

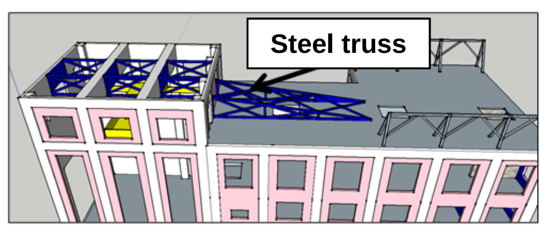


Figure 6. Steel Roof Truss Design

Cost Estimate

Table 1 provides a breakdown of the estimated costs for the proposed mitigation for the additional shear walls, roof truss, and demolition of the interior walls and cabinets in the second and third floors. The listed unit costs include labor and material and a 20% contingency to account for any unforeseen situations.

Table 1. Cost Estimate for Proposed Mitigations

Mitigation Design	Unit Cost, $	Quantity	Unit	Estimated Cost, $
Wall				
Concrete	300/yd^3	130	yd^3	39,000
Reinforcement	5/lb	18,200	lb	91,000
Roof Truss	5/lb	11,730	lb	59,000
Demolition	10/ft^2	5,250	ft^2	52,500
			Total Cost	241,500
			20% Contingency	48,300
			Final Cost	289,800

II. Collaboration of Faculty, Students and Licensed Professional Engineers

At our institution, senior Civil Engineering students are required to complete a year-long, real-world, capstone design project. Four students were assigned to this project and worked under the guidance of a faculty advisor who is a licensed professional engineer (PE) and a licensed professional and structural engineer (PE and SE) from the sponsoring company.

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. To accomplish these tasks, the student team held two weekly meetings: one with their faculty advisor and the other with both the faculty advisor and company liaison. Students gave three presentations to the sponsor: the first was late in the fall detailing their design proposal, the second one was early in spring showing some of the design concepts and getting feedback and the last presentation was late in the spring explaining the final design. These presentations were attended by other licensed professional engineers (PEs) and project managers from the company sponsor. The team also interacted with licensed professional engineers outside of the sponsor company by giving a presentation at the local chapter of the Structural Engineers Association (SEA) in winter.

III. Protection of Health, Safety and Welfare of the Public

The substation supplies power to a large city; therefore, ensuring it can be occupied after a design level earthquake protects public health, safety and welfare. Figure 7 illustrates the relationship between seismic hazard level and building performance level. For a typical structure (denoted by turquoise and triangles) the structure must remain operational after frequent earthquake events and must not collapse after very rare earthquakes. Essential facilities (denoted by green and circles) have more stringent design criteria. Because the substation serves a large city, the utility company considers it critical for it to remain operational after a design level earthquake. The team determined that the performance level of the building should, therefore, be immediate occupancy ensuring that employees are safe and that power can still be supplied to a large city. Considering the relationship between seismic risk, performance level and cost helped the students gain a better perspective on engineers' responsibility to consider the health, safety and welfare of the public in this project.

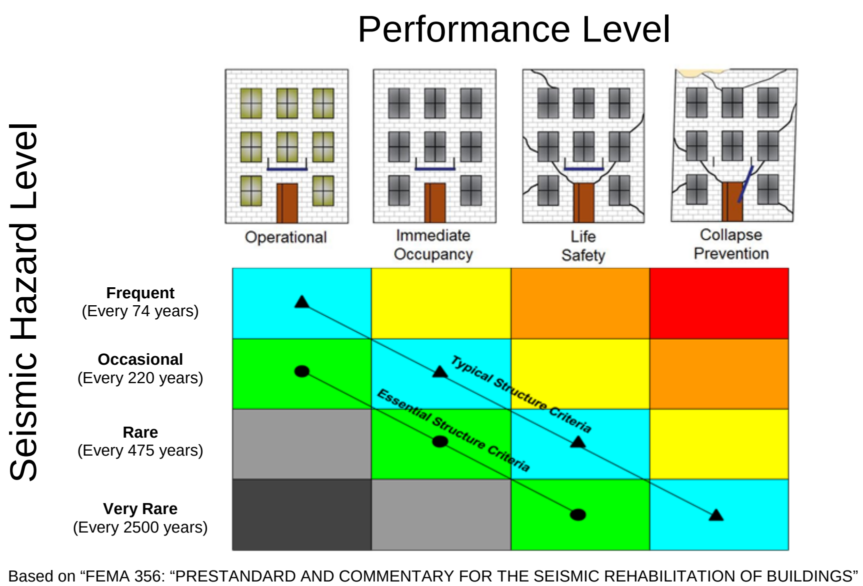


Figure 7. Relationship between Seismic Hazard and Performance Level

IV. Multidiscipline and Allied Profession Participation

The project included opportunities for the students to interact with other disciplines and licensed PEs.

Utility Company Interactions – During the site visit, the design team interacted with utility company workers and PEs to learn about the site. They also presented their proposal (late fall), preliminary design concepts (early spring) and final recommendations (late spring) at the utility company to an audience that included staff at the substation control building, project managers and engineers (all PEs).

Historical Preservation – The substation control building is a historical landmark. During the winter quarter, the students met a historical specialist who works at the utility company. They learned about the company's Historic Management Plan and that the aesthetics are to be preserved. In the spring they met again with the specialist to make sure that the proposed mitigation schemes did not significantly affect the historical appearance of the building.

Electrical Engineering – The substation control building houses important electrical equipment. To help the team better understand this equipment and the operation of the facility, they met with an electrical engineer from the utility company.

Art

The substation control building has an art budget to contribute to the aesthetics of the neighborhood. The building is painted pink and cultural images are projected through the windows at night. During their facility tour the team learned about the inclusion of art in public works projects. Their final mitigations had to preserve the art features of the building.

V. Knowledge and Skills Gained

The senior design experience helps students to develop a variety of important skills needed for practicing engineers.

Technical – The students learned to assess and analyze the **seismic performance** of an existing structure and prepare design recommendations to remedy structural deficiencies. This process included using:

- As-built drawings
- Building codes - *2012 International Building Code*, *ASCE Minimum Design Loads for Buildings and Other Structures (ASCE 7-10)*
- Computer-aided drafting - AutoCAD
- Design specifications –*American Institute Steel Construction Manual 14th ed.*, *American Concrete Institute Building Code Requirements for Structural Concrete (ACI 318-11)*
- Geotechnical report
- Presentation aid – Trimble® SketchUp
- Seismic analysis standard - *ASCE 31-03*
- Structural analysis software - SAP2000
- United States Geologic Survey (USGS) Seismic Design Maps

Additionally, the students had to take into account **constructability** issues in their design and perform **connection design**, topics not covered in traditional undergraduate course work. Their retrofit designs addressed **site-specific constructability issues,** such as allowing continued use of the building and containing dust, so as to not harm workers or the equipment.

Communication - During the year students developed both writing and speaking skills. In addition to the proposal and final report, the students also provided detailed engineering calculations and technical memoranda to the liaison throughout the year and received feedback. They were also responsible for sending professional emails to the project liaisons in order to request information and to plan meetings and site visits. The team prepared oral presentations for their senior design course, the project sponsor and a professional engineering society. For their final presentation, the team developed a detailed Trimble® SketchUp model of the substation control building, including a walkthrough of the building showing the proposed mitigations. This model was a powerful way to present their final retrofit options, particularly to a more general audience.

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.

VI. Summary

A local utility company requested that a capstone team from our civil engineering program perform a seismic evaluation of a substation control building that is critical for supplying power to a large city. The team worked closely with a licensed professional and structural engineer from the power company, as well as a faculty advisor who is also a licensed professional engineer, to identify deficiencies that could prevent the building from maintaining an immediate occupancy performance level following a design level earthquake. All mitigation designs considered the historic nature of the building and ensured that demolition/construction would minimize impact to building operations. The students developed valuable technical, communication, project management and cost estimating skills for their future careers as practicing engineers.