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Executive Summary Report

Structural Evaluation of LIC-310-0396 and FAY-35-17-6.82 Box Beams with Advanced Strand Deterioration

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Project Background

Adjacent prestressed concrete box beam bridges are popular in Ohio with approximately 1,100 bridges existing that are under ODOT maintenance responsibility, amounting to approximately 9% of all Ohio's bridges. However, these bridges are also very common at the local level and when all bridges in the state are considered, these bridges account for approximately 17% of all bridges in Ohio.

The typical box beam bridge in Ohio (and in many states) is a non-composite bridge consisting of side by side beams connected only by a grouted shear key and transverse tie bars. These bridges usually have an asphalt overlay. Over time, the grouted joints crack and the cracks reflect into the asphalt layer. Chlorides penetrate through cracked joints and can infuse into the side of the beam. Eventually, these chlorides accelerate corrosion of the prestressing strands. The sides of the beams are not visible due to their adjacent placement and the corrosion may not be observed during inspections. Although this problem is most prevalent with non-composite bridges, it can also occur in composite bridges when the shear key cracks reflect through the concrete deck. With such a significant portion of the bridges being prestressed concrete adjacent box beam bridges and being aware that deterioration of strands may not be visible during inspection, it is imperative to have well developed inspection, rating, and analysis procedures in place that can be supported by experimental data. Therefore, testing and evaluation of prestressed concrete boxes that have been in-service and are of varying degrees of visible deterioration were warranted.

However, these beams do not exist in bridges as single members. Unfortunately, research did not currently provide experimental results for the complete adjacent box beam bridge system behavior. The evaluation of the behavior of the complete bridge system is critical for several reasons. Adjacent box beam bridges are robust structural systems since the beams are placed adjacent to each other and tied together through shear keys as well as transverse tie rods. This adjacent placement causes a significant difference in the behavior of the bridge system compared to an individual beam. Though design standards provide analytical procedures to determine how loading transfers between the various beams, experimental evidence of these procedures is limited. In addition, determining how loads transfer in the beams of this structural system when members are damaged from deterioration does not exist analytically or experimentally. Typically, evaluation of damaged members are done assuming loads distribute to them as if they are not damaged.

This lack of analytical and experimental verification on the behavior of damaged prestressed box beam bridge systems is related to economics. An overly conservative approach to evaluating a bridge based on individual member capacity and undamaged load distribution behavior may lead to premature load restriction of the bridge, closing of the bridge, or replacement of the bridge. In addition, replacement of a bridge may be considered necessary when in fact a more economical solution may be repair of the bridge to extend its service life. Finally, not completely understanding the behavior of the bridge system compared to individual member behavior could lead to unexpected premature failure leading to damage of public property, personal injury, or worse. It has been noted that during removal of some damaged beams, collapse of the beams under their own weight have occurred once shear keys and transverse ties have been cut. If such as condition occurred in an operational bridge and went unnoticed, the consequences could be disastrous.

The project consisted of two phases. The first phase involved the forensic study and destructive testing of damaged individual beams removed from a non-composite prestressed concrete adjacent box beam bridge in Licking County, Ohio (LIC-310-0396). The second phase of the project involved the evaluation and full scale destructive testing of a similar type of bridge that had been in service for 43 years in Fayette County, Ohio (FAY-35-17-6.82).

Study Objectives

The primary objective of Phase I of the study was to evaluate and determine the behavior of prestressed concrete box beams removed from LIC-310-0396 with deteriorated strands (see Figure 1). The load capacity and ductility of these beams were evaluated. Geometric and material properties of the beams were also examined. From these results, recommendations were made on rating methods and structural capacity for deteriorated box girders. The primary objective for Phase II of the study was to evaluate, test, and analyze an existing full scale damaged prestressed concrete adjacent box beam bridge in Fayette County, Ohio (FAY-35-17-6.82). This included nondestructive evaluation of the bridge, full scale destructive field testing, data analysis of the experimental testing, and analytical assessment.

Figure 1: LIC-310-0396

Description of Work

In order to meet the objectives of Phase I, a variety of tasks were undertaken. The literature and related research on deteriorate box girders was reviewed to determine what had already been done. Three beams removed from LIC-310-0396 were externally inspected visually and sectioned to view the internal and cross-sectional dimensions. Nondestructive evaluation techniques were also utilized on these box beams. Samples were removed to measure chloride content within the concrete. Full scale destructive load testing of four beams with various levels of deterioration was also performed (see Figure 2). Cores were removed and tested for compressive strengths. Strands removed from the beams had various levels of deterioration and were tested for tensile capacity. Finally, the beams were assessed analytically utilizing the material property data and compared with the full scale experimental results.

Figure 2: Destructive Testing of Beam from LIC-310-0396

In order to meet the objectives of Phase II of the study, the project involved a variety of tasks on the spans of bridge FAY-35-17-6.82. Nondestructive testing was performed and involved the use of ground penetrating radar to assess the concrete of the bridge, a magnetic method to evaluate the procedure of the method on a small portion of the bridge for prestressing strand corrosion, and truck testing to determine initial behavior of the bridge prior to destructive testing. The destructive field testing of the three span bridge involved instrumenting and testing each span individually (see Figure 3). One span was left in its existing condition to serve as a control while the two other spans were damaged to varying magnitudes prior to testing. The data from the nondestructive and destructive testing was analyzed and comparisons were made to evaluate the behavior of the spans and damage. The bridge was assessed analytically using standard design procedures, as well as with simple and complex computer software. Load rating of the bridge was also performed.

Figure 3: Destructive Testing of Center Span from FAY-35-17-6.82

Research Findings & Conclusions

Phase I

For Phase I of the project, the forensic evaluation portion of the project resulted in the following conclusions. Visual inspection of the beams revealed the majority of damage existed near the sides of the beams. Sectioning of the beams revealed the cross sectional dimensions of the beams to be within the acceptable tolerance. Though the horizontal position of the strands varied somewhat from the plans, the concrete cover over the strands was within reasonable agreement of the design drawings. The nondestructive testing of the beams using the rebound hammer provided an approximate and conservative estimate of the magnitude of the concrete strength and assisted in determining areas of poor concrete. The radar used in the study provided a relatively good assessment of the condition of the concrete in the beams compared to visual and coring results. The chloride contents within the bridge typically exceeded 0.1% by weight of concrete, high enough to accelerate the corrosion of the prestressing strands. The chloride contents also showed that penetration of the chlorides consistently occurred from the outside surface of the beam inward. Webs of the beams also had significant chloride contents leading to the belief the longitudinal joints between beams leaked. Testing of the strands removed from the beams revealed even corroded strands could carry load. A table prescribing strand condition and a conservative expected strength was developed. The testing of concrete cores removed from the beams showed compressive strengths of 8 ksi (55 MPa) - 9 ksi (62 MPa) well above the specified strength of 5.5 ksi (38 MPa).

The full scale load testing of the four damaged beams resulted in the following conclusions. One beam (Beam 14) had did not have any visibly corroded strands. After testing, 2 of 14 strands were found to have some corrosion. However, the beam was still able to exceed the ultimate moment capacity determined by AASHTO (Standard Specifications) calculations. For the intact beam (Beam 14), loss of prestressing force was measured at 15%. This was in reasonable agreement with the value obtained from the AASHTO LRFD Specifications (18%), but well below that predicted by the AASHTO Standard Specifications (25%). Three beams with severe damage had significantly lower capacities, but still were highly ductile. In all cases, final deflections exceeded Span/45. A conservative, but reasonable estimate of ultimate strength can be found by:

- Removing any spalled or loose concrete from the beam
- Assuming that any visible, corroded strand has no strength and is ineffective
- Assuming any strand immediately adjacent to a corroded strand is also corroded, has no strength and is ineffective
- Assuming that all other strands are intact and effective
- Calculating the nominal moment strength using the number and vertical position of the effective strands and any reasonable method (AASHTO specifications; strain compatibility or a software program like Response 2000)
- A reasonable prediction of service level behavior is obtained by using the number and vertical position of the effective strands and the loss of prestressing force predicted by the AASHTO LRFD Specifications

All of the tested beams failed in flexure, so no assessment of shear strength was made.

The load rating analysis resulted in the following conclusions. The LFR of the bridge based on the center span and the deterioration from Beam 18 resulted in an inventory rating factor (RF) of 0.41, an operating RF = 0.68, and a posting of 20 tons (178 kN). The LFR of the bridge based on Beam 16 resulted in a RF = 0.78 and a posting of 21 tons (187 kN) when using an AASHTO calculated capacity and assuming 5 effective strands. The RF increased to 0.89 and the posting increased to 24 tons (214 kN) when the capacity of Beam 16 with 5 effective strands was determined with the Response 2000 program. The LRFR of the bridge based on Beam 16 resulted in a RF =0.53 and a posting of 9 tons (80 kN) when using an AASHTO calculated capacity and assuming 5 effective strands. The RF increased to 0.59 and the posting increased to 11 tons (98 kN) when the capacity of Beam 16 with 5 effective strands was determined with the Response 2000 program. Based on the rating results the LRFR procedure was more conservative than the LFR procedure. When ratings were based on the experimentally determined capacities for the beams, the rating factors were higher than when capacities were determined by AASHTO procedures or the Response 2000 program. In addition, the ratings were closest to the experimentally determined rating when using Response 2000 program with the greatest number of strands considered effective. The rating analysis initially assumed a simple span when, in fact, the span is continuous for live load. This is conservative by approximately 50% if full continuity can be assumed. Given the deterioration near the piers, it is not certain the beams remained fully continuous. However, the rating factors for both LFR and LRFR were higher and did not result in any posting when considering continuity. The rating analysis assumed a live load distribution factor (LLDF) based on AASHTO calculations. However, this assumes the beams are undamaged and of equivalent stiffness. No information exists to verify this assumption.

Phase II

For Phase II of the project, the following conclusions were drawn. The GPR technique can be difficult to implement on the underside of an adjacent box beam bridge if the prestressing strands are on the outside of the shear steel. This requires the bridge to be scanned transversely and causes difficulties analyzing the data due to the unevenness and longitudinal joints between the beams. However with additional effort interpreting the data, the GPR technique can be used to determine areas of beams that have lower quality concrete that may be the result of corroding reinforcement and also lead to reduced member capacity. The GPR technique was used on the top of the bridge to identify areas of lower quality concrete even with an asphalt wearing surface present.

In this case of the two magnetic nondestructive methods, magnetic flux loss (MFL) and induced magnetic field (IMF), it was determined that both methods gave results with reasonable accuracy to estimate the health of the prestressing strands. It was clear that MFL was in a more advanced stage of development, but IMF showed great promise. While the MFL method classifies corrosion into categories, such as mild, moderate, or heavy corrosion, the IMF method offers the potential advantage of determining the cross-sectional area of the strand with more precision and accuracy. Both magnetic technologies offer bridge inspectors and DOT's a valuable tool for assessing hidden damage to embedded strands in prestressed box beam bridges.

The truck testing on the West span provided significant data on the bridge behavior prior to destructive testing. The bridge behaved as a system even under very heavy truck loading. The behavior of the bridge was fairly symmetric showing that the stiffness of the members to be symmetric prior to damaging. The truck testing showed the bridge to behave in a continuous manner even after the continuity reinforcement over the pier was cut. The dynamic load factor (impact factor) was determined to be approximately 1.10 for the bridge.

The loading of the spans during the full scale destructive testing showed that all spans were able to distribute loads across the width of the bridge. The spans were relatively symmetric in stiffness across the width of the spans as determined by loading one side and then the other side. The full scale testing showed that the East span and the Center span had nearly the same total experimental capacity even though significant damage was induced into the East span (18 out of 243 total strands cut = 7%). The West span had a lower capacity than the East or Center span, but the West span had more damage and the damage was concentrated to 3 beams (42 out of 243 total strands cut = 17%). As all spans reached their total capacity, the upper flange of several beams crushed and the bridge failed to carry any additional load. However, all spans were still able to support and distribute load even at high total loads. In the extreme event where the load was continued to be applied well after the capacity of the bridge was reached, load was distributed across the bridge. The shear keys distributed the load among the beams and likely continued to do so even after failing due to the transverse tie bars producing friction between beams. Complete collapse did not occur until the transverse tie bars yielded and then fractured at several locations. All spans exceeded capacities determined by AASHTO Standard Specifications (>22%) and AASHTO LRFD Specifications (> 22%) when evaluating the span's total capacity as the sum of the individual capacity of the beams.

The load rating by both the LFR and LRFR methods showed that the bridge would have required posting considering the damage to the beams in the West span. However, if the bridge was considered to act as a system rather than individual beams, the bridge did not need to be posted. Using a summation of the capacities of the individual beams to arrive at the total capacity of the bridge, resulted in a conservative estimate of the total bridge capacity compared to that found by the full scale experimental testing. This also resulted in a conservative rating for the total bridge based on an analytical capacity compared to the rating based on the experimental capacity. Assuming the bridge to be continuous compared to simply supported bridge resulted in higher ratings, but did not consider the rating for negative moment over the pier. This is additional aspect may not justify the small increase in rating even if the continuity is intact. Rating the bridge based on the total bridge capacity requires the bridge to behave as a system. For the bridge to behave as a system, the shear keys and the transverse ties have to sufficiently transfer load between beams. For the bridge destructively tested in this research, the transverse ties allowed load transfer between beams even though the shear keys had likely failed.

The finite element modeling showed that the complete bridge could be modeled to predict the deflections and strains in the West span within reasonable accuracy and more importantly the trend of the behavior of the span. This was especially true in terms of the significant damage that was heavily concentrated within the middle portion of the span.

Implementation Recommendations

Phase I

The following recommendations are based on results from the Phase I portion of the research study. Though visual inspections can provide significant information on the level of damage of prestressed concrete box beams in adjacent member bridges, additional means should be employed to complement the visual inspections if there is any concern with the overall safety of the bridge. These additional means include:

- Sampling the bridge for chloride contents to determine if levels are sufficiently high for corrosion to be accelerated.
- Use of nondestructive techniques to evaluate the quality of concrete.
- Removal of any delaminated concrete to reveal any additional corroded strands.

The procedure of considering corroded strands and strands adjacent to a corroded strand as ineffective for analysis purposes should be adopted. This method seems to provide a conservative but reasonable estimates of a beam's flexural capacity, especially since all corroded strands are not likely visible. Though corroded strands may be able to take some stress, the amount of stress the corroded strand can take depends on the damage. The degree of damage can be difficult to assess even when a large portion of the strand is visible. In addition, the bond of the strand may be questionable. The research of this project provided significant information on the behavior of individual prestressed concrete box beams with varying degrees of damage and should assist ODOT engineers in providing confident evaluations of such beams. However, the research in this Phase I did not provide experimental results for the complete adjacent box beam bridge system behavior. Therefore, it was recommended that the experimental evaluation of the behavior of the complete bridge system be undertaken in Phase II.

Phase II

Based on the research performed in Phase II of the project, the following recommendations can be made. The load rating can be done assuming the bridge behaves as a system rather than individual beams. The bridge's total capacity can be found using the summation of the individual beam's capacities found by standard AASHTO procedures. LRFD analysis was more conservative than an analysis based on the Standard Specifications. The total span capacities based on LRFD were still conservative in excess of 20% compared to full scale destructive test results. However, the shear keys and the transverse ties must be able to transfer load to the beams if the bridge is to be considered to act as a system. The destructive testing showed that even though the shear keys appeared to fail, the transverse ties were able to perform sufficiently to transfer load for the bridge spans tested. The transverse ties in the bridge tested in this research appeared to be grouted within their ducts. The behavior of transverse ties that are grouted, as well as not grouted, or are in various levels of condition need to be investigated further.

The modeling of the bridge is possible and can predict the performance of the bridge with various levels of damage. This would allow for the further investigation of bridges with different levels of damage and assist engineers in the evaluation of this type of popular bridge.

Truck loading of these bridges with proper instrumentation can determine behavior and condition of the bridge for a more in-depth assessment. Ground penetrating radar (GPR) can be a tool used to evaluate the condition of the concrete on the bottom of the bridge if the data is carefully interpreted. The induced magnetic field (IMF) nondestructive evaluation technique must be further developed in order to overcome problems in the collection and measurement of data, but the technique shows to be a promising method for evaluating corrosion of prestressing strand.