PRESTRESSED CONCRETE BOX BEAM BRIDGES – Two DOTS' EXPERIENCE

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ABSTRACT

The prestressed concrete box beam bridge is a common superstructure type in the nation's bridge inventory. Two of the most prevalent superstructure types are adjacent and spread box beam bridges. Prestressed box beam bridges were first constructed in the late 1950's and early 1960's. The design, fabrication and construction techniques have evolved from the first generation beams to today's standards. Early and current details from the Pennsylvania Department of Transportation and Illinois Department of Transportation will be presented.

The in-service performance of prestressed box beams will be discussed. Results from investigations have lead to revised design and construction details, inspection and load rating analysis methods used by Pennsylvania DOT and Illinois DOT.

Keywords: Concrete, Prestressed, Box beam, Bridge safety inspection, Bridge load rating, Bridge maintenance

INTRODUCTION

This paper presents the experiences of Pennsylvania and Illinois with design, fabrication, inspection, load rating and maintenance of bridges constructed with noncomposite adjacent prestressed concrete box beams. Improvements in the construction practices have occurred since the first generation of prestressed concrete beams were designed and cast. Past and current design and construction requirements are documented. The latest techniques for management of the inventory of this bridge type with respect to proper bridge safety inspection, load rating and maintenance are discussed.

INVENTORY

Today, owners are striving to build cost effective and durable bridges that can be rapidly constructed. A similar mindset existed during the Interstate construction period. A structure type anticipated to meet these objectives consisted of a superstructure that did not require the forming, placing and finishing a concrete deck. The solution developed by designers and the prestressed concrete industry was a bridge type with a superstructure constructed of noncomposite adjacent prestressed concrete box beams with an asphalt wearing surface. This bridge type has the advantages of a shallow superstructure, rapid construction and low initial construction cost, resulting in a substantial inventory that owners must effectively manage. In many circumstances this bridge type is used on low volume roads, an exception occurs with several bridges located in the heart of Philadelphia, Pennsylvania. The bridges carry city traffic over I-695, the Vine Street Expressway. These bridges are very wide; one bridge has a cross section with an out to out width of 90 feet.

In conjunction with an investigation by Pennsylvania Department of Transportation (PennDOT) of noncomposite adjacent prestressed concrete box beam bridges in 2006, a survey of Departments of Transportation of selected states was conducted. The survey results for the top five states with the largest inventory of this bridge type are tabulated in Table 1. An unexpected result of the survey was the number of states that have experienced a structural failure of this type of bridge. A total of seven states (Illinois, Pennsylvania, Ohio, Indiana, Florida, Colorado and Virginia) have reported failures.

Table 1 - Top Five States by Number of Noncomposite Adjacent Prestressed Concrete Box Bridges

State	State Bridges	Local Bridges
Illinois	621	7,724
Ohio	801	2,493
Indiana	10	2,739
Pennsylvania	802	945
Florida	328	1,167

As demonstrated in Table 1, the advantages of low initial cost, rapid erection, uncomplicated construction and minimal maintenance requirements made this bridge type a preferred choice by local owners.

DESIGN AND CONSTRUCTION PRACTICES

Consistent with the continuous improvement philosophy in bridge engineering, the design and construction details of noncomposite adjacent prestressed concrete box beams have evolved since the initial details in the late 1950's and early 1960's. Through in-service experience, research and testing, and application of principles from other industries, the bridge engineering community has seen advances in design, material, fabrication and construction.

The design of prestressed concrete members has improved with respect to:
- Prediction of ultimate flexural capacity
- Prediction of shear capacity
- Prediction of prestress losses
- Prediction of prestress transfer and development length
- Increased concrete clear cover to the reinforcing
- Position of the mild steel stirrups in relation to prestressing strands for enhanced confinement

Advances in materials leading to improving the durability of the prestressed beams include:
- Increase in strength, decrease in permeability and overall increase in the quality of concrete
- Progression in prestressing strand technology from stress relieved strands to low relaxation strands
- Increase in strength of reinforcement both prestressing and mild steel
- Larger prestressing strand diameters and cross sectional areas- from 0.25 inch to 0.5 inch (special) diameter, resulting in 0.08 in^2 and 0.167 in^2 respectively
- Epoxy coated mild steel (soon to be implemented in Illinois)
- Use of corrosion inhibiting admixtures in concrete mixes
- Elimination of the use of calcium chloride as an admixture for high early strength concrete

Regarding fabrication, there have been improvements in:
- Concrete mix designs
- QA/QC methods and reliability
- Use of expanded polystyrene voids instead of cardboard forms (expanded polystyrene forms have been an option in Illinois and will soon be mandated)
- Curing practices

Figures 1 and 2 illustrate the key improvements in beam fabrication

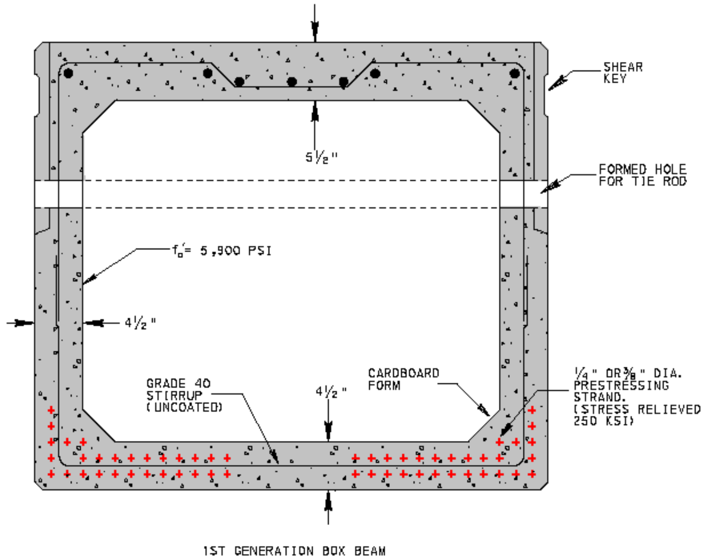


Figure 1 - PennDOT 1st Generation Noncomposite Adjacent Prestressed Concrete Box Beam

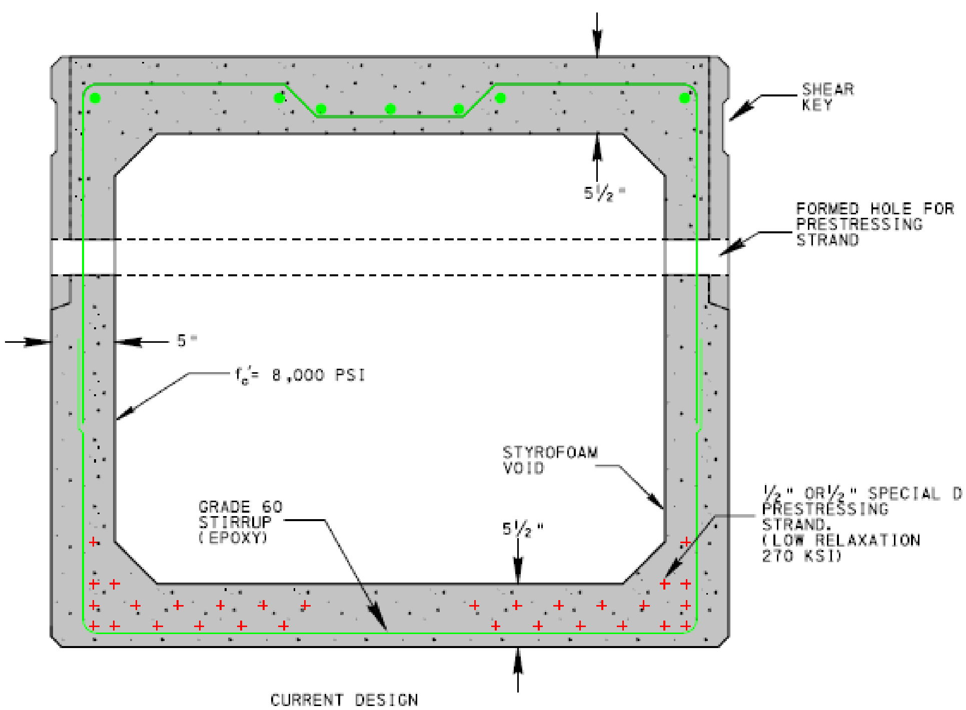


Figure 2 - PennDOT Modern Noncomposite Adjacent Prestressed Concrete Box Beam*

*2006 Moratorium on construction of adjacent noncomposite prestressed box beam bridges

Improvements in construction of noncomposite adjacent prestressed concrete box beam bridges include:

- Sandblasting of shear keys
- Higher strength grout in shear keys
- Non-shrink grout in shear keys
- Orientation (layout configuration) of the beams
- Lateral post-tensioning constraint of the cross section
- Waterproofing membranes
- Elimination of open deflection joints in barriers

DESIGN

The American Association of Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications is the current design code for prestressed concrete bridge members. This design code requires bridge engineers to evaluate various limit states, service and strength, and to consider various factors of bridge importance, ductility and redundancy.

Typically, multi-beam bridges are considered redundant structures, especially prestressed concrete beam bridges. A structural deck system composite with the structural beams contributes to the overall redundancy. As shown in Figure 3, an asphalt surface has no structural value. Therefore, noncomposite adjacent prestressed concrete box beam bridges must be evaluated appropriately for redundancy. Due to inconsistency in the quality of shear keys and the effectiveness of the tie rods to provide sufficient long term connectivity to interior girders, the fascia girder should be designed with the higher redundancy factor of 1.05 of the AASHTO LRFD Bridge Design Specifications.

Another analysis consideration is the number of beams to distribute the concrete barrier. The concrete jersey-type barrier (or older step barrier) weight is approximately 500 lbs/ft which is approximately 50 percent to100 percent of the selfweight of a box beam. As shown in Figure 3, the barrier is cast on top of the fascia girder and is connected with mild reinforcement. Unlike a composite structure, these bridges do not have a concrete deck to more evenly distribute the barrier dead load to other beams in the cross section. From surveyed states, Table 2 depicts the barrier distribution assumption used by other DOTs.

Table 2 - Barrier Dead Load Distribution Assumption

State	Dead load distribution to bridge beams
IL	33% each to the fascia, first interior and other interior beam
OH	50% each to the fascia and first interior beam
IN	Equally distributed to all beams
PA	Original Design Policy 50% each to the fascia and first interior beam Revised Policy for load rating 100% to the fascia girder when analyzing fascia 50% to first interior beam when analyzing first interior
FL	Equally distributed to all beams unless evidence shows beams acting independently, then 100% to fascia beam

As a result of PennDOT's review of redundancy of older noncomposite adjacent prestressed concrete box beam bridges, a new policy was adopted assuming the following barrier dead load distribution:

- Fascia girder - 100% of barrier
- 1st Interior girder - 50% of barrier

Illinois' practice is to avoid the use of concrete barrier on this type of structure whenever possible. This practice is based on the belief that a concrete barrier connected to the fascia girder with reinforcement stiffens the fascia girder relative to the first interior girder and may shorten the life of the keyway between the two girders resulting from differential live load deflection. Side mounted steel rails are used whenever possible.

A force effect that has not been explicitly considered in the analysis of noncomposite box beams is the eccentricity of the barrier load on the fascia girder. The weight of the barrier is not concentric with the center of gravity of the fascia girder (Figure 3), and thus some torsional force is present. Based on research conducted by the University of Pittsburgh[1], the eccentric barrier effects and lateral bending or torsional effects result in minimal reduction in the ultimate flexural capacity of the box beams. Thus, past practice of neglecting the eccentric effects is valid.

CONSTRUCTION

As previously mentioned, the rapid construction of the noncomposite adjacent prestressed concrete box beam bridge is one of the benefits of this bridge type. The top slabs of the boxes are the primary deck elements, thus the cost and time required to construct a concrete deck is eliminated. In particular situations, primarily for aesthetics, the fascia girder is placed vertical, while the remaining beams are placed on a cross slope (Figure 3). This arrangement results in a shear key between the fascia girder and 1st interior beam that is wider at the bottom resulting in a construction challenge to build a functioning shear key. This practice should not be used in current or future practice.

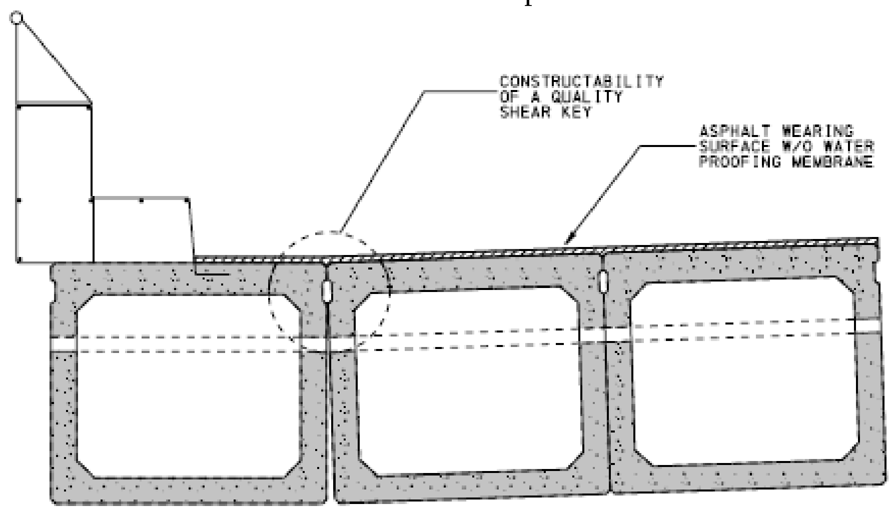


Figure 3 - PennDOT 1st Generation Noncomposite Adjacent Prestressed Concrete Box Beam Bridge

In an attempt to promote the individual beams to act as a unit, bridges are constructed with shear keys and transverse steel rods or strands to "tie" the beams together. For many years, PennDOT used a 1.25 inch diameter steel tie rod to induce connectivity. In practice, the beams were only minimally "pulled" together by tightening the nuts on the tie rods. In skewed structures, the tie rods were staggered resulting in girders connected transversely to the adjacent girder (Figure 4). For older bridges, deterioration of the grout in the shear key led to severe corrosion of the tie rod in some cases resulting in failure of the tie rod. Modern techniques, for both noncomposite and composite adjacent box beams, use prestressing strand that is continuous from fascia to fascia providing improved uniform beam action. The greased and sheathed strand is stressed, post-tensioned, to 0.75 f_u providing approximately 30 kips compressive force per location. The typical longitudinal spacing of the multi-strand tendons is 50 feet. The stressing operation is considered non-primary and therefore the stringent post-tensioning requirements for primary members (jack calibration, experience requirement, post-tensioning plan) are waived.

Relying solely on post-tension tendons as tie rods should be avoided. Robust cheekwalls to resist lateral movement of beams is recommended.

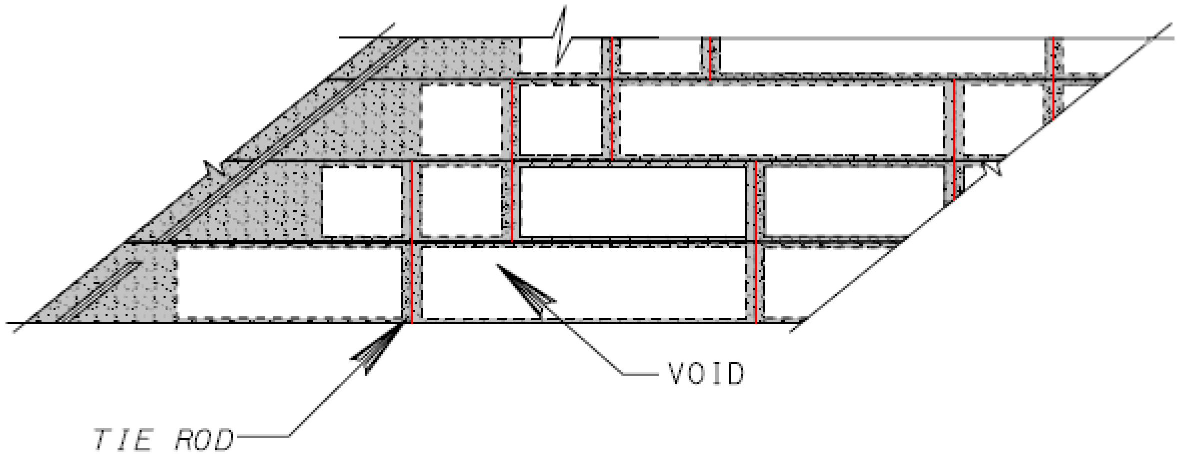


Figure 4 - PennDOT 1st Generation Noncomposite Adjacent Prestressed Concrete Box Beam Bridge Staggered Tie Rod Arrangement

Past and current practice in Illinois involves the use of 1" diameter steel tie rods placed as described above. Prestressing strand has not been used in Illinois for this purpose. Although the rods are only minimally pulled together by tightening the nuts on the tie rods, research by the University of Illinois[3] has shown that the tie rods, provided they remain snug, contribute significantly to load distribution among the beams.

Details of ancillary, non-primary or secondary components can lead to maintenance issues and shortened bridge service life. Prior to the mid 1980s, in Pennsylvania, barriers were constructed with open deflection joints. Detailing barriers as continuous from end to end of the bridge results in more durable bridges by eliminating a path for salt contaminated deck drainage to attack the exposed fascia girders and elimination of stress concentration due to a stiffness discontinuity. The effects of the stiffness discontinuity are discussed further in this paper.

BRIDGE MANAGEMENT

Bridge management is the safety inspection, load rating and maintenance of in-service structures. Substantial financial and manpower resources are required to properly manage the inventory of bridges. The continuous improvement in bridge safety inspections, load ratings and maintenance is a result of research in parallel with field observations and experience. The improvements associated with bridge inspections are readily transferred into practice by national and state training programs. Load rating and maintenance activities are primarily implemented at that state and local level through policies and procedures. Particular research and field experience with noncomposite adjacent prestressed concrete box beam bridges resulted in revised inspection practices, load rating and maintenance activities with the objective to improve the management of this bridge inventory.

BRIDGE SAFETY INSPECTION

The in-service safety inspection of bridges is one of the most important functions of state transportation departments. Bridge inspections provide bridge engineers with the condition of bridges based on uniform and consistent criteria. A challenge with the inspection of prestressed concrete members (I-beams, box beams, bulb Tees, and slabs) is the quantifiable determination of active corrosion of prestressing strands.

Visual inspection is the current state of practice used to document condition of the beams. A non-destructive test method that can provide quantifiable data on the remaining cross-section area of prestressing strand suitable for routine field inspections is not available at this time. Visual methods are unable to detect the corrosion of unexposed prestressing strands, especially, the strands in the top layer of the bottom flange of a box beam.

Studies conducted by the University of Pittsburgh[1] and Lehigh University[2] demonstrated the complexity of detecting corrosion in prestressed concrete box members. Through a combination of cross sectional slices, coring and chipping of concrete troughs, the researchers were able to document corrosion of prestressing strands. Figure 5 illustrates the corrosion of the upper layer of prestressing strands directly above a region of the beam of exposed bottom layer strands. The extent of corrosion in top layer or unexposed areas can be more significant than visual inspection indicates. The length of the prestressing strand which is corroded is limited to the exposed region. Beyond the regions of exposed strand, the passivity of the concrete protects the strand from corroding.

However, research by the University of Illinois[3] also identified that strands in the bottom layer, although they may still lie within sound concrete, are susceptible to corrosion when in contact with corroding shear reinforcement consisting of conventional reinforcing bars or welded wire reinforcement (WWR). The research also found that because of high tensile stress the strands corrode at a rate beyond that of the conventional reinforcing bars or WWR. In addition, this research also directed attention to areas on a beam’s surface that exhibit discoloration that may indicate the presence of active corrosion, even though reinforcing bars have not been exposed. Once corrosion has initiated within a prestressed strand, the research concluded that the rate of corrosion is sufficient to consider the strand as having lost its ability to carry load.

In recent years, Illinois has revised its condition rating criteria to reflect the significance of corrosion in strands and its effect on the load carrying capacity of this type of beam. When revising the criteria consideration was also given to how rapidly the strands can corrode and the significance of the signs that indicate corrosion is occurring such as spalls, delaminations, corroded shear reinforcement, cracks and rust stains.

Cardboard forms, a past construction practices for internal voids, are susceptible to damage from water entering the voids. Water can enter the voids in the box beams through seepage along the tie rod but is most likely through steam vent holes in the top flange of the box. All box beams should be constructed or remediated with drain holes in the bottom flange of the box. However, the cardboard forms degrade and can clog the bottom flange drain holes and bridge inspectors, or subsequently directed maintenance personnel, must take the time and effort to unclog these holes to prevent the voids from filling with water.

Figure 5 - Cross Sectional Slice of Test Beam[1]

Longitudinal cracks in the bottom flange are an indication of active corrosion. Corrosion has initiated in the bottom layer strand directly above the crack, but may also be occurring in the adjacent strands and the top layer strand. Transverse reinforcement, stirrup, provide a corrosion path to adjacent strands (Figure 6).

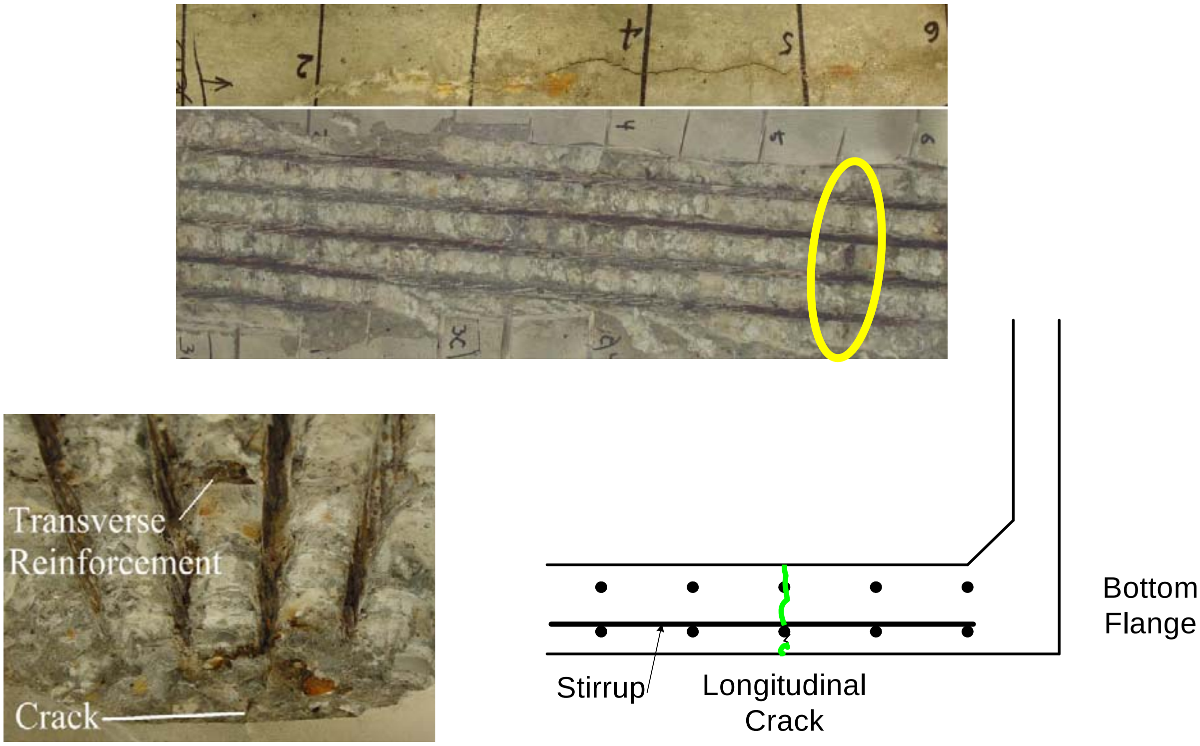


Figure 6 - Strand Corrosion[2]

Microscopic examination of prestressing wires reveals the difference between a corrosion related failure versus a tension related failure as shown in Figure 7. Wires and strands that fail due to corrosion have minimal structural capacity and ductility. Corroded strands do not have the ductility to offer advanced indication of pending failure.

Figure 7 - Prestressing Wires Corrosion Failure (left) and Tension Failure (right)

As the inventory of 1st generation bridges shows signs of deterioration, it is imperative to accurately and completely document the condition. Figure 8 is a schematic of potential deterioration and necessary information to document condition.

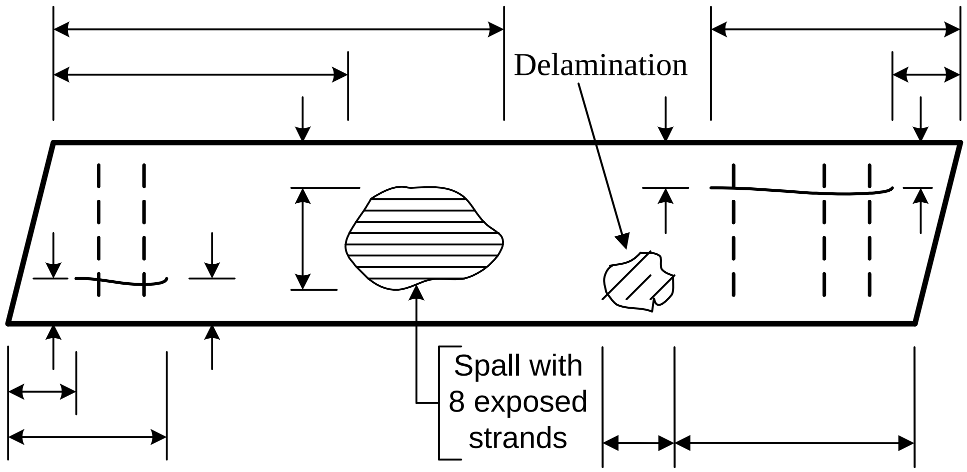
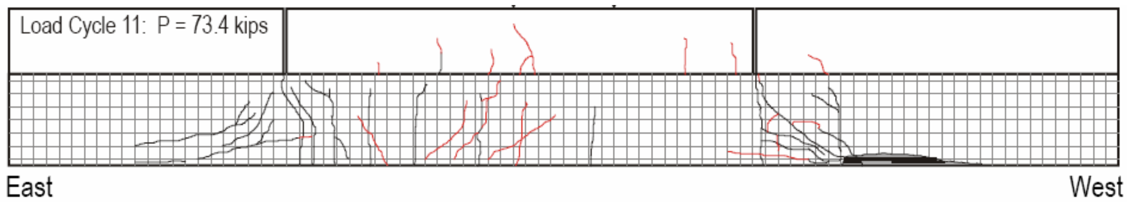


Figure 8 – Proper Inspection Documentation
(View of Bottom Flange of Box Beam)

Bridge inspectors must be aware of and understand the significance of shear cracking below open deflection joints in barriers. From load testing of a decommissioned fascia beam, essentially at ultimate beam capacity, Figure 9 illustrates the observed cracking. Although the concrete barrier is not considered to act compositely with the fascia girder, it behaves compositely. At the open deflection joint, a change in stiffness occurs resulting in stress concentration. If this cracking is observed for an in-service bridge, the Engineer should be notified immediately as the loads on the beam may be approaching the ultimate capacity of the beam.



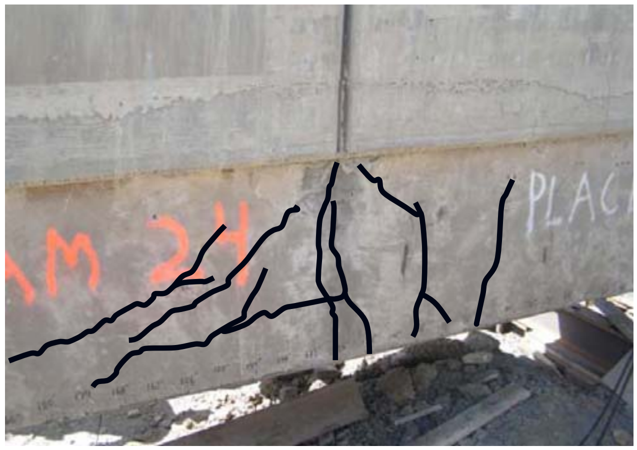


Figure 9 - Shear Flexure Cracking at Barrier Open Deflection Joint[1]

To summarize, key inspection requirements are to:

- Document exposed strands
- Document cracking patterns
- Document areas of spalled concrete
- Identify areas of delaminated concrete by sounding the entire underside of the beams and document those areas. (Note It is Illinois' current practice to remove all delaminated concrete. This practice is intended to minimize trapped moisture from accelerating the deterioration and to have visual reference of limits of the deterioration for future inspections.)
- Document visible rust stains
- Define Strand corrosion
- Measure Camber
- Investigate independent beam action
- Evaluate barrier and barrier connection
- Clear clogged drain holes in beam void (this may be accomplished by maintenance personnel after the bridge inspection)
- Evidence of tie rod failure
- Examination of wearing course for longitudinal cracking

LOAD RATING

The load rating analysis of bridges is to be conducted in accordance with the AASHTO Manual for Bridge Condition and Evaluation. As with any analysis, assumptions are necessary for load effects (dead loads and live load) and resistance capacity of the member.

- Dead Load - States have differing assumptions of the barrier dead load sharing as presented in Table 2
- Live Load - as a rule of thumb, the live load axle distribution factor for this bridge type is approximately 0.28 +/- 10%.
- Resistance Capacity - the most important parameter is the prestressing strand area

To determine the flexural resistance, the ultimate capacity is a function of the concrete strength, ultimate strength of the prestressing strand and the remaining cross sectional area of prestressing strands. Through bridge safety inspections, the documented strand corrosion must be accounted for in the load rating analysis. As depicted in Figure 10, the reduction in the ultimate moment capacity is directly related to the number of prestressing strands lost. At some point the loss of prestressing strands reduces the beam capacity to a level that the dead loads acting on the beam will cause failure. The analysis should account for un-observable strand corrosion by assuming more strands are corroded than documented by inspections. A sensitivity analysis should be performed similar to the analyses conducted to develop Figure 10 to determine the proximity to a point where the loads exceed the beam capacity based on failed/corroded prestressing strands. A reasonable boundary is to assume 25 percent more strands are corroded than documented, i.e., if the inspection documents 8 strands are exposed, perform the analysis assuming 10 strands are corroded.

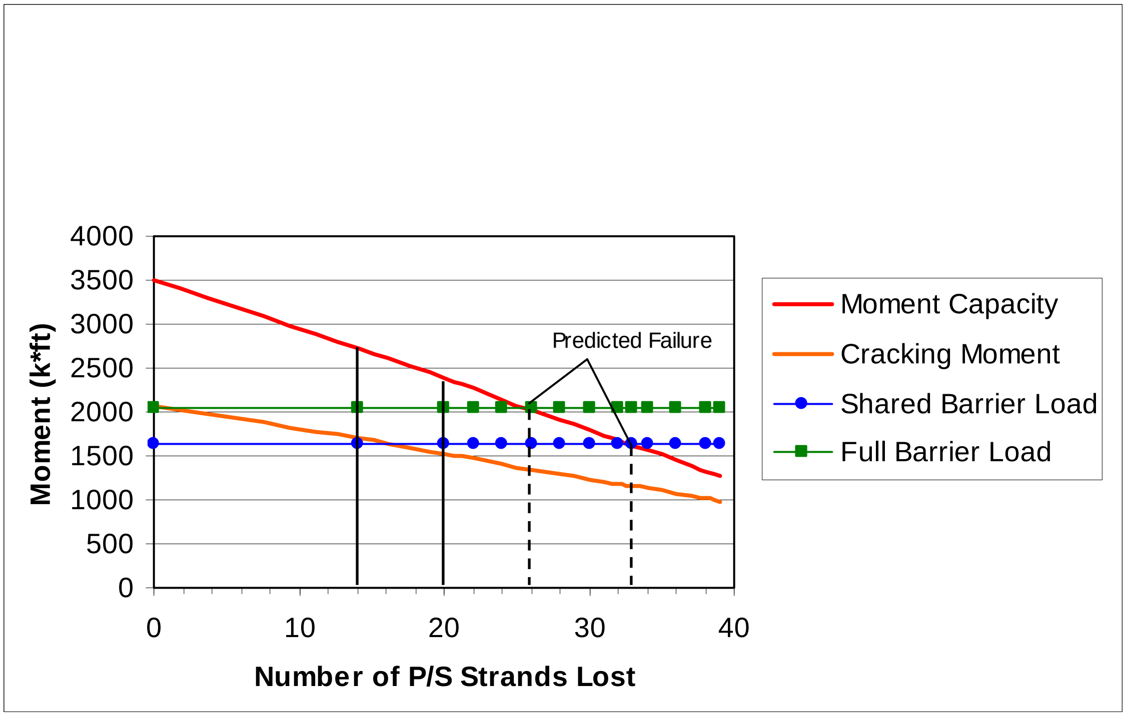


Figure 10 - Strand loss vs. Ultimate Moment Capacity Curve

Selection of a development length for exposed/corroded strand is a matter of engineering judgment. Adequate research has not been conducted to codify the redevelopment of exposed/corroded strands. The general analysis assumption is to totally deduct the exposed strand for the entire beam length when determining flexural capacities. An example of applying engineering judgment is a beam with exposed and corroded strands near the abutment, the prestressing strands could be assumed to be redeveloped in determining midspan flexural capacity.

In addition to revision of condition rating criteria, Illinois has recently adopted new guidelines, which are more conservative than those used in the past, for determining which prestressing strands are considered ineffective for load rating purposes. The guidelines are based on the University of Illinois research[3].

The bridge rater should use caution when analyzing fascia girders. Generally, due to the width of the barrier, little live load is carried by the fascia girder. Fascias with several strands lost may still exhibit adequate Inventory and Operating Ratings because live load is small compared to dead load. Pennsylvania's practice is to ensure the ultimate capacity of a fascia girder is 50% larger than the dead load demand; otherwise the fascia beam is more closely monitored.

MAINTENANCE

As discussed previously, the shallow structural depth is one advantage of this superstructure. The use as overpass structures, results in a risk of the bridge beams to be struck by overheight vehicles (Figure 11). Typical damage is loss of cover, exposure of prestressing strands leading to corrosion of the prestressing strands. The exposure and corrosion do not instantaneously result in loss of prestressing strand cross section area, but it will eventually occur. The current repair techniques for exposed strands do not provide a long term solution. Thin mortar repairs have been found to be ineffective and it is thought they may actually be detrimental by trapping moisture and thus accelerating the deterioration. Additionally, once the exposed strands are covered, visual inspection cannot detect the ongoing corrosion. However, the precast/prestressed industry is working on development of low cost microdevices that can be installed prior to the repair that will provide inspectors data on unobservable corrosion. Also, sacrificial anodes can be attached and embedded in concrete patching layers.

Figure 11 - Typical Impact Damage

There is limited maintenance activities associated with this bridge type. During removal and replacement of the asphalt wearing surface, a waterproofing membrane is installed before the new wearing surface. Another activity to improve the long term performance of the bridge is to close the open deflection joint in the barrier. This is accomplished by removing sufficient length of barrier on either side of the joint to develop the splice of the longitudinal barrier steel.

Asphalt wearing surfaces have been removed from many bridges of this type in Illinois and replaced with thicker reinforced concrete wearing surfaces. This is believed to be effective in prolonging the life of the beams if they are in good condition and have not experienced salt exposure from leaking keyways. Current practice in Illinois is for reinforced concrete overlays to be placed on new superstructures utilizing this type of beam at the time of initial construction.

SUMMARY

Since the first generation noncomposite adjacent prestressed concrete box beam bridges constructed during the Interstate building era, vast improvements occurred in the design and fabrication practices such as higher strength mild and prestressing steel, higher quality concrete with lower permeability and more accurate capacity predictions. These first generation bridges must be effectively managed with proper inspection, load rating and maintenance accounting for deficiencies in past design and fabrication practices. Through in-service bridge safety inspections thorough and complete condition of the beams must be documented especially exposed prestressing strands and shear cracking near open deflection joints in barriers. The load rating analysis must account for the exposed strands but also some additional strand loss that is not observable as seven states have reported failures of this beam type. Some effective maintenance practices are presented such as installing asphalt wearing surfaces with waterproofing membranes or concrete overlays. The experience of designing, constructing and managing this bridge type are presented for Pennsylvania and Illinois. Many practices of Pennsylvania and Illinois are consistent, however the differences are described.

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