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Monitoring and Assessment of Continuity in a Prestressed Concrete Girder Bridge

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ABSTRACT: A 96-channel monitoring system is designed and installed in a prestressed concrete bridge that is built using the positive moment continuity detail recommended in NCHRP Report 519. The Louisiana Department of Transportation and Development (LA-DOTD) is adopting the new detail in the construction of one of the new bridges that is part of the John James Audubon Bridge project crossing the Mississippi River between Saint Francisville and New Roads, Louisiana. One of the bridges utilizing the new detail employs Bulb-T girders and is skewed, which is different than the scope of the experimental program covered in Project 12-53 that produced NCHRP Report 519. Thus, it was decided to monitor the performance of that bridge. This paper presents details of the monitoring system developed for this project, which has been in service for almost two years. Temperature, strain, rotation, and elongation readings are also presented and data preprocessing challenges are described. The bridge continuity is being assessed based on the acquired cleaned readings. A summary, conclusions, and lessons learned are also presented.

1 INTRODUCTION

The construction of prestressed concrete (PSC) girder bridges normally relies on precast girders that are transported to the construction site for erection before pouring composite decks. Many PSC girder bridges are built as simply supported bridges as by sacrificing full continuity between the girders for the sake of ease of construction. Achieving full or even partial continuity has been the subject of many research efforts and field of applications. Fully integrating adjacent girders has been the focus of many of these efforts (Loveall 1985; Wasserman 1987; Oesterle et al. 1989; Russell & Gerken 1994). More recent studies (Alampalli & Yannotti 1998; Thippeswamy et al. 2002; Burke, Jr. 2004) discussed the attributes and limitations of integral bridges based on experiences gained from in-service bridges. Partial integration, in which expansion joints are eliminated by constructing continuous decks over separated girders, which is often referred to as jointless deck construction, was also the focus of many researchers (1991) (Pierce 1991; Caner & Zia 1998; Caner et al. 2002; Wing & Kowalsky 2005; 2005; El-Safty & Okeil 2007).

In a recent study (NCHRP Project 12-53), Miller et al. (2004) investigated a positive moment continuity detail for prestressed girder bridges. The findings of the project were published in

NCHRP Report 519, which presents the results from the experimental program, the recommended details, and analysis method. The recommended detail calls for positive moment reinforcement to extend from the girder ends at the bottom. Thus, creating a mechanism for transferring the tensile forces that would develop at the supports of a continuous girder due to live loads at far away spans, or more importantly, due to long-term effects such as creep and temperature gradients (see Figure 1). In addition to allowing for the more efficient designs (longer spans, fewer strands, etc.), adequate design of the positive moment continuity may reduce the potential for problems associated with continuity diaphragms such as cracking, spalling, and debris accumulation in joints; all of which lead to high maintenance costs.

The Louisiana Department of Transportation and Development (LA-DOTD) is adopting the recommended detail in the construction of the new John James Audubon Bridge crossing the Mississippi River in Saint Franciseville, LA. This detail is different than the current standard used in Louisiana. Furthermore, one of the bridges with the new detail utilizes Bulb-T girders and is skewed, which is different than the scope of the experimental program covered in Project 12-53. Thus, it was decided to monitor the performance of that bridge. This paper presents details of the monitoring system developed for this project. Data processing techniques used in the study are also presented using actual data from the bridge.

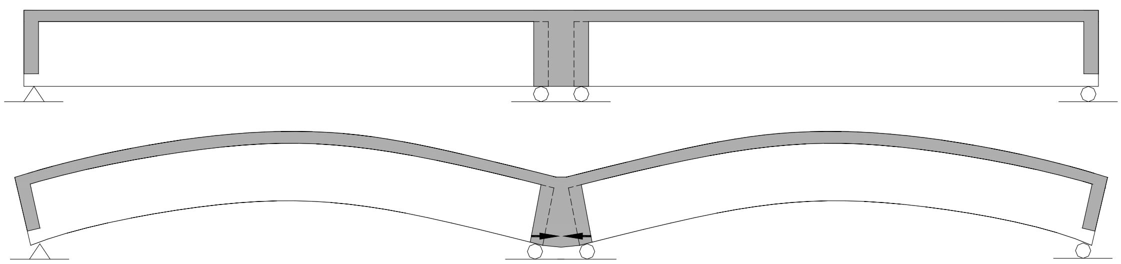


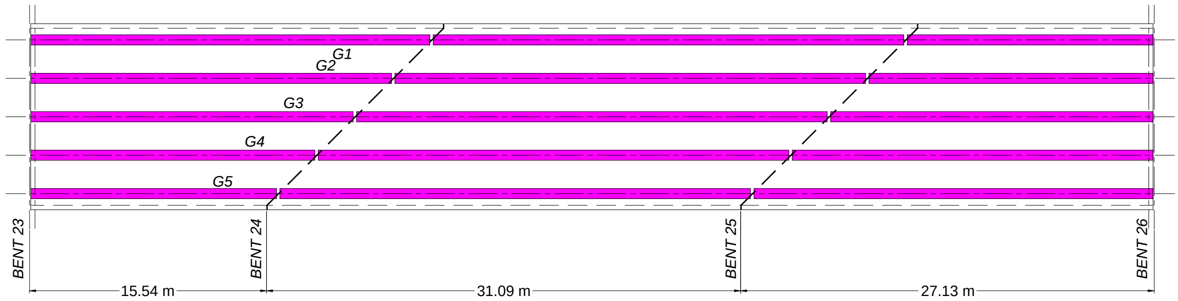
Figure 1. Development of positive moment in bridge connections with continuity diaphragm.

2 MONITORED BRIDGE DETAILS

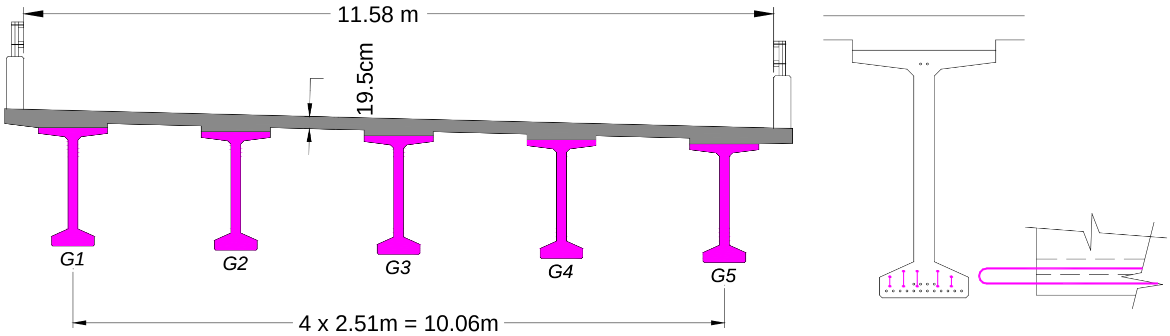
Bridge #2 is one of 8 bridges in the John James Audubon Project that will add a new transportation artery across the Mississippi River between the cities of New Roads and Saint Franciseville. The purpose of Bridge #2 is to cross an existing railway track. The 52-span bridge has a total length of about 1200 m which is divided into 14 continuous segments. The LA-DOTD chose a 73.76 m segment for monitoring the performance of the adopted continuity detail. The segment is a three span continuous superstructure with a skewed layout for its middle and longest span (31.09 meters). Because of the 45^{o}-skew of the middle span, the girders supporting the exterior spans ranged in length from 15.54 meters to 27.13 meters as can be seen in Figure 2-a. The chosen segment is constructed using AASHTO Bulb–T girders (BT-72). Because of the symmetry of the bridge, only one of the identical intermediate bents (Bent 24 and Bent 25). This segment was chosen because of its configuration, which has not been covered by the tests conducted in NCHRP Project 12-53; namely skewed configuration and Bulb-T girders.

Figure 2-b shows a cross section of the monitored bridge segment, which supports a clear roadway width of 11.58 meters on five prestressed BT-72 girders spaced at 2.51 meters. The 19.5 cm reinforced concrete deck is monolithically cast with the continuity diaphragm joining adjacent girders over intermediate bents. Hairpin bars were embedded in the girders and

extended 20 cm outside the girder ends to provide positive reinforcement. It should be noted that the girders are supported by rubber bearing pads over typical pile bents.



(a) Bridge layout



(b) Cross section and continuity detail

Figure 2. Configuration of Bridge #2.

3 STRUCTURAL HEALTH MONITORING SYSTEM

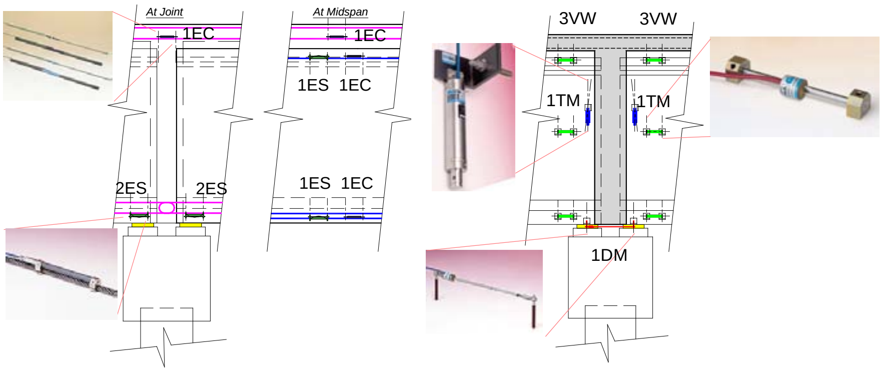
The monitoring system was designed to capture: (1) the tensile force in the positive moment reinforcement, (2) the strain distribution at key locations (intermediate bent and midspan), (3) differential shrinkage between cast-in-place (CIP) deck and precast girders, (4) degree of continuity between adjacent girders, (5) the development of cracks of gaps at the continuity diaphragm, and finally (6) the corresponding temperature for each of the recorded readings. In selecting the sensor locations, the research team identified the most critical locations that deliver the information required to assess the performance of the continuity detail. In most locations where embedded sensors were employed, two sensors were used to reduce the risk of losing sensors during the casting of girders. Furthermore, surge protection was provided to one of each two sensors at the same location in case of the bridge being hit by lightening since replacing embedded sensors is not possible.

One of the major causes of the development of positive moment is long-term effects such as creep and thermal deformations. Therefore, all the selected gages employed vibrating wire technology. Vibrating wire gages convert the change in resonant frequencies in an internal wire into an output reading that represents the relative movement between the wire ends. Gages that can measure strain, displacement, slope are available and were employed in the system. Table 1 lists the type and number of each of the employed sensors. Both embedded and external (surface mounted) sensors were used. The location of the sensors used in this study can be seen in Figure

3. Reducing the number of sensors was possible by taking advantage of the bridge's anti-symmetry under symmetric loading conditions such as long-term effects, which is the focus of this study.

Table 1. Types of sensors employed in this study

Sensor Type	Measurement	Location	Number
Sisterbars (EC)	Strain in concrete	Embedded	12
Strandmeters (ES)	Strain in reinforcement		18
Strain gages (VW)	Surface strains	External	30
Displacementmeters (DM)	Gap width		3
Tiltmeter (TM)	Slope		6
		Total:	**69**



(a) embedded sensors (b) external sensors

EC: sisterbar strain gage
ES: strandmeter strain gage
TM: tiltmeter
VW: external strain gage
DM: displacement meter

Figure 3. Layout of employed sensors.

Of special interest to this study is the performance of the hairpin bars. It can be seen from Figure 3-a that the strandmeters installed on the hairpin bars were placed inside the girders. While initially it was thought that installing the sensors inside the continuity diaphragm would yield better results on the performance of the detail, several factors convinced the research team that this choice is not feasible. First, the gage length for strandmeters is 8 inches, which is longer than the straight portion of the hairpin bars extending out of the girder ends. Second, transporting the girders with sensors installed would have been risky because of the lack of protection to the sensor. Installing the sensors after girder erection would have also been problematic because of the fact that the gap between adjacent girders is only 9 inches. Figure 4 shows two of the installed strandmeters prior to casting the girder.

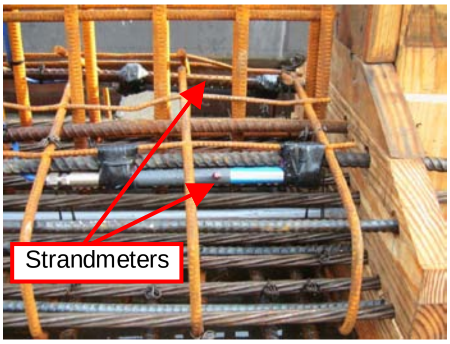


Figure 4. Strandmeters at girder ends (on hairpin bars).

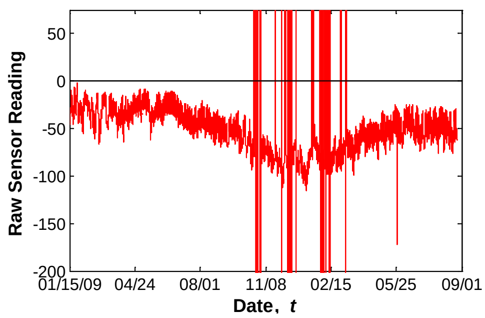
The installation of the embedded sensors was completed in June 2008. Sensors embedded in the cast-in-place (CIP) deck were installed in November 2008 prior to pouring the deck and continuity diaphragms. The external (surface mounted) sensors were installed in January 2009 at which the system was completed and became in service. All sensors were connected to a datalogger that is powered using a solar panel and rechargeable batteries to ensure continuous operational capabilities even in the case of power loss. Access to the datalogger is possible through a cellular modem via an internet IP connection. The datalogger collects one reading every 2.5 minutes from every sensor. During normal operation, only hourly averages from each sensor recorded, which reflects 24 readings taken during an hour. When needed, all collected readings may be recorded at the expense of longer download times and faster filling of the datalogger's buffer. The final setup has been in operation for almost 24 months. Several glitches in the system were fixed during that period. Furthermore, early readings during the time when the girders were stored at the precasting yard were obtained; albeit only for 18 out of the 30 embedded sensors because of logistics and for about 6 weeks right after the girders were cast.

4 DATA PROCESSING

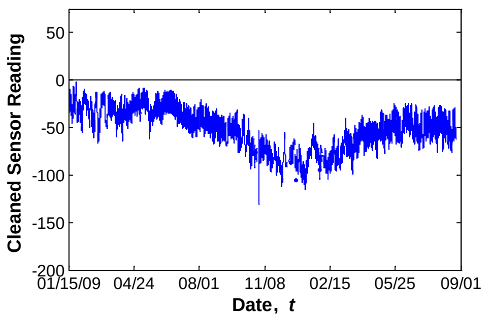
Raw data obtained directly from the logger had to be first processed before it could be interpreted. The processing includes cleaning the record from any outliers, joining or disjoining records in case data channel was changed during the monitoring period, and temperature correction as specified by the sensor manufacturer. The following few sections briefly describe all three steps of data processing.

4.1 Removal of Outliers

As stated earlier, average hourly readings are recorded during the normal operation of the datalogger. If for any reason one of the 24 readings averaged within an hour is bad (e.g. due to a lightning hit or low voltage input), the recorded hourly average is affected and become undesirable datapoint. The large size of data (69 sensors over 24 months) makes the task of removing outliers manually a daunting task. Several data cleaning scripts were tested before the research team developed its own data cleaning routine that performs the task on a global scale first before scrutinizing a smaller user-specified window for any datapoints that fall out of a user-specified range of acceptable tolerance. Figure 5 shows plots of the raw and cleaned data records for sensor #22. It should be noted that the erratic readings during the period between 11/2008 and 03/2009 were due to inadequate power supply from the solar panel, which affected three sensors and was remedied in March 2009. In all cases, outlier datapoints were replaced with an Not-A-Number (`NaN`) record.



(a) raw data

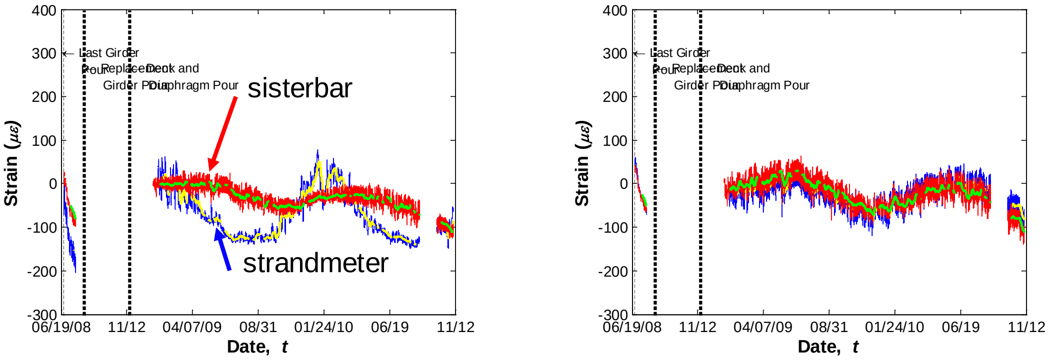


(b) cleaned data

Figure 5. Removal of outliers from raw data (sensor #22 – VW on G1 (bottom) at Bent 24 in Span 23).

4.2 Temperature Correction

The manufacturer of the vibrating wire gages used in this study recommends correcting the recorded raw data to account for temperature variations that affect the length of the vibrating wire inside the gages, and hence, affecting its readings. Temperature corrections were applied to all sensors used in this study except for tiltmeters, for which temperature correction is not highly recommended. Figure 6 shows a plot of raw and temperature corrected data for a sisterbar and a strandmeter at the same location (bottom of Girder 3 in the middle of Span 24). It can be seen in Figure 6-a that the recorded raw data are quite different. This is mainly due to the different characteristics of both sensors such as different gage lengths. Figure 6-b shows that once the temperature correction is applied, the trend and range of variations from both sensors match very well. The shift between the reading may be due to the condition at the initial stages when the girder concrete was poured. If another datum is chosen, the shift between the relative strain recorded by both sensor types would drop substantially.



(a) raw data (b) temperature corrected data

Figure 6. Temperature correction of sensors #88(ES) and #94(EC) in G3 (bottom) at Midspan 24).

4.3 Joining Data Records

During the fine tuning process of the system, two of the sensors were found to be malfunctioning. Both sensors were tiltmeters. In the trouble shooting phase, the malfunctioning tiltmeters were moved to different logger channels before ultimately replacing them. The records from different sensors at the same location had to be joined from different channels in the system after adjusting the relative readings at the begining of each phase to the relative reading at the end of each phase.Figure 7 shows readings from tiltmeters on Girder 1 at both ends of the continuity diaphragm. It can be seen that one of the records reflects expected due to seasonal temperature variations while the other one (on Span 24) was almost constant until it was replaced with a malfunctioning tiltmeter (period between June 2009 and October 2009). Finally, when the sensor was replaced on October 7, 2009, a similar trend can be seen on both sides of the continuity diaphragm.

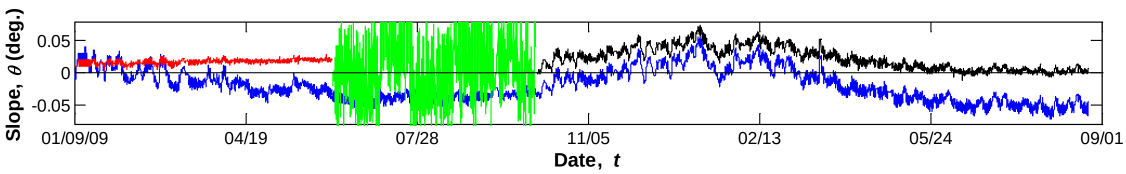


Figure 7. Joined data record for tiltmeter (TM) at G1 in Span 24.

5 ONGOING TASKS

The research team is currently interpreting the two-year record of data from this ongoing project. Preliminary results have been obtained in addition to conducting a live load test, which took place on August 20, 2010. Based on these results, the research team is in the process of preparing a final report that summarizes the findings of the project. At this stage it can be said that temperature effects, especially temperature gradients, cause the maximum straining actions on the continuity detail. The joint has demonstrated ability to transfer moments from one span to adjacent ones. This is true for negative as well as positive moment actions. The level of continuity is currently being assessed in terms of a continuity index that ranges from 0.0 to 1.0; where 1.0 indicates a fully continuous joint and 0.0 indicates a simply supported joint.

6 CONCLUSIONS

The development of a monitoring system for the evaluation of the performance of the new NCHRP 519 continuity detail is presented. The new detail calls for positive moment reinforcement to extend out of girder ends. Five different vibrating wire sensor types were employed in the monitoring system, which comprised of a total of 69 sensors. The monitoring system has been in service for about 24 months. Sensor readings (strains, displacements, and slopes) are obtained at hourly averages. Temperatures from each sensor are also obtained at the same rate and are used to correct the raw data as per the gages manufacturer's recommendation.

The success in developing such a monitoring system is a collaborative effort between many parties. The research team, general contractor, casting yard, sensor installation group, sponsoring agency had an open line of communication to plan tasks ahead of time and ensure proper installation of the sensors. Proper protection of the sensors during installation, transportation, and erection of the girders is essential for the success of the project. In this project, none of the sensors were lost during concrete pouring (100% survival rate). Protection of embedded sensors from power surge caused by lightening was also provided.

7 ACKNOWLEDGMENTS

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