ADJACENT BOX BEAM CONNECTIONS

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ABSTRACT

Adjacent box beam bridges are a popular bridge type, particularly for short to medium span length bridges. However, one of the recurring issues with this type of bridge is the shear key connection deterioration, resulting in substandard performance of overall bridge system. The research evaluated the performance of four connection details by conducting full-scale structural tests. The evaluation includes connection details that are considered current good practice utilizing high-strength non-shrinkage grout in combination with transverse post tensioning and innovative connection details utilizing the advanced mechanical and durability properties of ultra-high performance concrete (UHPC). Cyclic structural loading to simulate traffic live load was applied to the beams. It was found that the cyclic structural loading did not initiate any new cracks in previously uncracked locations. However, cyclic structural loading did cause propagation of preexisting cracks in or near the shear key regardless the transverse post-tension applied. The UHPC connection details, which did not include any transverse post-tensioning, exhibited superior performance, with no debonding or cracking observed in or near the connections throughout the structural loadings.

Keywords: Shear Key Connection, Box Beam, UHPC, Non-Shrinkage Grout, Cyclic Loading, Post-Tension

INTRODUCTION

Precast, prestressed concrete box beams are used throughout the United Stated. The box beams are normally prefabricated in a controlled environment, enabling production of durable structural elements. The box beams are assembled on job site with field-cast shear keys to form a complete bridge system. This type of bridge is easy and fast for construction and has been adopted by many state departments of transportation. However, one of the recurring issues for this bridge system is the shear key degradation, including debonding, cracking, and leakage at the shear key. This can allow chloride-laden water to reach the interior of the structure and can result in corrosion of the tie bars and bottom strand adjacent to the joints. Decades of experience has proven that the field-cast shear key is a weak link in the system and that has at times led to the substandard performance of the overall bridge system.

The shear key deterioration can be caused by many factors, such as drying shrinkage of the grouting material, the load transferred through the shear key when there are vehicles on adjacent beams, thermal effects, misalignment, and poor construction practices. Much research has been done trying to improve the shear key performance, mainly by using different grout materials (such as non-shrinkage grout, epoxy grout, rapid-setting grout, etc.) and/or developing different shear key designs (such as mid-depth shear key, shear key reinforced with U-bar details and headed reinforcement details).[1,2,3] This research evaluated the performance of connection details by conducting full-scale structural tests. The evaluation included connection details that are considered current good practice utilizing high-strength non-shrinkage grout in combination with transverse post tensioning, and details that are developed using ultra-high performance concrete (UHPC). The factors that affect shear key performance, including the simulated traffic loading and transverse post-tensioning, and the performance of different connection designs are presented in this paper. The findings of the research can be used to assist bridge owners in the use of this economical bridge type and can provide innovative solutions that advance the state-of-the-practice in bridge construction.

EXPERIMENTAL PROGRAM

The research involved full-scale testing of four shear key designs. The shear key and box beam design details are first introduced, followed by the tests setup, loading protocol, and grout material properties.

SHEAR KEY AND BOX BEAM DESIGN DETAILS

Four types of shear key are evaluated in this paper. The first two designs use conventional high-strength non-shrinkage grout, one with partial depth grout and one with full depth grout, as shown in Figure 1 (a) and (b). Note that the design with conventional grout is combined with transverse post-tension, which is currently considered good design practice. The other two designs are the new design details that engage the advanced mechanical and durability properties of UHPC, as shown in Figure 1 (c) and (d), one with partial depth and one with full depth. The UHPC connection design has extended reinforcing steel from each side of the precast box beams into the noncontact lap splice connection, which is thereafter filled with UHPC; no transverse post-tension is needed. With UHPC, a very short embedment length [5.5 in. (14 cm) in this study] can be used to further simplify the design and construction compared with the post-tensioned conventional grout connection. A similar design using UHPC in deck-level connections has been reported by Graybeal[4].

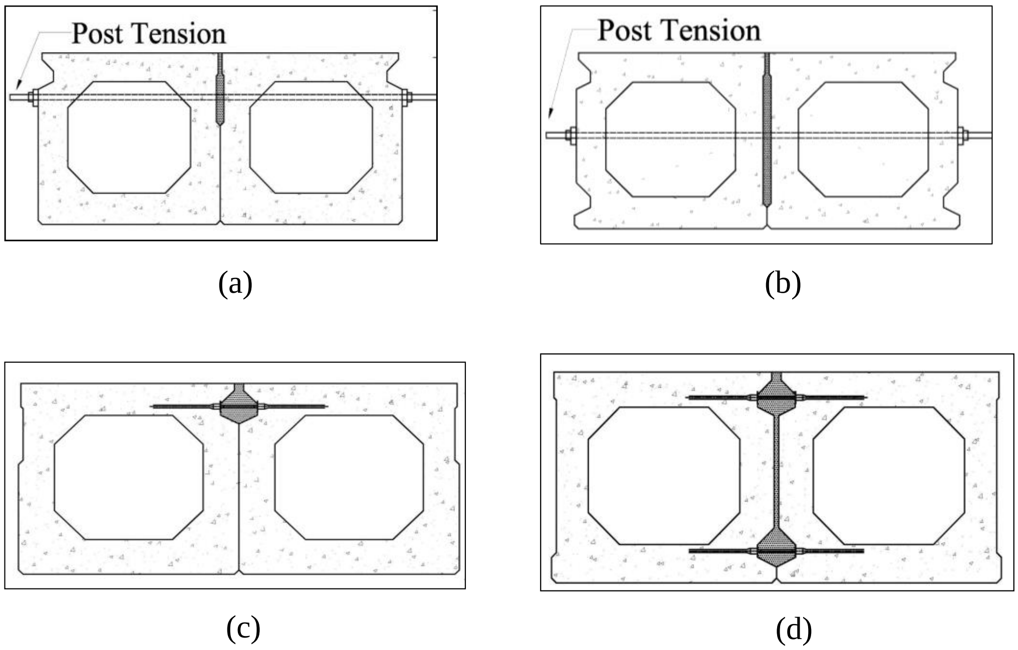
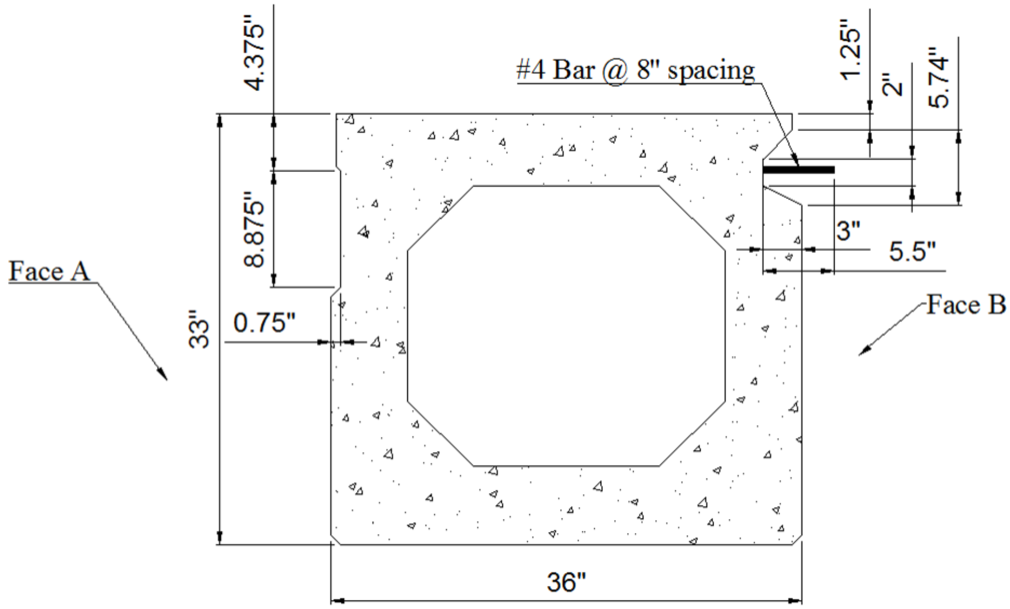


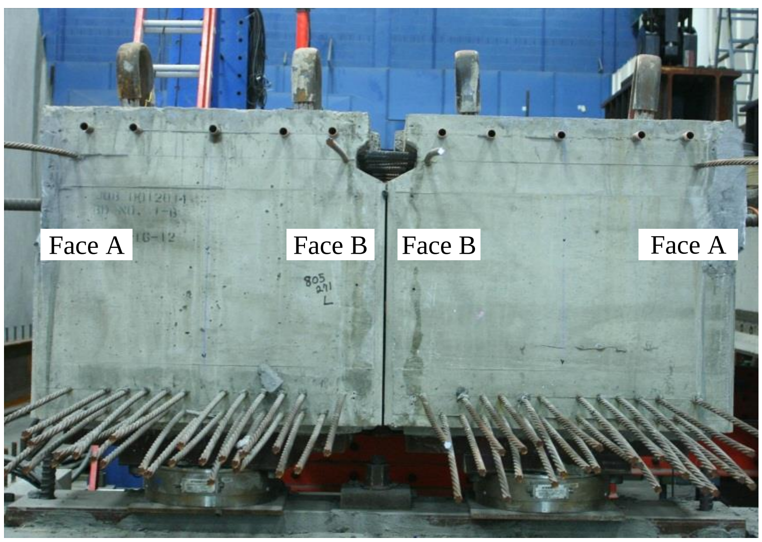
Fig.1 Shear Key Connection: (a) Partial-Depth Conventional Grout; (b) Full-Depth Conventional Grout; (c) Partial-Depth UHPC; and (d) Full-Depth UHPC.

The dimension details of the shear keys and box beam cross section are presented in Figure 2 and Figure 3. AASHTO Type BII-36 box beams were used, which have a cross section of 36 × 33 in. (91 × 84 cm) (width × height). Each box beam has two shear key design details, one on each side. For example, for the partial-depth shear key design in Figure 2, the face A of the box beam has the shear key detail for conventional grout and the face B of the same box beam has the shear key detail for UHPC. With this design, each beam can be used twice to test two shear key details. In the study, the shear key with conventional grout (face A─face A) was tested first, and then the two beams were separated and swapped to have faces B grouted with UHPC.

It should be noted that the surface of the shear keys for conventional grout is sandblasted (Figure 4a) and the beams are transversely post-tensioned after casting the connection (Figure 1 and Figure 4b). The shear key design for UHPC has a trapezoid shape and is reinforced with No. 4 steel rebar. A close view of the UHPC connection design is presented in Figure 5. The No. 4 bars, which are extended 5.5 in. (14 cm) from the box beam (as demonstrated in Figures 2 and 3), are lap spliced and the lap spliced length is approximately 4 in. (10 cm) in this study. The UHPC shear key has an exposed aggregate surface to provide better bond at the interface. No transverse post-tension is needed for the UHPC connections.

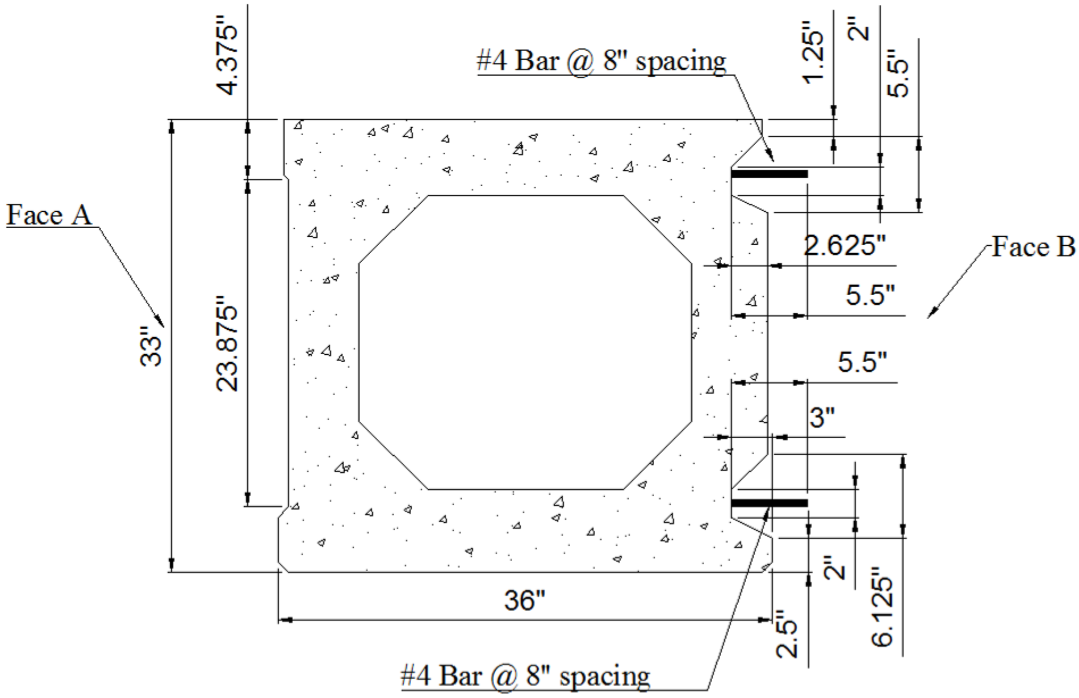


(a)

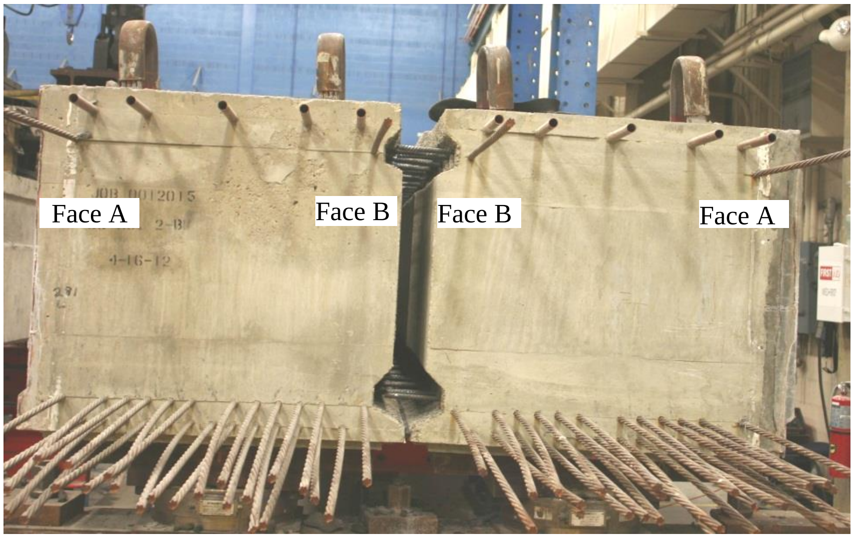


(b)

Fig.2 Shear Key Design for Partial-Depth Conventional Grout (Face A) and Partial-Depth UHPC (Face B): (a) Dimension of the Box Beam Cross Section and Shear Key; and (b) Picture of the Box Beams.

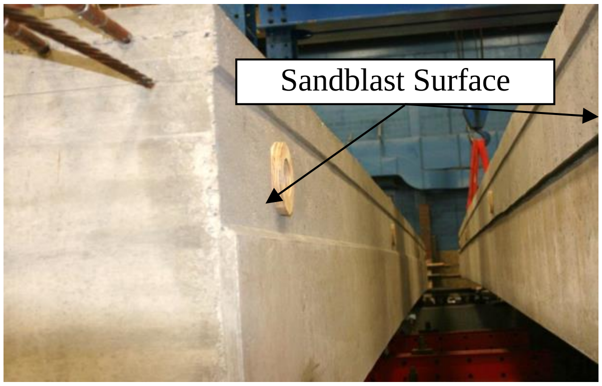


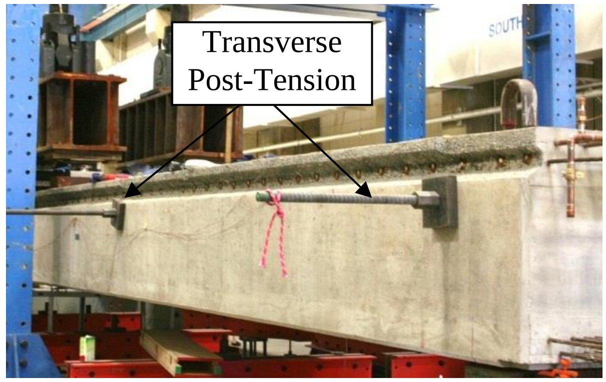
(a)



(b)

Fig.3 Shear Key Design for Full-Depth Conventional Grout (Face A) and Full-Depth UHPC (Face B): (a) Dimension of the Box Beam Cross Section and Shear Key; and (b) Picture of the Box Beams.





(a) (b)

Fig.4 Partial-Depth Conventional Grout Shear Key: (a) Sandblasted Surface; and (b) Transverse Post-Tension.

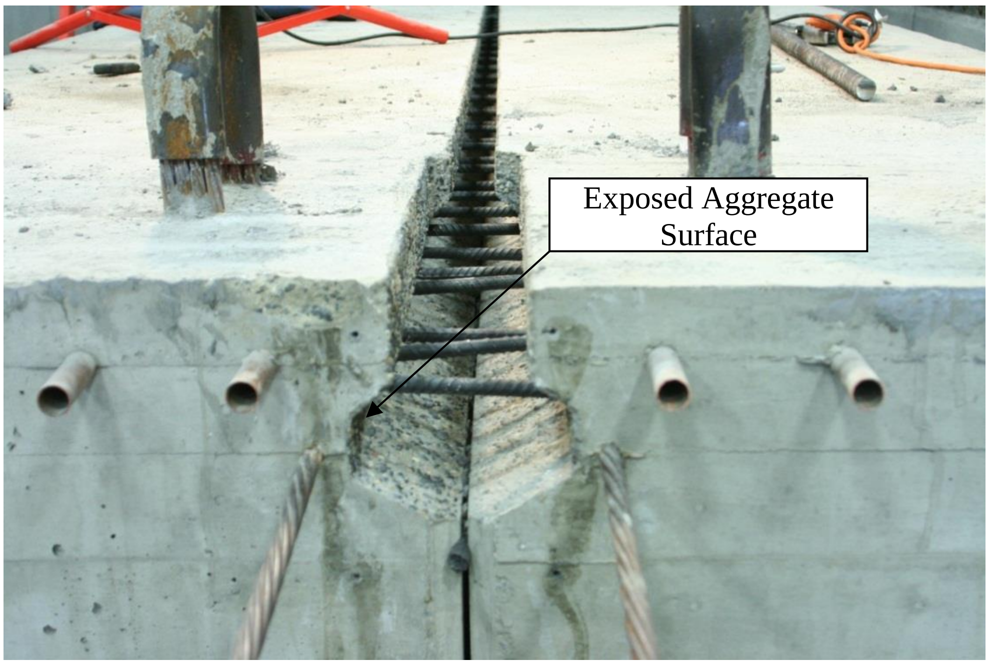


Fig.5 Picture of UHPC Shear Key Design.

LOADING

In this study, two box beams are grouted together and structurally loaded. The test setup and loading protocols are presented in the following.

Simply Supported

The loading setup on the two connected box beams is illustrated in Figure 6. The box beams are simply supported at two ends, providing a span length of 48 ft (14.6 m). Each individual beam is loaded through a spreader beam attached to an actuator, with the loading points located 3 ft (0.9 m) away from the midspan of the box beam, as shown in Figure 6-Side View. The loading is intentionally placed 6 in. (15 cm) off the center line of the box beam, as shown in Figure 6-End View, with the purpose of creating more severe torsional moment, thus more tension force at the connection compared to loading at the center line.

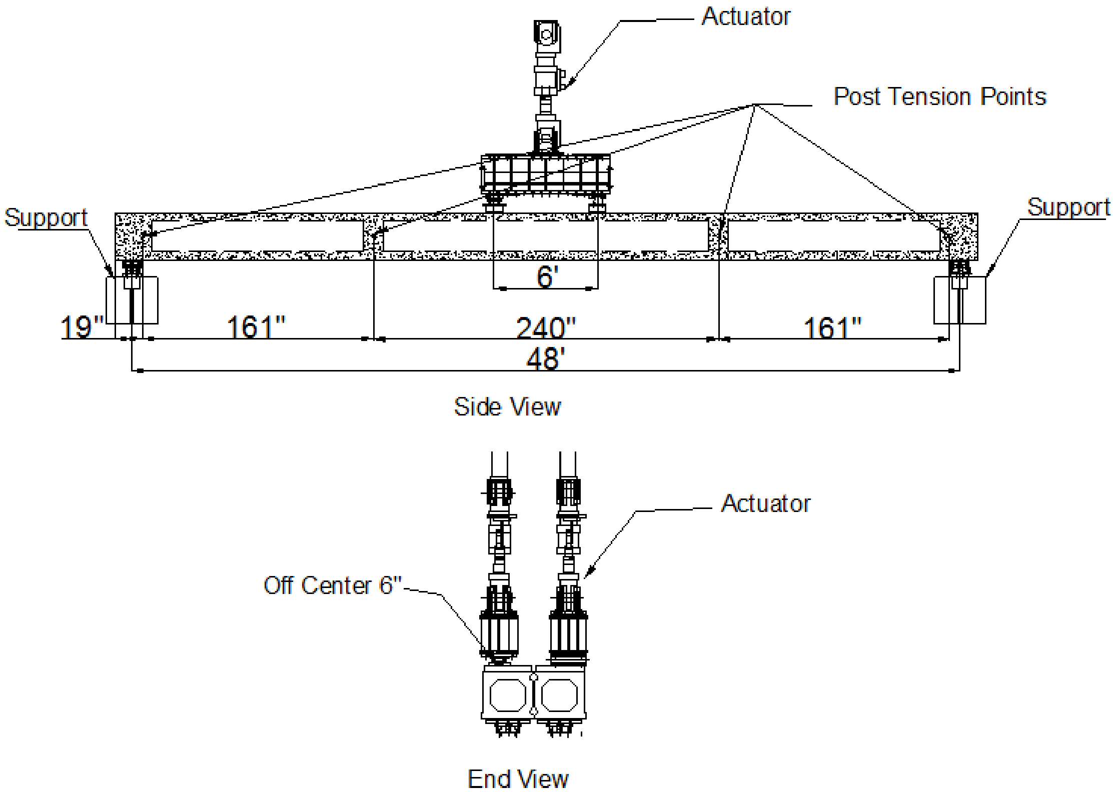


Fig.6 Tests Setup for Simply Supported Configuration.

The load is applied following a sine shape with a phase angle of 180 degree between the two actuators on the beams, as shown in Figure 7. When one beam is under maximum load, the other is under minimum load. A minimum load of 5 kips (22 kN) is always applied to avoid the hammer reaction between the loading point and the box beams.

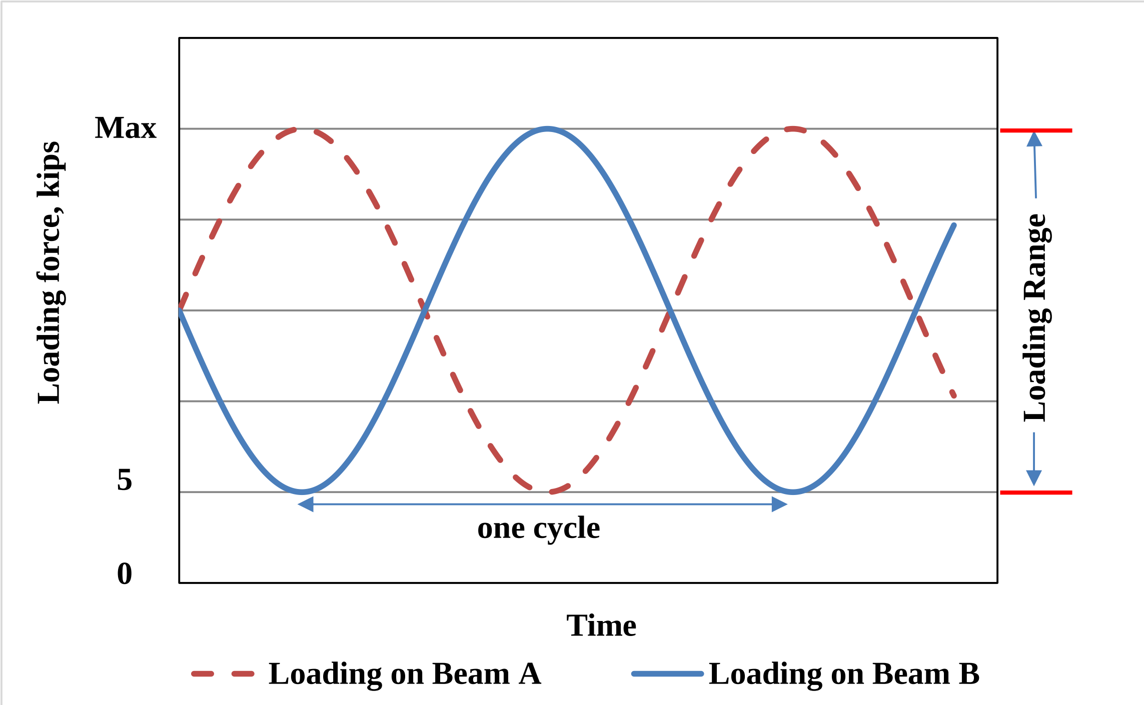


Fig.7 Loading Protocol for Simply Supported Beams.

Restrained Deflection

The two-beam system tested in the study, when they are simply supported, is more flexible compared to a multi-beam bridge. Considering the situation with a multi-beam bridge when load is applied to a beam, its adjacent member is forced to deflect simultaneously through the transfer of vertical shear force at the joints. When the deflection of this adjacent member is restrained by other beams in the bridge, a higher shear force at the joint can be expected, compared to the case when the deflection is not retrained by other members. With this consideration, for the two-beam system tested in this study, a few strategies are taken to provide more stiffness in the system, including clamping the beam ends to retain end rotation and providing extra supports underneath one beam. The clamp down force at each end is applied with two Double C channels with a total clamp down force of 100 kips (690 MPa). For the underneath support at the mid-diaphragms, the inside edge of the beam sits on a neroprene pad with dimensions of 6 × 24 × 2 in. (15 × 61 × 5 cm) (width × length × thickness), while the outside edge of beam is pulled down with a force of 35 kips (241 MPa) to minimize the torsional rotation of the cross section when the beam is loaded. The setup is illustrated in Figure 8 and the actual setup picture is presented in Figure 9. The effect of these extra boundary conditions will be discussed later in this paper.

When the beam ends are clamped down to restrain their rotation (without extra supports underneath one beam), the beams are loaded following the loading protocol in Figure 7. For the configuration with restrained deflection (clamp down the ends and extra supports underneath one beam), the cyclic load is applied to the beam that does not have extra supports while the load on the other beam is kept constant at 5 kips (22 kN). The loading protocol is presented in Figure 10.

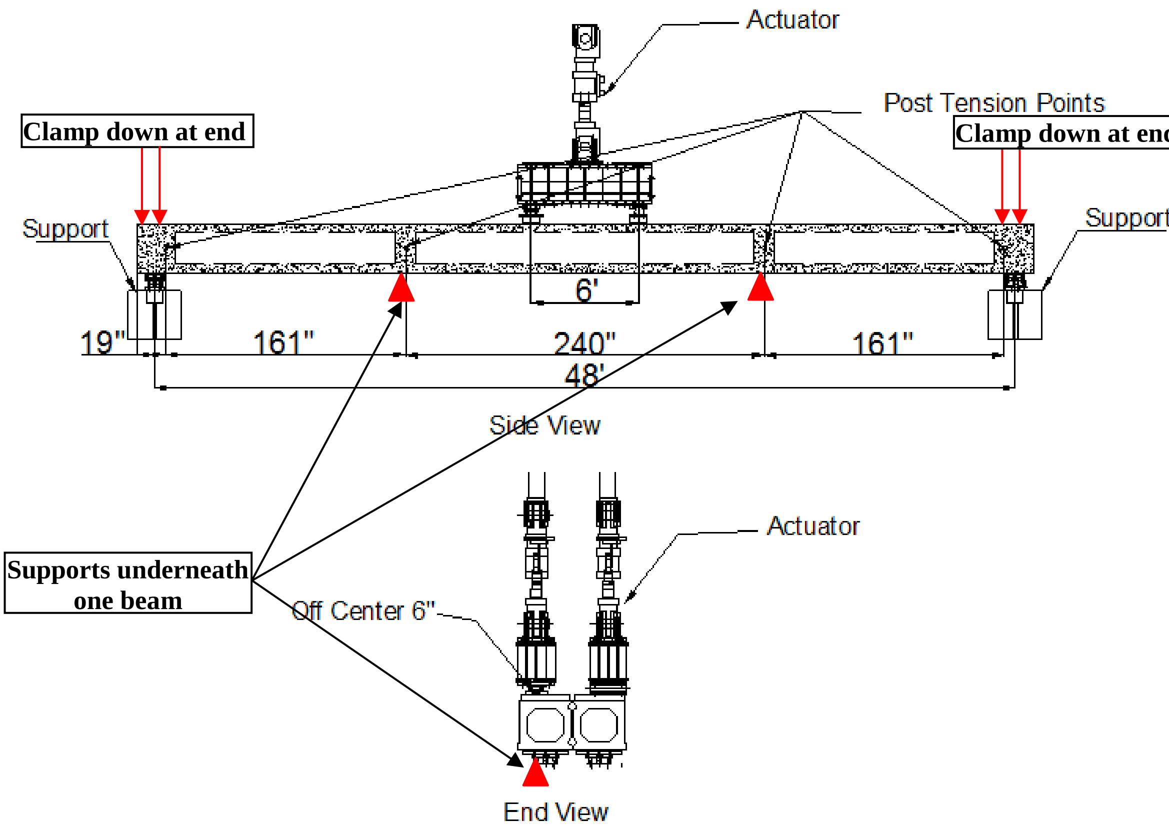


Fig.8 Tests Setup for Restrained Deflection Configuration.

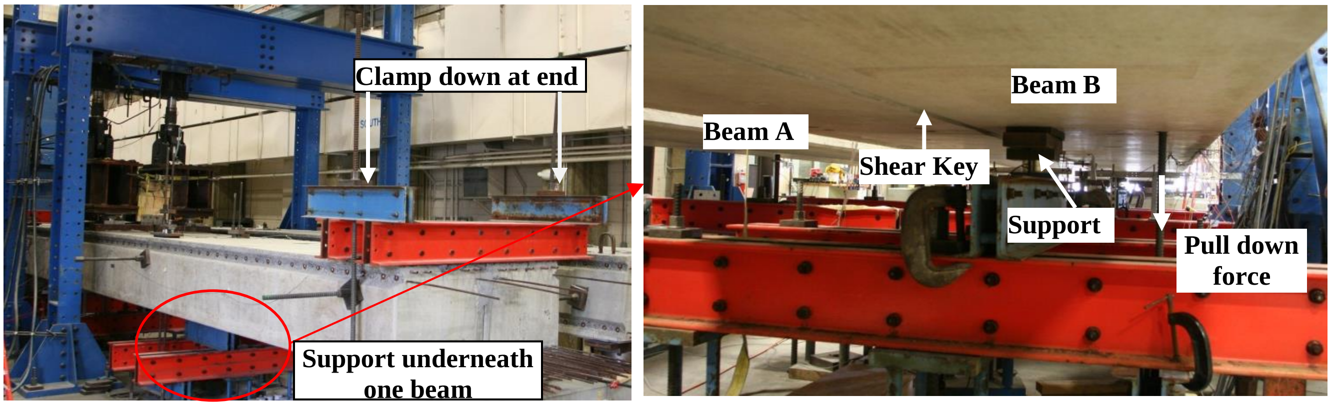


Fig.9 Pictures of Clamping the End and Providing Extra Support Underneath One Beam

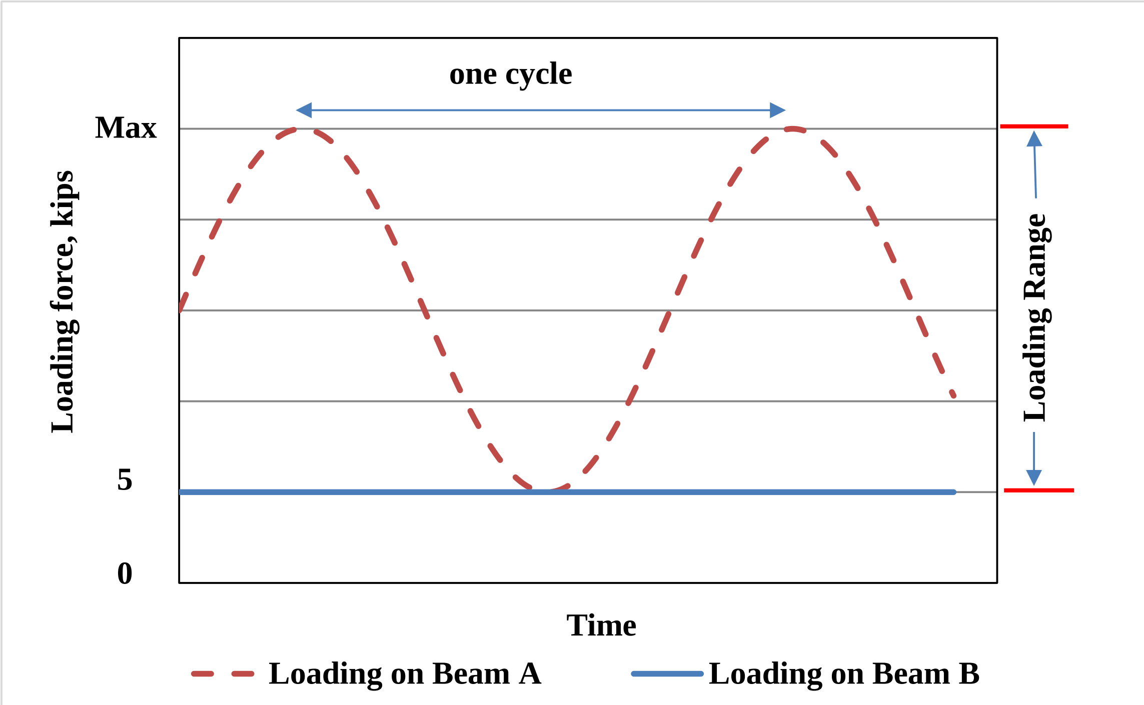


Fig.10 Loading Protocol for Restrained Deflection Configuration.

Loading Range

Different loading ranges, including amplitudes of 18, 36, 54, 72, and 90 kips (80, 160, 240, 320, and 400 kN), are applied in this study. It should be pointed out that the load range 18 kips (80 kN) is approximately the distributed load on a single beam from a fatigue truck based on the AASHTO LRFD Bridge Design Specifications.

GROUT MATERIALS PROPERTIES

The conventional grout used in this study is a cement-based grout. It reached an average compressive strength of 8000 psi (55 MPa) at time of testing.

UHPC is a new class of advanced cementitious materials. It tends to contain high cementitious materials contents and very low water-to-cementitious materials ratio, and to exhibit high compressive and tensile strengths. The discrete steel fiber reinforcement included in UHPC allows the concrete to maintain tensile capacity beyond cracking of the cementitious matrix. UHPC has been defined as follows:

> *UHPC is a cementitious composite material composed of an optimized gradation of granular constituents, a water-to-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement. The mechanical properties of UHPC include compressive strength greater than 21.7 ksi (150 MPa) and sustained post-cracking tensile strength greater than 0.72 ksi (5 MPa). UHPC has a discontinuous pore structure that reduces liquid ingress, significantly enhancing durability compared to conventional concrete.*[5]

The UHPC used for this research has a steel fiber content of 2% by volume and an average compressive strength of 26 ksi (179 MPa) at time of testing. More details about this UHPC material can be found in research by Graybeal[5-8].

SECTION ANALYSIS

EFFECTIVE BEAM STIFFNESS

After the two beams are grouted together, the beams are loaded and the deflection and tensile strain at midspan are measured to check the system stiffness. As shown in Table 1, the two beams are loaded with a force of 50 kips (222 kN) at each loading point and both the calculated and measured deflection and tensile strain at midspan are listed. When the deflection and tensile strain are calculated, the modulus of elasticity of concrete, E, is calculated based on concrete compressive strength of 8000 psi (55 MPa). The moment of inertia of the two jointed beams is calculated as $2 \times I_{beam}$, where I_{beam} is the moment of inertia of each individual beam and estimated based on the beam dimension details with consideration of all the reinforcement. The individual beam stiffness, EI, used in the calculation is 449×10^6 kip-in^2 (1.29×10^6 kN-m^2).

As shown in Table 1, the calculated deflection and tensile strain values are both slightly bigger than the measured values, which indicates a slightly under estimated beam stiffness. The effective beam stiffness, EI_{eff}, is then back calculated using Equations (2) and (3) with the actual measured deflection and strain and the results are listed in Table 1. The EI_{eff} based on deflection is 463×10^6 kip-in^2 (1.33×10^6 kN-m^2), the EI_{eff} based on tensile strain is 471×10^6 kip-in^2(1.35×10^6 kN-m^2), versus the calculated EI of 449×10^6 kip-in^2 (1.29×10^6 kN-m^2).

Table 1. Beam Stiffness Calculation

Load P†, kips	**$\delta_{calculated}$, in.**	**$\delta_{measured}$, in.**	**$EI_{eff,\delta}$*, ×10^6 kip·in^2**	**$\varepsilon_{calculated}$**	**$\varepsilon_{measured}$**	**$EI_{eff,\varepsilon}$*, × 10^6 kip·in^2**
50	0.43	0.42	463	190	156	471

† Refer to Figure 11. * Stiffness of each individual beam. 1 kip = 4.448 kN. 1 in. = 0.0254 m.

In a later section, the load distribution and the equivalent moment being transferred through the shear key will be calculated and presented. The calculation will use the average of the two effective beam stiffness obtained in Table 1, which is 467×10^6 kip-in. (1.34×10^6 kN-m^2). These are the main parameters used in this paper to evaluate the connection performance. Other measurements, like the strain in the grout and concrete beam in the transverse direction due to torsion tensile force, are also recorded in the research and will be presented in another paper.

LOAD DISTRIBUTION

The full-scale tests conducted in this research are trying to simulate the stress condition at the joints in a real bridge. When wheel loads are applied to a beam in a multi-beam bridge, its adjacent members are forced to deflect simultaneously and the applied load is distributed among the loaded beam and adjacent beams. The distribution of the load is through the shear key connection. One of the key parameters investigated in this study is the distribution factor between the loaded beam and the adjacent beam. The load distribution is calculated as following.

$$Load\ Distribution\ on\ Beam\ A = \frac{Moment\ carried\ by\ Beam\ A}{Moment\ carried\ by\ Beam\ A + Moment\ carried\ by\ Beam\ B} \quad \textbf{Eq. (1)}$$

When the two beams, which have the identical design, are under same boundary conditions, the moment carried by each beam is proportional to the deflection or tensile strain at the midspan. A demonstration for the simply supported case is presented in Figure 11 and Equations (2) and (3).

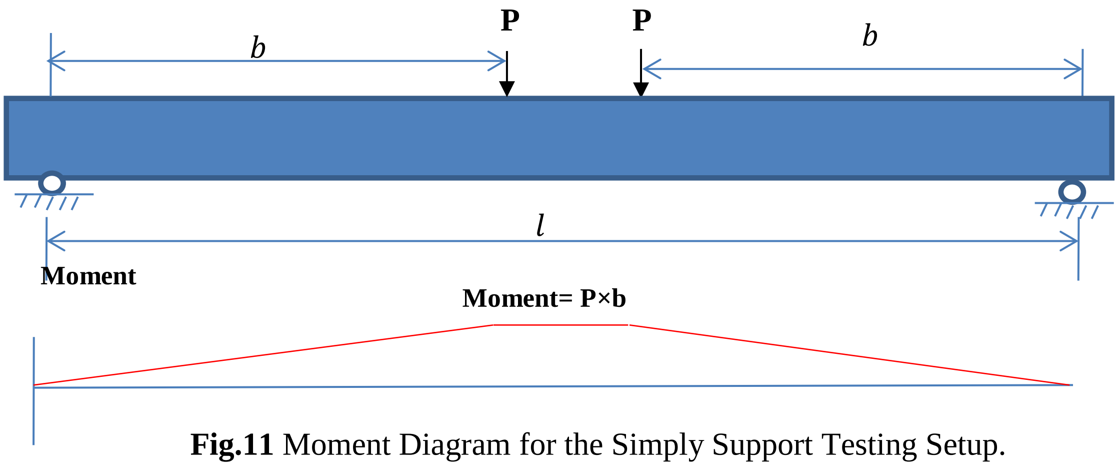


Fig.11 Moment Diagram for the Simply Support Testing Setup.

$$\delta = \frac{M}{24EI}(3l^2 - 4b^2) \quad \textbf{Eq. (2)}$$

$$-\frac{\varepsilon}{y} = \frac{M}{EI} \quad \textbf{Eq. (3)}$$

Where δ is the deflection at midspan, M is the moment at midspan, l and b are shown in Figure 11, ε is the tensile strain at the midspan, and y is the distance from where the tensile strain is measured to the neutral axis of the cross section. So the load distribution can also be calculated as:

$$Load\ Distribution\ on\ Beam\ A = \frac{\delta_A}{\delta_A + \delta_B} \times 100\% \quad \textbf{Eq. (4)}$$

$$Load\ Distribution\ on\ Beam\ A = \frac{\varepsilon_A}{\varepsilon_A + \varepsilon_B} \times 100\% \quad \textbf{Eq. (5)}$$

Figure 12 provides an example of the load distribution calculated based on deflection and tensile strain. The data is collected for the beams with partial-depth conventional grout connection, which are simply supported. A total of 1.5 million cycles are included. As shown in Figure 12, when beam A is loaded at 59, 77, and 95 kips (262, 342, and 423 kN) and beam B is kept constant at 5 kips (22 kN), beam A carries about 52% of the total moment, constantly, regardless of whether that analysis is based on deflection or strain. The load distribution based on tensile strain will be used in later discussions.

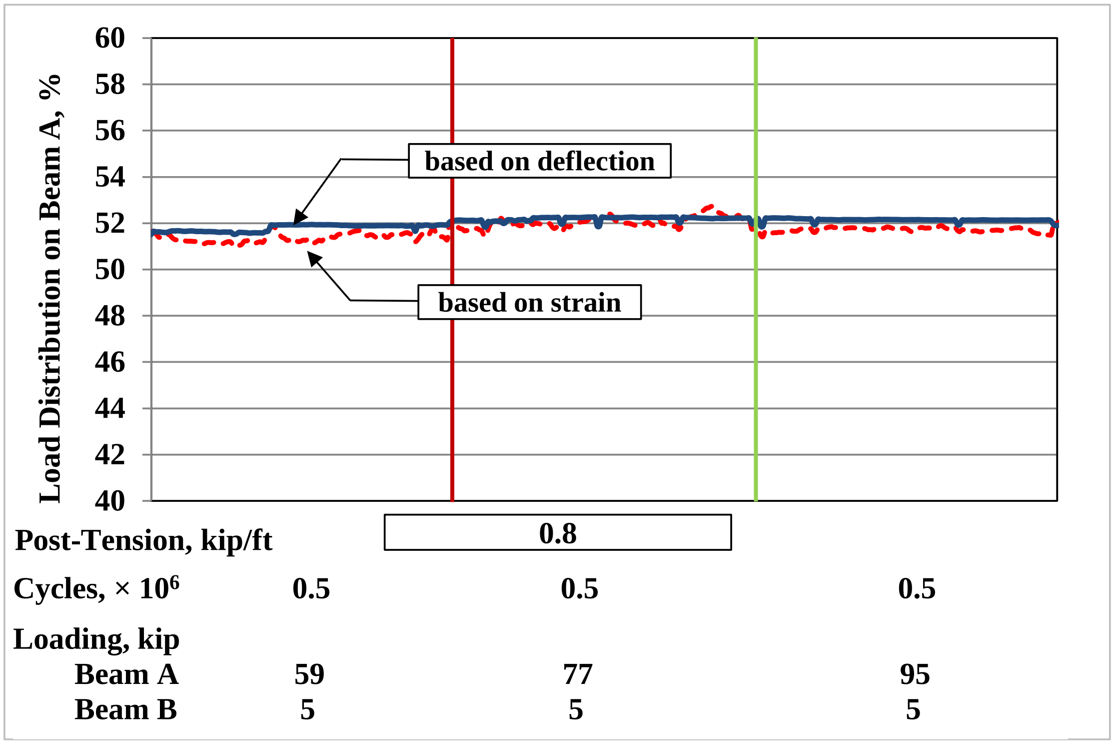


Fig.12 Load Distribution based on Deflection and Tensile Strain. Partial-Depth Conventional Grout, Simply Supported.

Figure 13 demonstrates the load distribution for the same beams as those in Figure 12, but the beam ends are clamped down instead of simply supported. In this case, the two beams still have the same boundary conditions and the load distribution can be calculated using Equation (5). As shown in Figure 13, when the beam ends are clamped down, the beam A, the more heavily loaded beam, has a load distribution close to 52%, which is about the same as that in the simply supported case. However, the load transferred though the joints must be different. The load distribution itself will not reflect the difference.

Moreover, for the configuration where the ends are clamped and extra supports are provided underneath one of the beams, the load distribution can not be calculated using Equation (4) or Equation (5) because the boundary conditions of the two beams are different.

To evaluate the effect of the extra boundary conditions, a new parameter, the equivalent moment transferred through the shear key, will be used.

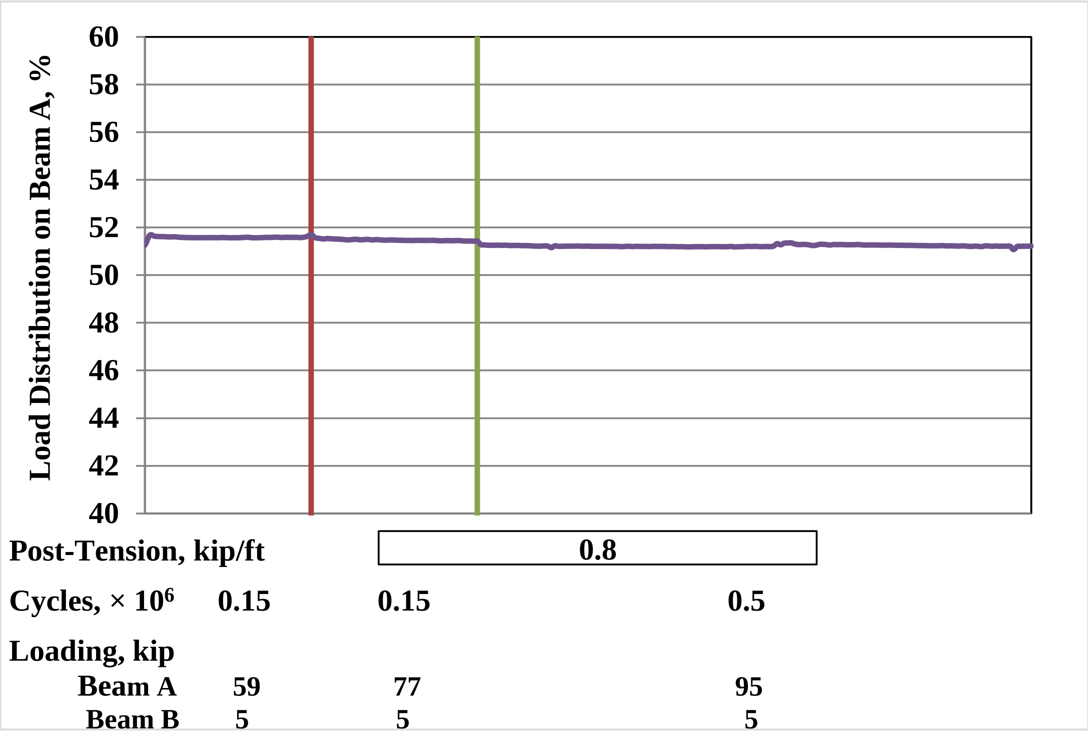


Fig.13 Load Distribution based on Tensile Strain. Partial-Depth Conventional Grout, Clamp Down Beam Ends (No Extra Supports Underneath the Beam).

EQUIVALENT MOMENT TRANSFERRED THROUGH THE SHEAR KEY

Instead of looking at the specific shear or tensile force being transferred through the shear key, the equivalent moment transferred is used in this analysis. The equivalent moment calculation is demonstrated in the following examples. For the two beams that are simply supported, when beam A is loaded at 59, 77, or 95 kips (262, 342, and 423 kN) and beam B is loaded constantly at 5 kips (22 kN), as shown in Figure 12, beam B has the same, if slightly less, deflection and tensile strain at midspan as the beam A. The extra deflection and tensile strain, beyond that which is due to the 5 kips (22 kN) loading, is driven by all the force transferred through the joint. The equivalent moment is introduced here to represent the force that being transferred through the joint. The equivalent moment for the simply supported beams can be calculated as:

$$\varepsilon_{measured} = \varepsilon_{5kips} + \varepsilon' \qquad \textbf{Eq. (6)}$$

$$-\frac{\varepsilon'}{y} = \frac{M_{equivalent}}{EI_{eff}} \qquad \textbf{Eq. (7)}$$

Where $\varepsilon_{measured}$is the measured strain in beam B when beam A is loaded at a maximum load and beam B is loaded at minimum of 5 kips (22 kN); ε_{5kips} is the strain in beam B when it is loaded at 5 kips (22 kN); ε' is the extra stain in beam B due to the equivalent moment transferred through the shear key; y is the distance from where the strain is measured to the neutral axis of the beam cross section; $M_{equivalent}$ is the equivalent moment that being transferred through the shear key; and EI_{eff} is the effective beam stiffness.

The measured strain for the simply supported beams with partial-depth conventional grout connection is presented in Figure 14, while the strain for the same beams except that the beam ends are clamped down is presented in Figure 15. In both figures, beam A is loaded to 95 kips (423 kN) and beam B is loaded to 5 kips (22 kN). As shown, for the simply supported case, beam A has an average strain of 160 με and beam B has an average strain of 152 με; the equivalent moment transferred through the joint (use Equation 6 and Equation 7) is about 386 kip-ft (522 kN-m). For the case where the beam ends are clamped, the beam A has an average strain of 122 με and beam B has an average strain of 112 με; the equivalent moment transferred through the joint is about 283 kip-ft (383 kN-m). Note that the load distribution on beam A in both cases is about the same, as demonstrated in Figure 12 and Figure 13.

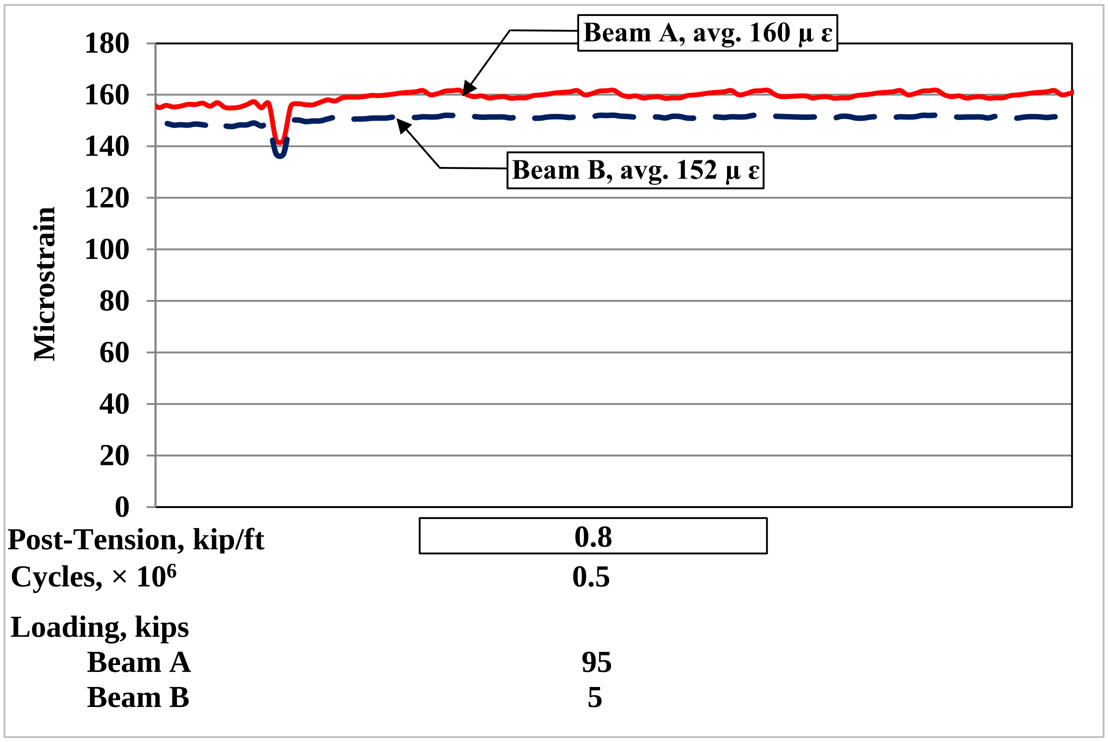


Fig.14 Tensile Strain at the Mid-Span. Partial-Depth Conventional Grout, Simply Supported.

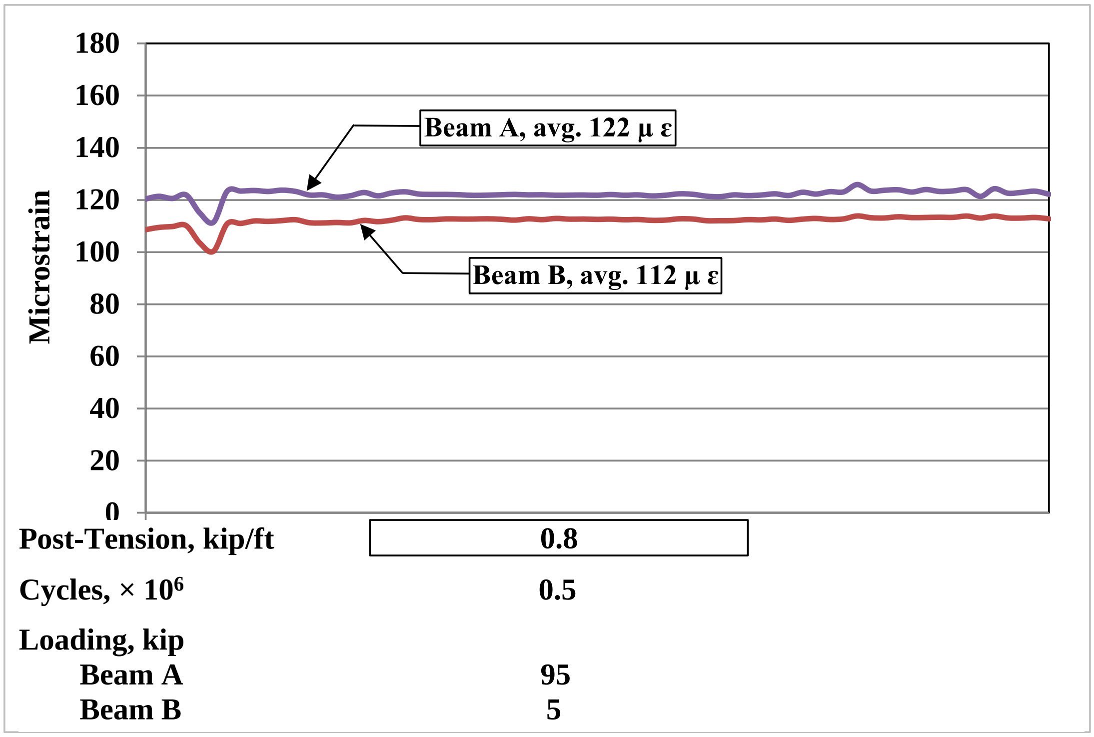


Fig.15 Tensile Strain at the Mid-Span. Partial-Depth Conventional Grout, Clamp Down Beam Ends (No Extra Supports Underneath the Beam).

Figure 16 presents the strain for the same beams in Figure 14 and Figure 15, but with extra supports underneath beam B. As the boundary conditions for beam B is different from beam A, Equation (6) and Equation (7) can not be applied here.

The case in Figure 16 is analyzed in two steps here. First, assume beam A, with ends clamped down as those in Figure 15, is loaded alone with a total force of 95 kips (423 kN), the tensile strain at midspan can be reasonably estimated with the tests in Figure 15, which would be (122+112 - ε_{5kips}) με. The ε_{5kips} is the strain at midspan of beam A when it is loaded with 5 kips (22 kN) and it was measured to be about 8 με. The corresponding moment can then be calculated using Equation 7, $-\frac{(122+112-8)\mu\varepsilon}{y} = \frac{M}{467\times 10^6 kip\cdot in.}$, which gives a moment value of 628 kip-ft (849 kN-m). Second, for the case in Figure 16, beam A still has the same boundary condition as it is in step 1 assumption, except that force being transferred through the joint. The moment at midspan of beam A in Figure 16 can be calculated using Equation 7 and compared with value obtained in step 1. The moment at midspan of beam A is calculated to be 150 kip-ft (203 kN-m). Therefore, an equivalent moment of 628 – 150 = 478 kip-ft (849 – 203 = 646 kN-m) is transferred through the joint, versus the 386 kip-ft (522 kN-m) equivalent moment transferred for the simply supported case. A more severe loading condition on the connection is created with the restrained deflection configuration.

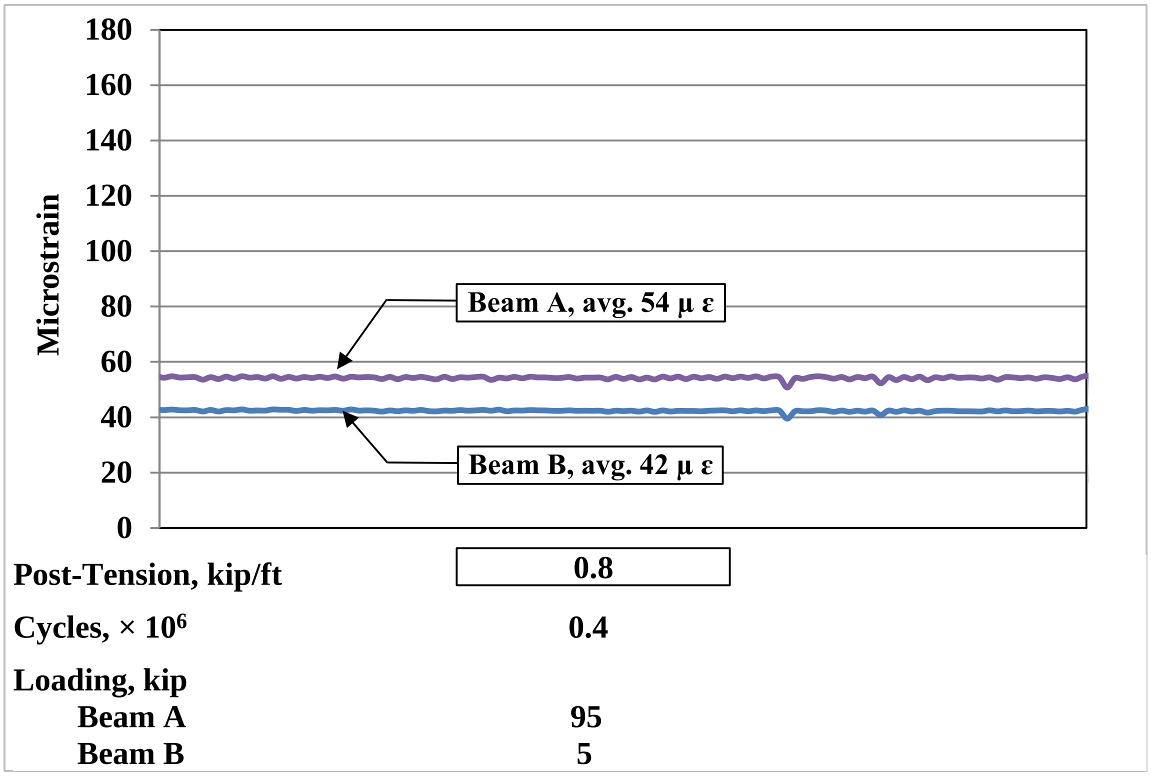


Fig.16 Tensile Strain at the Mid-Span. Partial-Depth Conventional Grout, Restrained Deflection (Clamp Down Beam Ends and Extra Supports Underneath Beam B).

RESULTS

The partial-depth conventional grout connection is first tested in the study, followed by the full-depth conventional grout connection, partial-depth UHPC connection and full-depth UHPC connection. The performance of each connection is presented.

PARTIAL-DEPTH CONVENTIONAL GROUT

The partial-depth conventional grout connection is first tested. The grout is cast, cured, and tested in a laboratory condition. After the grout is cast, it is cured with wet burlap covering on top for one day to minimize the drying shrinkage. At about seven days after casting, the transverse post-tension is applied. A 100 kips (445 kN) post-tension force is applied at each post-tension point (see Figure 6), which corresponds to a post-tension force of 8 kip/ft (117 kN/m). The beams are then thermally and structurally loaded. The thermal loading was not observed to initiate any local or global distress in the connections. The authors expect to present the details results of the thermal loading investigation at a later date. Before the structural cyclic loading, the connection was checked and no cracks were observed.

The beams are first loaded with a simply supported configuration with the loading protocol following Figure 7. Different loading ranges, starting from 18 kips (80 kN) increased to 36, 54, 72, and 90 kips (160, 240, 320, and 400 kN), were applied. A total of three million cycles were finished and no cracks were developed at the connection. Then the transverse post-tension was reduced from 8 to 6, 4, 2, and 0.8 kip/ft (117 to 87, 58, 29, and 12 kN/m) and at each transverse post-tension level, the beams are cyclic loaded with loading ranges of 54, 72, and 90 kips (240, 320, and 400 kN). A total of another four million cycles are completed and no cracks were observed at the connection. The tensile strain at the midspan and the load distribution at different loading range and transverse post-tension level are presented in Figure 17 and Figure 18, respectively. Note that under the post-tension of 8 kip/ft (117 kN/m), the data is only available for the loading range of 90 kips (400 kN). As shown, under the same loading but different transverse post-tension levels, the strain readings are about the same and the load distribution is nearly constant all the time. The results in Figure 17 and Figure 18 indicate that the amount of transverse post-tension does not seem to have an effect on the system performance when the connection is intact without any apparent cracking or debonding.

To create a more severe loading condition, the beams ends were clamped and extra supports were provided underneath one beam. A total of another 3.3 million cycles were applied with about 1.5 million cycles loaded with 95 kips (423 kN) on one beam and 5 kips (22 kips) on the other, with an equivalent moment transferred through the joint about 478 kip-ft (646 kN-m). Again, no cracks were observed at the connection and the transverse post-tension force was not observed to have an effect on the system performance.

Overall, more than ten million cycles of structural loading were applied to the beams with the partial-depth conventional grout connection. The structural loading applied is quite severe, with the most extreme case of a loading of 95 kips (423 kN) on one beam and 5 kips (22 kips) on the other, creating an equivalent moment of 478 kip-ft (646 kN-m) transferred through the joint. No cracks were initiated at the joint.

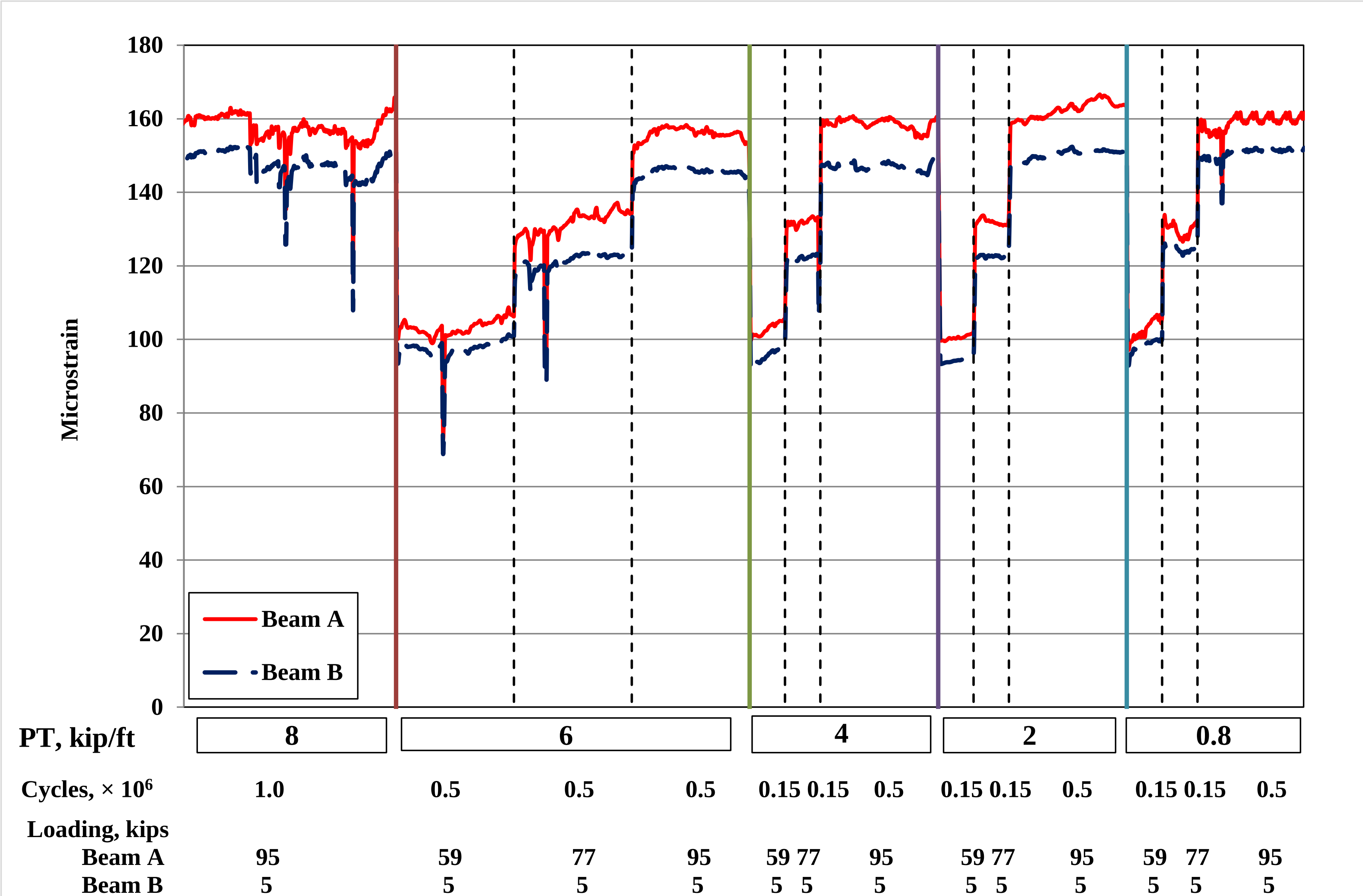


Fig.17 Tensile Strain at the Mid-Span at Different Loading Range and Transverse Post-Tension (PT) Level. Partial-Depth Conventional Grout, Simply Supported.

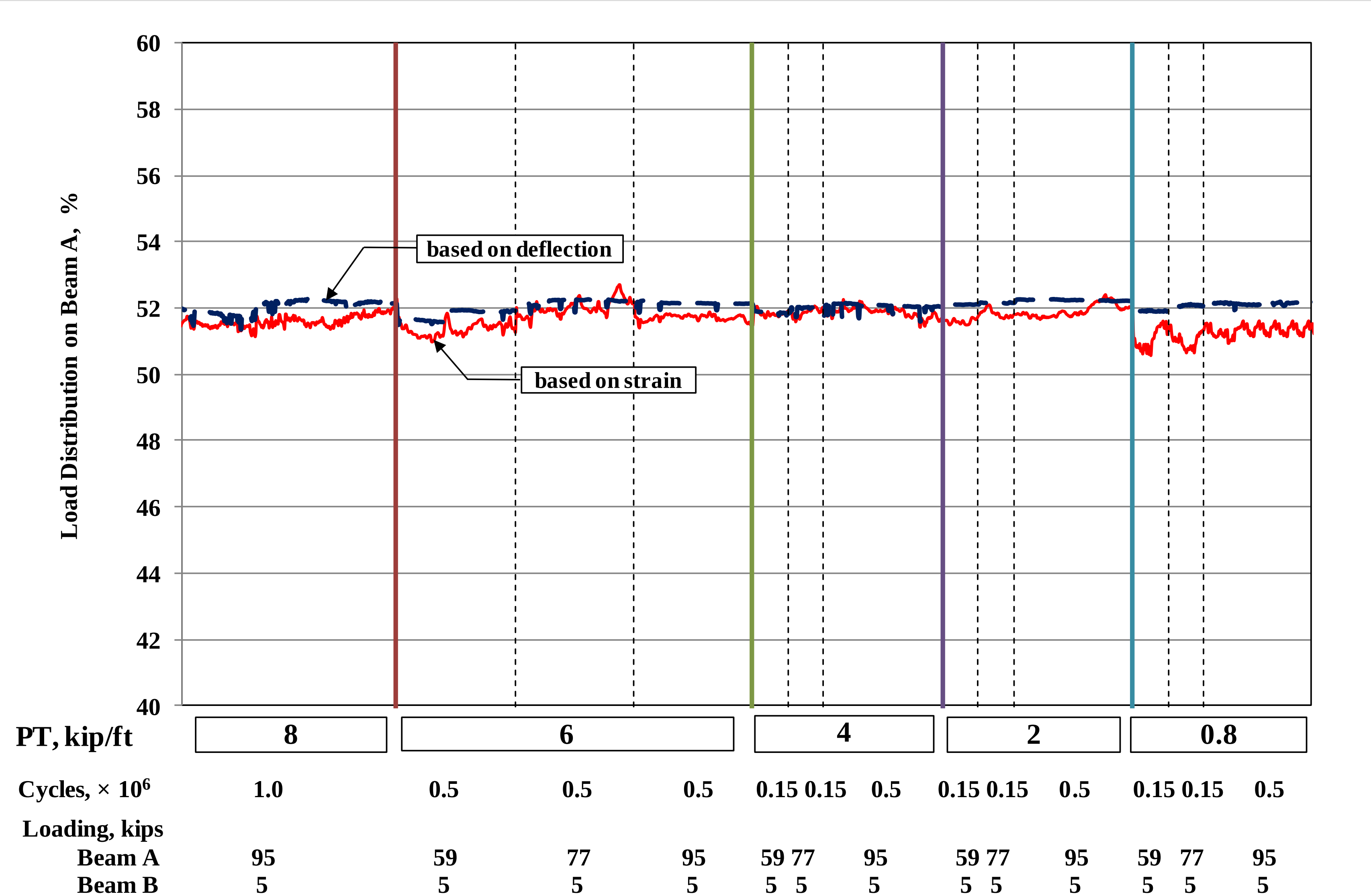


Fig.18 Load Distribution at Different Loading Range and Transverse Post-Tension (PT) Level. Partial-Depth Conventional Grout, Simply Supported.

The connection was then mechanically cracked by applying a direct tensile force on top of the connection, as shown in Figure 19. A crack at the interface of the grout and the concrete box beam was initiated and the crack extended about half of the length of the connection. The beams were then cyclic loaded with the loading configuration of restrained deflection (refer to Figure 8). Different transverse post-tension levels were tested, including 8, 4, 2, 0.8 and 0 kip/ft (117, 58, 12, and 0 kN/m) and a total of 0.8 million cycles were completed. The crack was found to propagate along the length of the connection regardless of the level of transverse post-tension force applied. The difference on the crack propagation rate under different transverse post-tension levels was not observed to be notable within the number of cycles applied in this portion of the study.

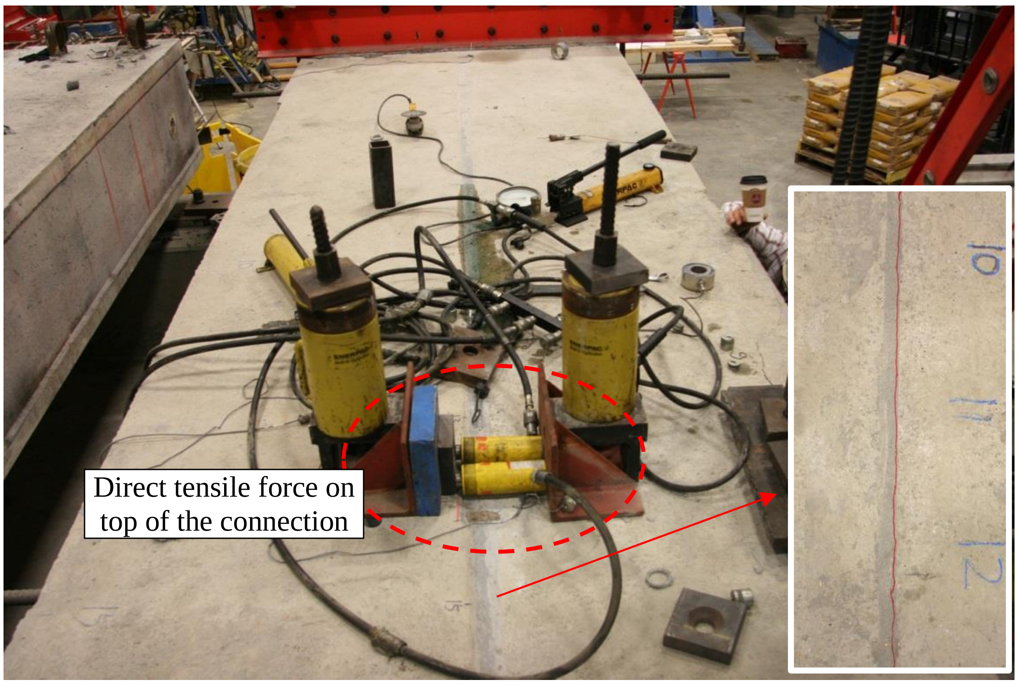


Fig.19 Mechanically Crack the Connection. Partial-Depth Conventional Grout.

The connection was further mechanically cracked so the full-length of the connection was cracked. Note that with the way the connection was cracked (as shown in Figure 19), it was managed that the two beams were not completed separated and the grout and box beam were still in very close contact. Visible cracks were observed on top of the beam, along the whole length of the connection. The beams were then subjected to further cyclic loading. The performance of the beams with an uncracked, partially cracked, and fully-cracked connection is compared and the tensile strain measured at the midspan during the loading cycles under the three conditions is presented in the Figure 20, Figure 21, and Figure 22, respectively. As shown, under the same loading level, the beams exhibit nearly the same strain, no matter the level of the transverse post-tension force and if the connection has cracks. The fully-cracked connection, even without any transverse post-tension force, can still effectively transfer the force from one beam to the other within the 200,000 cycles applied in this study, which is probably through the friction between the grout and the concrete box beam.

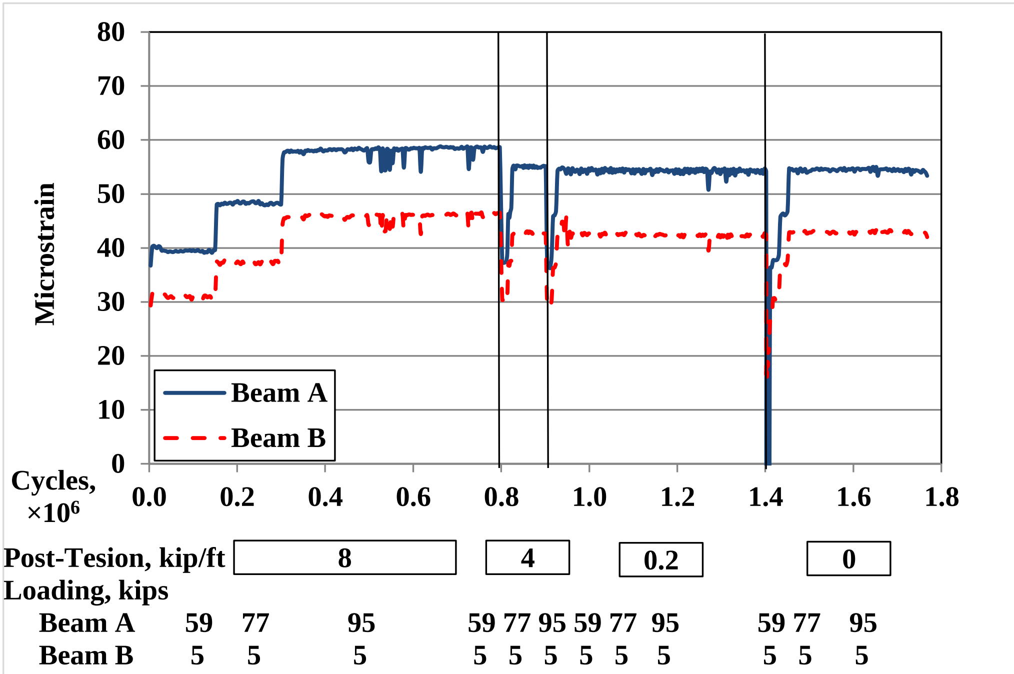


Fig.20 Tensile Strain at Mid Span. Uncracked Partial-Depth Convention Grout, Restrained Deflection (Clamp Down Ends and Extra Supports Underneath Beam B)

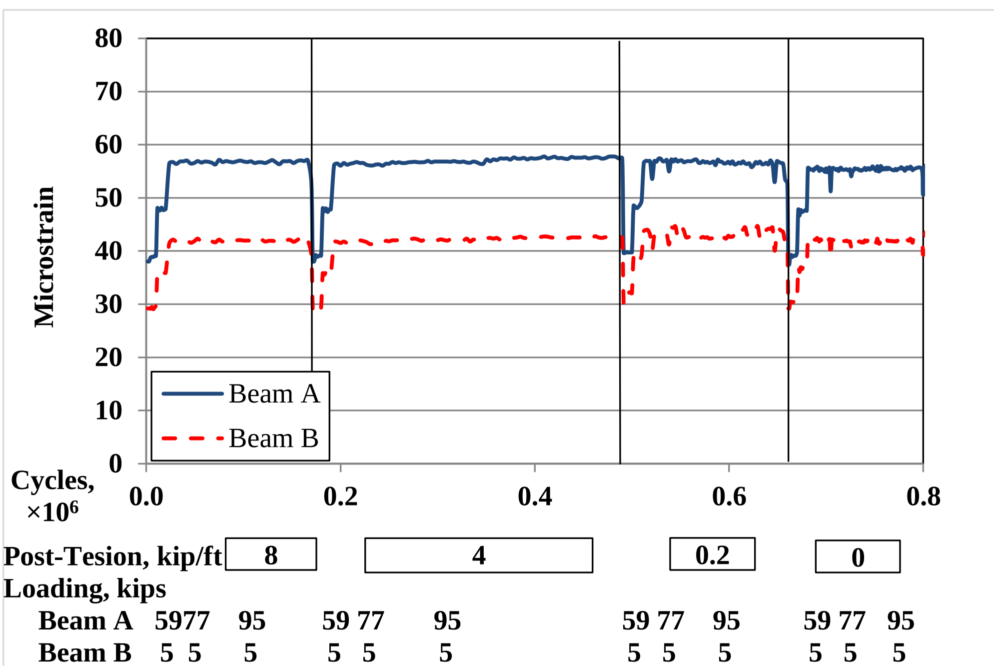


Fig.21 Tensile Strain at Mid Span. Partially-Cracked Partial-Depth Convention Grout, Restrained Deflection (Clamp Down Ends and Extra Supports Underneath Beam B)

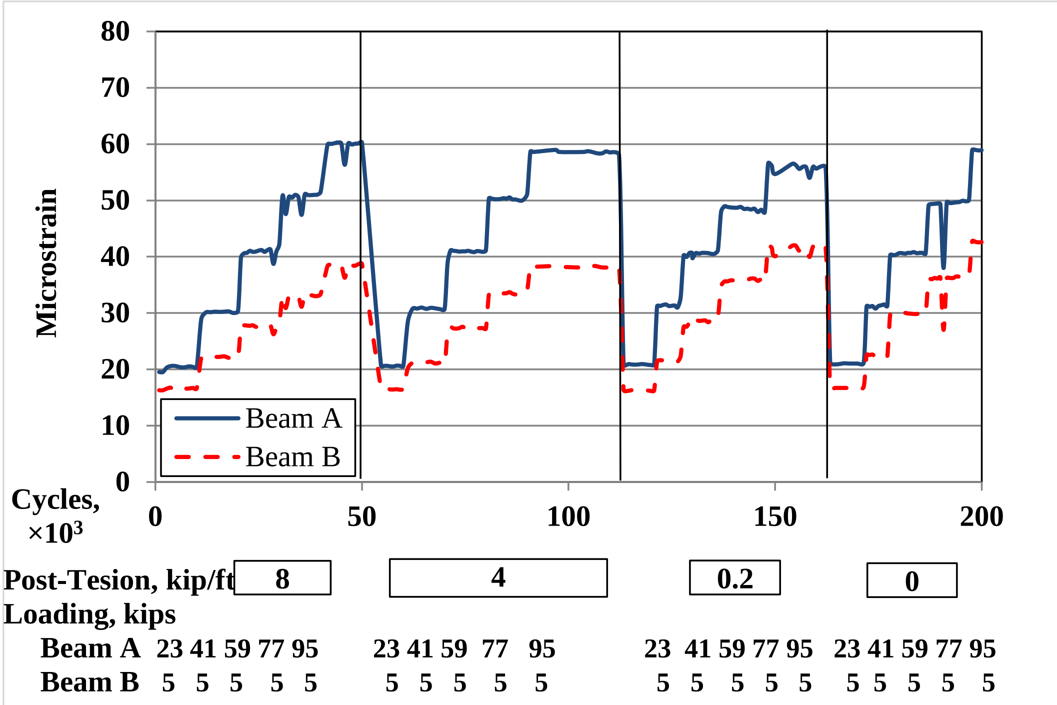


Fig.22 Tensile Strain at Mid Span. Fully-Cracked Partial-Depth Convention Grout, Restrained Deflection (Restrained End Rotation and Extra Supports Underneath Beam B)

FULL-DEPTH CONVENTIONAL GROUT

The same procedure that was used for partial-depth conventional grout casting was used for the full-depth conventional grout. The grout was wet cured for one day. One thing should be noted here is that to close the gap between the two beams before casting, a wrench-tight force was applied on the transverse post-tension bars. The force was approximately 10 kips (44 kN) at each transverse post-tension bar and the connection was cast while the force remained in the bars. Four days after the connection was cast, when the transverse force was removed, approximately two thirds of the length of the connection cracked. A similar operations had been done on the partial-depth conventional grout connection and no cracks had formed. The possible reason for the crack of the full-depth conventional grout connection can be explained as below.

The beam(s) may not have been perfectly straight and they may have been aligned in a way shown in Figure 23 (a) before casting. Then when transverse forces were applied, the beam(s) may have straightened due to the applied forces, as shown in Figure 23 (b). After the grout was cast, when the transverse forces were removed, the beam(s) would go spring back toward their original shape, which would introduce a direct tensile force and could crack the connection interface.

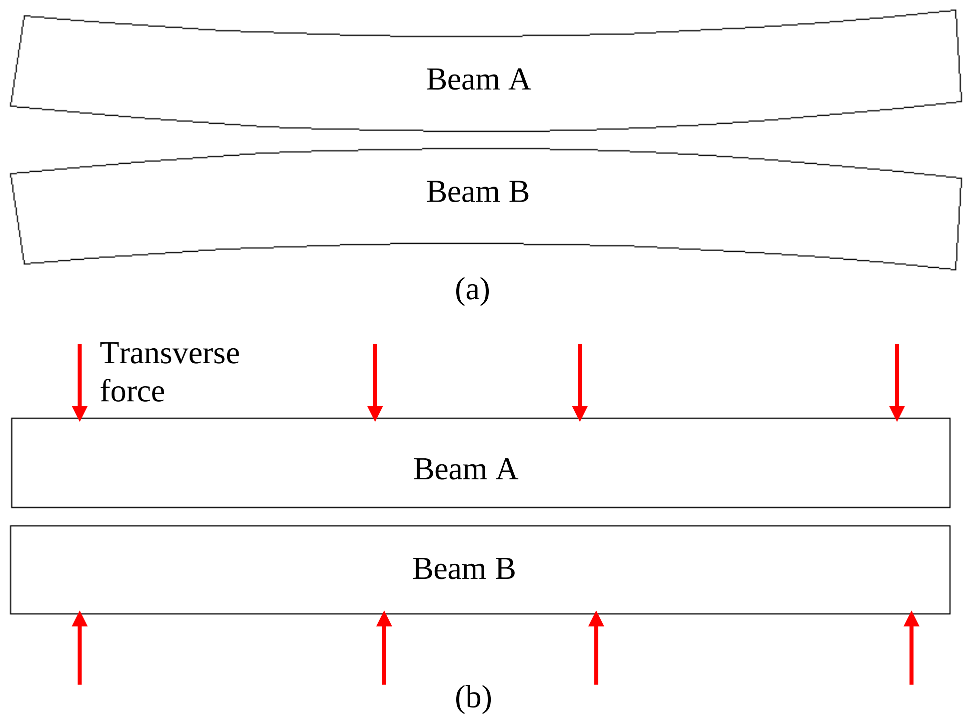


Fig.23 (a) Curved Box Beams; and (b) Straightened Box Beams due Applied Transverse Force. (Exaggerated)

Cyclic loadings were applied to the beams under different transverse post-tension forces. The beams were simply supported. A total of 1.2 million cycles were completed. Similar finding as those for partially-cracked partial-depth conventional grout connection were obtained. The crack propagates no matter the level of the transverse post-tension force applied. The partially cracked connection can still effectively transfer the force from the loaded beam to the adjacent beam, independent the transverse post-tension force applied.

PARTIAL AND FULL-DEPTH UHPC CONNECTION

Both the partial and full-depth UHPC connections exhibited good performance. Over one million cycles of structural loading were applied on each connection, and at least half million cycles were under the most server loading in this study [with configuration of restrained deflection and a maximum loading of 95 kips (423 kN)]. No cracks were initiated during the structural cyclic loading. When the connections were mechanically cracked, as that shown in Figure 24, cracks developed in the concrete box beam instead of the connection interface.

The performance of uncracked partial-depth conventional grout connection is compared with the performance of uncracked partial-depth UHPC connection by looking at the load distribution and the results are presented in Figure 25 and Figure 26. As shown, they have about the same load distribution when the connections are intact.

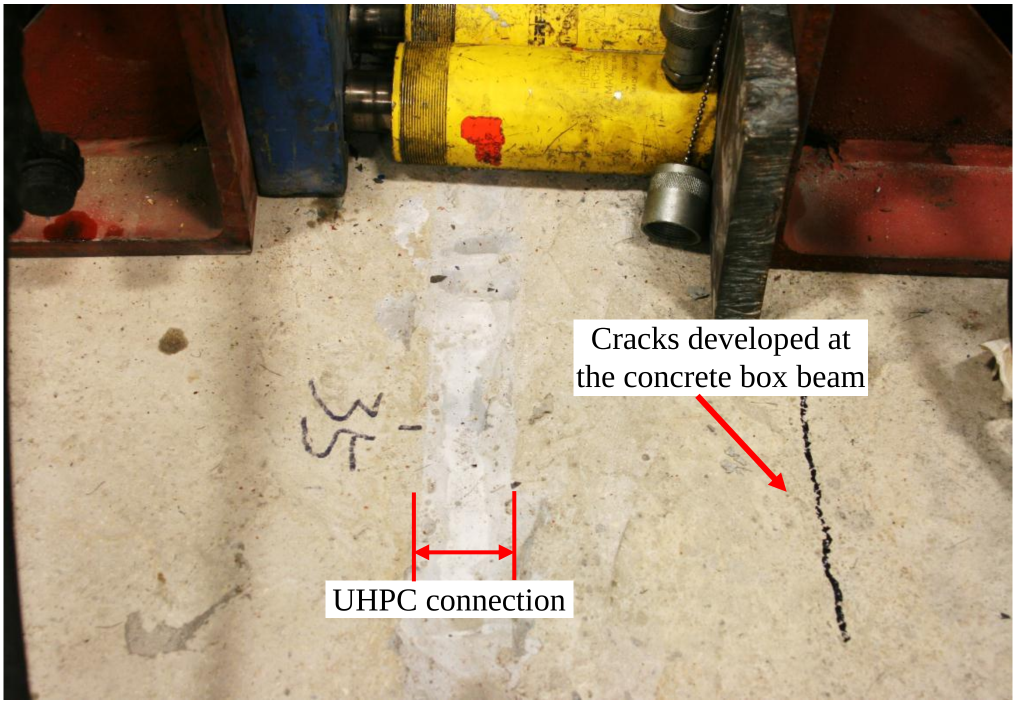


Fig.24 Mechanically Crack the Connection. Partial-Depth UHPC Connection.

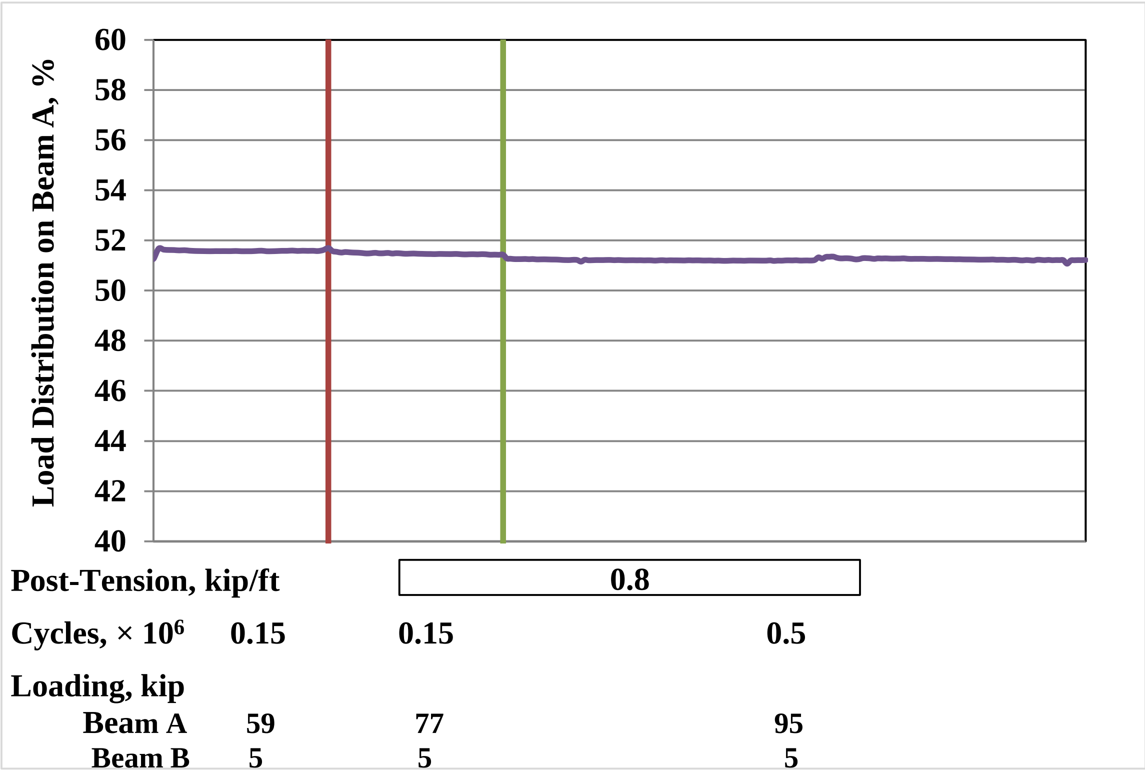


Fig.25 Load Distribution based on Tensile Strain. Partial-Depth Conventional Grout.

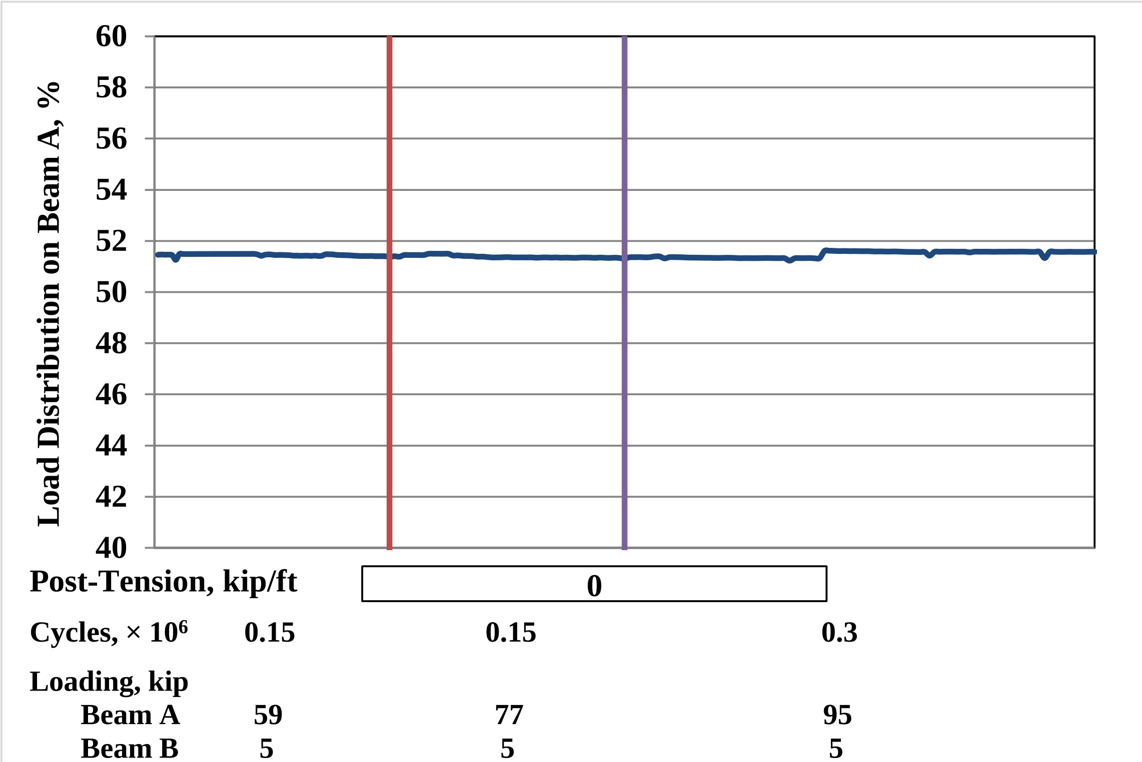


Fig.26 Load Distribution based on Tensile Strain. Partial-Depth UHPC Connection.

CONCLUSIONS

Four shear key connection design details for box beam bridges are evaluated. Two of the design details use conventional high-strength grout in combination of transverse post-tension, which is currently considered good practice in the field; the other two deigns use ultra-high performance concrete in connections where reinforcing bars are lap spliced and transverse post-tension is not needed. Full-scale structural testing were conducted with two box beams grouted together. Millions of cycles of structural loading were applied and the tests discovered that:

- The cyclic structural loading applied in this study is severe. The most extreme case in this study has a maximum loading of 95 kips (423 kN) on one beam and 5 kips (22 kN) on the other, which creating an equivalent moment of 478 kip-ft (646 kN-m) transferred through the joint.
- When the connection is intact without cracks, the beams with conventional grout connection have about the same performance as the beams with UHPC connection.
- When the connection is intact without cracks, the cyclic structural loading does not initiate any new cracks, no matter whether it is conventional grout connection with or without transverse post-tension, or UHPC connection.

- When there are pre-existing cracks in the conventional grout connection, the cracks propagate under cyclic structural loading, independent the level of transverse post-tension force applied.
- If the transverse post-tension force is applied before grout casting, the loss of post-tension force after grout casting may cause a tensile force in the connection and crack the connection when the beam(s) are not perfectly straight and aligned improperly.
- UHPC connections exhibit superior performance as evidenced by the performance when subjected to the direct tensile force on top of the connection. In this case, the UHPC and the interface were observed to exhibit sufficient tensile strength to cause first cracking to develop in the concrete box beam.

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