NON-POST-TENSIONED TRANSVERSE CONNECTIONS FOR ADJACENT BOX BEAM BRIDGES

Kromel Hanna, Ph.D., Post-Doctoral Associate, Dept. of Civil Engineering, University of Nebraska-Lincoln
George Morcous, Ph.D., P. Eng., P.E., Assistant Professor, Construction Engineering & Management, University of Nebraska-Lincoln
Maher K. Tadros, Ph.D., P.E., FPCI
Leslie Martin Professor of Civil Engineering, University of Nebraska-Lincoln,

ABSTRACT

Precast prestressed concrete adjacent box girder bridges are widely used in short and medium span bridges. Rapid construction and low construction cost are the main attractions of this system. Also, the continuous flat soffit and relatively high span-to-depth ratio make them aesthetically pleasing. Although the use of post-tensioned diaphragms to transversally connect adjacent box girders is an effective and practical solution in many cases, it has some disadvantages. Post tensioning of skewed bridges is difficult and may have to be staggered and done in stages. Staged construction leads to a significant increase in both the construction cost and duration, due to the variation in diaphragm location, large number of post-tensioning operations, and excessive traffic control required in case of replacement projects. Moreover, post-tensioned diaphragms depend on the shear keys to achieve the desired continuity. Shear keys need to be properly cleaned, sand-blasted, sealed, and grouted, which add complexity to the system and become susceptible to cracking and leakage.

This paper presents two continuous non-post-tensioned transverse connections as alternatives to the current discrete post-tensioned connections. Proposed connections are designed to transfer transverse shear and moment without end or intermediate diaphragms. The first connection "Narrow Joint" consists of top and bottom couplers and full depth grouted shear keys. The second connection "Wide Joint" consists of a wide full depth shear key filled with flowable concrete and top and bottom reinforcement. Finite element models were developed to determine the effect of design parameters, such as span length, bridge width, and girder depth, on the design of the proposed connections. The latest AASHTO LRFD live load and dynamic load allowance were applied to determine the required reinforcement in the two connections. The paper also presents design charts for each system to facilitate connection design in various brides.

Keywords: Box Girders, Shear Key, Post-Tensioning, Transverse Connections, Bridge Superstructure.

1- INTRODUCTION

Precast prestressed concrete box girder bridges represent about one third of all prestressed concrete bridges built in the United States. Adjacent box girder is the most prevalent box girder system for short and medium span bridges especially on secondary roadways. These bridges consist of multiple precast prestressed concrete box girders that are butted against each other to form the bridge superstructure and deck. These boxes are laterally connected at their interface using grouted shear keys, tie rods, transversal post-tensioning, or variations thereof. A 2 inch non-structural wearing surface or a 5-6 inch structural composite slab is often used as topping. The main advantages of this bridge system are: 1) ease and speed of construction because of eliminating concrete forming and pouring operations; 2) shallow superstructure depth that is necessary to maintain the required vertical clearance; 3) low construction cost compared to I-girder bridges and other competing systems; and finally 4) improved bridge aesthetics due to the flatness of the soffit and the slenderness of the superstructure.

The American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Highway Bridges do not provide adequate guidelines for designing and/or detailing of the transverse connection in adjacent box girder bridges (AASHTO 2002). Although the specifications stipulate that continuous longitudinal shear key and transverse tie reinforcement should be provided for using live load distribution factors of multi beam decks, no requirements were provided on whether transverse reinforcement should be prestressed. The AASHTO LRFD Bridge Design Specifications do not consider the use of transverse mild steel rods secured by nuts sufficient to achieve full transverse flexural continuity (AASHTO 2007). The specifications recommend a minimum average effective post-tensioning pressure of 250 psi between adjacent boxes. However, the specifications do not specify the contact area over which the required pressure is applied, such as intermediate diaphragms, shear keys, or entire box side surface.

The Precast/Prestressed Concrete Institute (PCI) Bridge Design Manual (BDM) presents charts for determining the post-tensioning force required to achieve adequate stiffness in the transverse direction for adjacent box girders. These charts were developed by El-Remaily et al. (1996) assuming that post-tensioned transverse diaphragms are the primary mechanism for the distribution of wheel loads across the bridge and differential deflection limit between adjacent boxes is 0.02 in. (PCI 2004). Hanna et al. (2007, 2008, and 2009) developed updated design charts to account for the latest AASHTO LRFD loads and governing parameters, such as bridge width, span-to-depth ratio, and skew angle.

Although the use of post-tensioning to transversally connect adjacent box girders is an effective and practical solution in many cases, it has some disadvantages. Post-tensioned transverse connections require the use of end and intermediate diaphragms to achieve continuity in the transverse directions. Construction of diaphragms in skewed bridges is difficult and may have to be staggered, or done in stages as shown in Figure 1. This leads to a significant increase in the construction cost and duration due to the variation in diaphragm location, large number of post-tensioning operations, and excessive traffic control required in case of replacement projects.

Moreover, post-tensioned diaphragms result in transversal continuity at discrete locations, which makes the system more susceptible to cracking and leakage.

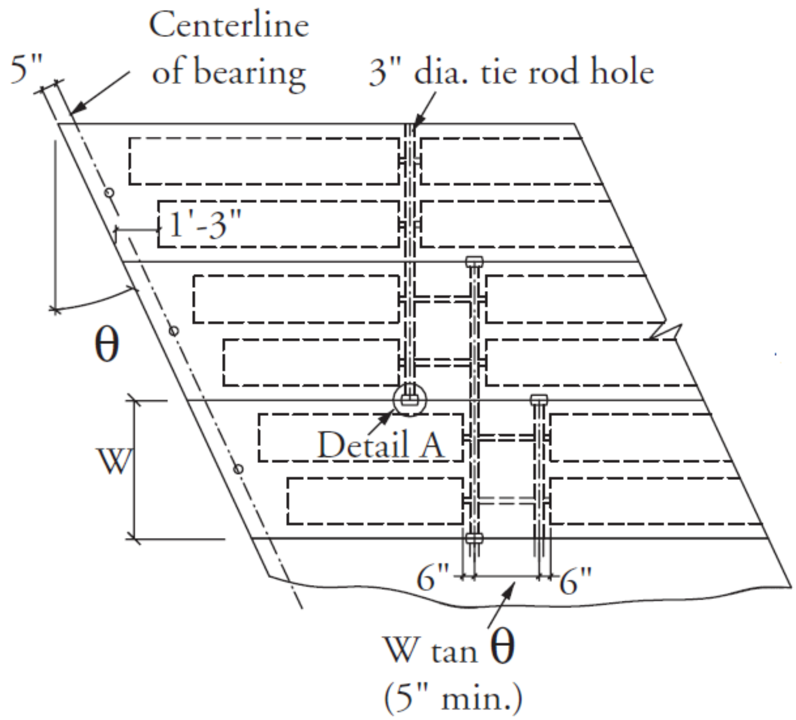

Figure 1: Post-tensioning of a skewed bridge (PCI 2003)
1 ft = 0.3048 m and 1 in. = 2.54 cm

There are several non-post-tensioned transverse connections used in adjacent box girders in the United State. One of these connections is the one used in the construction of the NASA Road 1 Bridge over I-45 between Houston and Galveston, TX. This bridge was built in 2002 as one of a pair of parallel bridges that carries 4 lanes of traffic; the other structure is a traditional steel girder bridge. The 300 ft (91.44 m) long bridge consists of four equal spans of 75 ft (22.86 m) with skew angles ranging from 0 to 30 degrees. Figure 2 shows a plan of two adjacent box girders in a skewed span as well as the arrangement of the elastomeric bearings used to stabilize the girders. Each span has nine adjacent Type "4B28" box girders that are formed using two side forms of a standard Texas I girder spaced approximately four feet apart. A unique transverse connection that eliminates the need for intermediate diaphragms, grouting, and post-tensioning was used in this bridge. Figure 3 shows a cross-section of the transverse connection between the 28 in. (71.12 cm) deep box girders. This connection consists of a wide and continuous half depth shear key that was poured monolithically with the reinforced concrete deck. In the connection, at least 6 in. (15.24 cm) thick composite concrete deck has to be used to provide adequate stiffness in the transverse direction.

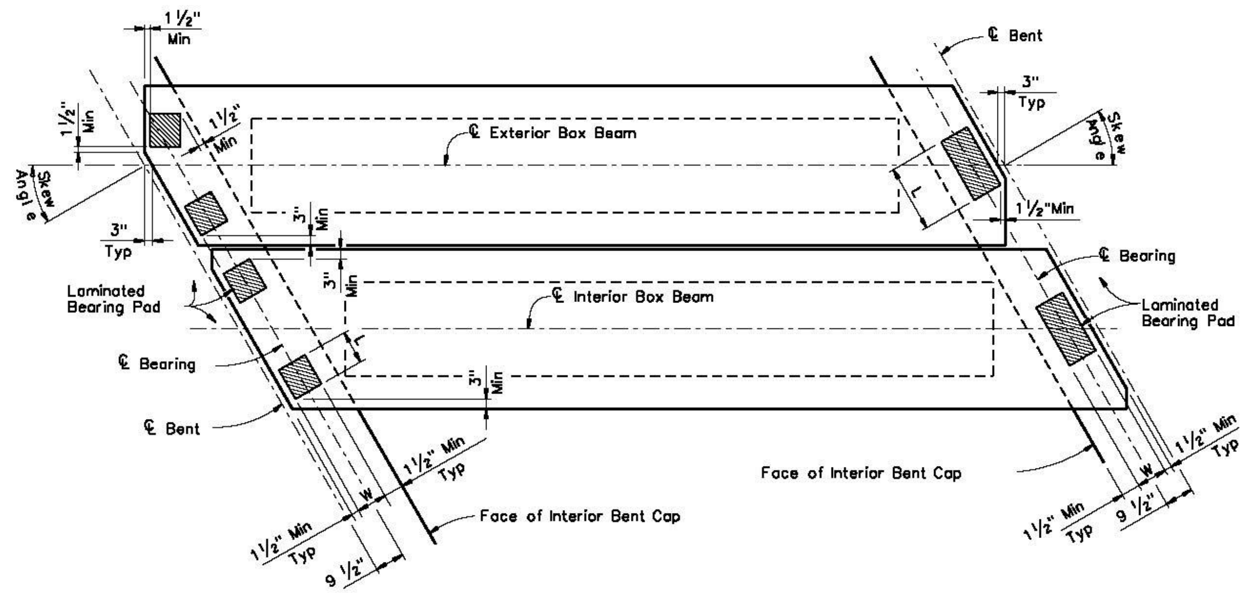

Figure 2: Plan of two adjacent boxes of the NASA Road 1 bridge in Texas (PCI 2007)
1 ft = 0.3048 ma and 1 in. = 2.54 cm

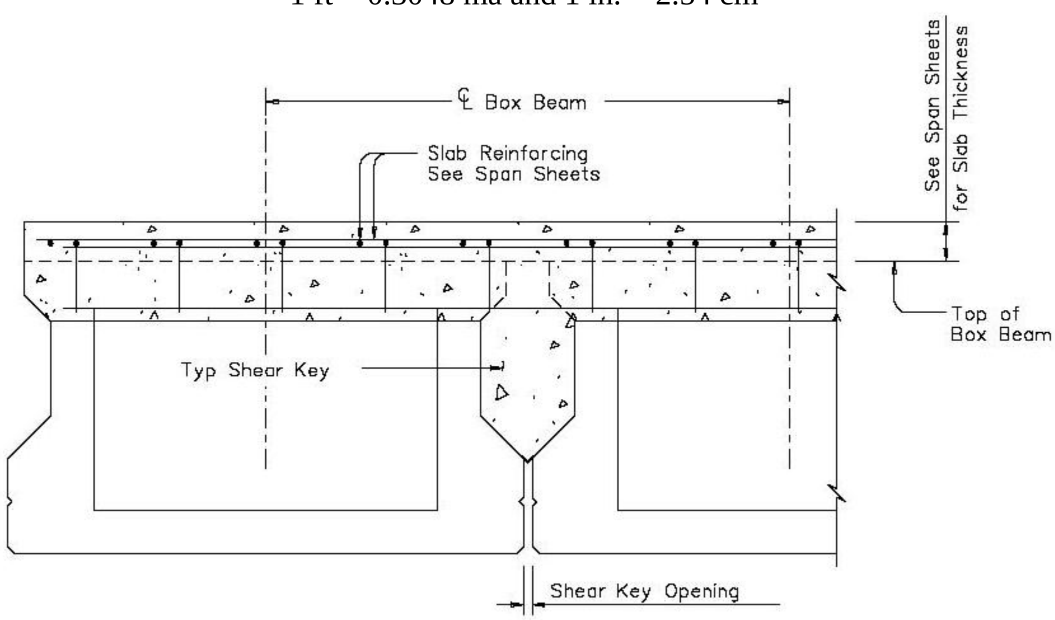

Figure 3: Cross section of transverse connection of the NASA Road 1 bridge in Texas (PCI 2007)

Another common non-post-tensioned transverse connection is the one adopted by Illinois Department of Transportation (IDOT). This connection consists of half-depth continuous shear key and transversal ties at the location of intermediate diaphragms. Figure 4 shows the latest IDOT connection detail that was updated in June of 2008. The plan view shows that the transverse ties are placed at the skew angle rather than at right angle and are used to connect the adjacent box girders in pairs in the transverse direction. Each tie consists of two 1” diameter and 46 in long rods that are threaded at the end 4 inches to be connected using a 5” (12.7 cm) long coupling nut. A 5 in (12.7 cm) non-composite reinforced concrete topping is used to distribute the loads uniformly across all girders and protect shear keys from cracking and leakage.

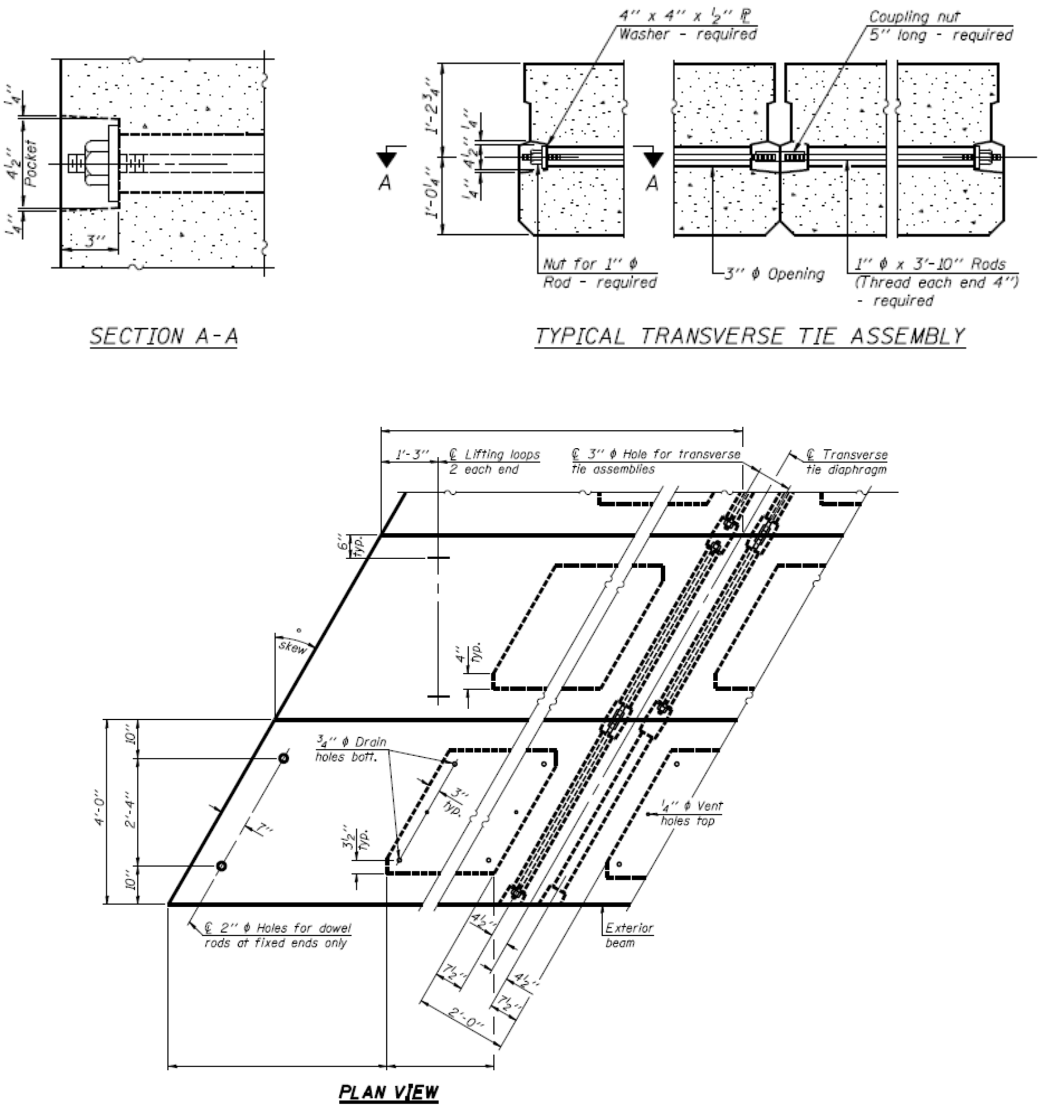

Figure 4 Current IDOT detail (IDOT 2008)
1 ft = 0.3048 m and 1 in. = 2.54 cm

The objective of this research is to develop non-post-tensioned transverse connections between adjacent box girders that have superior performance characteristics to those of currently used connections, while being more economical. Two non-post-tensioning connections are proposed to emulate monolithic construction and eliminate the need for diaphragms, post-tensioning, and cast-in-place topping. Continuous reinforced concrete connections are designed to transfer shear and moment between adjacent boxes similar to the connections between multi-cell cast-in-place box girders common used in California. Eliminating intermediate and end diaphragms provides several advantages, such as easier girder production, simpler inspection of voids, better drainage of moisture, lighter weight for handballing and shipping, and continuous rather than discrete (quarter point) connections. Eliminating post-tensioning and topping will result in faster and more economical construction.

The paper is organized as follows. The second section presents the Wide Joint (WJ) connection. The third section presents the Narrow Joint (NJ) connection. The forth section presents the analytical work performed to develop design charts for the two proposed connections. The fifth section presents the experimental work carried out to evaluate the ultimate capacity and fatigue capacity of the two proposed connection as well as of one of the current connections. The last section discusses the testing results and provides research conclusions.

2- WIDE JOINT (WJ) SYSTEM

This system differs from the one used in the NASA Road 1 Bridge in Texas in two major aspects: 1) eliminating topping; and 2) eliminating diaphragms. Top and bottom transverse reinforcement is used in a wide shear key filled with concrete to connect adjacent boxes instead of the reinforced concrete composite topping. This monolithic joint with top and bottom reinforcement will provide continuous connection that transfers shear and moment between boxes and eliminates the need for intermediate/end diaphragms. The elimination of topping and diaphragms will significantly speed the production and construction operations and reduce the material, labor, and erection cost. Shear keys used in the WJ system are wide full-length and full-depth shear keys that require slight modification to the standard box cross section and consequently the forms. Figure 5 shows the modified AASHTO PCI box section that is 33 in. deep and 48 in. wide as an example. These modifications include: a) 5 in.(12.7 cm) wide shear key (2.5 in. (6.35 cm) at each box side); b) two blockouts every 4 ft (1.22 m) at the top flange, which are 4 in. (10.16 cm) deep, 5.5 in (13.97 cm) long, and 5.5 in.(13.97 cm) wide; c) two blockouts every 4 ft (1.22 m) at the bottom flange, which are 8 in. (20.32 cm) long and 4” (10.16 cm) wide. Two reinforced concrete connections are used at the blockout locations (every 4 ft (1.22 m)) in the top and bottom flanges to connect adjacent boxes. Reinforcing steel bars extending from the top and bottom flanges of each box are lap spliced using short bars confined by 3 in. (7.62 cm) diameter, 1” (2.54 cm) pitch, 1/8” (0.317 cm) thickness spirals as shown in Figure 6. This confinement reinforcement is necessary to provide adequate development length for such short lap splices. It is also recommended that the top surface of the box and the shear keys have 0.5 in. (1.27 cm) extra thickness to be grinded to provide a roughened surface for skid resistance and shear transfer. The use of self consolidating concrete to fill the wide shear key is also recommended to eliminate the need for grouting, which is a costly and time consuming operation.

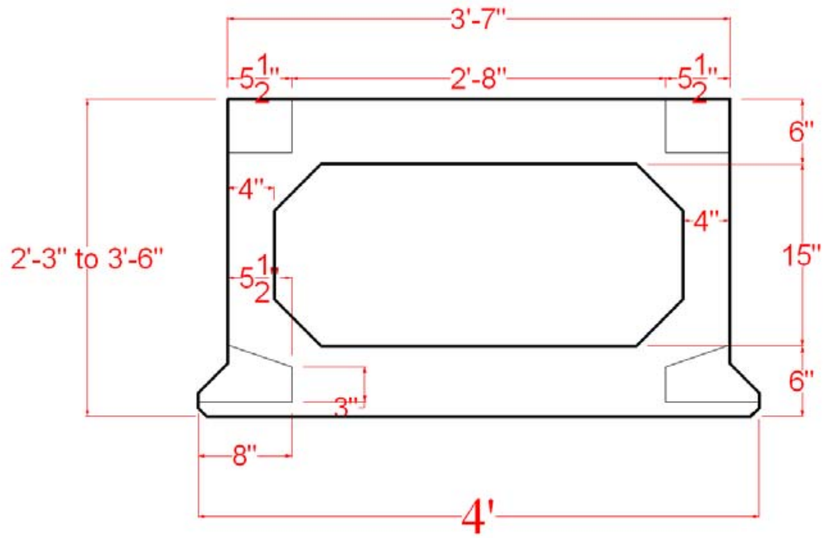

Figure 5 WJ System Box Dimensions
1 ft = 0.3048 m and 1 in. = 2.54 cm

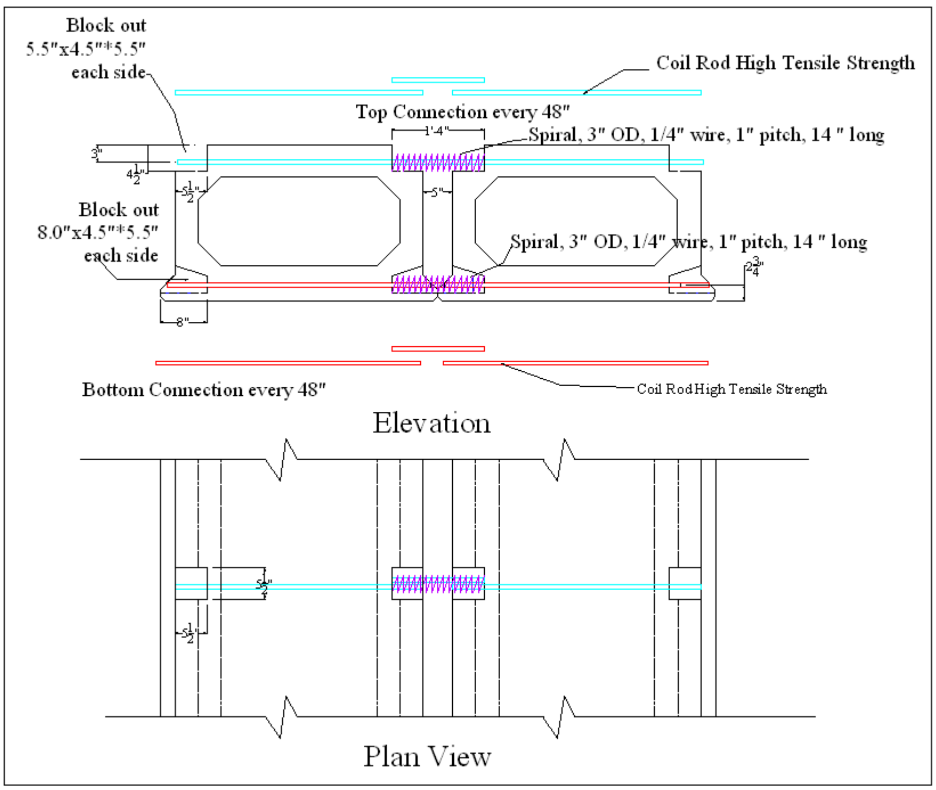

Figure 6 WJ connection details
1 ft = 0.3048 m and 1 in. = 2.54 cm

3- NARROW JOINT (NJ) SYSTEM

This system differs from the one currently used in Illinois in two major aspects: 1) eliminating diaphragms; and 2) replacing the single mid-depth transverse tie with top and bottom transverse ties. Grade 75 threaded rods are used every 8 ft (2.438 m) to connect each pair of adjacent boxes at the top and bottom flanges. These rods provide continuous connection that transfer shear and moment between adjacent boxes more efficiently than the mid-depth transverse ties at discrete diaphragm locations. A slight modification is made to the standard box cross section by developing full-length horizontal and full-depth vertical shear keys as shown in Figure 7.The boxes are fabricated with plastic duct at the top and bottom flanges to create openings for the threaded rods as shown in Figure 8. The bottom duct is inserted between the two layers of prestressing strands, while the top plastic duct is located three inches from the top surface to provide adequate concrete cover. Vertical vents are provided at one side from each box to allow the air to get out while grouting the ducts.

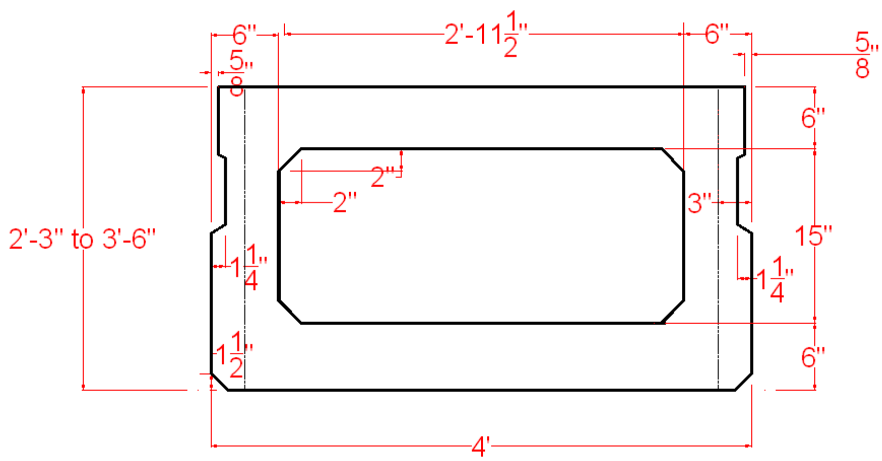

Figure 7 NJ System Box Dimensions
1 ft = 0.3048 m and 1 in. = 2.54 cm

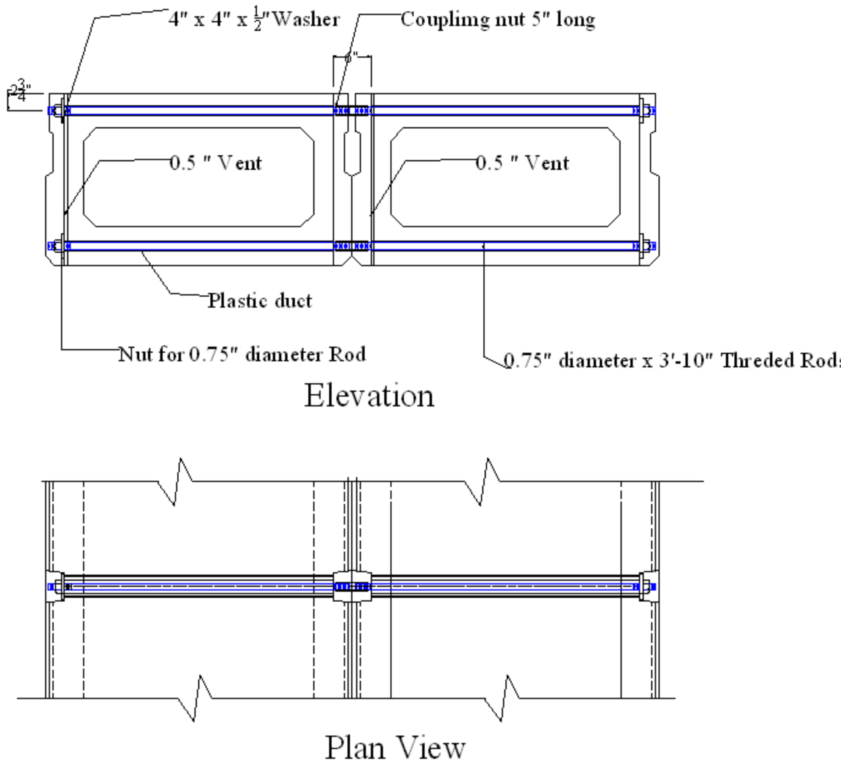

Figure 8 NJ Connection detail
1 ft = 0.3048 m and 1 in. = 2.54 cm

4- ANALYTICAL INVESTIGATION

To calculate the load effects on the proposed connections, 3D computer models are developed using SAP 2000 structural analysis program. Each box girder is modeled using shell elements that represent the flanges and webs of boxes, while the connections between boxes are modeled using frame elements. Figure 9 shows the 3D model used for analyzing the WJ and NJ systems. Below are the assumptions made for developing the computer models:

- Shell and frame elements represent the centerlines of the modeled components.
- The length of shell elements in the direction of the traffic is 12 in.
- The thickness of shell elements equals the total concrete thickness of the corresponding component (i.e. top flange, bottom flange, web)
- Frame elements are repeated every 4 ft (1.219 m) in the WJ system and every 8 ft (2.438 m) in the NJ system along the bridge length.
- The cross section of the connecting frame elements is rectangular. The width of this rectangle equals the spacing between frame elements, while its depth equals the thickness of the corresponding flange.

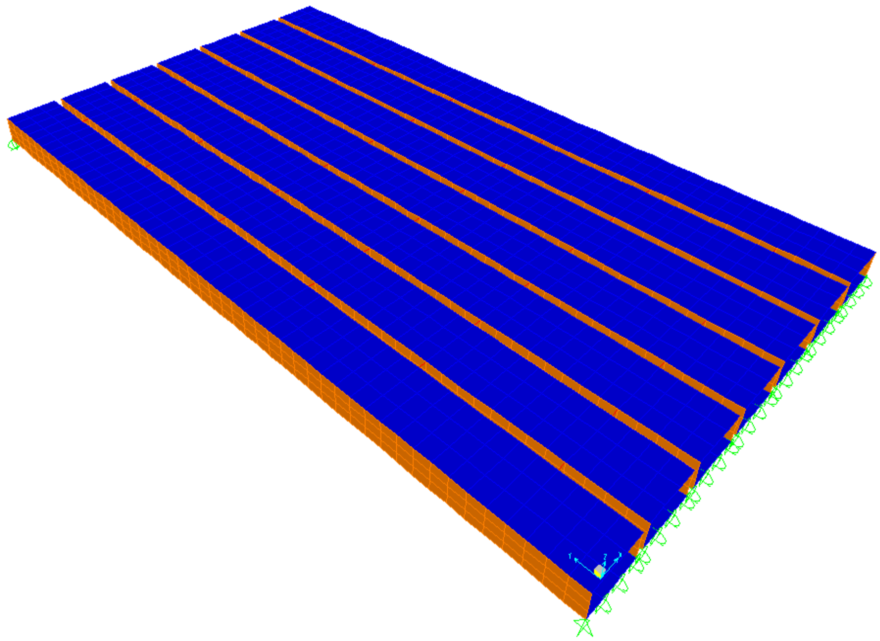

Figure 9 The 3D FE model used for analyzing the proposed systems

The loads applied for the analysis include the dead load of concrete curb and rail, and the HL 93 live load with dynamic load allowance of 0.33. Single and multiple lane loadings are applied to determine the most critical loading case for the design of the transverse connections. Dead load due to the self weight of box girders and wearing surface is not considered as it is uniformly distributed over the bridge and, therefore, does not generate load effects in the transverse direction. The weight of the concrete curb and railing is assumed to be 0.48 kips/ft (7.0 kN/m) applied to the outside box girders. Design charts are developed for the two proposed transverse connections using the 3D computer models. The effect of box girder depth, span width, and span-to-depth ratio are considered.

The effect of the box depth and bridge width on the tension force in the transverse connection for the WJ and NJ systems is shown in Figures 10 and 11 respectively. These figures are developed for zero skew angle and span-to-depth ratio of 30. The figures indicate that the tension force increases by increasing the bridge width and decreases by the increasing the box depth. Also, it can be noticed that the effect of bridge with on the required tension force is higher in narrow bridges (width is less than 52 ft (15.849 m)) than in wide bridges (width is higher than 52 ft (15.849 m)). To compare the required tension force for the two proposed connections, the force per unit length is calculated and plotted as shown in Figure 12. This figure indicates that the force required for the WJ system is higher than that for the NJ system for any given bridge width and box depth. These forces result from factored loads (1.25 DL + 1.75 LL) and can be divided by the yield strength of the steel used to determine the required area of reinforcing steel.

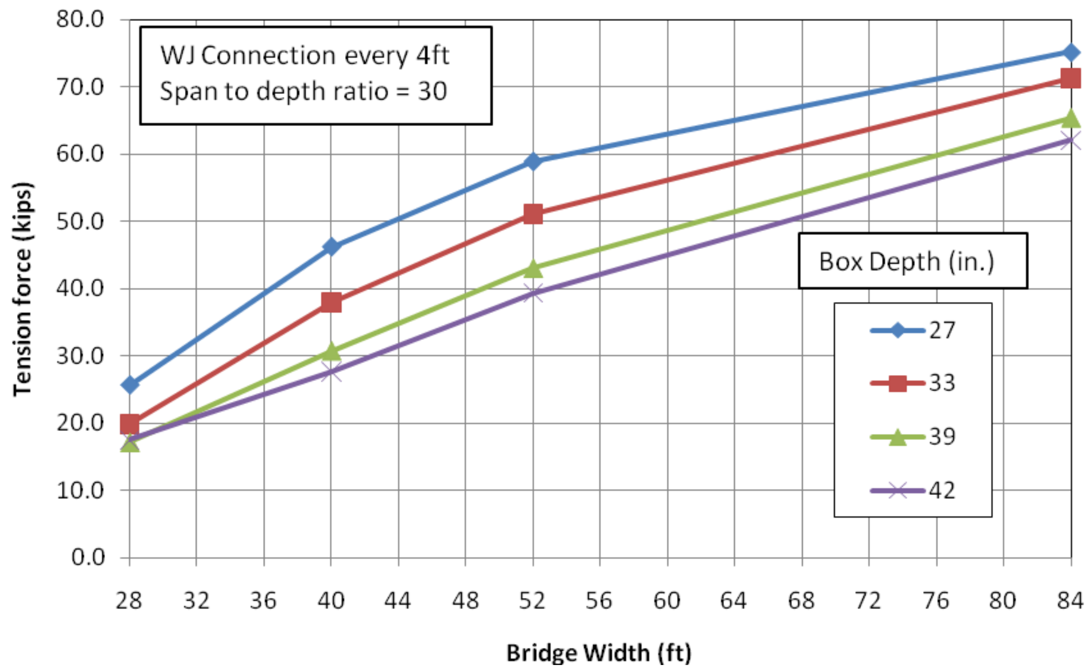

Figure 10 Effect of box depth and bridge width on the required transverse tension force (kips) for the WJ system

1 ft = 0.3048 m, 1 in. = 2.54 cm and kip = 4.448 kN

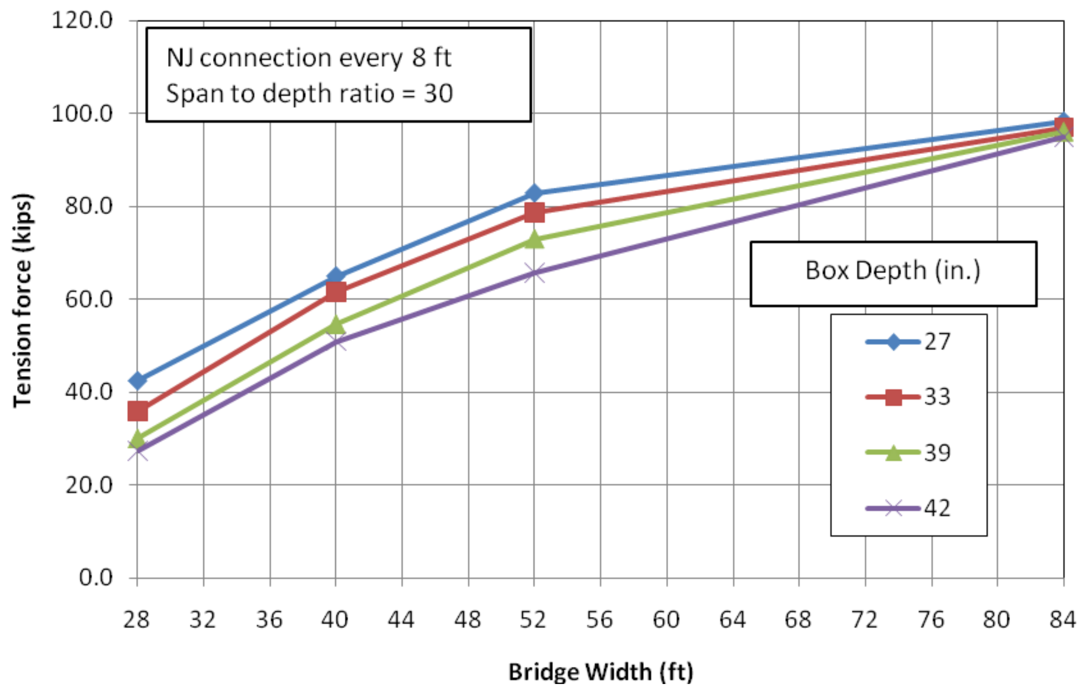

Figure 11 Effect of box depth and bridge width on the required transverse tension force (kips) for the NJ system
1 ft = 0.3048 m, 1 in. = 2.54 cm and kip = 4.448 kN

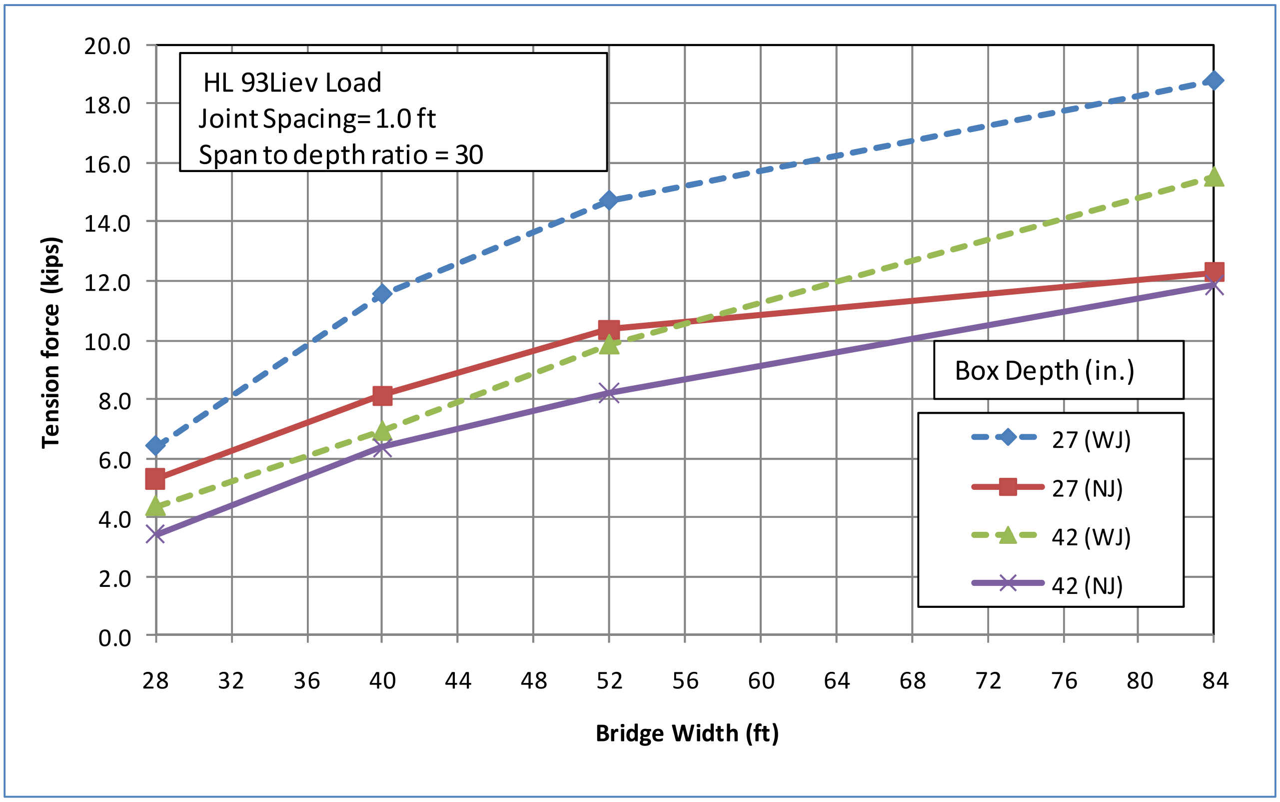

Figure 12 Comparing the tension force (kip/ft) required for the WJ and NJ systems
1 ft = 0.3048 m, 1 in. = 2.54 cm and kip/ft = 14.593 kN/m

Figures 13 and 14 show the effect of span-to-depth ratio and box depth on the transverse tension force in the WJ and NY connection respectively. These figures are developed for a bridge width of 52 ft (15.849 m) and zero skew angle. These figures indicate that the higher the span-to-depth ratio the higher the required transverse tension force. This effect is more pronounced in the NJ system than WJ system and in shallower boxes than deep boxes.

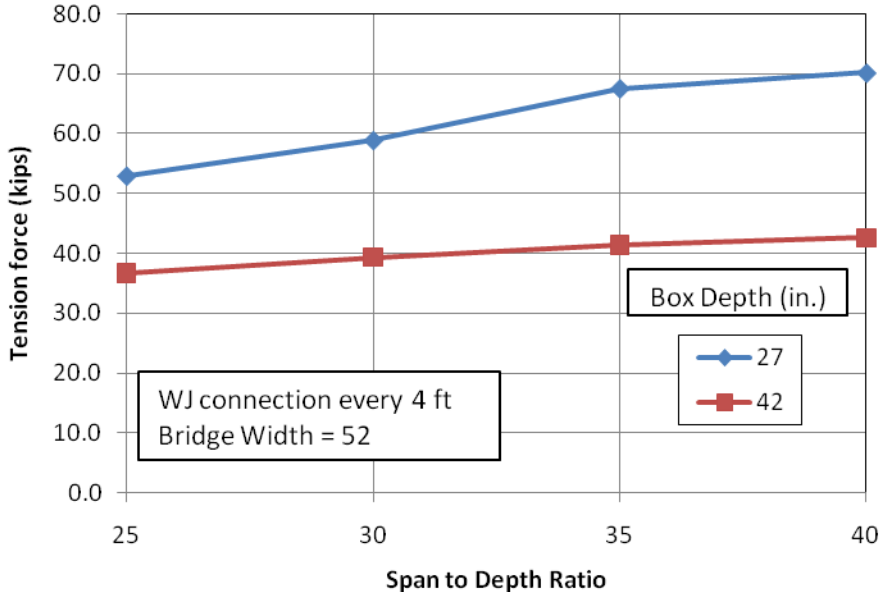

Figure 13 Effect of span-to-depth ratio on the required transverse tension force (kips) for the WJ System

1 ft = 0.3048 m, 1 in. = 2.54 cm and kip = 4.448 kN

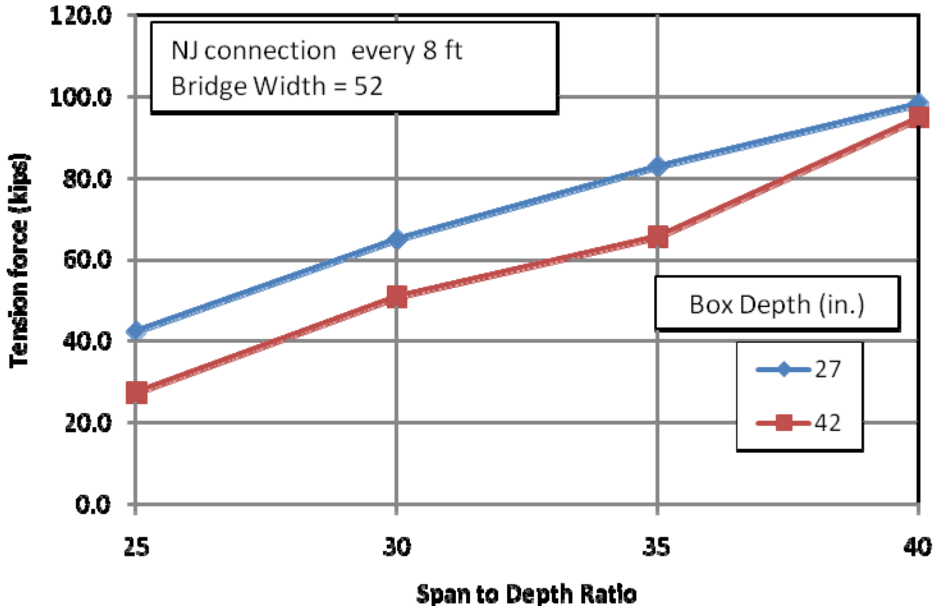

Figure 14 Effect of span-to-depth ratio on the required factored transverse tension force (kips) for NJ system

1 ft = 0.3048 m, 1 in. = 2.54 cm and kip = 4.448 kN

Conclusions

In this paper, two non-post-tensioned transverse connections in adjacent box girder bridges are presented, namely narrow joint (NJ), and wide joint (WJ). The proposed connections are developed to be structurally superior to existing connections yet more practical and economical. Both connections are designed to eliminate the need for post-tensioning, cross/end diaphragms, and concrete topping, which significantly simplify box production, speed bridge construction, and reduce the total cost. In addition, elimination of diaphragms facilitates inspection of voids, provides better drainage of moisture, results in lighter weight for handling and shipping, and allows for continuous rather than discrete (quarter point) connections. The proposed connections have top flange and bottom flange reinforcement to provide adequate moment transfer mechanism between boxes in addition to horizontal and vertical shear keys for shear transfer.

Finite element models were developed to determine the effect of design parameters, such as span length, bridge width, and girder depth, on the design of the proposed connections. The latest AASHTO LRFD live load and dynamic load allowance were applied to determine the required reinforcement in the two connections. Design charts were developed for each system to facilitate connection design in various bridge widths (28 ft – 84 ft) (8.5344 m – 25.603 m), span-to-depth ratios (25, 30, and 35), and 4 standard depths (27 in., 33 in., 39 in., and 42 in.) (68.58, 83.82, 99.06, and 106.68 cm). Based on the analysis results, the following conclusions can be made for both connections:

- The required reinforcement across the connection increases by the increasing the bridge width
- The required reinforcement across the connection decreases by increasing in the bridge depth
- The required reinforcement across the connection increases by increasing the span to depth ratio

REFERENCES

1. American Association of State Highway and Transportation Officials (AASHTO) (2007) "AASHTO LRFD Bridge Design Specifications", 4th Edition with 2008 interim revisions, Washington, DC.
2. American Association of State Highway and Transportation Officials (AASHTO) (1996) "Standard Specifications for Highway Bridges", 16th Edition, Washington, DC.
3. Precast/Prestressed Concrete Institute (PCI) (2003) "Precast Prestressed Concrete Bridge Design Manual", 2nd Edition, Chicago, IL.
4. El-Remaily, A., and Tadros, M. K., Yamane, T., and Krause, G. (1996) "Transverse Design of Adjacent Precast Prestressed Concrete Box Girder Bridges", PCI Journal, 41(4).
5. Hanna, K. E., Morcous, G and Tadros, M. K. "Transverse Design and Detailing Of Adjacent Box Beam Bridges", PCI National Bridge Conference, Phoenix, AZ, October 2007
6. Hanna, K. E. "*Behavior of Adjacent Precast Prestressed Concrete Box Girder Bridges*" Ph.D. Dissertation, University of Nebraska-Lincoln, December 2008.

7. Hanna, K.E., Morcous, G. and Tadros , M. K “Transverse Post-Tensioning Design and Detailing of Precast Prestressed Concrete Adjacent Box Girder Bridges” Scheduled for publication, PCI Journal, Fall 2009.
8. Subcommittee on Adjacent Box Beam Bridges , “Precast/Prestressed Adjacent Members Bridge ”, State of the Art Report, PCI Bridge Committee, Final Draft, October 2007.
9. Illinois Department of transportation (IDOT), “Bridge Manual”, May 2008.