TECHNOLOGY AND APPLICATION OF STRUCTURAL HEALTH MONITORING IN BRIDGES

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Bachelor of Science, Civil and Environmental Engineering
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ABSTRACT

Structural Health Monitoring (SHM) has become a useful tool for detecting when the characteristics of a structure have changed to indicate damage such that well-timed and effective maintenance may be planned and the remaining performance capacity may be assessed. SHM has also lead to a better understanding of the loads and the response within a structure in order to optimize future design. In this paper, research is compiled on the current practice of SHM with coverage of sensors used, system configurations, data management, analysis and a discussion of current issues. Recommendations on the current state and future of SHM are made and case studies investigate recent applications. A proposed procedure for the design and implementation of a SHM system is examined and then applied to the design project for the Master of Engineering program in High Performance Structures at MIT. Conclusions include a suggestion on the most effective way to design a SHM system, what the industry needs to mature and predictions of the future of the industry.

Thesis Supervisor: Jerome Connor
Title: Professor of Civil and Environmental Engineering

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1 INTRODUCTION

The properties of materials used in structures as well as the actual loads the structure will be subjected to are not fully understood (1). Despite these uncertainties, a structural engineer must still design a safe structure. This is achieved by applying factors of safety and adding redundancies. Deterioration is still an inevitable fate for a structure however, which is combated only by maintenance. Structural Health Monitoring (SHM) technologies are available that can help engineers to plan for strategic and effective maintenance of existing structures as well have a better understanding so that future design can be optimized. This introduction will cover the major definitions within this topic, a background on the development of the industry, the objectives of SHM and the components of a typical system.

1.1 Definitions

SHM is the process of detecting damage in civil structures through the use of sensing technologies. It is a result of needing to know more about the actual condition of a structure in such a way that not only can it be detected when performance has fallen below a certain threshold but also evaluate the remaining ability to perform (2). Structural damage as it relates to SHM is defined as a change in the material or geometric characteristics of the structure that correspond to a reduction in performance.

1.2 Background

SHM has arrived at its current definition through the development of small and low cost sensors and the ability to process and analyze vast amounts of data quickly. Current technology has made it cost effective and easy to implement monitoring systems. Conventional methods included human inspection at set time intervals and physical tests. Other industries, such as aerospace and mechanical engineering, adapted to the use of monitoring systems much sooner. Airplanes and vehicles have been relying on electrical sensing systems for years yet there is resistance when it comes to monitoring structures. Monitoring has finally transitioned into civil structures within the last 10 or 15 years though. Hardware and software are continuing to be developed because of the recent attention and this new field within engineering will continue to develop with them (1).

1.3 Objectives

Each structure will have specific objectives but the objectives of the overall SHM process can be summarized as follows:

- To detect when the characteristics of the structure have changed
- To assess remaining performance capacity
- To better understand the loads and the response within a structure

1.4 SHM System

These objectives are achieved by the installation of a monitoring system. A complete SHM system for a structure is comprised of the following components:

- Sensors
- Data Acquisition System
- Data collection, storage and processing mechanisms
- Analysis

The chapters that follow examine each part of the system in detail from technology to overall process. Chapters 2 through 5 will focus on the sensors used for SHM, data acquisition and management, and analysis techniques. Chapter 6 discusses current challenges to the industry while Chapters 7 and 8 examine a procedure for how to design a SHM system with examples through case studies. Chapter 9 is an application of SHM and finally Chapter 10 concludes.

2 SENSORS

SHM is dependent on the advancement of sensing technologies. The following sections will examine some of the most common sensors used to detect various structural features.

2.1 Strains

Strain is the displacement per unit length caused by an applied stress. There are several technologies available to monitor strains in a structure including resistive foil, vibrating wire gauges and fiber optics. Resistive foil gauges are the most common and consist of elastic plates with a grid of semi conductive wires throughout. The gauge is bonded to the structure with epoxy such that when the structures deforms under load, so does the wire network. The deformation causes a change in resistance which is converted to a voltage that the Data Acquisition System retrieves (3).

A more recent and more sensitive technology is fiber optic strain gauges, particularly fiber Bragg gratings (FBGs). FBGs detect changes in the wavelength of the optical fiber in response to strains. Broadband light is sent through the core of the fiber and a small range is reflected, when the FBG is shifted due to strain, a corresponding change in wavelength occurs. Advantages include no interference due to electromagnetic activity, lightweight and non-intrusive but they are also costly at about \$150 to \$200 per sensor and are better suited for aerospace applications (3), (4).

Vibrating wire strain gauges are another type of sensor to use for monitoring strains. In this sensor, a tensioned wire is inside the unit that is welded to the structure and changes in tensile strain results in changes in the tension in the wire. An electromagnet is used to induce vibrations in the wire and the change in frequencies is logged (5).

There are a few issues that arise when measuring strains. The first being that the sensors need to be bonded to the structure and this method results in incomplete transfer of all strains to the sensors. The second issue is the material sensitivity to temperature. Thermal strains need to be removed from the data and can be done by recording thermal strains alone (i.e. a few sensors are not bonded to the structure). Lastly, fiber optic sensors have problems when embedded within materials because they are difficult to replace and can weaken the composite material strength (3).

2.2 Loads

Engineers attempt to design structures for the loads that they will be subjected to; however this can be a difficult task due to complexities and unknowns. Sensors can be used to measure the actual loads within a structure which will help predict locations of potential damage as well as improve the knowledge of loadings for future design.

There are two main types of load sensors which are strain gauge and piezoelectric. Strain gauge types consist of a strain gauge bonded to a transducer. The transducer is deformed by strains due to an applied load and then calibrates the deformation into an applied force through the geometry of the sensor (3).

Piezoelectric load cells function by the use of piezoelectric crystals. The crystals create an electric charge in response to strains which is converted into a voltage for the Data Acquisition System to collect. The sensor can be modeled by a single-degree-of-freedom oscillator in that an applied load activates the piezoelectric material which makes the sensor respond by oscillating. The sensors are calibrated to respond in a certain measurement range (3).

There are a few challenges to overcome when working with load cells. Strain gauge types have the same issues as previously discussed. Another issue is that data can be incorrect if the sensor is mounted in a direction that is not in good alignment with what is being measured. Piezoelectric sensors are also sensitive to mounting in alignment with the direction of load but also have difficulties with operating outside of the frequency range that it was calibrated for (3).

2.3 Displacements

The displacement that a bridge undergoes is valuable information for diagnosis and tiltmeters can be used to monitor such displacements. These sensors have long been used in geotechnical applications to monitor ground movements but have been found useful for SHM. Modern tiltmeters function electronically using a bubble level filled with electrolytic fluid that has electrodes that can detect when the position of the bubble changes and track it in a data logger. Other types used lasers to track movements (6). Another available sensor is the displacement transducer which takes applied displacements and converts them into a voltage (7).

2.4 Accelerations

The physical parameters (mass, stiffness and damping) of a structure directly correspond to the mode shapes and frequencies and accelerometers can monitor these modal properties. Mechanical damage such as cracks, missing bolts or delaminations cause a change in the stiffness and/or damping and therefore a resulting change in the modal properties as shown in Figure 2-1. SHM uses sensors to detect these changes and indicate when damage has occurred and repair is needed (8), (9).

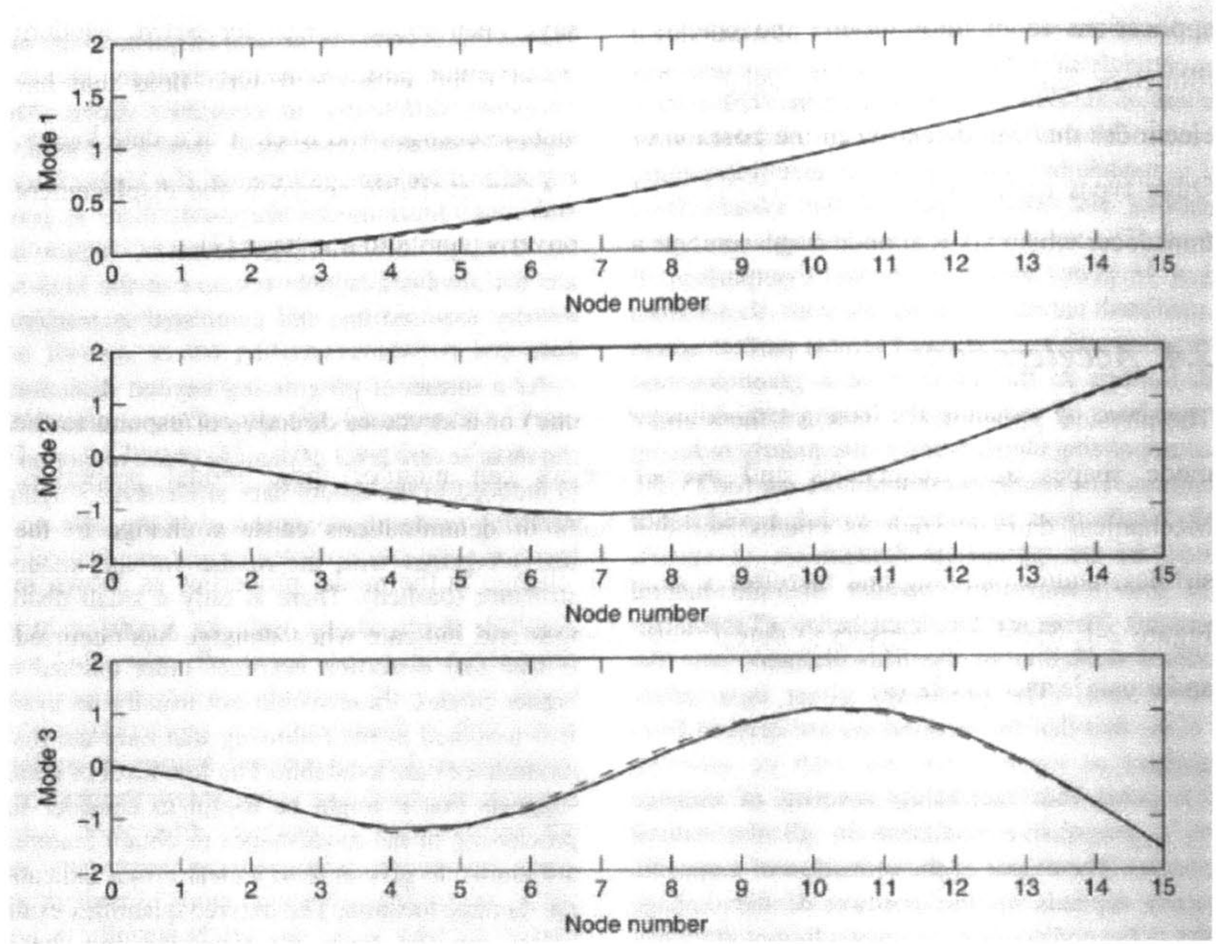


Figure 2-1: Undamaged (solid) and damaged (dashed) mode shapes (9)

The most common sensors used in SHM are accelerometers and there exist both piezoelectric and capacitance to collect the vibration data. Piezoelectric accelerometers use the same sensor as for load cells in that strains cause deformations of piezoelectric crystals that cause accelerations in a seismic mass that can be measured. Capacitance accelerometers use the same technology as resistive foil gauges in that as the structure vibrates there is a change in capacitance that can be calibrated into acceleration measurements. Accelerometers are relatively easy to install and can function for a wide range of frequencies (10).

2.5 Global Positioning System (GPS)

Recent developments in SHM have turned towards integrating GPS into bridge monitoring. GPS as a monitoring tool alone is not feasible because of positioning precision and trouble with satellite geometries. It is however, well suited for measuring low frequency movements which is a shortcoming of traditional accelerometers. GPS can be used to monitor displacements and accelerations and have inherent time synchronization. Research suggests that a complementary system that uses GPS simultaneously with other monitoring techniques and then fuses data in post processing will yield good results (11), (12).

2.6 Environmental Conditions

The data collected regarding the reaction of the structure will eventually be processed and information about the environmental conditions at the time of abstraction may be important for better understanding of the data. Thermocouples, temperature circuits, weather stations, anemometers and webcams are a few of the sensors that can be installed to monitor weather conditions that subject the structure to strains and loadings (13).

2.7 Static versus Dynamic Sensing

A summary of all sensors is shown in Table 2-1. Another way to distinguish sensors is between static and dynamic type sensing. The difference comes from what is being monitored, whether it is a dynamic loading or a static loading. Dynamic loadings include forces that vary with time such as wind, earthquake, and moving people or vehicles while static loads do not vary, such as the weight of the structure. Dynamic sensing usually includes monitoring of strains and accelerations while static sensing measures loads and displacements periodically.

Table 2-1: Summary of available sensors

Subject to Monitor	Tool
Strains	- Electrical resistance gauges - Vibrating wire strain gauges - Fiber optic sensors
Loads	- Load cells or derive from strains
Displacement	- Transducers - GPS - Tiltmeters
Accelerations	- Piezoelectric accelerometers - Capacitance accelerometers - GPS
Temperature	- Thermocouples - Thermistors

3 DATA ACQUISITION SYSTEM

The Data Acquisition System (DAS) is the complete sensor network and the unit or set of units that collect data from the sensors to be processed for SHM. Elements such as type and number of sensors, sensor placement and data transmission must be considered.

3.1 Wired versus Wireless

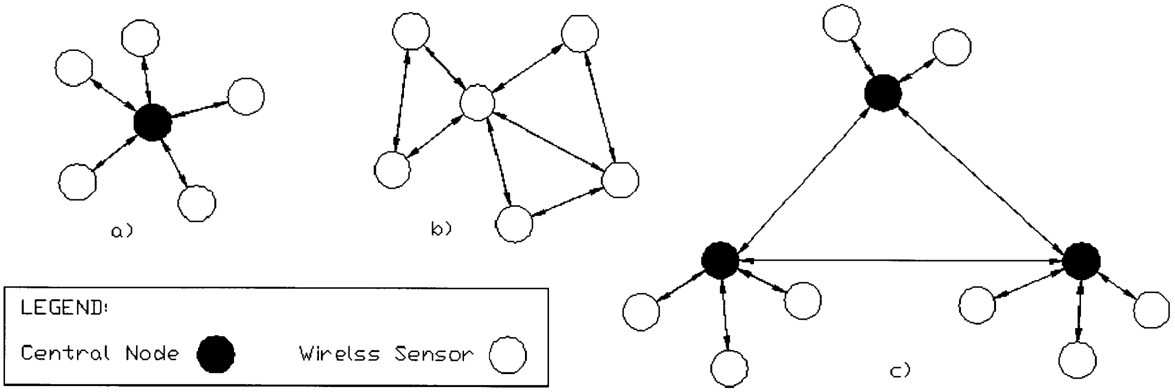
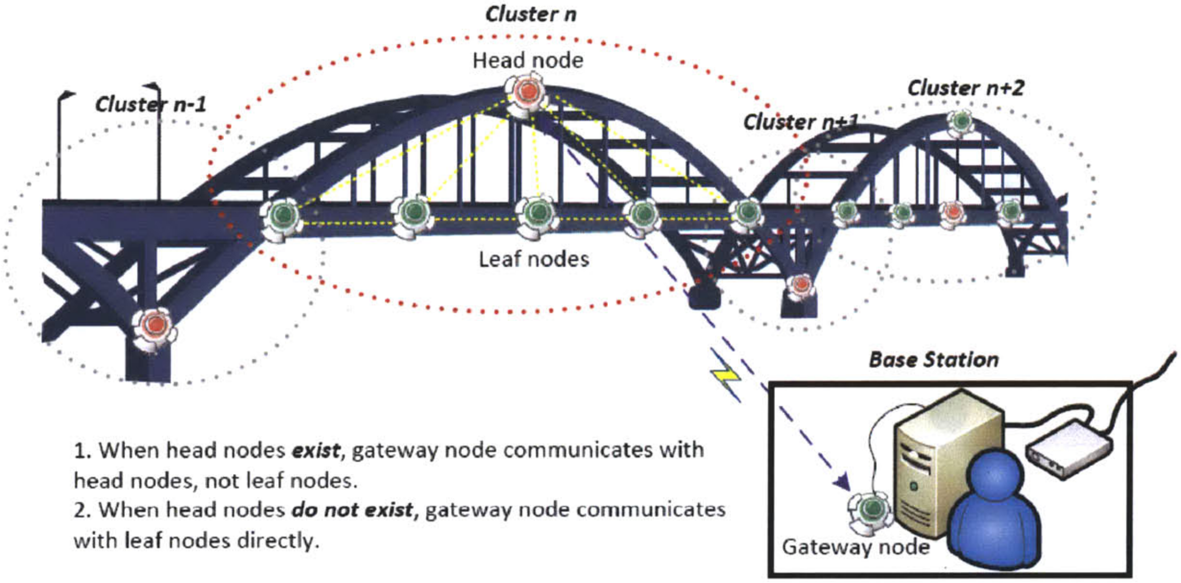


Figure 3-1: Wireless network topologies: a) star; b) peer-to-peer; c) multi-tier Adapted from (15)

Traditional SHM systems use wires to connect the sensors to the data acquisition units. The long system of cables is difficult and expensive to install, difficult to rearrange and is vulnerable to damage. The practicality of SHM was improved by the development of wireless systems. A node in the network refers to a small computer that is equipped with one or more sensors. The nodes communicate between one another through radio frequencies, eliminating the need for wires and allowing for preliminary data processing. The lower costs, typically only a few hundred dollars per node, are what made SHM a viable industry. There are some limitations however, such as power supply, bandwidth constraints, transmission range and possible security issues (14), (15).

There are a few solutions for power supply concerns since constant maintenance is not a realistic option. The nodes can be designed to use lower power consuming equipment, however this also means less functionality; a balance must be achieved. Another option is to have more data processing before transmission, since it drains less energy to send refined data. Other options include conserving energy between sampling periods (utilizing a sleep mode) and harvesting energy from the environment like solar power (15).



1. When head nodes ***exist***, gateway node communicates with head nodes, not leaf nodes.
2. When head nodes ***do not exist***, gateway node communicates with leaf nodes directly.

Figure 3-2: Wireless network communication (16)

Bandwidth issues can be mitigated by using protocols to set rules for the devices for data transmission so that bandwidth can be shared with other technologies but also ensure reliable transmission. Transmission range is dependent on power supply and can be much more effective when the nodes are set up in a multi-hopping network. Figure 3-1 shows some possible network topologies. In this type of network, nodes need only communicate with neighboring nodes and can pass information along as necessary as shown in Figure 3-2. A typical range for transmission is about 475 feet, as shown in a recent application (16). As far as security is concerned, encryptions can be used to defend against data theft but the wireless system is vulnerable against jamming, which is a flooding of information, and should not be used where the monitoring system would be critical (14), (15).

3.2 Sensor Layout

Sensor placement is a crucial part of any SHM application because the reliability of the data is dependent on it. It is impractical and costly to inundate a structure with sensors therefore strategic placement is required. Another important factor when determining sensor layout is what the objective of the monitoring system is because optimal sensor location may be different for each objective.

A good initial consideration for sensor placement can come from dynamic analysis with placement of sensors near the antinodes of the first few vibration modes. Another method, if resources allow, is to implement several configurations and test which one performs the best. Both of these methods are practical and require knowledge and experience of the person designing the layout (17).

Recent research has moved towards creating a mathematical optimization problem out of sensor placement and several methods have been developed in response. The basis for many of these techniques is that a set of all available sensor locations is developed and then an iterative process eliminates the locations that contribute the least amount of information. Another approach is to use genetic algorithms to locate optimal positions based upon an input force (17).

Out of the SHM systems that have been implemented in the United States, most have anywhere between 1 and 100 sensors. Load transferring elements such as beams, arches and cables are typically the focus of instrumentation with decks being the next common (18).

4 DATA MANAGEMENT

4.1 Collection

The sensors of a SHM system use transducers to convert physical phenomenon into an electrical signal, which is then converted into a digital measurement that is stored and analyzed. It is crucial that sensors are interrogated accurately in order to ensure that the final digital result is a true representation of the response. An example of poor interrogation is if the sampling rates are too low. The sampling rate must be at least twice the highest frequency that exists in a data set otherwise a phenomenon known as *aliasing* may occur as shown in Figure 4-1. In this example, the input signal is at 9 Hz but data is sampled at 12 Hz instead of a recommended 18 Hz and the result is a misinterpreted signal of 3 Hz. Hardware in the DAS as well as software used in processing can be set to filter the information from the sensors to disregard certain frequencies and allow analysis to proceed without the threat of aliasing (19).

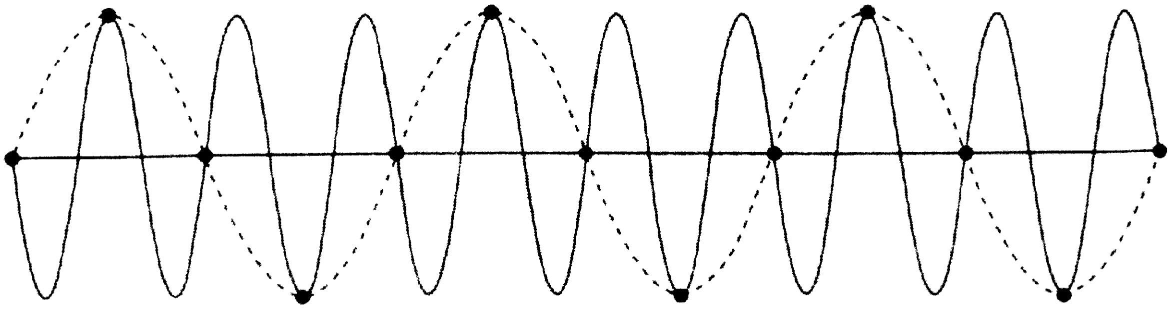


Figure 4-1: Sampling waveform showing aliasing (19)

Often SHM makes use of multiple sensors, types of sensors and multiple data acquisition units to study the same occurrence. Complete analysis of the event requires the data from all the separate pieces of measurement equipment to be compounded and therefore it is critical that all equipment be synchronized to the same time and resynchronized periodically if done manually (19).

4.2 Storage

Storage of data on-site is limited and therefore there is a need to transfer it off-site for storage and analysis. Options for this transmission of data include manually through data storage devices or wirelessly through the internet. Once off-site, commercial database systems can be used to store and backup all of the information. Data can be archived in online or offline sources however all the information from a complete SHM system would require an impractical amount of storage and therefore selective data archiving should be implemented. The benefits of processing what to be stored are that less space is needed for storage and health assessment is much quicker (19).

4.3 Processing

The data collected from the sensor network needs to be processed before it can be analyzed. There are several steps in data processing which includes mitigating errors due to noise or failed sensors as well as reducing the vast amounts of data that may be repetitive. *Noise* refers to parts of the data that are due to external sources such as electromagnetic interference or from the power source. The data can be preserved by putting shielding on the sensors and applying a filter respectively. Another source of error is from sensors becoming deficient and this can be mitigated by checking results with neighboring nodes (19).

Another technique used for data processing in SHM is *novel detection.* In this method, data that is repetitive or mundane is minimized and the focus is shifted to that which is more nonconforming through the use of a novelty index. Data is assigned a novelty index when compared to past information. The greater the novelty index value, the more unique the piece of data is. An example of a plot of novelty indexes over time is shown in Figure 4-2. A rare event occurs around 35 minutes that would warrant further exploration (19).

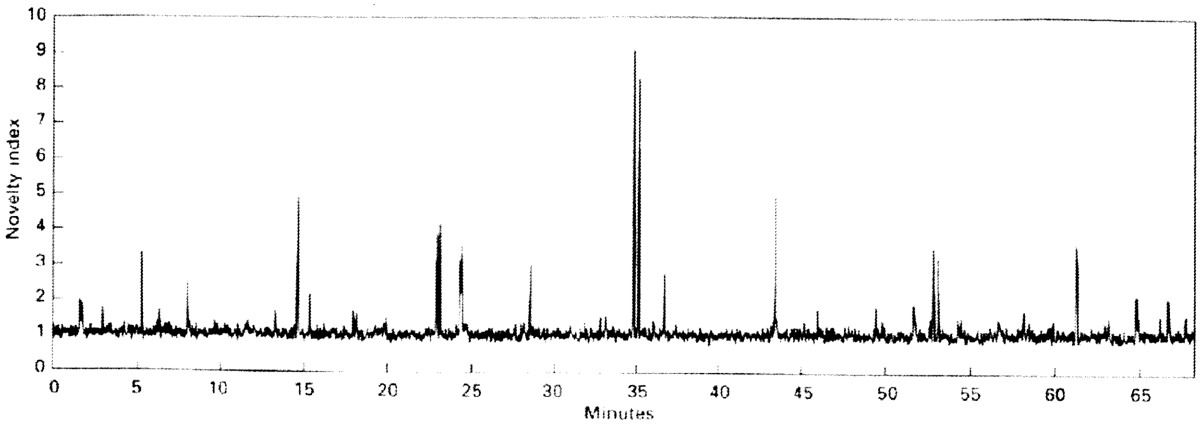


Figure 4-2: Example of *novelty detection* (19)

5 ANALYSIS

5.1 Damage Detection and Identification

The most basic objective of SHM is damage detection which is defined as simply the identification of when a structure changes from its normal condition. There is a hierarchy of damage identification which increases in sophistication summarized as follows:

- Level 1 – Diagnosis: system indicates that damage has occurred
- Level 2 – Localization: system identifies location of damage
- Level 3 – Assessment: system estimates extent of damage
- Level 4 – Prognosis: system estimates remaining service life

Several methods have been developed to attempt to diagnose structural health from the data collected by the sensor network (20).

5.2 Model versus Non-Model Driven Approaches

The two general approaches for damage detection are model-driven and data-driven. The more traditional model-driven, approach establishes a linear dynamic model of the structure through finite element analysis and then compares to measured data from the structure. Damage is detected when the explicit mathematical model of the current condition of the structure differs from the baseline (undamaged) model of the structure (20), (21).

Non-Model, also known as data-driven, approaches rely on signal processing to investigate changes over time of the vibration characteristics of the response of the system. This approach also creates a model but it is a statistical representation of the system and damage is detected when data from a healthy part of the structure and from a potentially damaged part of the structure are shown to be different. In other words, damage is detected when there are changes in the structural dynamic characteristics. Statistical methods for data-driven analysis include modal analysis, dynamic flexibility measurements, matrix updating and wavelet transform (20), (21).

5.2.1 Pattern Recognition

Pattern recognition in statistical data is one non-model way to interpret SHM information. Pattern recognition is the part of the broader topic of machine learning that is concerned with classification. Machine learning is when computational rules are derived from observational data as opposed to the more traditional method of imposing algorithms. Supervised and unsupervised are two types of learning algorithms. The difference between the two types of learning is that the supervised learning requires input and output data so that corrections of errors can be made simultaneously while unsupervised learning makes an initial algorithm and does not recalculate (20).

5.2.2 Artificial Neural Networks

Artificial Neural Networks (ANNs) are systems that have interconnecting computational nodes that are capable of working together and by trial and error to establish a relationship (an algorithm) between given inputs and an output as shown in Figure 5-1. In SHM applications, neural networks are trained to identify damage from measured responses of the structure (22). For model-based analysis, ANNs use system identification to estimate the dynamic properties (mass, stiffness and damping) of the structure. For non-model based analysis, ANNs use pattern recognition to detect damage from the response measurements from damaged and undamaged structures (21), (23).

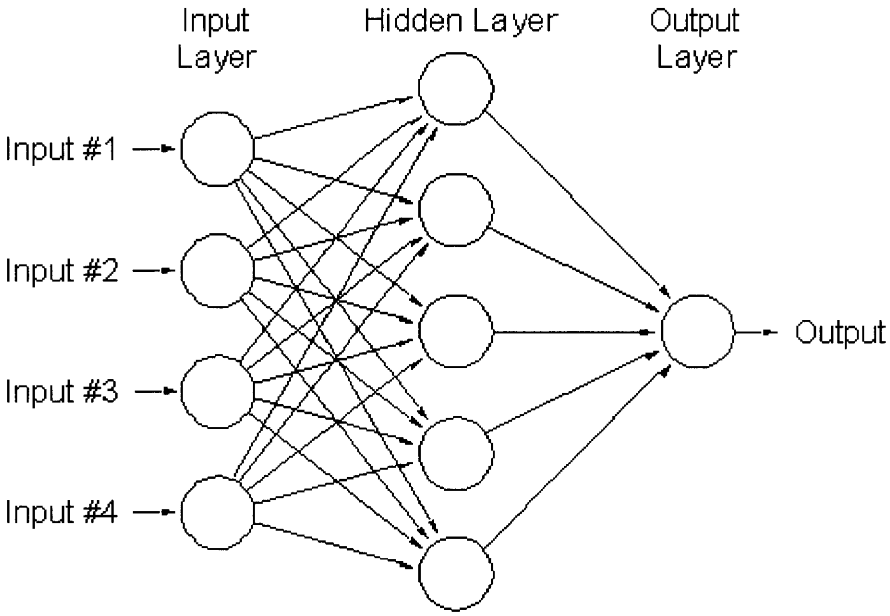


Figure 5-1: Neural network (33)

5.3 Local versus Global Approaches

Another way to classify the approaches is by local and global methods. Local methods investigate smaller areas of the structure and estimate location of damage by calculations or by comparison to existing knowledge. Global methods utilize the concept that local damage causes a change in the global behavior of a structure with respect to time and space. Global techniques basically determine the existence of damage rather than the location (22), (21).

All approaches rely on baseline information for the structure. One way to collect this initial data is through forced vibrations on the bridge after it is complete and before opening to traffic. Forced vibration tests make use of mechanical vibrators to identify the system properties of the healthy bridge as shown in Figure 5-2 (24).

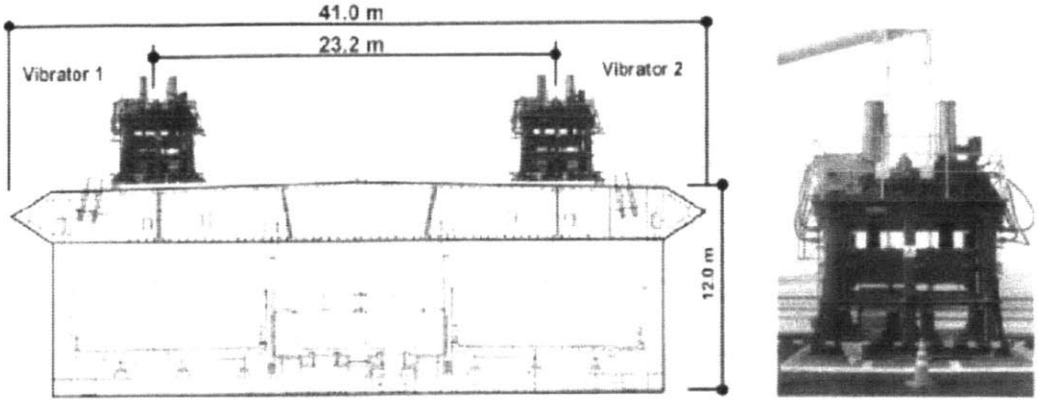


Figure 5-2: Forced vibration machines (24)

5.4 Data Normalization

The response of the system that indicates damage may be subtle and it is important that it is not overlooked due to changes in the response due to environmental and operational conditions. False-positive indications of damage may occur due to natural system variations and therefore data normalization is crucial to separate out the structural response when it is damaged. Conditions that may cause changes in the dynamic response included thermal expansion, variations in mass loadings and wind-induced vibrations (23).

There are three scenarios to consider for data normalization. The first situation is that data for the environmental variations is available and can be assessed so that the structural response can be refined to represent the structural damage only. The second circumstance is that direct measurements for the environmental variations are not available but the relationships between anomalies the structural response and environmental occurrences can be observed and data refined accordingly. The last situation is that data that corresponds to structural damage only and is completely nonresponsive to environmental variants exists and can be mined out (23).

6 CHALLENGES TO SHM

6.1 Confidence

Aviation and mechanical equipment has been relying on sensors to operate for years now yet there is hesitation when it comes to civil structures. Engineers and the public are not quite ready to let instrumentation determine the safety of structures. This trust issue is mostly due to the infancy of the industry. There are still many issues surrounding SHM that need to be improved or resolved but more applications of SHM are occurring and its use as a diagnostic tool is slowly becoming accepted (1).

6.2 Errors

SHM relies on the validity of the measurement data and poor data quality leads to incorrect interpretations and misdiagnosis. There are many sources for error and they are categorized into the two major types of systematic and random. Systematic error has to do with the setup of the measurement system and is most often due to mechanical or thermal mechanisms, electronics or referencing. These types of errors typically have a greater consequence on the accuracy of the data but can be mitigated by testing and calibrating the system. Random error is due to variations in the data due to uncontrolled variables. This type of error is assumed to follow a Gaussian distribution and confidence intervals can be developed to determine reliability of the information (25).

Another weakness in current application of SHM, although there exists some analysis tools for it, is the ability to distinguish between variations in data due to damage and that due to environmental conditions. Large variations in data prevent detecting small defects and false positives may also occur. Further research will need to examine this issue (26).

6.3 Maintenance

Maintenance of the SHM system is important as it relates to costs as well as maximizing the potential use. In wireless systems, the sensors rely on batteries and these will need to be replaced. The costs and effort involved in performing this replacement is troublesome to some owners (27). Technological advancements in batteries as well as power harvesting from natural sources will help with these concerns in the future.

6.4 Economics

Cost is a major consideration for many of the decisions made when implementing a SHM system. The optimal solution is when total cost is minimized and available monitoring data for performance prediction is maximized. The appeal of SHM is that the system saves money over the lifetime by planning for strategic and effective maintenance that prevents costly problems in the long term. SHM has implications on the design and cost of future structures as well in that material use may be optimized with a better understanding of structural response and lifetime of structures may be extended (28).

There are several applications of structural health monitoring and budgets for the cost of hardware and installation (excluding analysis and maintenance) are compiled. Out of 40 projects, over half were below \$50,000 with the rest up to \$500,000 and just one over \$500,000. When compared to the average costs of design and construction for new bridges, this is not a significant portion (18).

7 DESIGNING AND IMPLEMENTING A SHM SYSTEM

The most effective SHM systems are the ones that are designed to suit the needs of the owner as opposed to simply following the trend of implementing new technology. What can end up happening as a result of the latter is a system that works technically but will provide data that cannot be analyzed or practically used by the owner to make management decisions. The process for designing a SHM system is not yet formalized by code but does require the experience of professionals from all aspects of the industry from owners, to contractors to designers. In the SHM industry, there have been some steps towards drafting a procedure that will result in a useful and effective system and one such suggested procedure from D. Inaudi is outlined as follows (18).

STEP 1: Identify Structure

The purpose of Inaudi including this step was to make the designer think about whether the structure in question could really benefit from implementing a SHM system. It is important to consider this because it could justify the costs and a project implemented without clear goals would not be as successful. Structures shown to really benefit from a SHM system include new structures with innovative designs or materials, unusual risks or represent a larger group of similar structures, existing structures with known deterioration or up for rehabilitation or any structure that is part of a critical network (18).

STEP 2: Risk/ Uncertainty/ Opportunity Analysis

An important aspect of designing a SHM system is identifying the risks, uncertainties and opportunities specific to the structure. The risks associated with a structure include the possible events that may cause damage such as corrosion, loss of pre-stress, creep, overloading, earthquake or impact. The probability of these events occurring is also important because it helps weigh how important something is to monitor and whether it is worth the costs associated with it. Uncertainties of a structure are the structural performance issues that are not fully understood such as behavior of composites or actual loadings. Opportunity is the opposite of uncertainties in that structural aspects that are thought to be possibly overdesigned can be monitored to better understand if they are in fact overdesigned and material can be saved in the future (18).

STEP 3: Corresponding Responses

The next step is to find a corresponding structural response or responses that can be used to monitor the risk, uncertainty or opportunity. Some essential parts of this step include quantifying these responses, identifying where these responses could potentially occur and lastly how often data would need to be sampled to get a good representation, all to help facilitate sensor selection later (18).

STEP 4: Design SHM system and select sensors

Only after the initial considerations are realized should design of the system begin. In this step, sensors to collect the necessary data for the specified risks, uncertainties and opportunities can be selected. Budget and expected system lifetime will come into consideration here as well. The system should be designed with a balance between enough DASs to have good reliability in the data but not too many that costs become too high for the benefits (18).

STEP 5: Installation

After the system is designed, it can be installed as specified by the sensor distributors. At this step, the system must also be calibrated and initial measurements be taken if necessary (18).

STEP 6: Data Acquisition and Management

The system is now ready to operate and being logging data. Data acquisition and management is as specified in Chapters 3 and 4 (18).

STEP 7: Data Assessment

The last step in the process is to analyze the data received from the system. There are various analysis techniques as described in Chapter 5. The owner is then able to use the information to make management decisions for the structure that may include specific repairs or generate annual tasks as needed. Human inspections will most likely attempt to validate what the data reveals (18).

This procedure dictates a way to create an effective and useful SHM that will make the best use of the owner's money. Inexperienced designers or sensor developers may try to start the process at Step 4 but this will likely result in an implementation that is not optimal (18).

8 CASE STUDIES

SHM has been implemented on many bridges around the world. The following sections will briefly highlight the application of SHM to various types of bridges as examples of implementation in the industry. Table 8-1 shows the case studies that will be investigated in this chapter.

Table 8-1: Summary of case studies

Case Study	**Type of Bridge**	**Purpose**
I35W Bridge in Minneapolis	Concrete Beam	- Monitor for loss of pre-stress, functionality of bearings, cracks in concrete, settlement of piers and rebar corrosion - Study difference between FEM and reality - Study difference between predicted vibrations and real vibrations
Maslencia Bridge in Croatia	Arch	- Monitor for stresses, strains, corrosion and environmental conditions
Second Jindo Bridge in Korea	Cable Stayed	- Fully understand the structural behavior
Tsing Ma Bridge in Hong Kong	Suspension	- Monitor wind and structural responses

8.1 Concrete Beam Bridge

An example for a SHM system for a concrete beam bridge is the one installed on the replacement of the I35W Bridge in Minneapolis as shown in Figure 8-1. The bridge consists of two pre-stressed concrete box girders supported by concrete columns. It is approximately 1300 feet long and 180 feet wide. The main risks that the system is monitoring for are loss of pre-stress, functionality of bearings, cracks in concrete, settlement of piers and rebar corrosion. Other goals of the system are to study the difference between the stresses/ strains from the Finite Element Model and the real stresses/ strains, the difference between predicted vibration modes and real vibration modes as well as the ability to speed up construction by allowing less curing time for concrete (18).

The SHM system for this bridge consists of vibrating wire strain gauges, fiber optic sensors, accelerometers, corrosion sensors and concrete humidity sensors with one database that can be remotely accessed. Sensors locations are shown in Figure 8-2. Readings were taken during construction, during an initial load test and is currently collecting data to be managed and analyzed by the University of Minneapolis (18).

Figure 8-1: I35W Bridge (18)

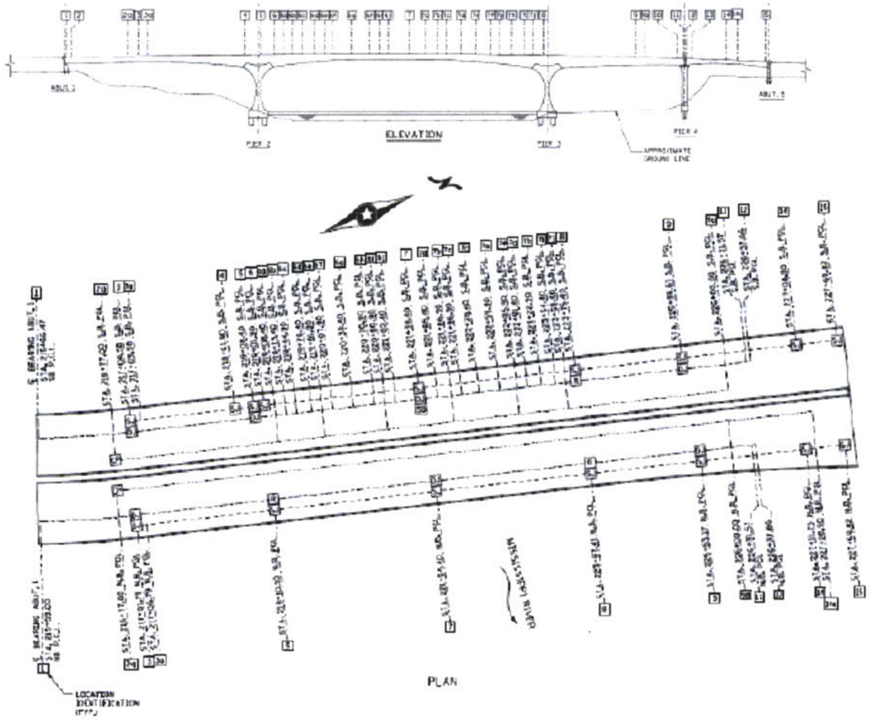


Figure 8-2: I35W Instrumentation layout (29)

8.2 Arch Bridge

Another example of implemented SHM is on the Maslencia arch bridge in Croatia that was completed in 1997. The concrete arch spans 650 feet and has a cross section of a double-cell. The deck consists of 8 precast prestressed simply-supported girders. The SHM system was installed to monitor stresses, strains, corrosion and environmental conditions with the intent to facilitate well-timed maintenance (13).

The SHM system includes 92 strain gauges, 40 temperature sensors and 21 corrosion sensors. Locations of sensors are shown in Figure 8-3. Like the previous bridge, readings were taken during construction and during an initial load test to get baseline data (13). The project unfortunately was not continued which often happens with SHM projects because owners lose interest.

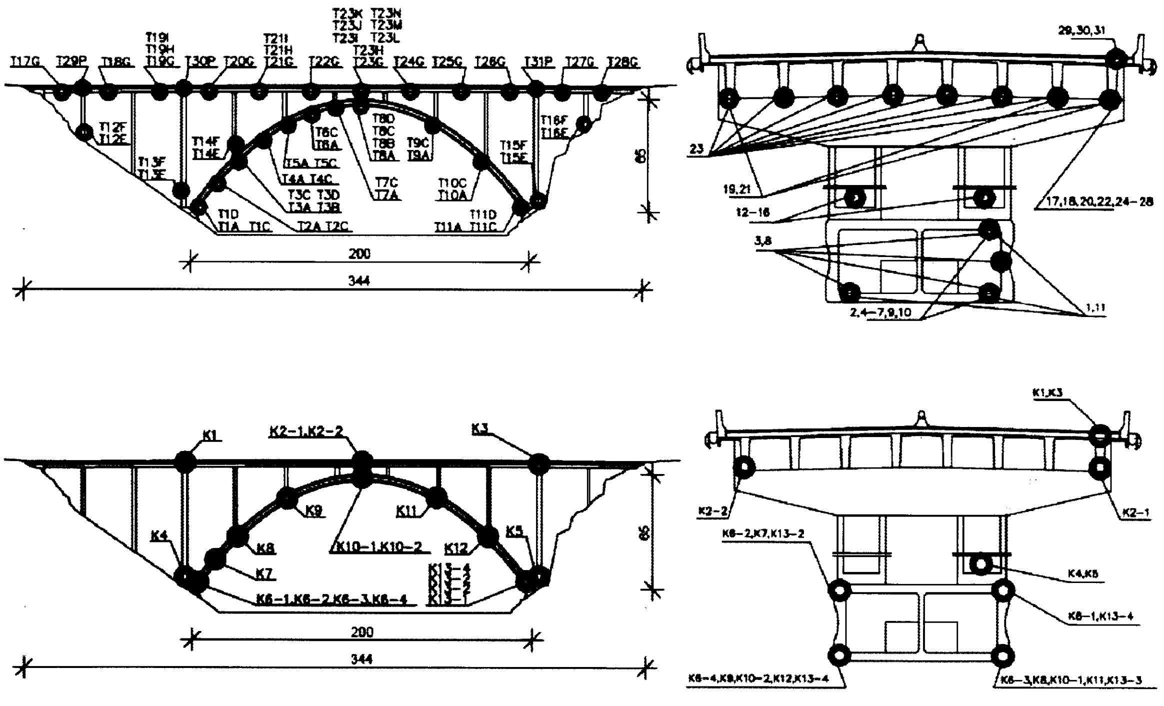


Figure 8-3: Maslencia Bridge Instrumentation Layout (13)

8.3 Cable Stayed Bridge

A case of SHM implemented in Korea is on the second Jindo Bridge. The 1130 foot long, 230 feet wide cable-stayed bridge connects Haenam and Jindo Island. The structure consists of a steel box girder supported by 60 parallel wire strand cables. The purpose of installing a SHM system was to fully understand the structural behavior of the bridge (16).

The SHM system consists of 70 sensors divided between two subsystems as shown in Figure 8-4. There are 33 sensor nodes on the Jindo side with 22 on the deck, 3 on the pylon and 8 on the cables. On the Haenum side, there are 37 nodes with 26 on the deck, 3 on the pylon and 7 on the cables. Most of the sensors are accelerometers and anemometers. The system was split into two because of distance limitations with transmitting data wirelessly (16).

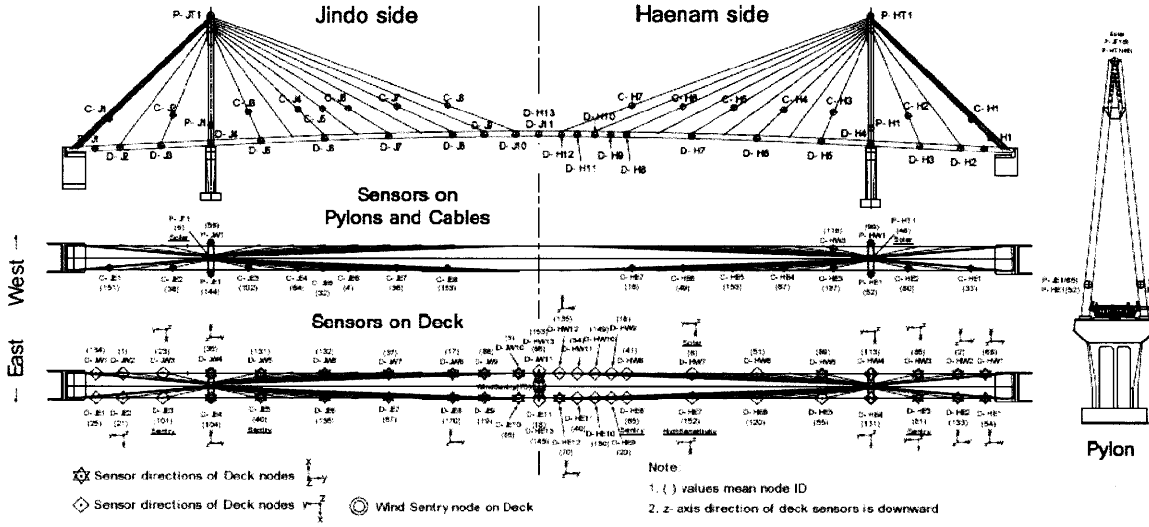


Figure 8-4: Instrumentation layout of a cable-stayed bridge (16)

This project employed the use of solar panels and rechargeable batteries to run the sensors with strategic periodic sensing to preserve battery. Results found that the sensors can monitor for 2 months before needing replacement demonstrating the feasibility of powering a wireless system. Sensors were placed in positions close enough to the deck in order to facilitate battery changes (16).

The implementation of this SHM system was a success because it verified the modal predictions from a finite element model. As shown in Figure 8-5, the observed mode shapes from the measured data corresponded well to those predicted by the finite element analysis.

(a) DV1 (MAC: 0.957)

(b) DV2 (MAC: 0.986)

(c) DV3 (MAC: 0.975)

(d) DV6 (MAC: 0.949)

(e) DV9 (MAC: 0.943)

Figure 8-5: Comparison of identified mode shapes (left) and mode shapes predicted from finite element model (right) (16)

8.4 Suspension Bridge

The Tsing Ma Bridge in Hong Kong is an example of SHM applied to suspension bridges. The 4500 foot long bridge carries both vehicle and rail traffic in a double deck formation of steel orthotropic decks. The bridge was opened in 1997 with a wind and structural health monitoring system (30).

The SHM system consists of accelerometers, strain gauges, displacement transducers, anemometers, temperature sensors, weigh-in-motion sensors and GPS sensors as shown in Figure 8-6. There are 110 strain gauges alone installed on the bridge deck. An initial check for the system was to see if it could successfully identify the dynamic strains caused by passing trains (30).

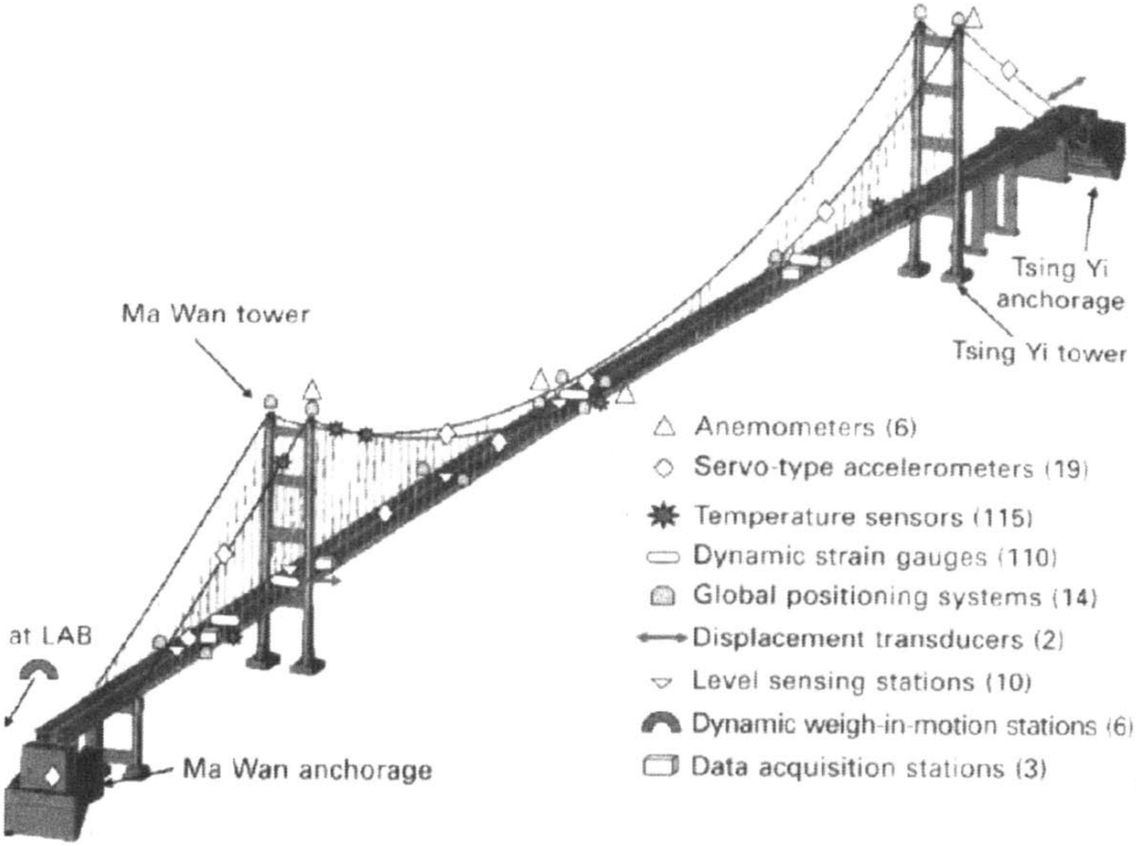


Figure 8-6: Instrumentation layout in Tsing Ma Bridge (31)

9 APPLICATION TO MASTER OF ENGINEERING PROJECT

The concepts covered in this paper are currently used in industry and will have many future uses. As an example of application, a SHM system is proposed for the design project for the Master of Engineering program in High Performance Structures at MIT. Steps 1 through 4 of the procedure explained in Chapter 7 are attempted and comments are made on the procedure.

9.1 Identification of the Structure to be Monitored (Step 1)

The existing Longfellow Bridge is about 1700 feet long and 105 feet wide. It consists of 11 steel arch spans supported by masonry piers. This bridge transports vehicle, rail and pedestrian traffic between Cambridge and Boston in Massachusetts. It has fallen into a state of disrepair and needs to be replaced. A suggestion was made for its replacement for the Master of Engineering program in High Performance Structures course at MIT. It is for this proposal for new design that a SHM scheme is proposed.

Figure 9-1: Final design proposal

Figure 9-1 shows the final proposal for design. The concept for this bridge is three arches for three types of circulation however all of the arches are interlaced and support different portions of deck below as in Figure 9-2. One arch is asymmetrical and tilting and supports half of the roadway and half of the railway. Another is symmetrical and tilting and supports half of the railway and half of the pedestrian way. The last is asymmetrical and plumb and supports half of the pedestrian way and half of the roadway. The different proportions of dead loads from the decks create corresponding asymmetries in the arch shapes.

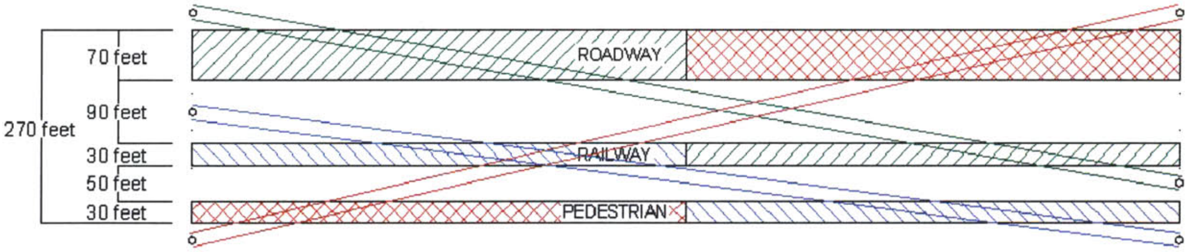


Figure 9-2: Arch/ Deck relationships

The arches are made of steel with rectangular cross-sections of varying heights and widths and sometimes with stiffeners to combat large moments due to wind and disproportionate live loadings. There are 108 standard parallel strand cables in total with 36 attached to each deck at the longitudinal girders. The structural system for the deck consists of steel girders with concrete slabs with the system slightly modified for the type of traffic it is carrying. There are six large foundations located at the abutments on each side.

This structure is a good candidate for a SHM system for the following reasons:

- structural behavior is difficult to predict due to being an innovative design that does not have many similar structures preceding it
- will undergo temperature extremes due to location
- difficult to predict reaction to wind due to location, shape and height
- difficult to predict behavior during construction due to complicated sequencing and method

9.2 Analysis and Responses (Steps 2 and 3)

In Table 9-1, the risks, uncertainties and opportunities particular to this structure are listed on the left and the corresponding responses that may be used to quantify them are on the right.

Table 9-1: Risks/ uncertainties/ opportunities analysis and corresponding responses

ANALYSIS	RESPONSE
Risks	
- Non-working bearings and expansion joints	- Reduced displacement of expansion joints
- Cracks in concrete slabs	- Changes in curvature
- Overstressing at cable connections	- Increased stresses
- Settlement	- Redistributed loads
- Corrosion	- Change in material properties
- Stresses in arches during construction	- Excessive stresses
Uncertainties	
- Correlations between finite element model predictions and real strains/ stresses	- Difference between predicted and real strains
- Correlations between calculated vibration modes and real mode shapes	- Difference between predicted and real vibrations
- Wind loads	- Wind velocities
- Effects of vortex shedding	- Vibrations
- Cable life	- Loads in cables
Opportunities	
- Deck Type	- Additional stiffness

Additional considerations at this step would include quantifying these responses, identifying where these responses could potentially occur and how often data would need to be sampled.

9.3 Select Sensors and Design System (Step 4)

Appropriate sensors are selected to correspond to the various risks, uncertainties or opportunities to be monitored and are shown in Table 9-2.

Table 9-2: Sensors and issue addressed

Sensor	Measurement	Purpose
Accelerometers	Traffic induced vibrations	Excessive vibrations
	Wind induced vibrations	Excessive vibrations
	Modal frequencies	Correspondence with analysis
Strain Gauges	Strains	Correspondence with analysis
	Curvature	Overloading
Load Cells	Load	Cable loadings
GPS	Accelerations	Verify/ supplement data from accelerometers
	Displacements	Verify/ supplement data from displacement transducers
	Time	Time synchronization
Anemometers	Wind speeds	
Thermistors	Temperatures	Temperature induced strains

Costs would also be considered when selecting the number of sensors. A signature span such as this one would have a corresponding SHM system and therefore costs are not a critical constraint however strategic placement is attempted.

Sensor placement is based on the results of the static and dynamic analyses. Some results of the static analysis are shown in Figures 9-3 through 9-5. Due to the geometry, many combinations of live loadings are possible and the static analysis explored which combinations were most critical. Locations of maximum deflections for various critical combinations are shown in Figure 9-3. These locations should be instrumented with strain gauges.

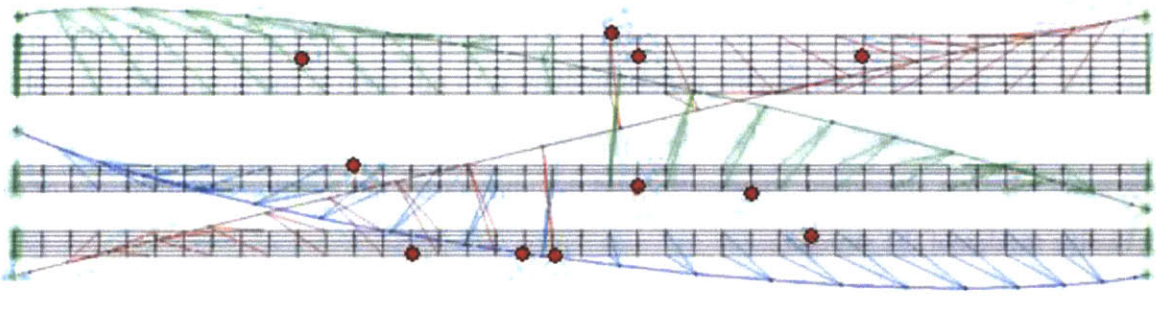


Figure 9-3: Locations of maximum deflection from all critical load case scenarios

The various live load scenarios were also applied in the finite element analysis of the concrete deck. Figure 9-4 shows the stresses in the deck for one such scenario with others located in the Appendix. Strain gauges should be installed at the areas showing maximum stress.

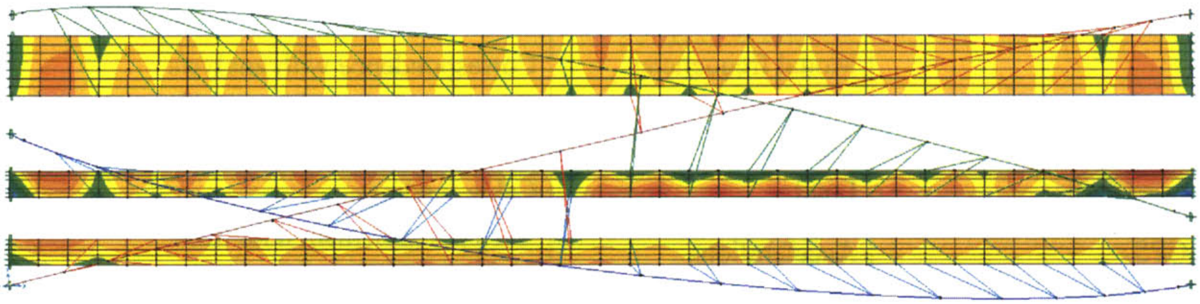


Figure 9-4: Global shear stress in deck slabs (Range from -5281 to 5281 psi)

The static analysis also resulted in shear and moment diagrams, as shown in Figure 9-5, for the arches so that locations of the extremes can be noted. It is at these locations that strain gauges should also be installed.

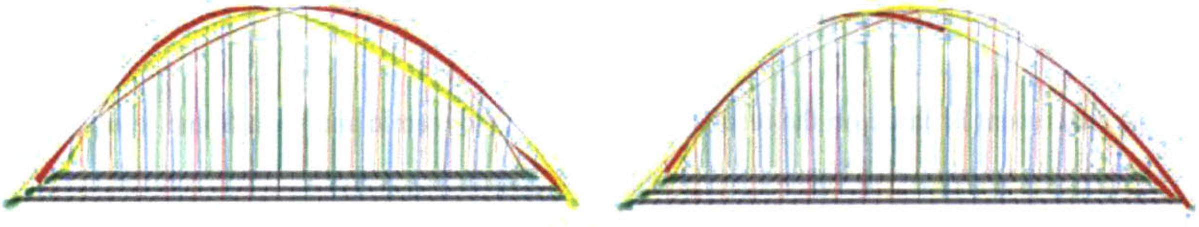
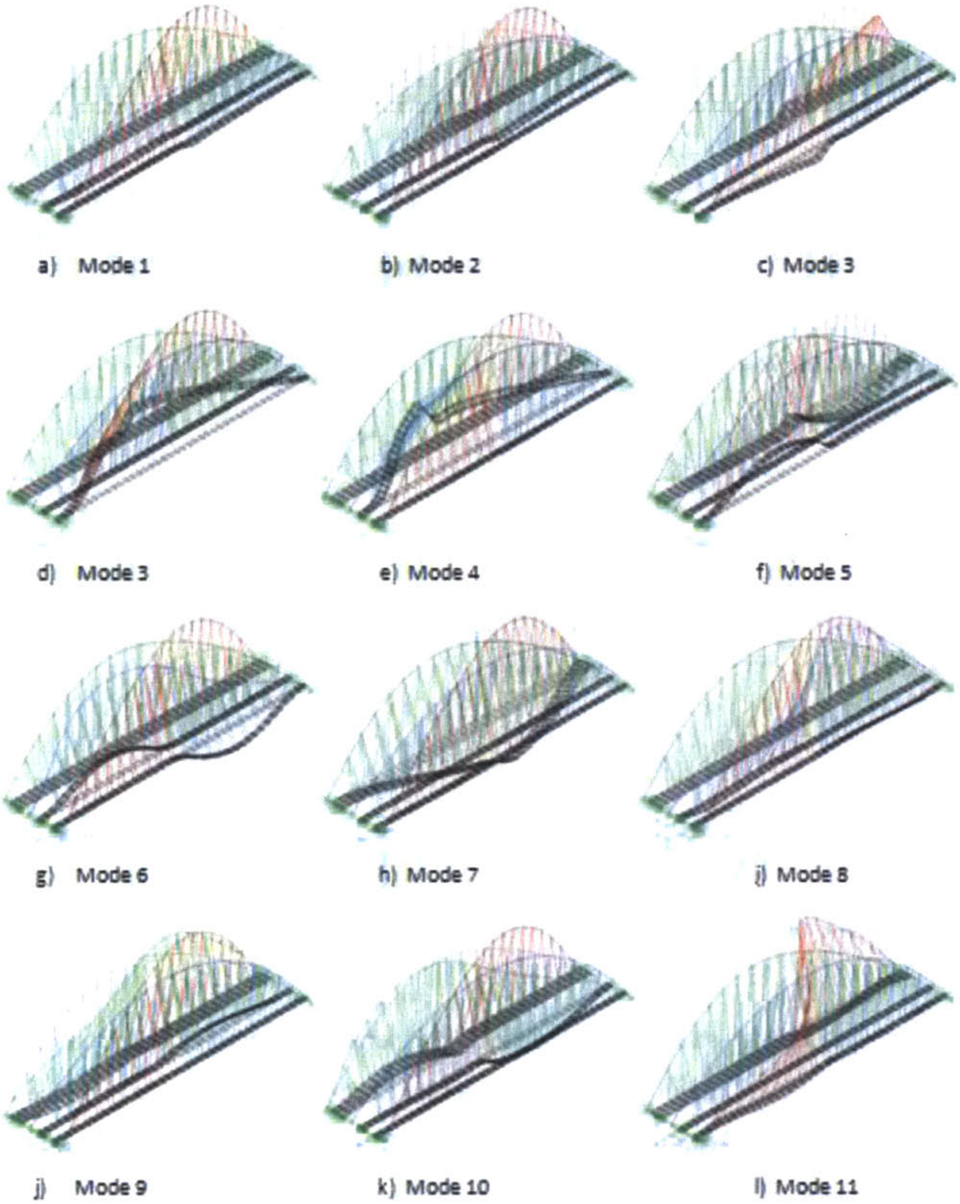


Figure 9-5: Moment and shear diagrams of the arches

Accelerometers can be placed based on the results of the dynamic analysis. The complexities of design create interesting modal analysis results. The first twelve mode shapes are shown in Figure 9-6. The strategy when placing accelerometers is to put them at the antinodes if possible. Antinodes are the locations were the mode shape experiences the most displacement, as opposed to the node which is stationary. Figures 9-7 and 9-8 summarize the locations of antinodes of the first twelve modes of the structure.



a) Mode 1
b) Mode 2
c) Mode 3
d) Mode 3
e) Mode 4
f) Mode 5
g) Mode 6
h) Mode 7
j) Mode 8
j) Mode 9
k) Mode 10
l) Mode 11

Figure 9-6: First twelve mode shapes

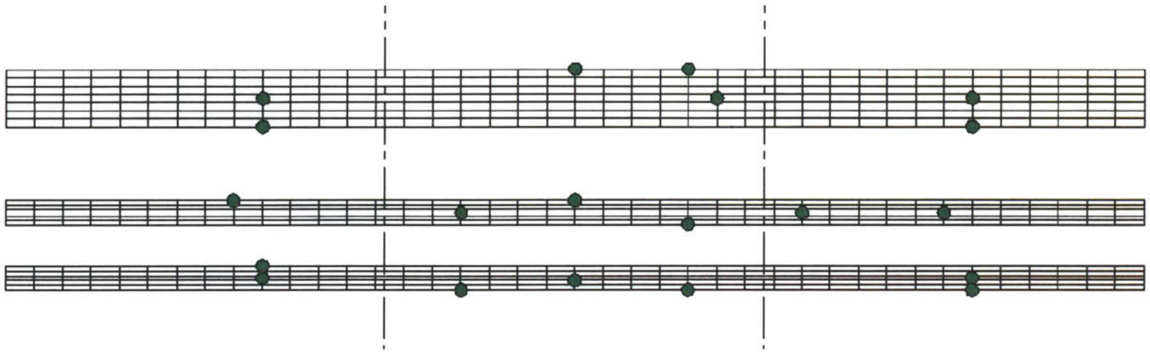


Figure 9-7: Locations of antinodes on the deck

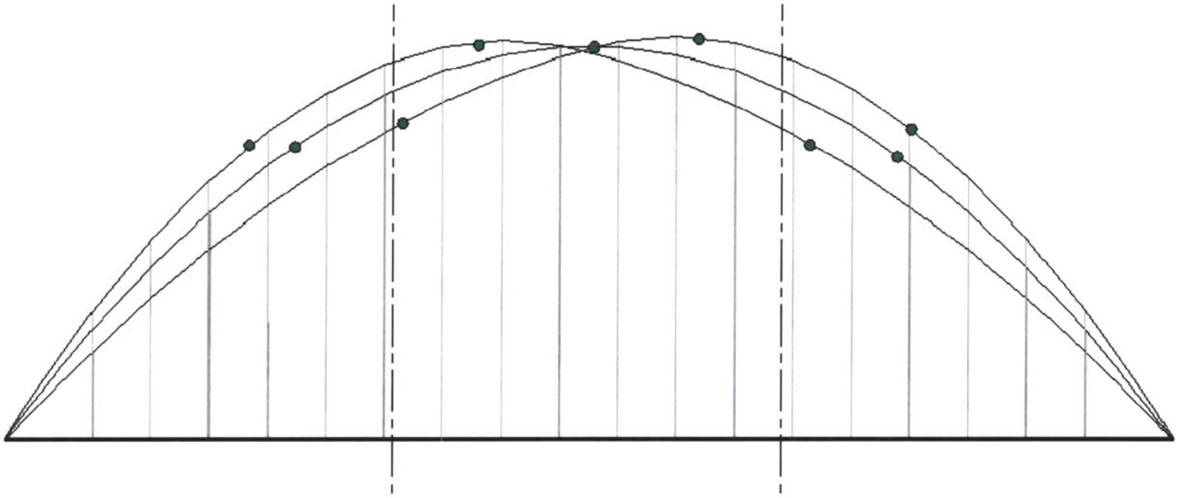


Figure 9-8: Locations of antinodes on the arches

Following these placement strategies and using the sensors selected by the analysis, a SHM system is designed for each major part of the structure. A wireless system is proposed in order to reduce costs and facilitate installation. The arches will be instrumented with strain gauges and accelerometers at each of the three antinodes on each arch, with GPS systems at the high points and five anemometers even spaced about each arch. Six cables from each arch will be instrumented with strain gauges, accelerometers and load cells. They shall be placed at a height that is easily accessible so as to facilitate service. The decks should have accelerometers and strain gauges placed at the antinodes as indicated. An extra ten strain gauges per deck shall be placed at transverse girders not connected to cables as these locations have higher potential for stresses and to help validate modal analysis. Temperature sensors should be installed at the abutments and midpoint of each deck.

Total sensor counts are 47 accelerometers, 77 strain gauges, 18 load cells, 3 GPS units, 15 anemometers and 9 temperature sensors. This system will need 3 sensor clusters in a multi-hop network topology divided as shown in Figures 9-7 and 9-8 due to transmission range of the wireless system. Solar panels and rechargeable batteries will allow for longer periods of monitoring without needing battery replacement. Baseline information of the healthy structure can be found by induced vibrations from forced vibration machines. Data should be initially processed to reduce the volume of information transmitted and then further reduced in analysis.

9.4 Comments on this Procedure

The most important part of the suggested procedure is the first three steps. It is clear after the application example that a focused and goal oriented system will lead to actionable results. It is also clear that a design that begins with choosing sensors will be misguided. This procedure is effective at forcing the user to start in a more appropriate place.

10 CONCLUSION

10.1 Future of SHM

SHM has a definite future in the maintenance and design of bridges and other civil structures. The applications of SHM to date have been successful at providing more knowledge about structures so that design may become more efficient and maintenance work more effective.

Technology developments will likely bring smaller, cheaper and more durable sensors with improved battery life. Energy harvesting will become more efficient and may be able to offset or replace battery use. The range of data transmission will increase and the capabilities of wireless systems will be expanded. Improvements in intelligent signal processing will result in being able to process more information and have better quality results. Data storage capabilities will increase and allow for detailed histories of structures.

SHM will help engineers to better understand the loads that a structure will endure and the response of the structure to specific loads. Modeling software can then be updated accordingly and design can become more efficient. It is possible that codes can change in response to having an improved understanding of structures.

Maintenance plans will be in response to need as opposed to time intervals and will extend the life of structures. Diagnosis of existing structures may be more challenging in that the characteristics of a healthy version of the structure are unknown but there is a need for these developments in SHM.

Optimal sensor placements will be developed more both mathematically and through trial and error in practice. Although probably 10 to 20 years away, SHM systems may potentially become standard with any new bridge design. SHM may also expand to other industries as the technology develops and new implementation scenarios arise.

SHM is a useful tool made possible by the development of affordable sensing technologies. The knowledge gained about structures is invaluable making it an industry that has a permanent future with civil structures.

10.2 Results

SHM is a diverse industry with many current and potential applications. The literature review, case studies and application example has lead to the following conclusions:

- The industry has a lot of room for growth, especially in the development of sensing technologies, analysis techniques and sensor placement optimization.
- As analysis techniques improve, the industry may be able to diagnose a deficient bridge without the baseline response.
- Design and implementation procedures that focus on the purpose of monitoring rather than the implementation of sensing technologies results in a more effective SHM system that is a better use funds and will have an effect on management decisions.
- SHM has a wide variety of application from short-term testing to lifetime monitoring.
- Maintenance will shift from time interval based to condition based which will improve safety and management costs.
- SHM has the potential to extend the life of structures, optimize future design and give engineers a better understanding of structures.

REFERENCES

1. **Boller, Christian.** Structural Health Monitoring - An Introduction and Definitions. [book auth.] Christian Boller, Fu-Kuo Chang and Yozo Fujino. *Encyclopedia of Structural Health Monitoring.* West Sussex : John Wiley & Sons, Ltd., 2009, pp. 3-25.

2. **Karbhari, Vistasp M.** Introduction: structural health monitoring - a means to optimal design in the future. [book auth.] Vistasp M Karbhari and Farhad Ansari. *Structural Health Monitoring of Civil Infrastructure Systems.* Great Abington : Woodhead Publishing Limited, 2009, pp. xv-xxiv.

3. **Todd, Michael D.** Data Interrogation Approaches with Strain and Load Gauge Sensor Arrays. [book auth.] Christian Boller, Fu-Kuo Chang and Yozo Fujino. *Encyclopedia of Structural Health Monitoring.* West Sussex : John Wiley & Sons, Ltd., 2009, pp. 277-286.

4. **Ansari, Farhead.** Fiber Optic Sensors for Structural Health Monitoring. [book auth.] Vistasp M Karbhari and Farhad Ansari. *Structural Health Monitoring of Civil Infrastructure Systems.* Great Abington : Woodhead Publishing Limited, 2009, pp. 260-282.

5. **Technique, Gage.** VW Spot-Weldable Strain Gauge. *Gage Technique - Geotechnical and Structural Intrumentation.* [Online] eBusiness UK, 2011. [Cited: April 26, 2011.] http://www.gage-technique.com/vw-spot-weldable-strain-gauge.htm.

6. **Geo-Enterprises, Durham.** Introduction to Tiltmeters. *Durham Table Slope Indicator - Geotechnical Instrumentation.* [Online] Durham Table Slope Indicator, 2011. [Cited: April 26, 2011.] http://www.slopeindicator.com/instruments/tilt-intro.html.

7. **Ltd., Penny & Giles Controls.** The DC-LVDT Displacement Transducer. *How They Work.* [Online] Penny & Giles Controls Ltd., April 26, 2011. [Cited: April 26, 2001.] http://www.sensorland.com/HowPage009.html.

8. **Haroon, Muhammad.** Free and Forced Vibration Models. [book auth.] Christian Boller, Fu-Kuo Chang and Yozo Fujino. *Encyclopedia of Structural Health Monitoring.* 2009, pp. John Wiley & Sons, Ltd.

9. **Worden, Keith and Friswell, Michael I.** Modal-Vibration-based Damage Identification. [book auth.] Christian Boller, Fu-Kuo Chang and Yozo Fujino. *Encyclopedia of Structural Health Monitoring.* West Sussex : John Wiley & Sons, Ltd., 2009.

10. **Karbhari, Vistasp M.** Vibration-based damage detection techniques for structural health monitoring of civil infrastructure systems. [book auth.] Vistasp M Karbhari and Farhad Ansari. *Structural Health Monitoring of Civil Infrastructure Systems.* Great Abington : Woodhead Publishing Limited, 2009, pp. 177-212.

11. *Detecting bridge dynamics with GPS and triaxial accelerometers.* **Meng, X, Dodsen, A H and Roberts, G W.** Nottingham : Engineering Structures, 2007, Vol. 29.

12. *Tower Bridge Movement Analysis with GPS and Accelerometer Techniques: Case Study Yonghe Tower Bridge.* **Kaloop, A R and Li, Hui.** 8, Harbin : Information Technology Journal, 2009, Vol. 8.

13. *Structural health monitoring of large arch bridges in croatia.* **Radic, Jure, Bleiziffer, Jelena and Kalafatic, Ivan.** Brijuni Islands : Chinese-Croatian Joint Colloquium, 2008.

14. **Bischoff, Reinhard, Meyer, Jonas and Feltrin, Glauco.** Wireless Sensor Network Platforms. [book auth.] Christian Boller, Fu-Kuo Chang and Yozo Fujino. *Encyclopedia of Structural Health Monitoring.* West Sussex : John Wiley & Sons, Ltd., 2009.

15. **Swartz, R. A. and Lynch, J. P.** Wireless sensors and networks for structural health monitoring of civil infrastructure systems. [book auth.] Vistasp M Karbhari and Farhad Ansari. *Structural Health Monitoring of Civil Infrastructure Systems.* Great Abington : Woodhead Publishing Limited, 2009.

16. *Structural Health Monitoring System of a Cable-Stayed Bridge using a Dense Array of Scalable Smart Sensor Network.* **Cho, Soojin, et al.** 2010, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems.

17. **Barthorpe, Robert J and Worden, Keith.** Sensor Placement Optimization. [book auth.] Christian Boller, Fu-Kuo Chang and Yozo Fujino. *Encyclopedia of Structural Health Monitoring.* West Sussex : John Wiley & Sons, Ltd., 2009.

18. *Long-term static Structural Health Monitoring.* **Inaudi, D.** 2010 Structures Congress, Manno : ASCE, 2010.

19. **McNeill, D K.** Data management and signal processing for structural health monitoring of civil infrastructure systems. [book auth.] Vistasp M Karbhari and Farhad Ansari. *Structural Health Monitoring of Civil Infrastructure Systems.* Great Abington : Woodhead Publishing Limited, 2009.

20. **Worden, K, Manson, G and Rippengill, S.** Statistical pattern recognition and damage detection in structural health monitoring of civil infrastructure systems. [book auth.] Vistasp M Karbhari and Farhad Ansari. *Structural Health Monitoring of Civil Infrastructure Systems.* Great Abington : Woodhead Publishing Limited, 2009.

21. **Saadat, Soheil, et al.** *Structural health monitoring and damage detection using an intelligent parameter varying (IPV) technique.* Raleigh : s.n.

22. **Fritzen, Claus-Peter.** Vibration-Based Techniques fro Structural Health Monitoring. [book auth.] Daniel Balageas, Claus-Peter Fritzen and Alfredo Guemes. *Structural Health Monitoring.* Great Britain : ISTE Ltd, 2006.

23. **Sohn, Hoon and Oh, Chang Kook.** Statistical Pattern Recognition. [book auth.] Christian Boller, Fu-Kuo Chang and Yozo Fujino. *Encyclopedia of Structural Health Monitoring.* West Sussex : John Wiley & Sons, Ltd., 2009.

24. **Koh, H M, Kim, S and Choo, J F.** Recent development of bridge health monitoring system in korea. [book auth.] Farhad Ansari. *Sensing Issues in Civil Structural Health Monitoring.* Netherlands : Springer, 2005.

25. **Zhang, Ruifeng and Aktan, Emin.** Design coniderations for sensing systems to ensure data quality. [book auth.] Farhad Ansari. *Sensing Issues in Civil Structural Health Monitoring.* Netherlands : Springer, 2005.

26. *A Summary Review of Vibration-Based Damage Identification Methods.* **Doebling, Scott W, Farrar, Charles R and Prime, Michael B.** Los Alamos : Identification Methods," The Shock and Vibration Digest, 1998, Vol. 30.

27. **Issa, Mohsen A, Shabila, Hameed I and Alhassan, Mohammad.** Structural health monitoring systems for bridge decks and rehabilitated precast prestress concrete beams. [book auth.] Farhad Ansari. *Sensing Issues in Civil Structural Health Monitoring.* Netherlands : Springer, 2005.

28. *Cost-Effective Lifetime Structural Health Monitoring Based on Availability.* **Kim, Sunyong and Frangopol, Dan M.** 1, Bethlehem : Journal of Structural Engineering, 2010, Vol. 137. ISSN 0733-9445/2011/1-22-33.

29. *Structural Health Monitoring System for the new I-35W St Anthony Falls Bridge.* **Inaudi, Daniele, et al.** Zurich, Switzerland : Structural Health Monitoring on Intelligent Infrastructure, 2009. unknown.

30. *Fiber Bragg grating sensors for structural health monitoring of Tsing Ma bridge: Background and experimental observation.* **Chan, T H T, et al.** 2006, Engineering Structures.

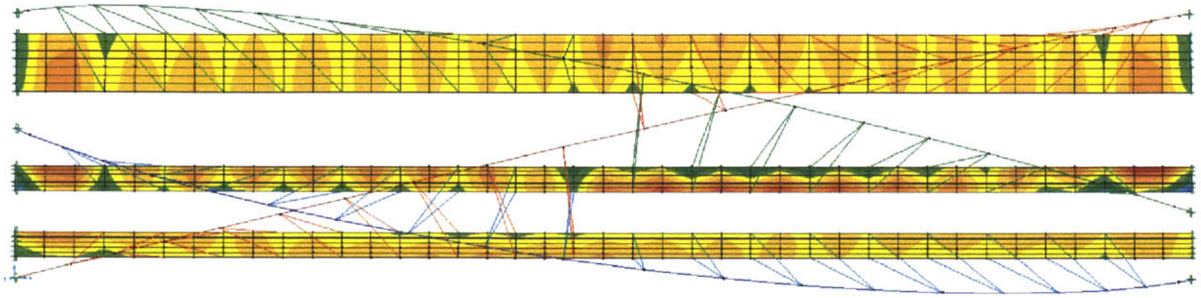
31. **Wong, K Y and Ni, Y Q.** Structural health monitoring of cable-supported bridges in Hong Kong. [book auth.] Vistasp M Karbhari and Farhad Ansari. *Structural Health Monitoring of Civil Infrastructure Systems.* Great Abington : Woodhead Publishing, 2009.

32. **Karbhari, Vistasp M.** Health monitoring, damage prognosis and service-life prediction - Issues related to implementation. [book auth.] Farhad Ansari. *Sensing Issues in Civil Structural Health Monitoring.* Netherlands : Springer, 2005.

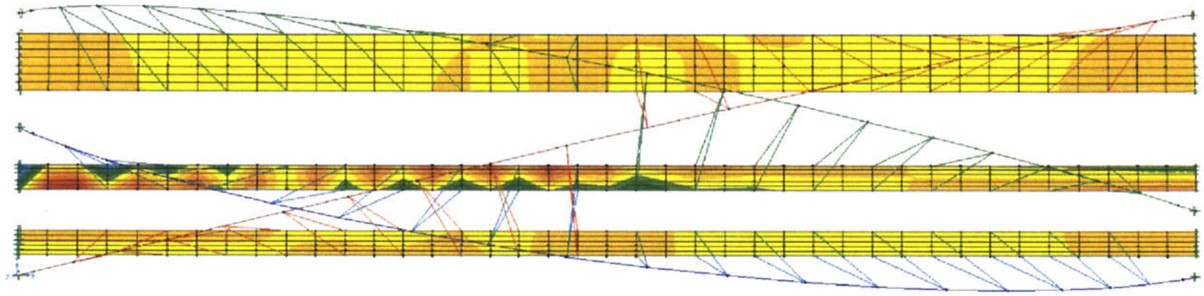
33. **Rounds, Stewart A.** Development of a Neural Network Model for Dissolved Oxygen in the Tualatin River, Oregon. *USGS Surface-Water Quality and Flow Modeling Interest Group.* [Online] USGS, July 2002. http://smig.usgs.gov/SMIG/features_0902/tualatin_ann.html.

APPENDIX

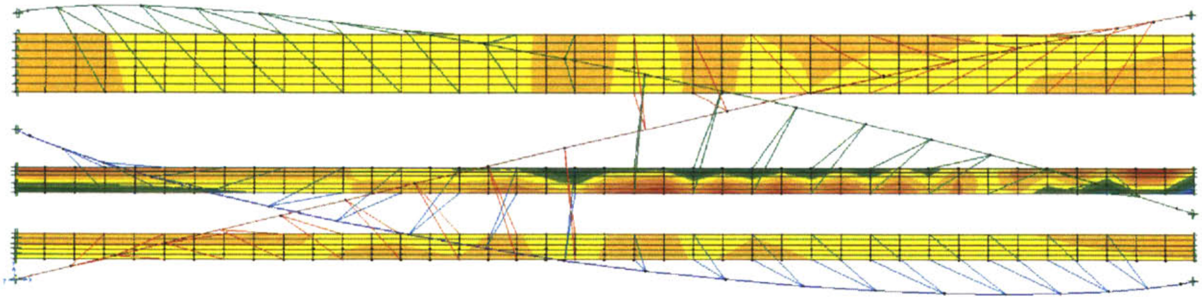
All Live Loads, Max = 5281 psi



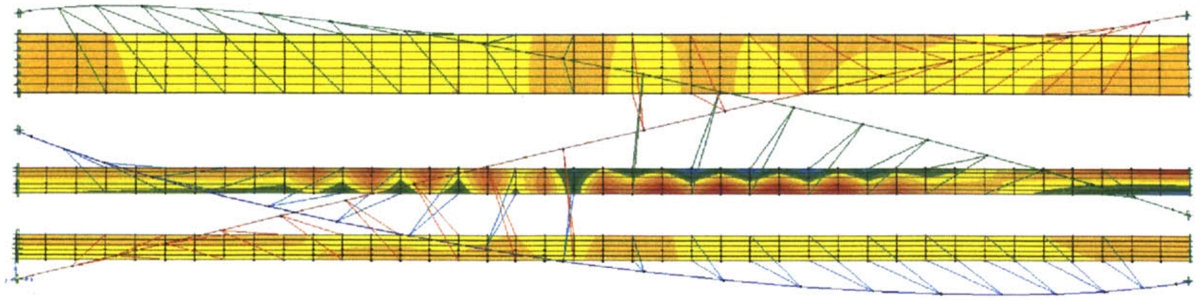
Train 1, Max = 1740 psi



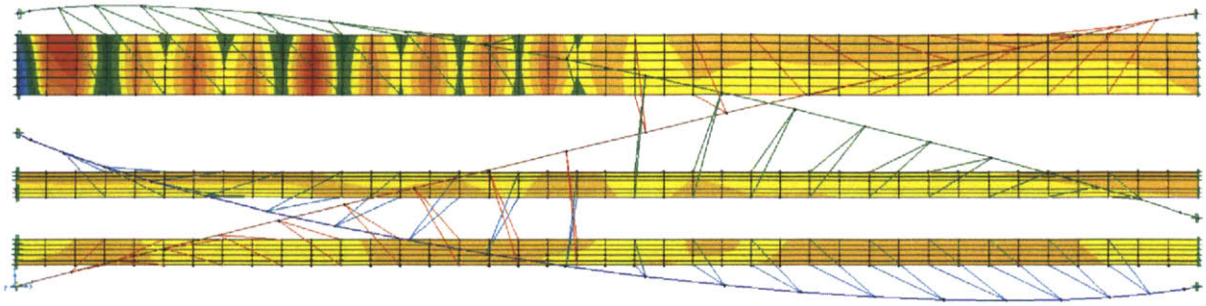
Train 2, Max = 2760 psi



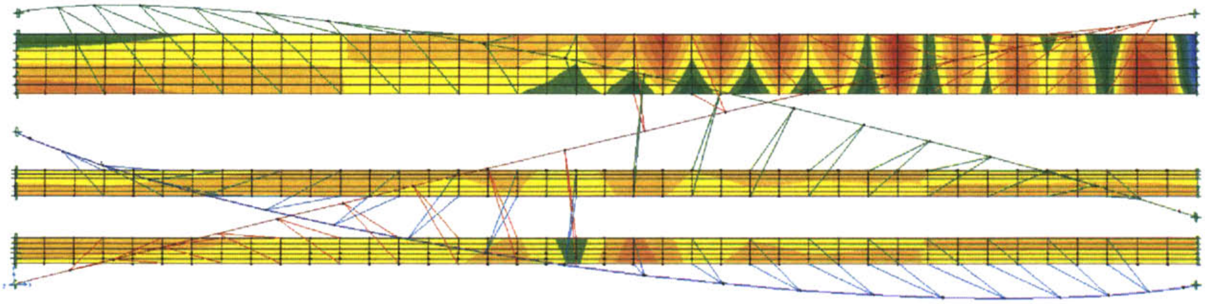
Train Mid, Max = 1279 psi



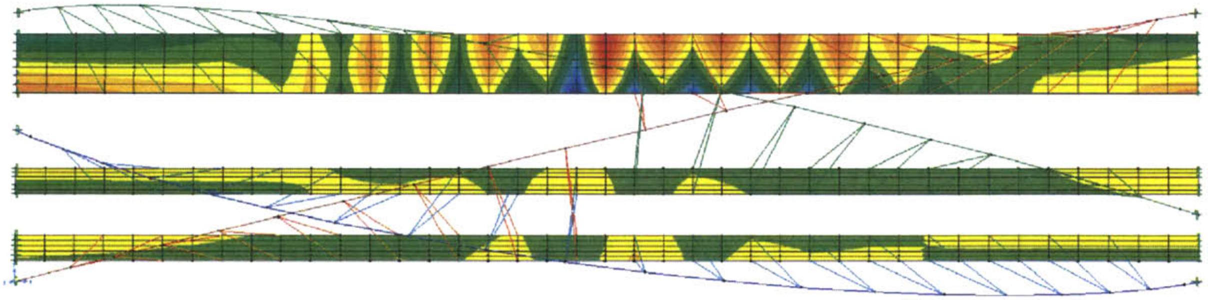
Road 1, Max = 678 psi



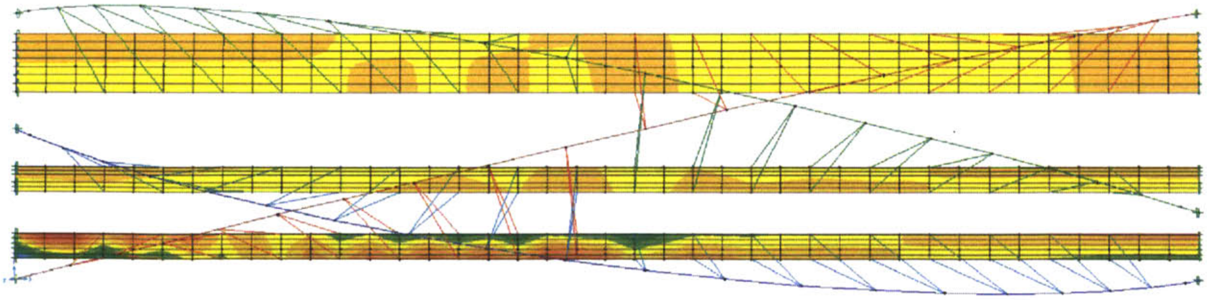
Road 2, Max = 677 psi



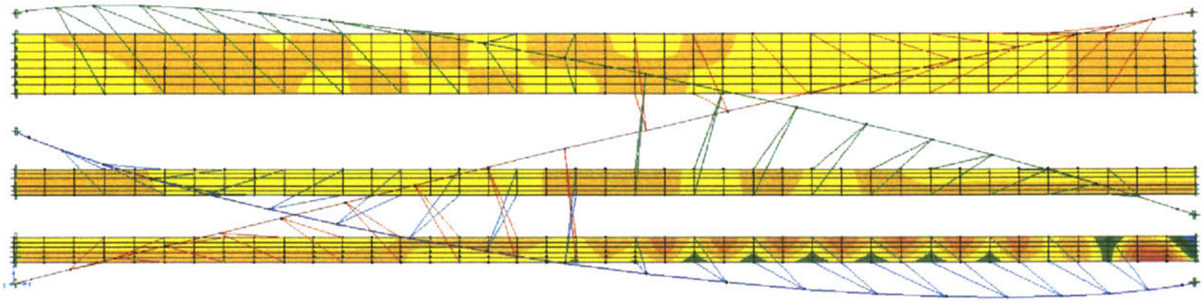
Road Mid, Max = 588 psi



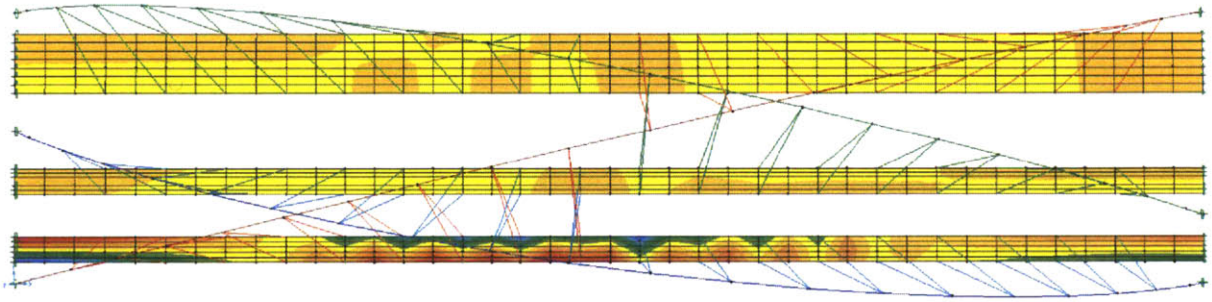
Pedestrian 1, Max = 2222 psi



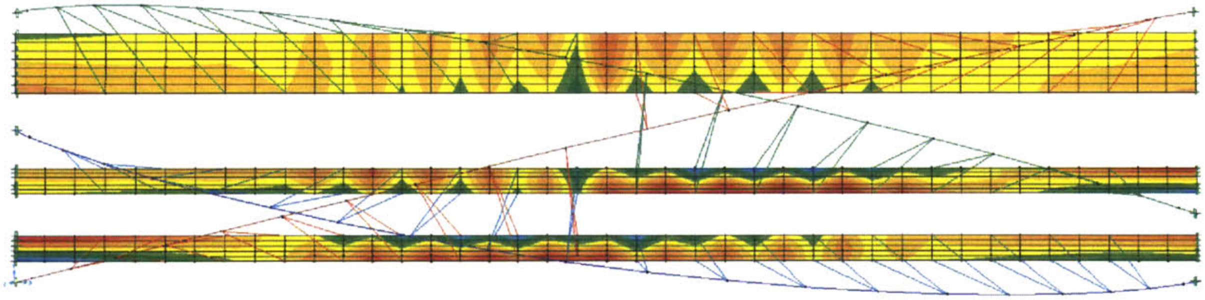
Pedestrian 2, Max = 1454 psi



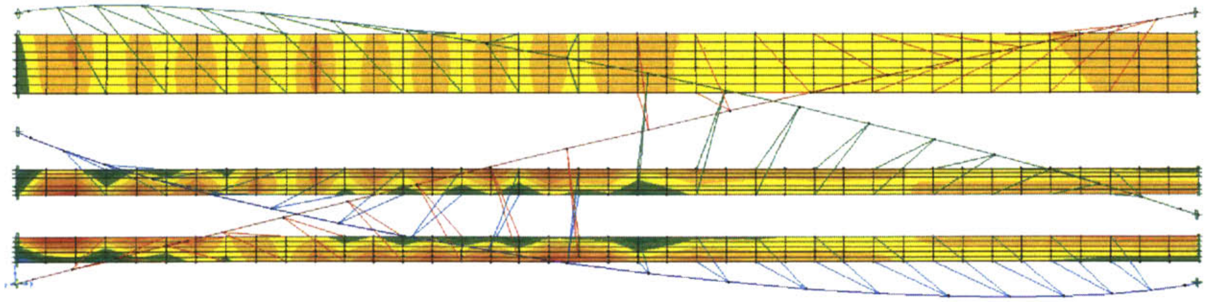
Pedestrian Mid, Max = 1289 psi



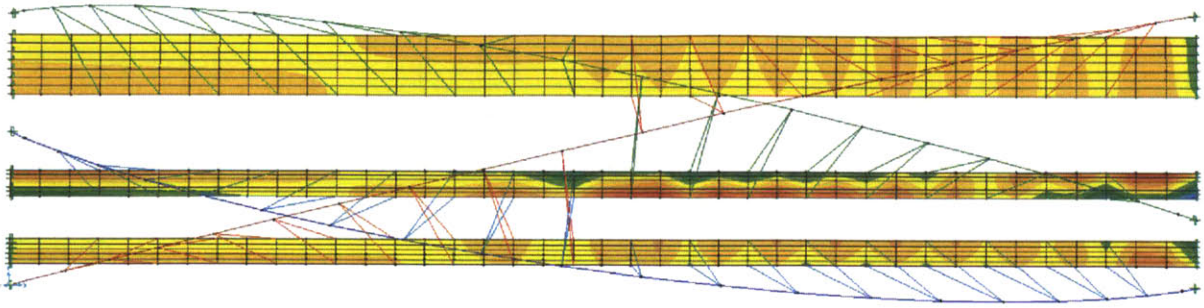
All Mid, Max = 1311 psi



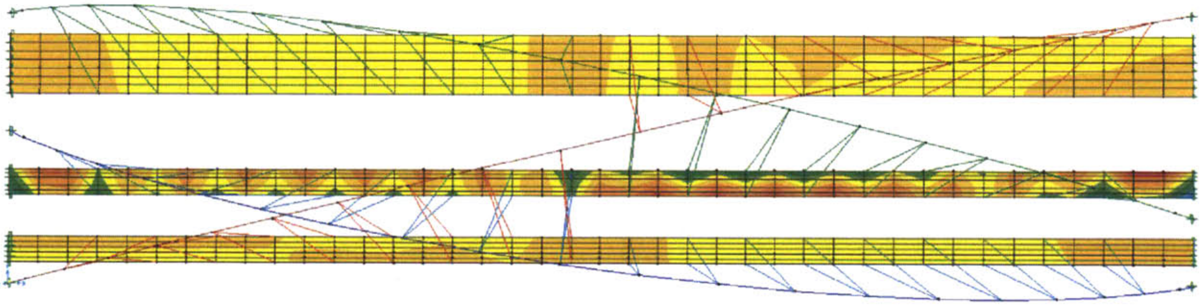
All 1, Max = 2224 psi



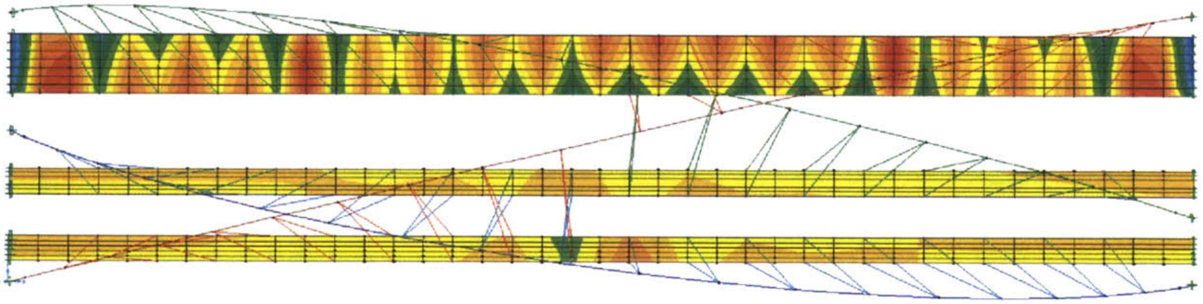
All 2, Max = 2758 psi



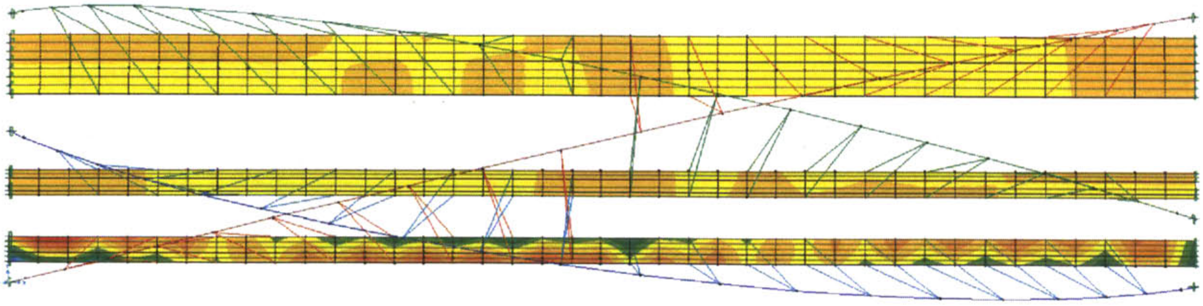
Train All, Max = 2213 psi



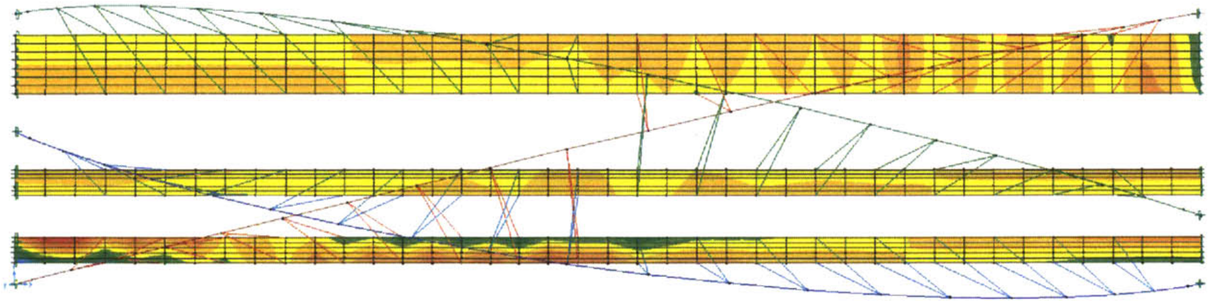
Road All, Max = 676 psi



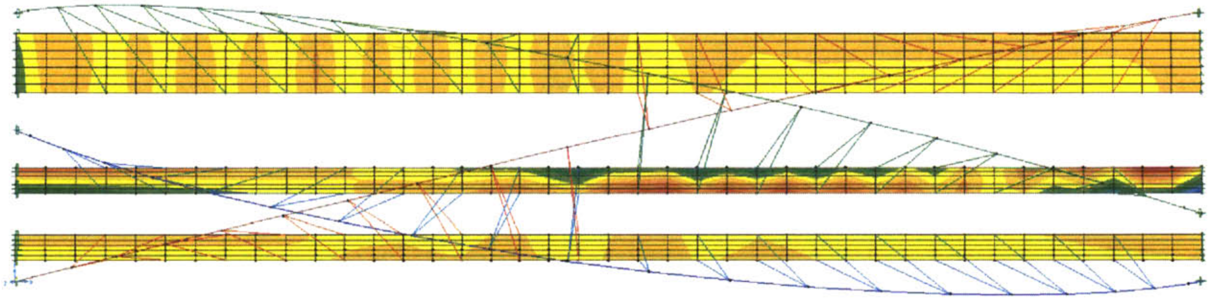
Pedestrian All, Max = 2018 psi



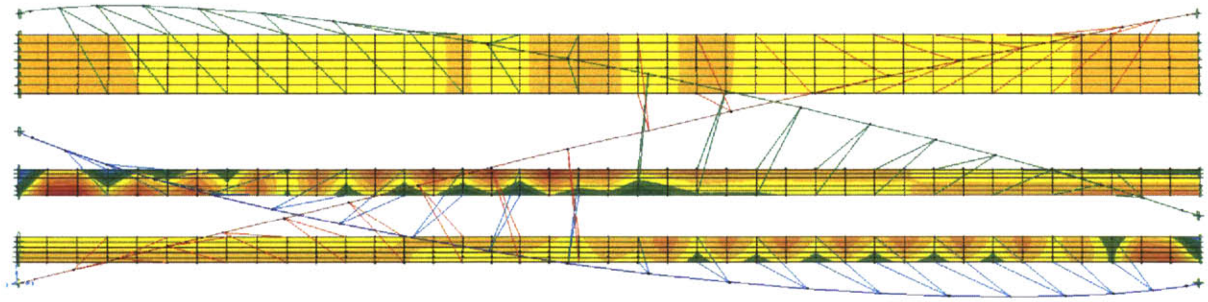
Red Arch, Max = 2228 psi



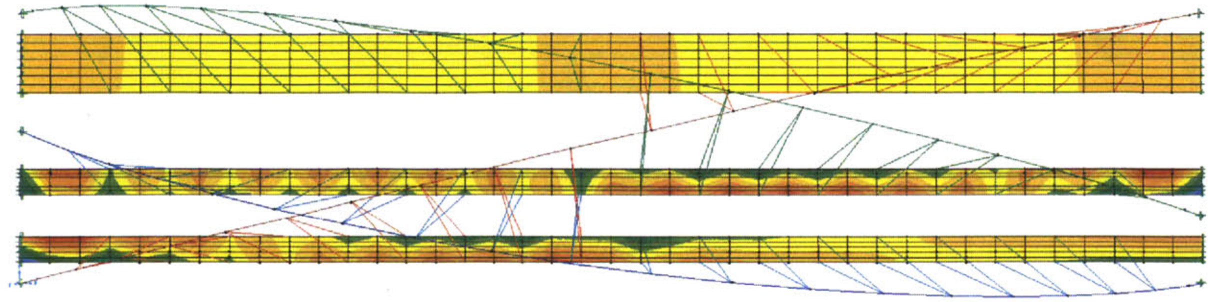
Green Arch, Max = 2759 psi



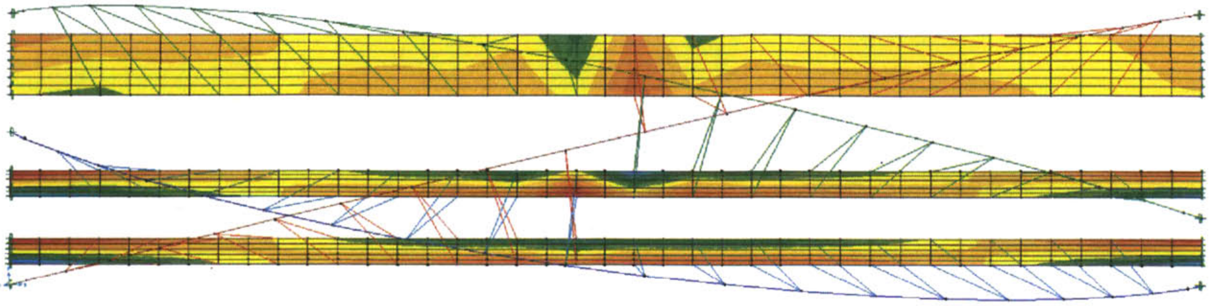
Blue Arch, Max = 1716 psi



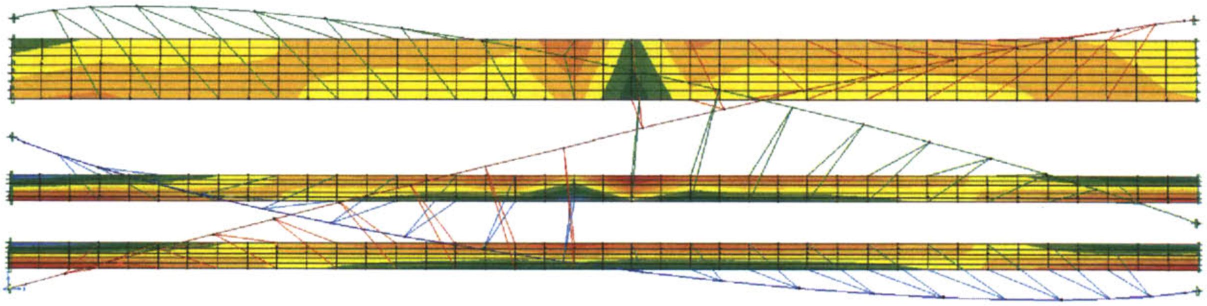
Worst Case (train 1, train 2, pedestrian 1), Max = 2227 psi



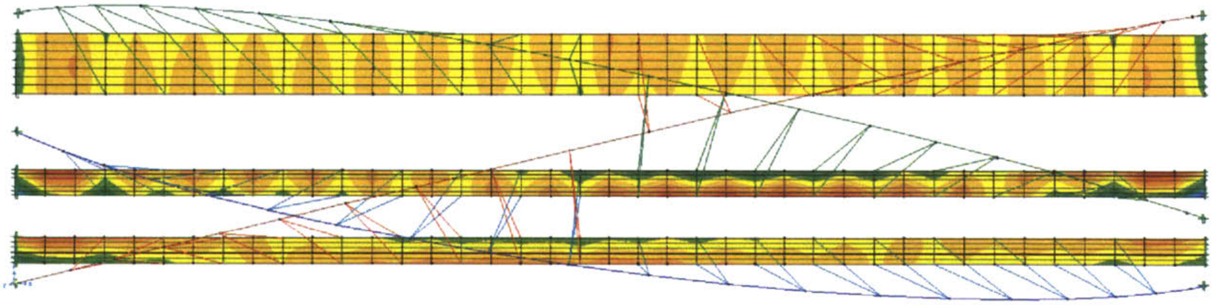
Wind, Max = 1463 psi



Wind Reverse, Max = 1488 psi



End of the World, Max = 4772 psi



End of the World Reverse, Max = 3148 psi