APPLICATIONS OF STRUCTURAL HEALTH MONITORING TO HIGHWAY BRIDGES

By Steven Lovejoy[1]

Abstract

The Oregon Department of Transportation's Bridge Engineering Section has developed and implemented a Structural Health Monitoring (SHM) program to facilitate the maintenance and performance measurement of selected highway bridges. Currently 10 bridges have dedicated SHM systems installed which measure and collect performance data and transfer the data to a central computer server for convenient monitoring and analysis.

Bridges that have received SHM systems fall into 1 of 6 categories: 1) bridge foundations, 2) concrete superstructures, 3) movable bridges, 4) steel fatigue, 5) structural dynamics and 6) corrosion protection.

Examples of the first category include a bascule movable bridge and a concrete arch foundation. Examples of the second category include two vintage RCDG structures suffering diagonal tension cracking in the girders. Examples of the third category include

---

[1] Senior Engineer , Oregon Department of Transportation Bridge Engineering Section, 355 Capitol St. NE, Room 301 Salem, Oregon 97301-3871 steven.c.lovejoy@odot.state.or.us

two vertical lift and one swing span movable bridges. Examples of the fourth category include two steel box girder bridges which have developed fatigue cracking related to either or both distortion and thermal strain loading. Other examples include aero-elastic vibration concerns on a large through truss and cathodic protection systems on concrete bridges.

Brief examples of each system will be presented including a description of the problem or deficiency of concern, the physical measurements being taken, example results of the performance data and cost breakdown of the SHM system design and installation. Recommendations on when and how to apply SHM to highway bridges are presented.

Key words: Structural Health Monitoring, SHM, Highway Bridge, Fatigue Cracking, Diagonal Tension Cracks, Movable Bridges, Bridge Foundations, Cathodic Protection

1.0 INTRODUCTION

Highway bridge performance and deterioration have been of great concern to owners and maintenance engineers for many years. A very large number of structures were put into service during the 1950’s and 1960’s which are now of the age where the performance or capacity of the structure has deteriorated or can no longer meet higher levels of demand [1,2]. Thus a large number of bridge structures in our infrastructure are past, currently or soon to be due for major maintenance, retrofitting or replacement.

The need for action has already exceeded the ability of many owners to respond with full implementation of these three common approaches to dealing with the problem. A limited amount of funding and personnel will require all owners to prioritize the structures for problem resolution. Even with a well thought out prioritization, many structures will be years out from being fully addressed. Yet the owner must provide a very high level of reliability in these structures if they are to remain in service. Knowledge of the history and current status of the in-service performance of these structures can greatly benefit both prioritizing the responses and assuring reliability of the structure. The latter is especially true on structures with significant performance concerns.

The Oregon Department of Transportation (ODOT), like most other bridge owners, is faced with addressing this aging bridge problem. One part of the response was to develop and implement a Structural Health Monitoring (SHM) program to supplement and enhance the bridge inspection, load rating and maintenance programs. This paper briefly describes Oregon DOT’s SHM program.

2.0 OVERVIEW OF OREGON DOT’S STRUCTURAL HEALTH MONITORING PROGRAM

Currently 10 bridges are functional components of the SHM program with 3 more in design. The type of performance or condition monitoring being performed can be divided into the following types: 1) bridge foundations, 2) concrete superstructures, 3) movable bridges, 4) steel fatigue, 5) structural dynamics and 6) corrosion protection.

Each bridge has had an engineering evaluation performed that identified specific performance issues of concern and a set of performance parameters was developed that can be measured, recorded and usefully interpreted. Sensors and data logging equipment were then installed on each structure to monitor and record the performance parameters. These data are then transferred to a central computer server. Providing system power and data transfer varies from site to site. Bridges in urban areas typically have direct power supply from the grid and either phone lines or fiber optic connections. Rural bridges typically use solar panels or wind turbines for power and radio modems or cellular phones to transfer data to the central computer server.

Once the data is transferred to the central server it is stored in a database which is accessible to all interested engineers. Various plotting and data presentation software are used to explore and analyze the data depending on the type of performance parameters being investigated. Geotechnical, structural, corrosion, mechanical and electrical engineers can all find this data useful.

3.0 EXAMPLE APPLICATIONS OF SHM TO BRIDGES

In order to demonstrate typical SHM applications that are useful for bridge owners a brief summary of each system will be presented. Table 1 provides a summary of the key features of each application.

3.1 Foundation stability and performance

Currently two bridges have SHM systems installed to monitor and record foundation performance. These are the Isthmus Slough draw bridge and the Spencer creek arch bridge.

3.1.1 Isthmus Slough Bridge Br.#01132F

Isthmus Slough bridge is a double leaf bascule movable bridge constructed in 1935. It has had a long history of pier motion which causes problems with opening and closing of the bascules. Both analytical studies and performance testing provided little information as to the nature of the instabilities. A SHM system was designed and installed in 2000 to monitor the tilting of the two bascule piers. In addition to long term tilts, an early warning system was included in this application to provide the owners with a higher level of confidence.

3.1.2 Spencer Creek Bridge Br.#02198

The Spencer creek concrete arch is currently under construction. It replaces a badly deteriorated bridge. The local community lobbied hard to get a deck arch bridge for the replacement for aesthetic reasons. From an engineering perspective the site is not well suited for an arch type substructure. A special substructure was designed to accommodate the conditions and various performance parameters such as soil pressure, anchor block reaction thrust, various linear and angular displacements were identified for monitoring. The system is monitoring these parameters currently during construction and will remain in-place for the foreseeable future.

3.2 Conventionally Steel Reinforced Concrete Bridges

Oregon has had significant load capacity problems with many of the vintage Reinforced Concrete Deck Girder (RCDG) bridges. Significant efforts have been made in research to address this problem [3,4,5]. Part of the outcome of this research came a much more clear understanding on how to apply an effective SHM systems on this class of structure. Two conventionally steel reinforced concrete deck girder superstructures are included in the SHM program. These are the Luckiamute river and Banzer bridges.

3.2.1 Luckiamute River Bridge Br.#06635A

The Luckiamute river bridge is a 5 span concrete deck girder bridge with continuous interior supports. Built in 1953, it has performed very well with only minor to moderate cracking in the girders. Conventional load rating methods indicate the girders do not have adequate capacity for the heaviest permit truck loads. A more detailed structural analysis including controlled and ambient load testing has shown that the structure has adequate reliability for current demands. Several diagonal tension cracks were fitted with displacement transducers as well as concrete and local air temperature and moisture sensors. This system monitors the performance and long term degradation of the diagonal tension cracks. With over four years of operation it has been observed that the crack motion is primarily responding to seasonal environmental changes and not live load induced damage.

3.2.2 Banzer Bridge Br.# 03140A

The Banzer bridge is another concrete deck girder bridge with diagonal and flexural tension cracking in the girders. This bridge was built in 1951. Conventional load rating has shown the girders have adequate capacity for all legal and permit truck loads. Controlled load testing also predicts sufficient capacity. Bridge inspection has shown extensive, severe cracking in the girders. Many cracks have been epoxy injected only to crack again with crack widths approaching 3 mm. Overloads are the suspected cause of this cracking. A new structure is currently in design and a SHM system was installed on the existing structure in 2005 to monitor crack widths, rebar strains and concrete and air temperatures. The system monitors and records both short duration axle load responses as well as long term seasonal and accumulated damage changes. The system could be easily expanded to provide photographic information on the nature of the overloads which occur periodically.

3.3 Movable Bridges

Three movable bridges are included in the SHM program to monitor drive system performance. One system is on the twin structure Columbia River bridges and the other is on the Umpqua river bridge.

3.3.1 Interstate 5 Over the Columbia River Bridges Br.# 01377(NB) and 07333(SB)

The Interstate 5 crossing of the Columbia river consists of two multi-span, through trusses with two side by side vertical lift spans over one of the three navigation channels. These two structures are extremely important to both marine and land based commerce. One of the two lift spans has long term tilting problems with the lift span and counterweight system. An investigation was performed and various parameters were identified to quantify the performance of this system including measuring counterweight and span tilts and drive system performance. The sister bridge has both drive torque and span position monitoring being recorded. These data have proven effective in isolating specific problems and developing effective repairs since their installation in 2006.

3.3.2 Umpqua River Bridge Br.# 01822

The Umpqua river bridge is a 430 foot swing span movable bridge built in 1933. Twice over the 75 years of service the center pivot bearing rapidly degraded and became inoperable, circa 1975 and again in 2006. Testing before and after renovating the bearing the second time showed that the change in bearing condition could be monitored by measured changes in friction. A SHM system was installed to monitor drive torque, span position and weather information. The data from these measurements will prove useful for the long term monitoring of the bearing condition and allow for planned, instead of emergency repairs to be made.

3.4 Steel Fatigue Monitoring

Out of plane bending and distortion induced fatigue cracking is fairly common in older steel structures. Many times the nature of the problem is obvious and the solution easily defined and implemented. Other times, on more complicated structures, the exact cause of the cracking is more subtle and requires study, testing and monitoring to resolve. Two bridge structures are included in the SHM program that monitor various parameters that are related to a complex fatigue cracking problem.

3.4.1 Fremont Bridge Br.#02529

The Fremont bridge is a steel tied arch in the heart of Portland, Oregon. The superstructure is very large and relatively complex. There are 11,500 horizontal web stiffener terminations inside the two arch tie girders that are considered to be fatigue category E details [6]. The population of these details is beginning to show fatigue crack development. Because of the large quantities and complex nature of the loading, a SHM system was designed and installed to monitor structural behavior throughout the length of the tie girders. Emphasis has been placed on strain and temperature measurements as fractographic examination of existing cracks has indicated thermal, as opposed to live, load stress as the primary driver of the cracking. The results of these data are being used to prioritize retrofitting efforts.

3.4.2 Kamal’s BridgeBr.#09743B

Kamal’s bridge is another application of SHM to help resolve fatigue cracking problems. This continuous multispan trapezoidal steel box girder bridge with composite concrete deck was built in 1969. It has developed very concerning fatigue cracks at the connections of the main girders to crossbeams. The high lateral and torsional stiffness of the superstructure along with the significant horizontal curve and super elevation have made assessing the nature and causes of the cracking very challenging. All of the cracked and suspect connections have been retrofitted and a SHM installed to measure strains, distortion displacements and environmental conditions. Since the load source causing the cracking has yet to be clearly identified, unlike the above example, both long term (environmental effects) and short term (live load effects) are recorded at this site. The data are used to help assess the effectiveness of the structural retrofits.

3.5 Structural Dynamics

Another component of the SHM system includes the monitoring of dynamic motions induced by aerodynamic forces. The Astoria bridge (Br.# 07949C) is a very large cantilevered through truss located in the weather exposed Columbia river bar. The structure was built in 1961. High velocity winds pound the steel superstructure on a regular basis. The long slender vertical truss members have often been observed and even videographed oscillating torsionally in moderate to high speed winds. The displacement magnitudes can be rather startling to the uninitiated. The repetitious oscillations impart fatigue damage at the connections of the members. One particular connection developed extensive cracking and had to be retrofitted in 1996. Currently the structure is being investigated analytically to develop a list of performance parameters that can be measured and evaluated by comparison with the finite element models. Once this work is completed a SHM system will be designed and installed both to validate the complicated models and to provide guidance for retrofitting strategies.

3.6 Corrosion Protection

Oregon has a significant number of very beautiful historic concrete bridges along the coast highway. These structures were built in the 1930's and have since developed significant problems with the reinforcing steel corroding. All of these structures have received or are scheduled to receive, cathodic protection systems. These systems include a sacrificial zinc anode covering over the concrete exterior tied electrically to the internal steel reinforcing. Most of the systems use the impressed current approach to cathodic protection and a few are passively driven. In order to maximize the use of the zinc coating and still maintain adequate protection for the rebar the system, performance needs to be measured and recorded over time.

Currently one bridge has had a fully operational SHM system since 2006 and two other bridges are having systems designed and installed. If the new systems prove useful, as the existing system currently has, all of these bridges will be added to the SHM program. On many of these structures extending the life of the zinc coating by 1 year easily pays for the SHM system costs. The potential increase in zinc coating life by using this data to continuously tune the system's protection currents is on the order of 10 years or more compared to leaving them to operate at the installed currents.

TABLE 1 SUMMARY OF SHM APPLICATIONS

Structure Name	Type of SHM Application	Year Installed	Types of Sensors	Total # of Sensors	Communication method	Power source
Isthmus Slough	Foundation	2000	Tilt,tide level,pressure,climate	12	Land phone line	Grid
Spencer Creek	Foundation	2008	Tilt,pressure,force,climate		Land phone line	Grid
Luckiamute River	RCDG	2002	Displacement, temperature,climate	14	Radio modem	Solar panel
Banzer	RCDG	2005	Strain,displacement, Temperature, climate	14	Land phone line	Grid
I-5 Columbia SB	Movable Bridge	2006	Tilt,displacement Torque,span position, climate	20	Fiber optic cable	Grid
I-5 Columbia NB	Movable Bridge	2008	Torque and span position	2	Fiber optic cable	Grid
Umpqua River	Movable Bridge	2006	Hydraulic pressure Span position,climate	5	Radio modem	Grid
Fremont	Steel Fatigue	2008	Strain, temperature climate	67	Fiber optic cable	Grid
Kamal’s	Steel Fatigue	2008	Strain,displacement Temperature, climate	83	Fiber optic cable	Grid
Astoria Megler	Structural Dynamics	2010	Accelerometers,strain, Temperature, climate	In design	Radio modem	Solar panel and wind turbine
Cummings Creek	Cathodic Protection	2004	Corrosion reference cells temperature		Land phone line	Grid
Cape Perpetua	Cathodic Protection	2009	Corrosion reference cells temperature	In design	In design	In design
Ten mile	Cathodic Protection	2009	Corrosion reference cells temperature	In design	In design	In design

4.0 Example Data Presentation

Once the appropriate performance parameters have been identified, instruments installed to measure the responses, data collected and transferred to the central computer server it is available for monitoring and analysis. It is important to have the information easy to access, manipulate and display so that is can be of the most use to the engineer. There are many ways to store, retrieve, manipulate and display test data. The earlier SHM systems used a popular spread sheet application to provide these functions. As the program grew, and given the large amount of data collected by multiple systems, the database was chosen as the most effective approach for this application. Separate programs are used for the display of the data depending on the nature of the plots. Long term parameters such as pier tilt, crack mouth displacements and the like are typically viewed with internal plotting routines of the data base. For more detailed plots such as strain time histories and drive motor torques other plotting software often proves more efficient and effective.

Below are three example plots of different types of performance measures. The first, shown in Figure 1, is a typical long term measurement showing crack mouth opening displacement (cmod) and concrete temperature versus time where the ordinate ranges over years. This plot shows that the crack mouth displacement motion is seasonal. This information has proven very helpful considering that the qualitative structural condition of RCDG bridges is often tied to changes in tension crack widths.

The second example plot in Figure 2 shows the thermal strains and temperature response in a steel box girder over a 24 hour period. These data are used to assess the fatigue life of welded web stiffener terminations. The third example in Figure 3 depicts the electric motor drive torque versus span position for a vertical lift draw bridge opening and closing. This presentation of data is commonly used by movable bridge engineers to assess the state of balance between counterweight and span on both vertical lift and bascule bridges as well as other performance diagnoses.

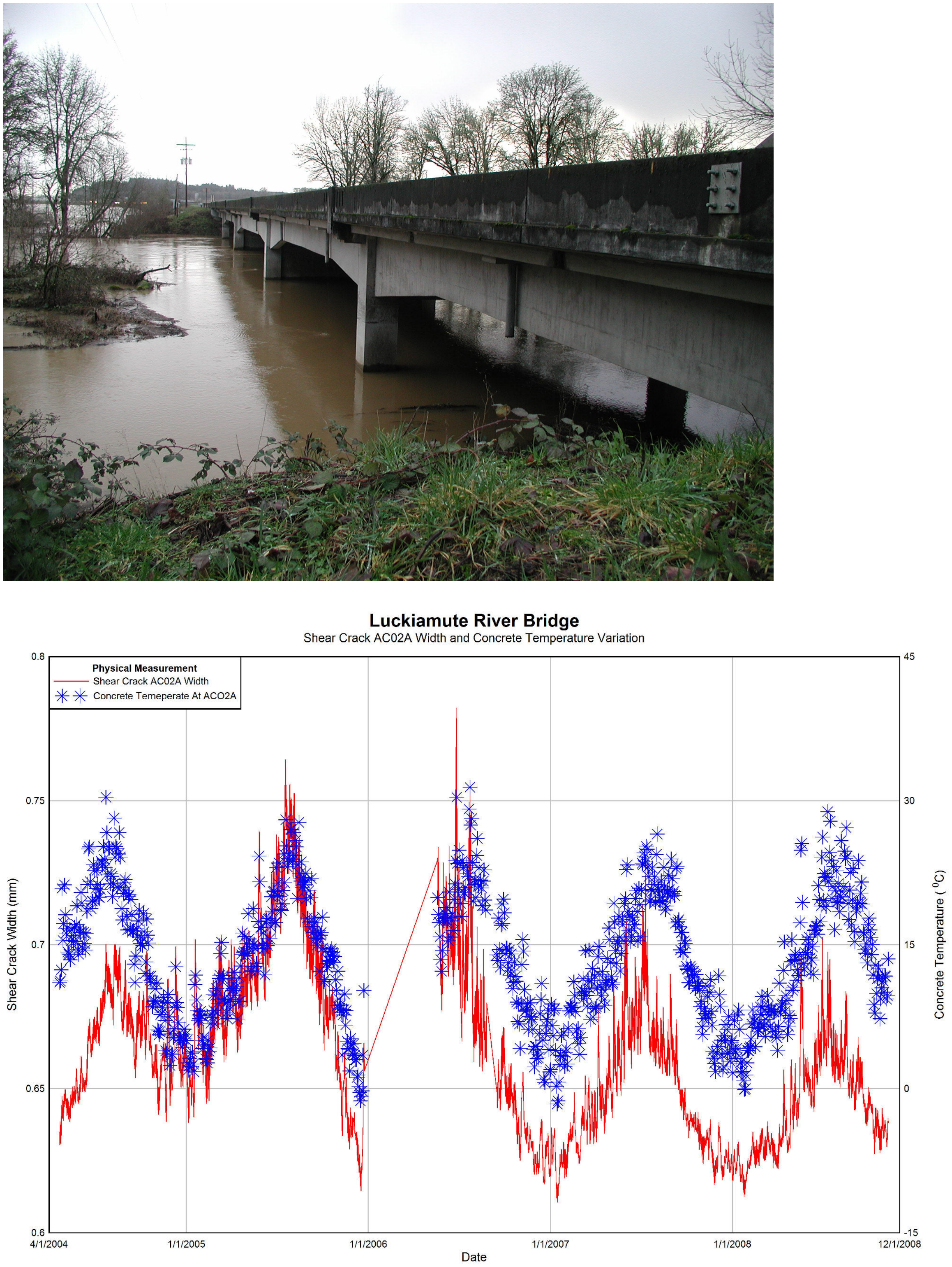

Figure 1 Luckiamute river bridge (upper) and example shear crack width and concrete temperature variation over 5 year period (lower).

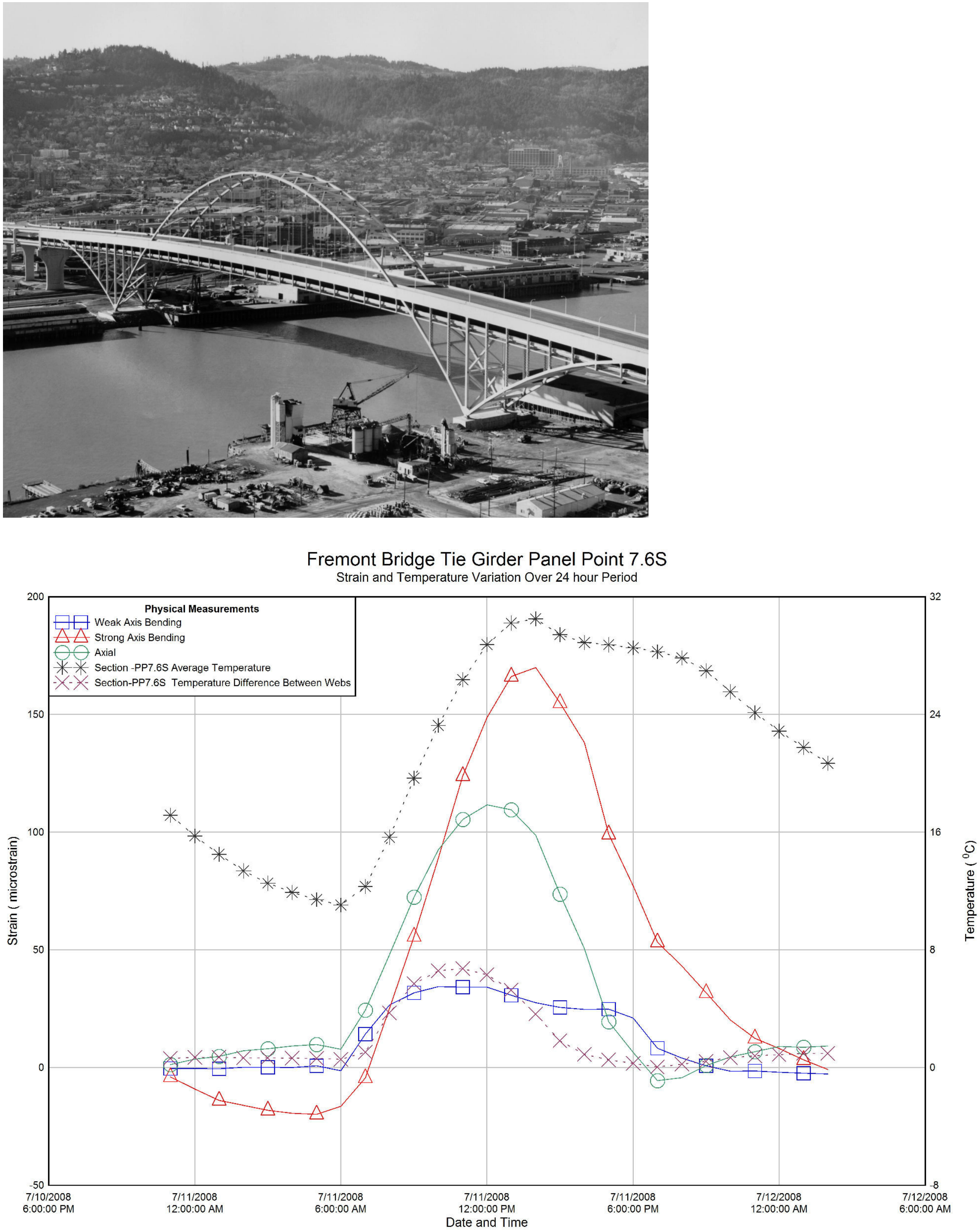

FIGURE 2 Fremont bridge crossing the Willamette river (upper) and example thermal strain time history from tie girder (lower).

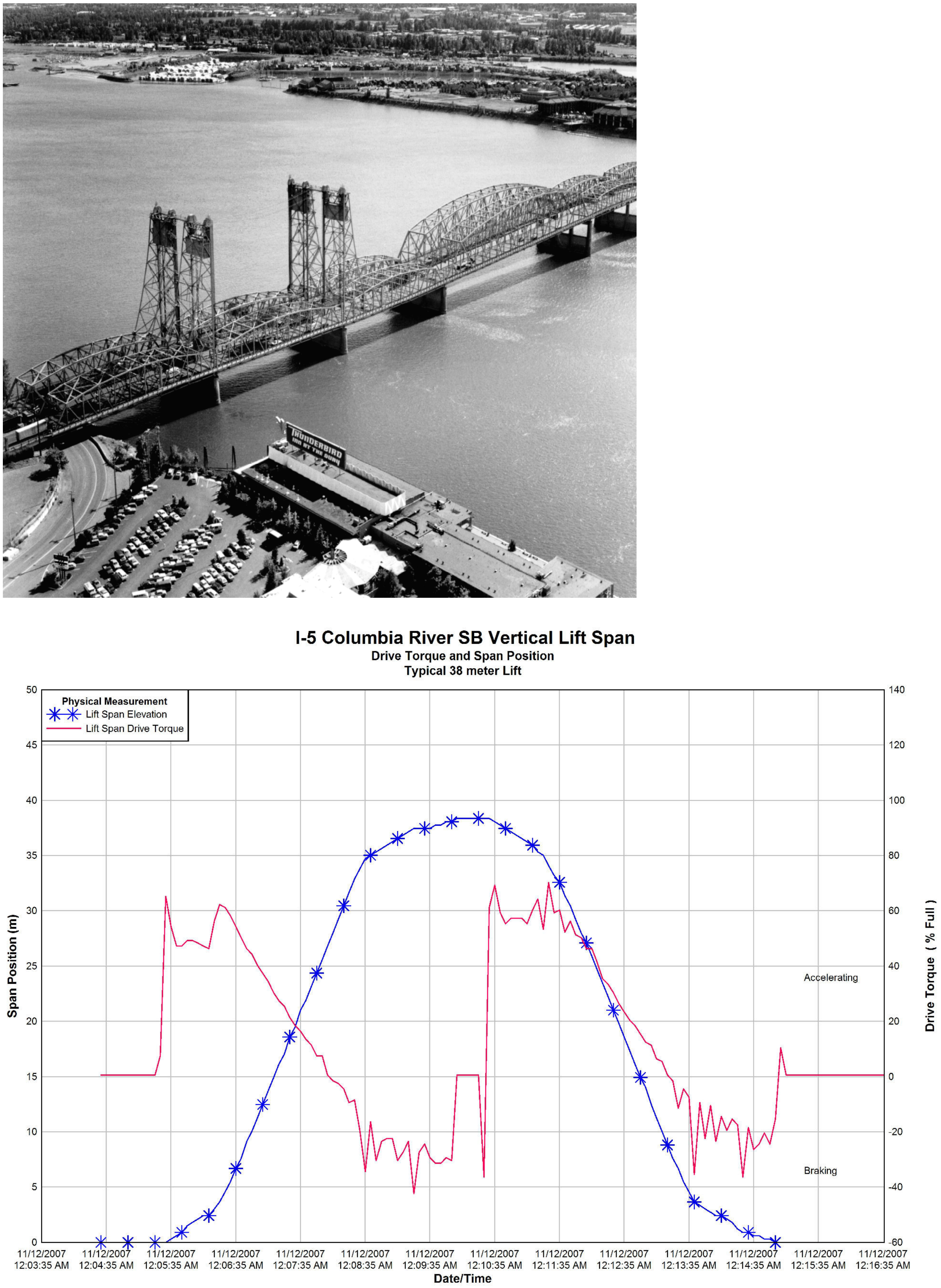

FIGURE 3 Interstate 5 bridge over the Columbia river vertical lift spans (upper) and example drive torque versus span position performance plot (lower).

5.0 WHEN TO EMPLOY A SHM SYSTEM

SHM system applications have become more common in the bridge community with the rapid increase in electronics technology and need for solution options to ailing infrastructure. Several approaches to the application of SHM systems to highway bridges have been presented in this and other journals. These applications include monitoring global structural behavior with the intention of identifying significant damage or deterioration [7], monitoring the performance of bridge designs incorporating new materials [8], quantifying the current levels of the reliability index [9] and monitoring the occurrence of structural damage in specific components of the superstructure [5]. Applying SHM systems to bridges with no specific problems or concerns is not likely the best use of resources for owners in the early stages of SHM program development. A more practical and tangible approach for SHM implementation is to identify structures that fall into one or more of the following categories for:

1) Bridges that have serious deficiencies and are programmed for repair or replacement; i.e., current inspection intervals are very short until repairs are made or loads are limited
2) Bridges with performance issues that are difficult to analyze and resolve analytically
3) Bridges with new materials, design and/or construction characteristics that need to be proven to perform as expected
4) Bridges with load rating factors near unity that show little or no physical signs of distress

5) System diagnosis and long term performance monitoring on movable bridges and cathodic protection systems.

The first three categories may only require monitoring until the structural performance issues are resolved and remedied, thus allowing the SHM hardware to be reused on other similar applications. The latter two categories are intended for permanent installation.

6.0 KEY INGREDIENTS FOR A SUCCESSFUL SHM SYSTEM

The utility and success of a SHM system applied to highway bridges can be optimized by incorporating a few basic ingredients or guidelines into the design, implementation, use and maintenance as follows:

1) The owner needs a clear understanding of what is being measured and how the responses relate to the performance or condition of the structure being monitored. If possible threshold levels for each critical parameter should be estimated. Appropriate responses to threshold crossing should also be identified. Sometimes this will require a moderate to significant effort in analytical studies prior to the SHM system design.

2) Determine if a monitor only system or a monitor and early warning system is needed. If the latter is chosen, develop a clear response plan; e.g. notify the maintenance engineer, trigger a visual inspection, etc.

3) Hardware redundancy is very desirable in critical applications such as early warning systems.

4) Use only high quality components and installation practices including environmental conditions protection. Often the cost of gaining access for hardware installation or maintenance far exceeds the cost of the hardware.

6) Optimize, if not minimize the number of sensor sites. Excessive data can often deter or prevent a clear understanding of the basic responses of the structure or system. Most data collection systems are easily expanded to more channels at a later date if desired.
7) The data must be easily collected, stored, manipulated and presented for the end user.
8) Routinely inspect the data to monitor for faulty or degrading sensor components to prevent lost or bad data.
9) Provide periodic inspection and maintenance on the hardware and installation materials.

7.0 EXAMPLE COSTS

For the 10 operational SHM systems currently in service on ODOT’s bridges, the installed prices ranged from $30K to $190K. The installed costs are primarily affected by the capabilities of the system (hardware costs), the difficulty of installation (access and traffic control) and the form of power supply and communications. Table 2 summarizes the cost break down of each system installed. The typical cost breakdown has 10 to 15% for design and nearly even remaining portions for equipment and installation costs.

The design, purchase, installation and programming of the central computer server that stores all of the data and provides access to the data for manipulation and presentation, including software licenses was approximately $110K. It is of course able to accommodate many more SHM sites then the current 10 on line.

TABLE 2 Summary of SHM System Cost Breakdown

Structure Name	**Design Cost**	**Equipment Cost**	**Installation Cost**	**Total Cost**
Isthmus Slough	11%	27%	62%	$130,000
Spencer Creek	20%	40%	40%	$73,205
Luckiamute River	In house 17%	33%	In house 50%	$30,000
Banzer	10%	60%	30%	$113,052
I-5 Columbia SB	12%	44%	44%	$185,300
I-5 Columbia NB	N/A	20%	80%	$15,105
Umpqua River	10%	22%	68%	$79,600
Fremont	10%	33%	57%	$172,400
Kamal’s	9%	43%	44%	$190,100
Astoria Megler	$28,210	In design	In design	N/A
Cummings Creek	In-house 12%	21%	67%	$45,630
Cape Perpetua	$15,726	In design	In design	N/A
Ten Mile	In house 11%	25%	64%	$48,000

8.0 CONCLUSIONS

The Oregon DOT began development and implementation of a SHM program in 2000. Since that time 10 bridges have operational systems installed which feed the monitoring data to a central computer server for long term secure storage and easy access by engineers. Three more structures are currently in design or installation to be added to the program. In each case a specific problem or performance measurement was identified and practical means of quantifying the condition or change in condition was found. Investing in analytical background work to determine what to measure and what ranges to expect was very important. Keeping the number of sensors and amount of data collected down to a reasonable level also greatly improved the ease of understanding the data collected without being overwhelmed. And finally having easy access to the data and its manipulation enhances utilization of the information.

Every application to date, including the very new additions to the SHM program are providing very reliable and useful information which is used to optimize the efficiency and effectiveness of maintenance resources. When properly applied and utilized, SHM systems can recover the installation cost in much less then one year. As most highway bridge owners know, disrupting the flow of commuters and commerce in very high use areas has a significant financial impact. In many of the examples discussed, preventing the emergency closure or inoperability of highway or navigation right-away for a single day covers the complete cost of design, purchase and installation of the SHM system.

REFERENCES

1. Farhey, Daniel N., (2007). Quantitative Assessment and Forecast for Structurally Deficient Bridge Diagostics. Structural Health Monitoring 6(39) p 39-48.
2. Farhey, Daniel N., (2005), Bridge Instrumentation and Monitoring for Structural Diagnostics. Structural Health Monitoring 4(4) p 301-318.

3. Strategic Planning and Research Report. (2004). Assessment Methods for Diagonally Cracked Reinforced Concrete Deck Girders, Contract# SPR-350, FHWA-OR-RD-05-04, Oregon Department of Transportation.
4. Strategic Planning and Research Report. (2004). Remaining Service Life of Reinforced Concrete Beams with Diagonal Tension Cracks, Contract# SPR-341, FHWA-OR-RD-04-12, Oregon Department of Transportation.
5. Lovejoy, S.C. (2008). Acoustic Emission Testing of Beams to Simulate SHM of Vintage Reinforced Concrete Deck Girder Highway Bridges. Structural Health Monitoring 7(4) p. 329-346.
6. AASHTO
7. Chang, Peter, C., Flatau, Alison and Liu, S.C. (2003). Review Paper: Health Monitoring of Civil Infrastructure. Structural Health Monitoring 2(3) p. 257-267.
8. Farhey, Daniel, (2006). Instrumentation System Performance for Long-term Bridge Health Monitoring. Structural Health Monitoring 5(2) p. 143-153.
9. Dissanayake, P.B.R., Karunananda, P.A.K., (2008). Reliability Index for Structural Health Monitoring of Aging Bridges. Structural Health Monitoring 7(2) p. 179-183.