CENTER FOR INFRASTRUCTURE ENGINEERING STUDIES

UTC R141

Remote Health Monitoring of Hillsborough County Bridges

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UTC R141		

4. Title and Subtitle	5. Report Date
Remote Health Monitoring of Hillsborough County Bridges	December 2005
	6. Performing Organization Code
7. Author/s Ashraf Ayoub, Ebrahim Mehrani	8. Performing Organization Report No. 00001452
9. Performing Organization Name and Address Center for Infrastructure Engineering Studies/UTC program University of Missouri - Rolla 223 Engineering Research Lab Rolla, MO 65409	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTRS98-G-0021
12. Sponsoring Organization Name and Address U.S. Department of Transportation Research and Special Programs Administration 400 7th Street, SW Washington, DC 20590-0001	13. Type of Report and Period Covered Final 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The objective of this research is to investigate the use of newly emerging types of sensors for remote health monitoring of concrete bridges in Hillsborough County. The findings of this work will provide a basis for selecting effective sensor systems suitable for the harsh environment in the county, which will enable practical, cost-effective, long-term assessment of concrete bridge structures. The outcome will form the basis of a full proposal that addresses corrosion diagnosis of prestressed bridges.

17. Key Words	18. Distribution Statement
Bridge maintenance, Fiber optic sensors, Remote sensing	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. Of Pages	22. Price
unclassified	unclassified		

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ABSTRACT

The research project concerns the construction, testing, and remote health monitoring of the first smart bridge structure in Florida, the East Bay bridge in Gibsonton, Hillsborough County. The East Bay bridge is a four span, continuous, deck-type structure with a total length of 120’and width of 55’. The superstructure consists of an 18’’ cast-in-place reinforced concrete slab, and is supported on prestressed pile bents, each consisting of 5 piles. The smart sensors used for remote health monitoring are the newly emerged Fabry –Perot (FP) Fiber Optic Sensors, and are both surface-mounted and embedded in the deck. Static and Dynamic testing of the bridge were performed using loaded SU-4 trucks, and a finite element model for the bridge was developed for the test cases using commercial software packages. In addition, the smart sensors were connected to a data acquisition system permanently installed on-site. This system could be accessed through regular phone lines, which permits the evaluation of the bridge behavior under live traffic loads. Currently, these live structural data under traffic loading are transmitted to Hillsborough county’s bridge maintenance office to assist in the health evaluation and maintenance of the bridge. The data collected, as well as the analytical studies, suggest that current design specifications for deck-type bridges are conservative. The technology developed under this work will enable practical, cost-effective, and reliable systematic maintenance of bridge structures, and the study will provide a unique opportunity for future growth of this technology in the state of Florida and in other states.

INTRODUCTION

Continuous health monitoring of bridge structures is a new area that has been driven by the necessity of efficient structural condition assessment. Most assessment, repair and replacement decisions of bridges today are based on visual observations, which are highly subjective (1,2). According to (3), subjective or inaccurate condition assessment has been identified as the most critical technical barrier to the effective management of bridges, which results in an annual $3 billion maintenance cost in the US (2). Nevertheless, an earlier study (4) confirmed that more than 40 per cent of the bridges in the U.S. are functionally obsolete or structurally deficient due to corrosion, scour, or fatigue effects. In addition, several bridges have experienced major damage or collapse recently due to extreme events (e.g. earthquakes, hurricanes).

With the emergence of today's new technologies, structures can now be monitored remotely from a central station that is located several miles away from the field. Sensors are placed at several critical locations along the structure, and send structural information (e.g. strains, accelerations) to the central station. The structure is thus thought of as a smart system that is capable of sending information and providing warnings before any major failure.

Several types of advanced sensors are used for remote monitoring and damage detection. Fiber Optic strain Sensors (FOS) are the most commonly used, especially in Canada by the ISIS center (5). The so-called WiMMS accelerometers have been developed at the Blume Earthquake Engineering Center at Stanford University (6). In addition, miniature micro-electro-mechanical systems (MEMS) or smart dust accelerometers (7) have been also used.

STATE-OF-THE-ART IN FOS TECHNOLOGY

The concept of wireless monitoring has proven to be successful in Canada, Europe and recently the US (5,8,9). Fiber Optic strain Sensors are in general better suited for this application since they are easily bonded to reinforcement bars and embedded in the structure, and they can provide a complete strain history including strains from concrete curing, construction loads and in-situ service loads, and creep and thermal changes. FOS sensors have proven to be accurate, inexpensive, and easy to use. FOS sensors are not only limited to surface sensing, but are also capable of extracting 3D strain components as confirmed by a recent study (10).

Fiber optic sensors have numerous advantages: small size, light weight, long term stability, large selection of gauge length, corrosion-resistance, wide variety of packaging for surface mounting and embedment in the structure, distributed capability, immunity to electromagnetic and radio frequency interference, and multiplexing capabilities among others. Their main advantage though lies in their remote sensing capabilities. The most commonly used (FOS) are: (a) the Fiber Bragg Grating (FBG), (b) the Fabry Perot (FP), and (c) the long gauge sensors.

A Fiber Bragg Grating (FBG) sensor can be fabricated from a continuous germanium doped fiber core, surrounded by germanium-doped silica. The grating portion consists of a modulation in the index of refraction along a length of the continuous fiber core. Changes in length of the grating due to mechanical or thermal strain in the material in which it is embedded or bonded is detected as a shift in the wavelength of the reflected light. A reflectance spectrum obtained when a light source sends a signal on the grating is shown in Figure (1-a). FBG sensors were successfully used to monitor the behavior of prestressed beams (11), and were installed on several structures such as the Beddington Bridge in Calgary and the Taylor bridge in Manitoba (5). They has also been used in monitoring of pavement structures (12,13). A Fabry-Perot sensor (FP) measures a gap shift between two facing fiber ends contained in a glass capillary as shown in Figure (1-b). The reflected gap between the two faces is represented on a screen. FP sensors have been used to monitor the behavior of several structures such as the Morristown bridge in Vermont (14), and the Joffre bridge in Sherbrooke, Canada (15) among others.

Long gauge sensors come in two types: conventional telecom optical fibers, and Brillouin scattering. Although expensive, Long gauge sensors were used to monitor the behavior of several bridges such as the Rio Puerco bridge in New Mexico (16), and Highway 401 in Toronto (5).

REMOTE HEALTH MONITORING SYSTEM

The proposed remote sensing system consists of the following as shown in Figure (2):

a) Fabry-Perot (FP) Fiber Optic Sensors attached to critical locations of the structure

b) Fiber Optic Cables to connect the FP sensors to their signal conditioner system

c) Signal conditioner system housed in a secured on-site location

d) Power supply for charging the signal conditioner provided from nearby power lines

e) A phone line or fast DSL connection to connect the signal conditioner to the internet

The embedded FP sensors transmit the data to their signal conditioner through Fiber Optic Cables placed in conduits to be protected from the environment. The signal conditioner is connected through a phone line (or DSL connections if available) securely to the internet, where data could be retrieved and processed easily from the office with software like LabView.

CONSTRUCTION OF THE FIRST SMART BRIDGE IN FLORIDA

This section describes in details the construction of the East Bay bridge in Hillsborough county, the first smart bridge in the state of Florida. The installed remote sensing technique was conducted in accordance with the system described in the previous section. Hillsborough County decided to replace an existing concrete bridge with a cast-in-place reinforced concrete bridge on East Bay Drive in Gibsonton, Florida. The original bridge was a low profile concrete structure built in early 1970, and is shown in Fig. (3-a). The bridge was classified as functionally obsolete due to severe deck cracking from frequent heavy traffic loading, corrosion of the longitudinal reinforcements, as well as due to its narrow width.

Coordination of installation of smart sensors with the contractor and Hillsborough County project management team was crucial to the success of the research. Under no circumstances, the work related to health monitoring was allowed to delay construction. The critical time to install embedded sensor was when placement of reinforcing steel was in progress. The time was of essence for installation of sensors since pouring of concrete would begin as soon as reinforcing steel was in place.

The replacement bridge is a four-span 120’ long and 55’ wide structure and is shown in Fig. (3-b). The interior spans are 33’ and the exterior spans are 27’ long. The intermediate spans are continuous, and the middle span is fixed over the central bent. The superstructure is composed of 18” thick cast-in-place reinforced concrete slab. The substructure is composed of 24” square pre-stressed concrete piles and 3.5’ wide by 3’ high cast-in-place reinforced concrete caps. The top and bottom mats consisted of # 9 rebar (1.125” diameter) placed 6” on center. The clear space between the bars was 4.87”.

A total of sixteen Fiber Optic strain sensors were installed on this bridge. The sensor locations are described in the next section.

Determination of sensors location

Transversely, the embedded strain sensors were placed under the expected wheel locations, assuming trucks to occupy 10’ out of 12’ lane. Figure (4-a) illustrates the position of truck wheels with respect to the bridge width. This wheel position meets AASHTO 3.6 requirement. In addition, sensors were placed also on the shoulder lane. The shoulder lane was strategically selected for installation of sensors in order to be able to test the bridge under truck loads while it is still open to traffic.

Longitudinally, the embedded strain sensors for positive moments were placed at mid-spans and for negative moments over the bents. This is a simplified location very close to points of maximum moments. Four sensors at mid-spans were bonded to the bottom longitudinal reinforcing bars using special adhesive materials, and four other were surface-mounted to the concrete bottom deck surface. In addition, four sensors were bonded to the top reinforcing bars over the bents, and two were surface mounted to the concrete top deck surface. Two more sensors for temperature compensation were installed on the top and bottom rebars respectively. Figure (4-b) shows the location and description of all sensors.

Figure (4-c) depicts detailed location of sensors within concrete slab. Step-by-step procedure and techniques of installation are outlined in subsequent sections. Three types of sensor are used and are identified as 1). Surface mount, known as FOS-B (blade), 2). Embedded sensors 3). Embedded temperature sensors.

Installation of FOS sensors

The manufacturer of fiber optic sensors provided guidelines for installing sensors within and on structural members. However, the quality of installation would be as good as the knowledge and experience of the installer. Accuracy and good quality of data is directly related to proper installation of sensors. The researchers have exercised a great deal of patience and care during each step of every sensor installation. Numerous photographs and detailed description would be presented in every step of the sensors and equipment installation process.

a- Embedded Sensors

An electric angle grinder connected to an inverter and to a car's battery was used to grind (mill) the surface of steel rebar flat. An area of approximately 3" long and 3/8" wide on #9 grade 60 rebar (deformed) was milled flat. A straight edge was used to verify the flatness of the area. The milled area was wiped with Isopropyl alcohol and rinsed liberally with M-prep Neutralizer 5A. The sensors were placed on the rebars and held down with electric tape, one inch away from micro capillary. A very small drop of 5 minutes epoxy was placed on the incoming fiber optic, approximately 1/8" from micro capillary. As soon as the 5-minute epoxy was cured, adhesives were prepared per the manufacturer's recommendation and were applied with a linear motion along the entire length of the gage. Figures (5-a) and (5-b) show a close view of the installation process of sensors on rebars.

The remainder of adhesive was applied to the optical fiber up to the fiber jacket. For additional protection, an M-coat Protective coating was applied to the sensor. After this protective coating was dried, a rubberized waterproof sheet, nitrite rubber sheet was wrapped around the sensor. Immediately after application of adhesive over sensitive region of sensor, a piece of Mylar tape was placed over it to keep the sensor in good contact with surface of rebar. Figures (6-a) and (6-b) show the application of protective coating to sensitive region of gauge (M-coating), and application of nitrite rubber sheet over sensor and optical fiber.

Soon after sensors were bonded to rebars, FTI-10, a single channel data logger was used to test the sensors and verify they are properly bonded to the rebar surface, as shown in Fig. (6-c). The reading on the FTI-10 represents the cavity length of FOS-FP sensors in nm.

The micro capillary section of sensor is glass and thus is very sensitive to scratch and impact. Also, optical fibers are very sensitive to bends, kinks, sharp curves and impact. During final step of installation, a thick wrap of nitrite rubber sheet protected the gauge. Fiber optic cables were inserted into one-inch diameter schedule 40 PVC pipe. The conduits were guided through the crowded rebar mats to the edge of slab. The openings in the conduits were sealed with nitrate rubber sheet and caulking. The conduits were tightly secured to rebars. Figures (7-a) and (7-b) illustrate this process.

Conduits containing fiber optic cables were brought unto the forms for the slab. At this area, the fiber optic cables are most vulnerable to the construction activities such as worker's traffic and placing and removing the forms. A 2" diameter hole was drilled out to allow the conduit to exit the slab. Three small boxes (12"x12"x12") were fabricated to house the cables at the point of exit. A larger piece of form around the conduit was cut out to allow slab's side form to be removed safely and without struggle. The process is illustrated in Figures (8-a) and (8-b). Other alternatives for the cables to exit the forms were evaluated. One option was at the bottom of slab at the abutment. However, removal of slab forms would have severed the cables during dissembling the forms.

b- Surface-mounted sensors

Six FOS-B (blade) sensors were surface-mounted to the concrete deck, two on the top surface and four on the bottom. The sensors are designated as ASM, BSM, CSM and DSM as shown in Fig. (4-b). The bonding surface was sanded thoroughly using a 100 grids sandpaper to remove the latent and loose debris. The surface was sanded again using a 200 grids sand paper to provide a smooth bonding surface. The sanded surface was dusted and wiped off with non-lint paper tissues (facial tissue) wetted with 75% by volume isopropyl alcohol. The surface was wiped several times, each time with a new tissue and in one direction to avoid surface contamination. A thin layer of epoxy was evenly spread on the concrete and sensor was firmly placed against it. The sensor was held up with duct tape. The remainder of epoxy was spread on the blade for extra protection, as shown in Figure (9). The process was repeated for two sensors surface-mounted to the top deck surface.

Housing of Acquisition System

Conduits carrying the Fiber Optic cables were attached to the bridge with pipe clamps and tapcon screws. The acquisition system (DMI unit) was attached to the face of concrete parapet with tapcon screws, as shown in Figure (10-a). All conduits were attached to the side of bridge and to DMI case, as shown in Figure (10-b). The tip of each fiber optic cable was cleaned with cotton swap and alcohol thoroughly prior to connecting to DMI ports. The owner's tag was then attached to the DMI case, which was subsequently secured with a lock. The cost of the acquisition system (DMI unit) used with 16 channels is around $14,000, which accounts for less than 1% of the overall cost of the bridge ($1.5 Millions). The acquisition system weights only 4.8 Kg (10 lbs), and its sampling rate is 20 Hz.

Installation of Electricity and Telephone Line

Remote communication with DMI is established via internal modem. DMI has a 12 volts rechargeable battery to power up the equipment. However, the life of battery during the operation is short. To operate DMI efficiently and continuously, telephone and electric services were required. Telephone and power lines were brought to the bridge from about 200 feet south of the structure. The lines were in conduits and buried 30 inches below the surface. Figures (11-a) and (11-b) show the installation of telephone box and electric meter.

STATIC AND DYNAMIC TESTING OF THE FIRST SMART BRIDGE IN FLORIDA

In order to evaluate the accuracy of FP sensors, static and dynamic tests were performed on the bridge using single unit four axels SU4 trucks as shown in Fig. (12-a). SU4 trucks are most effective due to their short configuration and heavy weight (35.5 tons). Static tests were performed for six different loading conditions, but only one case is reported herein. In this case, the second axle of a 70kip SU4 truck was positioned in the middle of span 2. The strain contour lines of the 16 FP sensors are shown in Figure (12-b). These results are compared in the next section with a detailed finite element model. Dynamic tests of the bridge under moving trucks with different speeds were also performed in order to confirm the sensors accuracy under dynamic loading. The dynamic strain history response of sensor C for the case of a truck running with the maximum speed of 35 mph, is shown in Figure (12-c).

FINITE ELEMENT MODELING

A finite element model for the bridge was developed using the commercial software SAP2000 (17). The bridge deck was modeled using 4-node shell elements. The nodes along the bent lines were assumed to be fixed in the vertical direction only. The nodes along the central bent #3 were assumed to be fixed for both displacements and rotations due to the presence of hook anchorages extending from the bent. Only half of the deck was modeled as the presence of the fixed supports along the central bent prevents any forces to be transferred from one side of the deck to the other. The model was used to study the behavior of the bridge under the same loading condition of the static test described in the previous section. In this case eight point loads were used to represent the wheel loads. The analytical strain contour lines are shown in Figure (13) and are compared to the experimental contours of Figure (12-b). The maximum strain value obtained under the wheels is 35 μ. The corresponding recorded experimental value was 32 μ. From these results and the outputs of Figures (12-b) and (13), it is rather obvious that the FP sensors are capable of providing a high degree of accuracy in evaluating the response of the bridge under truck loads.

REMOTE HEALTH MONITORING OF THE EAST BAY BRIDGE

The data logger (DMI) located 35 miles from the office was remotely connected to, via modem. DMI was set to direct data acquisition, which shows the graph of vehicular activities. Screen shots of dynamic strain profiles taken in the office are shown in Figures (14-a) and (14-b). The observed small spikes in the graph indicate the passage of cars, and large spikes indicate the passage of much heavier trucks such as predominantly SU4 trucks traveling over the Bridge. The traffic data are currently being continuously collected and analyzed with the purpose of evaluating the bridge behavior under traffic loading, comparing maximum recorded stresses with predicted design values, and detecting possible future deficiencies.

EVALUATION OF COLLECTED DATA

The results of the SU4 truck tests along with the outputs of the finite element model, as well as the data collected from remote monitoring suggest that the bridge deck did not experience cracking under traffic loads, or experienced only secondary widely spaced cracks. Visual observations also confirmed this fact. To evaluate the performance of the bridge under service loads, the moment-curvature relationship of 1ft strip of the bridge section was developed using inelastic fiber beam models (e.g. 18 and 19). The fiber constitutive models used for confined and unconfined concrete followed the modified Kent and Park model (20), and the reinforcing steel stress-strain behavior was assumed to be elasto-plastic. From the moment-curvature plot in Figure (15), it could be concluded that:

(a) The bridge is over-reinforced, as the concrete crushing point (ultimate strength level) occurs before steel yielding.

(b) The cracking point is higher than the traffic level point. The bending moment corresponding to traffic level was evaluated from finite element analysis of the bridge under SU4 trucks. These values also match with the data recorded through remote monitoring.

(c) The ultimate strength of the bridge highly exceeds the ultimate moment demand assumed in the design process.

The preceding observations, along with the data collected through remote monitoring suggest that the current design specifications for deck-type bridges are highly conservative under service loading. Further studies and data collection are needed to confirm this conclusion. In addition, research and data analysis needs to be performed at the ultimate stage.

SUMMARY AND CONCLUSIONS

The paper presents a case study for the application of Fiber Optic Sensors (FOS) for remote health monitoring of bridge structures. A total of sixteen Fabry-Perot FOS sensors were installed on the East Bay bridge, in Hillsborough County, Florida. The bridge is a 4-span continuous reinforced concrete deck-type structure. The bridge is considered the first smart structure in the state of Florida. The FP sensors were both bonded to the longitudinal reinforcing bars and surface-mounted to the concrete deck. Detailed step-by-step description of the installation process is presented. Static and dynamic tests of the bridge under SU4 trucks were conducted. A finite element model was developed, and its output was compared to the experimental data obtained from the truck tests. The results confirmed the accuracy of FP sensors in evaluating the bridge behavior under traffic loads. A remote communication system was established through phone lines in order to connect the acquisition system to the internet. This technique enables live traffic monitoring from a central station located in the county’s maintenance office. Live traffic data are currently being collected and stored, and are being used to facilitate the bridge maintenance process, receive early warnings regarding possible structural deficiencies, and assist in decision-making processes regarding functionality of bridges. The proposed remote health monitoring technique with FOS sensors proved to be practical, cost-effective, and efficient providing its installation is performed in a very careful and accurate manner. Data analysis and evaluation confirmed current specifications for deck-type bridges are highly conservative.

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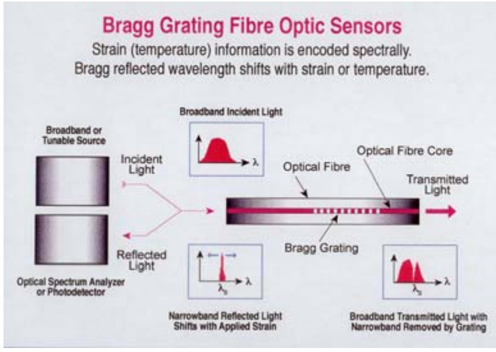
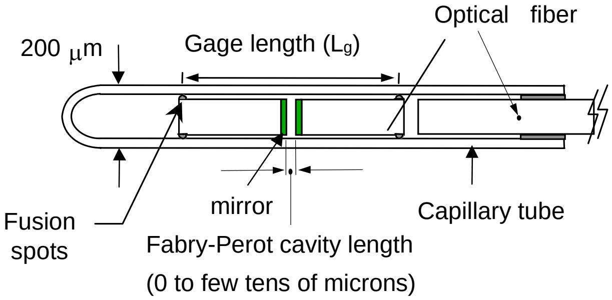


(a) Fiber Bragg Grating Sensor (from [5])



(b) Fabry-Perot Sensor (from [5])

FIGURE 1 Types of Fiber Optic Sensors

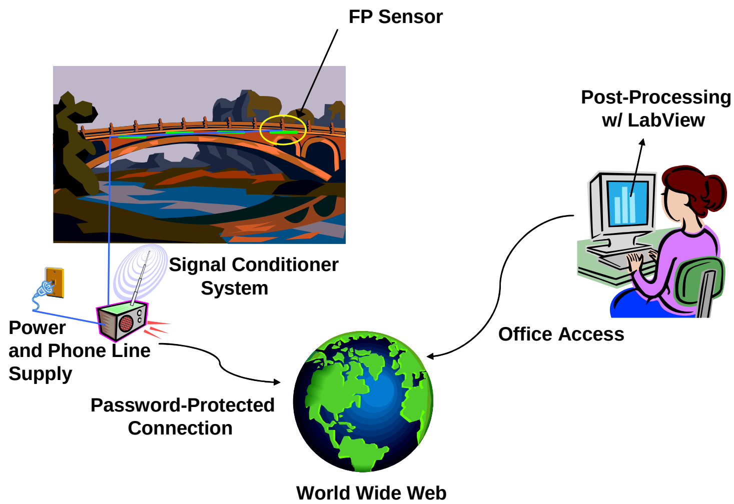
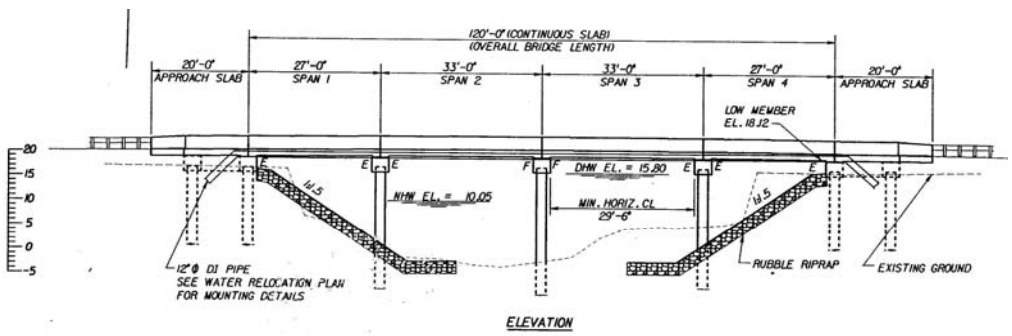


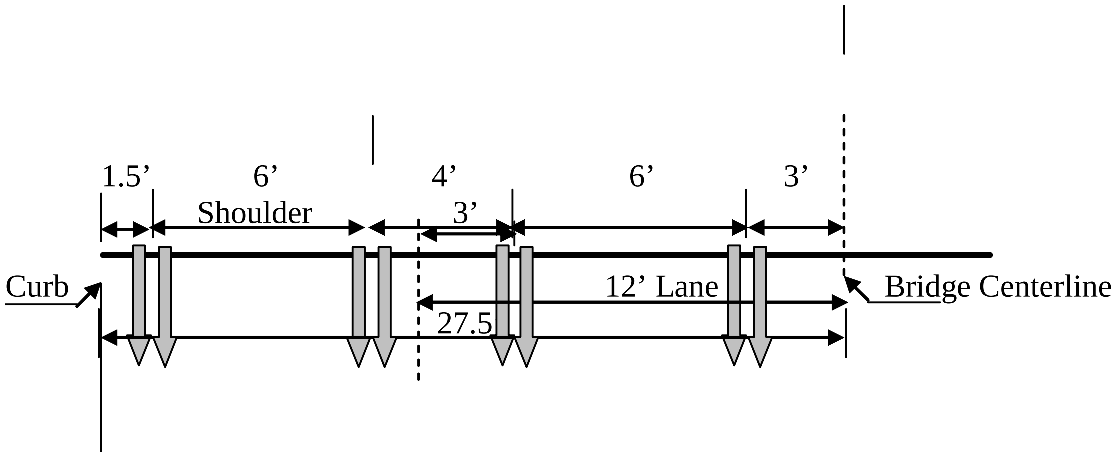
FIGURE 2 Remote Sensing System

(a) Original Bridge

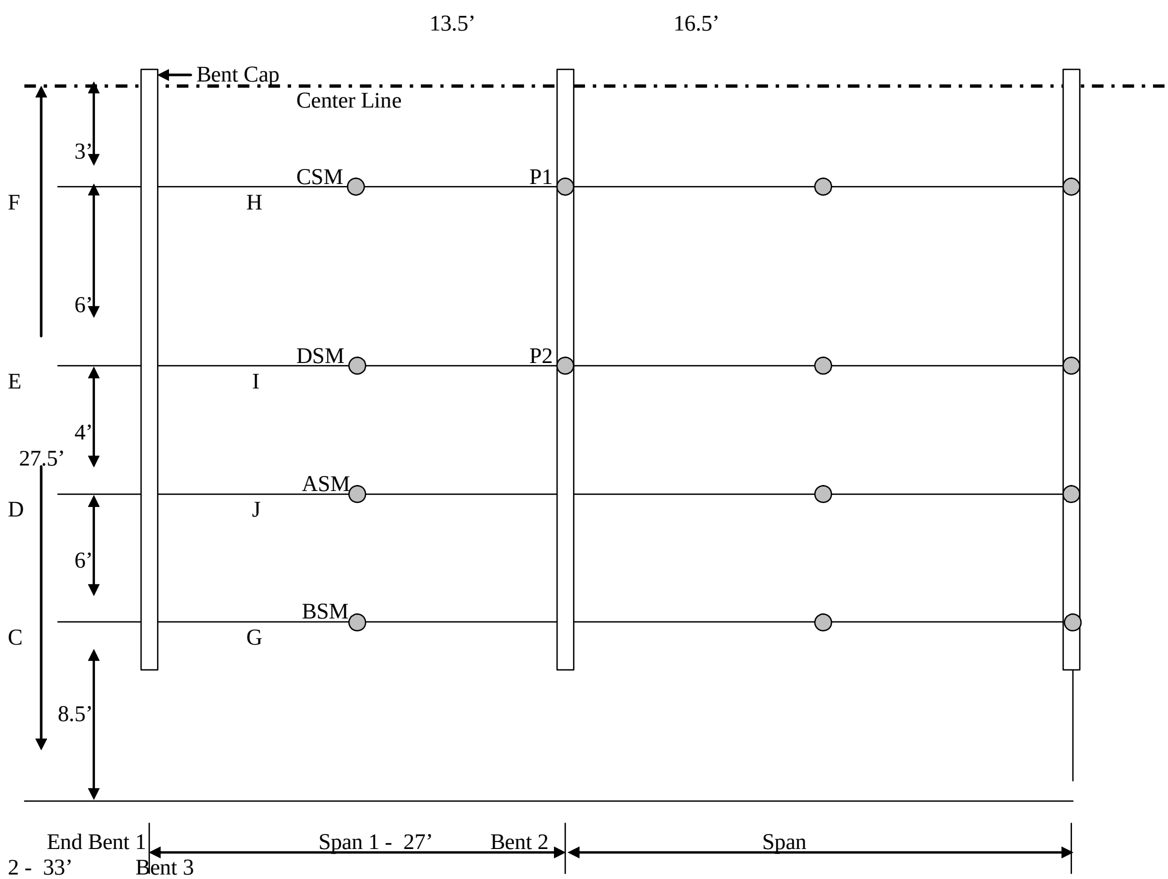


(b) New Bridge

FIGURE 3 Elevation view of the East Bay Bridge



(a) Transverse View



(b) Plan View

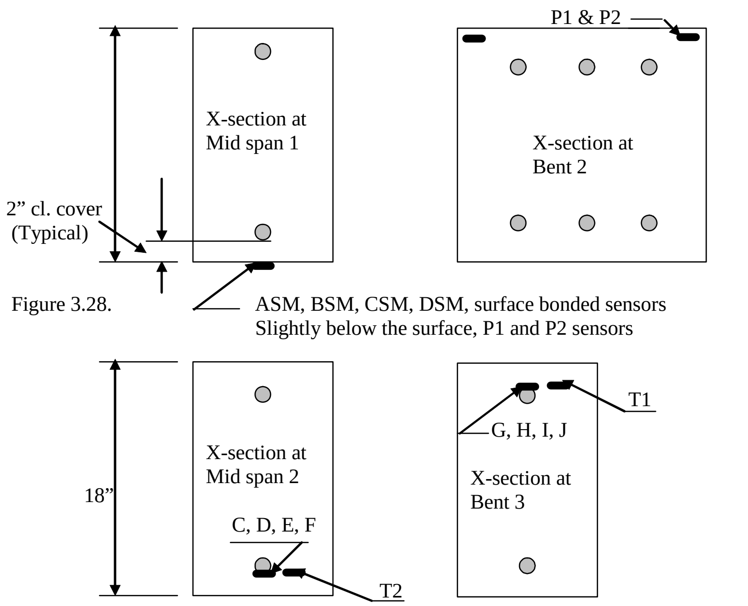


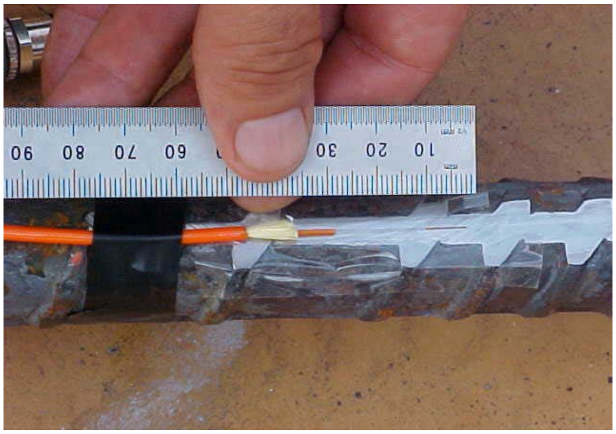
Figure 3.26. Embedded sensors C, D, E, F& T1 -Embedded sensors G, H, I, J & T2

(c) Location across the Depth

FIGURE 4 Sensors Location

Legend

1. Surface mount sensors ASM, BSM, CSM, DSM (FISO-B, Blade) = Sensors bonded with epoxy to the bottom surface of concrete deck.
2. Surface mount sensors P1 and P2 = these sensors were bonded to concrete, 3/4” below the surface of deck.
3. Embedded sensors C, D, E, F = Bonded to the bottom surface of rebar on bottom reinforcing steel mat.
4. Embedded sensors G, H, I, J = Bonded to the bottom surface of rebar on top reinforcing steel mat with epoxy.



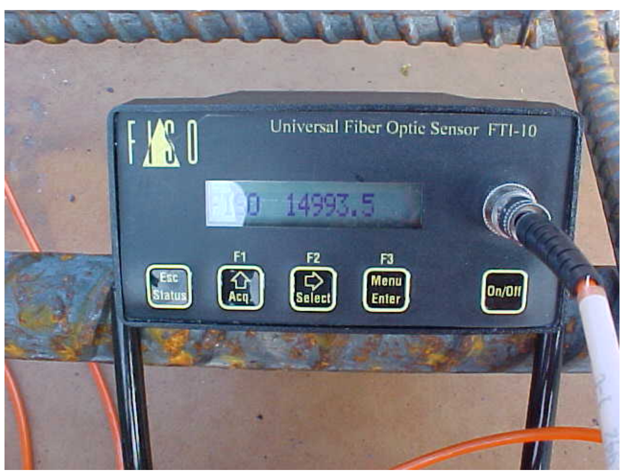
(a) Position of sensor on rebar

(b) Sensor bonded to rebar

FIGURE 5 Installation of sensors on rebars

(a) Placing Mylar tape on sensor

(b) Sensor wrapped in Nitrite rubber



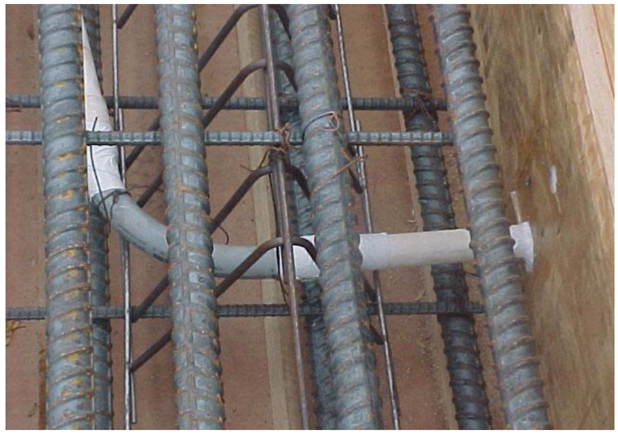
(c) Single channel data logger

FIGURE 6 Protection of sensors on rebars

(a) Close view

(b) Plan view

FIGURE 7 PVC conduit protection



(a) Cable safely moved out of deck

(b) Box housing cables

FIGURE 8 Protection of Fiber Optic cables

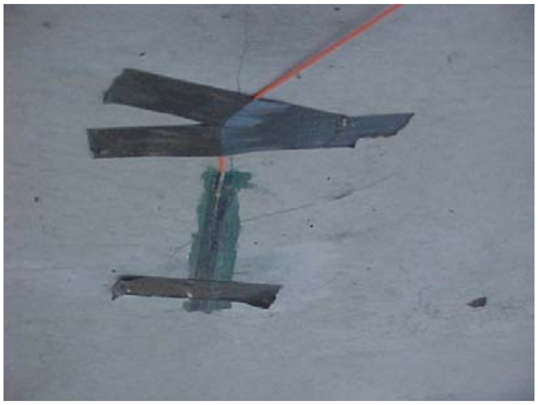
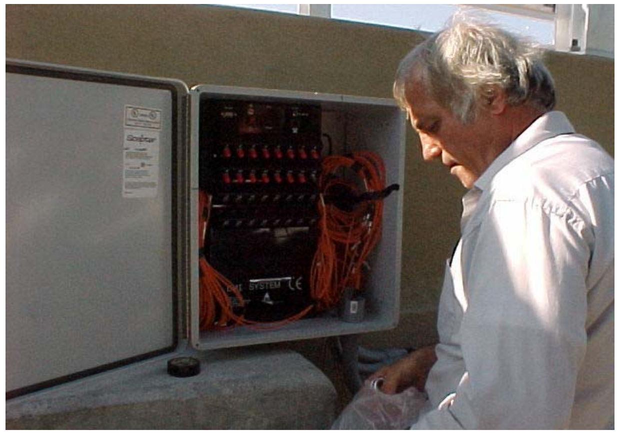


FIGURE 9 Surface-mounted sensors on bottom deck



(a) Acquisition system DMI

(b) DMI and utility conduits

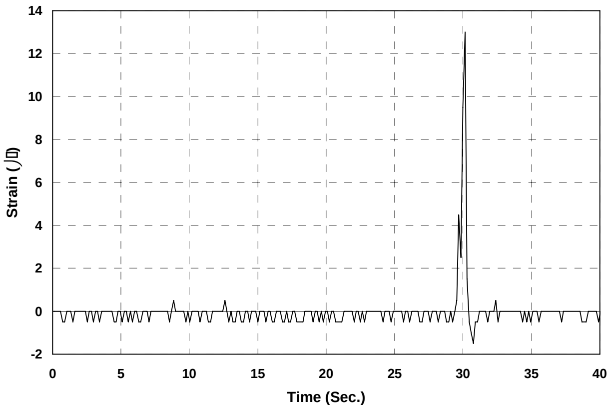
FIGURE 10 Housing of acquisition system

(a) Telephone box

(c) Electric meter and disconnect

FIGURE 11 Electric and phone supply

(a) Testing of bridge under SU4 trucks



(c) Dynamic strain history

FIGURE 12 Testing of the East Bay Bridge

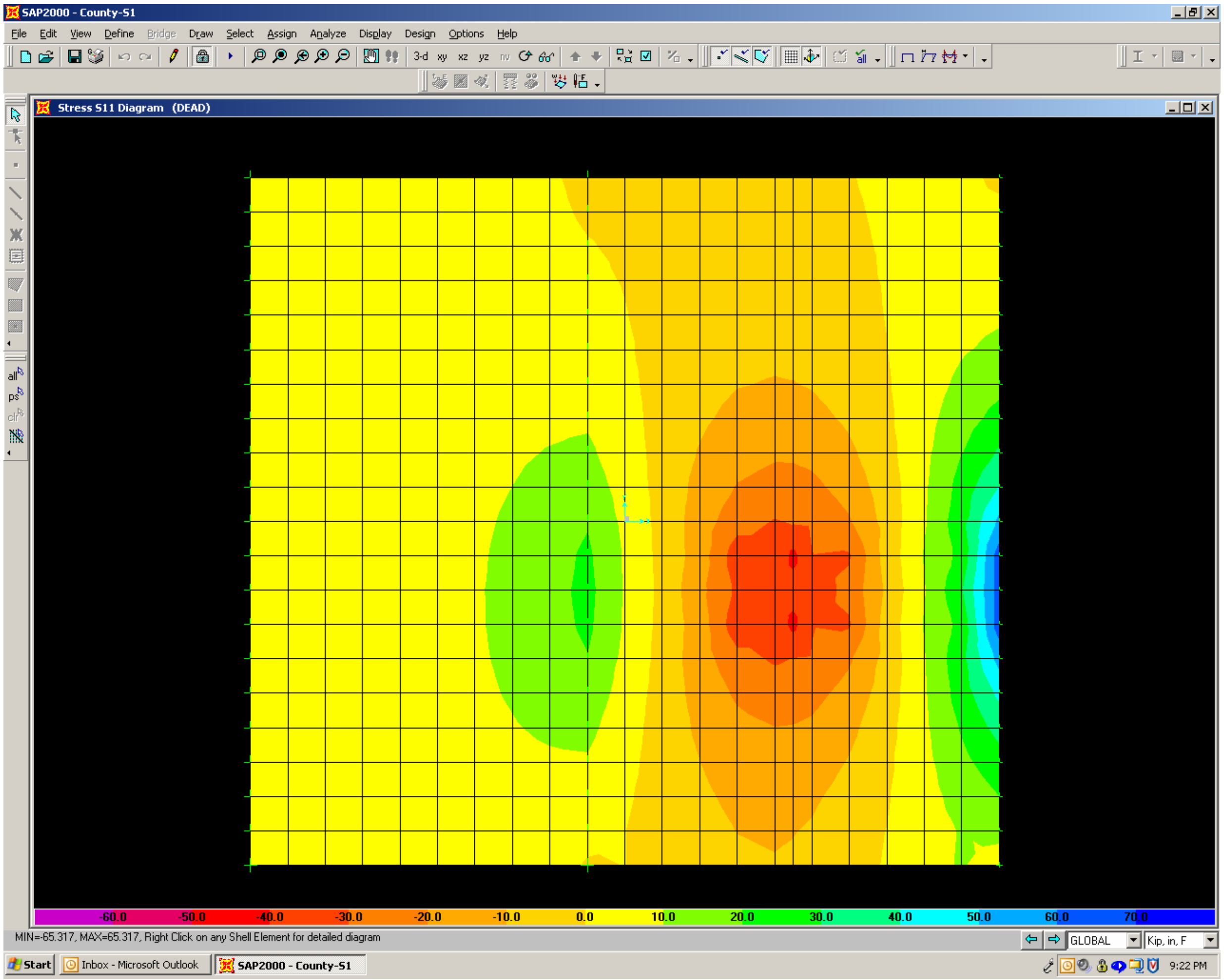
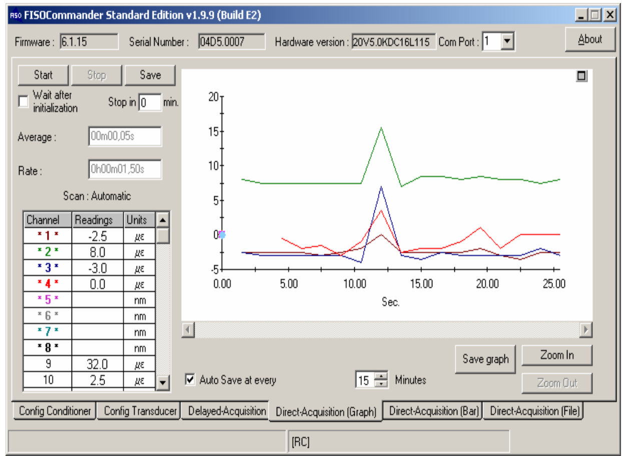
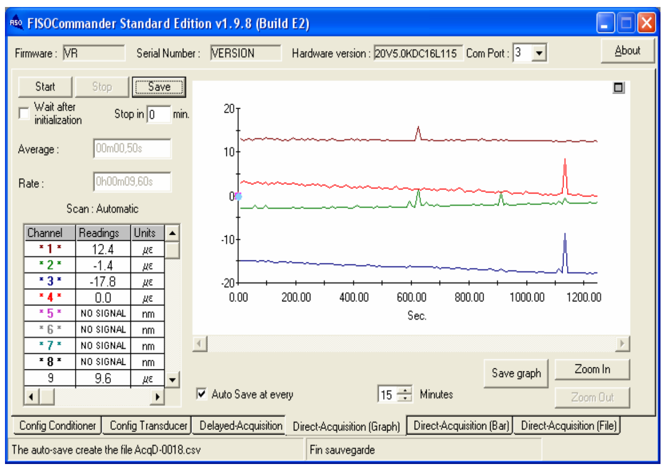


FIGURE 13 Analytical strain contour lines



a- Heavy Trucks



b- Small Trucks/Cars

FIGURE 14 Remote Live Data

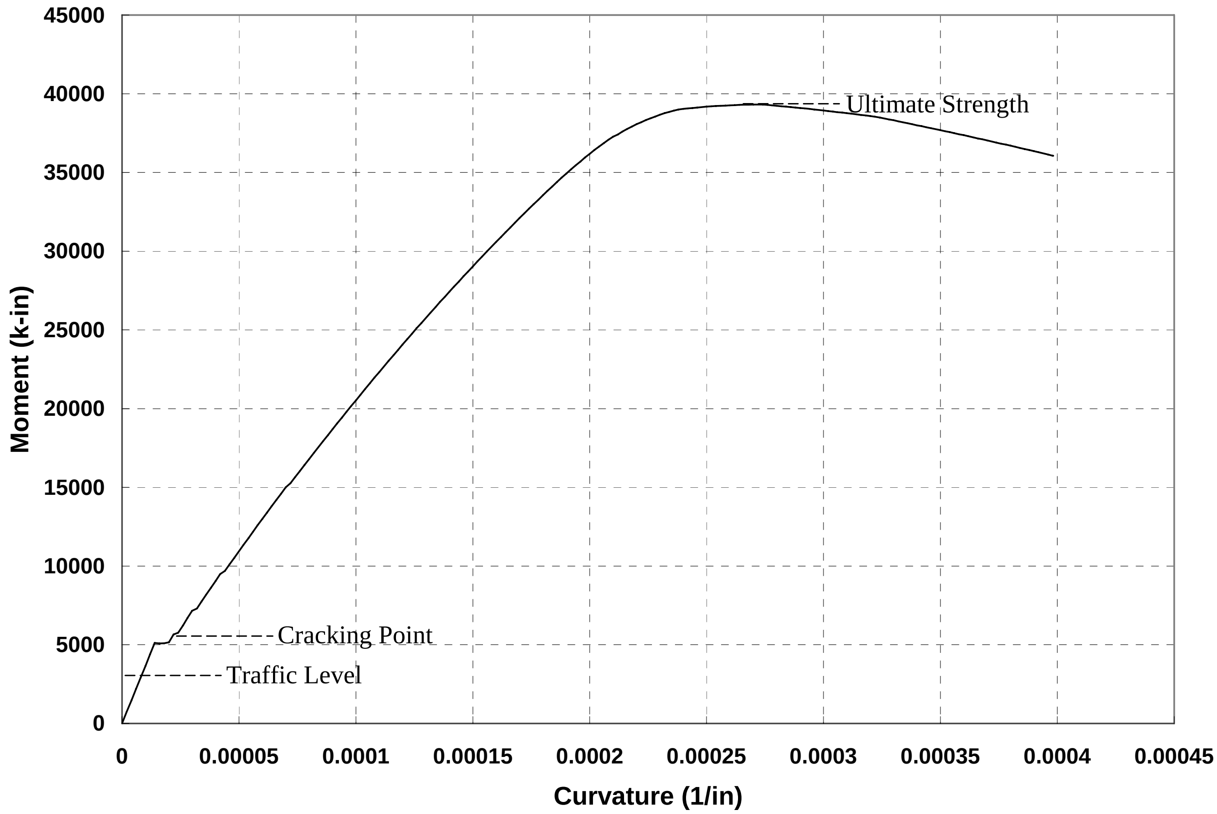


FIGURE 15 Moment-Curvature relationship for bridge section