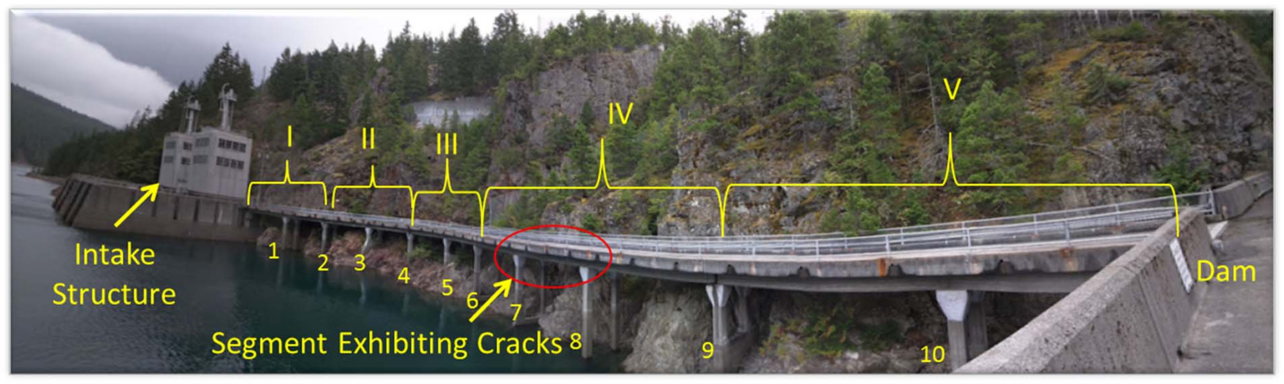
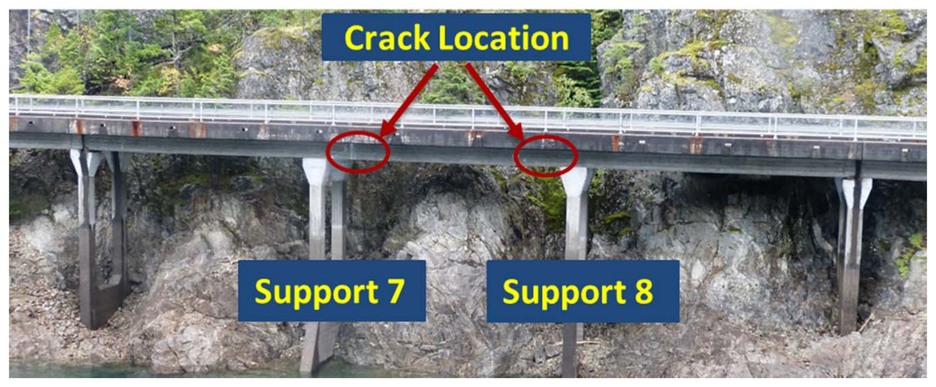
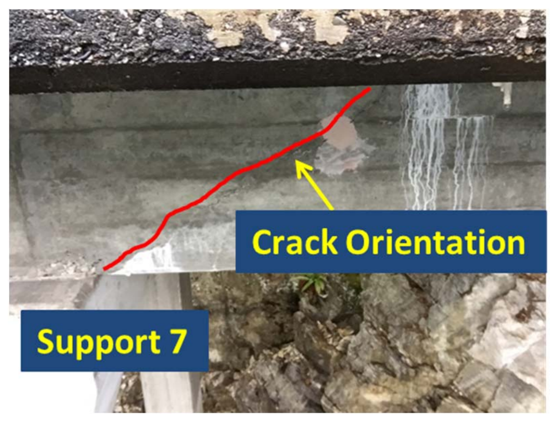
Load Rating and Repair Options for Bridge Connecting Dam and Intake Structure

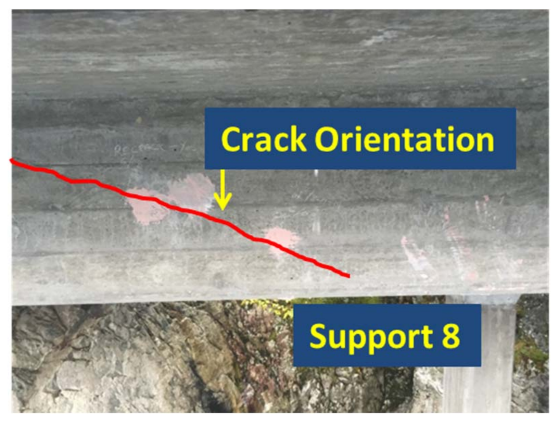
Introduction

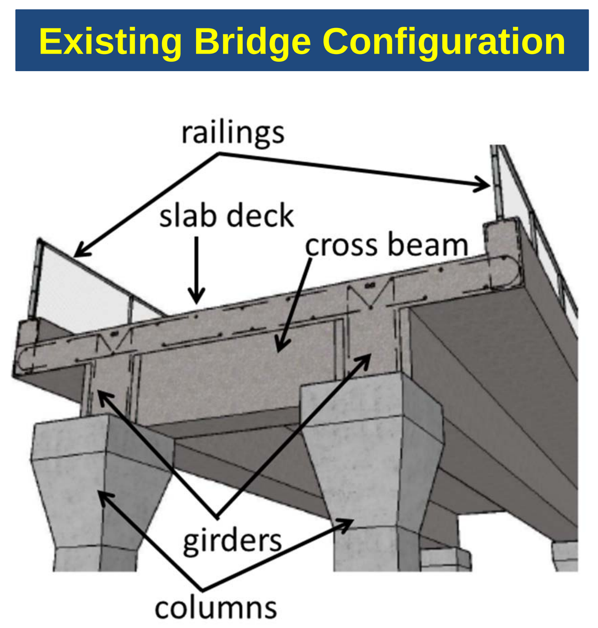


A local hydroelectric power utility company noticed cracks in a bridge connecting the dam and its intake structure. The company requested one of our civil engineering capstone teams to perform load rating of the bridge, and recommend retrofit options to control further cracking enabling safe use of the bridge by maintenance vehicles.









Site and Project Constraints

- Site located within a national park; thus strict environmental regulations apply.
- Facility on registry of historic sites; therefore the original appearance of the structure must be preserved.
- Remote location of site poses challenge transporting any construction materials.
- Due to load limitations on the bridge, no cranes to be used in the retrofit; any construction should be done from barges on lake.

Engineering Analysis

Field Reconnaissance

Team visited site, talked to utility maintenance crew to understand operational practices, and measured accessible parts of the bridge.

Document Review

Team reviewed engineering drawings in various formats (microfiche, as built plans, AutoCAD reproductions), and bridge inspection reports.

Findings

- Used field measurements to confirm accuracy of as-built drawings.
- Obtained steel and concrete properties used in construction from drawings and literature review.
- Compiled list of three trucks to use in analysis based on discussion with maintenance crew, site constraints and AASHTO recommended generic vehicle specifications.

Load Rating Analysis

- Team computed demand and capacity of bridge in shear, tensile flexure, and compression flexure for the three design vehicles.

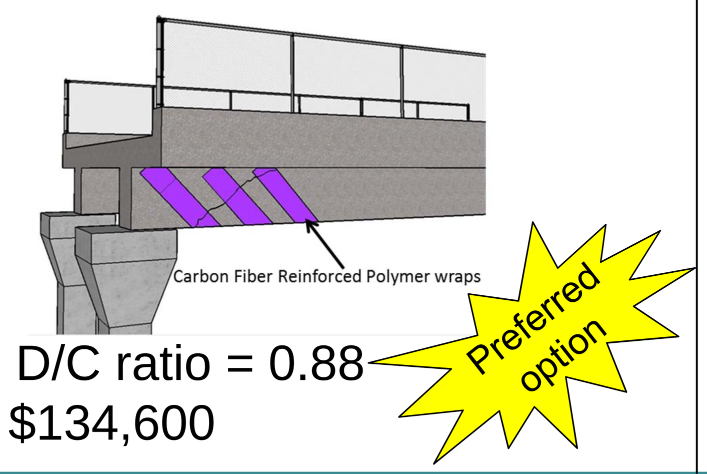
	Demand to Capacity Ratio (D/C)		
	HL-93 Truck	HL-93 Tandem	RT750-XL Crane
Shear (kips)	1.20	1.12	1.31
Tensile Flexure (kip-ft)	0.76	0.83	0.86
Compressive Flexure (kip-ft)	0.68	0.66	0.73

D/C < 1 for safe performance

- Bridge has insufficient shear capacity; therefore team considered retrofit options to increase shear capacity.

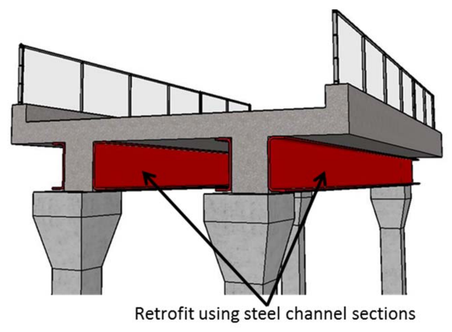
Retrofit Options Considered to Increase Shear Capacity

Option 1: Carbon Fiber Reinforced Polymer (CFRP) Wraps



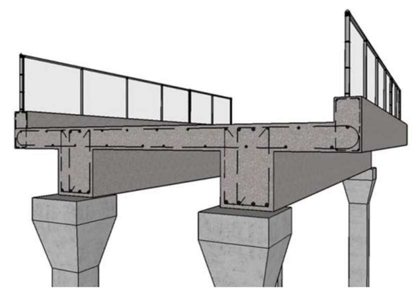
Critical D/C ratio = 0.88
Cost ~ $134,600

Option 2: Attaching steel channels to girders



Critical D/C ratio = 0.69
Cost ~ $1.5 Million

Option 3: Replacement of slab and girder

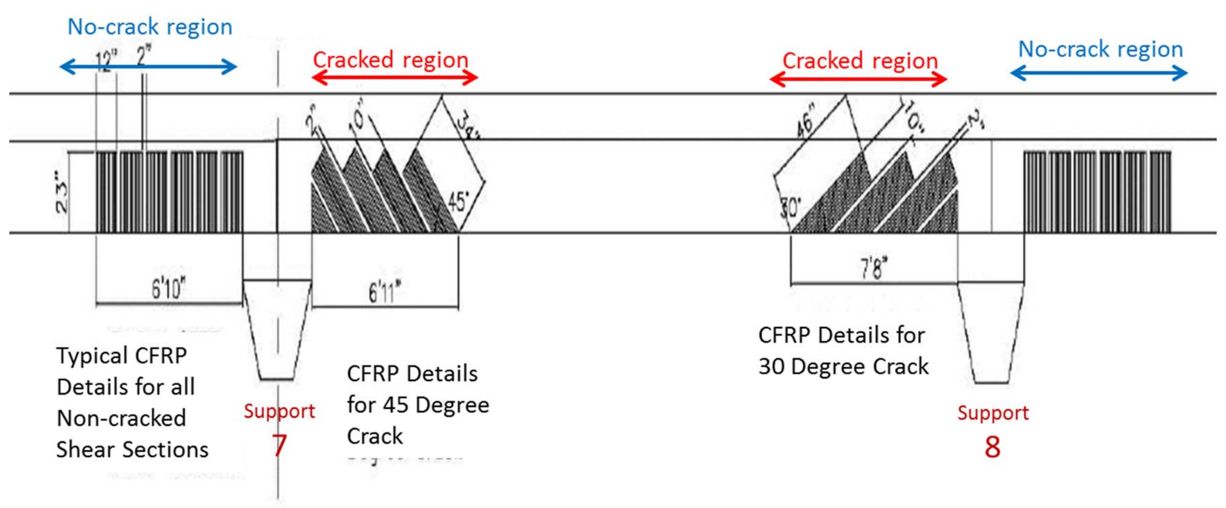


Critical D/C ratio = 0.64
Cost ~ $3.5 Million

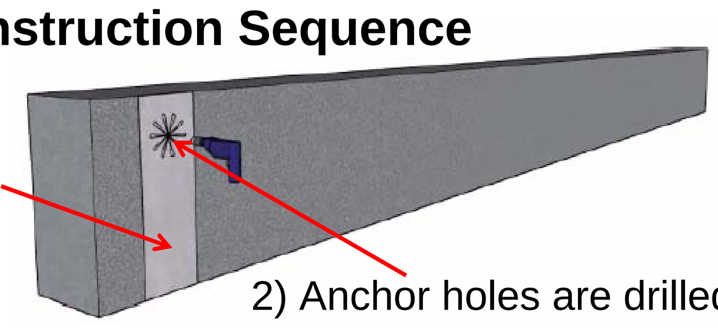
Design Details of CFRP Wrap, the Preferred Option

Design of CFRP Wrap Placement

Team compared shear capacity to demand along span where cracks were observed and determined the distance from either support where demand exceeded capacity. In the cracked zones, CFRP wraps will be applied perpendicular to the crack preventing further crack propagation. In the uncracked regions, CFRP wraps will be applied vertically.

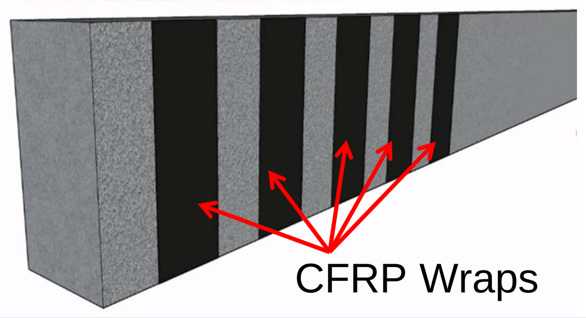


Construction Sequence



1) A layer of concrete is removed from girder.
2) Anchor holes are drilled.
3) Sharp edges are rounded to prevent puncture of CFRP wraps; surface is cleaned and polished for proper binding. Then epoxy is injected into anchor holes.

4) Anchor dowel end and anchor slot are saturated with primer. Then anchor dowel is impregnated into anchor hole and anchor fan fanned out.



5) Epoxy is applied to the girder and CFRP is installed. Finally another coat of epoxy is applied.

Multi-Professional and Multi-Disciplinary Collaboration

- Two licensed faculty members advised the team.
- A licensed engineer from the utility company served as a client liaison and mentor to the team.
- Department advisory committee consisting of a dozen professional engineers provided feed back on the presentations.
- At a local ASCE presentation competition a panel of five professional engineers served as judges and chose this project to be presented at the monthly ASCE section meeting.
- Utility crew personnel educated the team on the usage of the bridge and provided insight on retrofit option.
- Team consulted with a CFRP manufacturer to learn the technology and the installation technique.
- A drafter from the utility company assisted the team to develop a professional quality project.
- A historian helped the team to understand the historical significance of the project site and design criteria to abide by.
- Team presented its final recommendations to project managers and staff members at the utility company.

Benefit to Public Health, Safety Welfare

- Health and safety of the utility company maintenance crew was the impetus for the project.
- Safety of construction crew was taken into account in design.
- Interruption of power supply would adversely impact the welfare and quality of life for consumers.
- Experience dealing with nation's aging infrastructure issues.

Knowledge and Skills Gained

Engineering & Technical Skills

Use of Design Documents: 2014 AASHTO LRFD Bridge Design Specifications, ASCE/SEI 7-10 Minimum Design Loads for Buildings and Other Structures, American Concrete Institute Guide for the Design of Construction of Externally Bonded Fiber Reinforced Polymer Systems for Strengthening Concrete Structures

Use of Software: SAP 2000 software, MS Excel, Trimble Sketchup, AutoCAD

Experience in construction sequence, cost estimation

Professional Skills

Oral presentations to peers, Professional Engineers on department advisory committee, utility company personnel, and to local ASCE and Structural Engineering societies

Developed technical writing skills through proposal, final report, and professional emails

Interacted with engineers and non engineers

Project management and leadership: ran meetings with agenda, tracked action items, managed schedules and budgets, worked as a team

Load Rating and Repair Options for Bridge Connecting Dam and Intake Structure

Abstract

Project Description: A local hydroelectric power utility company found diagonal cracks in a concrete bridge connecting the dam to its intake structure. The utility company requested our senior capstone team to perform a load rating of the bridge and recommend retrofit options to ensure safe operation of the maintenance vehicles using the bridge.

The bridge, built in the 1930's, is in a remote area within a national park and is on the National Registry of Historic Sites. Using measurements collected during the site visit and as-built drawings, the team computed the demand and the capacity of the bridge for various vehicular loadings. From this analysis the team concluded that the bridge had insufficient shear capacity leading to cracking.

The team proposed three retrofit options: i) Wrapping the girders with Carbon Fiber Reinforced Polymer (CFRP) wraps, ii) attaching steel channels to the girders, iii) replacing the slab deck and the girder. Based on the cost, ease of installation and reduced environmental impact, with input from the company, the team selected CFRP as the preferred alternative. The team took the CFRP option to 60% design.

Collaboration of Faculty, Students, Licensed Professional Engineers and other Allied Professionals: Four civil engineering seniors worked under the supervision and guidance of two faculty members and a liaison representing the company, all three Professional Engineers (PEs). Several times during the year the students presented their project to PEs from the local professional societies and the department advisory board; the team also presented to a diverse group of utility company personnel and received valuable feedback. The team interacted with utility company maintenance crew to understand the operations of the facility and met with a historian to understand the historical significance of the site. CRFP technology was brand new to the team – therefore, it contacted a CFRP manufacturer to learn about their products, specifications and installation process.

Knowledge and Skills Gained: The students applied their technical skills gained through coursework to solve a real life problem. To successfully complete the project, the students had to research other technical resources such as design manuals, specifications, and new construction techniques. Through this capstone experience students learned the importance of professional skills needed to complete a project - oral and written communication, team work and project management skills. The students also became aware of the multi-faceted nature of the engineering profession. They learned that they had to interact with engineering and non-engineering personnel to come up with the final deliverable which involved structural design, construction management and environmental considerations.

Benefits to Public Health, Safety and Welfare: The team was aware that the impetus for the project was to provide a safe work environment for the utility company maintenance crew who use the bridge on a regular basis. The team had to consider the safety of the construction crew when selecting the retrofit option for the bridge. The utility company aimed at providing uninterrupted power supply to its customers. This was considered important for the overall welfare of the public. The project made the students aware of the basic tenet of engineering which is protecting the health, safety and welfare of the public.

LOAD RATING AND REPAIR OPTIONS FOR BRIDGE CONNECTING DAM AND INTAKE STRUCTURE

I. Project Description

Introduction

A hydroelectric power utility company in our region (or the client) found one of its concrete bridges connecting a dam and its intake structure exhibiting diagonal cracking. The client requested that our senior capstone team perform a load rating of the bridge and recommend retrofit options to ensure the bridge remains safe to support ongoing maintenance vehicle traffic loads.

The project site is in a remote location within a national park. The bridge was built in 1930's, and consists of five concrete slab sections (numbered I through V) supported on 10 pairs of reinforced concrete columns (numbered 1 through 10) and connects the intake structure to the dam (Figure 1). The columns are anchored to the steep rock face.

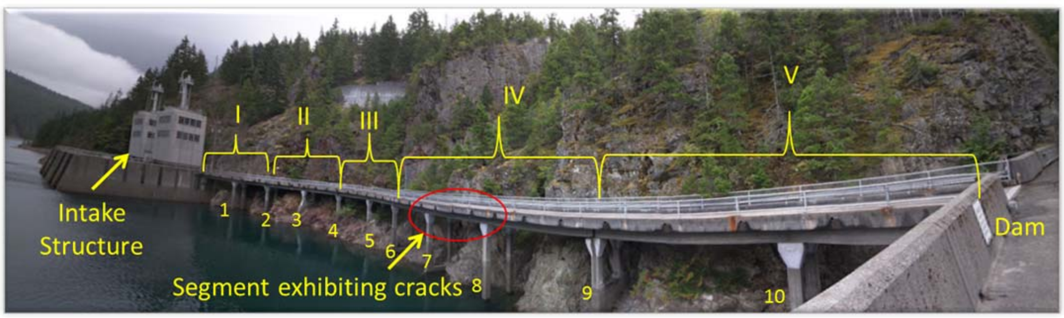


Figure 1. View of the Bridge

The client first observed the cracks in section IV during a routine inspection in 2004. Since then, the cracks have grown over time and consequently the client has limited the movement of heavy machinery onto the bridge until a complete load rating is conducted. Figure 2 shows the cracks observed close to supports 7 and 8.

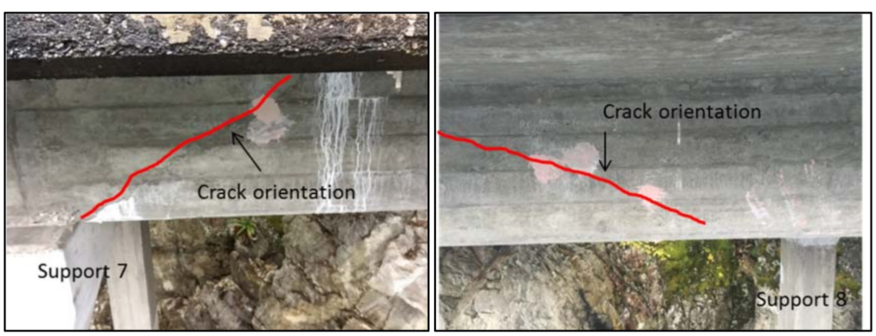


Figure 2. Orientation of Cracks in Span IV at a) Support 7, b) Support 8

The client requested the student team to perform a load rating of the bridge and to propose repair options to mitigate the effects of cracking allowing the dam personnel safe access to the intake structure.

Site Constraints and Project Challenges

During the site visit the team was made aware of a number of site constraints to consider when selecting repair options:

- the remote location poses difficulty transporting materials to the project site - a series of hairpin bends limits the length of materials and equipment to be transported and a rock tunnel with low clearance limits the height of equipment to be transported.
- the client did not want cranes to access Section IV via the bridge due to load limitations. Instead, cranes had to work from barges on the lake; water levels had to be monitored for worker safety.
- because the project site is designated as a national park, strict environmental regulations had to be complied with.
- the site is on the National Registry of Historic Sites, therefore, original appearance of the structure had to be preserved.

Structural Configuration of Bridge

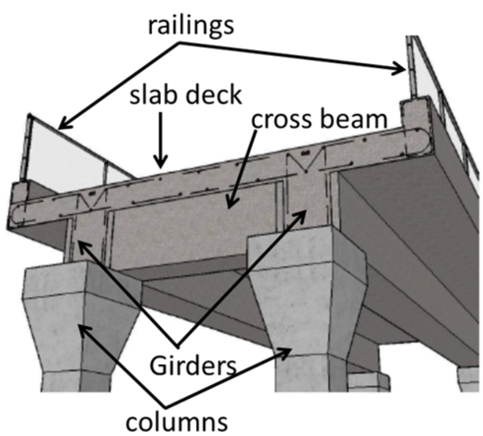


Figure 3. Structural Detail of Bridge

Figure 3 shows the structural configuration of the bridge. The reinforced concrete (RC) bridge deck is supported by two longitudinal RC girders. At each bridge support, a RC cross beam connecting the girders rests on the column supports. The cross beams provide additional deck stiffening and resistance to twisting. Steel railings are attached to either side of the built-in curbs. The bridge has a 0.6% slope in the lateral direction allowing water to drain into the lake via openings in the curb.

Design Parameters: Material Properties, Loads, and Bridge Measurements

The team reviewed a set of engineering drawings for the bridge which consisted of microfiche, as-built plans, AutoCAD reproductions, and bridge inspection reports. During the site visit the team measured the accessible parts of the bridge and found that they matched the as-built drawings. Through literature review and inspection of the drawings, the team estimated the material properties of steel and concrete used at the time of bridge construction.

The client specified a list of vehicles that they plan to use for future maintenance. The team reviewed the vehicle dimensions and compared them against site constraints as explained earlier and decided to use the crane model RT 750-XL for the load rating. In addition to the client specific vehicle, the team used American Association of State Highway and Transportation Officials (AASHTO) recommended generic design vehicles 'HL-93 Design Truck' and 'HL-93 Design Tandem' in their analysis.

Load Rating of Bridge
Load rating of the bridge involved calculating the capacity of the structural members and the demand imposed when subjected to design loads. From these values the demand to capacity ratios (D/C) were computed. The D/C ratio had to be less than 1.0 for safe performance of the structure.

The team computed the demand and capacities for shear, tensile flexure and compressive flexure for the three design vehicles and the values are presented in Table 1. The D/C values are higher than 1.0 for all three loading cases for shear. Therefore, the team concluded that repair options they select should focus on increasing the shear capacity of the bridge. The 30° and 45° orientation of the cracks with the horizontal axis (Figure 2) also supported the team's initial suspicion that the cracks could be related to high shear stress.

Table 1. Demand to Capacity Ratios of the Bridge for the Various Design Vehicles

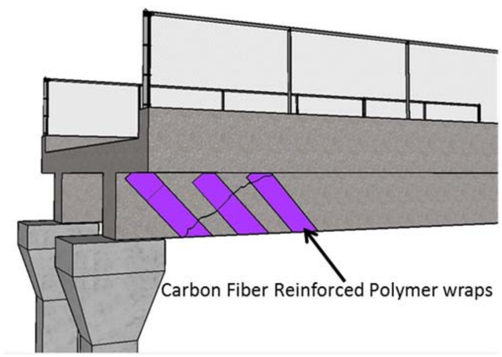
	HL-93 Truck	HL-93 Tandem	RT750-XL Crane
Shear (kips)	1.20	1.12	1.31
Tensile Flexure (kip-ft)	0.76	0.83	0.86
Compressive Flexure (kip-ft)	0.68	0.66	0.73

Repair Options
Based on the finding that the bridge has insufficient shear capacity, the team considered three options to mitigate the cracking in Section IV of bridge. The team took each option to a 30% design by performing preliminary calculations and cost estimate.

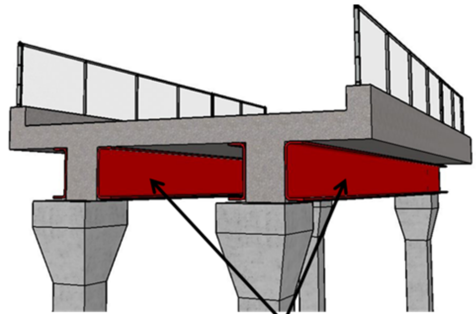
Option 1: Application of Carbon Fiber Reinforcement Polymer (CFRP) Wraps
CFRP wraps are composite materials made of a polymer matrix reinforced with carbon fibers. They are used to strengthen concrete elements damaged by overload, impact, corrosion, deterioration or settlement. The team came up with the recommendation using the American Concrete Institute (ACI) 440.2R-08 CFRP design guideline. This is shown in Figure 4a.

Option 2: Retrofitting Girders with Steel C-Channels
The girders are to be retrofitted by installing C-channels on either side of the member as shown in Figure 4b. The team sized the C-Channel and designed the bolt connections between the C-channel and the girder.

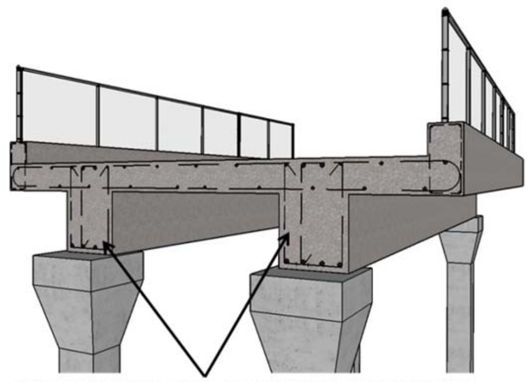
Option 3: Slab and Girder Replacement
This involved removing the existing bridge and replacing it with a new bridge. To keep the bridge deck elevation unchanged the girder width was increased while keeping the slab deck depth unchanged. Figure 4c shows option 3.



a)



b)



c)

Figure 4. Retrofit Options, a) CFRP wrap, b) Steel C-Channel installation, c) Slab-girder replacement

The team computed the D/C ratio for the three options and the associated cost of materials and labor. Table 2 summarizes the team's findings. All options resulted in D/C ratios of less than 1.0. The CFRP wrap was selected as the preferred alternative because of the cost, ease of installation and reduced environmental impacts. The team took this preferred option to 60% design.

Table 2. Demand to Capacity (D/C) Ratios of the Shear Capacity for the Three Retrofit Options and the Associated Costs

	Option 1 – CFRP Wrap	Option 2 C-Channel	Option 3 Replacement
HL-93 Truck (D/C ratio)	0.81	0.63	0.58
HL-93 Tandem (D/C ratio)	0.75	0.59	0.54
RT750-XL Crane (D/C ratio)	0.88	0.69	0.64
Cost for Span IV Retrofit only	$34,600	$382,900	$877,700
Cost for Entire Bridge	$136,400	$1,484,000	$3,460,000

60% Design of Preferred Alternative
The 60% design of the preferred alternative involved the design of the CFRP in the cracked portion and the undamaged spans to prevent future cracks, CFRP anchorage design, preparation of AutoCAD drawings, and construction sequencing.

CFRP Design: Because insufficient shear capacity was determined to be the cause of the cracks, the team compared the shear capacity to the demand between supports 7 and 8 and determined the distance from either support where demand exceeded capacity. In these two regions 10 in. wide CFRP wraps were to be applied perpendicular to the cracks with 2-in.spacing as shown in Figure 5. Before applying the wrap, grout or epoxy is to be injected into the cracks to seal and protect the reinforcing bars from water intrusion.

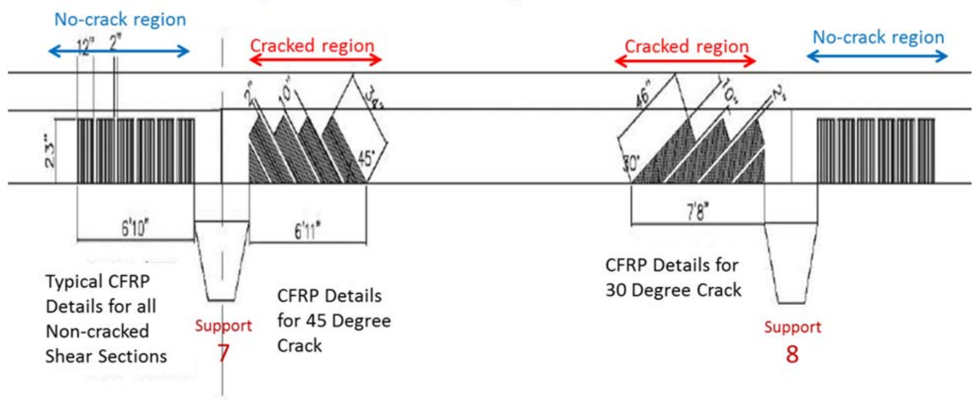


Figure 5. Design of CFRP wraps in the Cracked and Uncracked Regions

Through similar shear demand-capacity analysis the team found that up to 7 ft from each support on the uncracked side of the girder the demand exceeded capacity. To prevent the development of future cracks, six 12" wide vertical wraps were to be applied with 2 in. spacing as shown in Figure 5.

CFRP Anchorage and Installation: Premature delamination of CFRP from concrete is the primary failure mechanism for CFRPs. To prevent this, the team selected an anchor system to secure the CFRP to the girder and also developed a construction sequence for the CFRP installation procedure. Due to page limitations the anchorage and installation details are included in the poster.

Mobilization and Environmental Considerations: The team developed a mobilization plan prior to CFRP installation. This encompassed closing off public access to the bridge, establishing a staging area for material and equipment storage, and installing scaffolding beneath the bridge for the workers. Because the work takes place over water, the team also identified the applicable permits.

II. Collaboration of Faculty, Students and Licensed Professional Engineers
Students in our engineering program complete a year-long, industrially-sponsored, real life capstone project. A team of four students worked on this project under the supervision of a liaison engineer from the client and a structural engineering faculty member from the university, both licensed professional engineers. The senior design course is taught by a

faculty member who is also a licensed professional engineer. The students met weekly with the faculty advisor and with the client liaison biweekly. The faculty members provided feedback on the proposal and report throughout the academic year.

In fall and spring quarters the team presented their work to the client. Diverse groups of professionals attended these presentations. Although the students found these presentations to be quite challenging due to the extensive knowledge and experience of the audience and the questions asked, they believed it provided an opportunity for professional growth.

The team made an oral presentation to the department's advisory committee consisting of a dozen local licensed practitioners in early winter quarter describing their project scope and plan of action. Members of the advisory committee also attended the end of the academic year presentation at a University event, details of which are provided under Section V. In addition the team presented its proposed plan in early winter quarter to the local Structural Engineers Association.

III. Benefit to Public Health, Safety and Welfare

The **health and safety of the utility company maintenance crew** who use the bridge was of paramount importance. The project when completed enables the maintenance crew to perform their work in a safe environment. The team also considered the **safety of the construction crew** when repairing the bridge. The dam is a major hydroelectric power generator for the region. Any interruption of power production could adversely affect the **quality of life of the consumers**.

Our nation's aging infrastructure is currently of major concern. The skills the students developed through this project are valuable for the health, safety and welfare of the public in the long run.

IV. Multidiscipline and/or Allied Profession Participation

In the initial stages of the project, the team interacted with the **utility company maintenance crew** to understand the use of the bridge. CFRP technology was new to students. Therefore during the design phase the team contacted a **CFRP manufacturer** to learn the specifications, and the installation method. At the latter stages of the project, the client assigned a **drafter** to assist the team with developing professional quality engineering drawings of the student design. The team met with the client's **historian** to understand the historical significance of the project site.

V. Knowledge and Skills Gained

The project enabled the students to develop the following: technical skills, oral and written communication skills, project management and leadership skills, ability to work in a team setting and to interact with clients.

a) Technical skills

The students learned how to take a project from brainstorming stage to final design. During this project they acquired the skill to use the following tools:

- <u>Design Specifications</u>: 2014 AASHTO LRFD Bridge Design Specifications, ASCE/SEI 7-10 Minimum Design Loads for Buildings and Other Structures, American Concrete

Institute (ACI) Guide for the Design and construction of Externally Bonded Fiber Reinforced Polymer (FRP) Systems for Strengthening concrete structures,

- Software: SAP2000 for the determination of internal force demands, AutoCAD 2014 for engineering drawings.
- Microsoft Excel to organize and automate design calculations
- Trimble Sketchup for visual aids

Students have had limited exposure to the above design manuals and specifications, codes and software in their classes. But they had the opportunity to work with them intensively on the project with the help of the faculty advisor and the liaison engineer. Furthermore, students interacted with a CFRP manufacturing company to learn about their products and the installation process.

b) Communication skills

The students submitted a written proposal to the client at the end of fall quarter outlining their understanding of the project, scope of work, plan of implementation, and schedule. At the end of spring quarter, they submitted a final report describing the work done, supporting calculations, renderings and other deliverables requested by the sponsor.

Throughout the year the students presented their project progress to their peers and the department faculty members with audio visual aids. The team was placed first in a student presentation competition sponsored by the local chapter of ASCE. In addition, students presented their proposed work to the client at the end of fall quarter and then presented their final design at the spring. The year culminated with a major academic celebration on campus at which the team presented its work to the academic community, sponsors and industry representatives, and advisory committee members, through an oral presentation and a poster session.

c) Project Management and Leadership skills

Each team member served as the project manager (PM) for part of the academic year. The PM was responsible for setting up the weekly team meetings, developing the meeting agenda, conducting the meetings, assigning tasks, and following up on action items. The PM was also responsible for contacting the liaison and the faculty advisor in between team meetings, when needed.

VI. Summary

A utility company observed cracks in one of their bridges connecting a hydropower dam to its intake structure. A civil engineering capstone team performed load rating of the bridge, evaluated three retrofit options to prevent future cracking, and then took the preferred alternative to a 60% design. The team worked under the supervision of a liaison engineer from the client and two faculty members all licensed professional engineers. Through this project the team learned how to apply the technical skills learned in the engineering courses to a real life project. Moreover, the students developed project management, leadership and communication skills, and client relationships with licensed professional engineers. This project made the students aware of an engineer's responsibility safeguarding the health, safety and welfare of the public.