TRANSVERSE DESIGN AND DETAILING OF ADJACENT BOX BEAM BRIDGES

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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. However, reflective cracking and leakage have been reported along the longitudinal joints between adjacent boxes on a number of bridges. The cracking and leakage are mainly due to inadequate design and detailing of the transverse connection between adjacent boxes, which eventually leads to excessive differential rotation of adjacent boxes. The corresponding reflective cracking allows chloride-induced corrosion of reinforcing steel and prestressing stands.

This paper presents a review of the various practices currently used in the design and detailing of adjacent box girder bridges for transverse effects. The basis for calculating the transverse post-tensioning force according to the PCI Bridge Design Manual is discussed. Design charts for various combinations of span length, bridge width, skew angle, and girder depth are developed using the latest AASHTO LRFD loading. These aids may be viewed as an update of the information in the PCI BDM, which was based on an earlier version of the AASHTO Bridge Design Specifications.

Finally, a non-post-tensioned transverse design alternative is proposed for possible simplification of this already efficient system. The proposed system would result in elimination of end as well as intermediate diaphragms, and is based on monolithic emulation of multi-cell cast-in-place box girder superstructure, similar to the system common in California.

Keywords: Adjacent Box Beams, Transverse Post-Tension, Shear Key.

INTRODUCTION

Prestressed box girder bridges represent about one third of all prestressed concrete bridges built in United States. Precast adjacent box beam bridges are the most prevalent box girder system for short and medium span bridges (typical spans vary from 20 ft to 127 ft) especially on secondary roadways. These bridges consist of multiple precast box beams that are butted against each other to form the bridge deck and superstructure. These boxes are laterally connected at their interface using grouted shear keys, tie rods, transverse 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 adjacent box beam bridges are:

1. ease and speed of construction because of eliminating concrete forming and pouring operations (e.g. the Arbor rail line bridge in Nebraska City was erected and opened to traffic within 72 hours)
2. shallow superstructure depth that is necessary to maintain the required vertical clearance (e.g. an interstate bridge in Colorado has a span to depth ratio of 39)
3. low construction cost compared to I-girder bridges and other competing systems; and finally
4. improved bridge aesthetics due to the flat soffit and the slender superstructure.

Several studies and surveys have reported frequent longitudinal reflective cracking over the grouted shear keys, early in the service life of adjacent box beam bridges. This cracking indicates inadequate design and/or construction of the transverse connection between adjacent boxes. This eventually leads to two serious problems: 1) insufficient distribution of live load across the bridge and excessive differential deflection and twisting between adjacent boxes, which further propagates cracks; 2) leakage of water and deicing chemicals used in winter through longitudinal joints, which result in concrete staining and spalling due to the corrosion of reinforcing steel and prestressing strands along the bottom and sides of box beams. Some problems are as simple as careless omission of drain holes in the box voids, resulting in moisture accumulation, increased deflections and possible eventual collapse.

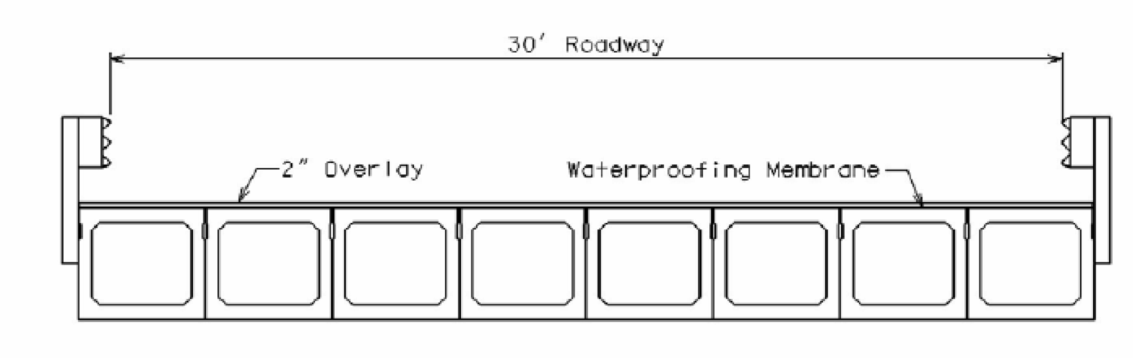
These seemingly unimportant construction details during production and installation of these bridge systems have led to severe deterioration and premature replacement of several bridges in Illinois. Collapse of a bridge over the highway I-70 in Pennsylvania in 2005, has been attributed to lack of adequate inspection and maintenance to correct for the consequences of cracking and leakage. Unfortunately, public attention gets focused on the few failed cases, and not the successful installations. Realizing that the weaknesses of some practices can be corrected through issuance of recommended practice, the PCI Bridges Committee has placed design and detailing of adjacent box beam bridges as a top priority on its agenda in the last few years. The committee also formed a subcommittee to study the performance of adjacent box beam bridges built nationwide. A brief summary on the state-of-the art report prepared by the subcommittee is presented in the last paragraph of the next section.

The *general objective* of this research is to improve the performance of adjacent box beam bridge system. The *specific objectives* are to provide adequate structural capacity of this system in the transverse direction, and to prevent longitudinal joint leakage.

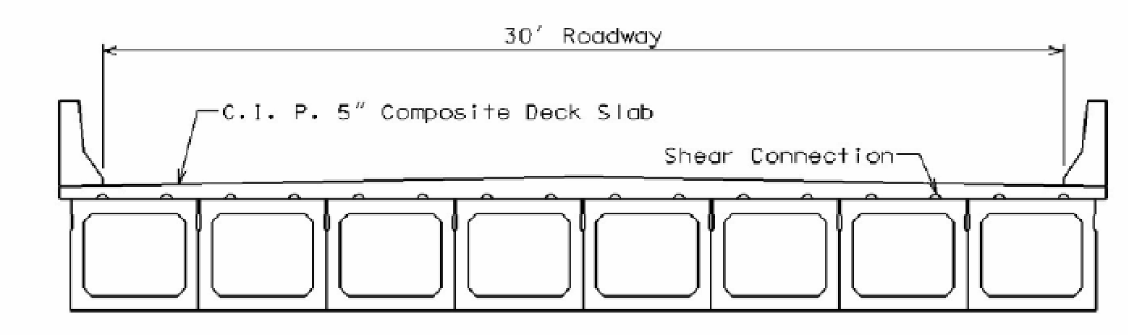
The scope of this research includes single span and multiple span adjacent box beam bridges constructed with a skew, or square, both with and without a composite topping The study includes single stage new construction and multistage replacement scenarios when transverse post-tensioning of the entire width in one stage is not feasible.

CURRENT PRACTICES

Adjacent box girder bridges incorporate various practices in the design and detailing of transverse connecting systems. Fig. 1(a) shows a non-composite construction system with a non-structural overlay as riding surface applied directly to the top flange of the adjacent boxes. This system depends only on the grouted shear key to provide the shear transfer mechanism between adjacent boxes. Fig. 1(b) shows a thick cast-in-place reinforced concrete slab anchored to the supporting boxes using shear connectors to act as a composite superstructure system. Fig. 1(c) shows a typical transverse connection made between the adjacent boxes using a post-tensioning tie or a threaded rod. This transverse connection system can be used in conjunction with the composite or non-composite systems to prevent differential deflection.



(a)



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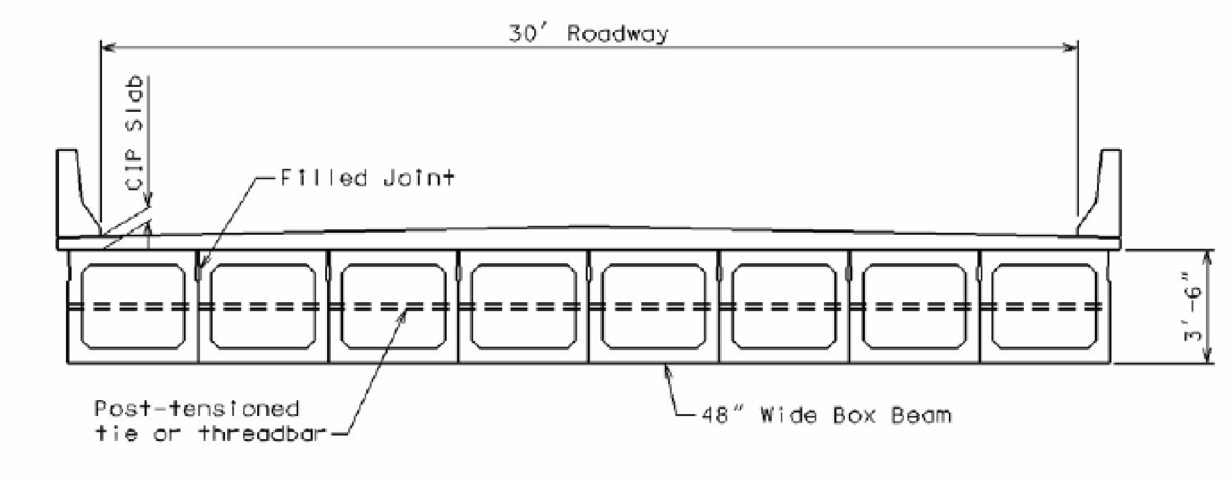


(c)

Fig. 1: Typical Sections of Adjacent Box Girder Bridge

According to the Ontario Bridge Design Code, the general design philosophy of adjacent member systems assumes that the transverse shear transfers the entire load between adjacent boxes and the transverse flexure rigidity is completely ignored. Also, grouted shear keys are considered inadequate to transfer the shear force and, therefore, a structural concrete slab of a minimum thickness of 5.9 inch is required. The transverse shear force is determined as function of the bridge width-to-span ratio, longitudinal flexural rigidity, and longitudinal tensional rigidity[1]. Some state DOTs, such as Michigan, combine the use of a structural concrete slab and transverse post-tensioning. This is based on the assumption that both shear and flexure forces must be transversally transferred at the joints between adjacent boxes to control both translational and rotational deformations[2].

In Japan, adjacent box girders are designed using similar sections and design criteria to those used in United States. However, longitudinal joints are detailed differently and transverse post-tensioning is significantly higher. Cast-in-place concrete is placed in full-depth joints that are 6.7 in wide and 22 in long. After grouting, post-tensioning is applied through severalducts located at different elevations. All boxes are covered with 2 to 3 in asphalt concrete wearing surface. Using the Japanese practice, longitudinal cracking and concrete deterioration has rarely been reported. For post-tensioning arrangement and joint dimensions, refer to El-Remaily, et al[3].

In Korea, transverse connection is achieved by using a mid-depth shear key fully filled with cast-in-place concrete in addition to heavy transverse post-tensioning applied similar to the Japanese practice. The choice of a mid-depth shear key was based on a detailed analysis and full-scale testing[4].

The State of Oregon has developed empirical transverse design and detailing procedures for adjacent box girders that have demonstrated satisfactory performance over the years. The developed system is based on using transverse threaded ties at several locations according to the span length, grouting partial-depth shear keys, and providing recesses as ¼” chamfer at the bottom edges of the beam to prevent spalling due to stress concentration. For more details on this system, refer to section 8.9.2 of the PCI Bridge Design Manual[5].

According to Lall, et al[6]. New York State has used a significant number of precast prestressed adjacent box beams for short and medium span bridges. Prior to 1992, partial depth grouted shear keys (9 to 12 in) were used to transversally connect adjacent boxes in addition to a cast-in-place deck, at least 6 in thick, and transverse tendons. This practice has resulted in frequent longitudinal deck cracking over the joints. After 1992, full-depth shear keys used instead and the additional transverse tendons have substantially reduced the frequency of longitudinal deck cracking above the shear keys.

An experimental study on the shear keys for adjacent box beams was carried out to determine the effect of shear key location and grouting material on longitudinal cracking[7]. The full-scale testing of four adjacent box beams has indicated that mid-depth shear keys are less susceptible to cracking due to load induced movements and thermal stresses than top shear keys. Also, the study has concluded that epoxy grout is more effective than non-shrink grout for shear keys. This conclusion has been confirmed by another investigation conducted by West Virginia DOT, which also recommended that the surfaces to be grouted are sand-blasted and high strength post-tensioned ties to be used[8].

The PCI subcommittee on adjacent member bridges has recently conducted a survey on the current practices in the design and construction of adjacent box girder bridges in United States and Canada. This survey has indicated that 29 states and 3 provinces are currently using adjacent box girder bridges. Most of these transportation agencies have experienced premature reflective cracks in the wearing surface on the bridges built in the late 1980s and early 1990’s. These agencies have emphasized the importance of eliminating these cracks that allows the penetration of water and deicing chemicals leading to the corrosion of reinforcing steel in the sides and bottoms of concrete boxes. Below are examples of the preventive actions that the states and provinces have recommended based on the lessons learned in the last two decades:

1. Use of cast-in-place deck on top of the adjacent boxes to prevent water leakage and to uniformly distribute the loads on adjacent boxes.
2. Use of non-shrink grout or appropriate sealant instead of the conventional sand/cement mortar in the shear keys, in addition to blast cleaning of key surfaces prior to grouting. Also, a few states have recommended the use of full-depth shear keys due to their superior performance over the traditional top flange keys.
3. Use of transverse post-tensioning to improve load distribution and minimize differential deflections among adjacent boxes. Adequate post-tension force should be applied after grouting the shear keys to minimize the tensile stresses that cause longitudinal cracking at these joints.
4. Use of end diaphragms to ensure proper seating of adjacent boxes and intermediate diaphragms to provide the necessary stiffness in the transverse direction.

5. Use of wide bearing pads under the middle of the box to eliminate the rocking of the box while grouting the shear keys. Also, using slopped bearing seats that match the surface cross slop is recommended.
6. Use of adequate concrete cover and corrosion inhibitor admixtures in the concrete mix to resist the chloride-induced corrosion of reinforcing steel.
7. Eliminating the use of welded connections between adjacent boxes and avoiding dimensional tolerances that result in inadequate sealing of the shear keys.

PCI BRIDGE DESIGN MANUAL METHOD

The PCI Bridge Design Manual (BDM) method was developed by El-Remaily et al[3]. In this method, the post-tensioning force required to achieve adequate stiffness in the transverse direction to keep differential deflection within the acceptable limit (i.e. 0.02 in) is calculated. This method assumes that post-tensioned transverse diaphragms are the primary mechanism for the distribution of wheel loads across the bridge. Five diaphragms are provided in each span: one at each end and one at each quarter point. Without diaphragms, each box must be designed to carry a full set of wheel loads without contribution from adjacent boxes. As a result, large differential deflection between adjacent girders will take place and reflective cracking are generally expected. However, if the box girders are transversally connected using diaphragms, the loads are distributed over the entire bridge width and the deflected shape becomes a smooth curve. The transverse diaphragms are made continuous across the entire width of the bridge using grouted full-depth shear keys and post-tensioning tendons.

To determine the required amount of post-tensioning, the bridge is analyzed using a grid model. A series of longitudinal beam elements located at the center line of each box is used to represent the box girders, and a series of transverse beam elements located at the ends and quarter points is used to represent the diaphragms. The joints between elements allow the transmission of shear, bending and torsion. The weight of barrier rails and live loads are the main source of transverse bending moments generated in the diaphragms. This is because self weight, deck weight, and wearing surface weight are considered uniform on all the elements and, therefore, do not generate any differential movements. Transverse post-tensioning force is calculated so that diaphragm concrete stresses due to both loads and post tensioning are within the allowable limits (i.e. compression = $0.6 f_c'$ and tension = 0). Tensile stresses are not permitted in the diaphragm to prevent possible cracking at the interface between precast components and the grout at shear key locations. Also, post-tensioning force is applied without eccentricity because diaphragms experience significant alternating positive and negative bending moments in different loading conditions.

The design chart currently available at the PCI BDM, and shown in Fig. 2, was developed for the AASHTO standard box girders (depths 27, 33, 39 and 42 in) assuming mild skew angles (i.e. less than 15^o), average span lengths, and using the HS-25 truck loading with impact. New charts need to be developed to accommodate the cases of highly skewed bridges with maximum span lengths and using the latest AASHTO LRFD truck and lane loads in addition to dynamic load allowance.

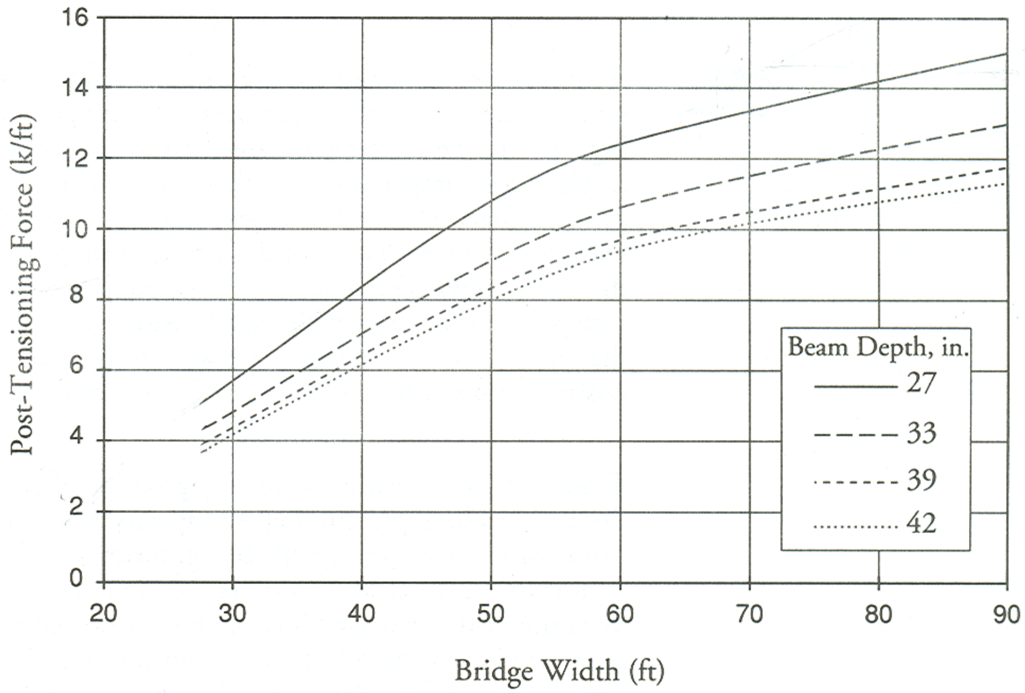


Fig. 2: PCI BDM design chart for required effective post-tensioning force[5]

PROPOSED DESIGN CHARTS AND EQUATION

The proposed design charts are developed using the same PCI DBM method for the same standard AASHTO box girder depths. For each depth, several combinations of bridge width, span length, and skew angle are considered. The latest AASHTO LRFD truck and lane live loads (HL-93) and dynamic load allowance (33% for truck load only) are applied in addition to the self weight of a solid concrete barrier (0.48 kip/ft)[9].

The proposed design charts are developed to demonstrate the effect of each design parameter on the required amount of post-tensioning force. Fig. 3 shows the effective post-tensioning force (kip/ft) versus bridge width (ft) for the four standard box girders assuming a 0^o skew angle and a span length to depth ratio equals to 30. Fig. 3 indicates that for any girder depth, the wider the bridge, the higher the required post-tensioning force. It also indicates that the required force is higher in shallower girders than in deeper girders for the same bridge width This is mainly to compensate for the reduction in the transverse stiffness due to the use of shallower diaphragms.

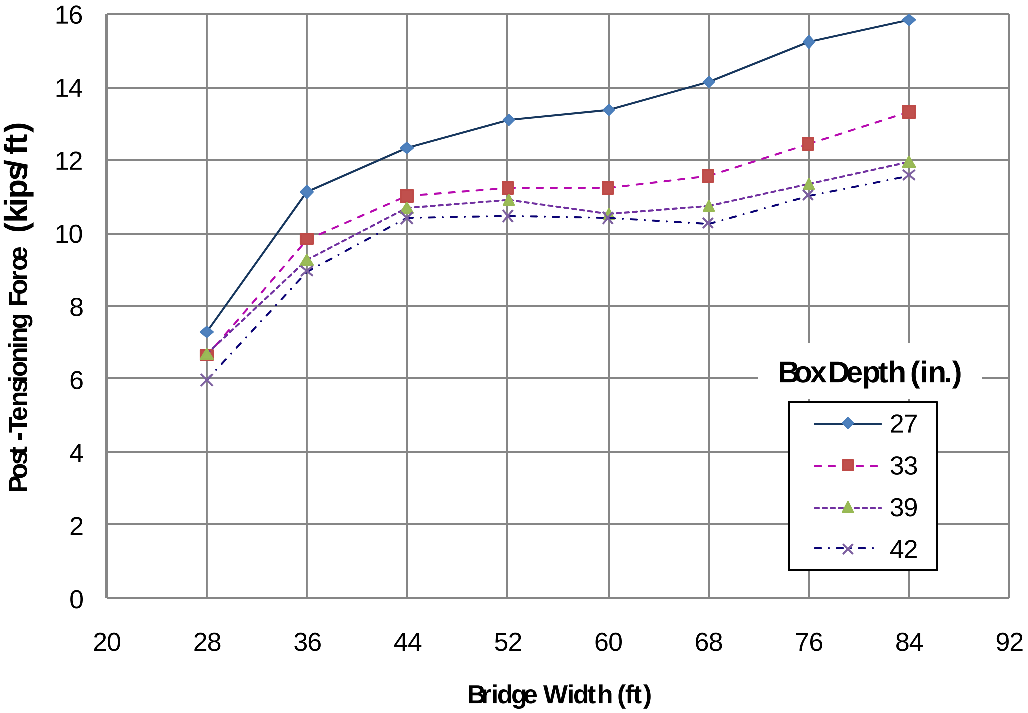


Fig. 3: Effect of deck width on post-tensioning force at mid span diaphragm

By comparing the PCI BDM design chart shown in Fig. 2 and the proposed design chart shown in Fig. 3, it can be concluded that there is a significant increase in the required post-tensioning force (up to 50% in some cases) due to the use of the latest AASHTO LRFD live load and dynamic load allowance specifications. This increase varies depending on the box depth and the bridge width and it is more noticeable in narrow bridges than wide bridges. It should be noted that the PCI BDM values correspond to a skew angle of 15^o and average span length, while the proposed values correspond to a skew angle of 0^o and span–to-depth ratio of 30.

Fig. 4 shows the required post-tensioning force versus bridge width for a 0^o skew angle and span-to-depth ratios equal to 30 and 50. Although the effect of the span-to-depth ratio has been evaluated for the four standard AASHTO box depths, only the 27 in and 42 in deep boxes are plotted for clarification. This plot indicates that the span-to-depth ratio has a variable effect on the required post-tensioning force per unit length. In most of the cases, the higher span-to-depth ratio increases the required force (positive effect) and it decreases the required force (negative effect) in few cases. The positive effect is more noticeable in deep girders than shallow girders.

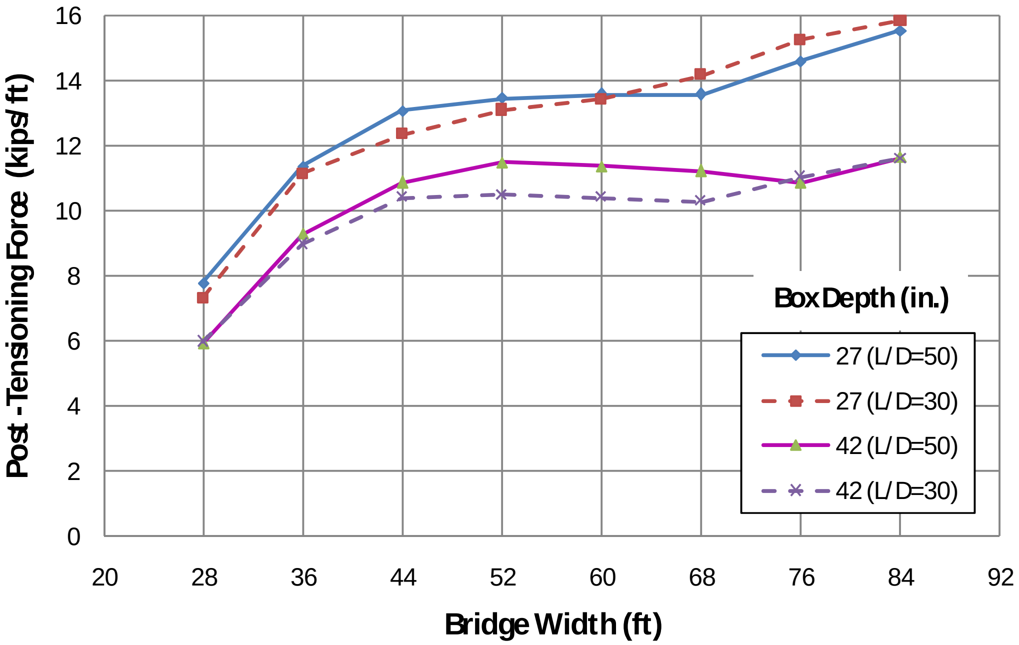


Fig. 4: Effect of span-to-depth ratio on post-tensioning force at the mid-span diaphragm

Fig. 5 shows the effect of skew angle on the required post-tensioning force at the mid-span diaphragm for a bridge width of 52 ft and a span-to-depth ratio of 30. Fig. 5 indicates that the impact of the skew angle on the required post-tensioning force is minimal especially on deep girders that usually correspond to longer spans. For shallow girders, used in short span bridges, the higher the skew angle, the more the required post-tensioning force.

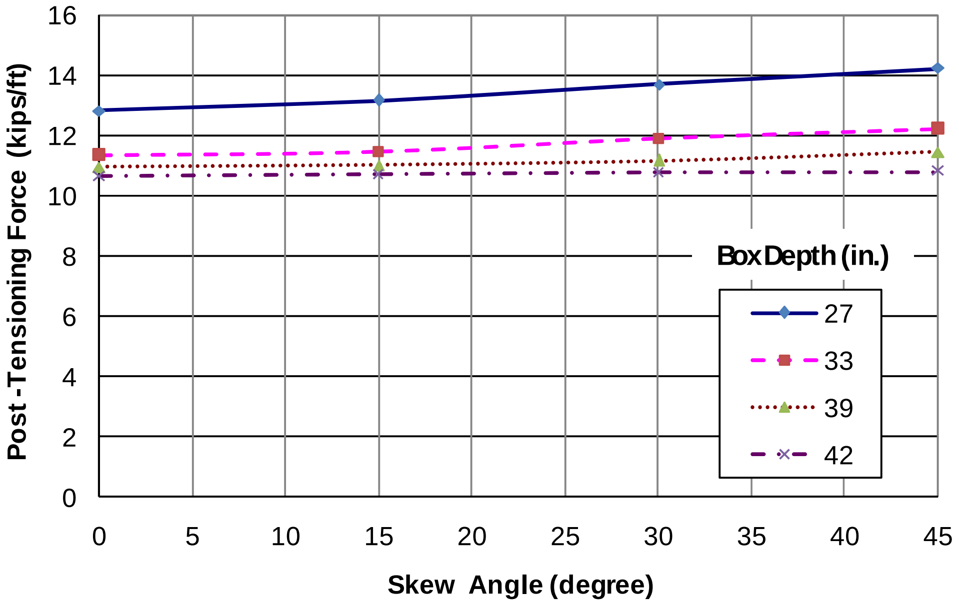


Fig. 5: Effect of bridge skew angle on post-tensioning force for mid span diaphragm

Fig. 3, 4, and 5 clearly indicate that the bridge width and box depth are the most important parameters in determining the required post-tensioning force per unit length of the bridge. Therefore, the designer should first estimate the force based on the bridge width and girder depth using the proposed design chart shown in Fig. 3. The obtained values correspond to a span-to-depth ratio of 30 and 0^o skew angle and should be corrected using Figures 4 and 5, respectively, when higher span-to-depth ratio and/or skew angle are used.

Data obtained from the grid analysis are used to develop a simplified design equation for calculating the required post-tensioning force (P) for intermediate diaphragm per unit length of the bridge (kips/ft). The following equation was found to best fit the data points of all cases while eliminating sophisticated formulations.

$$P = \left(\frac{0.9 \times W}{D} - 1.0\right) \times K_L \times K_S \leq \left(\frac{0.2 \times W}{D} + 8.0\right) \times K_L \times K_S$$

Where,

D	box depth (ft.)
W	bridge width (ft.)
L	bridge span (ft.)
θ	skew angle (degree)
K_L	correction factor for span-to-depth ratio more than 30

$$K_L = 1.0 + 0.003 \times \left(\frac{L}{D} - 30\right)$$

K_S	correction factor for skew angle more than 0^o

$$K_S = 1.0 + 0.002 \times \theta$$

To evaluate the accuracy of the developed equation, the post-tensioning force values obtained using the equation are compared against those obtained using the grid analysis for several combinations of bridge width and depth. Span-to-depth ratio and skew angle are kept constants to evaluate the accuracy of the basic equation without any correction factors. Fig 6 shows that the design equation provides a conservative estimate of the required post-tensioning force in most of the cases with an average deviation of 7.7%.

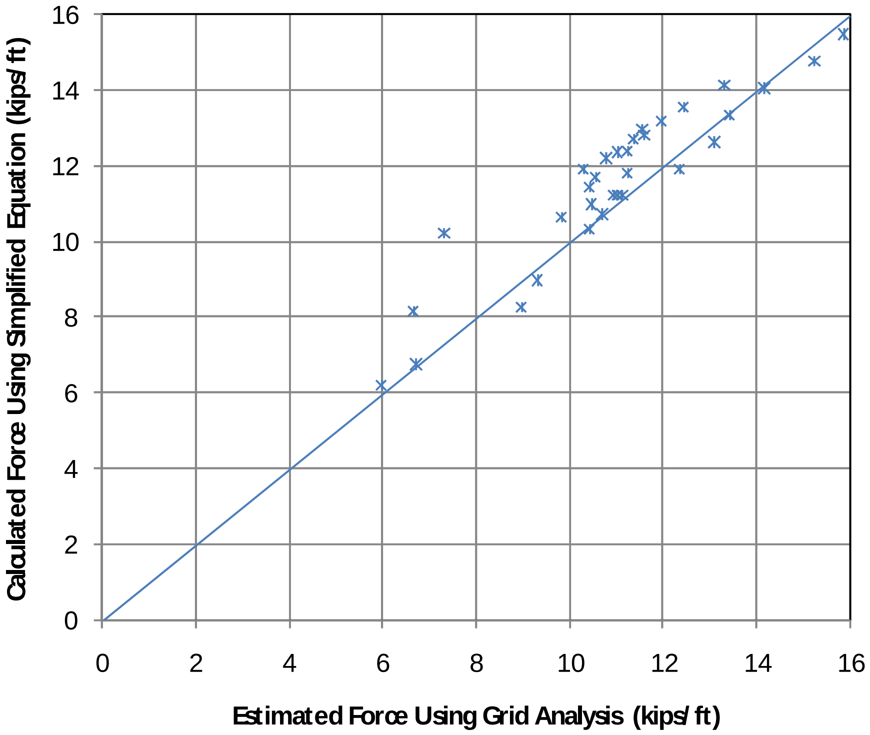


Fig. 6 comparison between the Post Tensioning force from grid analysis and from the proposed equation.

DESIGN EXAMPLE

In order to compare the proposed design chart and equation versus the existing design chart, the design example presented in the BDM section 8.9.3.7 is considered. In this example, the post-tensioning force is calculated for the mid-span diaphragm in a bridge that has five diaphragms (2 end diaphragms and 3 intermediate diaphragms at quarter points). The bridge is 95' long, 28' wide, 0^o skew, and made of AASHTO BII-48 that is 39 in deep without topping.

D = 39/12 = 3.25 ft
W = 28 ft
L = 95 ft
θ = 0 degree
K_L = 1.0
K_S = 1.0

1- Using the Proposed charts:
Span-to-depth ratio = 95/3.25 = 29.2 ~ 30
Using Fig. 3, P = 6.7 kips/ft
Total post-tensioning force = 6.7 x 95/4 = 159 kips

2- Using the proposed Equation:

$$P = \left(\frac{0.9\times 28}{3.25} - 1.0\right)\times 1.0 \times 1.0 \leq \left(\frac{0.2\times 28}{3.25} + 8.0\right)\times 1.0 \times 1.0 = 6.75 \text{ kips/ft}$$

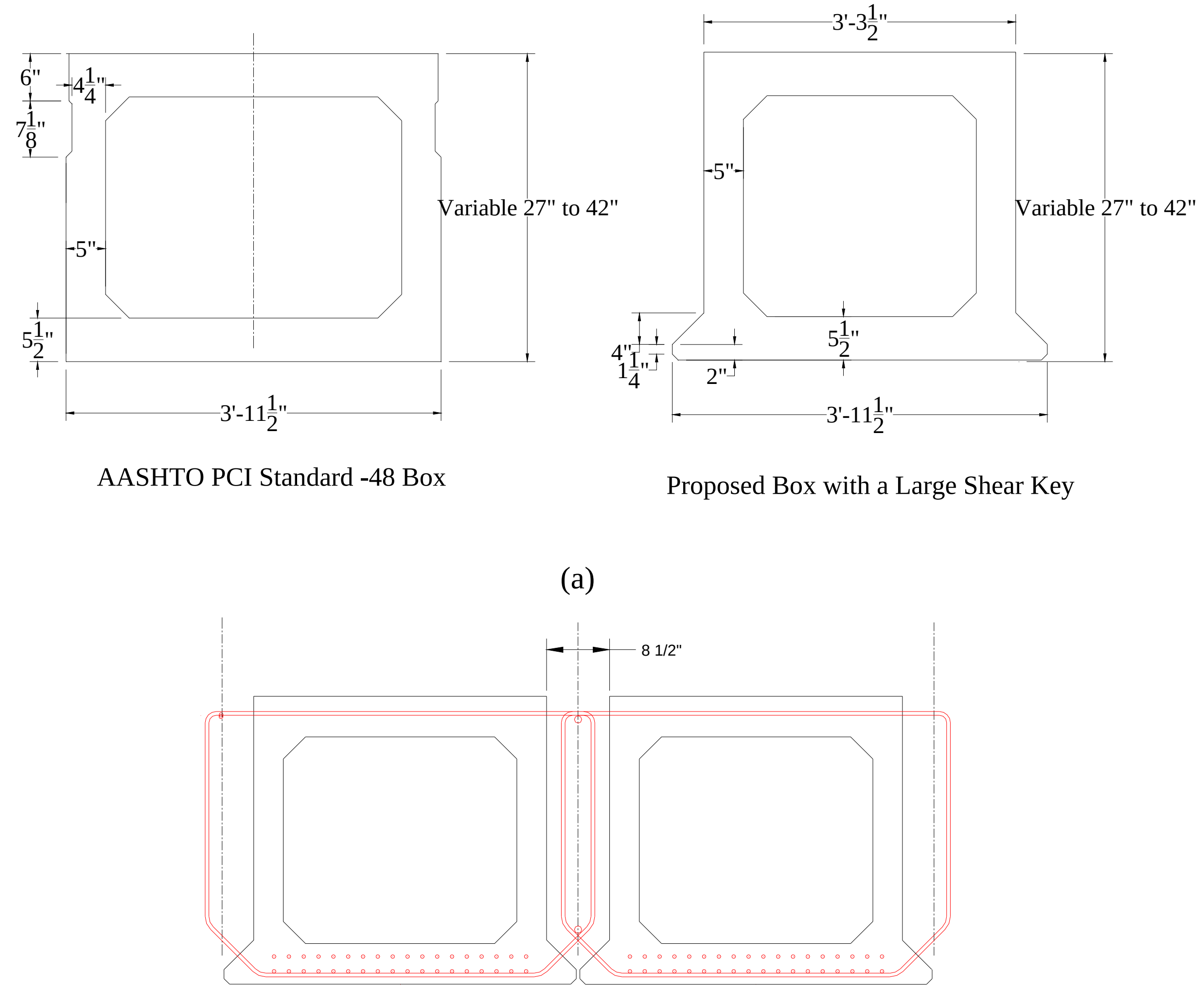
Total post-tensioning force = 6.75 x 95/4 = 160 kips

This force is significantly higher than the one calculated using the existing chart (95 kips) mainly due to using the latest AASHTO LRFD specifications for live loads and dynamic load allowance.

PROPOSED NON-POST-TENSIONED TRANSVERSE DESIGN ALTERNATIVE

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.

In this section, a non-post-tensioning alternative is proposed to emulate monolithic construction and eliminate the problems associated with post-tensioning and shear keys in general and in skewed bridges in particular. In this alternative, a reinforced concrete connection is proposed along the entire bridge length between the adjacent boxes to transfer moment, shear and torsion similar to the system common in California. A modification to the current AASHTO-PCI box girder is also proposed to provide enough spacing between the adjacent boxes for the CIP reinforced concrete connection. Fig. 7 (a) shows the standard AASHTO PCI box section and the proposed modified box section with preliminary dimensions. Fig. 7 (b) shows the proposed reinforcing details of the connection that will be constructed using form savers, bar splices and, additional longitudinal bars dropped in the spacing between the boxes before pouring the concrete. These reinforcing details are tentative and will be finalized in the near future. Fig. 8 shows another non-post-tensioned proposed connection details using the standard AASHTO PCI box section without modifications. The proposed top and bottom connections will include splicing bars, confinement spirals, and grout. The detailed design of this alternative is also in progress. This work is supported by the 2007-2008 PCI Daniel P. Jenny Fellowship and will be completed by the end of the academic year.



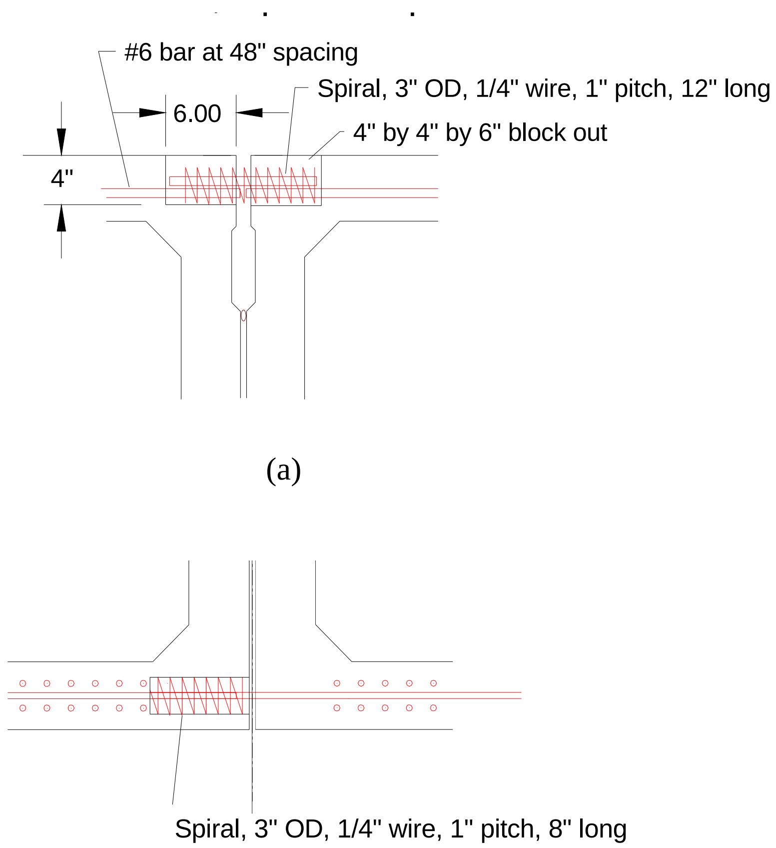
AASHTO PCI Standard -48 Box

Proposed Box with a Large Shear Key

(a)

(b)

Fig. 7: First alternative a) proposed box section compared to the standard AASHTO-PCI box b) proposed shear key and reinforcing details.



(a)

(b)

Fig. 7: Second alternative: a) proposed top spliced connection b) proposed bottom connection

CONCLUSIONS

This paper presents a brief review on the current practices of the transverse design and detailing of adjacent box girder bridges. The experience and recommendations of several transportation agencies in USA, Canada, Japan, and Korea regarding grouted shear keys, composite superstructure, and transverse post-tensioning has been summarized.

The paper also presents the concepts and assumptions of the PCI BDM method of calculating the required post-tensioning force for connecting quarter point diaphragms. This method has been used to update the PCI BMD design chart according the latest AASHTO LRFD live load and dynamic load allowance specifications. Additional design charts have been proposed to account for the effect of design parameters, such as span length and skew angle, in addition to the existing parameters (i.e. bridge width and girder depth). Comparing the proposed design charts with the existing PCI BDM design chart has shown significant differences. A simplified design equation has been developed to determine the required post-tensioning force per unit length of the bridge as a function of its width and box depth. Also, the effect of span length and skew angle have been presented using correction factors that are calculated as a function of the deviation from the default values (span-to-depth ratio = 30, and skew angle = 0^o).

Two non-post-tensioning alternatives have been proposed to eliminate the shortcomings of the post-tensioned diaphragms and grouted shear keys. One alternative emulates monolithic construction by modifying the standard box section to provide adequate spacing between adjacent boxes that accommodate a full-depth full-length, shear- and moment-resistant reinforced concrete joint. The other alternative comprises top and bottom connection using splicing bars, confinement spirals, and grout, while maintain the standard box section.

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