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Adjacent Box Beam Connections: Performance and Optimization

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This document is a technical summary of the Federal Highway Administration (FHWA) report, *Box Beam Bridges: Testing of Conventional Grout and Ultra-High Performance Concrete Connection Details* (FHWA-HRT-17-093).⁽¹⁾

Introduction

Precast, prestressed concrete adjacent box beams are widely used in short- and medium-span bridges in the United States. However, a recurring issue with this type of bridge is the deterioration of shear key connections resulting in substandard performance of the overall bridge system. This research used full-scale structural tests to investigate four different shear key connection designs, including partial- and full-depth connections constructed with either conventional non-shrink grout or ultra-high performance concrete (UHPC). Quantitative measures to assist in evaluating the connection performance are suggested in the study. Parameters for the connection design were developed using the shear and tensile stresses in the connection. The behaviors of the connections using conventional grout and UHPC are presented. It was found that UHPC connections can be a resilient and innovative solution to prevent connection degradation in adjacent box beam superstructure systems, advancing the state of the practice in bridge construction.

Background

Most shear key connections are designed using regional standard details. The origins of these details are not always known and do not include information on the magnitude of forces induced in the connection or the ability of a given detail to resist these loads.⁽²⁾ Neither the American Association of State Highway and Transportation Officials' (AASHTO) *Standard Specifications for Highway Bridges*, the *AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications*, nor the *AASHTO LRFD Bridge Construction Specifications* provide specific guidance for the design or construction of

the connection between adjacent box beams.⁽³⁻⁵⁾ The *AASHTO Standard Specifications for Highway Bridges* states that “the interaction between the beams is developed by continuous longitudinal shear keys used in combination with transverse tie assemblies which may, or may not, be prestressed” (p. 34).⁽³⁾ The shear key design details and the calculation of the transverse forces are not provided. The *AASHTO LRFD Bridge Design Specifications* suggests a minimum of 0.25 ksi (1.7 MPa) transverse prestress but provides no further details.⁽⁴⁾ The *Precast Prestressed Concrete Bridge Design Manual* presents an empirical design procedure based on research conducted by El-Remaily et al. and Hanna et al.⁽⁶⁻⁸⁾

This study, completed as part of the FHWA Structural Concrete Research Program, investigated two conventional non-shrink grout connections and two novel UHPC connections. Designs for partial- and full-depth connections were investigated for each connection material, and quantitative measures to evaluate the shear key performance are suggested. Design parameters, including the transverse post-tensioning force, the transverse shear strength of the connection, and the interface bond between the grout and box beam concrete, were also assessed. The full results of this study can

be found in a separate report.⁽¹⁾ A peer-reviewed journal paper also presents the results of this study.⁽⁹⁾

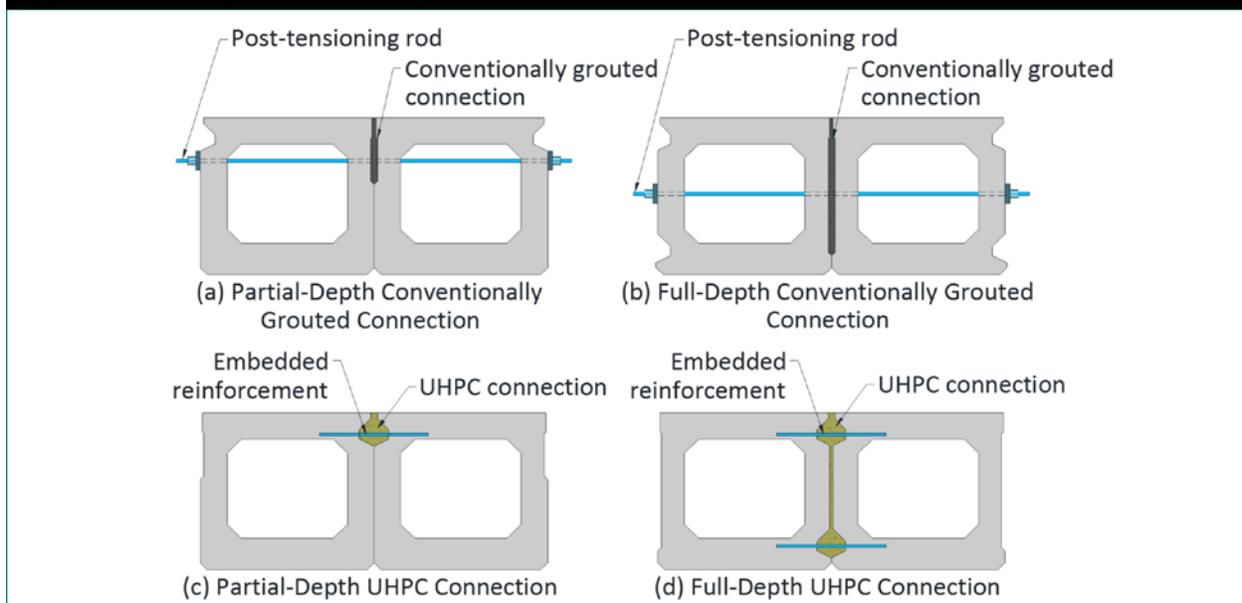
Testing Program

The testing program included multiple shear keys, test setups, and performance assessment tools, which are discussed in the following subsections.

Shear Key Design Details

Four connections were evaluated in this study. The first two used conventional high-strength, non-shrink grout in tandem with transverse post-tensioning. The partial- and full-depth connections are shown in parts A and B in figure 1, respectively. The surface of the precast concrete in the connection had a sandblasted surface finish. The other two connections investigated were new design details that take advantage of the advanced mechanical and durability properties of UHPC, as shown in parts C and D in figure 1. These were also investigated as partial- and full-depth connections. The UHPC connections included an exposed aggregate surface finish on the precast concrete and reinforcing steel that extended from the precast box beams into the connection to form a non-contact lap splice. No transverse post-tensioning

Figure 1. Shear key connection designs used in the study.



was included. The exposed aggregate surface preparation is emerging as a preferred surface finish for both UHPC and conventional grout applications.^(10,11) The enhanced mechanical properties of UHPC allow for reduced embedment lengths for embedded deformed reinforcement, which simplifies the design and construction. An embedment length of only 5.5 inches (140 mm) for the No. 4 (i.e., M13) bars used in these connections has been demonstrated to develop the yield strength of the bar.⁽¹²⁾ The dimensions of the connections are presented in figure 2.

Grout Materials

The conventional grouting material used in this study was a portland cement-based, prepackaged, non-shrink grout. It reached an average compressive strength of 7,800 to 8,120 psi (54 to 56 MPa) at the time of testing. The UHPC used is a commonly available prepackaged product with a steel fiber content of 2 percent by volume and an average compressive strength of 26 ksi (179 MPa) at the time of testing.

Test Setup

The test setup included thermal loading, cyclic structural loading, and transverse post-tensioning, which are all described further in the following subsections.

Thermal Loading

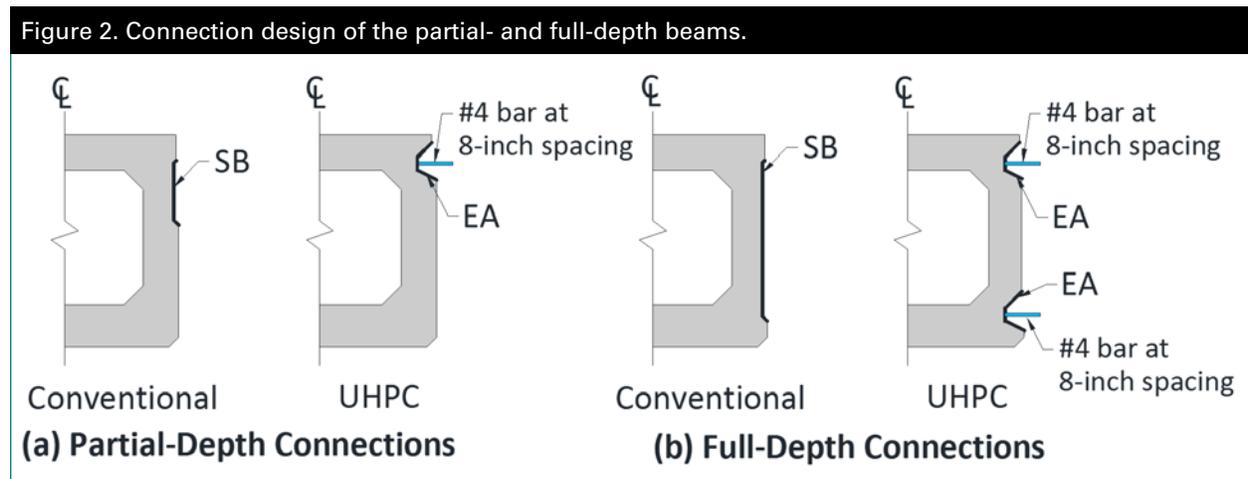
Thermal loading was simulated by pumping steam through copper tubes cast in the top

flange of each box beam. A temperature gradient between the top and bottom flanges of approximately 50 °F (28 °C) was created. A total of 10 thermal cycles were applied to each test specimen, and visual inspection was conducted.

Cyclic Structural Loading

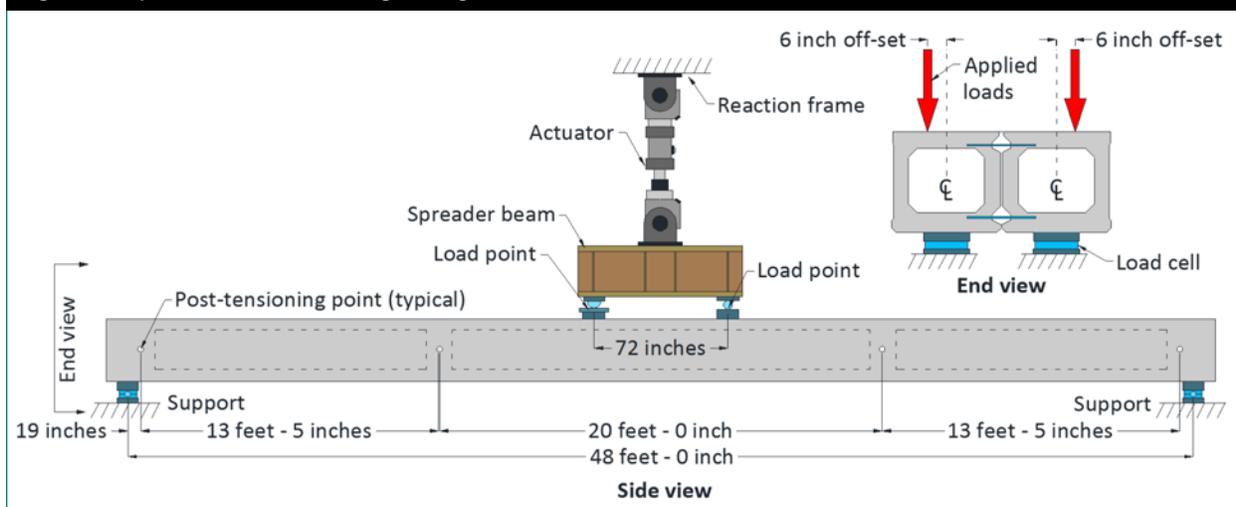
The cyclic structural loading was applied by four-point bending, as shown in figure 3. The loading was intentionally placed 6 inches (152 mm) off the center-line of the box beam to create a more severe torsional moment. This generated a greater transverse tensile force in the connection compared to centrally loading the beam.

The cyclic load was applied as a sinusoidal wave with a 180-degree phase angle between the beams. An analysis of a representative adjacent box beam bridge indicated that a loading range of 18 kip (80 kN) is the approximate distributed load on a single beam from a fatigue truck, as indicated in the *AASHTO LRFD Bridge Design Specifications*.⁽⁴⁾ Based on this information, loading ranges of 18, 36, 54, 72, and 90 kip (80, 160, 240, 320, and 400 kN) were applied. Three different boundary conditions were used in this research: an unstiffened simply supported case, a partially stiffened case, and a fully stiffened case. The unstiffened simply supported case is shown in figure 3. A partially stiffened case was employed where the end



1 inch = 25.4 mm
 CL = Centerline.
 SB = Sand-blasted surface.
 EA = Exposed aggregate surface.

Figure 3. Cyclic structural loading configuration.



1 ft = 0.305 m
1 inch = 25.4 mm

transverse rotation was restrained by clamping the ends of beams (see figure 4). The last boundary condition was a fully stiffened case that restrained the deflection of one beam with extra supports at diaphragm locations (see figure 5) in addition to the end restraint of the partially stiffened case. The stiffer boundary conditions were intended to provide a more realistic representation of a full superstructure system. More details of the test setup and loading protocol can be found in the associated full report and in papers by Yuan and Graybeal.^(1,9,13)

Transverse Post-Tensioning

The transverse post-tensioning force used with the conventional connections varied. Post-tensioning levels of 8, 6, 4, 2, 0.8, and 0 kip/ft (117, 87, 58, 29, 12, and 0 kN/m) were tested. Figure 3 shows the transverse post-tensioning locations for the conventional grout connections. These connections received a small post-tensioning force prior to connection grouting with the full post-tensioning force being applied after the grout had gained strength. Transverse post-tensioning was not applied to the UHPC connections.

Quantitative Measures to Evaluate the Connection Performance

To compare the connection performance and efficiency under different conditions, quantitative

measurements are needed. Deteriorated connections can compromise both the strength and serviceability of bridges. When the connection becomes cracked, the load distribution between the box beams is compromised, and the live load may remain concentrated in a few beams under the wheels. This can potentially exceed the allowable loads of the beams. Beams with failed connections will not deflect equally under live loads. Excessive differential displacements between adjacent girders may further degrade the connection and lead to reflective cracking in the overlay if one is present. Cracks can allow chloride-laden water to infiltrate the structure and can corrode the reinforcing bars and pre-stressing strands adjacent to the connection.

This study adopted two parameters to measure the performance of the connection. The first was the moment distribution factor that evaluated the ability of the shear key to transfer loads; it relates to the strength condition of the bridge. The second was the differential deflection that measured the relative displacement between the adjacent beams and corresponds to the serviceability of the bridge.

For the case of the fully stiffened support condition used in this study, the moment distribution could not be calculated using the ratio of carried moments because the boundary conditions on the two beams were different. In

this case, the equivalent moment transferred through the shear key was used. This method calculated the moment using the additional strain in the beams rather than the recorded

strain at the maximum load. This measure of moment approximated the amount of moment transferred through the shear key from the loaded beam to the unloaded beam.

Figure 4. Clamping at the end of beams used in partially and fully stiffened cases.



Figure 5. Intermediate support on one beam used in the fully stiffened case.



Performance of Different Connection Designs

With the pre-wetting and curing procedures adopted in this study, the four connections investigated were constructed successfully in the laboratory. Each test specimen was first thermally loaded and then structurally loaded. Note that the full-depth conventionally grouted connection cracked upon release of the small post-tensioning force that was used to stabilize the specimen during grout casting. This was likely due to differential sweep in the beams.

Thermal Effect

Each beam was thermally loaded to create a temperature gradient between the flanges of approximately 50 °F (28 °C) for 10 cycles. The thermal loading generated an upward deflection at the mid-span of 0.425 to 0.570 inch (10.8 to 14.5 mm). The behavior of the beams used in the tests was generally the same. Visual inspection conducted during the thermal loading detected only minor, non-structural cracking in the partial-depth conventionally grouted connection. No debonding was caused by thermal loading for any of the connections.

Performance of Conventional Grout Connections

For the partial-depth conventional grout connection, nearly 7 million loading cycles were applied. The cyclic structural load was not observed to propagate the minor cracks formed during thermal loading or initiate any new cracks. The uncracked connection effectively transferred the load and limited differential deflection regardless of the level of transverse post-tensioning force. The partial-depth conventionally grouted connection was intentionally cracked by applying a direct tensile force to the connection, as shown in figure 6. The interface between the grout and concrete was the weak link in the conventionally grouted connection, as cracking occurred primarily at this interface. Mechanical cracking of the connection ceased when about two-thirds of the connection was cracked. The partially cracked connection was then cyclically loaded and performed similarly

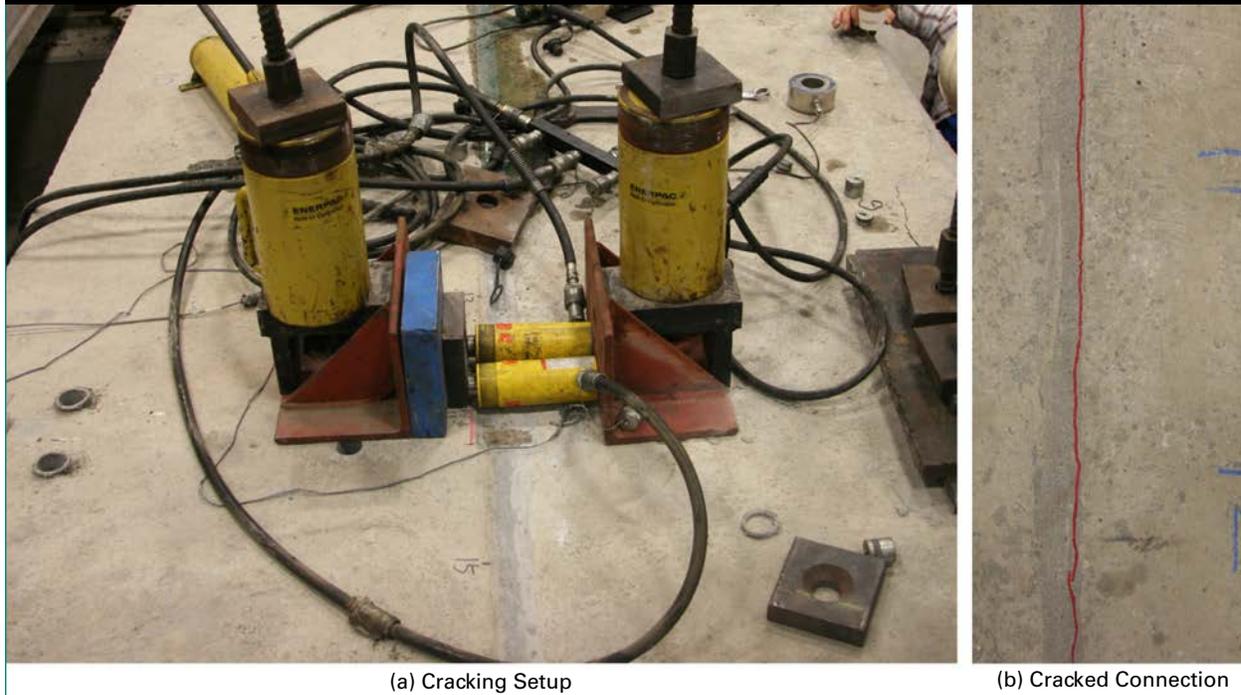
to the uncracked connection in terms of moment distribution and exhibited a slight increase in differential deflections. The crack propagated as loading cycles progressed. Differential deflection and crack propagation increased as the level of transverse post-tensioning decreased. When the connection was mechanically cracked so the full length of the connection was cracked, the same observations were made. The distribution of longitudinal strains was not substantially affected, and differential displacements were seen to slightly increase, particularly when little to no post-tensioning was applied. The loadings imparted were not sufficient to significantly degrade the shear interlock across the cracked connection. Moving loads and/or water ingress combined with freezing temperatures, neither of which were applied in this study, would likely serve to widen cracks and commensurately decrease the ability of beams to share loads across connections.

The full-depth conventionally grouted connection was intact after casting and curing but cracked when the post-tensioning force was removed. When the cracked full-depth conventionally grouted connection was cyclically loaded, similar observations to those for cracked partial-depth connection were observed.

Performance of UHPC Connections

Both the partial- and full-depth UHPC connections performed well. No cracks were observed during either the thermal loading or the structural loading cycles. The UHPC connections performed similarly to the uncracked conventionally grouted connections in terms of longitudinal strain, moment distribution, and differential deflection. When a direct tensile force was applied to the UHPC connections to intentionally crack the connection, the box beam concrete cracked instead of the connection interface or the UHPC. This indicates that the interface bond between the UHPC and concrete with exposed aggregate surface preparation was significantly enhanced. This was also observed in a study by De la Varga et al., where interface bond strength of different grout materials with concrete was investigated.⁽¹⁴⁾ They found that for connections between UHPC and

Figure 6. Mechanical cracking of the partial-depth conventionally grouted connection, including cracking setup and cracked connection.



concrete with an exposed aggregate surface finish, failure is likely to occur in the concrete instead of at the interface or in UHPC. This is not true for conventionally grouted connections, as failure often occurs in the interface.

Shear Key Design Parameters

Three parameters are considered important in the design of connections: transverse post-tensioning force, transverse shear strength of the connection, and the transverse tension at the connection (i.e., in the grout and at the interfaces) between the grout and box beam concrete.

Transverse Post-Tensioning Force

Transverse post-tensioning force is widely used with precast prestressed box-beam bridge systems, although more than 80 percent of designers surveyed did not perform any design calculations to determine the level of transverse post-tensioning force needed.⁽²⁾ The *AASHTO LRFD Bridge Design Specifications* recommends installing transverse post-tensioning force to produce at least 0.25 ksi (1.7 MPa) of compression in the connection.⁽⁴⁾ The *Precast Prestressed*

Concrete Bridge Design Manual recommends post-tensioning forces ranging from 6 to 16 kip/ft (88 to 233 kN/m).⁽⁶⁾ If the post-tensioning force is evenly distributed along the span, it will improve the system performance by increasing the confining pressure and therefore the connection shear strength.⁽¹⁵⁾ It can also help compensate for some of the transverse tensile strain induced by structural loading, shrinkage, and thermal stress. However, transverse post-tensioning force is commonly deployed only at the beam ends and diaphragm locations; it is not capable of distributing uniformly along the span. The strain data collected in this study showed that the post-tensioning force only effectively compressed a small area around the post-tensioning locations. The compression force dissipated quickly; locations even only a few feet away from the post-tensioning points did not experience notable levels of confinement.⁽⁹⁾

The effect of transverse post-tensioning force was evaluated in this study by comparing the moment distribution and differential deflection between the two beams under different levels of transverse post-tensioning force. It was found

that the partial-depth conventionally grouted uncracked connection could effectively distribute the moment and limit the differential deflection independent of the level of transverse post-tensioning force applied. The differential deflection was nearly constant and kept at a low value of approximately 0.0025 inch (0.064 mm). When the connection became partially or fully cracked, the level of post-tension had a more pronounced effect on the differential displacement. As cracks developed in the connection, differential displacements quickly increased and led to further damage. Differential displacements grew to as high as 0.012 and 0.019 inch (0.305 and 0.483 mm), respectively, in the fully cracked partial-depth connection and partially cracked full-depth connection with no post-tensioning force.

Transverse Shear Strength

A fully functioning connection should transfer the load from one beam to the other, and the two beams are expected to have the same deflections. The *Precast Prestressed Concrete Bridge Design Manual* states that the acceptable amount of differential deflection between adjacent box beams is 0.020 inch (0.508 mm) for spans up to 100 ft (30.5 m).⁽⁶⁾ The forces being transferred through the connection drive the unloaded beam to have the same deflection. The Canadian Standards Association code

assumes that the load is transferred from one beam to another primarily through transverse shear; transverse flexural rigidity is neglected.⁽¹⁶⁾ The present study used the same assumption. When two beams are connected and only one beam is loaded, the magnitude of the transverse shear force generated in the connection is related the deflection of the beams. At locations where there is no potential deflection, such as at the supports, no transverse shear force is generated. One possible transverse shear distribution is presented in figure 7 where V_y is the shear force per unit length. If the shear distribution and the moment transferred through the shear key are known, the shear force transferred through the connection can be calculated. As the variable of interest for design is the maximum shear force in the connection, the shear force calculation can be simplified by assuming a triangular shear force distribution, V'_y , in figure 7. The maximum distributed shear force, v'_{max} of V'_y should be larger than the maximum value of V_y . v'_{max} can be calculated using the equation in figure 8, where M_{max} is the maximum moment transferred through the connection and l is the span length.

The most severe loading case evaluated in the study had the fully stiffened boundary condition loaded under the 90-kip (400-kN) loading range. In this case, M_{max} was calculated to be 498 kip-ft

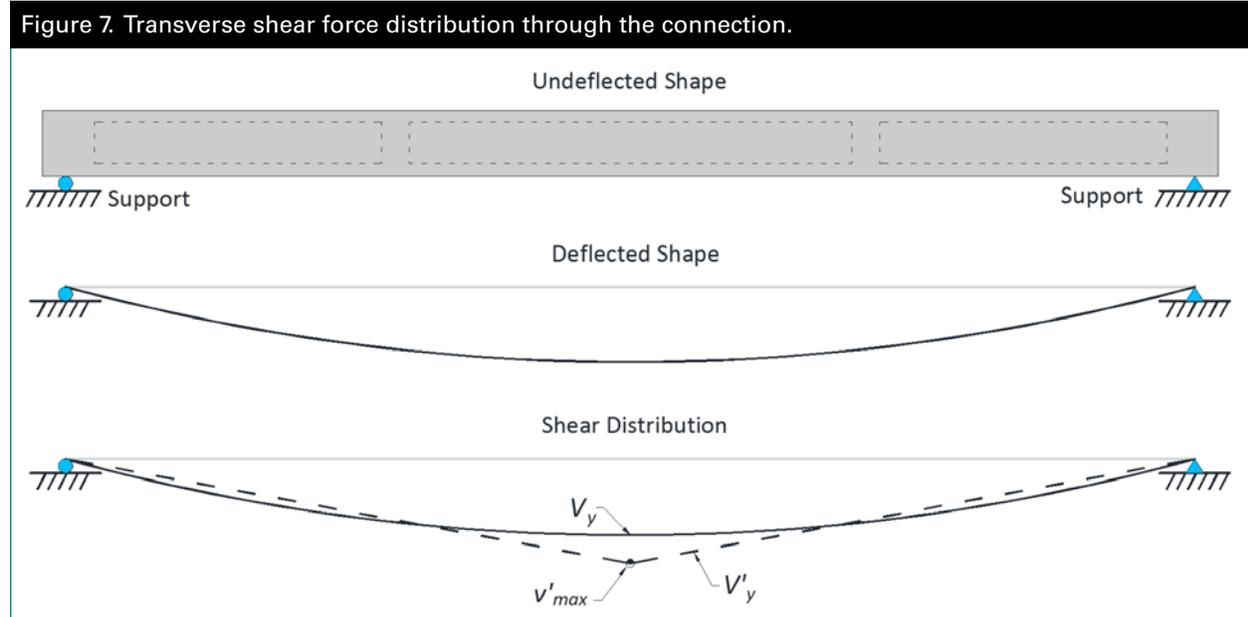


Figure 8. Maximum shear distribution through the connection.

$$v'_{max} = \frac{M_{max} \times 12}{l^2}$$

(673 kN-m).⁽¹³⁾ The equation in figure 8 calculates v'_{max} as 216 lb/inch (37.8 kN/m) for this case. For the partial-depth conventional grout shear key in this study, the connection was 8.875 inches (225 mm) deep, resulting in a shear stress of 24.3 psi (168 kPa).

The interface shear strength of the conventional grout with the precast concrete has been reported by other researchers. For example, a study by Buyukozturk et al. found that the shear strength at the interface between the grout and concrete for a flat joint was 85 psi (590 kPa) under 100 psi (690 kPa) of confining pressure and increased to 210 psi (1.4 MPa) with 300 psi (2.07 MPa) of confining pressure.⁽¹⁵⁾ They also found that the shear strength of a keyed joint would be 10 times greater than a flat joint under the same confining pressure. Another study found that the shear strength for keyed joints in the absence of transverse confinement can range from 150 to 358 psi (1.03 to 2.47 MPa).⁽¹⁸⁾ Based on these values, the shear strength of a conventionally grouted connection is sufficient to transfer the estimated shear stress calculated in this study.

The Canadian Standards Association provides charts to determine the transverse required shear force to be resisted based on the study by Bakht et al.^(16,17) Using this chart, the maximum transverse shear force due to an AASHTO HS-20 truck is calculated to be approximately 207 lb/inch (36.3 kN/m) for the beams tested in this study.⁽³⁾ This assumed the minimum bridge width available in the charts, which is 25 ft (7.6 m).⁽¹⁶⁾ While the estimated shear distribution measured in this study was low, the transverse shear force due to an AASHTO HS-20 vehicle can be as high as 1,300 lb/inch (228 kN/m).^(3,15) The typical partial-depth shear key can be assumed to have a depth of about 8 inches (203 mm).⁽²⁾ This would result in a minimum suggested connection shear strength of 160 psi (1.1 MPa).

Transverse Tension at the Connection

The connection mainly transfers the load from one beam to another through transverse shear, which drives adjacent beams to have the same deflection. The connection needs to provide transverse flexural rigidity to resist transverse tensile forces due to eccentric loads. This study intentionally placed the loading 6 inches (152 mm) off the centerline of the beams to induce more transverse tensile stress. The transverse strain in the connection was recorded.

The transverse tensile strain generated by the loading was observed to be less than 40 microstrain. This transverse tensile strain must be transferred by the connection, so the interface bond between the grout and box beam concrete should have sufficient strength to resist this strain. A 40-microstrain deformation in a 6,000-psi (41-MPa) concrete would be expected to produce a stress of approximately 150 psi (1 MPa). Early age dimensional stability of the grout is also important, as shrinkage strains can be large, resulting in cracking and interface debonding.

When the connections were placed under direct tensile load, the conventional non-shrink grout connections cracked at the interface between the grout and concrete, while the UHPC connections cracked in the concrete beam. Selection of a precast concrete surface preparation, grout, and curing methodology can ensure that the tensile resistance of the connection is at least as strong as the tensile resistance of the precast concrete. This can be beneficial in mitigating interface cracking.

Findings, Conclusions, and Recommendations

Full-scale testing on four adjacent box-beam connection designs was conducted. These included partial- and full-depth conventional non-shrink grout and UHPC connections. The beams were subjected to thermal and cyclical structural loading. The main findings, conclusions, and recommendations are provided in the following subsections.

Findings

The main findings are summarized as follows:

- The thermal loading generated in the study produced a temperature gradient between the top and bottom flanges of approximately 50 °F (28 °C) and resulted in an upward deflection of approximately 0.47 inch (11 mm). The applied thermal loading cycles did not initiate any penetrating cracks in the connections.
- The cyclic structural loading applied in this study was severe. The most extreme case in this study utilized a maximum loading range of 90 kip (400 kN) with a 5-kip (22-kN) minimum load. Within the most restrained test setup, this created an equivalent moment of 498 kip-ft (673 kN-m) transferred through the connection.
- When a connection was uncracked, cyclic structural loading was not seen to initiate cracking. This was true regardless of the level of post-tensioning in conventionally grouted connections.
- The calculated shear forces transferred through the connection in this study were small. Maximum shear stress in the partial-depth beams was 23 psi (161 kPa).
- When there were preexisting cracks in conventionally grouted connections, cyclic structural loading was observed to propagate the cracks independent of the level of transverse post-tensioning force applied. Cracks propagated more quickly under lower levels of post-tensioning.
- With higher levels of transverse post-tensioning force, the cracked connection could still effectively transfer the load, though differential deflections increased. When the transverse post-tensioning force was removed, the cracked connection could quickly lose its ability to limit differential deflection; this could reduce its capability to effectively transfer the applied loads between adjacent beams.
- If the transverse post-tensioning force was applied before casting the grout, the loss

of the post-tensioning force after casting may cause transverse tensile forces to develop in the connection. This could lead to cracking if the beams exhibited a large enough amount of relative sweep in their as-fabricated shape.

- When the connection was uncracked, beams with conventional grout connections had similar load distribution performance as beams with UHPC connections. However, the interface between the conventional grout and box beam concrete was the weak link of the system and could crack if a sufficient load or deformation occurs.
- The behavior of the adjacent box-beam bridges with UHPC connections could be expected to be comparable with an equivalent structural system with no field-cast connections. The mechanical capacity of the UHPC connection was observed to enhance connection capacity so that under the application of large transverse tensile stresses, tensile rupture occurred in the precast concrete box beams.
- Full-depth connections showed slight improvements in load distribution between beams. This was likely due to the increased depth of the connection, which significantly increased the transverse flexural and shear stiffnesses of the connection. However, increasing the depth of the connection increased construction costs and possibly construction complexity.
- A partial-depth UHPC connection appeared to deliver good performance, including elastic distribution of loads across the connection without cracking of the connection.

Conclusions and Recommendations

Conclusions and recommendations related to adjacent box beam connection design and performance evaluation are presented as follows:

- The performance and efficiency of the shear key can be evaluated for load transfer by determining the moment distribution between beams.

- Differential deflection between adjacent beams can be a good indicator of the serviceability performance of a connection. Based on the tests in this study, the differential deflections for in-tact connections were below 0.005 inch (0.127 mm). The *Precast Prestressed Concrete Bridge Design Manual* seeks to limit differential deflection between adjacent box beams to 0.02 inch (0.51 mm) for spans up to 100 ft (30.5 m).⁽⁶⁾
- The concept of “equivalent moment,” which calculates the moment transferred through the connection from a loaded beam to adjacent beams, can be used to compare the test results from this study with other bridge designs that have different geometries and loading conditions.
- Transverse post-tensioning can limit differential movement between beams, compensate for some transverse tensile strains across the connections, and assist with load transfer between beams after connection cracking. Increased transverse post-tensioning force distribution along the length of the connections could enhance system performance as the keyway shear strength increases with more confinement force. However, as commonly deployed today, transverse post-tensioning only effectively confines a small area near the post-tensioning locations. This transverse post-tensioning would likely be most valuable after connection degradation has already begun, thus serving to limit large differential deflections between adjacent beams.
- Based on the concurrent research by De la Varga et al., a minimum interface bond strength of 150 psi (1.0 MPa) is recommended when selecting a grout material.⁽¹⁴⁾ This will help to avoid interface cracking due to eccentrically placed external loads. The possible transverse tensile forces and deformations due to thermal loads and material shrinkage are not included here.

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