Field monitoring of positive moment continuity detail in a skewed prestressed concrete bulb-tee girder bridge

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The precast, prestressed concrete girder bridge alternative is considered one of the most economical construction choices. Erecting precast, prestressed concrete girders eliminates the need for cumbersome and costly formwork, which usually negatively affects daily activities around the construction site. As a result, construction speed benefits from the use of precast, prestressed concrete, especially because the girders are only erected after being cured in the casting yard. Precast concrete elements are not monolithically connected by default. Therefore, many of the existing precast, prestressed concrete girder bridges are constructed as simply supported spans (Fig. 1).

Expansion joints between spans can cause serious problems, such as joint maintenance and the deterioration of elements in their vicinity. Elimination of joints avoids many of these problems. Several continuity details have been used over the years for slab-on-girder bridges. However, introducing continuity in large structures such as bridges has potential drawbacks (for example, thermal movements). Two major categories of continuity solutions are commonly used, full integration details and partial integration details. Full integration details (Fig. 1) result in a fully continuous structure (both deck and girders) that can resist the bending moments that develop at the supports due to long-term, thermal, and live-load effects. Alternatively, partial integration (Fig. 1), where the expansion joints are eliminated by casting a continuous deck over the support...
In 1989, the National Cooperative Highway Research Program (NCHRP) published the findings from project 12-29 in report 322, which is a comprehensive study on converting precast, prestressed concrete girders into a continuous system. More recently, NCHRP sponsored project 12-53 to investigate the performance of bridges made continuous and make recommendations. The recommendations, published in NCHRP report 519, were adopted by the designer of a major project in Louisiana. The John James Audubon project connects the cities of Saint Francisville and New Roads across the Mississippi River in Louisiana. Many of the spans of its eight bridges use hairpin bars to establish continuity between adjacent girders.

Researchers have investigated the behavior of continuous bridge superstructures. Continuity details have to resist moments that develop as a result of establishing continuity. Negative moments develop due to live loads and superimposed dead loads. Positive moments develop mainly due to long-term effects such as creep and shrinkage as well as thermal variations. Deck reinforcement over continuity diaphragms resists negative moments. Conversely, special arrangements need to be made for resisting positive moments. Extending reinforcement from girder ends for development in a continuity diaphragm is a common solution.

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![Figure 1. Typical continuity conditions in precast, prestressed concrete girder bridges.](image1)

![Figure 2. Difference between National Cooperative Highway Research Program (NCHRP) 519 and Louisiana Department of Transportation and Development (DOTD) continuity details. Note: no. 5 = 16M; no. 6 = 19M; 1 in. = 25.4 mm.](image2)
essential performance measures for evaluating the continuity detail. Several sensor types were chosen to measure temperatures, strains, rotations, crack widths, and gaps. All sensors used the vibrating wire technology, which is known to be more suitable for long-term monitoring projects because they do not suffer from drifting.\textsuperscript{13,14} Embedded as well as surface-mounted sensors were employed. In all, six types of sensors were used and the monitoring system included 66 active sensors. The sensors were strategically located at midspan and on both sides of the continuity diaphragm to capture the important measures that are most influenced by continuity, such as strains in hairpin bars and the gap between adjacent girder ends. All measurements were corrected for temperature changes per recommendations of the gauge manufacturer. Figure 4 shows a schematic of the sensor locations. Okeil and Cai provide more details about the instrumentation.\textsuperscript{12}

**Monitored bridge and monitoring system**

The monitored bridge segment is a three-span continuous superstructure, 242 ft (73.8 m) long with a 45-degree skewed layout. It constitutes spans 23, 24, and 25 of bridge no. 2. American Association of State Highway and Transportation Officials (AASHTO) bulb-tee girders (BT-72) were used for the construction of this segment. Because of the bridge’s symmetry, only one of the identical intermediate bents (bent 24 and bent 25) was monitored. This segment was chosen because of its configuration, which was not covered by the tests conducted in NCHRP project 12-53, namely skewed configuration and bulb-tee girders. Figure 3 shows a cross section of the monitored segment. Okeil and Cai provide more details about the bridge.\textsuperscript{12}

A 96-channel monitoring system was designed to record added to the lack of positive moment reinforcement, the Louisiana detail calls for a bond breaker to allow girder ends to move freely with respect to the diaphragm.

The Louisiana Department of Transportation and Development (LA DOTD) called for an investigation into the performance of this new detail on a full-scale bridge to assess its long-term performance. One of the bridges included a skewed segment with bulb-tee girders. Neither of these attributes was within the scope of the experimental program covered in project 12-53. The segment was therefore chosen for the study that lasted more than two years. A structural health monitoring approach was used in the investigation. This paper presents the study’s results, which include monitoring data for more than 24 months. Also, results from a live load test are presented.

**Temperature data**

Figure 5 shows the temperatures at midspan sections of girder G3 in span 24 at the deck, top girder flange, and bottom girder flange. The seasonal changes caused temperature fluctuations from about 20 to 115°F (-7 to 46°C). The highest temperatures were always recorded in the deck because of the direct exposure to sunlight. Sunlight exposure also caused larger daily variations in the deck temperature than at other locations, as is evident when comparing the range of daily amplitude from deck and girder flanges. The deck sensors were installed on the bottom mesh of the deck reinforcement to protect them during concrete placement. This position was at least 4 in. (100 mm) below the deck surface. The higher temperature was checked on the deck surface and compared with those recorded by the deck sensors, which showed a difference from 10 to 15°F (6 to 8°C).
Figure 4. Distribution of sensors at each monitored location. Note: DM = gapmeter gauge; EC = sisterbar gauge; ES = strandmeter gauge; TM = tiltmeter gauge; VW = vibrating wire strain gauge.

Figure 5. Temperature readings in deck and top- and bottom-girder flanges (girder G3 – span 24). Note: °C = (°F – 32)/1.8.
Figure 6 shows a plot of the measured temperatures across the midspan section of girder G3 in span 24, which did not benefit from any shading to the deck offered by the barriers. Also shown in the figure is the design gradient per the AASHTO LRFD Bridge Design Specifications.\(^1\) Two representative dates were selected to illustrate the severity of the temperature gradient. In hot summer months (Fig. 6), the difference between the top recorded temperature and the bottom one was 18 to 20ºF (10 to 11ºC), not accounting for the higher deck surface temperature. Overnight in wintertime (Fig. 6), the temperature gradient was almost zero. The design gradient matched the measured temperatures well. The temperatures shown covered the entire height of the girder and deck, up to where the sensors were located. In other words, the higher temperatures at the top of the deck were not captured by the monitoring system because of the position of the deck sensors as discussed earlier. These results give confidence that designing precast, prestressed concrete girder bridges using the AASHTO LRFD specified temperature gradient is adequate. It will be shown later that the temperature gradient has a significant effect on the performance of continuous precast, prestressed concrete girder bridges.

Hairpin strain data

Strain sensors on the hairpin bars on both sides of the diaphragm (Fig. 4) revealed important information about the performance of the continuity detail. Seasonal and daily temperature variations impose strains on the hairpin bars. By comparing strain readings (Fig. 7) for girder G3 at two similar dates (for example, 01/2009 and 01/2010), it seems that permanent residual strains took place due to creep. Continuity was established 101 days after the casting of girder G3, which is more than the 90 days required by AASHTO LRFD specifications if the designer opts to ignore creep effects on the detail. As a result, the creep effect was small and seemed to diminish with time.

The more interesting observation from these strain plots is the daily strain variations. The hairpin bars were subjected to large strains especially during summer. This is due to the temperature gradient effect discussed in the previous section. Diurnal strain fluctuations were measured in the hundreds of με. These strains are capable of initiating cracking near the continuity diaphragm, especially if combined with other tensile stresses (for example, creep and live load effects). Thus temperature gradients should be considered in the design of continuous precast, prestressed concrete girder bridges. Finally, Fig. 7 shows that strains on both sides of the continuity diaphragm are symmetrical, which is an indication of force transfer between adjacent girders. This observation was corroborated by readings obtained from the live load test discussed later in the paper.

Relative movement between adjacent girders

The relative movement between the bottom flanges at the ends of the adjacent girders on both sides of the continuity diaphragm was investigated using the gapmeters installed at girders G1, G3, and G5. Positive displacements imply that the distance between the bottom flanges increased. That is, the girders applied tension on the diaphragm, and vice versa. Figure 8 shows a plot of the temperature-corrected displacement readings from all three gapmeters, which were installed on girders G1, G3, and G5 across the continuity diaphragm at bent 24.

Girders G1 and G5 experienced far smaller seasonal and daily changes than girder G3 experienced because of their proximity to the barrier, which shaded the deck over these girders. Quantitatively, the gauge lengths for these extended gapmeter gauges were 46.0, 43.0, and 45.5 in. (1170, 1090, and 1160 mm) for girders G1, G3, and G5, respectively. This means that if a joint was cast monolithically with the girders, the resulting daily strain changes would

**Figure 6.** Measured temperature gradient (girder G3 – span 24). Note: 1 in. = 25.4 mm; ºC = (ºF – 32)/1.8.
Figure 7. Strains in hairpin bars at both sides of continuity diaphragm (girder G3).

Figure 8. Gapmeter displacements for girders G1, G3, and G5. Note: 1 in. = 25.4 mm.
As can be expected, not all sensors were highly strained by all loading positions because of their locations with respect to the position of the trucks. One interesting observation was that the hairpin strain records confirmed that forces were transferred from span 25 (loaded span) to span 23 (monitored span) for load positions P3 and P6. These two cases caused positive moments on the monitored continuity detail. Figure 11 shows the magnitude of the strains, which are larger for girder G3 than G1. A similar observation was related to the recorded negative strains for load positions P2 and P5. Both were load cases that target the positive moment in the middle of span 24. Therefore, trucks were positioned over span 24. The trucks would, however, apply negative moments on the continuity diaphragm if it performed as intended. In both load positions (P2 and P5), the hairpin bars experienced negative strains that were, as expected, greater than the positive strains discussed earlier. Like the P3 and P6 load cases, the sensors were in one span and the loads acted on another for these two cases. Hence, the ability of the new detail to transfer forces between spans was confirmed. Results from girders G1 and G3 were presented because girder G5 was not instrumented on the hairpin bars in span 23 and, therefore, a plot was not provided.

Constructability

Discussions with the precaster and the contractor revealed that construction cost of the detail is not substantial. Nevertheless, the precaster would rather build girders without the detail. The contractor’s critique of the new detail was stronger than that of the precaster. The contractor is of the opinion that the continuity diaphragm, especially for skewed bridge configurations, is cumbersome and adds to the construction time mainly because of the diaphragm’s formwork. Simpler details that require less formwork would expedite the construction of slab-on-girder bridges.
Seasonal and daily temperature variations can induce large restraint moments in the bridge, especially temperature gradients. The level of restraint moment due to the combined seasonal and daily temperature effects is probably the most important factor in the design of this detail because the designer has no influence on the temperatures at the bridge site. The other positive-moment-inducing factor (girder creep caused by prestressing forces) can be greatly reduced by not establishing continuity until after a large portion of the creep takes place.

Positive restraint moment can cause cracking in the diaphragm or girder ends if the total effect of moment-inducing factors is not considered in the design (that

**Conclusion**

Based on the presented results, the following can be concluded:

- Positive moments develop in bridges employing the new continuity detail. They are caused by creep and thermal effects that cause upward camber at midspans, which leads to positive moments at continuous girder ends.

- The continuity detail has the ability to transfer forces from one girder to the adjacent girder across the continuity diaphragm, as evidenced by the recorded data under long-term effects as well as live loads.

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**Figure 10.** Load test truck positions (distance with reference to middle of rear drive axle). Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.
Figure 11. Strains in hairpin bars showing positive values due to loads on other spans.
is, creep in addition to thermal gradient). Girder cracking may adversely affect the durability and shear capacity of the girders. Therefore, special care should be given to the magnitude of positive restraint moment during design. The authors believe that temperature gradient effects need to be considered in the design regardless of the girder’s age at establishment of continuity.

- The live load test revealed that the continuity detail transferred negative and positive moments across the diaphragm. The strains from the live load test were lower than long-term effects. Even if the actual design load was to be applied (approximately twice the test live load), the strains would still be small. Therefore, the live load case should be considered in the design; however, it is not the most demanding action on the detail.

- The monitored segment was skewed. Skewed configurations cause additional straining actions that do not develop in nonskewed bridge configurations. Therefore, the skew effect may have exacerbated the straining actions on the continuity detail. However, this hypothesis will need to be explored further through analytical or field investigations before it is confirmed.

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References


Abstract

This paper presents the results from a recently completed field study in Louisiana investigating the performance of a skewed prestressed concrete bulb-tee girder bridge made continuous. The bridge is part of the design-build John James Audubon Project that connects the cities of Saint Francisville and New Roads across the Mississippi River in Louisiana. A 96-channel monitoring system was designed and installed prior to bridge construction. The bridge used the positive moment continuity detail recommended in National Cooperative Highway Research Program (NCHRP) report 519. The Louisiana Department of Transportation and Development chose to monitor the skewed segment with bulb-tee girders because neither the skewness nor the bulb tee section was within the scope of the experimental program covered in project 12-53 that produced NCHRP report 519. This paper presents details of the monitoring system developed for this project, which has been in service for more than two years. Temperature, strain, rotation, and elongation readings are also presented. The bridge continuity is assessed based on the acquired postprocessed readings. Conclusions, lessons learned, and recommendations for future research are also presented.

Keywords

Bridge, creep, girder, restraint moment, structural health monitoring.

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