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Role and Impact of Structural Retrofit Capstone Projects*

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Robust capstone experiences in civil engineering can be built around modifications to existing structures as opposed to the design of new structures. They require students to not only analyze the systems and identify deficiencies, but also to develop mitigation measures that are feasible and constructible with the existing system. Structural retrofit design projects also expose students to topics that are not covered in a standard undergraduate curriculum. These topics include building codes, lateral loads (wind and seismic), aluminum, timber, and reinforced masonry design, constructability issues, specialized computer programs (Hilti Profis™, SAP™) and visualization tools (Solid Works™, Trimble SketchUp™) that can convey the design to the client clearly. In our curriculum, students start working on these projects before taking structural design courses and, as a result, spend much of their time learning as they go. Due to the complex nature of engineering retrofit projects, having a good relationship between the department and the project sponsor is important. In this paper we present the students' experiential learning experience through three structural retrofit projects as case studies as well as discuss the technical and professional skills that students develop. We also provide assessment data, which indicate that graduates believe these projects were beneficial in preparing them for professional practice.

Keywords: structural retrofit; constructability; visualization; assessment

1. Introduction

In civil engineering as well as other disciplines, capstone projects forge an important connection between education and personal experience within the context of authentic, real-world problems [1–3]. Experiential learning opportunities have been investigated for structural engineering students. Palmer et al. [4] and Unterweger [5] incorporated simple structural design projects in first year civil engineering courses and found that these projects enhanced student learning. Fernández-Sánchez and Millán [6] used hands-on truss building and design projects that culminated in a final rapid bridge-building competition in their structural analysis course. Students performed calculations by hand and using structural analysis software and then tested the structure in the laboratory to see how it actually behaved in comparison with their predictions. Students were motivated to learn by this process and felt they had learned more about civil engineering building materials from the experience than from conventional class lectures. Labossière and Bisby [7] reported on the development of a design competition of a pedestrian walkway in which graduate students participated. The students indicated that involvement in the competition improved their understanding of basic structural engineering principles, relationships between these principles and real-world applications and also improved their professional skills. Albano [8] developed a practice-oriented steel design term project in which students designed a low-rise steel building. He found that this realistic activity better met the course goal of developing their ability to apply knowledge. Quinn and Albano [9] reported on using problem-based learning as part of a structural engineering senior project at Worcester Polytechnic Institute. Students chose a building type (steel, reinforced-concrete or timber) that they wanted to design and used an actual building on campus to serve as a reference for their design. They also identified a faculty mentor. Students liked the hands-on nature of the project, direct faculty involvement and increased knowledge of previous concepts covered in their coursework. These studies all suggest that student learning is improved when they can learn by doing. However, student assessment data are limited because students were not directly surveyed and the projects described do not involve authentic experiential learning. This study seeks to add to this body of knowledge by including these two aspects.

At Seattle University, civil engineering students participate in a real-world senior capstone project that involves authentic experiential learning. This paper presents the senior capstone program at Seattle University and its relationship to structural engineering projects within the department. In the past 27 years, the civil engineering department has completed almost 150 projects, of which 27 are structural and include the design of buildings, bridges, transmission towers and building expansions. In our curriculum, structural projects provide a unique opportunity for experiential learning because the students encounter analysis and design before they have had coursework in these areas. In contrast, students have taken most of the

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required coursework in other sub-disciplines within civil engineering, for example, for environmental, geotechnical and water resources projects before senior year begins.

Structural projects can primarily be classified into two main categories: brand new design of a structure or retrofit of an existing structure. In the case of the design of a brand new structure, the designer starts with a clean slate and has to design structural elements/systems that meet the current building codes. However, in the case of structural retrofit projects, the designer is constrained by the existing structure. Design of a new structure or system requires the analysis of loads, selection of materials and constructability. In retrofit designs, students must learn how to analyze existing systems, including reading as-built drawings, conducting site visits, and understanding older building codes. From there, they must identify deficiencies and then propose mitigation measures that are constructible, compatible with the existing conditions and that minimize disruptions to the operation of the existing facility. In this paper, we describe the special considerations in structural projects through three recent example retrofit projects completed by our students. Student survey assessment data are also presented. Finally, we present faculty perspectives on best practices for carrying out these types of projects.

2. Background

Civil Engineering seniors at Seattle University participate through authentic involvement in a year-long capstone project that is sponsored by industry. Students work in teams of three to four under the guidance of a project coordinator, faculty advisor and a liaison from the sponsoring company. Fig. 1 shows the timeline for the capstone course, including typical deliverables. The capstone course meets regularly in the fall quarter, during which professional skills sessions are held about teamwork, team dynamics, technical writing, oral communication and project management. These sessions are often offered by outside experts. During the winter and spring quarters, the class meets less frequently, allowing the teams to have more time to focus on their individual projects. As part of the capstone course, students complete: (1) a written proposal during the fall quarter, (2) most of the analysis and design work during the winter quarter and (3) a final report in the spring quarter. In addition, they give two presentations to the sponsor—one in the fall detailing their project understanding, scope of the project and their plan of implementation and another in the spring explaining the final design. Teams typically spend about 700–1000 hours per project during the nine-month period. Throughout the year, the student teams meet weekly with their faculty advisor and sponsor liaisons to discuss project details and progress.

In structural capstone projects, students have the opportunity to learn the main elements of the design process (analysis, use of codes/specifications/standards, and the holistic design approach) before they have had structural design courses. In our curriculum, reinforced concrete design and steel design are offered in the winter and spring quarters of senior year. Thus, students carry out many of their design project calculations for courses that they have not yet seen formally in the classroom. Furthermore, during these projects students are exposed to topics outside the curriculum including aluminum, timber and reinforced masonry design, lateral load analyses (wind and seismic), and computer software programs (Hilti Profis™, SAP2000™, Solid Works™, Trimble SketchUp™, etc.)

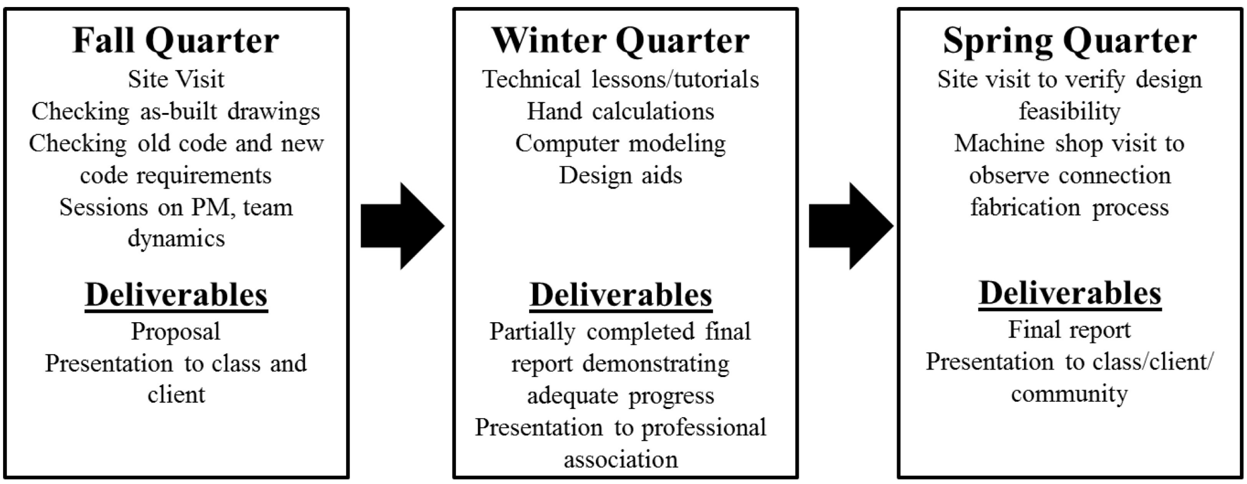


Fig. 1. Senior capstone course timeline with deliverables for retrofit projects.

3. Retrofit project case studies

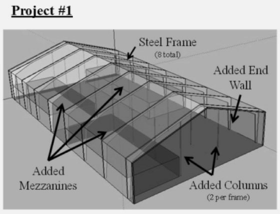
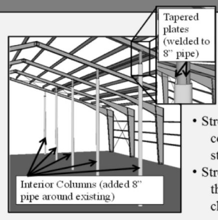
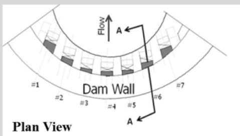
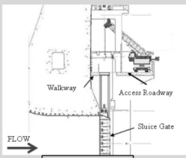
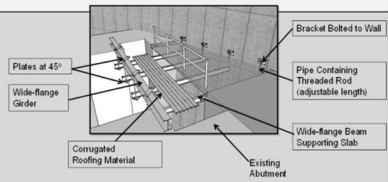
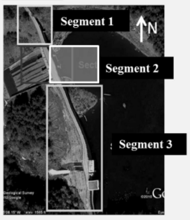
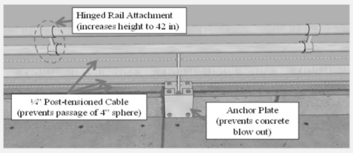
Table 1 shows three examples of structural retrofit projects completed at Seattle University. The projects include the structural retrofit of a relocated steel warehouse, dam maintenance walkways and safety features on a dam. These three projects cover a wide range of structural types and materials, design codes and specifications and constructability issues. They were all sponsored by the same local utility company, Seattle City Light (SCL). Table 1 provides a brief description of each project, the challenges faced, examples of retrofit recommendations and pedagogical considerations. Specific details of the three projects are highlighted below with special considerations due to the nature of these being retrofit project, as opposed to new structures, *italicized.*

The first project involved a structural evaluation and retrofit designs of a warehouse that was originally constructed in the north east corner of Washington State in the city of Boundary and later moved over 300 miles and reconstructed at its current location in northwest of Washington State in the city of Newhalem in the late 1980's. During reconstruction, multiple modifications were made without formal structural analysis. As a result, the building was not up to current codes and thus posed a life-safety threat to its employees. The capstone project began with a site visit and *creation of as-built drawings* describing the existing structure, since none existed. Next, the design loads were determined according to applicable modern building codes. Finally, a structural analysis was performed and retrofits were designed for those members that were found to be deficient. Due to the operational importance of the structure, *mitigations had to be able to be completed while the building was in use*. In addition to weekly project meetings with the liaison engineer, a SCL structural engineer offered weekly steel design tutorials to the students, since they had not yet taken a steel design course. The team used Trimble SketchUp^{TM} to create a three-dimensional model of the structure, which helped them to visualize and communicate the retrofit options to the client. They also went on a *second site visit in the spring quarter to verify that their designs were constructible*. This visit also involved discussions with the users of the facility.

In the second project Seattle City Light requested a capstone team to develop repair and replacement designs for damaged reinforced concrete walkway slabs that are located at each of Boundary Dam's (Boundary, WA) seven sluice gates. The walkways are routinely used by staff for dam maintenance, posing a life-safety issue. During the site visit the team observed a number of site-specific challenges, including remote location, variable slab geometry, limited walkway access and an aggressive environment. The team prepared two separate design concepts: (1) steel retrofit and (2) reinforced concrete slab demolition and replacement plan. While the analysis and designs required the students to learn reinforced concrete and steel design, they also needed to *visualize the demolition/construction sequencing and connections that are compatible with the existing structure and do not affect facility operations*. The team used Trimble SketchUp^{TM} to build a three-dimensional model of the two alternative solutions. They also visited the SCL's fabrication shop to observe one of their proposed wall bracket connections being made. This experience was helpful because it showed the team what the fabrication process was like and also allowed them to watch someone interpret their drawing. *Construction of either option was challenging due to the existing structure posing worker safety and environmental issues* because there is no access below the slab without the use of complex scaffolding. The final design considered worker safety by not requiring any person to go below the slabs during repairs, protecting workers from being struck by falling debris. Because construction work would occur directly over the river, all *designs include methods to prevent debris from falling into the water and causing contamination*.

In the final project SCL asked SU's capstone program for the retrofit design of safety features (concrete parapet, handrail and vehicle barrier) on the walkway located at the crest of the historic Cedar Falls Dam (Cedar Falls, WA) that pose a life-safety concern. The design was to consider current loading and geometric standards, the *historic aesthetics of the original dam*, and to *minimize the environmental impact* from any proposed construction. *To evaluate the condition of the existing safety features, the team used historic drawings, site visit data, and experimental data*. The team prepared replacement and retrofit options to address the geometrical and strength deficiencies for each of the safety features. Much of this work required an understanding of reinforced concrete behavior before the students had taken any related coursework. They also needed to understand aluminum specifications, a topic not covered in our curriculum. To analyze and design anchorage connections, they used commercially-available software, Hilti Profis^{TM}, with assistance from the project liaison and faculty advisor. Designs of the dam safety features for each section were presented to the client using Trimble SketchUp^{TM} and SolidWorks^{TM}. The team also met with SCL specialists to discuss the *historical and environmental concerns* of the project. Because the dam is part of a

Table 1. Summary of Structural Retrofit Projects Completed at Seattle University

Project Description	Problem/Challenges	Example Retrofitting Scheme	Pedagogical Considerations and Design Impact
Project #1  **Relocated Steel Warehouse** • 150 x 80ft footprint • Provides office space, gymnasium, and storage of key replacement parts for SCL's powerhouses and dams	• After relocation multiple modifications were made without formal design • Typical steel frame inadequate in flexure to sustain extreme snow loads thus posing a safety concern	 • Strengthening of interior columns through added structural tubes • Strengthening of roof beams through insertion of a steel channel (not shown)	• Students had to consider constructability as mitigation schemes needed to be implemented while the building was in use. • Students used 3D visualization tools to better define the solutions and explain them to the client
Project #2   **Section A-A** **Boundary Dam Walkway Slabs** • Walkway slabs located above the sluice gates • Staff routinely use the walkways for dam maintenance	• Life-safety concern for staff using the deteriorated walkways • Excessive cracking and large deflections observed in slabs. • Limited access for hauling of construction materials and construction • Irregular slab geometry • Environmentally sensitive project site	 • Installation of steel beams to facilitate demolition of existing slab and also as supports for the construction of new slabs. • Installation of steel beams to serve as supports and reduce deflections/cracking. • No slab demolition required (shorter service life of repair).	• Students saw the fabrication process of a component of their design and how a machinist interpreted their drawings. • Students had to think about worker safety and environmental issues • Use of 3D visualization tools .
Project #3  Plan View **Cedar Fall Dam Safety Features** • Cedar falls provides power and water to Seattle • Dam walkway is used for maintenance as well as public tours	• Walkway safety features were too short • Vertical spacing between the horizontal bars of the handrail and vehicle barrier is too large • Severely degraded concrete parapet • Maintain historic features of the dam while minimizing the environmental impact	 • Retrofit design of the vehicle barrier, including rail attachments, post-tensioned cable, and anchorage plate. • A reconstruction of concrete parapet for the pedestrian walkway was also developed (not shown here)	• Students learned about standard code requirements for safety features. • Students had to consider environmental and historical aspects of their project • Students learned to use commercially-available software for anchorage connections.

watershed, construction is regulated to *reduce contamination of the water*. With this consideration in mind, the team delivered designs that minimize on-site work that could pollute the water.

4. Transferability of capstone model to new structures

The three retrofit project case studies presented previously show that some common overall themes exist in retrofits. The projects posed many challenges that are unique to retrofit projects, such as the ability to read as-built drawings, understanding the old and new building codes, constructability and realizing the compatibility of the proposed solutions with the rest of the structure, aesthetic issues, environmental conditions during demolition, disposal of demolition materials, and ensuring that the structure remain functional/usable during the retrofit. Fig. 2 summarizes the three main considerations in retrofit projects: (1) analysis and design, (2) environmental and historic impact and (3) constructability with the aim of ensuring public health, safety and welfare.

The authentic experiential learning model presented in this paper for structural engineering retrofit projects also applies to projects involving new designs and other branches of engineering. Faculty believe that the main difference between new designs and retrofit designs is the added constraints imposed by an existing structure. With our nation experiencing aging infrastructure and increasing population growth, the retrofit of existing facilities and/or systems will become a common occurrence in the future. Therefore, the project issues discussed in this paper have a wider applicability within other branches of engineering.

5. Student skill development

Retrofit capstone projects provide students the opportunity to develop both technical and professional skills.

5.1 Technical skills

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

- As-built drawings and field work—Students had to interpret and verify existing drawings in the field. They also evaluated the feasibility of implementing their final designs on site.
- Building codes—2012 International Building Code, American Society of Civil Engineers Stan-

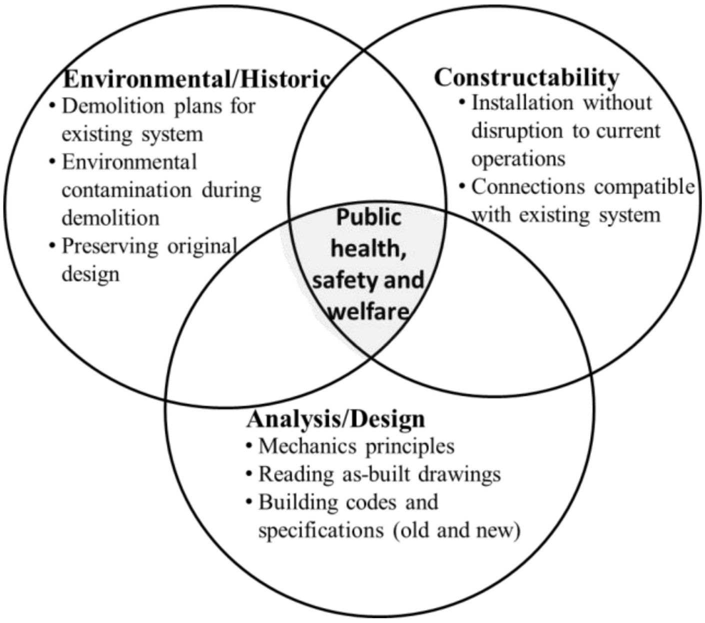


Fig. 2. Main considerations in retrofit projects.

dard 7–10, local county code as well as researched historic codes from the time of original construction

- Computer-aided drafting—AutoCAD™ to develop the engineering drawings
- Cost estimate catalogs—RS Means
- Design specifications—American Institute Steel Construction Manual (AISC) 14th ed., American Concrete Institute (ACI): 318-11, American Standards for Testing and Materials (ASTM)
- Structural analysis software—SAP2000™, Hilti Profis™
- Presentation aid—Trimble SketchUp™, Solid Works™

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 retrofit designs addressed *site-specific constructability issues* (such as severe winter weather, issues related to construction in a remote location, demolition). Finally, they learned about other topics not covered in our undergraduate curriculum such as lateral loads (wind and seismic), aluminum, masonry and timber design, concrete materials testing, structural load testing and anchorage of components to reinforced concrete.

5.2 Professional skills

During the year students developed both writing and speaking skills. The students submitted a written proposal and a final report. They provided detailed engineering calculations to the liaison throughout the year and received feedback. The students were also responsible for sending professional emails to the project liaisons. 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 detailed Trimble SketchUp™ virtual models of their designs. This model was a powerful way to present their final retrofit options, particularly to a more general audience.

The students also developed project management and leadership skills, including organizing weekly meetings with the faculty advisor and sponsor liaisons. Throughout the year, students took turns serving as the project manager and, thus, being responsible for preparing the agenda, leading meetings, assigning tasks, and tracking overall progress.

6. Student learning assessment

After the projects had been completed, alumni were sent a survey asking various questions about their experience participating in a structural retrofit design project. We administered the survey this year (2014) to all of the alumni. Of the thirteen alumni who had worked on the three projects described previously, nine (70%) responded. The results of this assessment follow.

6.1 Quantitative assessment

Table 2 presents responses to survey questions based on a Likert scale in which alumni were to rank their agreement to the statements provided (1 being strongly disagree and 5 being strongly

Table 2. Statistical Analysis of Structural Retrofit Project Survey Responses based on a Likert scale (1 being strongly disagree and 5 being strongly agree) (number of responses = 9)

Question	Mean ± St. Dev.
Working on an existing structure was beneficial towards achieving my educational goals	4.8 ± 0.4
Compared to working on an existing structure, I believe working on a new structure would have been more beneficial towards achieving my educational goals	2.7 ± 0.7
It was challenging to do structural analysis and design before taking Reinforced Concrete or Steel Design courses	3.9 ± 0.9
The design work I did in my project prior to taking structural design courses (Reinforced Concrete or Steel Design) strengthened my learning experience when I took my structural design courses	4.4 ± 0.7
Sponsor-provided resources, such as machine shop fabrication, meeting with an environmental specialist or historical expert, or training sessions for design, enhanced my senior design experience	4.4 ± 0.7

agree). Alumni's perceptions of working on existing structure versus a retrofit project were surveyed in the first two questions. Overall, alumni strongly felt that working on an existing structure was beneficial toward achieving their educational goals (mean response = 4.8). Furthermore, they did not feel that working on a new structure would have been more valuable (mean response = 2.7).

The effect of the experiential learning components of the retrofit projects was also assessed. Alumni found it was challenging to conduct structural analysis and design before taking design courses, with a mean response = 3.9. They also agreed that the senior project design work later helped them in their reinforced concrete design and steel design (mean response = 4.4). Finally, alumni agreed that sponsor-provided resources, such as machine shop fabrication, meeting with an environmental specialist or historical expert, or training sessions for design, enhanced their learning experience (mean response = 4.4). Overall, these responses indicate that the structural retrofit project was a beneficial experience for the alumni to achieve their educational goals and that the experiential learning of the project enhanced their learning experience when they took subsequent coursework.

We asked alumni to assign a percentage to various aspects of the project that contributed to their technical and professional skills that they gained from the project. Fig. 3 presents the results for the technical skills. Overall, alumni found that independent or student team work contributed the most to the technical skills that they gained from the project (38%). Interestingly, they ranked faculty mentoring (25%) and discussion with the liaison (23%) to be almost the same. They found that field visits/fieldwork constituted 14% of their overall development. Fig. 4 presents the results for the professional skills gained in the project. The respondents believed that the most significant contribution to these skills came from technical communication (writing proposals, engineering documents and the final report (45%) and presentations (40%)). Alumni attributed 15% to faculty mentoring.

Finally, we asked the alumni about the importance of the sponsor liaison relationship to the success of the project. The alumni unanimously agreed that the liaison was familiar with the senior capstone program. Respondents were then asked if the project scope was unclear, reasonably defined or well defined. Seven of the respondents felt the project scope was reasonably defined, one respondent believed the project scope was unclear and another felt the project was well defined. We believe the close relationship we have with the liaison (Seattle City Light), and their past experience sponsoring projects, contribute significantly to having projects with well-defined scopes.

6.2 *Qualitative assessment*

In addition to the quantitative assessment, we also asked alumni what were the most and least valuable

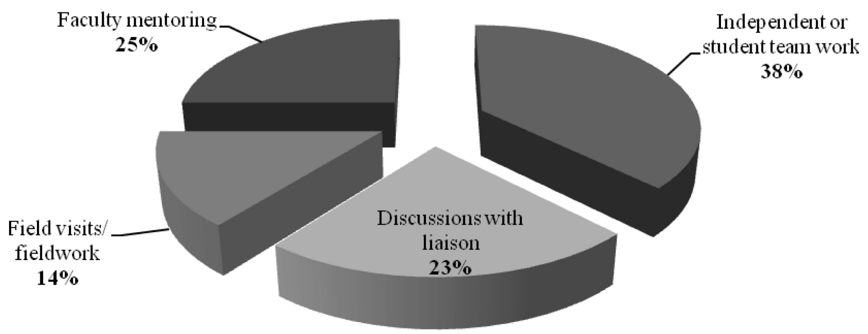


Fig. 3. Capstone student survey responses about perceived sources of technical skill development (number of responses = 9).

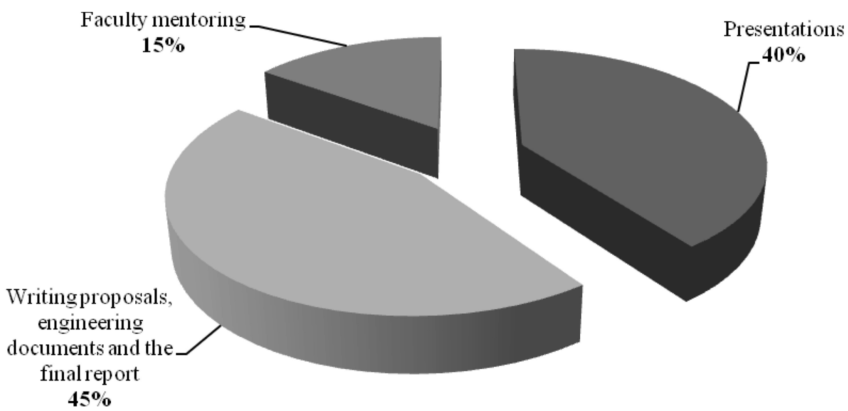


Fig. 4. Capstone student survey responses about perceived sources of professional skill development (number of responses = 9).

aspects of their structural retrofit senior project experience. Of the most valuable responses, the common themes are the real-world nature of the projects and professional skills development. Some of the alumni feedback is presented below:

- "Experiencing a project from start to finish, from learning to manage the team, develop a scope of work that the client would approve of, implementing the scope, and time management all helped build the big picture of what a real world project would be like. Completing a cost estimate was also instrumental in helping define what is actually feasible."
- "The most valuable aspect of the project was growth of strong technical writing and report organization skills, along with becoming proficient in high level operation of Word for report writing. I prepare many basis-of-design reports for many projects in my daily work that document the technical basis for project archives. The project also fostered many professional contacts and a higher proficiency in presentation and interview skills that have carried me through the first several years of my career."
- "I found that the focus from professors was on the "soft skills" such as presenting, holding productive meetings, communicating technical subject matter to a general audience and working with a team. These aspects of the senior design experience were invaluable as I started my professional career."
- "Although not specific to a retrofit, constructability was something we really needed to focus on. Constructability is a real world problem that is difficult to replicate in faculty created simulations."
- "The most valuable part was the process of struggling through a problem. From understanding the larger picture to applying basic principles to small parts. Weighing when to ask for help and when to keep trying."

Of the responses for least valuable aspects, two commonalities exist. First, two of these alumni decided not to pursue structural engineering after they graduated (one response was: "The least valuable was some of the civil engineering specific calculations as I left the Civil field,") and two of the alumni would have appreciated more project management training (another response was: "The project management aspect of the program, while useful, was very underemphasized. Workload allocation, budgeting, resource tracking, etc are all extremely important skills for engineers to have to survive in the consulting world. More emphasis on planning out a schedule and action plan for the project would be very beneficial for future students.") Interestingly, both alumni who left the civil engineering field strongly agreed that working on an existing structure was beneficial towards achieving their professional goals (both responses = 5) and disagreed that working on a new structure would have been more beneficial (both responses = 2). These responses suggest the more holistic and overall benefit of working on a retrofit project regardless of the technical specialization.

6.3 *Assessment summary*

Overall, the assessment data show that the alumni valued a structural retrofit senior design project and provided a similar learning opportunity than working on the design of a new structure. Alumni also felt that participating in these projects before taking formal design coursework enhanced their learning later when they took reinforced concrete and steel design courses. The responses also support the authors' belief that the liaison/sponsor relationship plays an important role in alumni' experience. Finally, it is clear that alumni valued the real-world nature of the projects and the professional skills that they developed over the course of their senior year.

7. Faculty perception of retrofit projects and their success

The faculty members perceive the retrofit projects to be more challenging than design of new structures for reasons discussed previously. Nevertheless some of the following factors were instrumental for the successful completion of the three retrofit projects. These projects were all sponsored by a company, Seattle City Light, with which we have had a long working relationship. Seattle City Light has sponsored several civil, electrical and mechanical engineering capstone projects at Seattle University over the past 23 years. This long-term relationship has resulted in project liaisons who understand our engineering program and curriculum, know the skill sets of the students and who can define work that is feasible to finish within a school year. Project scopes have evolved significantly over the years to become complete, stand-alone analysis and designs, with final deliverables that may include calculations, drawings, cost estimates, construction specifications, and recommendations.

Faculty also believe that additional activities are needed for structural retrofit projects to succeed. The faculty/sponsor should hold tutorial sessions on unfamiliar codes and specifications to help students better understand these new subjects. As possible, the students should visit fabrication shops to see how their drawings are interpreted. Liaison engineers who have been in the practice for a long time are valuable because they can guide the students through common construction practices, helping bridge the gap between theory and practice.

8. Summary

Senior design projects at Seattle University have provided our students the opportunity to learn design principles through authentic experiential learning. Engineering retrofit of existing structures is often more difficult than the design of new systems because the former has additional constraints imposed by the existing structure. Unlike the design of new structures where one calculates the forces and sizes the members, retrofit projects require that students analyze existing systems, identify deficiencies, and then develop retrofit techniques that are feasible, constructible and compatible with the existing system. We have discussed three recent structural retrofit project case studies, highlighting aspects that are specific and common to retrofit projects. With our nation experiencing aging infrastructure and increasing population growth, retrofit of existing facilities and/or systems will become a common occurrence in the future. Therefore, the project issues discussed in this paper have a wider applicability within other branches of engineering.

In addition to being exposed to topics that are not covered in a standard undergraduate curriculum, students also developed many valuable technical and professional skills through these capstone projects. Assessment results suggest that our alumni appreciate the real-world experiences as well as the close relationship the program has with the sponsoring company. They also believe that working on a retrofit project was as valuable as designing a new structure.

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