EVOLUTION AND PERFORMANCE OF BOX BEAM BRIDGES IN INDIANA

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ABSTRACT

Adjacent prestressed concrete box beam bridges are known to exhibit common deterioration patterns and often experience significant distress prior to reaching their expected service lives. Cracking between the joints of adjacent members have been observed at early ages. Chloride-laden water enters into the cracks and travels through the depth of the joints, causing the initiation and acceleration of corrosion. A database investigation of over 4,000 bridges was conducted to relate the details of box beam bridges implemented in Indiana over the past several decades to the observed performance of the bridges. Specific details of box beam bridges were compared to condition ratings to identify trends that may relate design and construction practices to poor performance. In-depth inspections of six bridges exhibiting deterioration were also conducted by the research team to supplement the database investigation. The results of the study reveal trends in the levels of deterioration that correspond to some details, such as the type of wearing surface and bridge location, and help identify details or scenarios that may promote corrosion. The findings provide a basis for decision-making related to the construction of new box beam bridges, the inspection of current bridges, and measures that could potentially slow deterioration.

Keywords: Box Beam, Shear Key, Deterioration, Bridge Inspection, Condition Rating, Prestressed Concrete

INTRODUCTION

Adjacent box beam bridges account for approximately 4,000 of the 15,860 bridges in Indiana. This equates to over a quarter of the bridges in the state. Adjacent box beams are ideal for bridges requiring a shallow superstructure and/or rapid construction. They are generally used for short to medium span applications and require minimal formwork compared to other bridge types. A schematic of an adjacent box beam bridge is shown in Figure 1.

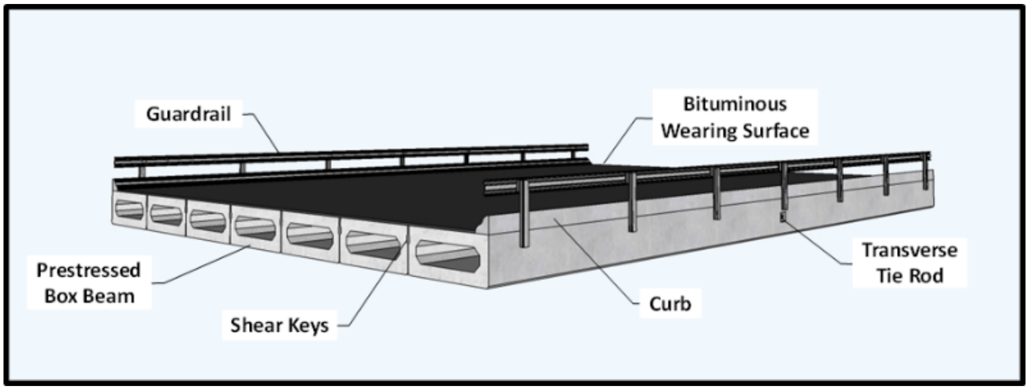
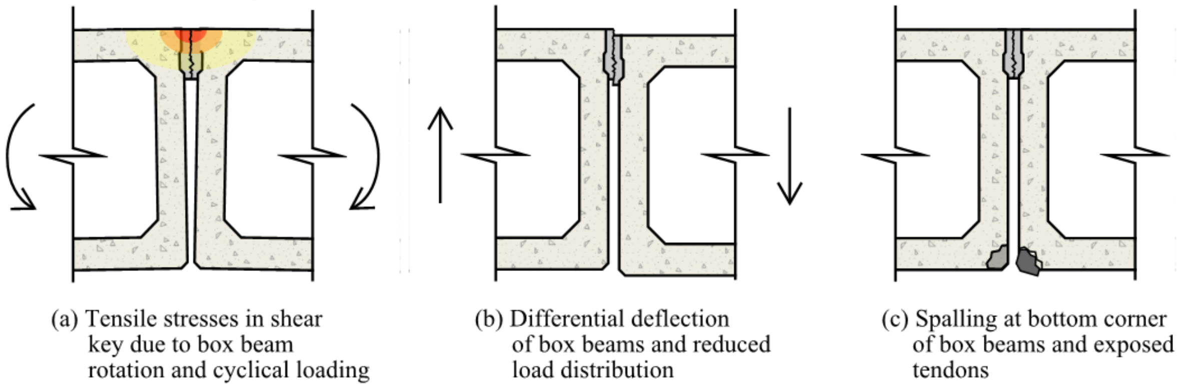


Fig. 1 Typical Adjacent Box Beam Bridge

Adjacent box beam bridges gained widespread popularity in the late 1950s and early 1960s due to their low cost, aesthetic design, and accelerated construction. Beams are placed alongside each other to align shear key cutouts that have been traditionally filled with nonshrink grout. Shear keys, or keyways, located in the top flange extend longitudinally over the length of the box beams. Transverse steel tie rods are often installed to improve the composite behavior of the bridge assembly. The tie rods may be post-tensioned to induce compression across the joints between adjacent beams. A box beam superstructure can be erected in as little as three days, which typically involves placing the precast beams, connecting the beams with grout and transverse ties, and adding a wearing surface.[1]

Most of the adjacent box beam bridges in Indiana (an estimated 52% of the box beam bridges currently in service) were built in the 1970s and 1980s. Box beam standards of the Indiana Department of Transportation (INDOT) include beams that range from 12 in. to 42 in. in depth. The span lengths of approximately 90% of box beam bridges in Indiana are less than 60 ft. The number of beams needed for a bridge depends on the width of each box beam and the desired width of the overall bridge. In Indiana, overall bridge widths are generally under 40 ft. For some bridges, a combination of box beams that are between 3 ft and 4 ft wide are used to meet the desired width of the bridge, but a bridge is typically constructed with box beams of the same width.

As early as the 1970s, adjacent box beam bridges in Indiana began to display signs of deterioration such as cracking, spalling, and corrosion of the prestressing strands. Cracked shear keys in combination with reflective cracking in the wearing surface can lead to puddling of chloride-laden water on the top of the superstructure and in the shear keys.[2] With exposure to cyclical loading, deicing salts, or environmental factors such as freeze-thaw cycles, longitudinal cracking can propagate down the key (Figure 2(a)). In turn, deteriorated shear keys can impact the load distribution between adjacent beams (Figure 2(b)). Moreover, a completely fractured key allows salt water to ingress through the joint and curl onto the underside of the box beams. This phenomenon promotes corrosion of the prestressing strands and spalling at the bottom corners of the members (Figure 2(c)).


(a) Tensile stresses in shear key due to box beam rotation and cyclical loading

(b) Differential deflection of box beams and reduced load distribution

(c) Spalling at bottom corner of box beams and exposed tendons

Fig. 2 Deterioration Mechanisms of Adjacent Box Beams

Field inspectors can visually identify a cracked shear key based on evidence of significant water leakage and differential deflection between adjacent beams. As deteriorated shear keys became a reoccurring pattern, the construction of adjacent box beam bridges was slowed. In fact, INDOT reduced construction of box beam bridges by approximately 85% in the 1980s, and the current INDOT bridge design manual only allows new adjacent box beams to be used as temporary bridges in the state system.[3]

Despite efforts to repair adjacent box beam bridges, there have been a number of documented collapses in the last few decades. In 1998, an exterior beam collapsed in Illinois.[4] Similarly, on December 27, 2005, an exterior beam of an adjacent box beam bridge collapsed under dead load in Pennsylvania.[5] A survey conducted by PennDOT determined that these failures are not isolated to the Midwest. States such as Colorado, Florida, Illinois, Indiana, Ohio, Pennsylvania, and Virginia have all reported failures of box beam bridges.[6]

Because these bridges have a history of poor performance, premature distress, and failures, identifying specific design or construction practices that exacerbate box beam deterioration is of interest. Box beam bridges constructed in Indiana over the years incorporated different details based on the box beam standards in effect at the time of construction, making it unclear whether distress is related to design practices of a certain time period. Therefore, a study was conducted to document the historical evolution of adjacent box beam design standards in Indiana. The current inventory of adjacent box beams in Indiana was evaluated, and bridge characteristics affecting long-term performance were identified. To provide a close-up perspective of typical deterioration observed in Indiana, individual bridges were inspected, and performance issues were identified. The complete historical investigation of adjacent box beam bridges in Indiana and details of the box beam inspections that are summarized in this paper are provided in Molley.[7]

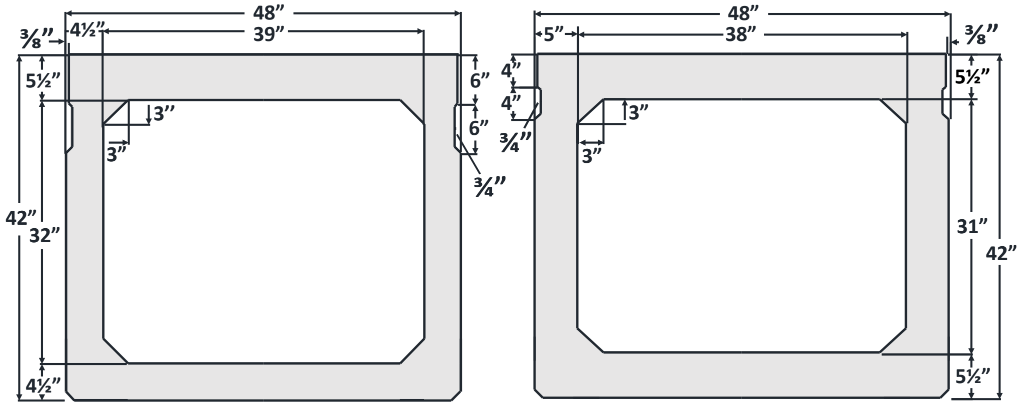
The following sections will summarize the findings from the historical investigation of adjacent box beam bridges in Indiana.

BOX BEAM HISTORY IN INDIANA

In 1961, INDOT published the first set of standard drawings for prestressed, precast concrete box beams. The standard drawings included beam cross-sections with six standard depths (12 in., 17 in., 21 in., 27 in., 33 in., and 42 in.) and three standard widths (36 in., 45 in., and 48 in.). The void geometry and steel reinforcement for each standard section was also provided. The number of Grade 250 ⅜-in. diameter prestressing strands for each section was indicated in a design table that accompanied each section and depended on the required span of the bridge.

Between 1961 and 1965, several revisions were made to the standard drawings (refer to Figure 3):

- Standard shear key depth was decreased from 6 in. to 4 in.
- The void size for all sections was reduced.
- Design tables were updated to include ½-in. diameter prestressing strands and Grade 270 prestressing strands.



WS - 42
(1961)

WS - 42
(1965)

Fig. 3 Box Beam Geometry Changes in 1965 Compared to the 1961 Standard

From 1965 to the 1980s, the standard box beam drawings remained fundamentally unchanged. In the 1970s, INDOT bridge inspectors began noticing compressive failure of the top flange caused by moisture between the bituminous wearing surface and the superstructure.[8] In 1979, INDOT instituted a program for a statewide inspection of all adjacent box beam structures located on state highways. Severely deteriorated box beams were replaced, and bridges were resurfaced with a concrete overlay. Despite efforts to repair the bridges with concrete overlays, adjacent box beam bridges continue to display signs of deterioration. After the 1980s, most state-owned box beam bridges were designed on a case-by-case basis with the designs being approved by a licensed state engineer. County bridges, however, were designed using the 1965 INDOT box beam standard drawings through the 1990s.

BOX BEAM INVENTORY IN INDIANA

A review was performed in Molley[7] to highlight design and construction features as well as geographical factors that may correlate to bridge performance in terms of durability. This was accomplished by evaluating the current inventory of adjacent box beams bridges in Indiana and analyzing this inventory for trends in performance.

A full record of all bridges in Indiana is documented in a database and is available through the Bridge Inspection Application Software (BIAS). The database consists of inspection reports and load ratings for each bridge. The software allows users to extract information from current inspection reports and evaluate selected groups of bridges based on various details. This is a very powerful tool which gives the user the ability to analyze all of the bridges in the state in a simple manner.

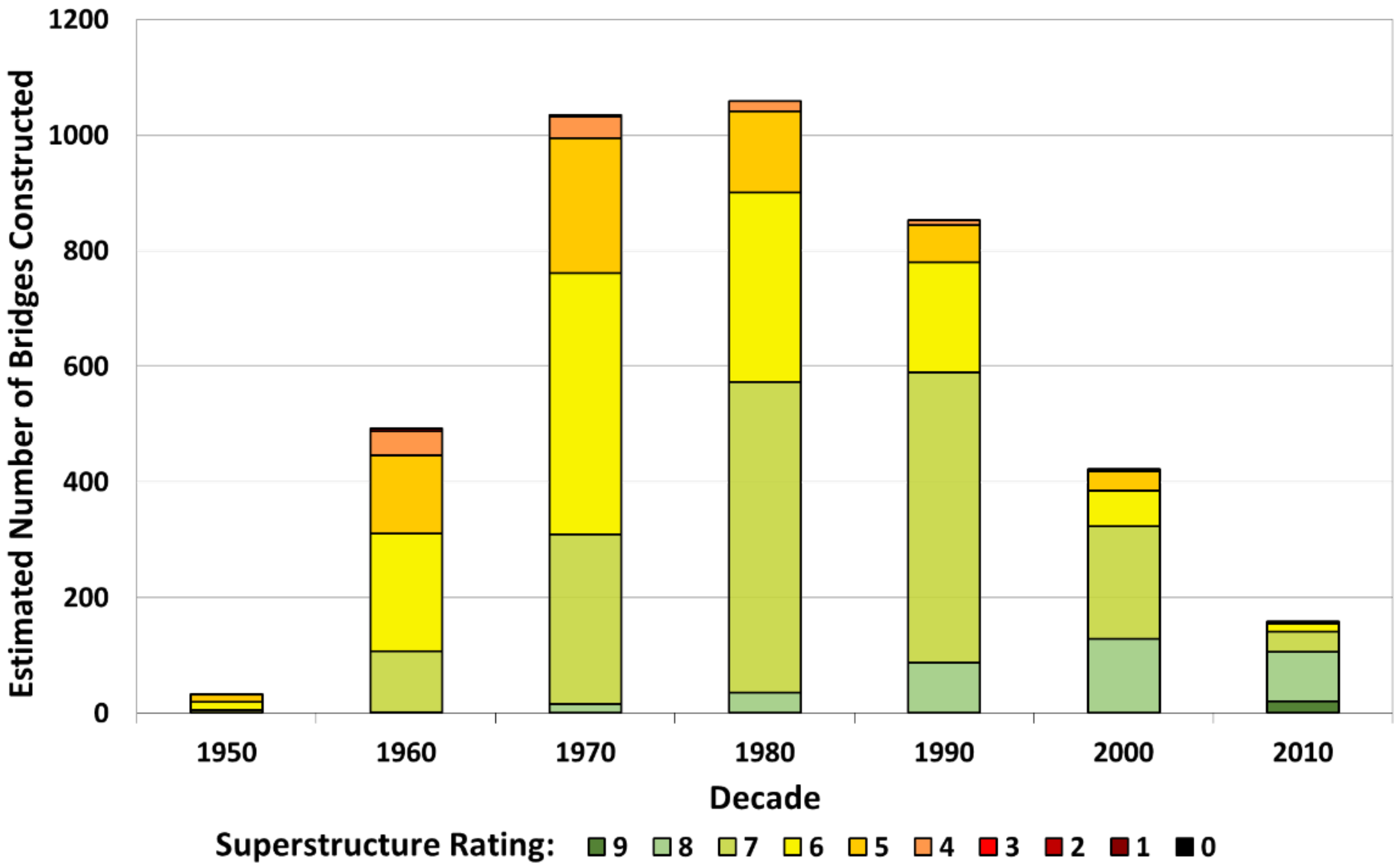
A numerical-based scale established by the Federal Highway Administration's National Bridge Inspection Standards (NBIS) requires bridge inspectors to describe each bridge in an objective manner.[9] This is especially imperative when describing the condition of the bridge elements. For the wearing surface, superstructure, and substructure, condition ratings are based on a 0 to 9 scale, with 9 denoting an excellent condition and 0 denoting a bridge that is out of service.

To investigate specific bridge details and their potential effects on aging and deterioration, 4,054 adjacent box beam bridges, including both state and county bridges accessible through BIAS, were analyzed. Bridge condition ratings were compared to age, location, type of wearing surface, presence and type of membrane, span length, bridge width, and skew.

AGE OF SUPERSTRUCTURE

To evaluate performance over time, the dataset of box beam bridges was sorted by age. Bridges were separated into 10-year increments based upon "year built" dates and "year reconstructed" dates indicated in BIAS. While the "year reconstructed" date may refer to repair work according to the definition presented by the Federal Highway Administration (e.g., deck is repaired while original box beams remain), INDOT generally defines "reconstruction" to mean that an entire bridge (deck, superstructure, and substructure) was removed and replaced with a new bridge.[10] Further, Molley[7] showed that the reconstruction dates of many bridges with prestressed concrete superstructures aligned with the advent of prestressed concrete in Indiana. Because of this, the "year reconstructed" date was found to provide a reasonable estimate of age. If the bridge had a "year reconstructed" date, that date was used instead of the "year built" date for the analysis. Otherwise, the "year built" date was used. This modification of the dates is denoted as the "estimated" year built.

Figure 4 shows the correlation between the estimated year built and the superstructure ratings for all bridges in the state. As expected, the superstructure condition decreases with increased age.



*Most of the state bridges that are indicated as being reconstructed in 1980 were part of an INDOT program for the statewide inspection of box beam bridges. Although some of the deteriorated beams were replaced before resurfacing a bridge during this program, the majority of the superstructure was still from the original "year built." Therefore, the "estimated" year built is taken as the "year built" date instead of the "year reconstructed" date for these bridges.

Fig. 4 Estimated Number of Box Beam Bridges Built Per Decade by Superstructure Rating

The most frequent condition rating, or the rating corresponding to the largest percentage of bridges in each decade, can be determined from Figure 4. For the bridges built in the 1980s, 1990s, and 2000s, the most frequent condition rating is 7. The percentage of bridges with this rating in each decade are 51%, 59%, and 46%, respectively. For older bridges constructed in the 1960s to 1970s, the most frequent condition rating decreases to a value of 6. This rating accounts for 41% of bridges built in the 1960s and for 44% of bridges built in the 1970s. The trend continues for bridges built in the 1950s with the most frequent rating split between 5 and 6 with 39% of bridges corresponding to each rating. Moreover, a significant decrease can be seen in the frequency of ratings with a value of 8 over the past five decades (54% - 2010s, 31% - 2000s, 10% - 1990s, 3% - 1980s, and 1% - 1970s). The decrease of condition rating, in terms of frequency, highlights a lack of durability.

Furthermore, average condition ratings of box beam superstructures decrease with age. Table 1 shows a steady decrease in the average superstructure condition rating per decade between the 1950s and 2010s.

Table 1 Superstructure Condition Based on Estimated Decade Built

Estimated Decade Built	Number of Bridges	Superstructure Condition										
		9	8	7	6	5	4	3	2	1	0	Average Rating
1950	33	0	0	6	13	13	1	0	0	0	0	5.7
1960	492	0	2	105	204	135	41	5	0	0	0	5.8
1970	1035	0	15	294	452	233	38	3	0	0	0	6.0
1980	1059	0	36	537	327	141	18	0	0	0	0	6.4
1990	854	0	87	502	191	64	9	0	0	0	0	6.7
2000	422	0	129	194	62	34	3	0	0	0	0	7.0
2010	158	20	86	35	14	3	0	0	0	0	0	7.7

LOCATION OF BRIDGE

The winter weather conditions of Northern Indiana tend to be more severe than the winter weather in Southern Indiana. The difference in severity has the potential to translate into more salt on the wearing surface of bridges and exposure to more freeze-thaw cycles within a given winter season. Bridge coordinates accessed through the BIAS database were used to map the locations of all the adjacent box beam bridges as shown in Figure 5. Each dot in the figure represents a box beam bridge and is colored based on the logged superstructure condition rating in the most recent inspection report. As indicated in Figure 5, the northern part of Indiana is primarily covered with orange and red dots. Despite a few dark orange and red dots, the majority of the bridges in central Indiana have a condition rating of 5 to 7. The bridges in Southern Indiana are primarily represented by a mix of yellow and light green dots. Because the northern bridges, on average, have lower condition ratings, it appears that the location of box beam bridges plays a role in the extent of deterioration.

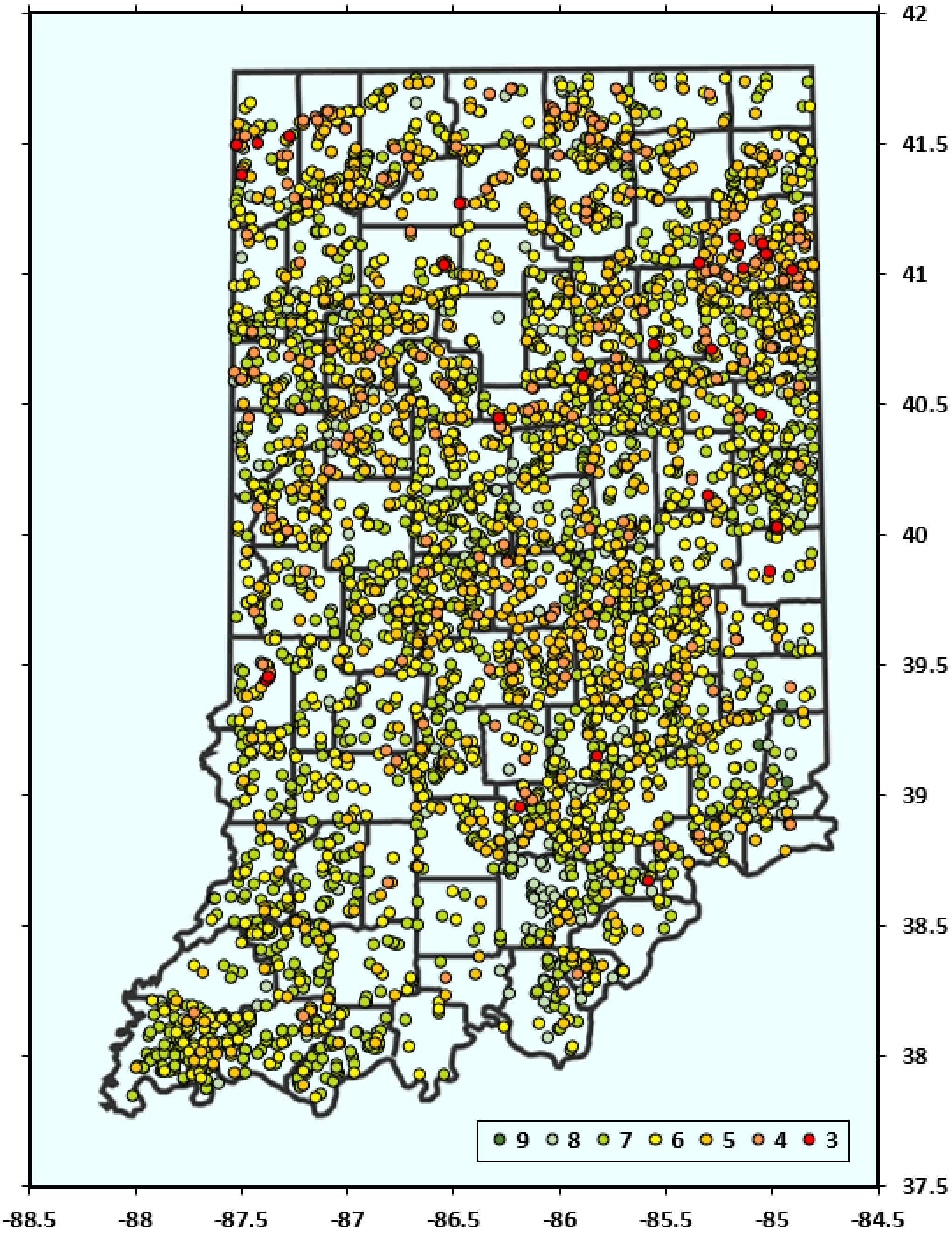


Fig. 5 Mapped Superstructure Condition of All Adjacent Box Beam Bridges[12]

Average superstructure ratings and deterioration rates were also calculated based upon ranges in latitude. Condition rating data for all the box beam bridges in the state are included in Table 2, while only the box beam bridges built in the 1970s are included in Table 3. As shown, the average rating tends to increase from North to South. The central portions of the state (North-Central to South-Central) have very similar average ratings, but there is a notable difference in the condition ratings of bridges in the North and South regions.

Table 2 Superstructure Condition Based on Regions of Indiana, All Box Beam Bridges

Region	**Latitude Range**	**Number**	**Superstructure Condition**										
			9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**	**Average Rating**
North	41.75°* - 40.97°	767	2	40	229	256	186	50	4	0	0	0	6.0
North-Central	40.97° - 40.19°	1173	7	117	462	377	181	26	3	0	0	0	6.4
Central	40.19° - 39.41°	857	2	55	362	297	116	25	0	0	0	0	6.4
South-Central	39.41° - 38.62°	756	5	85	335	231	93	6	1	0	0	0	6.5
South	38.62° - 37.84°**	498	4	58	286	101	45	3	0	0	0	0	6.7

Table 3 Superstructure Condition Based on Regions of Indiana, Box Beam Bridges Built in the 1970s

Region	**Latitude Range**	**Number**	**Superstructure Condition**											**Average Age**	**Deterioration Rate *****
			9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**	**Average Rating**		
North	41.75°* - 40.97°	256	0	1	44	113	78	18	2	0	0	0	5.7	44	0.067
North-Central	40.97° - 40.19°	263	0	6	77	118	56	5	1	0	0	0	6.1	45	0.060
Central	40.19° - 39.41°	236	0	2	64	110	49	11	0	0	0	0	6.0	44	0.061
South-Central	39.41° - 38.62°	165	0	0	50	79	33	3	0	0	0	0	6.1	44	0.060
South	38.62° - 37.84°**	115	0	6	59	32	17	1	0	0	0	0	6.5	44	0.052

* Northernmost adjacent box beam bridge in Indiana

** Southernmost adjacent box beam bridge in Indiana

*** Deterioration rate is the average decrease in superstructure rating divided by the average age (average age equals present year, 2019, minus average estimated year built)

TYPE OF WEARING SURFACE

Each type of wearing surface is listed with the corresponding average condition rating of the bridge superstructures in Table 4. Of the 4,054 adjacent box beam bridges in Indiana, 2,640 of those bridges have a bituminous wearing surface. This accounts for more than 65% of the bridges. The superstructures of box beam bridges with a bituminous wearing surface have an average rating of 6.3. The bituminous surface provides a similar average rating compared to bridges without an overlay (gravel and none). The concrete decks (monolithic, integral, and epoxy), however, correspond to an average superstructure rating of 6.7. It is important to note, however, that the bridges with a latex concrete (or similar) wearing surface have the lowest average superstructure rating of 5.9. Even though bridges with a concrete wearing surface deteriorate over time, the average superstructure rating is higher compared to bridges with a bituminous wearing surface. In general, it appears that the concrete deck provides improved performance and durability for the superstructure.

Table 4 Superstructure Rating Based on Wearing Surface

Wearing Surface	Number	Superstructure Condition										
		9	8	7	6	5	4	3	2	1	0	Average Rating
Monolithic Concrete	970	12	209	413	182	128	24	2	0	0	0	6.7
Integral Concrete	91	2	10	46	27	4	2	0	0	0	0	6.7
Latex Concrete or Similar Additive	86	0	5	21	30	21	7	1	0	0	0	5.9
Low Slump Concrete	0	0	0	0	0	0	0	0	0	0	0	0.0
Epoxy Overlay	3	0	0	2	1	0	0	0	0	0	0	6.7
Bituminous	2640	6	119	1070	925	442	74	4	0	0	0	6.3
Wood or Timber	0	0	0	0	0	0	0	0	0	0	0	0.0
Gravel	67	0	4	32	27	3	0	1	0	0	0	6.5
Other	0	0	0	0	0	0	0	0	0	0	0	0.0
None	167	0	8	64	67	25	3	0	0	0	0	6.3
N/A (Unknown)	30	0	0	26	4	0	0	0	0	0	0	6.9

To further evaluate if the wearing surface has an influence on overall deterioration, the rating of the superstructure was plotted with respect to the rating of the wearing surface in Figure 6. The number of bridges with each wearing surface condition rating is noted. In general, the condition of the wearing surface has a direct correlation to the condition of the superstructure. Figure 6 shows an approximately linear decline in the average superstructure rating as the wearing surface rating declines. The increase in the average superstructure rating as the wearing surface rating decreases from 4 to 3 is explained by the small sample size (two bridges) that have a wearing surface rating of 3. From the data presented in Figure 6, it can be reasonably concluded that the condition of the wearing surface impacts the condition of the superstructure.

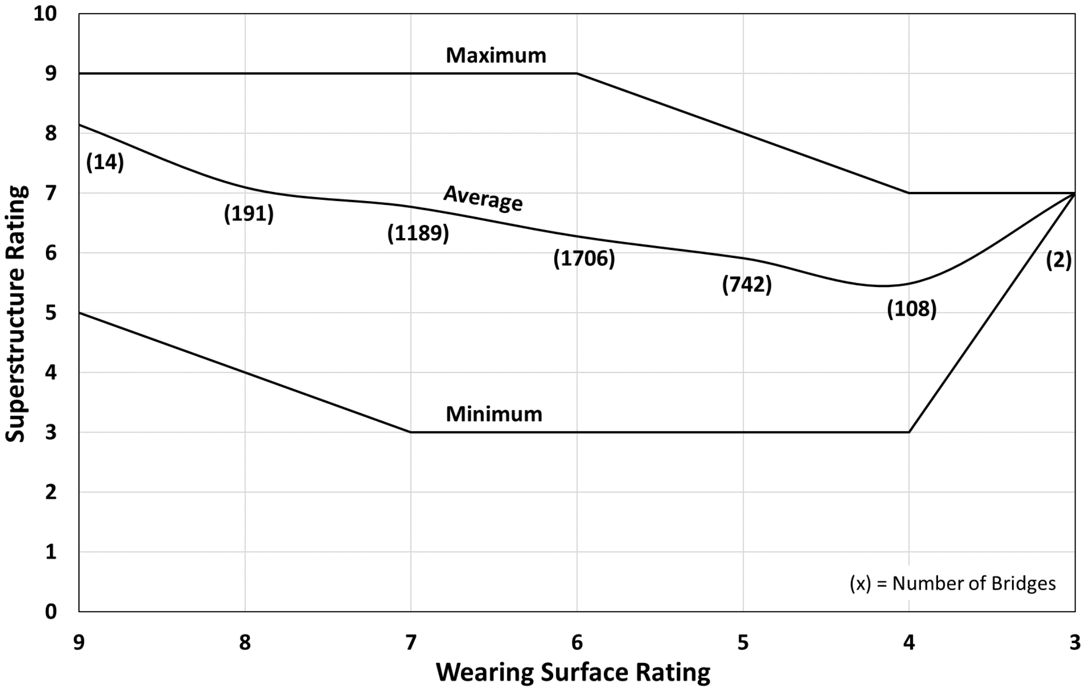


Fig. 6 Correlation of Superstructure Rating and Wearing Surface Rating

MEMBRANE

The average superstructure rating was calculated based on each type of membrane (Table 5). Bridges that have some type of membrane (built-up, preformed fabric, or epoxy) are performing better on average than bridges that do not have membranes (none). Although the sample size for built-up and epoxy membranes is small, the average rating for preformed fabric membranes (6.6) is higher than those bridges with no membrane (6.3). Therefore, the presence of a membrane appears to decrease deterioration of adjacent box beam bridges in Indiana.

Table 5 Superstructure Rating Based on Membrane

Membrane	**Number**	**Superstructure Condition**										
		9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**	**Average Rating**
Built-up	2	0	0	2	0	0	0	0	0	0	0	7.0
Preformed Fabric	253	3	42	107	69	23	9	0	0	0	0	6.6
Epoxy	3	0	1	0	2	0	0	0	0	0	0	6.7
Unknown	122	0	15	61	34	10	2	0	0	0	0	6.6
Other	10	0	0	5	3	2	0	0	0	0	0	6.3
None	3416	16	252	1389	1105	552	95	6	0	0	0	6.3
N/A	248	1	45	110	50	36	4	2	0	0	0	6.6

SPAN LENGTH, BRIDGE WIDTH, AND SKEW

To determine if bridge geometry plays a role in the deterioration of adjacent box beam bridges, the database was sorted based on span length, bridge width, and skew as presented in Tables 6 through 8. Approximately 90% (3,655) of the adjacent box beam bridges in Indiana have a maximum span length between 20 ft and 60 ft. Box beam bridges in Indiana are typically constructed with widths ranging from 21 ft to 40 ft. A majority of the bridges, 59%, do not have any skew angle (0˚). If a bridge has a skew angle, it is generally less than 30 degrees.

Table 6 Number of Bridges Based on Maximum Span Length

Max. Span Length (ft)	Number
0-19.9	10
20-39.9	2,096
40-59.9	1,559
60-79.9	347
80-99.9	38
Over 100	4

Table 7 Number of Bridges Based on Width

Bridge Width (ft)	Number
0-10	0
11-20	65
21-30	3,338
31-40	527
41-50	76
51-60	18
61-70	15
71-80	8
81-90	5
Over 90	2

Table 8 Number of Bridges Based on Skew

Skew (˚)	Number
0	2,381
1-10	196
11-20	460
21-30	577
31-40	221
41-50	198
51-60	21

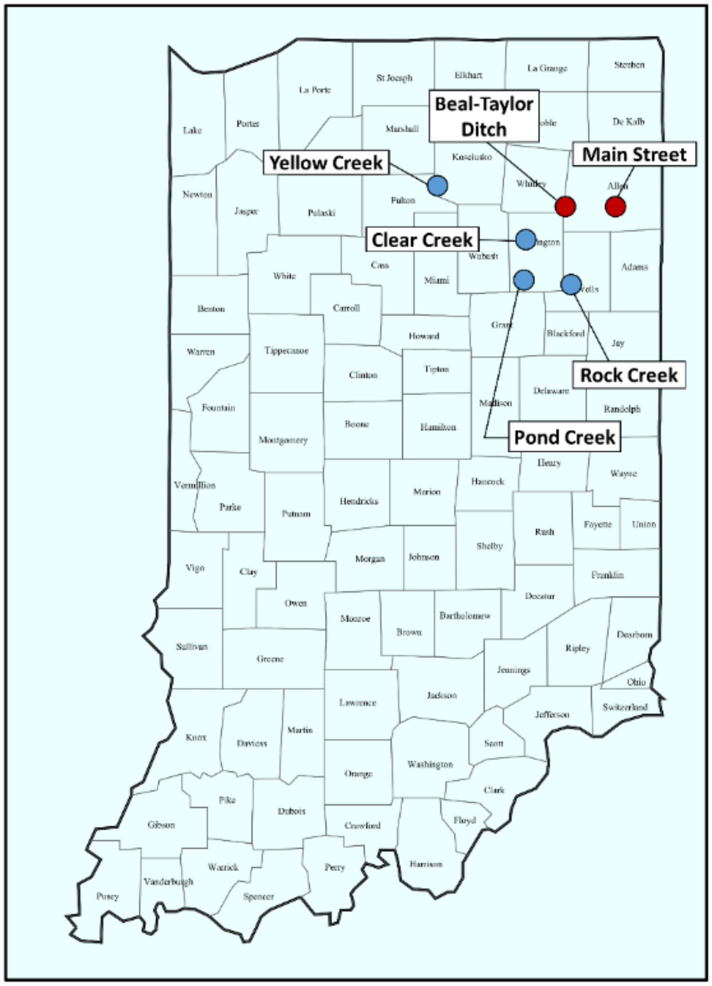
Average superstructure ratings were calculated for each of the aforementioned bridge characteristics. No correlations were found when comparing the span lengths to average superstructure ratings. In addition, no correlations were found between superstructure rating and bridge width or skew angle.

FIELD OBSERVATIONS

While review of the entire state database of adjacent box beam bridges provides a high-level perspective of the extent of deterioration, it does not provide a detailed view of the specific problems being experienced by the bridge type. Therefore, a total of six bridges were identified for inspection to enable a close-up perspective of damage and to assist in identifying common patterns and features of deterioration. Bridge selection was based upon the location analysis presented in Figure 5, and the focus was on areas with increased levels of deterioration within the state. A list of bridges that were inspected is provided in Table 9. The approximate location of each bridge is shown in Figure 7.

Table 9 Bridges Inspected

Bridge Name	Structure Number	Jurisdiction	Max Span, S (ft)	Depth, D (in.)	S/D
Pond Creek	35-00013	County	34.6	21	20
Rock Creek	90-00079	County	36	17	25
Clear Creek	005-35-05912 B	State	70	42	20
Yellow Creek	019-43-06147 B	State	38	21	22
Beal-Taylor Ditch	02-00221	County	34.6	21	20
Main Street	02-00601	County	36	17	25


Beal-Taylor Ditch
Main Street
Yellow Creek
Clear Creek
Rock Creek
Pond Creek
Lake
Porter
La Porte
St Joseph
Elkhart
La Grange
Steuben
Marshall
De Kalb
Kosciusko
Whitley
Allen
Newton
Jasper
Pulaski
Fulton
Wabash
Cass
Miami
White
Adams
Benton
Carroll
Blackford
Jay
Warren
Tippecanoe
Howard
Clinton
Tipton
Delaware
Randolph
Fountain
Montgomery
Boone
Hamilton
Madison
Henry
Wayne
Vermillion
Parke
Putnam
Hendricks
Marion
Hancock
Rush
Fayette
Union
Shelby
Vigo
Clay
Morgan
Johnson
Franklin
Owen
Decatur
Monroe
Brown
Bartholomew
Dearborn
Sullivan
Greene
Ripley
Jennings
Ohio
Lawrence
Jackson
Switzerland
Jefferson
Knox
Daviess
Martin
Scott
Orange
Washington
Clark
Pike
Dubois
Floyd
Gibson
Crawford
Harrison
Warrick
Perry
Posey
Vanderburgh
Spencer

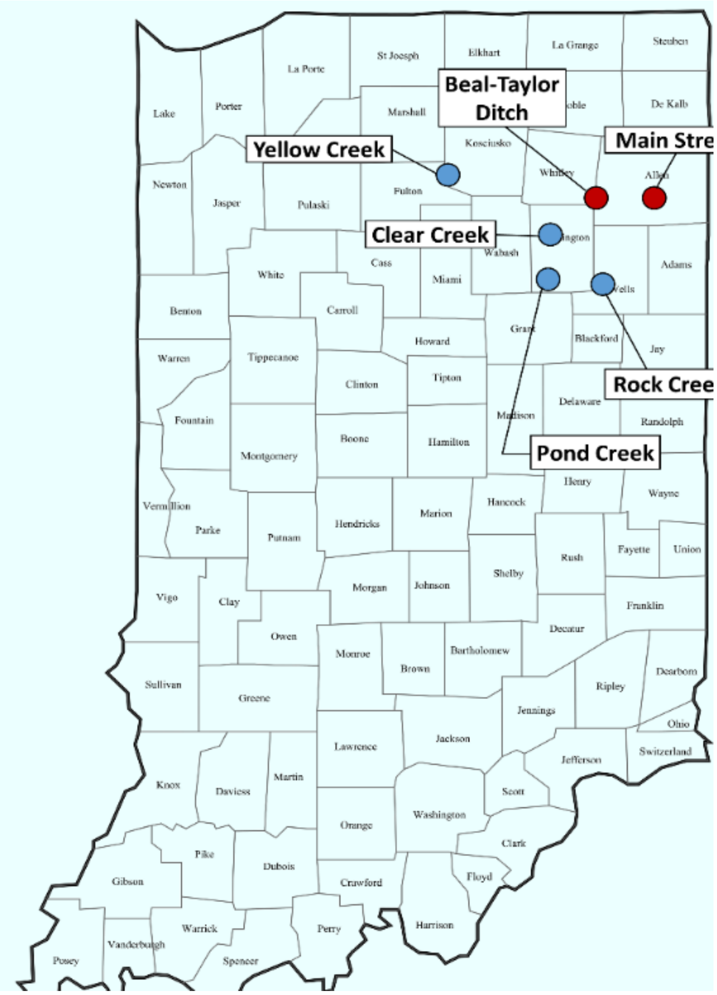


Fig. 7 Locations of Bridges Inspected[12]

During the field observations, signs of deterioration were documented. Each instance of deterioration (cracking, spalling, exposed reinforcement, etc.) was noted to create deterioration maps that display the type and location of damage for each bridge superstructure. The maps were then used to draw correlations between deterioration type and location on the superstructure. The deterioration maps for all six bridges are presented in Molley.[7]

In reviewing all of the deterioration maps, common locations of damage were identified. It was observed that the exterior beam and the exterior longitudinal joint are most susceptible to deterioration. The beams and longitudinal joints under wheel loads also tend to have more deterioration compared to other beams and joints. Additionally, spalling and corrosion tend to be located at the bottom edge of the box beams near leaking longitudinal joints.

Common deficiencies were also noted based on the review of the deterioration maps. The most common deficiencies were classified as follows:

- Leaking shear key joints

- Spalling at longitudinal joints
- Longitudinal cracking in bottom flange
- Corrosion of reinforcement
- Clogged drain holes
- Rotation and deterioration of exterior beams
- Top flange deterioration

The following sections discuss the most common deficiencies noted during the field inspections.

LEAKING SHEAR KEY JOINTS

A combination of fractured shear keys and reflective cracking in the wearing surface leads to water seepage through the joints. Water staining on the bottom side of box beams near longitudinal joints was frequently observed. The Pond Creek bridge exhibited water staining and efflorescence at the exterior longitudinal joint. The staining revealed that the water was seeping through the joint and curling onto the bottom side of the first interior beam (Figure 8(a)). The Main Street bridge also had efflorescence and rust staining near the longitudinal joint (Figure 8(b)). In both cases, staining occurred between the exterior and first interior beams. This leakage may be an indication that the exterior shear keys are not performing as well as the interior shear keys. Rotation of the exterior beam may be a contributing factor.

(a) Pond Creek (b) Main Street

Fig. 8 Water Staining at the Exterior Longitudinal Joint

SPALLING AT LONGITUDINAL JOINTS

As chloride-laden water penetrates through the shear key and curls onto the underside of a box beam, the concrete and prestressing strands are susceptible to deterioration. Corroded prestressing strands accompanied by spalled concrete along the bottom corners of the beams are a common deficiency. For example, the Yellow Creek bridge had a small region of spalled concrete in the bottom corner of an interior box beam. The spalling was located at midspan. Exposed strands, however, were not observed. The Clear Creek bridge had a larger region of spalled concrete that occurred on both sides of a longitudinal joint. The spalled concrete exposed prestressing strands in the bottom corners of each box beam near the joint (Figure 9).

Fig. 9 Spalling Near Longitudinal Joint (Clear Creek)

LONGITUDINAL CRACKING IN BOTTOM FLANGE

Longitudinal cracking was found on the bottom flanges of several adjacent box beams. Considering the bridges that were inspected, cracking usually occurred near midspan and was generally observed in the exterior or first interior beams. The three-span Rock Creek bridge had two locations of longitudinal cracking. One was on the first interior box beam of the middle span. Rather than being in the center of the flange, the longitudinal crack was closer to the joint with the exterior beam. This crack may be indicative of corrosion of the prestressing strand in the bottom corner of the beam. Longitudinal cracking was also observed on an exterior beam in one of the end spans of the Yellow Creek bridge. This crack was closer to the center of the bottom flange; however, the crack propagated toward the shear key as it extended toward the abutment (Figure 10). A large region of spalling was observed in the center of the crack and exposed three prestressing strands. A group of clogged drain holes was noted near the damaged location. Deterioration may have initiated due to standing water in the void, causing corrosion of the prestressing strands, ultimately resulting in cracking and spalling.

Fig. 10. Spalling and Exposed Strands (Yellow Creek)

CORROSION OF REINFORCEMENT

Corrosion of the reinforcement, both prestressing strands and stirrups, was frequently observed during the inspections. The worst case of corrosion was observed on the Main Street bridge as shown in Figure 11. Spalling of concrete exposed a large number of stirrups and prestressing strands. In one span, prestressing strands had fractured and debonded from the concrete, leaving them hanging from the underside of the beams (Figure 11).

Fig. 11. Fractured Prestressing Strands and Corroding Shear Reinforcement (Main Street)

CLOGGED DRAIN HOLES

Internal cardboard forms were used in the fabrication of older box beams in Indiana. Because cardboard is susceptible to degradation upon contact with moisture, remnants of the cardboard can build-up around drain holes and prevent drainage. Therefore, standing water can accumulate in the box beams and accelerate deterioration. Furthermore, this added dead load reduces the live-load carrying capacity of the bridge. In many cases, staining and efflorescence were observed around the perimeter of drain holes. As an example, brown-colored staining was observed around the drain holes of the Pond Creek bridge (Figure 12(a)). In contrast, the staining around the drain holes on the Main Street bridge was black in color (Figure 12(b)). For a number of the bridges, it was clear that water was being retained in the voids due to the clogged drain holes. In many cases, the clogged drain holes allow slow release of water while the drainage capacity of others is questionable.

(a) Pond Creek (b) Main Street

Fig. 12 Staining and Residue Around Drain Holes

ROTATION AND DETERIORATION OF EXTERIOR BEAMS

The presence of the curb, railing, and/or barrier on an exterior beam may lead to rotation of the member, especially if the transverse tie rods have failed or no continuity is provided by the wearing surface across longitudinal joints between beams. The rotation of the exterior beam may cause tension in the top region of the shear key, which may be the reason why the joint between the exterior and first interior beam is frequently observed to be leaking (Figure 8).

Rotation of the exterior beam was observed at the Clear Creek bridge. The exterior beam on the west side appeared to have rotated away from the bridge (Figure 13). In this case, there was no staining at the bottom of the joint, and both the exterior beam and the first interior beam appeared to be in good condition. For this bridge, it is believed that the differential rotation may have been caused by improper seating on the bearing pads. Referencing previous inspection reports, this rotation appears to have been in place since the reconstruction in 1980.

Fig. 13 Rotation of Exterior Beam (Clear Creek)

TOP FLANGE DETERIORATION

For the Rock Creek bridge, deterioration in the form of a hole in the top flange of an exterior beam was discovered. The deterioration was so significant that the void of the box beam could be observed. Standing water, spalled concrete, and small wildlife were found in the void. A longitudinal bar and stirrups were also exposed (Figure 14).

Fig. 14 Opening in Top Flange of Exterior Beam (Rock Creek)

Many of the box beams in Indiana have a thin bituminous wearing surface over the driving path. In many cases, the bituminous wearing surface does not extend to the curb of the bridge. Rather, the asphalt discontinues at the edge of the design lane and gravel covers most of the shoulder (Figure 15). As there are no waterproofing membranes on most of these bridges, chloride-laden water can easily migrate through the gravel shoulder and penetrate the exterior box beams of the bridge, leading to deterioration.

Fig. 15 Discontinuous Bituminous Wearing Surface and Reflective Longitudinal Cracking (Beal-Taylor Ditch)

Reflective cracking was also commonly observed in the wearing surface, especially over the exterior joint. These reflective cracks at the joints also allow penetration of moisture and chlorides into the top surface of the beams (Figure 15).

DURABILITY IMPROVEMENTS

In consideration of the database analysis and field observations, the durability of adjacent concrete box beams can be improved with the following recommendations:

- Provide drip beads along the corners of the box beam to prevent chloride-laden water from curling onto the underside of the bottom flange.
- Increase the horizontal clear distance between the outer-most prestressing strands and the edges of the beam, and ensure the strands are enclosed in stirrups. Increased cover reduces the probability of chloride ingress to the strands.
- Replace gravel and bituminous wearing surfaces with concrete topping slabs.

SUMMARY AND CONCLUSIONS

Adjacent box beam bridges are economic, aesthetic structures which allow for fast construction, require minimal formwork, and result in shallow superstructures. Unfortunately, these bridges often exhibit significant deterioration before reaching the 50-year design life of past practice or the 75-year design life defined in current specifications.[11] Concrete cracking and spalling as well as corrosion of the prestressing strands near the longitudinal joints are common forms of deterioration observed in the field.

Changes to the design standards and construction practices were investigated to obtain a perspective on the evolution of adjacent box beam bridges in Indiana. The first set of standards for adjacent box beams was published in 1961, providing the basis of design in Indiana. Revised standards were introduced in 1965 and incorporated modifications to the 1961 standards. The state used the 1965 standards until the 1980s. After the 1980s, most of the state adjacent box beam bridges were designed on a case-by-case basis. The counties, however, continued to use the 1965 standards well into the 1990s.

The current inventory of adjacent box beams in Indiana was analyzed to identify trends in performance. An investigation of the inventory provided a broad view of performance and durability of this bridge type, and correlations were made to design and construction features. In addition, geographical trends affecting performance were analyzed. The INDOT Bridge Inspection Application Software (BIAS) was used to generate a complete list of all adjacent, prestressed box beam bridges in Indiana. The list was sorted, and superstructure ratings were analyzed based on age, location, wearing surface, type of membrane (if any), span length, overall width, and skew. The primary findings of the analysis are as follows:

- There is a correlation between bridge age and the superstructure rating of adjacent box beam bridges. As expected, superstructure condition decreases with age.

- Location plays a role in the deterioration of adjacent box beam bridges in Indiana. Northern bridges, on average, have lower superstructure condition ratings compared to southern bridges.

- An analysis of superstructure ratings based on wearing surfaces revealed that bridges with bituminous wearing surfaces have experienced more deterioration than bridges with concrete wearing surfaces. Even though bridges with a concrete wearing surface deteriorate over time, the average superstructure rating is higher compared to bridges with a bituminous wearing surface.

- Wearing surfaces, regardless of material, allow water and deicing salts to be introduced to the adjacent box beam superstructures. The presence of a membrane appears to decrease deterioration of box beam bridges in Indiana. The average superstructure rating with a preformed fabric membrane is 6.6 compared to 6.3 without a membrane.

- No correlations were found between the superstructure rating and span length, bridge width, or skew.

Furthermore, a total of six bridges were identified for inspection to enable a close-up perspective of damage and to assist in identifying common patterns and features of deterioration. Common deficiencies observed during the inspections were listed and discussed. The overall findings from the visual inspections are as follows:

- Leaking longitudinal joints are a common deficiency of box beam bridges. Cracked shear keys and reflective cracking in the wearing surface allow water to seep through the joints. Leakage is most common at joints between the first interior beam and the exterior beam. This localization may be due to rotation of the exterior beam which causes tensile stresses in the joint. The location of the wheel path may also create stress on the exterior joints, resulting in cracking and leakage.
- Seepage of salt water through longitudinal joints leads to chloride penetration adjacent to the joint, resulting in the corrosion of reinforcement (prestressing strands and stirrups). As corrosion progresses, cracks form along the reinforcement, eventually causing spalling.

- Water and deicing salts also penetrate into the void of the box beams. A lack of drain holes, or plugged drain holes, leads to water accumulation within the void. Standing water in the void causes corrosion of the reinforcement, especially in the bottom flange. Regardless of drain holes, water and chlorides inside the void can lead to corrosion and deterioration of the box beam.

The historical study of adjacent box beam bridges in Indiana presented in this paper and detailed in Molley[7] emphasizes that these bridges are experiencing premature deterioration. Analytical and observational studies were completed to provide a broad view of performance and durability of this bridge type. Potential improvements to box beams are recommended to enhance durability. In a future study, destructive evaluations and load tests will be performed on box beams obtained from decommissioned bridges to improve understanding of the extent of deterioration and the impact of deterioration on structural behavior and load capacity. This work is expected to result in improved inspection and load rating procedures.

ACKNOWLEDGMENTS

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Replies to reviewer comments are shown in **red**.

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PCI Call for Papers 2019 Reviews for Submission #24
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Title: Summary of the Evolution and Performance of Adjacent Box Beam Bridges in Indiana

Authors: Ryan Molley, Ryan Whelchel, Christopher Williams and Robert Frosch

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REVIEWER #1
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Comments

I found this paper to be very readable. This information and conclusions have been known for many years to the producers of Box Beams. Nothing here (though very informative) is new and is available in other IDOT States as well. Again I find this information to be informative and supportive of other findings I do not enjoy reading of problems without going into a more supportive repair and improvement of product. Publish would be the most I would recommend to inform further....

The authors are aware that similar information on box beams is available in other states. However, this research was focused on identifying trends in deterioration in an inventory of bridges that previously had not been conducted. Regarding repair and improvement of box beams, a section has been added before the summary and conclusions that outlines recommendations for improving durability.

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REVIEWER #2
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Comments

This paper provides good summary of issues related to adjacent box beam bridges designed using the older AASHTO design specifications and incorporated bridge deck treatment according to Indiana DOT policies. All the issues appear to be common resulted from as-constructed details and to confirm known cause and effect of the issues typical for this type of deck-girder bridges.

This paper would be useful from bridge inspection community but may not appeal to the precast/prestressed concrete community.

Since the majority of the bridges are 30-50 years old (built in 1970s - 1990s), it would improve the paper tremendously, if the authors can add detailed description of repair or strengthening methods for this type of bridges to extend the service life. In the current form, I think the paper is a brief version of combined bridge inspection reports.

A detailed description of repair and strengthening methods is not available as this research was focused on identifying deterioration trends in the Indiana bridge inventory. Recommendations to increase box beam durability have been added and are likely of interest to engineers in the precast/prestressed concrete community. The recommendations are based on the results of the database analysis and observations made during field inspections. One of the recommendations, replacing gravel and bituminous wearing surfaces with concrete topping slabs, is a measure that can be taken to extend the service lives of existing bridges.

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REVIEWER #3

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Comments

A well written paper on existing database analysis. It is not clear why all six inspected bridges located in the North region. It would be nice to have a few in the south region to compare.

On page 13, in the paragraph introducing the field observations, an explanation is given for why bridges in the North region were chosen:

"Bridge selection was based upon the location analysis presented in Figure 5, and the focus was on areas with increased levels of deterioration within the state."

In other words, many heavily deteriorated bridges are in the North region of the state. This is consistent with the database analysis considering geographical location and levels of deterioration.

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REVIEWER #4

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Comments

This paper presents a summary of an author's masters thesis.
I would like to see a comparison of the following:

1. Adjacent prestressed concrete box beams with tie rods versus those without tie rods.
2. Adjacent prestressed concrete box beams with stressed tie rods versus those with unstressed tie rods.

The authors agree that this comparison would be helpful. Unfortunately, information regarding the use of tie rods (prestressed or non-prestressed) is not coded into the BIAS

database. Moreover, specific trends related to tie rods were not noted during our field inspections.

The paper would also be more interesting if authors offered recommendations to improve the performance of adjacent prestressed concrete box beams based on this data.

A section on durability improvements has been added before the summary and conclusions that outlines recommendations for improving durability.

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REVIEWER #5

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Comments

Excellent job in summarizing a large data base, with field observations as well. More focus and specifics on how to improve design and construction based on this study would be of interest to the readership in general. Consider that many graphics are not suitable for reading/distinguishing markers/legends if printed out in black and white.

A section has been added before the summary and conclusions that outlines recommendations for improving design and durability. Regarding the graphics, the use of color makes it easier to visualize condition ratings, especially for Figure 5. The authors feel that the paper will be primarily viewed in an electronic format (the papers are typically only distributed in electronic format to conference attendees), and the advantages of using color outweigh the benefits of greyscale figures.