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**STRAIN MONITORING OF EMBEDDED REINFORCING STEEL WITHIN PRECAST CONCRETE BRIDGE DECK SYSTEM USING A WIRELESS STRUCTURAL HEALTH MONITORING SYSTEM**

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**Abstract:** Goal Engineering recently completed installation and commissioning of a Structural Health Monitoring (SHM) system for the new 12th Street SE Bridge in Calgary, Alberta. The monitoring system configuration was designed in collaboration with CH2M and The City of Calgary to monitor strain and load transfer through grouted keyway joints between precast concrete bridge deck panels. The monitoring system consists of 40 electrical resistance strain gauges mounted on modified stainless-steel reinforcing dowels. A wireless, battery & solar powered SHM system was installed to monitor the instrumented dowels. Strain readings are recorded every 6 minutes, perpetually. Wireless transmitters are connected to the strain gauges and are discretely mounted below the concrete bridge deck within the steel box girders. An onsite datalogger receives data from the transmitters. The datalogger then sends packets of data through the wireless cellular network to an offsite data storage server. The server can be accessed via the internet from anywhere in the world. The data obtained from the system is used to analyze the behavior of the structure. This paper will review the strain gauge installation methodology and present data from the system. This project is an example of how SHM systems can be used to monitor load transfer through structural elements of new bridges.

1. **INTRODUCTION**

The new 12th Street SE bridge in Calgary is the first of its kind in Alberta. The bridge is a composite structure featuring three arched shaped steel box girders and a bonded concrete deck. The bridge consists of three spans, 50, 70 and 50 m in length and spanning the Bow River south of the Calgary Zoo. Figure 1 below shows a profile view of the bridge.

The defining characteristic of the bride is the concrete bridge deck, which comprises full-depth and full-width precast concrete panels. The panels, after being delivered to site were bonded together, and to the steel structure, with an Ultra High-Performance Concrete (Lafarge Ductal). The objective of this work, and the topic of this paper, is to understand the load transfer mechanism through the joints between the precast panels.

This work is important as the structural design engineers have used Ultra High-Performance Concrete (UHPC) to transfer longitudinal forces in relatively short splice lengths (~200 mm). The results are useful as it will help structural engineers better understand the load transfer performance of the joints, contributing to the effective design of future bridges.

It is understood this is the first time that full-depth, full-width precast deck panels have been used in a continuous vehicular bridge in Alberta. Traditionally, the continuity of the bridge with full-depth, full-width precast panels is provided by longitudinal post-tensioning. This was not the preferred system for the Owner (The City of Calgary) due to concerns about future deck rehabilitations. Therefore, the design relies on reinforcement splices for the continuity.

Monitoring load transfer through concrete elements is a difficult task. 40 strain gauges were attached to the reinforcing steel dowels and embedded in both the precast panels and within the UHPC grouted joints. While this was a meticulous process, it was made manageable using battery powered sensors, wireless communications and by premanufacturing steel dowels prior to installation.

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Figure 1 – Profile view of the 12th Street SE Bridge.

1. **SENSOR CONFIGURATION**

Strain sensors were installed at a negative moment zone for the bridge deck, directly above a bridge pier. Sensors were attached to 20 reinforcing steel dowels, two (2) strain sensors per dowel. Figure 2 below provides a partial plan view of the bridge deck, showing the monitoring locations.

Each of the dowels spans from within the precast concrete panels to the grouted joints along the top mat of reinforcing steel. Dowels were located opposite each other within the joint to establish a ‘series’ of strain sensors with a configuration of Panel-Joint-Joint-Panel. The result is an effective method of monitoring strain (and load) flow. Figure 3 provides a section of the typical joint showing the location of the dowels and the mounting location of the strain gauge sensors on the dowels.

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Figure 2: Partial plan view of the 12th Street SE bridge deck showing the full width precast concrete panels, UHPC joints and the location of monitored reinforcement dowels.

BACKER ROD

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| ROUGHEN  SURFACE  ROUGHEN  SURFACE  2 – 15m SS    20  2-15M SS OR  4-10M SS  GROUTED KEYWAY  PRECAST PANEL  STRAIN GAUGE  LOCATIONS |

Figure 3: Typical section through joint between precast concrete panels and grouted joints showing typical locations of strain gauges on intersecting reinforcing steel dowels.

1. **SHM SYSTEM INSTALLATION & DATA ACQUISITION**
   1. **Strain Gauge Installation**

The strain gauges used for this project were electrical resistance full Wheatstone bridge strain gauges. The stainless-steel dowels were prepared for the strain gauges by locally smoothing the bar deformations. The smoothing process was performed carefully to limit removal to the deformations and not affect the un-deformed cross-sectional area of the bar (see Figure 4).

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| 1. View of typical stainless-steel reinforcing bars with deformations removed to allow for installation of strain gauges | 1. View of typical strain gauge installed on the smooth sections of stainless steel bar with wire harness attached. |

Figure 4: View of typical stainless-steel bar with deformations removed to allow for installation of strain gauges.

At all locations, redundant strain gauges were installed to build robustness into the monitoring system. It was expected that some damage may occur to the fragile strain gauges during the fabrication of the precast panels, transportation to site and site works to complete joint grouting (see Figure 5).

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| PRIMARY STRAIN GAUGES  REDUNDANT STRAIN GAUGES |

Figure 5: View of completed dowel fitted with 2 primary strain gauges and 2 redundant strain gauges.

* 1. **Reinforcing Dowel Installation**

Once laboratory assembly of dowels was complete, the dowels were installed into the precast panels at the precast manufacturing plant. Dowels were installed through the precast panels forms, which positioned the first bar strain gauges in the precast concrete and the second within the joint. Lead wires for the strain gauges ran back to an electrical junction box, sealed to the formwork for field access and connection. The section of dowel extending into the joint was marked with red paint to warn workers to be careful handling the panel around that dowel.

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| Figure 6: View of prepared dowel installed within the forms of the precast concrete panel. Form represents future location of joint cast with UHPC. | Figure 7: View of reinforcing steel within the precast concrete panel prior to casting concrete. Wire connection and electrical junction box sealed to the base of the precast form. |

* 1. **Strain Gauge Calibration & Correction** 
     1. **Lateral Contraction (Poisson’s Ratio)**

The selected strain gauge is in a full Wheatstone bridge configuration, strain readings are measured in the longitudinal and the perpendicular (transverse) direction. This is a standard configuration and is designed to account for temperature effects. For large structural elements or for elements subject to flexural stresses, lateral contraction is a negligible issue. However, as the reinforcing steel dowels are slender, the contraction of the dowel diameter is significant when the dowel is subjected to axial loads and needs to be corrected.

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| TRAN  LONG  REINFORCING STEEL DOWEL |

Figure 8 – Depiction of typical full Wheatstone bridge strain gauge configuration (image courtesy of Omega Engineering). Note the four quadrants of the strain gauge measuring longitudinal and transverse strain.

For a full Wheatstone bridge strain gauge configuration, to account for temperature affects, the output strain measurement is calculated by subtracting the transverse strain reading from the longitudinal strain reading, shown here as output strain:

[1] out = 0.5(Long - Tran)

Using Poisson’s Ratio for stainless steel (Wilson 2005), it can be shown that:

[2] Tran / Long = - 0.29, Tran = - 0.29 \* Long

Combining equation [1] and [2], it can be shown that the output strain measurement is skewed.

[3] out = 0.5(Long + 0.29 Long) = 0.645 Long

Therefore, to obtain the true longitudinal strain, the output needs the following correction:

[4] Long = 1/ 0.645 out = 1.55 out

Where, out Strain output reading, Long Longitudinal Strain reading, Tran Transvers Strain reading

To confirm the correction factor, a sample steel reinforcement dowel was instrumented with a strain gauge and four trials of load tensile testing were completed. The load (calculated stress) and strain measurement

readings were used to estimate the Modulus of Elasticity (MoE) of the stainless-steel. The results of the tensile testing trials are summarized in Table 1 & Figure 9 below.

Table 1: Summary of load trials on sample reinforcing steel bar.



Figure 9: View of stress-strain curves from sample reinforcing steel bar test trials (after correction), with equation of slope for Trail #4 shown.

The slope of the stress-strain curve shows the MoE for trial #4 is 203.6 GPa. The average calculated MoE for all trials was 204.5 GPa. This compares reasonably well with the reported range of 190 - 210 GPa (Ashby 2016). This result provides confirmation that the strain gauge (with the applied correction factor) is accurately measuring the true longitudinal strain within the reinforcing steel.

* + 1. **Thermal Contraction**

Thermal contraction was not corrected for as the strain gauges feature a full Wheatstone bridge which are self temperature correcting (Hewlett Packard 1981). As such, longitudinal thermal elongation is equivalent to the tangential elongation and correction is not required.

* 1. **Data Acquisition**

The data acquisition and processing system, manufactured by Resensys LLC, was selected for this application for its wireless communication capabilities. Strain sensors are connected to battery powered wireless transmitters located on the soffit of the concrete bridge deck, within the bridge girders. Data is collected every 6 minutes perpetually and transmitted to an on-site battery and solar powered datalogger. Here, data is collected and transmitted through a cellular network to an offsite database for storage and analysis. Wireless communication provided time and cost savings during installation by avoiding the need to rough in extensive cabled connections. This was critical in allowing the system installation to keep pace with construction.

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| 1. General view of wireless transmitters within the steel box girders attached to underside of precast concrete deck panels | 1. Close view of wireless transmitters connections to pre-installed wire harness contained in the junction boxes as shown in Figure 7. |

Figure 10 - View within 12th Street SE Bridge box girder showing wireless strain gauge transmitters.

1. **RESULTS**

The monitoring system was commissioned in June 2017 and the UHPC joints were cast August 20th, 2017. Figures 11 & 12 below shows strain data retrieved from reinforcing steel dowels ‘N’ and ‘K’ (see Figure 1) from August 14th to August 27th, 2017 and from September 7th to September 21st, 2017. The purple and dark blue plots (“East D09 N Panel” and “East D08 S Panel”) represent the data from the panel sensors located opposite each other across the joint, while the red and green (“East D08 S Joint” and “East D09 N Joint”) represent data from strain sensors from within the UHPC joint. The light blue plot represents ambient temperature recorded from the Calgary Airport (data courtesy of Environment Canada). It is noted that each of the transmitter components of the data acquisition system feature a temperature sensor, however as these are located below the deck of the concrete, in the steel box girders, they are not necessarily representative of the ambient conditions of the bridge structure.

Figure 11: Plot of strain data from reinforcing steel dowels ‘N’ and ‘K’, August 14th to August 27th, 2017.

Figure 12: Plot of strain data from reinforcing steel dowels ‘N’ and ‘K’, September 7th to September 21st, 2017.

* 1. **Observations & Discussion from Figures 11 & 12**

1. Near the mid-point of the plot on Figure 11, a clear change is noted in the data. This change likely represents the casting and setting of the UHPC. Once sufficient strength is gained by the UHPC, it is expected the structure begins to behave as a composite element and load is transferred through the precast panels.
2. Following August 20th, the amplitude of the strain measurement of all gauges increases and a cyclic pattern is observed.
3. The peaks of the strain readings (tension loading) appear to correspond to the lowest ambient temperatures and the valleys (compression loading) correspond to the highest ambient temperatures. It is noted that the zero mark of the readings is arbitrary and does not necessarily correspond to compression load, and rather could also indicate a reduction in tensile load.
4. The magnitude of the strain readings (both negative and positive) in the UHPC joint is greater than within the precast concrete panels. This may be due to the differences in strength and MoE between the conventional concrete and the UHPC and/or differences in proximity of the strain sensors to the cold joint separating the precast concrete and UHPC (see Figure 3).
   * Quality control testing completed during construction indicate the specified compressive strength of the precast concrete is 45 MPa, with some test results exceeding 60 MPa (at 28 days). The MoE can be estimated from compressive strength (Neville 1996) and is estimated to be ~33 GPa.
   * The UHPC has a tested compressive strength of 175 MPa and a measured MoE of ~54 GPa (Ahlborn et al. 2011) when in air cured conditions.
5. The magnitudes of the strain readings within the joint are similar for both reinforcing steel dowels.
6. The magnitudes of the strain readings within the adjacent precast panels are similar. This may suggest load is effectively transferred from one precast panel to the next.
7. **CONCLUSIONS**

There is much work to be completed for this monitoring project which could include seasonal strain monitoring and live-load testing. However, in this first portion of the project, some conclusions can be drawn from this work and include:

1. A wireless based structural health monitoring system has been shown to be an effective tool for monitoring loads on a bridge structure.
2. Electrical resistance strain gauges have been shown to be capable of measuring reinforcing steel strain in situ.
3. Full Wheatstone bridge strain gauges mounted on reinforcing steel require a correction factor to account for the transverse strain deformation.
4. The designed UHPC joint detail for the 12th Street bridge appears to sufficiently transfer thermal expansion and contraction forces, as shown in the short term of monitoring.
5. Further monitoring is required to measure and observe long-term load transfer between reinforcing steel dowels.
6. Areas for further work include monitoring load transfer while the structure is subject to live service loads.

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