Strengthening of Deteriorated Concrete Bridge Girders Using an External Posttensioning System

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Introduction

External posttensioning (PT) has been used to strengthen existing bridges in many countries since the 1950s and has been found to provide an efficient and economic solution for a wide range of bridge types and conditions (Daly and Witarnawan 1997). Available strengthening techniques, in addition to external posttensioning, include (a) cross section enlargement with mild steel rebars, (b) cross section enlargement with mild steel and/or interior posttensioning, and (c) externally bonded carbon fiber reinforced polymer (CFRP) reinforcement.

Need for Strengthening

Improving the load-carrying capacities of existing bridges may be required for various reasons, including

- Increase in volume of traffic;
- Increase in legal vehicle loads;
- Design errors found after construction is completed;
- Deterioration of the bridge owing to spalling of concrete and corrosion of steel reinforcement; and
- Loss of prestress owing to creep and relaxation, which results in loss of strength.

Factors Affecting the Selection of the Strengthening Technique

The selection of an appropriate method for strengthening a bridge depends on a number of factors, including

- The type of structure and the magnitude of the strength increase required;
- Availability of funds or cost of the strengthening technique;
- Aesthetics/appearance;
- The age of the bridge and the condition of the member to be strengthened;
- Fire rating, meaning the selected system must be chosen to provide the code-specified fire rating;
- Constraints affecting the constructability of the selected technique; and
- Required maintenance of the selected strengthening technique.

Posttensioning System

Posttensioning is the introduction of external forces to the structural member using high-strength cables, strands, or bars. The PT cables are connected to the existing member at anchor points, typically located at the ends of the member. When stressed, the cable will produce upward forces (at the lower side of the member) or downward forces (at the upper side of the member) to create reverse loading on the member (Alkhrdaji and Thomas 2009).

External and Internal Posttensioning Systems

Posttensioning strengthening systems can be classified into two categories: external PT and internal PT. The external PT system involves anchoring cables or steel bars to the outside faces of the structure (either on the sides or underside of a beam, or on the underside of a slab). To improve fire rating and durability, one of the following could be used: (a) sheathed cables; (b) coated anchors; or (c) external cables placed inside plastic ducts and then filled with grout (Alkhrdaji and Thomas 2009). The internal PT system consists of cables placed inside the original member. This can be achieved by coring (either longitudinally or transversely) inside the member or by chipping the sides (creating a cavity) along the span of the member. An internal PT system is used if the original cross section of the member cannot be changed. Alternatively, if the member cross section can be increased, then a new concrete enlargement bonded to the existing member can be installed.

Active and Passive Strengthening Techniques

Strengthening systems can be classified into two categories: passive systems and active systems (Alkhrdaji and Thomas 2009). Passive strengthening systems do not introduce forces to the structure or its components. Passive systems include the use of reinforced concrete enlargement, addition of structural steel plates or members, or externally bonded CFRP. Passive systems contribute to the resistance of the member when it deforms under external loads. Active strengthening systems involve the introduction of external forces to the structural member that would resist part or all of the effects of external loads. Active systems are engaged in load sharing immediately after installation.

Advantages of an External Posttensioning System

- Increases flexural strength;
- Increases shear strength (Aravinthan 2006);
- Corrects excessive cracks and controls future crack formation;
- Increases stiffness, which will reduce deflection and vibrations;
- Reduces stress range, which will improve fatigue performance;
- Is economical compared to other methods;

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Fig. 1. External posttensioning using straight profile cables

Fig. 3. External posttensioning using draped profile cables

- Substantially increases the performance of the member, with minimal increase in the dead load;
- Eases inspection of posttensioning rods and brackets;
- Requires minimal disturbance to traffic; and
- Is speedy to construct.

Disadvantages and Limitations of External Posttensioning

- The method can be applied only if the concrete is in relatively good condition and can resist the stresses from the PT cables;
- Installation of anchorage can be difficult, and careful detailing is required to account for stress concentrations;
- External tendons are more susceptible to corrosion;
- The shear capacity of beams with external tendons is difficult to determine, and for this reason, the method has been generally confined to flexural strengthening;
- The effect of axial load (owing to posttensioning) may be detrimental to the carrying capacity and needs careful consideration (where this is the case, increasing the eccentricity of the tendons can improve the PT contribution to strengthening the member without a corresponding increase in axial load);
- Concrete beams with posttensioning tendons might lack ductility because the tendons will never reach yield and failure of the beam will be in compression in the top of the girder;
- The external PT cables and the anchoring brackets may not be acceptable aesthetically to the stakeholders (aesthetics will depend on the type and location of the bridge);
- Existing reinforcement (mild or prestressed) might be cut during the installation of the new PT system, and this needs to be accounted for during the design of the system; and
- To avoid overstressing the member and/or creating cracks, different combinations of PT force and profile need to be investigated to achieve the final solution.

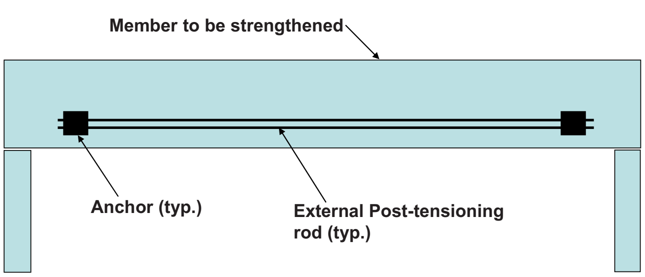

Fig. 2. Schematic of external posttensioning using straight profile cables

Profiles of External Posttensioning Tendons

External posttensioning cables could be either straight tendons (Figs. 1 and 2) or draped tendons using deviators (Figs. 3 and 4). The cable profile and anchor locations are based on the required combination of axial load, bending, and shear strength (Macoveo-Benczur and Rogowsky 2002)

Case Study: Lake Shore Drive Bridge over Lasalle Drive

The bridge in this study is one of the Lake Shore Drive bridges in Chicago (Figs. 5 and 6). The bridge was built in 1937 and carries a relatively high traffic volume of over 120,000 vehicles in average daily traffic (ADT).

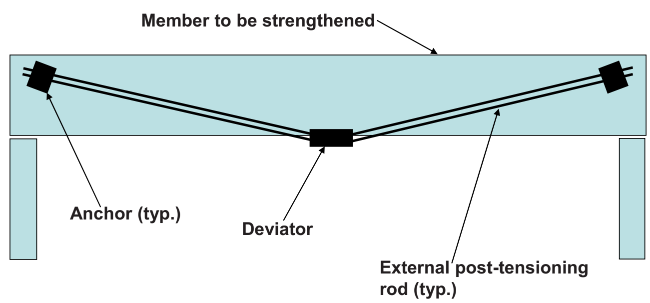

Fig. 4. Schematic of external posttensioning using draped profile cables

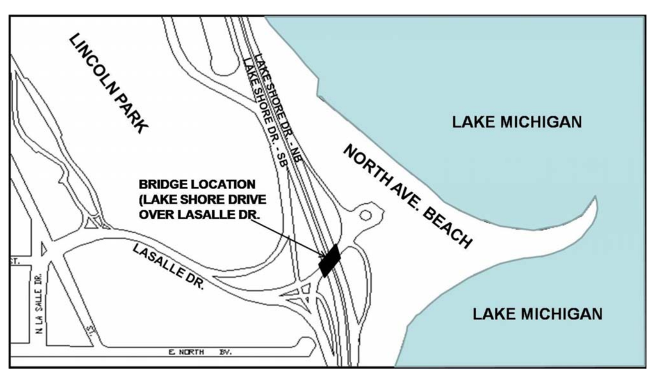

Fig. 5. Location of Lake Shore Drive Bridge over LaSalle Drive

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Fig. 6. Profile of Lake Shore Drive Bridge over LaSalle Drive

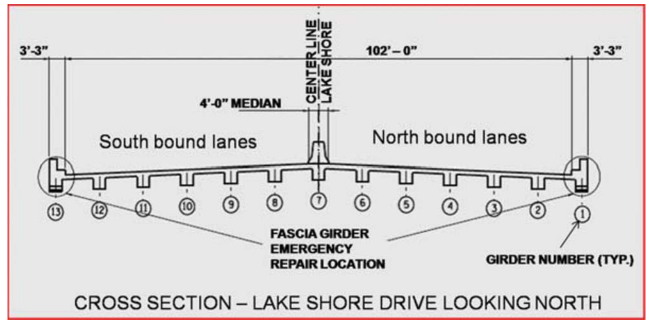

Fig. 8. Bridge cross section

Bridge Structural System

The bridge structural system consists of reinforced concrete rigid frames with variable girder and column cross sections (Fig. 7). The deck thickness is 25.4 cm (10 in.), beam width varies from 0.91 to 0.76 m (3 to 2.5 ft) at midspan, and the beam depth also varies (Fig. 8). The bridge length is 30.49 m (100 ft), the deck width is 32.93 m (108 ft), the skew angle is 35 degrees, and the skew direction is right.

National Bridge Inspection Standards

The U.S. Congress passed the National Bridge Inspection Standards (NBIS) in 1968 in response to the collapse of the Silver Bridge in Point Pleasant, Ohio, which killed 46 people. According to the NBIS, all bridges must be inspected biennially and bridge components must be given a numerical rating. If the NBIS rating is less than or equal to 4, then the bridge is classified as structurally deficient (SD), the load rating of the bridge must be assessed, and the operating loading must be less than HS20. Load restriction signs displaying the maximum allowed truck load are posted on these bridges. The bridge in this case study was inspected in accordance with the NBIS standards, and the findings are given in the following section.

Bridge Conditions prior to Strengthening with Posttensioning Rods

The deck slab and beams were repaired in 1990. Based on the 2005 inspection report, the beam patches had debonded, exposing the corroded reinforcement. Significant concrete spalling and steel section loss at the exterior girders were found (Fig. 9).

The NBIS ratings were 6 for the decks, 4 for the superstructures, and 8 for the substructure. The inventory rating was calculated to be 9.2 tons, and the operating rating was 12.5 tons. Accordingly, an emergency remedial action was required to improve the condition of the bridge and ensure public safety.

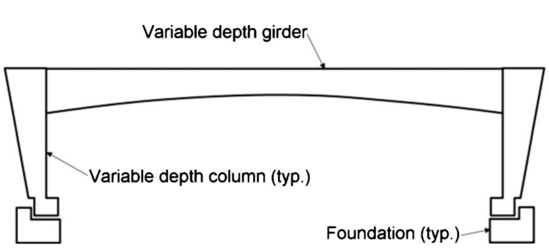

Fig. 7. Elevation of the reinforced concrete rigid frame

Exterior Girder Strengthening Using an External Posttensioning System

Two strengthening systems were considered: (a) an external posttensioning system and (b) a CFRP system. Either system could have been used. However, the external posttensioning system was selected for the rehabilitation of this bridge.

An external posttensioning system was designed to increase the flexural capacity of only the two exterior girders, since they had the most deterioration. Prior to installing the posttensioning system, the exterior girders were repaired (Fig. 10).

The longitudinal external posttensioning system consisted of four 25.4 mm (1 in.) diameter longitudinal posttensioned rods, two on each face of the girder (Fig. 11). The rods used were 1,034 MPa (150 ksi) grade steel threaded bars ASTM A722, type II, Galvanized (ASTM A123) Dywidag.

Owing to the significant longitudinal posttensioning force [the final posttension load per rod $= 0.7\ f_{pu}\ A_{ps} = 397.2$ kN (89.3 kips)], a very stiff bracket and transverse pretensioning rods were required (Fig. 12). The transverse pretensioning of the rods provided sufficient friction between the bracket and the concrete beam.

Fig. 9. Heavy spalling of exterior girder with corroded reinforcement

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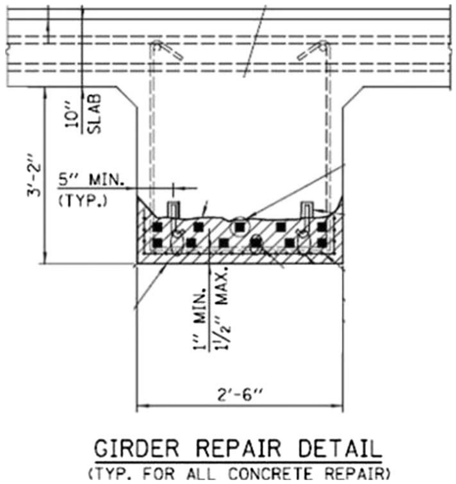

Fig. 10. Repair of exterior girder prior to installation of the posttensioning system

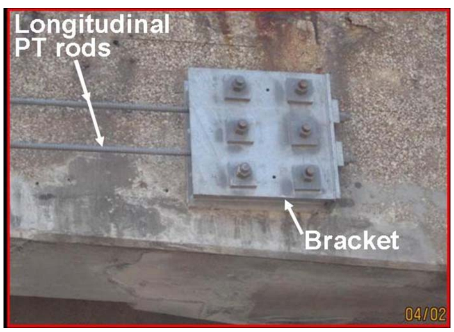

Fig. 11. Longitudinal posttensioning rods and bracket

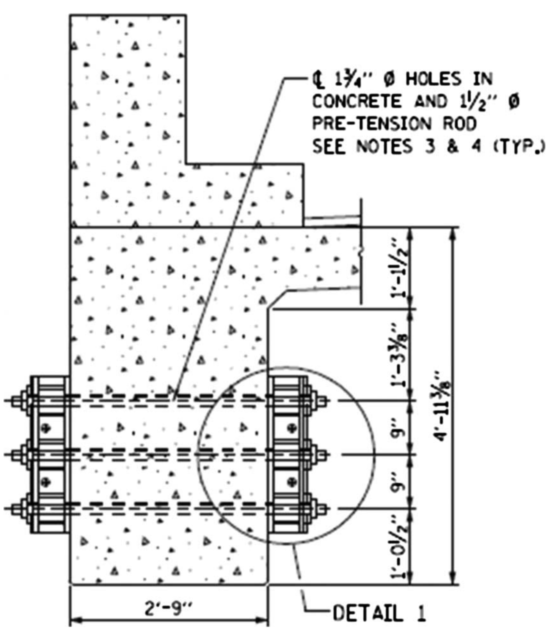

Fig. 12. Transverse pretensioned rods across the girder

Fig. 13. Transverse pretensioned rods (six rods per bracket)

Fig. 14. Drilling holes through the exterior girder in the transverse direction

Fig. 15. Six holes drilled through the exterior girder in the transverse direction

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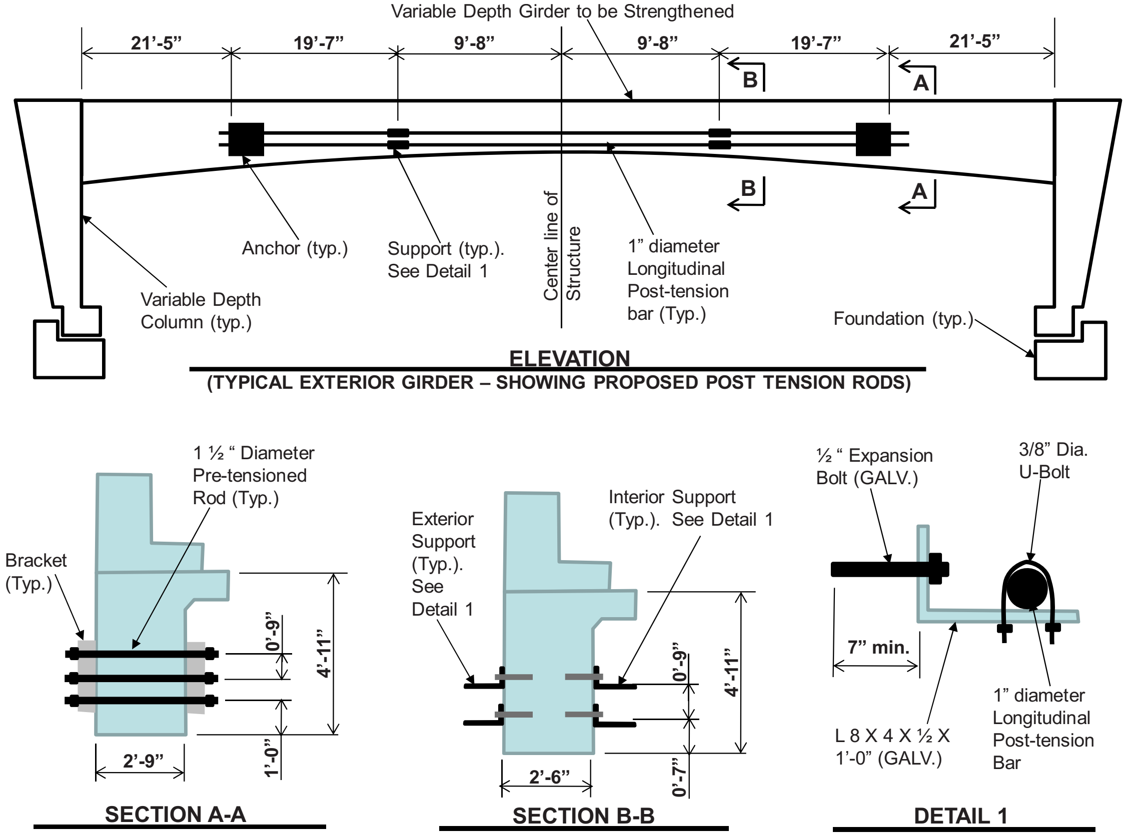

Fig. 16. Longitudinal posttensioned rods, support angles, and brackets

Six 38.1 mm (1.5 in.) diameter pretensioned transverse rods (per bracket) were used (Fig. 13). The final pretensioned loadper bolt was 444.8 kN (100 kips). The transverse pretensioned rods were threaded ASTM A193 (AISI 4140) Grade B7 steel rods with a minimum yield strength of 724 MPa (105 ksi) and an ultimate strength of 862 MPa (125 ksi).

Installation Procedure for the External Posttensioning System

Prior to the installation of the PT system, the existing large cracks were injected with epoxy, the corroded steel rebars were cleaned, the damaged rebars were replaced, and the areas of spalled concrete were repaired. This was a necessary step to ensure that thenew posttensioning force was uniformly distributed to the girder. The steps to install the PT system were as follows:

1. Drilled 44.45 mm (1.75 in.) holes in the transverse direction (Figs. 14 and 15).
2. Installed the interior and exterior brackets with 12.7 mm (0.5 in.) expansion anchors.
3. Pretensioned the 38.1 mm (1.5 in.) transverse bolts. Each bolt was pretensioned to a 50% increment of the final load.
4. Attached the interior and exterior support angle with 12.7 mm (0.5 in.) expansion anchors (Fig. 16).
5. Posttensioned the 25.4 mm (1 in.) diameter longitudinal rods in pairs, one at each face of the girder (Fig. 17). A 25% increment was used to posttension the top and bottom rods.

The completed exterior posttensioned rods, brackets, and sup-

Fig. 17. Posttensioning the longitudinal rods

Fig. 18. Completed exterior posttensioned rods, brackets, and support angles

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port angles are shown in Fig. 18. Repair of the exterior girders and installation of the PT system were completed while the bridge was open to traffic.

Summary

Existing bridges are strengthened rather than replaced for various reasons, including: to resolve existing structural deficiencies, to resist seismic forces, to increase member capacity in order to carry new traffic loads, to make repairs within budget constraints, and to fulfill immediate safety or capacity requirements. This paper discussed the use of an external posttensioning system to strengthen existing bridges. A case study of strengthening a bridge in Chicago using external posttensioning was detailed. External posttensioning systems provide many benefits, including improved strength, service performance, and durability.

References

Alkhrdaji, T., and Thomas, J. (2009). "Structural strengthening using external post-tensioning systems." *Structure Magazine*, July, 8–10.

Aravinthan, T. (2006). "Is external post-tensioning an effective solution for shear strengthening of bridge elements?" *Structural Faults and Repair, 2006: 11th Int. Conf. on "Extending the Life of Bridges, Concrete and Composites, Buildings, Masonry, and Civil Structures,"* Univ. of Edinburgh, Edinburgh, UK.

Daly, A. F., and Witarnawan, W. (1997). "Strengthening of bridges using external post-tensioning." *2nd Conf. of Eastern Asia Society for Transportation Studies*, Seoul, Korea.

Macoveo-Benczur, S., and Rogowsky, D. M. (2002). *4th Structural Specialty Conf. of the Canadian Society of Civil Engineers*, Montreal.

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