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Evaluation of Bridge Fiber Optic Sensor Systems

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EVALUATION OF BRIDGE FIBER OPTIC SENSOR SYSTEMS

Final Report
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16. Abstract

Over a duration of a six days, each bridge's fiber optic sensor systems were evaluated. It was found that approximately 90% of the embedded sensors were still viable providing capabilities to establish a long term structural health monitoring program at these bridges. Additionally, data was collected (when possible) under ambient conditions, modified load tests were performed, and recommendations for the repair, required equipment, and potential uses of data collected are provided.

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PREFACE

The broad objective of the Task Order NM12SP-07-012 was to evaluate the fiber optic sensor systems installed in three New Mexico bridges. Based on the findings of the evaluation, recommendations for the repair, required equipment, and potential uses of data collected through a long term monitoring program are provided.

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ABSTRACT

Over a decade ago at the time of construction, three New Mexico bridges (9234, 9266, 9336) were instrumented with fiber optic sensors for structural health monitoring purposes. The sensors were installed with the intention of monitoring the performance of the bridges throughout their life cycle to provide a better understanding of bridge behavior and ensure public safety. These bridges were some of the first New Mexico bridges constructed with High Performance Concrete (HPC) and the first to use robust, embedded fiber optic sensors. The ultimate goal of the instrumentation and monitoring was to gain information on the prestress losses, deformations / strains, thermal effects, and curvature over the life of the bridge. The last monitoring of these bridges occurred nearly 10 years ago. Since that time, the instrumentation has been dormant. Over a duration of a six days, each bridge's sensors were evaluated. It was found that approximately 90% of the embedded sensors were still viable providing capabilities to establish a long term structural health monitoring program at these bridges. Additionally, data was collected (when possible) under ambient conditions, modified load tests were performed, and recommendations for the repair, required equipment, and potential uses of data collected are provided.

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INTRODUCTION AND BACKGROUND

Over a decade ago at the time of construction, three New Mexico bridges (9234, 9266, 9336) were instrumented with fiber optic sensors for structural health monitoring purposes. The sensors were installed with the intention of monitoring the performance of the bridges throughout their lifecycle and ensuring public safety.

These bridges were some of the first New Mexico bridges constructed with High Performance Concrete (HPC) and the first to use robust, embedded fiber optic sensors. The ultimate goal of the instrumentation and monitoring was to gain information on the prestress losses, deformations / strains, thermal effects, and curvature over the life of the bridge. The last monitoring of these bridges occurred nearly 10 years ago. Since that time, the instrumentation has been dormant.

The goal of the current project is to evaluate the state of the sensors at each bridge. Over a duration of a six days, each bridge's sensors were evaluated. When possible, data was collected for future studies. Based on the findings of the evaluation, recommendations for the repair, required equipment, and potential uses are provided.

The report is divided in the following sections: Fiber Optic Sensors; Bridge 9234; Bridge 9266; Bridge 9336; Recommendations; and Summary. Within each bridge section, the current state of the sensors is described and, if available, samples of collected data are provided.

FIBER OPTIC SENSORS

The measuring system is based on the principle of low-coherence interferometry. Infrared radiation light is injected into a single mode fiber and directed towards two fibers contained in the sensor through a coupler. The two fibers provide a measurement and a reference fiber. The measurement fiber is mechanically fastened to the girder and will deform (shorten / elongate) as the structure does. The reference fiber is installed freely within the same protection tube. Mirrors are placed at the ends of the two fibers and reflect the light back to the couple, which combines the two light beams and directs them back to the analyzer. The analyzer, also made of two fibers, can introduce a well-known path difference by means of a mobile mirror. When this mirror is moved, a modulated signal is obtained on the photodiode when the difference in length between the analyzer fibers compensates the difference in length of the structure fibers. Each measurement gives a new compensation position reflecting the deformation experienced by the structure to the previous measurement. Essentially, the difference in the return time of the light beams is directly correlated with the variation of the length of the fibers which is a result of the deformation of the structure. When subjected to temperature changes, both fibers expand or contract, and thus, the sensor does not need to be compensated for changes in temperature.

The type of sensors used in Bridges 9266 and 9234 are long gage, SOFO sensors. The SOFO system was developed in the 1990s and has been used in a wide range of civil structures. The advantage of the long gage is that it averages the strain over a longer distance, and thus, is not influenced by local defects in materials (e.g., cracks). Bridge 9336 uses the MuST sensor system. These deformation sensors are transducers that transform a static or dynamic distance variation into a change in reflected wavelength of a Fiber Bragg Grating. More information on the two types of sensors can be found in Appendix A.

BRIDGE 9234

Bridge Number 9234 spans the Rio Puerco on the Frontage Road (Old Highway 66) parallel to I-40 at Mile Marker 140 near the Route 66 Casino Hotel. Located in Bernalillo County, it was constructed in 2000. The bridge is a three span structure, with two end spans of 96.13 ft (29.3 m) and a middle span of 101.0 ft (30.8 m) for a total length of 296.6 ft (90.4 m). It is simply supported between spans and continuous for live loads. High Performance Concrete (HPC) was used for the cast-in-place deck as well as the prestressed concrete beams. A picture of the bridge can be seen in Figure 1.

Figure 1: **Bridge No. 9234 (Old Highway 66 over the Rio Puerco).**

The bridge consists of four BT-1600 HPC girders spaced at 12.63 ft (3.85 m) prestressed by 42, Grade 270 steel tendons (26 straight and 16 draped). The average compressive strength of the concrete at 28 days was 9076 psi (62.6 MPa); at 56 days, it was 10,151 psi (70.0 MPa). The deck, 8.66 in. (0.22 m) thick, was fabricated with cast-in-place HPC reinforced with 420 Grade steel. For complete details on the bridge design see Solano (2001).

The main objective of the monitoring system of Bridge 9234 was to determine the prestress losses. The four north girders in the west and center spans were chosen to monitor. Five pairs of deformation sensors were installed in each of the four girders, for a total of 40 sensors. Figures 2 and 3 provide sketches of the sensor locations and naming scheme. These long gauge fiber optic sensors were used to measure deformation at each support, at ¼ span, at midspan (Solano 2001). Additionally, to account for the curvature changes caused by temperature gradients, thermocouples were installed near the fiber optics sensors at the girder ends and at midspan. Temperatures at quarter points was interpreted from the data collected at the girder ends and midspan (Solano 2001). Measurements from the sensors and thermocouples were read by a 40 channel reading unit containing an internal 10-channel multiplexer supplemented by an external 30-channel multiplexer.

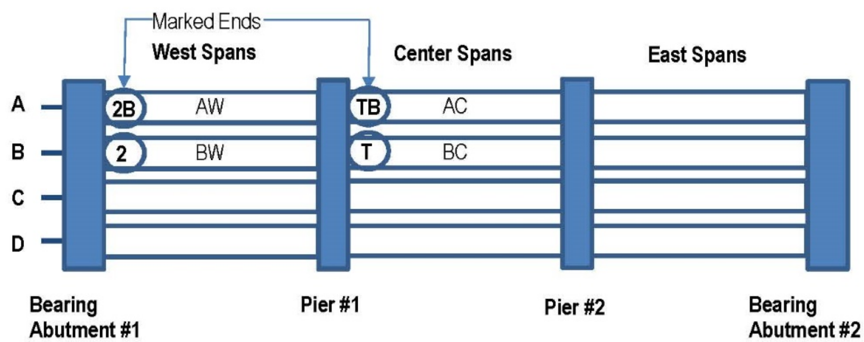


Figure 2: Bridge No. 9234 sensored spans (provided by Smartec).

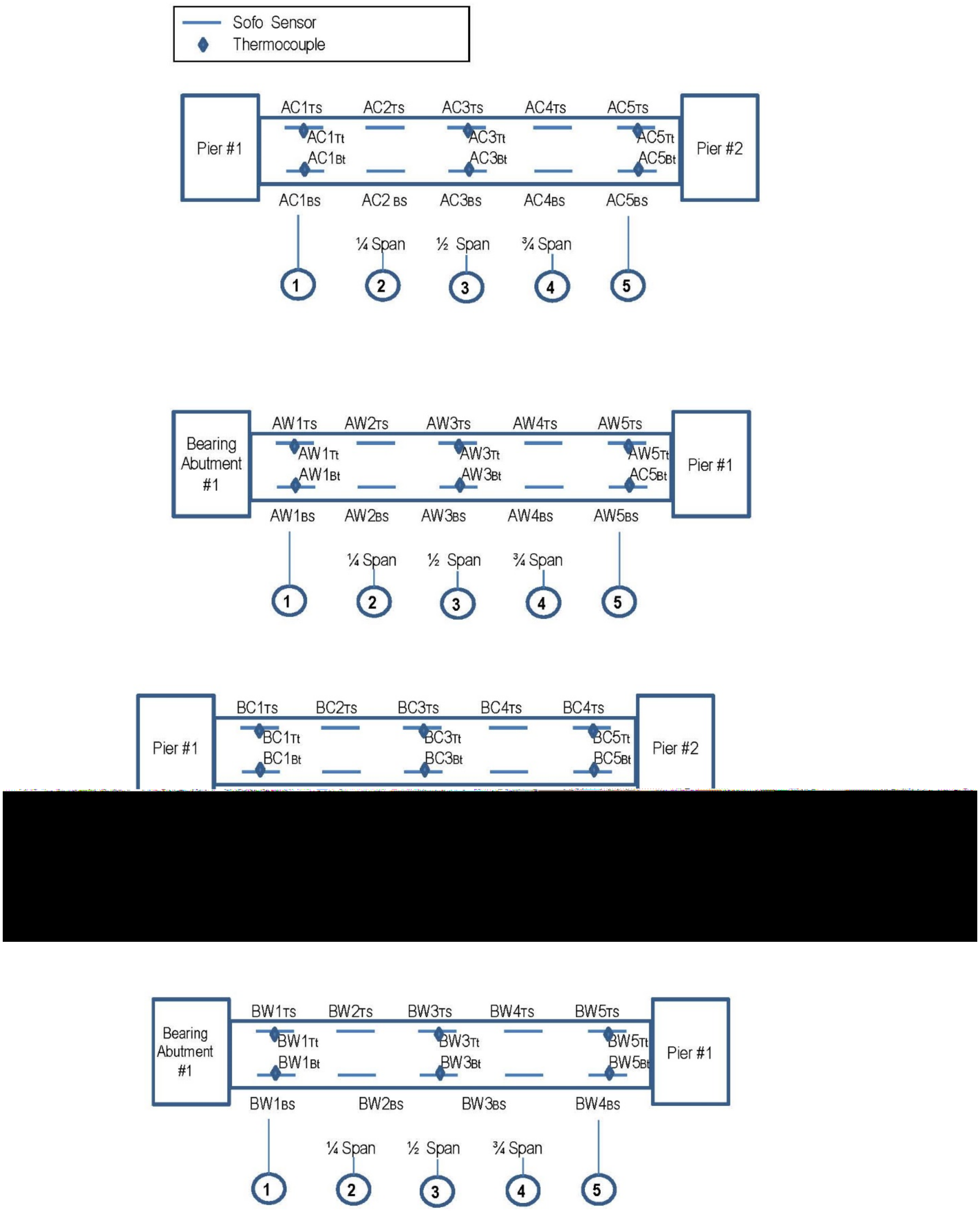


Figure 3: Bridge No. 9234 sensor naming and location (provided by Smartec).

Current State of Sensors – Bridge 9234

Tables 1 and 2 provide information on the current state of the sensors in Bridge 9234. Of the 40 fiber optic sensors originally installed, 37 sensors are currently still functioning properly. An additional sensor is also reading; however, additional measurements are still needed to determine if the measurements are reliable. All 24 thermocouples are still viable.

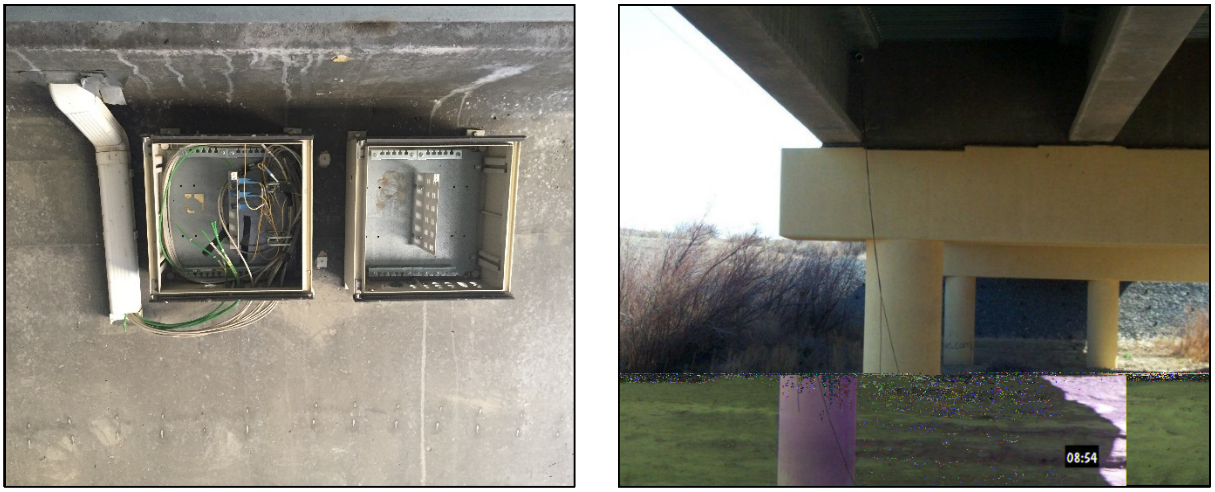
Table 1: Status of fiber optic sensors embedded in Bridge 9234.

Sensor Name	Serial Number	Type	Working	Notes
AC1Bs	1300	Deformation	Yes	
AC1Ts	1337	Deformation	Yes	
AC2Bs	1307	Deformation	No	
AC2Ts	1304	Deformation	Yes	
AC3Bs	1315	Deformation	Yes	
AC3Ts	1312	Deformation	Yes	
AC4Bs	1324	Deformation	Yes	
AC4Ts	1322	Deformation	Yes	
AC5Bs	1332	Deformation	Yes	Additional measurements needed to verify reliability.
AC5Ts	1329	Deformation	No	
AW1Bs	1299	Deformation	Yes	
AW1Ts	1298	Deformation	Yes	
AW2Bs	1308	Deformation	Yes	
AW2Ts	1303	Deformation	Yes	
AW3Bs	1316	Deformation	Yes	
AW3Ts	1311	Deformation	Yes	
AW4Bs	1323	Deformation	Yes	
AW4Ts	1321	Deformation	Yes	
AW5Bs	1331	Deformation	Yes	
AW5Ts	1330	Deformation	Yes	
BC1Bs	1301	Deformation	Yes	
BC1Ts	1295	Deformation	Yes	
BC2Bs	1309	Deformation	Yes	
BC2Ts	1306	Deformation	Yes	
BC3Bs	1317	Deformation	Yes	
BC3Ts	1313	Deformation	Yes	
BC4Bs	1326	Deformation	Yes	
BC4Ts	1319	Deformation	Yes	
BC5Bs	1333	Deformation	Yes	
BC5Ts	1327	Deformation	Yes	
BW1Bs	1302	Deformation	Yes	
BW1Ts	1296	Deformation	Yes	
BW2Bs	1310	Deformation	Yes	
BW2Ts	1305	Deformation	Yes	
BW3Bs	1318	Deformation	Yes	
BW3Ts	1314	Deformation	Yes	
BW4Bs	1235	Deformation	Yes	
BW4Ts	1320	Deformation	Yes	
BW5Bs	1334	Deformation	Yes	
BW5Ts	1328	Deformation	Yes	

Table 2: Status of thermocouples embedded in Bridge 9234.

Sensor Name	Serial Number	Type	Working	Notes
AC1Bs	18	Thermocouple	Yes	
AC1Tt	12	Thermocouple	Yes	
AC3Bt	24	Thermocouple	Yes	
AC3Tt	22	Thermocouple	Yes	
AC5Bt	31	Thermocouple	Yes	
AC5Tt	29	Thermocouple	Yes	
BC1Bt	15	Thermocouple	Yes	
BC1Tt	11	Thermocouple	Yes	
BC3Bt	26	Thermocouple	Yes	
BC3Tt	19	Thermocouple	Yes	
BC5Bt	32	Thermocouple	Yes	
BC5Tt	27	Thermocouple	Yes	
AW1Bt	16	Thermocouple	Yes	
AW1Tt	14	Thermocouple	Yes	
AW3Bt	25	Thermocouple	Yes	
AW3Tt	21	Thermocouple	Yes	
AW5Bt	34	Thermocouple	Yes	
AW5Tt	28	Thermocouple	Yes	
BW1Bt	17	Thermocouple	Yes	
BW1Tt	13	Thermocouple	Yes	
BW3Bt	23	Thermocouple	Yes	
BW3Tt	20	Thermocouple	Yes	
BW5Bt	33	Thermocouple	Yes	
BW5Tt	30	Thermocouple	Yes	

While most of the sensor in the bridge are still functioning, there has been a significant amount of vandalism to the instrumentation boxes and connection cables. Due to this damage and time restrictions, limited data was collected for Bridge 9234. To evaluate the sensors, the data acquisition system had to be connected to each junction box which housed approximately 10 fiber optic sensors. When repaired, measurements will be taken for all gauges from a single location. Figure 4 shows some of the damage to the instrumentation system. Pictures of the evaluation of the sensors are shown in Figure 5.



(a) (b)

Figure 4: Bridge 9234 – (a) damaged instrumentation boxes and cables; (b) broken fiber optic cables.


(a) (b) (c) (d)

Figure 5: Bridge 9234 sensor evaluation – (a) dynamic evaluation; (b) repaired connections; (c) and (d) under-bridge access unit.

To demonstrate some of the potential information that could be collected samples of data were taken during the evaluation of the sensors. Figure 6 shows a sample of data collected under ambient traffic conditions for a two minute duration. Figure 7 focuses on the data between 20 and 30 seconds, showing the behavior of the data more clearly for this time frame. Additionally, Figure 8 shows a collection of static data taken over a short duration of time. In this plot, strain measurements taken at regular time intervals are plotted. It can be seen how the strain changed with temperature. Note that this data does not show actual strain, rather the strain change due to the increase in temperature.

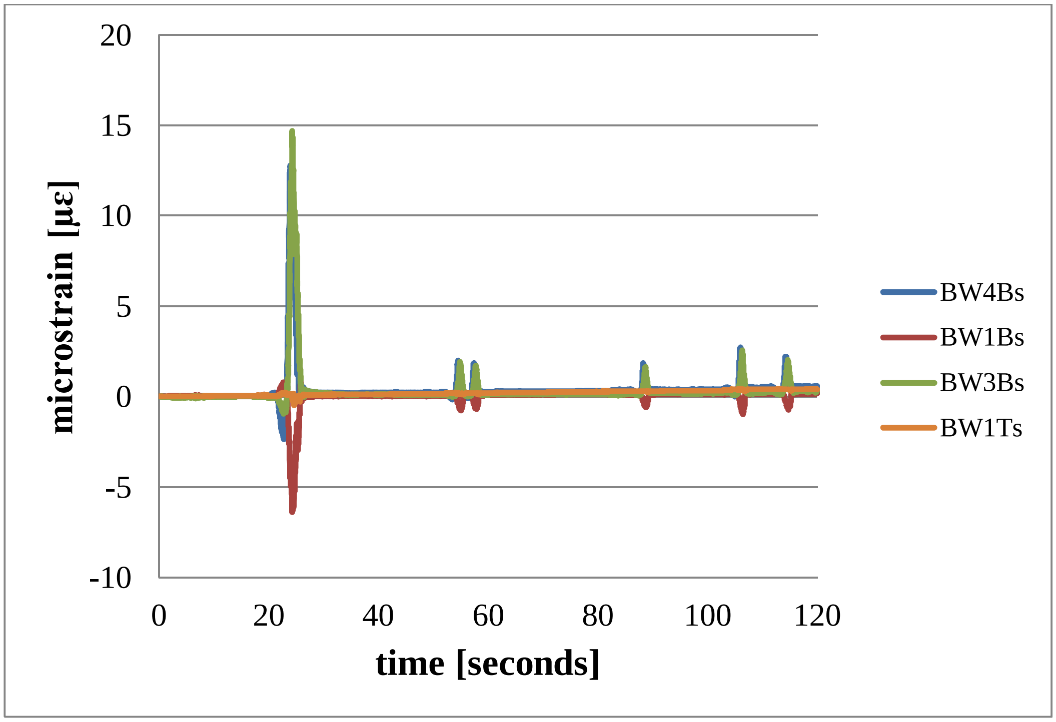


Figure 6: Dynamic data for Bridge 9234, girder BW.

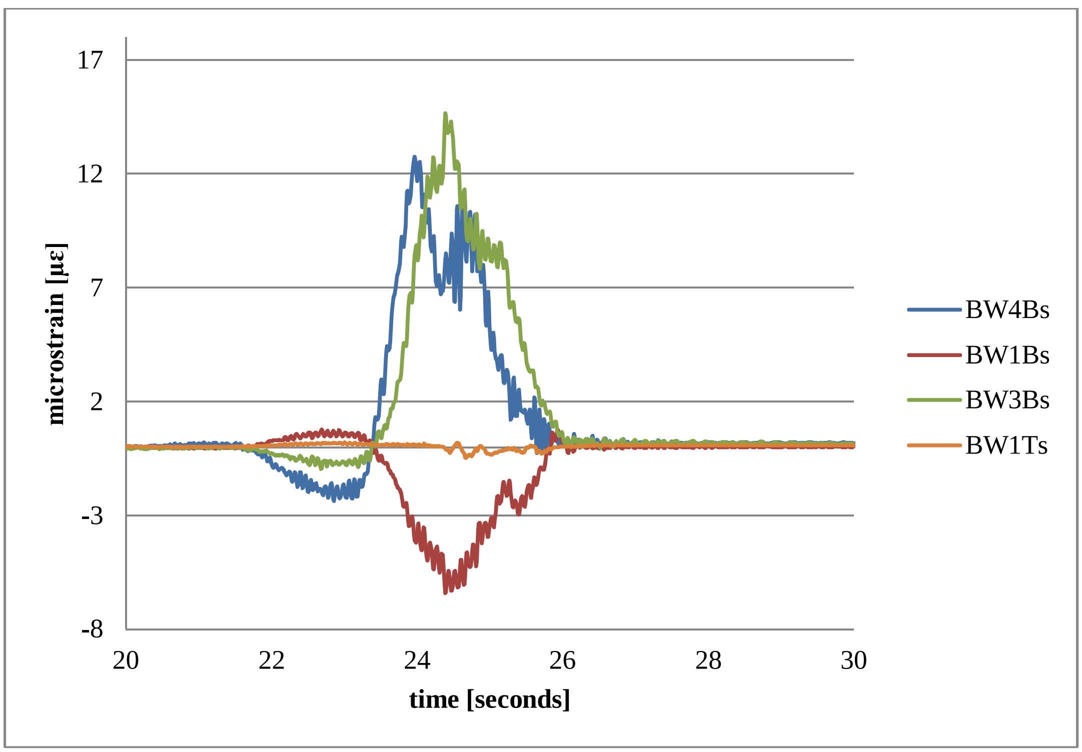


Figure 7: Dynamic data for Bridge 9234, girder BW (20 – 30 seconds).

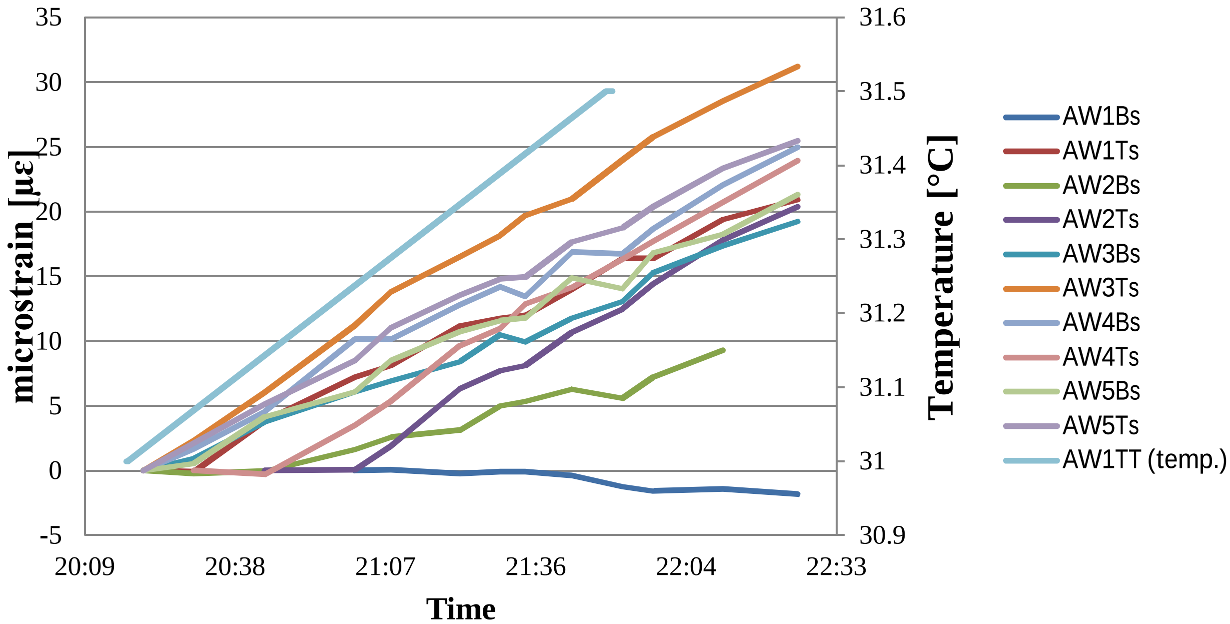


Figure 8: Static data for Bridge 9234, girder AW.

Bridge 9234 – Required Repairs / Recommendations

The following repairs are needed for Bridge 9234 to bring the system back to the original installation:

- Replace multifiber cable from junction box on girder AC to the central monitoring point;
- Replace multifiber cable from junction box on girder BC to the central monitoring point;
- Replace the mating of junction box on girder AW to the junction box on girder BW;
- Replace the cable for the data communication from all ADAM modules (thermocouple input modules) to the central monitoring point;
- Replace ADAM module in junction box on girder AW;
- Replace ADAM module in junction box on girder AC; and
- Repair or replace the junction box on girder AW (door is missing).

The following recommendation are made to improve the instrumentation system at Bridge 9234:

- Provide secure heated/cooled housing unit for the central monitoring point (similar to those used on Bridges 9266 and 9336);
- Add a fence near the junction boxes on girders AW and BW;
- Provide cable covering for multicable fiber running between junction boxes;
- Use screw-anchored hangers for running of replacement multifiber cable;

- Provide power supply to bridge (solar and / or direct line); and
- Provide internet access (wireless or hardline).

BRIDGE 9266

Bridge Number 9266, at I-10 Miler Marker 141.5 over Main Street and University Avenue, was constructed in 2004. The bridge consists of an eastbound and westbound bridge. The westbound bridge consists of five spans with various lengths for a total length of 643 ft (196 m). The eastbound bridge consists of four spans with various lengths for a total length of 511 ft (156 m). Span 5 of the westbound bridge was chosen for instrumenting and monitoring. A picture of Bridge 9266 is shown in Figure 9.

Figure 9: Bridge No. 9266 (I-10 over Main Street and University Avenue).

The bridge was designed in accordance with AASHTO Standard Specifications for Highway Bridges, 1996 edition and current interims. The 28-day design compressive strength of the concrete beams was 10 ksi (68.9 MPa) at 28-days. The prestressing of the girders was done using 0.6 in. (15.2 mm) diameter seven wire low relaxation strands with and ultimate stress of 270 ksi (1862 MPa). The bridge has a reinforced concrete 8 in. (0.203 m) composite deck with 28-day design compressive strength of 4 ksi (27.6 MPa) and Grade 60 reinforcement (cast on stay-in-place forms).

The bridge consists of six U54B beams as shown in Figure 10. The detailed view of the U54B beam is shown in Figure 11. A total of 53 strands were placed at the bottom of the girder with 25 strands in the top row, 15 strands in the middle row, and 13 strands in the 13 strands in the bottom row. Full design details can be found in Liang (2004).

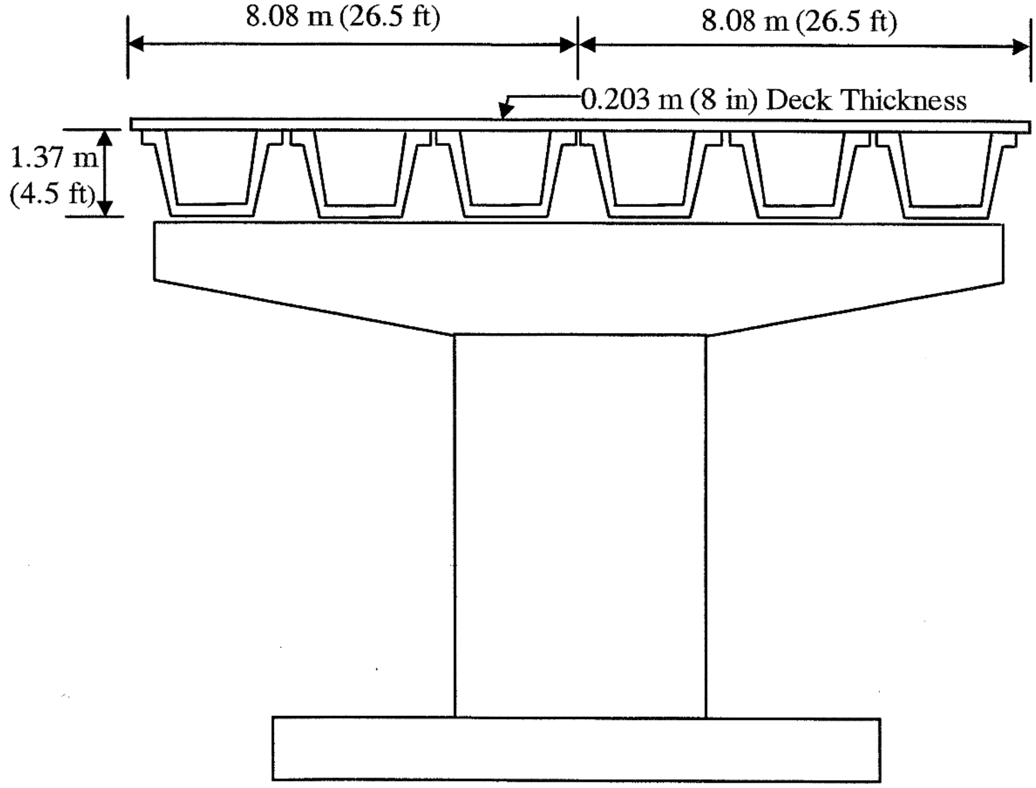


Figure 10: Bridge No. 9266 – typical cross-section (Liang 2004).

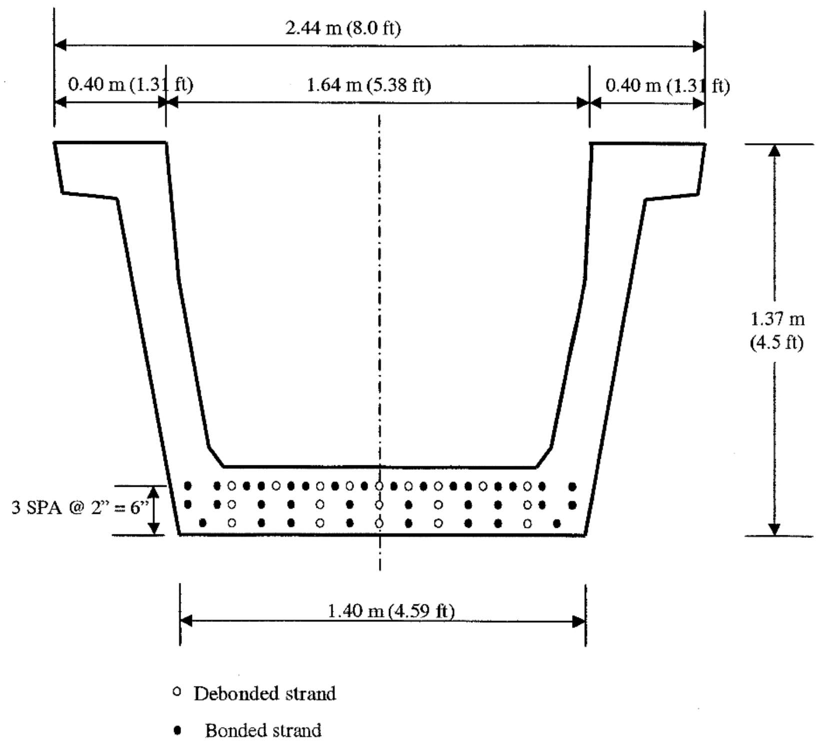


Figure 11: Bridge 9266 – typical U54B cross-section (Liang 2004).

Span 5 of the westbound bridge was chosen to instrument for monitoring of Bridge 9266. The sensor system consisted of a dynamic SOFO monitoring system consisting of long-gauge fiber optic sensors, a central connection box, a reading unit, and data analysis software (Idriss and Tercero 2009). The fiber optic sensors were used to measure deformation along the span at different locations along the girder, shear and moment forces within the structure, and prestress losses (Hughes 2004, Liang 2004).

There were a total of 72 deformation sensors installed to monitor the 6 girders of Span 5. The sensors were installed in parallel and crossed topology (Idriss and Tercero 2009). Thirty-six (36) temperature sensors (thermocouples) were installed in the top and bottom of the flanges of each girder near the deformation sensors to account for thermal changes. Figure 12 shows the layout of the sensors embedded in Span 5 of Bridge 9266.

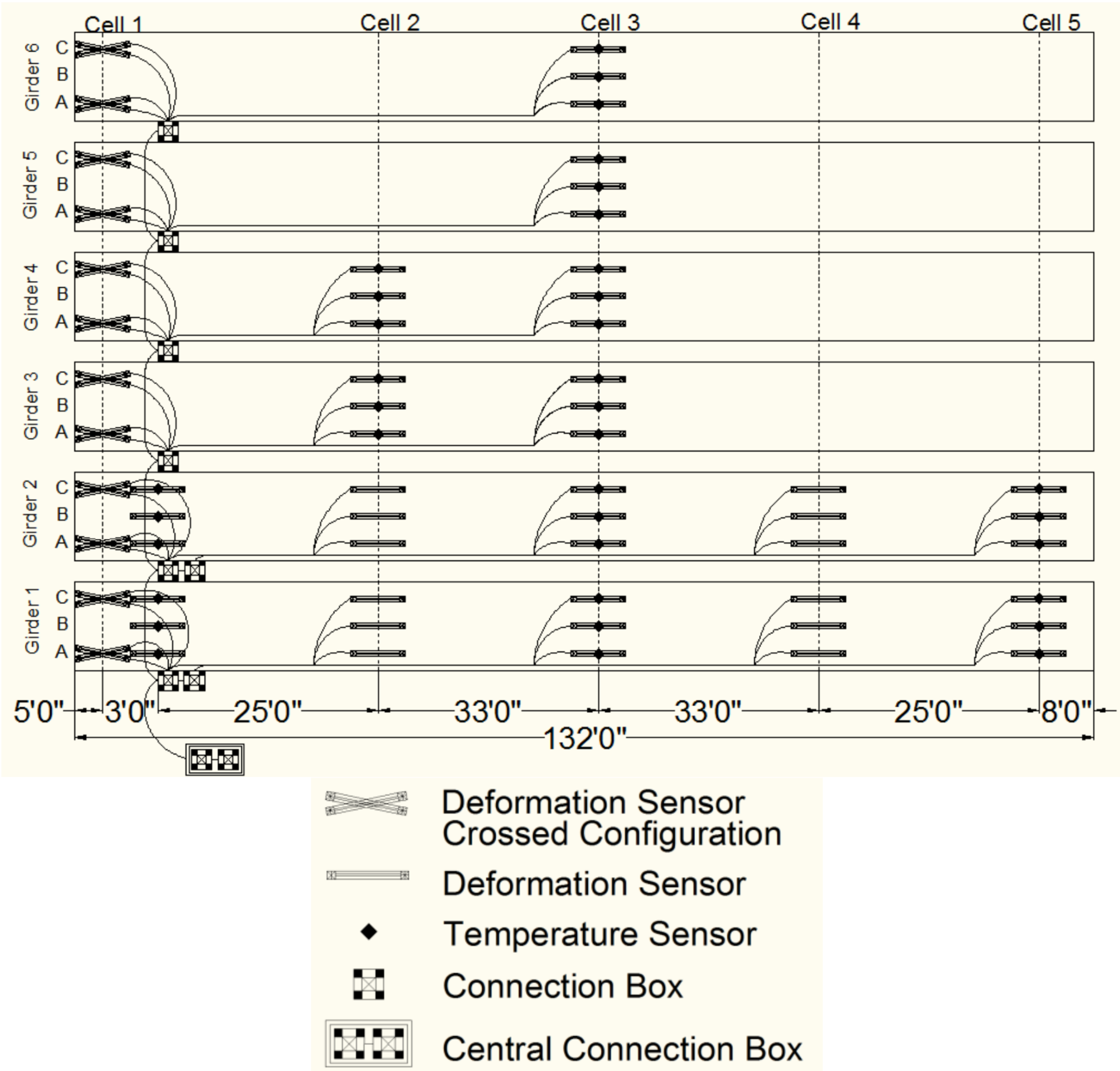


Figure 12: Bridge 9266 – Span 5 sensor plan view [Idriss and Tercero (2009)].

Current State of Sensors – Bridge 9266

Tables 3 and 42 provide information on the current state of the sensors in Bridge 9266. Of the 72 fiber optic sensors originally installed, 67 sensors are currently still functioning properly. All thermocouples are still viable; however, all ADAM input modules need to be replaced on Bridge 9266. It was unclear why all modules stopped working; therefore, one ADAM module was sent to Smartec for investigation.

Table 3: Status of fiber optic sensors embedded in Bridge 9266.

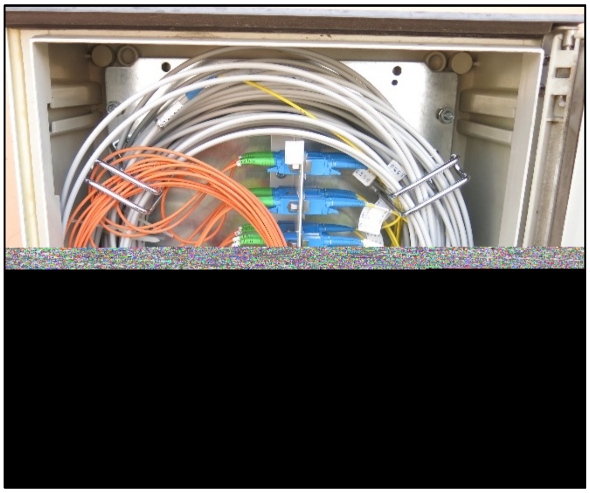
Sensor Name	Serial Number	Type	Working	Δ (mm) from 2004
25-G5C3-A(1-1)	2915	Deformation	No	--
25-G5C3-B(1-2)	2923	Deformation	No	--
25-G5C3-C(1-3)	2929	Deformation	Yes	-0.11226
25-G5C4-AT(1-4)	2875	Deformation	Yes	-1.4099
25-G5C4-AB(1-5)	2881	Deformation	Yes	-0.56173
25-G5C4-CT(1-6)	2893	Deformation	Yes	-1.48735
25-G5C4-CB(1-7)	2899	Deformation	Yes	-1.87616
2A5-G6C3-A(1-8)	2916	Deformation	Yes	-0.28514
2A5-G6C3-B(1-9)	2924	Deformation	Yes	-1.90887
2A5-G6C3-C(1-10)	2930	Deformation	Yes	-1.4835
2A5-G6C4-AT(1-11)	2876	Deformation	No	--
2A5-G6C4-AB(1-12)	2882	Deformation	Yes	-1.50263
2A5-G6C4-CT(1-13)	2894	Deformation	Yes	-0.29555
2A5-G6C4-CB(1-14)	2900	Deformation	Yes	-1.19923
2C5-G1C1-A(1-15)	2937	Deformation	Yes	-0.24647
2C5-G1C1-B(1-16)	2939	Deformation	Yes	1.354326
2C5-G1C1-C(1-17)	2941	Deformation	Yes	-1.2158
2C5-G1C2-A(1-18)	2931	Deformation	Yes	0.003201
2C5-G1C2-B(1-19)	2933	Deformation	Yes	-0.69987
2C5-G1C2-C(1-20)	2935	Deformation	Yes	7.906642
2C5-G1C3-A(1-21)	2911	Deformation	Yes	-1.03635
2C5-G1C3-B(1-22)	2919	Deformation	Yes	-0.20628
2C5-G1C3-C(1-23)	2925	Deformation	Yes	-1.39616
2C5-G1C2S4-A(1-24)	2887	Deformation	Yes	-0.63382
2C5-G1C2S4-B(1-25)	2903	Deformation	Yes	-1.44699
2C5-G1C2S4-C(1-26)	2905	Deformation	Yes	-1.73894
2C5-G1C1S4-A(1-27)	2883	Deformation	Yes	-0.28941
2C5-G1C1S4-B(1-28)	2885	Deformation	Yes	-15.4235
2C5-G1C1S4-C(1-29)	2901	Deformation	Yes	-1.28262
2C5-G1C4-AT(1-30)	2871	Deformation	Yes	-0.73083
2C5-G1C4-AB(1-31)	2877	Deformation	Yes	-1.49856
2C5-G1C4-CT(1-32)	2889	Deformation	Yes	-0.0976
2C5-G1C4-CB(2-1)	2895	Deformation	Yes	-1.19951
2B5-G2C1-A(2-2)	2938	Deformation	Yes	-0.32771
2B5-G2C1-B(2-3)	2940	Deformation	Yes	0.557534
2B5-G2C1-C(2-4)	2942	Deformation	Yes	-1.82321
2B5-G2C2-A(2-5)	2932	Deformation	Yes	3.695211
2B5-G2C2-B(2-6)	2934	Deformation	Yes	-3.54352
2B5-G2C2-C(2-7)	2936	Deformation	Yes	-2.13512
2B5-G2C3-A(2-8)	2912	Deformation	Yes	-1.0447
2B5-G2C3-B(2-9)	2920	Deformation	Yes	-2.11621
2B5-G2C3-C(2-10)	2926	Deformation	No	--
2B5-G2C2S4-A(2-11)	2888	Deformation	Yes	-1.48019
2B5-G2C2S4-B(2-12)	2904	Deformation	Yes	-1.85758

2B5-G2C2S4-C(2-13)	2906	Deformation	Yes	-2.30341
2B5-G2C1S4-A(2-14)	2884	Deformation	Yes	-1.41895
2B5-G2C1S4-B(2-15)	2886	Deformation	Yes	-0.11182
2B5-G2C1S4-C(2-16)	2902	Deformation	Yes	-1.42145
2B5-G2C4-AT(2-17)	2872	Deformation	Yes	-2.20648
2B5-G2C4-AB(2-18)	2878	Deformation	Yes	-0.85059
2B5-G2C4-CT(2-19)	2890	Deformation	Yes	-2.36334
2B5-G2C4-CB(2-20)	2896	Deformation	Yes	-1.7918
2B5-G3C3-A(2-21)	2913	Deformation	Yes	-1.33634
2B5-G3C3-B(2-22)	2921	Deformation	Yes	-1.99946
2B5-G3C3-C(2-23)	2927	Deformation	Yes	-0.1107
2B5-G3C3S4-A(2-24)	2907	Deformation	Yes	-14.9679
2B5-G3C3S4-B(2-25)	2909	Deformation	Yes	0.213372
2B5-G3C3S4-C(2-26)	2917	Deformation	Yes	-1.67334
2B5-G3C4-AT(2-27)	2873	Deformation	Yes	9.946124
2B5-G3C4-AB(2-28)	2879	Deformation	Yes	0
2B5-G3C4-CT(2-29)	2891	Deformation	Yes	-0.93361
2B5-G3C4-CB(2-30)	2897	Deformation	Yes	-1.40435
2B5-G4C3-A(2-31)	2914	Deformation	Yes	1.280227
2B5-G4C3-B(2-32)	2922	Deformation	Yes	0.674917
2B5-G4C3-C(0-3)	2928	Deformation	Yes	-0.85921
2B5-G4C3S4-A(0-4)	2908	Deformation	Yes	-1.51571
2B5-G4C3S4-B(0-5)	2910	Deformation	Yes	0.050275
2B5-G4C3S4-C(0-6)	2918	Deformation	Yes	-1.84696
2B5-G4C4-AT(0-7)	2874	Deformation	Yes	-2.45266
2B5-G4C4-AB(0-8)	2880	Deformation	No	--
2B5-G4C4-CT(0-9)	2892	Deformation	Yes	2.521027
2B5-G4C4-CB(0-10)	2898	Deformation	Yes	-1.69589

Table 4: Status of thermocouples embedded in Bridge 9266.

Sensor Name	Serial Number	Type	Working	Notes
T25-G5C3-A	TS1G5C3-A	Thermocouple	Yes	
T25-G5C3-B	TS1G5C3-B	Thermocouple	Yes	
T25-G5C3-C	TS1G5C3-C	Thermocouple	Yes	
T2A5-G6C3-A	TS1G6C3-A	Thermocouple	Yes	
T2A5-G6C3-B	TS1G6C3-B	Thermocouple	Yes	
T2A5-G6C3-C	TS1G6C3-C	Thermocouple	Yes	
T2B5-G2C1-A	TS1G2C1-A	Thermocouple	Yes	
T2B5-G2C1-B	TS1G2C1-B	Thermocouple	Yes	
T2B5-G2C1-C	TS1G2C1-C	Thermocouple	Yes	
T2B5-G2C3-A	TS1G2C3-A	Thermocouple	Yes	
T2B5-G2C3-B	TS1G2C3-B	Thermocouple	Yes	
T2B5-G2C3-C	TS1G2C3-C	Thermocouple	Yes	
T2B5-G2C1S4-A	TS2G2C1-A	Thermocouple	Yes	
T2B5-G2C1S4-B	TS2G2C1-B	Thermocouple	Yes	
T2B5-G2C1S4-C	TS2G2C1-C	Thermocouple	Yes	
T2C5-G1C1-A	TS1G1C1-A	Thermocouple	Yes	
T2C5-G1C1-B	TS1G1C1-B	Thermocouple	Yes	
T2C5-G1C1-C	TS1G1C1-C	Thermocouple	Yes	
T2C5-G1C3-A	TS1G1C3-A	Thermocouple	Yes	
T2C5-G1C3-B	TS1G1C3-B	Thermocouple	Yes	
T2C5-G1C3-C	TS1G1C3-C	Thermocouple	Yes	
T2C5-G1C1S4-A	TS2G1C1-A	Thermocouple	Yes	
T2C5-G1C1S4-B	TS2G1C1-B	Thermocouple	Yes	
T2C5-G1C1S4-C	TS2G1C1-C	Thermocouple	Yes	
T2B5-G3C3-A	TS1G3C3-A	Thermocouple	Yes	
T2B5-G3C3-B	TS1G3C3-B	Thermocouple	Yes	
T2B5-G3C3-C	TS1G3C3-C	Thermocouple	Yes	
T2B5-G3C3S4-A	TS2G1C3-A	Thermocouple	Yes	
T2B5-G3C3S4-B	TS2G1C3-B	Thermocouple	Yes	
T2B5-G3C3S4-C	TS2G1C3-C	Thermocouple	Yes	
T2B5-G4C3-A	TS1G4C3-A	Thermocouple	Yes	
T2B5-G4C3-B	TS1G4C3-B	Thermocouple	Yes	
T2B5-G4C3-C	TS1G4C3-C	Thermocouple	Yes	
T2B5-G4C3S4-A	TS2G2C3-A	Thermocouple	Yes	
T2B5-G4C3S4-B	TS2G2C3-B	Thermocouple	Yes	
T2B5-G4C3S4-C	TS2G2C3-C	Thermocouple	Yes	

Figure 13 shows pictures during the evaluation including pictures of the junction boxes and central monitoring tower. Additionally, Figure 14 shows pictures from a modified load test. Due to traffic remaining on the bridge, further investigation is needed; however, data was collected under load to potentially investigate the behavior of the bridge particularly in the shear region. Bridge 9266 has a significant number of large shear cracks (see Figure 15). Further data collection and analysis could provide insight into the behavior of the bridge leading to formation of the shear cracks.



(a)

(b)

(c)

(d)

Figure 13: Bridge 9266 evaluation – (a) typical junction box; (b) under-bridge access lift; (c) central monitoring tower; (d) thermocouple cables in junction box.

(a) (b)

(c) (d)

Figure 14: Bridge 9266 load test – (a) and (b) shear region; (c) truck location; (d) near midspan.

(a) (b)

Figure 15: Shear cracks on Girder 1.

To demonstrate some of the potential information that could be collected samples of data were taken during the evaluation of the sensors. The last column in Table 4 shows the changes in measurements from the previous data taken in 2004. It can be seen that most gauges show a change in deformation, particularly gauges within the shear regions (where several cracks have formed). Further analysis of this data and comparison with historical findings could provide valuable insight into the behavior of the bridge, improved design methods, and maintenance needs.

Figure 16 shows the strain evolution measured by the fiber optic sensors over a 24 hour period. It can be seen that the strains increase during the day as the bridge is heated and the strains decrease at night. Note that this data does not show actual strain, rather the strain change due to the thermal changes.

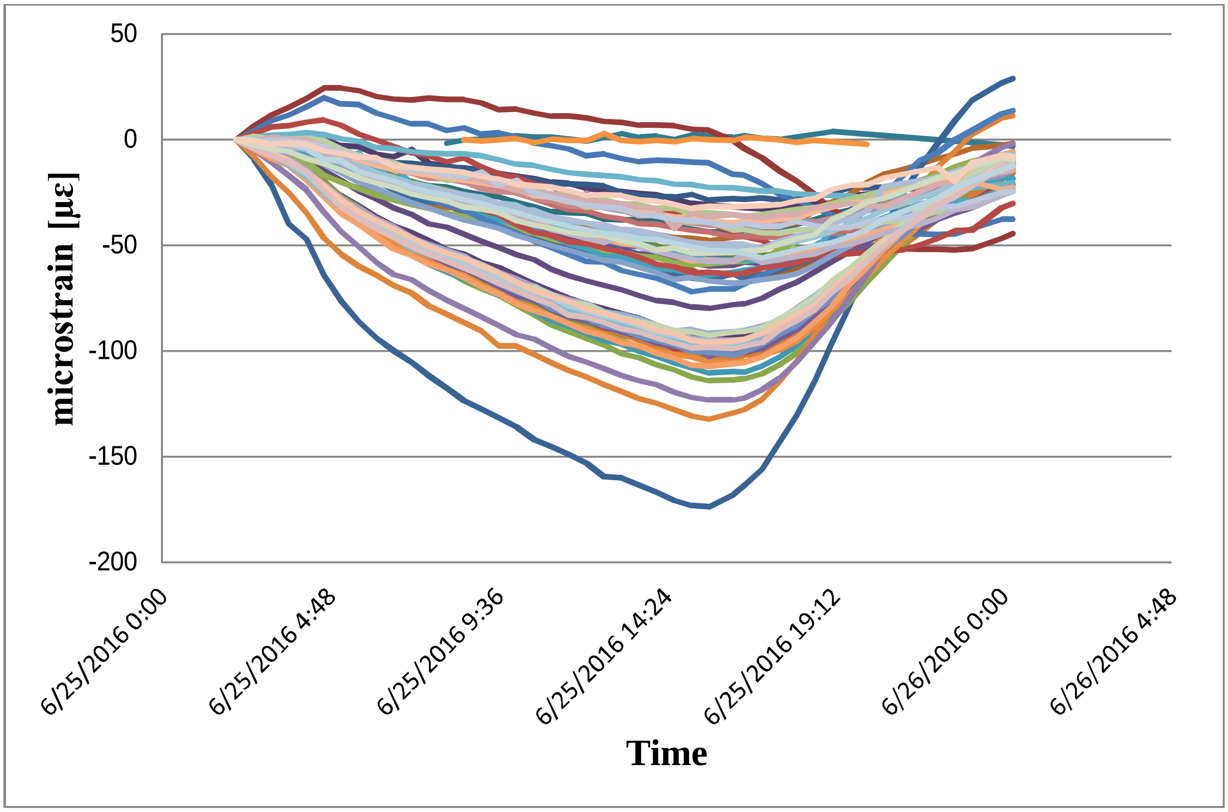


Figure 16: Strain evolution of all fiber optic gauges for a 24 hour period.

Figure 17 shows dynamic data taken under ambient traffic loads for two minutes. Figure 18 focuses on the data during the 7-22 second interval. Examining the dynamic data will provide information on the natural frequency of the bridge and how the bridge vibrates. This can be provide information of the performance of the bridge over time as large changes in the natural frequency of the bridge are indications of changes in the bridge.

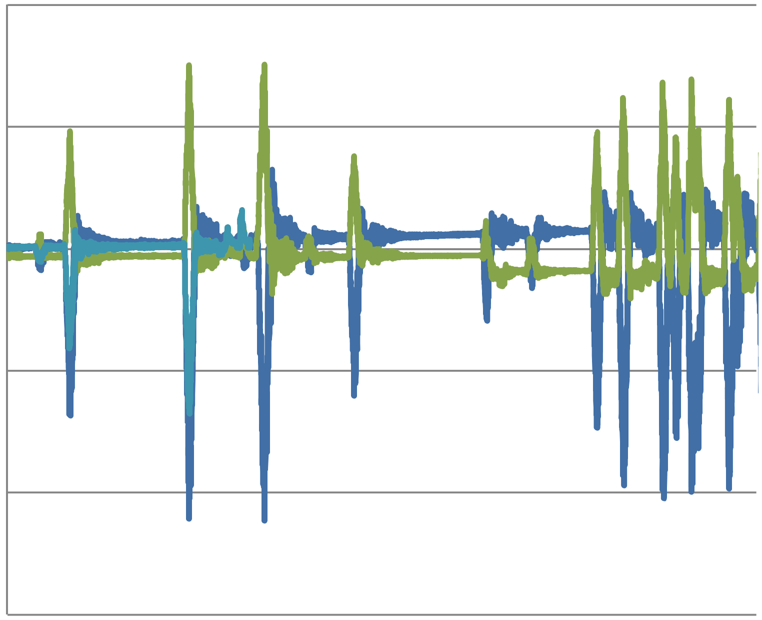


Figure 17: Bridge 9266 – dynamic data, Girders G1 and G2.

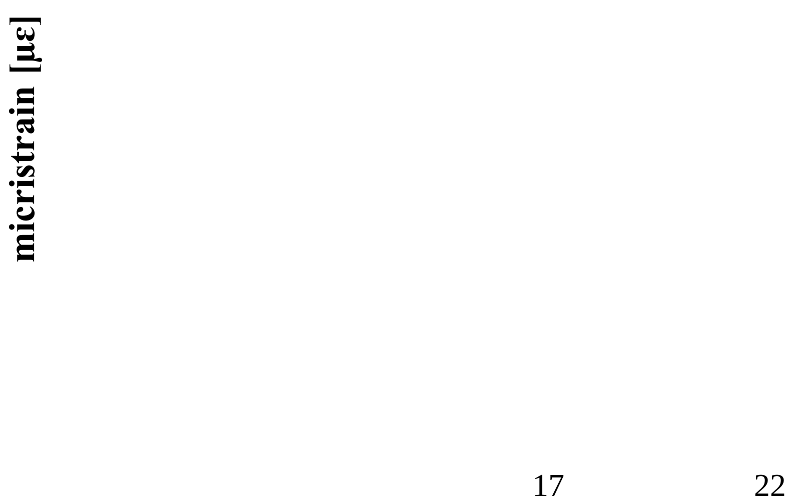


Figure 18: Bridge 9266 – dynamic data, Girders G1 and G2 (7 – 22 seconds).

Figures 19 and 20 show data collected during the load tests. From these plots, it can be seen how the strains increase under loaded conditions. A full load test, with additional trucks and the bridge closed, could provide additional behavioral data. Please note that times are 8 hours different than times the measurement were taken and are for illustrative purposes only.

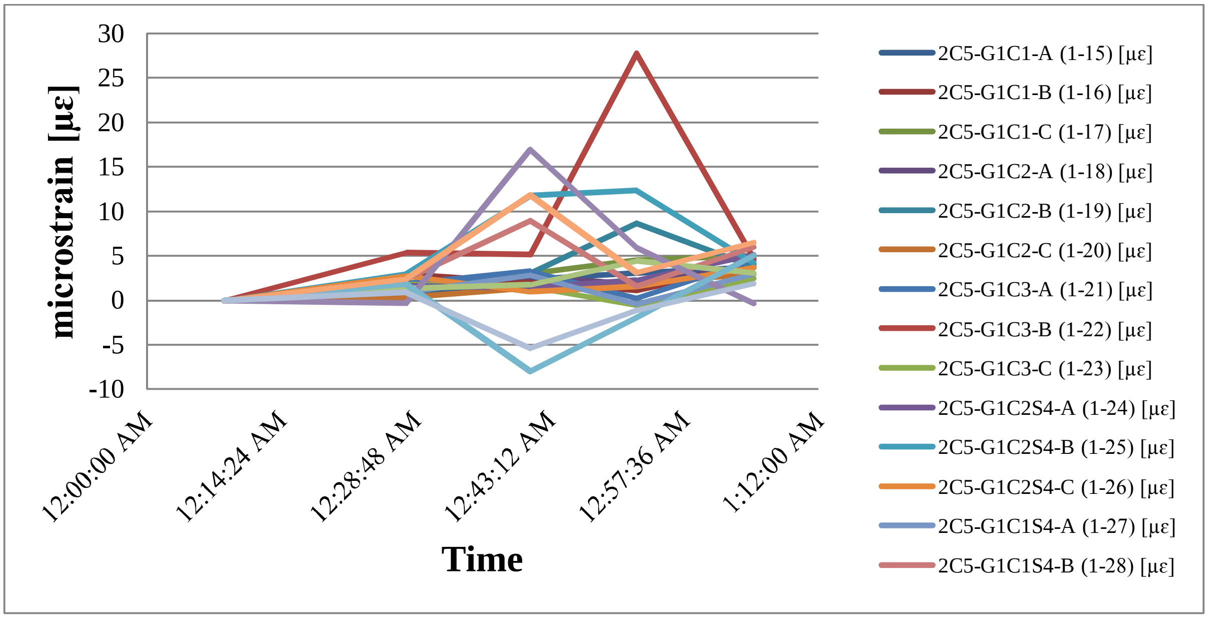


Figure 19: Bridge 9266 – load test, Girder G1.

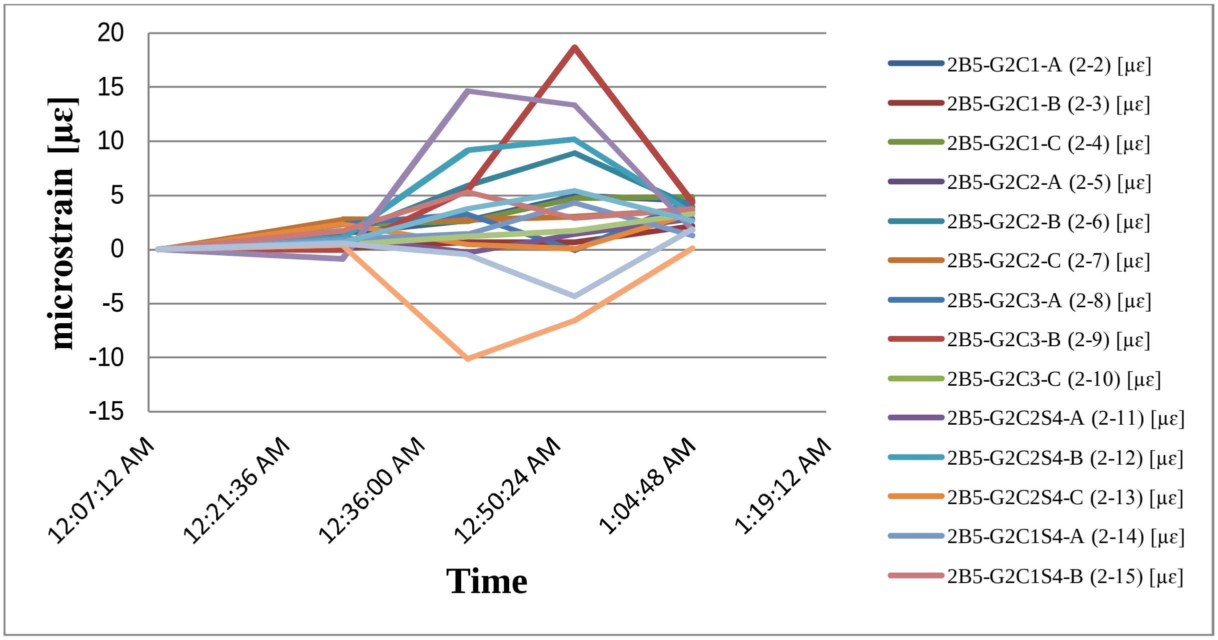


Figure 20: Bridge 9266 – load test, Girder G2.

Bridge 9266 – Required Repairs / Recommendations

The following repairs are needed for Bridge 9266 to bring the system back to the original installation:

- Replace all ADAM modules (thermocouple input modules), 8 total;
- SOFO bridge or ADAM convertor to communication with ADAM modules;
- Repair central monitoring housing cooling/heating system; and
- Power turned back on at facility.

The following recommendations are made to improve the instrumentation system at Bridge 9266:

- Provide internet access (wireless or hardline).

BRIDGE 9336

Bridge Number 9336, I-25 at Dona Ana Interchange at Mile Marker 9.7 in Las Cruces, was constructed in 2005. The bridge consists of a northbound and southbound components. The northbound was selected for evaluation. The bridge has one simple span with a length of 112.5 ft (34.3 m). The bridge consists of six BT-63 prestressed high performance concrete girders. The deck is a 7.5 in. (191 mm) thick reinforced concrete deck with Grade 60 reinforcement. A picture of the bridge can be seen in Figure 21.

Figure 21: Bridge No. 9336 (I-25 at Dona Ana Interchange).

The bridge was designed in accordance with AASHTO Standard Specifications 2002, Seventh Edition and current interims. The 28-day design compressive strength of the concrete was 9,500 psi (65.5 MPa). The girders were prestressed using 0.6 in. (15.2 mm) diameter seven wire low relaxation strands with and ultimate stress of 270 ksi (1862 MPa). Full design details can be found in Liang (2008).

The monitoring system used in Bridge 9336, was the MuST (Multiplexed Strain and Temperature) Monitoring System designed by Smartec. The systems consisted of a MuST reading unit with 16 channels, 6 connection boxes, 32 Fiber Bragg Grating (FBG) sensors, 26 thermocouples, and extension cables. The extension cables were used to connect the sensors to the connection box and reading unit. Figure 22 shows the instrumentation layout.

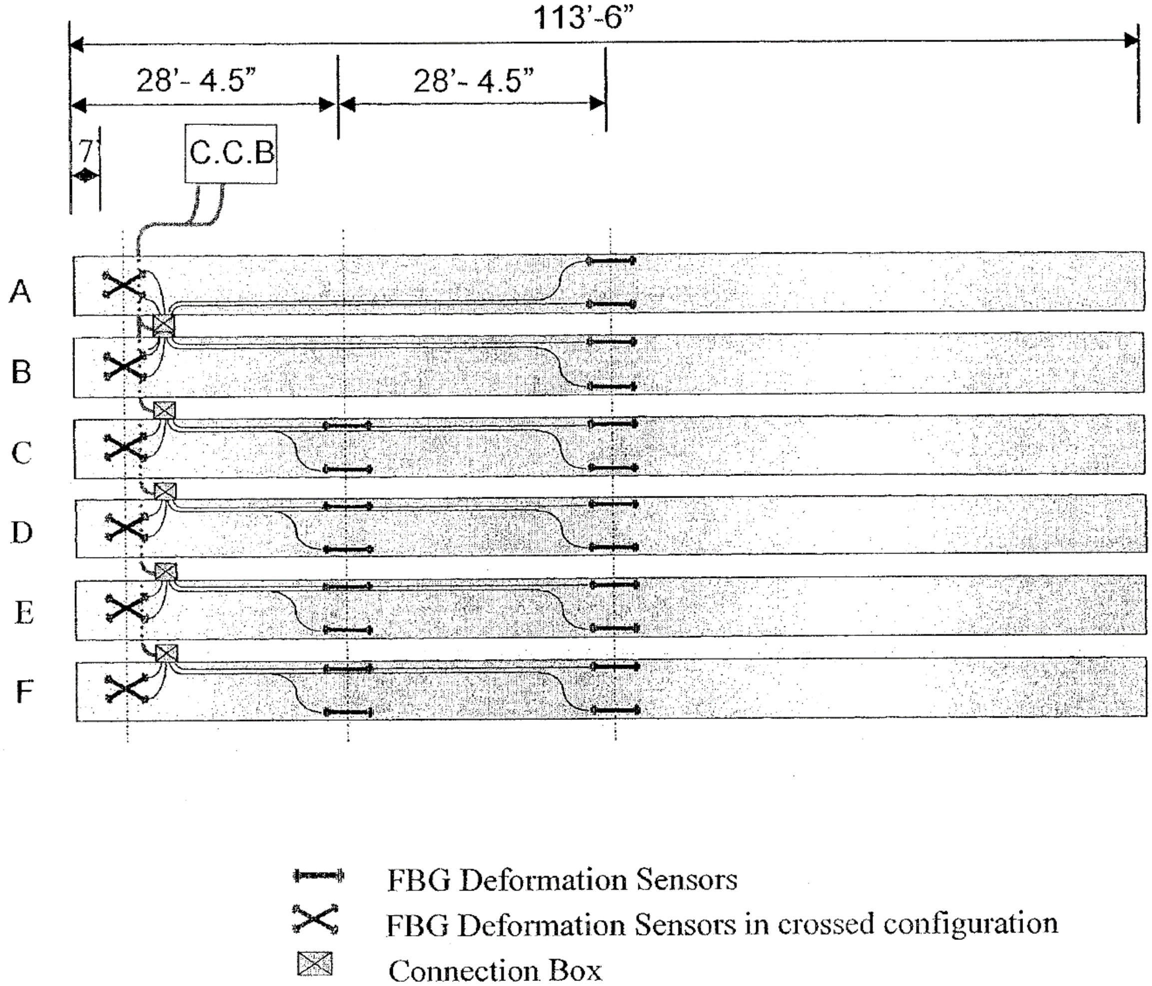


Figure 22: Bridge 9336 instrumentation layout (Liang 2008).

The FBG deformation sensor is a 3.28 ft (1 meter) long, single end deformation sensor with integrated temperature sensor. This enables the sensor to compensate for the change in temperature. The FBG sensor measures the deformation by transforming a static or dynamic distance variation into a change in reflected wavelength of a pre-stressed Fiber Bragg Grating that can be measured with the MuST reading unit (Liang 2008). The sensors have the capability of taking strain measurements in the range of -0.0035 to 0.0065, which is in the range of typical concrete behavior. Further information on the MuST sensors can be found in Appendix A. Tables 5 and 6 describes the location of each sensor in each girder.

Table 5: Sensor Location for Girders A, B, and C [adapted from Liang (2008)].

Sensor	Type	Away from bottom/top	Away from CL*
AMB	Parallel	2.36 in.	2 in.
AMT	Parallel	3.25 in.	0
AEB	Cross	8 ft away from the end	
AET	Cross	2’ 7” away from the bottom	
BMB	Parallel	2.46 in.	2 in.
BMT	Parallel	2 in.	0
BEB	Cross	8 ft away from the end	
BEY	Cross	2 ft - 6.5 in. away from the bottom	
CMB	Parallel	2.36 in.	2.36 in.
CMT	Parallel	3.25 in.	0
CQB	Parallel	2.75 in.	0
CQT	Parallel	3 in.	0
CEB	Cross	8 ft away from the end	
CET	Cross	2 ft - 7 in. away from the bottom	
* On the side of the connection box			

Table 6: Sensor Location for Girders D, E, and F [adapted from Liang (2008)].

Sensor	Type	Away from Bottom/top	Away from CL*
DMB	Parallel	2 3/8 in.	2 1/2 in.
DMT	Parallel	3.0 in.	0
DQB	Parallel	2 5/8 in.	0
DQT	Parallel	3 3/8 in.	0
DEB	Cross	8 ft away from the end	
DET	Cross	2 ft - 7.5 in. away from the bottom	
EMB	Parallel	2 1/4 in.	2 1/4 in.
EMT	Parallel	3 1/8 in.	0
EQB	Parallel	2 5/8 in.	0
EQT	Parallel	3 3/8 in.	0
EEB	Cross	8 ft away from the end	
EET	Cross	2’ 7” away from the bottom	
FMB	Parallel	2 1/4 in.	2 1/4 in.
FMT	Parallel	3 1/8 in.	0
FQB	Parallel	2 5/8 in.	0
FQT	Parallel	2 ¾ in.	0
FEB	Cross	8 ft away from the end	
FET	Cross	2 ft - 6.5 in. away from the bottom	
* On the side of the connection box			

Current State of Sensors – Bridge 9336

Table 7 provides information on the current state of the sensors in Bridge 9336. Of the 58 gauges originally installed, 56 sensors are currently still functioning.

Table 7: Status of fiber optic sensors embedded in Bridge 9336.

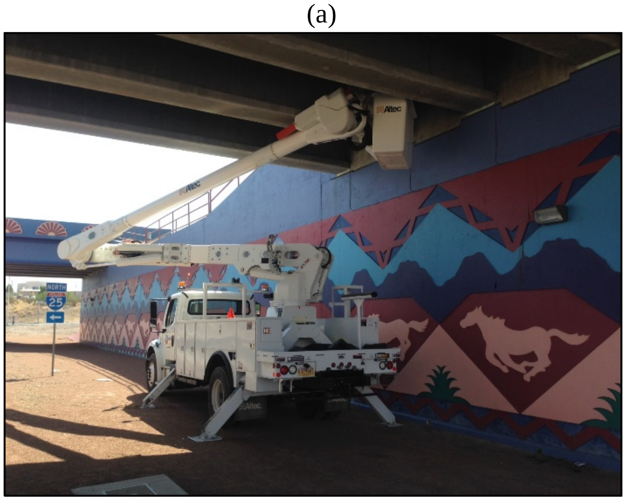
Sensor Name	Serial Number	Type	Working	Notes
GA_MB_AL_Ch1_4762	4762	Temperature	Yes	
GA_MT_B_CH1_4772	4772	Temperature	Yes	
GA_ET_Csh_Ch1_4782	4782	Temperature	Yes	
GA_EB_D_CH1_4788	4788	Deformation	Yes	
GA_MB_AL_Ch1_4762	4762	Deformation	Yes	
GA_MT_B_CH1_4772	4772	Deformation	Yes	
GA_ET_Csh_Ch1_4782	4782	Deformation	Yes	
GB_MB_AL_CH2_4763	4763	Temperature	Yes	
GB_MT_B_CH2_4773	4773	Temperature	Yes	
GB_ET_Csh_Ch2_4783	4783	Temperature	Yes	
GB_EB_D_CH2_4789	4789	Deformation	Yes	
GB_MB_AL_CH2_4763	4763	Deformation	Yes	
GB_MT_B_CH2_4773	4773	Deformation	Yes	
GB_ET_Csh_Ch2_4783	4783	Deformation	Yes	
GC_MB_AL_CH3_4764	4764	Temperature	Yes	
GC_MT_B_CH3_4774	4774	Temperature	Yes	
GC_QT_CL_Ch3_4778	4778	Temperature	Yes	
GC_MB_AL_CH3_4764	4764	Deformation	Yes	
GC_MT_B_CH3_4774	4774	Deformation	Yes	
GC_QT_CL_Ch3_4778	4778	Deformation	Yes	
GC_QB_Ash_CH4_4768	4768	Temperature	Yes	
GC_ET_Csh_Ch4_4784	4784	Temperature	Yes	
GC_EB_D_CH4_4790	4790	Deformation	Yes	
GC_QB_Ash_CH4_4768	4768	Deformation	Yes	
GC_ET_Csh_Ch4_4784	4784	Deformation	Yes	
GD_MB_AL_CH5_4765	4765	Deformation	Yes	
GD_MT_B_CH5_4775	4775	Temperature	Yes	
GD_QT_CL_Ch5_4779	4779	Temperature	Yes	
GD_MB_AL_CH5_4765	4765	Deformation	Yes	
GD_MT_B_CH5_4775	4775	Deformation	Yes	
GD_QT_CL_Ch5_4779	4779	Deformation	Yes	
GD_QB_Ash_CH6_4769	4769	Temperature	Yes	
GD_ET_Csh_Ch6_4785	4785	Temperature	Yes	
GD_EB_D_CH6_4791	4791	Deformation	Yes	
GD_QB_Ash_CH6_4769	4769	Deformation	Yes	
GD_ET_Csh_Ch6_4785	4785	Deformation	Yes	
GE_MB_AL_CH7_4766	4766	Temperature	No	
GE_MT_B_CH7_4776	4776	Temperature	Yes	

GE_QT_CL_Ch7_4780	4780	Temperature	Yes	
GE_MB_AL_CH7_4766	4766	Deformation	No	
GE_MT_B_CH7_4776	4776	Deformation	Yes	
GE_QT_CL_Ch7_4780	4780	Deformation	Yes	
GE_QB_Ash_CH8_4770	4770	Temperature	Yes	
GE_ET_Csh_Ch8_4786	4786	Temperature	Yes	
GE_EB_D_CH8_4792	4792	Deformation	Yes	
GE_QB_Ash_CH8_4770	4770	Deformation	Yes	
GE_ET_Csh_Ch8_4786	4786	Deformation	Yes	
GF_MB_AL_CH9_4767	4767	Temperature	Yes	
GF_MT_B_CH9_4777	4777	Temperature	Yes	
GF_QT_CL_Ch9_4781	4781	Temperature	Yes	
GF_MB_AL_CH9_4767	4767	Deformation	Yes	
GF_MT_B_CH9_4777	4777	Deformation	Yes	
GF_QT_CL_Ch9_4781	4781	Deformation	Yes	
GF_QB_Ash_CH10_4771	4771	Temperature	Yes	
GF_ET_Csh_Ch10_4787	4787	Temperature	Yes	

Figure 23 shows pictures during the evaluation of Bridge 9336. Due to the state of the sensor systems, minimal repair work had to be done. Figure 24 shows picture from the load tests performed on Bridge 9336.

(a)

(b)



(c)

(d)

Figure 23: Bridge 9336 evaluation – (a) typical junction box; (b) inside junction box; (c) under-bridge access unit; (d) NMDOT personnel examining data.

(a) (b) (c) (d)

Figure 24: Bridge 9336 load test – (a) dynamic test; (b), (c), and (d) static load test.

Samples of data taken for Bridge 9336 are provided in Figures 25 through 27. Figure 25 shows the strain evolution over a several day period. Figures 26 and 27 provide data collected from the static load test. Figure 28 shows a sample of dynamic data from Bridge 9336.

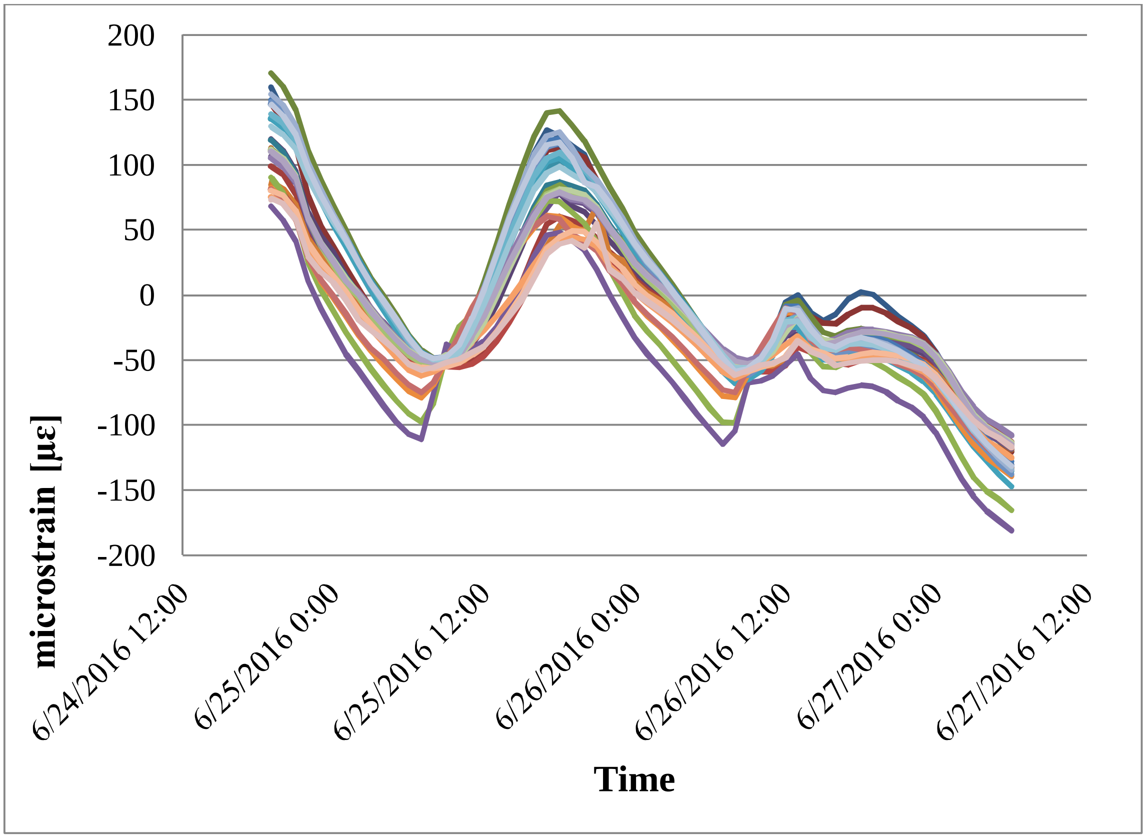


Figure 25: Bridge 9336 – strain evolution, all sensors.

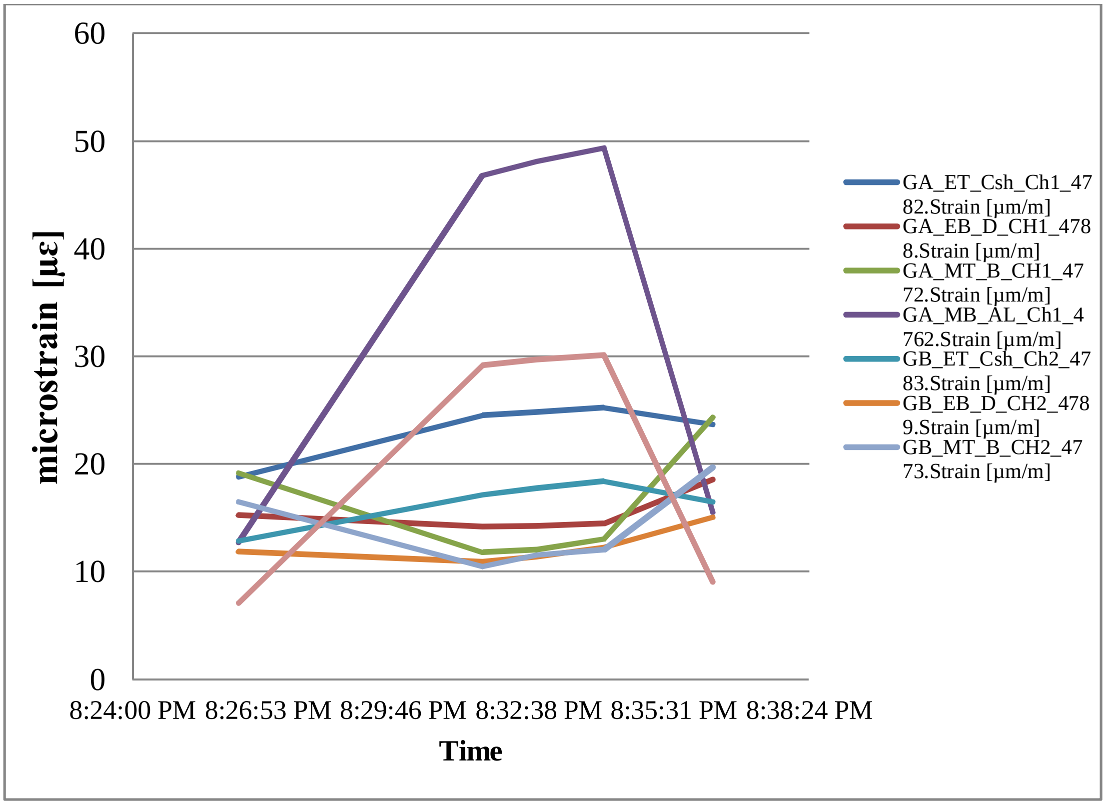


Figure 26: Bridge 9336 – static test – southbound, west lane with truck at quarter point.

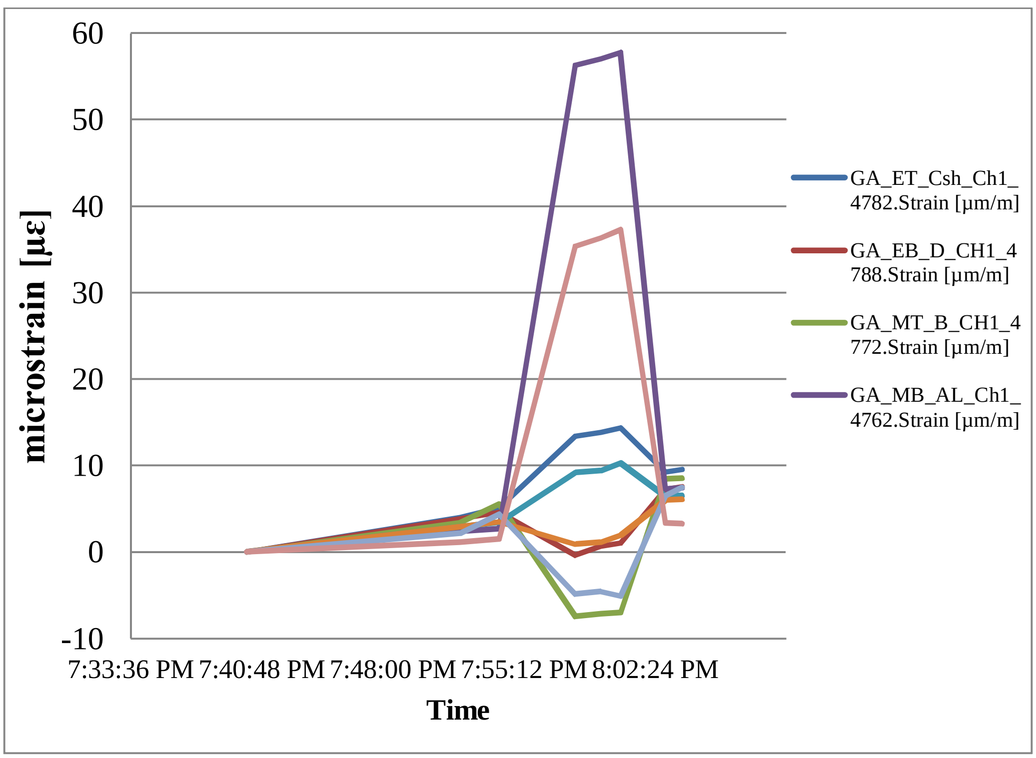


Figure 27: Bridge 9336 – static test – southbound, west lane with truck at midspan.

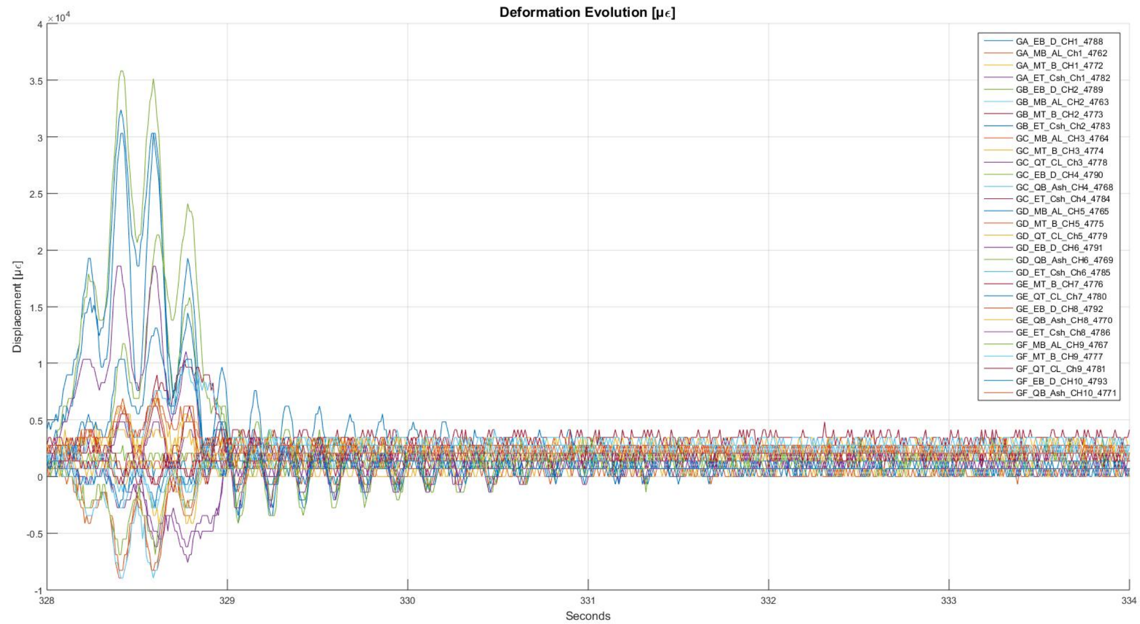


Figure 28: Bridge 9336 – sample of dynamic data.

Bridge 9336 – Required Repairs / Recommendations

The following repairs are needed for Bridge 9336 to bring the system back to the original installation:

- Repair heating / cooling unit on the central monitoring housing unit.

The following recommendations are made to improve the instrumentation system at Bridge 9336:

- Provide internet access (wireless or direct connection).

SUMMARY

Bridges 9234, 9266, and 9336 located near Albuquerque and Las Cruces, New Mexico were originally instrumented with fiber optic sensors in 2000, 2004, and 2005, respectively. The last time data was collected for these bridges was over a decade ago. Since that time, the instruments have been dormant and future use was uncertain. From June 20 - 26, 2016, the functionality of the sensors in each bridge were evaluated. It was found that approximately 90% of all gauges in all three bridges were still working properly. Basic repairs, such as broken connection ends, were made to the systems when possible; however, some repairs, such as replacing/repairing of multifiber cables, were outside the scope of this project. The specific repairs are described in detail for each bridge in this report. In addition, recommendations for improvements of the systems at each bridge are given.

On June 21, 2016, RocTest gave a presentation on the basic operation and applications of the different fiber optic sensors. This was followed by a site visit to Bridge 9234, located by Albuquerque, NM by NMDOT personnel to gain further experience with the sensor systems and the data being collected under ambient traffic.

Data was collected for each bridge and varied based on the site conditions. Due to the damage and time restrictions at Bridge 9234, minimal data was collected. For Bridges 9266 and 9336, located in Dona Ana County, it was possible to collect more data and modified load tests were conducted under dynamic and static conditions for future data analysis. All data collected can be found on the accompanying data-stick.

RECOMMENDATIONS FOR IMPLEMENTATION OF LONG TERM MONITORING

With over 90% of the sensors embedded in each bridge working, there is an excellent opportunity to gain a significant amount of useful information for the future evaluation of each bridge. Upgrading the systems for long-term monitoring will provide supplemental resources to the visual-based bridge inspections, provide a more quantitative approach to assessing bridge condition and identifying maintenance needs, provide data for future durability studies, and lead the way for New Mexico to move toward long-term monitoring of bridges through the FHWA Long Term Bridge Program. Through the reboot of the embedded fiber optic sensors, the following parameters can be monitored in the future:

- average longitudinal strain;
- average shear strain;
- beam curvature;
- internal temperature; and
- temperature gradient.

Furthermore, the following parameters can be estimated using appropriate algorithms and data analysis:

- deformed shape;
- displacement distribution;
- crack distribution and characterization; and
- prestress losses.

From this information, a better understanding of the bridge behavior will be gained. This data will also provide the resources necessary to develop a fully calibrated finite element model. With these tools, the following potential applications will be possible:

- understanding the formation of shear cracks in prestressed concrete bridges;
- providing needed information for permitting purposes, including the development of a fee schedule based on potential damage caused by overloads;
- quantitative data (i.e., non-visual) for bridge inspection;
- help to guide inspections by identifying changes in behavior of load carrying members based on recorded strains / deformations;
- correlation of crack size to strain measurement;
- evaluation of shear/moment distribution factors;
- evaluation of dynamic impact factors;
- monitoring of key corridors throughout the State;
- provide background and instrumentation / data acquisition needs for implementation in future monitoring projects; and
- help identify maintenance needs and evaluate repairs.

Long-term monitoring of these instrumented bridges will provide the NMDOT with new tools to improve the management of the transportation assets in the State. The quantitative data collected by the structural health monitoring systems will improve inspection procedures, design methods, overload permitting, and maintenance decisions. With the continued push to move more toward non-destructive testing technologies, utilizing the sensors that are already in-place to conduct diagnostic and proof load tests on these bridges provides more objective data to establish current conditions and performance trends over time as affected by environmental conditions and high truck traffic volumes.

Long-Term Equipment Needs

To establish a long-term monitoring program, the main equipment needs are the data acquisition reading units. Two types of reading units are required: static and dynamic. Three options are provided below for obtaining the reading units in order of most expensive (1) to least expensive (3). Estimates are provided for cost of each option – please note that these estimates provide a range of cost based on assumed equipment and software needs only (based on prices as of July 14, 2016) and excludes the cost associated with data collection, data interpretation, and reporting. These values are only estimates and could change based on the scope of the services / project.

1. Purchase reading units and accessories for each bridge to provide continuous monitoring capabilities at all three bridges. (Estimated cost range: $150,000 - $200,000)
2. Purchase reading units and accessories that are transportable between bridges for monitoring for a limited time at each bridge. Note that the bridges will not be continuously monitored under this option. (Estimated cost range: $60,000 - $100,000)
3. Rent equipment from RocTest / Smartec for specific time periods. Bridges will only be periodically monitored under this option. (Estimated cost range: $15,000 - $30,000 / per time period)

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APPENDIX A: FIBER OPTIC SENSOR INFORMATION

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ROCTEST

SOFO Deformation Sensor

SOFO

LONG-GAUGE DEFORMATION SENSOR
ROBUST AND TEMPERATURE INDEPENDENT

For surface mounting or embedding in concrete and mortars.
Ideal for long-term structural deformation monitoring.
20 year track record in field applications.

Description

The SOFO deformation sensors are the ideal transducers to monitor large civil structures. Their long-gauge and insensitivity to temperature variations, make them ideal for long-term monitoring of structural deformations. The sensors can be quickly and easily surface mounted or directly embedded in concrete and mortars.

SOFO sensors have been the standard in fiber optic deformation monitoring for the last 20 years.

The sensor is composed of two main parts, an active and a passive one. The active part contains the reference and the measurement fibers and measures the deformations between its two anchors. The passive part is insensitive to deformations and is used to connect the sensor to the Reading Unit. The output is terminated with an E-2000 connector with a built in protective cover.

Key Features

- High resolution
- Embeddable or surface mountable
- Temperature insensitive
- Insensitive to corrosion and vibrations
- No calibration required
- Easy to install
- Long term reliability
- Waterproof
- Static measurements

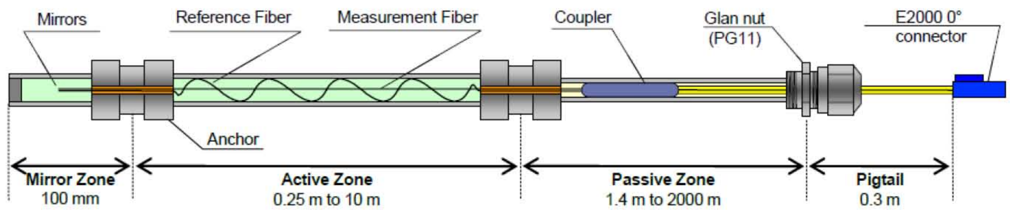
Applications

- Bridge Structural Health Monitoring
- Building monitoring
- Dam instrumentation
- Tunnel deformation monitoring
- Pipeline local deformation analysis

Specifications

Length of active zone (LA, measurement basis)	25 cm to 10 m, standard lengths 10 m to 20 m, customized lengths upon request
Length of passive zone (connecting cable)	1 m to 100 m
Measurement range	0.5% of LA in shortening, 1% of LA in elongation
Measurement precision	0.2% of the measured deformation or better
Measurement resolution	2 µm RMS
Connecting cable protection options (see specific datasheet for details)	Standard (recommended for embedding or surface mounting in normal conditions) Stainless steel protecting tube (recommended in harsh conditions) Simple cable without protecting tube (recommended for laboratory conditions)
Operating temperature	Standard active zone: -50 °C to +110 °C Special active zone (upon request): -50 °C to +170 °C Passive zone: -40 °C to +80 °C
Waterproof	5 bars (15 bars with extra protection on anchoring points)
Calibration	Not required

Sensor Configuration



Not to scale

Ordering information

- Length of active zone
- Length of passive zone
- Connecting cable type

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12.1010 MUST DEFORMATION SENSOR

Fiber Bragg Grating (FBG)

SMARTEC

GENERAL DESCRIPTION

The FBG deformation sensors are transducers that transform a static or dynamic distance variation into a change in reflected wavelength of a pre-stressed Fiber Bragg Grating that can be measured with SMARTEC Reading Units.

TECHNICAL DESCRIPTION

The sensor is composed of an active and a passive part. The active part contains the measurement fiber and measures the deformations between its two ends, transforming it into a wavelength shift of the Fiber Bragg Grating. The passive part is insensitive to deformations and is used to connect the sensor to the Reading Unit. In the passive part of the sensor, it is possible to install a loose Fiber Bragg Grating for temperature sensing and compensation.

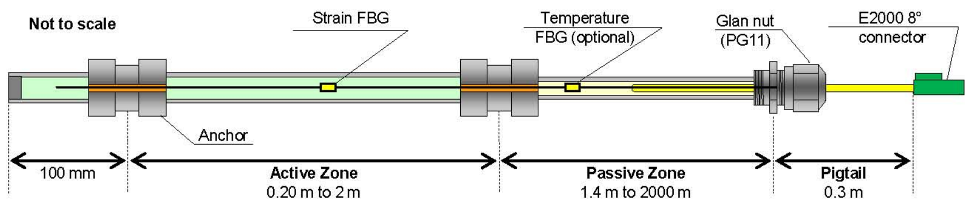
The sensors are available in single-ended, double-ended and chained configuration. It is possible to connect up to 7 full-range temperature compensated sensors. The sensors are terminated with E2000-APC connectors or on user's specifications.

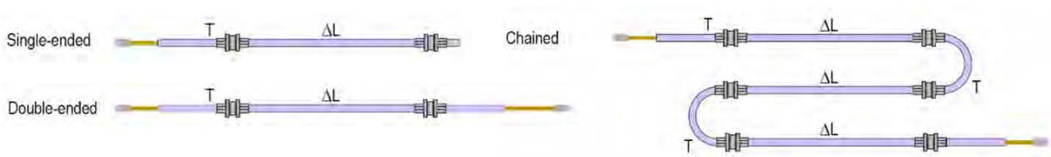
The sensors can be quickly and easily installed without affecting the construction schedule. They can be directly embedded in concrete and mortars, or surface mounted.

FEATURES

- High resolution
- Static and dynamic measurements
- Long Gauge-length
- Embeddable in concrete or surface mountable
- Temperature compensation
- Available in single-ended, double-ended and chained configurations
- Insensitive to corrosion
- Immune to electromagnetic fields
- Easy to install
- Long lifetime
- Waterproof

SENSOR CONFIGURATION





TECHNICAL CHARACTERISTICS

Length of active zone (measurement basis)	20 cm to 2m
Length of passive zone (connecting cable)	1 to 200 m (longer distances available on request)
Pre-tensioning of the measurement fiber	0.5% of the length of active zone (others on special request)
Connecting cable protection options (see Fiber Optic cable datasheet 40.1020 for details)	Standard cable: Gray (for embedding or surface mounting in normal conditions) Stainless steel reinforced cable: Black (recommended in harsh conditions) Simple unprotected cable: Yellow (only for laboratory conditions)
Measurement range	Strain: 0.5 % in shortening, 0.75 % in elongation -2500 με to +3000 με (for chain configuration) Temperature: -40 °C to +80 °C
Strain resolution / accuracy	0,2 με / 2 με (using SMARTEC Reading Units)
Optical connectors	E-2000 AC (8°)
Temperature measurement range	-40 °C to +80 °C
Operating temperature	Passive zone: -40 °C to +80 °C Standard active zone: -50 °C to +110 °C Special active zone (upon request): -50 °C to +170 °C
Waterproof	5 bars (15 bars with extra protection on anchoring points)

ORDERING INFORMATION

- Active Length, Cable length, FBG Wavelength, Temperature compensation (Yes/No), Single/Double Ended, Cable type

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