FINAL REPORT

S2_Guidelines for Monitoring of Existing Structures

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Authors: Anthony Rooke

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SUMMARY

The Department of Transport and Main Roads Queensland (TMR) is responsible for the management of over 3000 bridges, 3900 major culverts and a further 33 000 minor culverts (2013 figures). Monitoring of these structures can be a cost-effective way of managing the risk of serious damage and/or failure by providing information which can assist TMR in the management of limited funding with respect to prioritising maintenance and refurbishment funding.

TMR currently manages structural health through an inspection program with inspection frequencies dependent on the risk profile of the structure or its strategic importance. This does not necessarily provide the asset management team information on how at-risk structures are behaving or deteriorating in response to the perceived hazard (e.g. under heavier and/or more frequent vehicle loading, in response to flood events, etc.).

An effective program of monitoring will increase TMR's knowledge of the performance of existing at-risk bridges. The outcome of an effective health monitoring program will lead to a better understanding of bridge and network risks, enabling TMR to better manage risks and, as a consequence, utilise limited resources more efficiently. With better information, decisions can be made regarding increased freight on particular routes.

Specifically, the following benefits can be achieved:

- improved safety of network
- increased confidence
- potentially reduced costs.

These guidelines have been developed to provide TMR with a quick reference guide of appropriate technologies and techniques to enable the one-off, periodic or continuous monitoring of at-risk structures. The guide includes an overview of structures monitoring and its framework, definitions/glossary of terms, and a review of monitoring applications to address TMR-specific issues.

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1 INTRODUCTION

1.1 General

The Department of Transport and Main Roads Queensland (TMR) is responsible for the management of over 3000 bridges, 3900 major culverts and a further 33 000 minor culverts (2013 figures). Monitoring of these structures can be a cost-effective way of managing the risk of serious damage and/or failure by providing information which can assist TMR in the management of limited funding with respect to prioritising maintenance and refurbishment funding.

Currently TMR manages the performance and conditions of its structures through a program of different inspection types at various frequencies dependent on the risk profile of the structure, or its strategic importance. This, however, does not necessarily provide the asset management team with appropriate information on how particular at-risk structures are behaving or deteriorating in response to the identified hazards (e.g. heavier and/or more frequent vehicle loading, or flood events).

TMR needs to establish methodologies, standards and procedures to undertake a program of structural monitoring (SM), including practical guidelines in the use of appropriate SM technologies. A better understanding is required regarding what technologies exist, when and how they should be used and what benefits exist for their consideration, with respect to deploying SM state-wide.

An effective program of SM will increase TMR's knowledge of the performance of existing at-risk bridges, as well as the possibility of proactively instrumenting new bridges for future monitoring. The outcome of an effective SM program will be a better understanding of structures and network risks, enabling TMR to better manage these risks. This can result in more targeted spending with the ability to stretch the budget for structures maintenance investment. With better information, more informed decisions can be made regarding increased freight on particular routes. Specifically, the following benefits can be achieved:

- improved safety on the network
- increased confidence in data
- potentially reduced costs.

SM can reduce the requirement for frequent inspections, enable real-time data capture on critical bridges for rapid analysis and assist in the management of specific risks. Given the number of structural assets TMR manages, having reliable information on bridge condition, deterioration and performance is critical. A well-designed SM system will provide TMR with valuable decision support.

SM systems can be applied to the following common applications:

- static load tests to assess the capacity of structures
- investigations into the performance/response of structures under specific loading conditions
- dynamic load tests to determine structural dynamic characteristics and quantify dynamic effects of loads
- monitoring of structural behaviour after an event has occurred
- monitoring the development/propagation of defects (e.g. cracks in concrete structures, scour) under normal operational conditions or under environmental effects.

As a general guide, structures that would benefit from deployment of an SM program will typically fall into one or more of the following categories (Lovejoy 2010):

- structures that have serious deficiencies and are programmed for repair or replacement but require monitoring until refurbishment has been completed
- structures with performance issues that are difficult to analyse or resolve analytically
- structures employing new materials, design and/or construction characteristics where in-service performance requires validation
- structures that fail load rating assessment but show little or no physical signs of distress
- structures where external events/factors may impact on performance/integrity (e.g. flooding, scour or vehicle impact).

The benefits of implementing an SM program include (ISIS Canada 2004):

- decreased ongoing inspection and maintenance costs
- increased structural safety
- improved understanding of behaviour and durability of monitored structures
- improved understanding of in situ structural behaviour
- early damage detection
- assurances of the structure’s strength and serviceability
- reduction in downtime due to assessment or maintenance procedures
- improved maintenance and management strategies for better allocation of resources
- enabling/encouraging the use of innovative materials.

1.2 Scope of the Guidelines

The objective of these guidelines is to provide TMR with a quick reference guide of appropriate technologies and techniques to enable the one-off, periodic or continuous monitoring of at-risk structures. The guide includes an overview of SM and its framework, definitions/glossary of terms, and a review of SM applications to address TMR-specific issues.

The following specific areas are included in the guidelines:

- existing structures
- TMR-related projects
- event response
- quick selection of technology
- periodic and continuous monitoring.

Non-destructive testing (NDT) equipment is excluded from the scope of this document. These include:

- quality and strength testing
- concrete geometry testing
- defect location testing
- corrosion testing
- concrete state testing

- testing platforms
- general testing
- geotechnical instrumentation.

Destructive testing of decommissioned bridges is also excluded; however, some of the information presented may be used as a reference.

1.3 References

In preparing this guide, an extensive literature review of current practice was undertaken, including extensive reviews that have previously been completed by several road authorities and research institutions. Key documents referenced include:

- FHWA (2003) – Development of a Model Health Monitoring Guide for Major Bridges
- ISIS Canada (2001) – Guidelines for Structural Health Monitoring
- ISIS Canada (2004) – An Introduction to Structural Health Monitoring
- Gastineau, A, Johnson, T, Schultz, A 2009, Bridge Health Monitoring and Inspections – A Survey of Methods
- Enkell, M (2011) – Lessons learned in Structural Health Monitoring of bridges using advanced sensor technology (Thesis)
- Czichos (2013) – Handbook of technical diagnostics: Part IV Structural Health Monitoring and Performance Control
- Wenzel (2008) – Health Monitoring of Bridges.

1.4 Definitions

The following definitions are used throughout this document.

Accuracy

The closeness of a measurement to the value defined to be the true value of the measurand. The true value refers to an accepted and traceable standard, and is usually compared to the sensor measurement during calibration. Accuracy is a qualitative concept and is the combined error of nonlinearity, repeatability and hysteresis. Accuracy is usually expressed as a maximum positive or negative per cent of the full scale (FS) output.

Ambient condition

The environmental conditions that surround a given area, especially with reference to parameters, which may influence the functioning of devices, equipment, or the readings of instruments. These conditions include temperature, pressure, humidity, noise, and light.

Channels

Communication ports that are used to connect sensors to a data logger. Each sensor generally takes up one channel. Depending on the data logger configuration, the number of channels can be increased by using extension units.

Continuous monitoring

Continuous monitoring is conducted to investigate the change in the behaviour of a structure over a period of time. Most components of static and dynamic load tests can be used in a continuous monitoring application. Continuous monitoring can be applied in the following circumstances:

- Structures that are either extremely important, or if their structural integrity is in doubt.

- Structures likely to be exposed to extreme events such as flood, earthquake, fire and vehicle/vessel impacts.
- Structures with innovative designs that do not have a history of performance to prove their long-term worthiness.
- Structures with uncertainties on the actual operational conditions, such as overloading, bridge with load limits, and ground movement/settlement.

Damage

Any defect on a structural component that may adversely affect durability, strength or appearance (e.g. cracks, corrosion, or erosion).

Data acquisition system (DAS)

A DAS comprises hardware and software. The hardware, which may consist of data loggers, extension units and base stations, connects with the sensors to record data and stores or transfers the data to the storage devices. The software is used to control the data-recording process such as setting parameters, calibrating sensors, and to post-process the test data.

Data loggers

An electronic instrument that records digital or analogue measurements over time. They are typically battery-powered devices equipped with an internal microprocessor and data storage, and connected with a wide range of voltages and sensor types. Data loggers are typically housed in a hard plastic, or metal, casing that is weatherproof and/or tamper resistant.

Frequency response

This characteristic is important for dynamic measurements. It represents two relationships between a set of inputs and outputs. The first relates frequencies to the input/output amplitude ratio. In other words, it describes the change of the sensor input/output amplitude ratio within a range of frequencies of a sinusoidal varying input applied to a sensor. It is usually specified in terms of +/- decibels (dB) within a certain frequency range given in Hz. The second relates frequencies to the phase difference between the output and input.

Hysteresis

The maximum difference between output readings for the same measured point, one point obtained while increasing from zero and the other while decreasing from full scale. The points are taken on the same continuous cycle. The deviation is expressed as a percentage of full scale (%FS). Hysteresis is a static sensor performance characteristic.

Intelligent processing

The goal of intelligent processing is to remove unwanted information and to make data interpretation easier, faster, and more accurate. In many cases, intelligent processing is also required to remove the influence of thermal or other unwanted effects in the data.

In addition, to deal with the sometimes overwhelming amounts of data generated by SM systems, various data management strategies have been developed to eliminate unnecessary data without sacrificing the integrity/accuracy of the overall system. One simple technique is to record only changes in readings, along with the times that these changes occurred. In this way, long periods in which nothing changes are omitted from the data. Alternatively, an SM system may record readings only above a certain threshold value, or perhaps only the peak readings measured over a designated length of time.

Isolation

This is a measure of how much a sensor must be isolated from the disturbances and effects that may compromise data integrity or sensor reliability. Examples of such disturbances that are commonly encountered on or near bridges are electromagnetic and radio frequency interference (EMI/RFI), static electricity, lightning, and vibration. If a sensor features electromagnetic or electrostatic isolation, for example, the overall accuracy of the signal will be improved.

Linearity

The output of a linear sensor is directly proportional to the measurand. Linearity is therefore the degree to which the calibration curve of a sensor agrees with a straight line. The amount of deviation from the linear curve is referred to as nonlinearity error. Linearity is a static sensor performance characteristic and is usually expressed as a maximum positive or negative %FS output.

Range

This is the difference between the maximum and minimum values of sensor output in the intended operating range. This is a static performance characteristic and is the natural limits of a sensor. A similar dynamic performance characteristic is frequency response.

Resolution

The smallest measurable change in input that will produce a small but noticeable change in the sensor output. Resolution is a static performance characteristic, and will often have different values in varying portions of a sensor’s full range.

Repeatability

The closeness of the agreement between results of successive measurements of the same measurand performed under identical conditions of measurement. Repeatability is a static sensor performance characteristic, and is a qualitative concept that is often used synonymously with the term precision. It is usually expressed in terms of a maximum positive or negative %FS output.

Response time

This is the amount of time required for a sensor’s output to reach a stable value and is a dynamic performance characteristic. It describes how rapidly a sensor will respond to changes in the measurand. Response time is usually defined by the amount of time required for the sensor output to reach a certain percentage of its final value.

Sampling rate

The sampling rate is a measure of how many samples per second are converted from an analogue signal into a digital signal. The sampling rate must be high enough to acquire a sufficient number of points in a given time to accurately represent the original signal. If the original signal is changing faster than the conversion is occurring, then errors are introduced into the measured data. Data that is sampled too slowly can appear to be at a completely different frequency. The distortion of the signal in this manner is referred to as aliasing.

Sensitivity

This is the amount of change in the output of a sensor in response to a change in a sensor’s input. Sensitivity is a static performance characteristic and is generally defined over the sensor’s entire range. Sensitivity provides an indication of a sensor’s ability to detect changes in the measurand.

Sensor

A device that detects events or changes in quantities and provides a corresponding output, generally as an electrical or optical signal.

SM system

A SM system can be defined as the framework to support the collection, interpretation and analysis of data for an SM activity, and to transmit this data back to the asset owner. An SM system can be divided into various categories dependent on the intended function of the system.

Stability

This refers to the ability of a sensor to maintain its calibration value over an extended time period. It is a measure of a sensor's ability to give the same output when measuring a constant input. Stability is a static performance characteristic and is generally dictated by environmental effects such as temperature, humidity, radio frequency/electromagnetic interference (RFI/EMI), and corrosion. The term 'drift' is often used to describe the continuously upward or downward change that occurs. Specific examples of drift include thermal sensitivity drift and thermal zero drift. Thermal sensitivity drift describes a slope change in the sensitivity curve due to thermal effects, while zero drift describes the parallel change due to thermal effects when the parameter being measured is zero.

Structural monitoring

Clause 15 of AS 5100.7-2015 (draft) defines structural monitoring as involving 'the use of various sensing devices and ancillary systems to monitor the in situ behaviour of a structure to assess the performance of the structure and evaluate its condition. The assessment may be conducted using test vehicles under ambient conditions'.

Thermal effects

Most sensors will respond to temperature in addition to the parameter that they are intended to measure. This in turn will affect the measurement, changing it from its true value. A sensor's sensitivity to thermal effects is a function of both its sensing element and packaging, and therefore will vary for different types of sensors. In many cases, sensors are compensated to minimise undesirable thermal effects. This may be accomplished by the way the sensor is constructed or by the manner in which it is used.

1.5 Classification of Structural Monitoring

Structural monitoring applications can be classified into the following types:

- load testing, including static and dynamic load tests (Section 3)
- response to events (Section 4)
- specific applications, such as crack monitoring (Section 5), complex structures (Section 6), structures influenced by thermal effects (Section 7), and culverts (Section 8)

1.5.1 Load Testing

Static load tests

Static load tests can be subdivided into static performance load tests and static proof load tests (AS 5100.7-2004). Brief definitions of these tests are provided below:

- Static performance load tests (to assess the structural behaviour of the bridge and provide input for the calibration of analysis models): The test can provide information on the load distribution mechanism among the structural components; however, direct information on the capacity of components is not usually obtained. The test loads are usually kept at, or below, the maximum service loads or the legally permitted maximum loads.
- Static proof load tests (to determine the load-carrying capacity of a bridge): These involve testing the bridge with gradually increasing loads to exceptionally high static loads that cause larger responses in the bridge than the static maximum service load. Monitoring is essential during testing to ensure that the loads are not allowed to increase beyond the limit of linear elastic behaviour to avoid permanent damage to the bridge.

Dynamic load tests

These tests are similar to static load tests, with added functionality of movement, accelerations and impacts such as vehicles running at different speeds and/or over a ‘bump’.

Dynamic load tests may include stress history tests, dynamic load allowance (DLA) tests, ambient vibration tests and pull back tests (ISIS 2004).

Brief definitions of these tests are provided below:

- Stress history tests (establish the distribution of stress ranges in fatigue-prone components of a bridge): The tests involve continuous recording of strains at a reasonable sampling rate due to the passage of vehicles on the bridge. The test data are then processed to obtain the frequency distribution of different stress ranges.
- DLA tests (to measure the dynamic effects of moving vehicles to determine the DLA factor or dynamic increment factor (DI)): The tests involve measurement of static and dynamic deflections and/or strains for the same bridge component and same vehicles.
- Ambient vibration tests (to measure the dynamic response to determine the vibration characteristics of a structure): Accelerometers are used to record the dynamic response of the structure due to an impact force or traffic loading. Results obtained include natural frequencies, forced frequencies, modal shapes, and damping characteristics of the structure.
- Pull back tests (to measure the lateral vibration characteristics of a bridge): The tests involve pulling the structure laterally by means of cables anchored in the ground or to a fixed object, and releasing the cables suddenly. Accelerometers are used to record the resulting vibrations.

1.5.2 Response to Events

- SM can be deployed to detect responses within/or adjacent to a structure due to external events that may affect the performance of the structure. These are typically one-off or trigger-driven monitoring events with predetermined intervention or response levels determining the appropriate management response

1.5.3 Specific Applications

Crack monitoring: Where structures require monitoring for the evolution or progression of cracking. Examples include concrete and masonry structures, structures affected by corrosion and alkali aggregate reactivity (ASR/AAR).

Complex structures: Where monitoring of unique or complicated structures is required. Examples include trusses, suspension or cable-stayed bridges, masonry structures, arches, fatigue-prone structures.

Environmental factors: Where structures require monitoring due to environmental factors such as temperature variations, moisture levels etc. Commonly affected structural elements include expansion joints, bearings and components with defects where durability is compromised.

Culverts: Where thin-walled culverts (buried corrugated metal culverts) require monitoring.

1.6 Corporate Ownership, Management and Monitoring of Data

The TMR Bridge Inspection Manual (TMR 2004) specifies that bridge inventory and condition data are to be recorded in the Bridge Information System (BIS), which is maintained by the Executive Director (Road Network Management). The BIS provides accessible and timely information to all TMR personnel involved in bridge management. However, there is no specific reference to the storage of, and management requirements for, captured monitoring data.

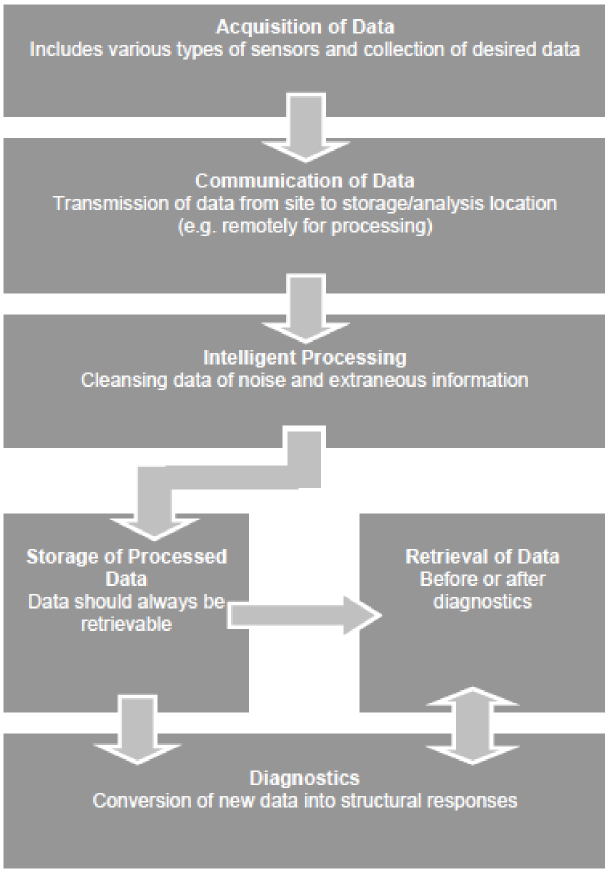
In general, TMR's policy is to obtain full control and ownership of the data acquired by consultants/contractors for its projects, in prescribed formats.

2 STRUCTURAL MONITORING SYSTEM

2.1 Introduction

An SM system includes sensor instrumentation, data collection and processing, data storage, and data transmission. These are customisable to the specific monitoring objectives and the data being collected. While an SM system will be developed to meet the specific needs of the project, a typical SM system will comprise the components illustrated in Figure 2.1.

Figure 2.1: Components of a typical SM system

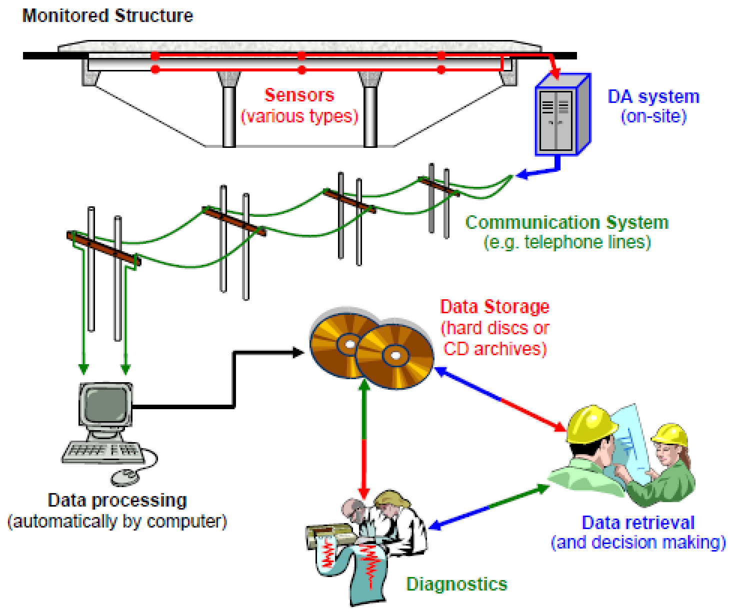


Source: ISIS Canada (2004).

These components are discussed further in Section 2.1 below.

Figure 2.2 presents a visual schematic of how the components of a typical SM system relate. The main components of an SM are discussed in the following sections.

Figure 2.2: Visual schematic of a typical SM system



Source: ISIS Canada (2004).

It should be noted that there are exceptions in the above definition of an SM system, where targets/markers are placed on structure components instead of sensors. Technologies included in these exceptions comprise photogrammetry, interferometry radar (IBIS-S), and 'video gauge' technology (iMETRUM).

2.1.1 Acquisition and Collection of Data

The collection of raw real-time data is central to an SM system. Data typically collected include strains, deformations, deflections, accelerations, environmental data (such as temperature and moisture levels), acoustic emissions and loads. These data are captured using various sensor types including:

- strain gauges
- load cells
- potentiometers
- accelerometers.

Sensors will typically be embedded in, or installed on, the structure. Various sensor technologies are discussed in more detail in Section 2.4 to Section 2.9.

Captured data are transferred to the on-site Data Acquisition System (DAS), where they are filtered and stored pending transfer off-site for further processing and analysis.

A key consideration when developing an SM application is the sampling rate required to achieve the desired goal. A high sampling rate, particularly where numerous sensors are installed in a continuous monitoring scenario, will very rapidly generate large volumes of data. Conversely, a low sampling rate may not provide sufficient data to achieve the required goal. The optimum sampling rate for given applications will vary considerably and it is essential that specialist advice be sought when considering this aspect.

2.1.2 Data Processing and Management

Intelligent processing of data captured by sensors is typically required prior to storage of the data for subsequent analysis. This could be due to a number of reasons, as follows:

- Data cleansing – data captured by sensors often include extraneous information (noise) that is of no use. Noise sources can include transmitting devices, power lines or telephone lines in the vicinity of the sensors.
- Data normalisation – where multiple sensors are used, it is important that the data from each source can be related back to a common reference such as a time stamp.
- Thermal effects – data should be processed so that thermal effects are either included, or excluded, from all readings.
- Data acquisition method – SM systems can rapidly generate large volumes of data, much of which may be of no interest, particularly in continuous monitoring applications. Selection of the most appropriate data acquisition algorithm is a critically important aspect of SM, as it will affect both the volume of stored data and the type of diagnostic information that can be obtained. A combination of the above acquisition methods may be used on the same project if required. Various strategies are available to minimise unnecessary data including:
  - only recording changes in readings (along with the time the change occurred)
  - only recording instances where values exceed a predetermined threshold (trigger) and data can continue to be captured for a set period of time once triggered
  - using more sophisticated algorithms that have been developed to detect and isolate characteristic signal patterns of interest.

The selection and specification of appropriate intelligent processing methods is essential to make interpretation of stored data more efficient and accurate.

2.1.3 Communication of Data

Data collected and stored in the DAS must somehow be transferred from site back to base for further processing and analysis. In most cases the base will be remote from the structure. Traditionally this required visits to site to manually transfer the data; however, the evolution of SM systems to allow transmission of data via fixed telephone lines or wireless technologies (e.g. radio or cellular) provides alternative solutions that allow structures to be monitored remotely.

The following issues should be taken into consideration when developing and specifying data communication requirements:

- data conversion/formatting requirements prior to transfer
- site connectivity
  - proximity of required infrastructure for fixed-line transfer
  - signal coverage for wireless transfer
  - 3G/4G network availability for wireless transfer
- transfer times (how long, when, i.e. peak vs off-peak)
- security (of communications equipment and of data during the transfer process)
- TMR IT access rights/permissions required
- amount of data is being transferred
- frequency of data transfer required
- who is receiving the data

- cost of implementing.

2.1.4 Storage of Recorded Data

Once data have been subjected to the various intelligent processing techniques adopted, the refined data will require storage for subsequent analysis and interpretation. Key considerations when selecting the method/manner of storage include:

- Storage format/medium – processed data may need to be stored for long periods of time. It is essential that, once retrieved, data can be read. This requires storage in a universal file format and on a secure/stable medium with appropriate redundancies to prevent corruption of the data.
- Volume of data – storage capacity requirements should be clearly understood prior to commencing to ensure there is sufficient storage to capture all of the data that will be generated.
- Ease of interpretation – data files should contain sufficient supporting information such that the data could be interpreted by anyone for the intended life of the data.
- Data retrieval – it is necessary to decide what data are to be stored for retrieval. Dependent on the volume of data generated, it may be appropriate to retain raw 'observed' data along with the cleansed/processed data. However, in the case of dynamic field tests or continuous monitoring scenarios, the volume of raw data generated may be too great for storage along with the processed data and it may be appropriate to discard the raw data. Once the raw data have been discarded they are lost forever and cannot be reinterpreted. Therefore the final decision should also take into account confidence in the initial interpretation of the raw data.

2.1.5 Diagnostics

Diagnostics refers to the interpretation of the cleansed data in order to translate the data into meaningful figures that can be used to evaluate the responses of the structure.

This is essentially the goal of monitoring a structure. It includes interpreting/analysing the cleansed data in order to, amongst other things:

- detect external stimuli/events
- understand a structure's response
- understand how that response changes over time or in response to damage or some other change in condition.

The complexity of analysis will be dictated by the goals of the SM program.

Examples of typical diagnostic activities include:

- converting strain readings into stress for assessment against critical limits
- converting deflections into flexural stiffness.

It must be recognised that conversion of these data will be based on some basic assumptions, the limitations of which must be clearly understood.

Issues that need to be considered when specifying the diagnostic/interpretation component of an SM system include:

- what analysis is required, i.e. what are the goals of the SM, and what analysis is required to achieve these goals?
- understanding the limitations of the required analysis
- is calibration of field measurements against numerical modelling of the structure required?

- responsibility for diagnostics, i.e. who does what?.

2.2 Data Acquisition System

The data acquisition system (DAS) comprises the hardware and software required to collect, condition, cleanse and communicate the raw data from various sensors attached to the structure.

2.2.1 Hardware

The three main components of the hardware forming a DAS are the signal conditioning circuitry, analogue-to-digital converter and computer bus. In addition, DAS may also include other functions for automating measurement systems and processes such as digital-to-analogue converters, digital input/output lines and counters/timers.

- For structural load testing and monitoring applications, based on the data communication method, there are three main types of systems: Stand-alone USB systems are compact, reusable, and portable, and offer low-cost and easy set-up and deployment. Internal-sensor models are used for monitoring at the logger location, while external-sensor models (with flexible input channels for a range of external sensors) can be used for monitoring at some distance from the logger. Most stand-alone loggers communicate with a PC via a USB interface. For greater convenience, a data shuttle device can be used to offload data from the logger for transport back to a computer.
- Web-based systems: enable remote, around-the-clock internet-based access to data via GSM cellular, wi-fi, or ethernet communications. These systems can be configured with a variety of external plug-in sensors and transmit collected data to a secure web server for accessing the data.
- Wireless data nodes: transmit real-time data from multiple points to a central PC, eliminating the need to manually retrieve and offload data from individual data loggers.

Suppliers and proprietary products

The following is a brief overview of a sample of proprietary DAS available from selected vendors.

Inclusion of any particular system or provider does not imply endorsement by TMR. All references to specific manufacturers are included only as a reference for examples of available systems and solutions.

Bridge Diagnostics Inc. (BDI) - STS data loggers

The Structural Testing System by BDI (BDI-STS) is advertised as being designed expressly for performing live-load tests on highway and railroad bridges. The current iteration of the BDI-STS is the STS4 (refer Figure 2.3) which offers the following features:

- complete wireless ‘turn-key’ load testing system
- easy to use software, no programming required
- sensors automatically identify themselves — no tracking channel numbers
- standard 802.11b/g/n wireless protocol with wired ethernet backup
- sample rates of up to 1000 Hz
- programmable shunt capabilities to verify sensor functionality
- internal Li-Ion battery with integrated charging capability using Power over ethernet (PoE)
- power conservation modes
- fully IP67 rated

- compatible with existing BDI software and hardware
- custom programming ability using LabVIEW
- wireless repeater capabilities (no cables between multiple base stations), increased range, and PoE support
- long-term monitoring capabilities.

Figure 2.3: BDI wireless structural testing system

Source: BDI Bridge Diagnostics Inc. viewed on 12 May 2015, <http://bridgetest.com/products/sts4-wireless-structural-testing-system/>.

National Instruments

National Instruments supply multi-channel modular PC-based data loggers such as the NI CompactDAQ system. They are available in several different form factors and include free data-logging software. They can also be programmed with custom functionality using NI LabVIEW software.

Traditional data loggers include fixed configurations for measuring different sensor types. Using the NI C Series platform, users can build a flexible system to connect to any sensor type. Currently, over 50 C Series modules are available for different measurements including thermocouple, voltage, resistance temperature detector, current, resistance, strain, digital, accelerometers, and microphones. The modules contain built-in signal conditioning for extended voltage ranges or industrial signal types.

An NI DAQ system includes general-purpose I/O modules, chassis and controllers units, and software:

- CompactDAQ chassis and controllers control the timing, synchronisation, and data transfer between up to eight I/O modules, including PC-based chassis and integrated controller.
- General-purpose I/O modules provide a range of analogue and digital input and output options to meet the measurement needs.
- Software enables customisation of the automated measurement system to acquire, analyse, visualise, and log the data.

Measurement Computing (MCC)

Various data acquisition solutions are available at MCC, including USB, ethernet, stand-alone loggers, wireless, PCI/PCIe.

Free technical support for the life of the product is available with a worldwide network of 40 countries (Australia representative is Firetail DAQ in Melbourne).

MCC DAQ hardware includes free software including out-of-the-box options (DAQami, TracerDAQ, TracerDAQ Pro) as well as support for the most popular programming languages, operating systems, and applications, and other third-party software (MATLAB, DASYLab, LabVIEW, Linux).

For example, an ethernet-based strain gauge measurement system, StrainBook/616 is shown in Figure 2.4.

Figure 2.4: Measurement computing StrainBook/616

Source: Measurement Computing, viewed on May 16 2015, <http://www.mccdaq.com/products/strainbook616.htm#>.

Key features

- 8 channels built in, expandable up to 64 channels per StrainBook
- multiple StrainBooks can be synchronised for applications over 64 channels
- expansion options for voltage, temperature, vibration, and sound measurements
- high-speed ethernet interface for continuous measurement transfer to the PC
- 1 MHz scanning A/D converter, with simultaneous sample-and-hold on each channel
- 100% programmable
- independent filter per channel
- programmable excitation source
- DC operable for in-vehicle applications
- software: WaveView *Out-of-the-Box* software application for effortless data logging and analysis
- support for Visual Studio® and Visual Studio® .NET, including examples for Visual C++®, Visual C#®, Visual Basic®, and Visual Basic® .NET

- comprehensive drivers for DASYLab®, MATLAB®, and NI LabVIEW®.

The systems described above are for use with traditional sensor types. Fibre optic sensors utilise different DAS.

2.2.2 Software

DAS software can be categorised into three basic types as follows:

- turnkey software — fixed-functionality software without the ability to scale, configure, or customise beyond its original state.
- configurable software — provides basic functionality out of the box with the ability to add or modify functions, algorithms, and other user-defined steps; It does not require the user to modify software through programming.
- programmable software — features an open environment where the user can create custom user interfaces, execution logic, signal processing and analysis, and file formats and logging.

Turnkey data logging software requires very little user interaction and allows users to log data to disk in seconds. Configurable solutions expand on this functionality to allow the user to configure multiple aspects of their data logging application, including alarms, triggers and analysis without programming. Programmable data logging software is the most powerful and gives users the widest scope of functionality. The selection of the most suitable data logging solution depends on the system requirements and application needs.

The characteristics of several common data logging software are provided below.

STS-LIVE Structural Testing Software

STS-LIVE Structural Testing Software is the software supplied by BDI for use with their STS4 DAS hardware. Advertised features are as follows:

- no programming ability required
- for configuration of BDI STS4 systems for both short-term diagnostic load testing and long-term monitoring
- view data in real time either using time history, load position (custom x-axis), or in the frequency domain
- real-time filtering options available
- programmable test lengths with sampling rates up to 1000 Hz
- programmable excitation voltages and sensor gain settings
- automatic or manual sensor zeroing routine
- automatic temperature compensation for sensors equipped with thermistors
- stores all test data and configuration into TDMS files for easy importation into either STS-VIEW, STS-CFA, or spreadsheets
- runs on Windows 7 and Windows 8.

LabVIEW

National Instruments supplied software. Advertised features include:

- compatible with hardware from most vendors
- customisable user interface with graphs, charts, thermometers, meters, gauges, and LEDs
- alarms, dynamic events, and start and stop conditions for data logs

- channel view for simultaneously configuring multiple channels
- data view for interactive graphing and logging
- connection diagram for easy signal connection
- one-click data export to Microsoft Excel
- built-in time and frequency analysis functions for maximum and minimum values, averages, root-mean-square (RMS), masks, limits, fast Fourier transforms (FFT), octave analysis, tone extraction, low-pass filtering, and high-pass filtering
- project report generation.

MATLAB

Various modules are available for data acquisition and processing, including Data Acquisition Toolbox, Instrument Control Toolbox, Image Acquisition Toolbox, Image Processing Toolbox. Key features include:

- support for a variety of industry-standard data acquisition boards and USB modules
- support for analogue input, analogue output, counters, timers, and digital I/O
- direct access to voltage, current, IEPE accelerometer, and thermocouple measurements
- live acquisition of measured data directly into MATLAB or Simulink
- hardware and software triggers for control of data acquisition
- device-independent software interface.

Open source software

A number of open source software for numerical computation are available for free download and use, such as Scilab (<http://www.scilab.org/>), FreeMat (<http://freemat.sourceforge.net/>) and GNU Octave (<https://www.gnu.org/software/octave/>). Key features of these software are provided as follows:

- *Scilab* is available for GNU/Linux, Mac OS X and Windows XP/Vista/7/8. It can be used for signal processing, statistical analysis, image enhancement, fluid dynamics simulations, numerical optimisation, and modelling, simulation of explicit and implicit dynamical systems and symbolic manipulations.
- *FreeMat* is a free environment for rapid engineering and scientific prototyping and data processing. It is similar to commercial systems such as MATLAB from MathWorks, and IDL from Research Systems, but is open source. In addition to supporting many MATLAB functions and some IDL functionality, it features a codeless interface to external C, C++, and Fortran code, further parallel distributed algorithm development, and it has plotting and 3D visualisation capabilities.
- *GNU Octave* is a high-level interpreted language, primarily intended for numerical computations. It provides capabilities for the numerical solution of linear and nonlinear problems, and for performing other numerical experiments. It also provides extensive graphics capabilities for data visualisation and manipulation. Octave is normally used through its interactive command line interface, but it can also be used to write non-interactive programs. The Octave language is quite similar to MATLAB so that most programs are easily portable. Octave is distributed under the terms of the GNU General Public License.

Selection criteria for software

The following criteria should be taken into consideration when selecting software:

- Required functionality is a key criterion. Simple monitoring applications may only justify turnkey solutions. Conversely, configurable and programmable software provide much greater flexibility and can be used for many different applications.
- Review of proprietary systems
  - Ease of use, user friendly, user interface quality, viewing quality
  - Data acquisition functionality
    - application and control of triggers/limits
    - range control
    - responsiveness
    - range of transducers/applications
  - Post-processing functionality
    - interpretation capabilities
    - data cleansing/filtering capabilities
  - Time to install, time to set up new project
  - Storage/server/IT requirements
  - Integration with other software/programs (proprietary or custom-made)
  - Compatibility with different vendors' hardware
- User interface for data logger.

2.3 Design of a Structural Monitoring System

The following section is intended as a general guide for the design of a structural monitoring system. Common technical issues to consider are discussed along with a general methodology to be adopted for design. It is imperative to consult SM specialists throughout the design stage to ensure the system's successful implementation.

2.3.1 Define the System Objectives

Once the structure/structures of interest have been identified, the first step in design is to define the objectives of the system. This involves the following steps:

- Identify the mechanism/event of interest. For example:
  - load capacity/distribution: this will typically involve investigating a structure's response to live load, either due to a theoretical deficiency or as a consequence of deteriorating condition/accident damage
  - condition monitoring: monitoring of defects to determine rate of deterioration
  - performance monitoring: monitoring performance of key components in service (e.g. bearings, expansion joints, etc.)
  - detect/measure external event: detect instances and, where appropriate, measure extent of external events that may impact on serviceability of structures (e.g. flood/scour, seismic activity, fire, bridge strike/overload).

- Categorise influence of the mechanism/event on the physical response of the structure or its principal components: how is the structure/principal component(s) expected to respond to the mechanism/event. This may include the development of theoretical or numerical models of the structure.
- Establish the characteristic response level of key parameters (e.g. strain, vibration, displacement, etc.) experimentally and/or theoretically and establish the sensitivity of each to the mechanism/event of interest.
- Select the most appropriate parameter(s) for measurement, the required type/duration of monitoring (e.g. static, dynamic, continuous, periodic, etc.), required sampling rate, along with the number of and location of measurements required.

It is vital to establish a complete understanding of why the structure is being monitored. Without this understanding it will be difficult to design an appropriate SM system that provides the desired information.

2.3.2 Designing the System

Having defined the system objectives, consideration can now be given to selecting the appropriate sensors, data acquisition systems and data interpretation requirements.

Key issues for consideration at this stage are:

Site considerations

Site geometry/condition and environmental factors can have a significant influence on the choice of system, instrumentation and/or method of installation. The following should be considered when planning the system:

- Environmental protection and cultural heritage issues - these can have a significant impact on access requirements, permissible activities and timing.
- Site location/security – accessibility of the site/installed componentry to the general public. Systems installed for sustained periods of time may require additional protection against interference/vandalism.
- Access requirements – what, if any, access equipment will be required to gain access in order to install sensors, cable runs and control equipment. Will the use of alternative sensors avoid or reduce specialist access requirements?
- Traffic control (installation) – what, if any, traffic control will be required during installation of the system.
- Traffic control (testing) - what, if any, traffic control will be required during monitoring activities (this is particularly relevant to load testing applications). Carriageway alignment, sight distances, traffic volumes and speed environment will all influence the traffic control requirements.
- Turning points for long test vehicles – location of the nearest turning bays (in both directions) for test vehicles, especially when long vehicles such as road trains are involved.
- Maintenance requirements - what, if any, maintenance will be required prior to installation and during the life of the system, e.g. vegetation clearance, waterway clearance, etc.
- environmental factors to be considered include:
  - temperature variation (expected temperature range at the site)
  - humidity
  - maximum water levels
  - sources of electric/magnetic interference

All of the above factors can have a significant impact on the choice of system (particularly the selection of sensors), the method of installation and ongoing system maintenance.

Selection of sensors

As shown in Figure 2.2 the most important components in any SM system are the sensors (transducers), which are physically attached to or embedded in the structure in order to measure the phenomena of interest.

Key considerations when selecting sensors include:

- response parameter – what is being measured. With respect to SM applications, the most common phenomena of interest are:
  - strain
  - acceleration and vibration
  - displacement
  - tilt and rotation
  - force and pressure
  - load position
  - temperature.
- range of measurement
- resolution
- level of accuracy
- temperature operating range
- sensor durability: length of time sensor is required to be in place (some sensor types are not suitable for long-term monitoring applications).
- sensor reliability
- number of sensors required
- location of sensors
- power requirements
- installation limitations
- signal transmission limitations
- cost – when considering cost, the cost of associated wiring and signal conditioning requirements should be incorporated.

Section 2.4 to Section 2.10 discuss sensor technologies in more depth.

Reference to any particular system or provider in these sections or any other part of this guide does not imply endorsement by TMR or ARRB. All references are included only as guidance on examples of available systems and solutions.

When it comes to selecting sensors, accuracy and precision will be very important considerations. It is important to recognise that these terms are not interchangeable. The accuracy of a sensor will relates to how close the measured results are to the ‘true’ value, while precision reflects how repeatable the measurement is.

Another issue to be aware of when considering accuracy is how it is presented by manufacturers. Sensor manufacturers will typically specify individual performance characteristics that may/may not influence performance in a given situation (e.g. linearity, temperature stability, etc.) without any attempt to combine them. In addition, errors (and resolution) will normally be specified as a percentage of full scale (%FS), i.e. as a percentage of their full operating range. In most instances, sensors will not be employed over their full range, particularly when users specify sensors with a far greater operating range than expected in order to be conservative.

Key issues for consideration when selecting/specifying sensors include:

- Repeatability of measurement is paramount.
- Thermal errors (where applicable) will typically dominate. Therefore the expected temperature range will impact on the choice of sensor.
- It is good practice to calculate the total error that can be expected from the sensor.
- Selection of sensors based on a realistic operating range (rather than the greatest available) will reduce errors.
- Sensor durability/stability becomes an issue for long-term monitoring applications. Sensor deterioration over time can have a major impact on results and recalibration requirements must be clearly understood.

Installation issues

Installation requirements for specific sensor types must be considered to ensure that the selected sensors can be easily installed without changing the behaviour of the structure or impeding its performance. Furthermore, requirements for cabling, conduits, junction boxes and any other ancillary components required to complete the sensor installation must be considered. Poor detailing/installation of these components can result in reduced functionality/failure of the SM system.

For the most part, sensors can either be attached to the surface of the structure or (in the case of concrete) embedded within the structure. As this guide relates to the monitoring of existing structures, emphasis is placed on surface-mounted sensors rather than embedded sensors. Methods of attaching sensors to structures include welding (steel components only), fixings, magnets (steel component only) and adhesives.

For any surface-mounted sensor, it is of vital importance that the surface on which the gauge is to be mounted be free of irregularities. A procedure for ensuring the cleanliness of surfaces is as follows:

- Surface must be sanded smooth to the touch.
- Wash the sanded surface with water using a stiff bristle brush.
- Let dry for 24 hours and then brush the surface again and spray with an air hose.
- Make sure that the surface is dry.

Table 2.1 below is intended as a brief summary of recommended attachment options for commonly available sensor types.

Table 2.1: Summary of sensor attachment methods

	Attachment method			
Sensor type	**Welding**	**Magnets**	**Anchor fixings**	**Adhesives**
Foil strain gauge	X	X	X	√
Strain transducer	X	X	X	√
Vibrating wire strain gauge	√	X	√	√
Fibre optic strain gauge	√	√	√	√
LVDT	X	X	√	X
Fibre optic displacement	√	√	√	√
String potentiometer	√	√	√	X
Vibrating wire crackmeter	X	X	√	X
Piezoelectric accelerometer	X	√	√	√
Fibre optic accelerometer	X	√	√	√
Proximity sensor	√	X	√	√
EL tiltmeter	X	X	√	X
Vibrating wire tiltmeter	X	X	√	X
MEMS tiltmeter	X	X	√	X
Compression load cells	NA	NA	NA	NA
S-beam load cells	NA	NA	NA	NA
Bending beam load cells	NA	NA	NA	NA
Canister load cells	NA	NA	NA	NA
Low profile load cells.	NA	NA	NA	NA
Interferometric radar	NA	NA	NA	NA
iMetrum	NA	NA	NA	NA

In order to measure acceleration and vibration accurately it is necessary to ensure that:

- the useful frequency and dynamic ranges are not limited by poor mounting
- the addition of the accelerometer mass does not alter the vibration characteristics of the test object
- the measurement point can be exactly located for repeatable measurements.

Welding

Attachment by welding is only suitable for steel structures/components and surface preparation will be required in accordance with welding best practice. Welding should only be considered for long-term monitoring applications.

Magnets

Magnetic mounting bases offer a very convenient, temporary attachment to magnetic surfaces. Magnets offering high pull strengths provide the best high-frequency response.

Anchor fixings

Where permitted, resin anchors are most suited for attaching sensors on concrete, masonry or brick surfaces as, due to their method of fixity, they are much less likely to absorb strain than surface adhesives.

Stud/screw mounting provides the best transmissibility at high frequencies for acceleration and vibration measurement, as the accelerometer is virtually fused to the mounting surface. The addition of any mass to the accelerometer, such as an adhesive or magnetic mounting base, lowers the resonant frequency of the sensing system and may affect the accuracy and limits of the accelerometer's usable frequency range. Also, compliant materials, such as a rubber interface pad, can create a mechanical filtering effect by isolating and damping high-frequency transmissibility.

Adhesives

- Key properties required for adhesives include:
  - excellent creep characteristics, i.e. large elastic modulus and minimal change with temperature or humidity
  - peel strength, i.e. ample bond strength for the temperature, humidity and amount of strain
  - good electrical insulation
- Adhesive types include cyanoacrylate, polyester, epoxy, and phenol resin. Selection of adhesive type is based on gauge type, specimen material, and operating temperature range.
  - Cyanoacrylate: widely used as strain gauge adhesives, colourless and clear, non-solvent, instant adhesives, dry at room temperature, short time required to install a strain gauge, and easy to use.
  - Polyester: two-component adhesive including main component and a hardening agent and excellent resistance to moisture and chemicals. While the adhesion strength is not as great as an epoxy adhesive, they are used to install strain gauges on concrete and metal surfaces due to their creep characteristics and resistance to heat. Care must be taken to apply appropriate pressure during application.
  - Epoxy: these adhesives can be used with almost any specimen material, and can be used to form a good bond with most materials. They are used for low-temperature and long-term measurement applications. Epoxy adhesives harden at room temperature, but require roughly 24 hours to harden. Care must be taken to maintain pressure during installation.
  - Phenol resin: this is a typical single-component heat-curing adhesive. Because it has excellent adhesive strength and long-term stability, it is used for long-term measurement and in transducers. Installation requires a heating unit capable of heating to 200 °C and a clamping tool.
- It should be noted that double-sided adhesive tape used in many domestic and industrial applications should not be used, since double-sided tape absorbs the strain in the test specimen rather than conveying the strain to the gauge base.
- For accelerometers, the use of separate adhesive mounting bases is recommended to prevent the adhesive from damaging the accelerometer base or clogging the mounting threads. Most adhesive mounting bases available also provide electrical isolation. The type of adhesive recommended depends on the particular application and should be selected in consultation with the sensor supplier.

Temperature effects

- When a foil strain gauge or strain transducer is attached to a structure, it is forced to have the same deformation as the structure, which means that changes in temperature can result in contraction or expansion of the strain transducer. If the transducer is to be mounted on the structure for a long period of time, it will need to have its zero reset periodically as it drifts with temperature changes.

- As the mass of a strain transducer is much smaller than the structural member being monitored, the rate of temperature change and thermal expansion in the strain transducer is much faster, which leads the transducer to result in relative compression. It is very difficult to separate temperature effects on the gauge itself from the actual temperature-induced strains.

Wired vs wireless sensor networks

When considering the transfer of signals to the DAS, the advantages and disadvantages of wired vs wireless sensor networks for electronic systems should be taken into account. Wired networks employ cables to connect sensors to the central DAS, while wireless networks utilise transmitters and receivers in lieu of cables.

Wired systems have the benefit of being able to reliably transmit large volumes of data (high bandwidth) and supply power to sensors. Balancing these advantages are the cost, time and potential disruption associated with installing cable runs between sensors and the DAS, particularly where sensors are being installed in areas that are difficult to access.

Further to the above, the use of cables must also take onto account the effects of cable length and temperature changes on signal quality, along with the potential for electromagnetic/radio interference. This is particularly relevant for strain measurement. As a general rule, cable lengths should be kept as short as possible.

When installing instrument cables, they should be installed as far away as practical from sources of electrical interference such as powerlines, generators, motors, etc. Furthermore, cables should never be buried or run with AC power lines as the cables will pick up the electrical noise and this is likely to cause problems when trying to obtain stable readings.

Wireless sensor networks, as the name implies, do not require purchase and installation of cabling (or associated componentry); however, they tend not to have as great a bandwidth as wired networks. Wireless systems are also limited by range and, for larger structures, repeater nodes may be required. In addition, wireless sensors require their own power source. While wireless sensors will typically be more costly than wired sensors, the additional cost must be offset against the reduced cabling costs.

Fibre optic vs electronic sensors

Fibre optic sensors (FOSs) are becoming increasingly available for the monitoring of civil structures. Traditionally FOS systems were prohibitively expensive. However, as technology has improved and demand has increased, the cost of FOS systems has reduced to the point that, where the distinct advantages of FOS are required, they are now a viable alternative to electronic systems.

The key benefits of FOSs include:

- lightweight
- small
- immune to EMI/RFI interference
- large bandwidth
- high sensitivity
- long-term stability
- suitable for multiplexing (multiple sensors on one fibre)
- no power requirements for sensors
- environmentally robust (high temperature operating ranges, resistance to corrosion and damage from vibration and shock).

As stated previously, FOSs and their associated signal condition equipment have traditionally been more expensive than conventional systems; however, they are becoming more affordable. Typically, the greater the number of sensors required, the more cost-effective FOS systems become.

For long-term applications their environmental robustness and long-term stability in particular make them a viable alternative.

Selection of DAS

The selection of DAS should take into account the following considerations (NI website):

- Measurement type – types of signals being measured. Sensors convert the physical phenomenon being measured into a measurable electric signal. The type of signal being measured will dictate the input functions required in the DAS. Analogue signals require analogue input while digital signals require digital input functionality. Many DAS have dedicated input functions that mean they may not be adaptable to other applications. Multifunction and modular DAS systems provide greater flexibility.
- Channel count – number channels required. Each sensor requires one channel therefore a typical monitoring application is likely to require multiple channels. Channel configurations available include single, multichannel and modular devices (with a mixture of measurement types).
- Signal conditioning – most sensors will require some form of signal conditioning (such as amplification or filtering) before a DAS can effectively and accurately measure the signal.
- Sampling rate – required speed of sample acquisition. The sampling rate for any given application will depend on the maximum frequency range of interest. In practice, sampling rates of 5 – 10 times the maximum frequency component of interest should be specified.
- Signal resolution – the smallest change in signal that must be detected. This will determine the required resolution of the DAS.
- PC-based or stand-alone system – PC based systems are more common than stand-alone systems and are preferable where practical due to a number of advantages including real-time visualisation, inline analysis, user-defined functionality, large data storage, and network connectivity. For long-term monitoring applications, stand-alone systems are preferred due to power requirements
- Bus type (connection of a data logger to a PC), including USB, ethernet, and wireless.
  - USB – easier to use than many other PC buses because computers automatically detect the devices.
  - ethernet – the backbone of almost every corporate network and, therefore, widely available. Although ethernet requires more configuration and networking knowledge than USB, it allows cable runs up to 100 m, or further if used with a hub, switch, or repeater.
  - Wireless – extends measurement capabilities to applications where cables are inconvenient or impractical. It can also dramatically reduce costs by eliminating cables and installation time.

System protection

Once the various components of the system have been identified, consideration must be given to the level of protection required once installed. This will be determined by:

- intended duration of the monitoring (length of time components will be exposed for)
- site location (urban, rural or remote location)

- probable hazards (theft, vandalism, inundation, deterioration, etc.)
- accessibility (how easily components can be reached).
- Most sensors and associated hardware can be supplied with proprietary covers/enclosures.

2.3.3 Instrumentation Plans

In order to ensure the unambiguous specification of the SM system being developed, it is essential that all key decisions/criteria are captured in a systematic and consistent manner. To this end it is recommended that an instrumentation plan be completed for all SM projects.

The instrumentation plan should clearly document the following:

- monitoring objectives
- duration of monitoring
- parameters being measured
- required sampling rates
- sensor types
- cabling requirements
- DAS
- ancillary equipment (sensor/DAS protection, ducting, power supply, etc.)
- sensor identification
- installation methodology (access requirements - including environmental restrictions, permitted activities, traffic control, monitoring equipment - sensors, cables, DAS, etc., installation requirements, calibration of instruments, etc.)
- monitoring methodology (access requirements, traffic control, intervention thresholds, etc.)
- maintenance requirements
- removal of system components on completion
- signal conditioning requirements
- intelligent processing requirements (including trigger levels)
- communication of data from site
- data storage and backup requirements (location, media, file format and length of time data are required to be stored)
- diagnostic requirements (what interpretation is required and by whom).

An example instrumentation plan is included in Appendix A.

2.4 Strain

Strain measurement is generally undertaken to:

- determine the amount of deformation caused by applied loading
- determine the stress caused by strain and the safety margin of a structural component
- indirectly determine various physical quantities by converting them to strain.

Common types of instruments used for strain measurement include:

- foil strain gauges
- strain transducers

- vibrating wire strain gauges
- fibre optic strain gauges.

The selection of an appropriate sensor type depends on various factors, including specific applications, specifications and costs.

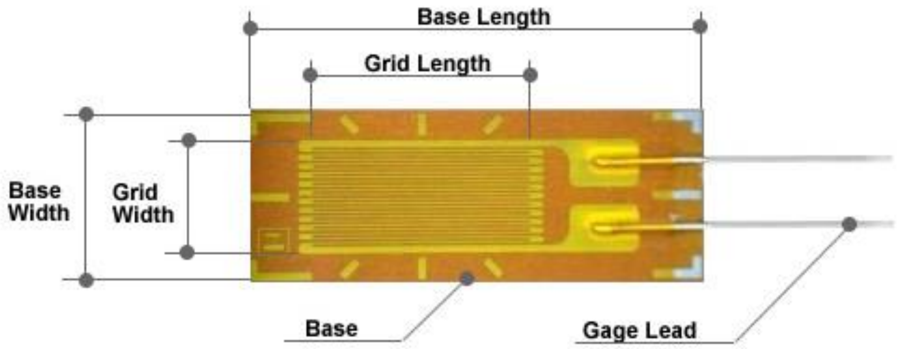
In order to avoid adopting a strain gauge with a strain range far greater than expected, preliminary calculations should be undertaken at the system development stage to determine what strain values are expected.

The following sections provide detailed information on each sensor type.

2.4.1 Foil Strain Gauges

The foil (or bonded metallic) strain gauge is the most widely used strain measurement tool for experimental stress analysis (Figure 2.5). It works on the principle that the electrical resistance of the grid material varies linearly with strain.

Figure 2.5: Foil strain gauge (prewired)



Source: <http://www.showa-sokki.co.jp/english/products_e/Strain_Gage_e/strain_gage_config_e.html>, viewed on 16 Jan 2015.

Applications

- Measuring strains in any structural material: steel, concrete, fibre reinforced polymer (FRP), and timber.
- Suitable for measuring both static and dynamic strains.

The following common definitions are used for foil strain gauges:

- Gauge base: backing material or carrier. The gauge base maintains the shape of the grid and passes the strain in the test specimen to the grid. The gauge base also acts as an electrical insulator.
- Gauge factor K: ratio of the rate of resistance variation caused by uniaxial stress applied along the gauge axis of the strain gauge ($\Delta R/R$) to the strain along the gauge axis. The gauge factor for foil strain gauges is typically around 2.0.
- Gauge length: the length of the grid in the strain gauge.
- Gauge lead wires/cables: fine conducting wires that are connected to the gauge’s grid or gauge tab.
- Gauge tab: areas where the grid wires widen to allow gauge lead wires to be soldered.
- Grid: metallic foil arranged in grid pattern, with the most common materials being Cu-Ni and Ni-Cr alloys.
- Measurement axis: an axis running through the centre of the grid.

- Cover film: thin film used to protect the grid.

Key features

When a strain gauge is installed on the test specimen, and if external loading creates some strain in the test specimen, the strain is passed via the gauge base to the resistance foil in the gauge. This strain changes the dimensions of the wire or foil, which causes a corresponding change in the resistance. By measuring the variation in the resistance, the strain in the test specimen can be derived.

Table 2.2 below summarises the benefits and limitations of foil strain gauges.

Table 2.2: Foil strain gauge attributes

Benefits	Limitations
Simple construction with a small physical size and low mass so as not to interfere with the stresses on the specimen	Susceptible to temperature variations
Short distances between measuring points for localised evaluation	Low resistance to moisture and humidity, necessitating waterproofing or other protective measures
Good frequency response for tracking rapid fluctuations in stress	Require skilled technicians to install
Simultaneous measurement of multiple points and remote measurement	
Range of measurement: tensile and compressive strains ranging up to 10% (10^5 $\mu\varepsilon$)	
Resolution: 0.1 $\mu\varepsilon$ (e.g. Kulite strain gauge)	
Low-cost	

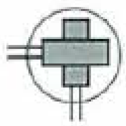
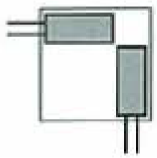
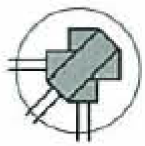
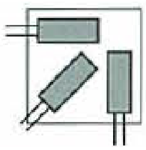
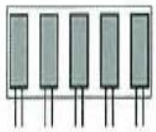
Specifications

- Strain gauge frequency response - determined by the gauge length and the longitudinal elastic wave speed of the test specimen. For steel, with a gauge length of 0.2 mm, 1 mm, 3 mm, 5 mm, and 10 mm, the corresponding frequency response is 660 kHz, 530 kHz, 360 kHz, 270 kHz and 170 kHz, respectively. For concrete, a gauge length of 10 mm , 30 mm, and 60 mm has the corresponding frequency response of 120 kHz, 50 kHz, and 20 kHz. With a typical required sampling rate of 200 Hz for load testing, there is no problem with strain gauges frequency response.
- Gauge resistance - the electrical resistance of an unbonded gauge at room temperature and subject to no external pressure. The most common resistance for strain gauges used in stress strain measurement is 120 Ω. Other resistances are 60 Ω, 350 Ω and 1000 Ω. The high-resistance gauges yield the higher bridge output when high voltages are applied, but they are also more susceptible to noise.
- Operational temperature range: depending on gauge materials, Cu-Ni or Ni-Cr alloy. For example, for TML strain gauges, normal temperature range is -20 °C to 80 °C, high temperature is -20 °C to 300 °C, and low temperature is -269 °C to room temperature.
- Self temperature-compensated strain gauges are available to minimise the thermal output of the strain gauge when it is bonded to a test specimen with a specific coefficient of linear thermal expansion in a stipulated temperature range.

Selection criteria

- Selection of gauge length – for a heterogeneous material, a gauge length is required that can average out the irregular stresses in the material. In concrete for example, the length of the gauge used should be three times the size of the aggregate so as to give an averaged evaluation of the concrete. The following gauge lengths are used for different applications:
  - stress concentration: 0.2 mm to 1 mm
  - steel and general use: 2 mm to 6 mm
  - mortar, timber and FRP: 10 mm to 20 mm
  - concrete: 30 mm to 120 mm
- Strain gauges can be configured in various orientations as illustrated in Table 2.3. Options include uniaxial, two-element rosette (0^o and 90^o) or three-element rosette (0^o, 45^o and 90^o). Uniaxial gauges are used for axial strain on steel truss components, bending strain on steel and concrete beams; while rosettes are used for measuring strains in more than one direction, e.g. principal strains on the web of concrete girders, etc.

Table 2.3: Strain gauge configurations

Gauge configuration						
Gauge type	Single element, uniaxial	2-element rosette, stacked (0^o and 90^o)	2-element rosette, plane (0^o and 90^o)	3-element rosette, stacked (0^o, 45^o, 90^o)	3-element rosette, plane (0^o and 90^o)	5-element rosette, uniaxial

- A strain gauge selection chart is usually available as part of a vendor's user manual.

Coating material type and selection

- Due to the fact that strain gauges work by measuring changes in resistance, the strain gauge resistance must be extremely stable. Stable measurement requires that the strain gauge and the lead wires be protected from various environmental factors once they are installed on the test specimen. While a strain gauge may be sufficiently stable for short-term strain measurement, it may not be adequate for measurement over extended periods. While the degree of stability required varies depending on the material being measured, protecting the strain gauge against moisture is vital to maintaining the strain gauge stability. Required characteristics of coating materials include:
  - excellent resistance to moisture and water and good electrical insulation
  - good adhesion to the strain gauge, lead wires and test specimen surface
  - no constriction of the test specimen.
- Different types of protection include moisture/water, oil, low/high temperature, and mechanical protection.
- Coating application methods include hot melted, air-drying rubber solvent, pressure-sensitive rubber, and coating tape for reinforcement bars.

Permissible voltage

- The current flowing through a strain gauge is directly related to the output voltage from the gauge bridge. The greater the current, the larger the output obtained. On the other hand, current flowing through a strain gauge generates Joule's heat. While the extent of this effect is dependent on the test specimen material and the surface area of the strain gauge, it produces a change in the strain gauge temperature. This temperature change in turn changes the resistance, thereby indicating apparent strain where none exists. In general, a permissible current of 30 mA is safe for metallic test specimens, while 10 mA or less is a safe current for wood or plastic.

Suggested vendors

- BDI - foil strain gauge bridge completion units, reusable with replaceable gauge lead wire.
- Kyowa prewired general purpose strain gauges - KFG series.
- MicroMeasurement - Tech Note TN-505-4 *Strain gauge selection-criteria, procedures, recommendations.*
- TML strain gauges, including various types which can be selected depending on application, e.g. general purpose strain gauges for composite or timber material, surface strains for concrete and mortar, magnetic field strain gauges for metal and concrete, etc.
- Omega Engineering.
- Microstrain.

2.4.2 Strain Transducers

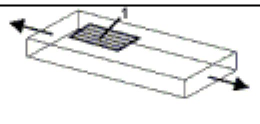
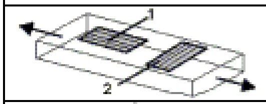
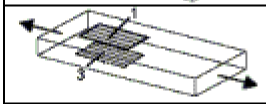
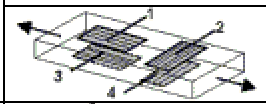
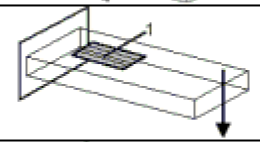
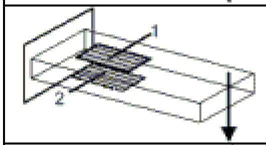
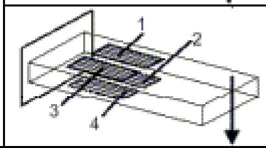
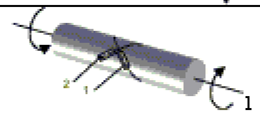
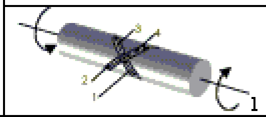
As stated previously, foil strain gauges work on the principle of measuring changes in resistance. In practice, the strain changes required to be measured are very small and require very accurate measurement of very small changes in resistance.

For some applications, foil strain gauges alone do not have the required sensitivity. In these instances, strain transducers, incorporating Wheatstone bridge foil transducer class strain gauges, are employed.

The more strain gauges employed, the quicker and more precise the measurement response. Wheatstone bridge types are ¼-bridge (one strain gauge/arm of circuit employed), ½-bridge (two strain gauges/arms of circuit employed) and full bridge (four strain gauges/arms of circuit employed).

Figure 2.6 summarises the relative sensitivity of various gauge configurations.

Figure 2.6: Gauge configuration sensitivity

Strain	Gauge Setup	Bridge Type	Sensitivity MV/V @ 1000 uE	Details
Axial		¼	0.5	Good: Simplest to implement, but must use a dummy gauge if compensating for Temperature. Also responds to Bending Strain.
		½	0.65	Better: Temperature compensated, but it is sensitive to bending strain.
		½	1.0	Better: Rejects Bending Strain, but not temperature. Must use dummy gauges if compensating for temperature.
		Full	1.3	Best: More sensitive and compensates for both temperature and bending strain.
Bending		¼	0.5	Good: Simplest to implement, but must use a dummy gauge if compensating for Temperature. Responds equally to Axial Strain.
		½	1.0	Better: Rejects axial strain and is temperature compensated
		Full	2.0	Best: Rejects axial strain and is temperature compensated. Most sensitive to bending strain.
Torsional and Shear		½	1.0	Good: Gauges must be mounted at 45 degrees from centerline. Axial and Bending forces produce equal strain and are hence rejected.
		Full	2.0	Best: More sensitive full-bridge version of previous setup. Rejects both axial and bending strains.

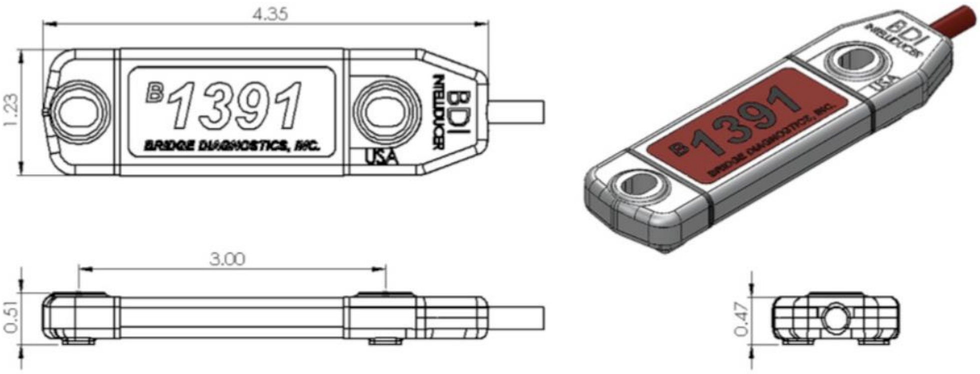
Source: *Choosing the right strain gauge for your application,* National Instruments, viewed on March 26 2015, <http://www.ni.com/white-paper/3092/en/?.

The following definitions are common for strain transducers:

- Wheatstone bridge - An electrical circuit used to measure an unknown electrical resistance by balancing two legs of a bridge circuit, one leg of which includes the unknown component.

Figure 2.7 shows the general configuration of a typical strain transducer.

Figure 2.7: General dimensions of BDI ST350 strain transducer



Note: All dimensions in inches.
Source: *ST350 Operations Manual,* BDI, viewed on 13 May 2015, <https://s.campbellsci.com/documents/au/product-brochures/b_st350.pdf>.

Key features

Table 2.4 below summarises the benefits and limitations of strain transducers.

Table 2.4: Strain transducer attributes

Benefits	Limitations
Simple construction with a small physical size and low mass so as not to interfere with the stresses on the specimen	Higher cost (but are reusable)
Short distances between measuring points for localised evaluation	Skilled installation
Good frequency response for tracking rapid fluctuations in stress	
Simultaneous measurement of multiple points and remote measurement	
Greater response and higher precision than foil strain gauges (in half and full bridge configuration)	
Range of measurement: tensile and compressive strains ranging up to 10% (10^5 $\mu\varepsilon$)	
Much higher cost than foil strain gauges but are reusable and can last for many years	
Durable and weatherproof	
Manufactured to have thermal coefficients of expansion similar to that of concrete; this reduces sensitivity to temperature	
Installations of strain transducers can be carried out in five minutes.	

Specifications

Table 2.5 below lists specifications for various strain transducers from selected vendors:

Table 2.5: Specifications for various strain transducers from selected vendors

Vendor	BDI	KYOWA
Model Number	ST350	BS-15CT
Mounting Method	BDI mounting tab and adhesive or mechanical connection	Surface mounted using fixing screws
Gauge Length (mm)	76.2	150
Range (με)	+/- 4000	+/- 2000
Nonlinearity (% RO)	-	+/- 2
Hysteresis (% RO)	-	+/- 2
Accuracy (%)	< +/- 1	-
Sensitivity (με/mV/v)	500	-
Operation temperature (°C)	-50 to 85	-30 to 80

Selection criteria

Maintenance

- As strain transducers are susceptible to temperature variations, they are best suited to capturing live load responses applied to structures during periods where there is little or no temperature change. They may, however, be re-zeroed when monitoring is required over longer periods of time.

Suggested vendors

- Bestech
- Bridge Diagnostics Inc.
- HBM Australia
- Kyowa.

2.4.3 Vibrating Wire Strain Gauges

Vibrating wire strain gauges consist of two end blocks which may be surface-mounted (or embedded in concrete) with a length of steel wire tensioned between them. Deformation of the structure under load results in movement between the two end blocks and a change in wire tension which corresponds to a change in resonant frequency. This change in resonant frequency is then used to determine the strain in the material being measured. A thermistor incorporated into the gauge supplies information on temperature effects.

Standard end blocks can also be mounted on materials other than concrete and steel including timber or rock/masonry. Epoxy bonding can be used for these applications (and for surface mounting on concrete members) or special concrete mounting blocks can be used. Figure 2.8 illustrates the general arrangement of a vibrating wire strain gauge.

The following definitions are common for vibrating wire strain gauges:

- gauge coil housing: body containing electromagnetic coils used to produce electromagnetic field for subsequent oscillation of tensioned wire at resonant frequency
- gauge flange: end block used to mount strain gauge to material being measured
- resonant frequency: natural frequency of vibration determined by the physical parameters of the vibrating object
- thermistor: temperature-sensing element composed of sintered semiconductor material which exhibits a large change in resistance proportional to a small change in temperature.

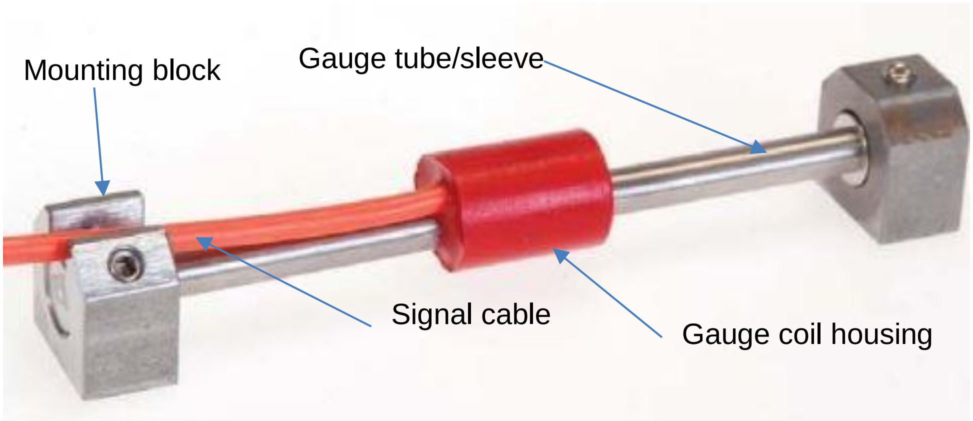
Applications

Vibrating wire strain gauges can be used for following applications:

- stress and strain monitoring in steel structures such as, but not limited to, girders, struts, piles, pipelines and pressure vessels
- stress and strain monitoring in concrete structures such as, but not limited to, bridges, retaining walls and hydraulic structures
- underground works including supports, linings and piers.

Figure 2.8 illustrates a typical surface-mounted vibrating wire strain gauge.

Figure 2.8: Typical surface-mounted vibrating wire strain gauge



Source: *Vibrating Wire Strain Gauge – Surface Mount*, PCTE, viewed on 13 March 2015, <http://www.pcte.com.au/vibrating-wire-strain-gauge-surface-mount>.

Key features

Table 2.6 below summarises the benefits and limitations of vibrating wire strain gauges.

Table 2.6: VW strain gauge attributes

Benefits	Limitations
Robust design, suitable for demanding environments	Not suitable for dynamic applications
Thermally aged to minimise long-term drift	
Output is a frequency signal: therefore insensitive to resistance changes in connecting cables caused by contact resistance or leakage to ground	
Immune to voltage surges	

Benefits	Limitations
Surface-mountable to steel, concrete, timber, rock/masonry and FRP	
Built-in temperature sensor	
Reliable long-term performance monitoring	
Cable may be readily and simply extended on site without special precautions	
Accurate readings even with long cable lengths	
Totally waterproof	

Specifications

Table 2.7 lists specifications for various vibrating wire strain gauges from selected vendors:

Table 2.7: Specifications for various VW strain gauges from selected vendors

Vendor	Sisgeo	PCTE	PCTE	Encardio-rite
Model Number	**0VK4200VC00**	**VW S-2100**	**VW S-2120**	**EDS-20V-SW**
Active gauge length (mm)	165	150	50	50.8
Range (με)	3000	3000	3000	3000
Resolution (με)	1	1	1	1
Accuracy (% FS)	+/-0.5	+/-0.1-0.5	+/-0.1-0.5	-
Stability (% FS/yr)	0.1% FS/yr	-	-	-
Nonlinearity (% FS)	-	<0.5	<0.5	-
Typical frequency (Hz)	500-1200	850-1550	1500-3500	-
Operating temperature range (°C)	-20 to 80	-20 to 80	-20 to 80	-20 to 80

Selection criteria

The selection of appropriate vibrating wire strain gauges should be based on the following:

- required accuracy of the strain gauge
- expected strain range.

The coil housing for most vibrating wire strain gauges is waterproof, which is an advantage over conventional strain gauges that may require extra waterproofing or weatherproofing measures at additional cost.

Suggested vendors

Vendors most suitable to supply vibrating wire strain gauges include:

- BDI
- Encardio-rite Geotechnical Instruments
- Envco
- Geokon
- Papworths Construction Testing Equipment (PCTE)

- Sisgeo.

2.4.4 Fibre Optic Sensors

Fibre optic sensors work by measuring changes in the properties of light travelling through the optical fibre. These changes, or modulations, relate to changes in the external environment surrounding the fibre which alter the fibre's material and structural properties. Common external factors include applied forces and changes in temperature.

Developments over the last decade have resulted in a series of different fibre optic sensor technologies including:

- Fibre Bragg Grating (FBG) - Optical fibres that have been modified by length to create periodic variations in the refractive index along the fibre, which dictate what wavelengths of light will be reflected back through the fibre. Variations in the component being measured result in changes to the gratings which allows the FBG sensor to record data relating to the measured properties.
- Brillouin scattering - Optical fibre sensors that utilise principles similar to FBG sensors. Strain profiles are measured along a single optical fibre by measuring down-shifts in the frequency of the reflected light and relating them to changes in fibre properties.
- Fabry-Perot technology - Sensors that use cut optical fibres. The gaps between cut optical fibres are measured and can be related to the parameter measurement being obtained.
- Michelson and Mach-Zehnder interferometric sensors - Sensors that utilise one fibre as a sensory component and another fibre as a reference component whereby the parameter being measured is related to the difference between properties of the sensory and reference fibres.

The following definitions are common for fibre optic strain gauges:

- Extrinsic sensor - An optical fibre sensor that uses optical fibre cables to transmit modulated light from a non-fibre-optical sensor or an electronic sensor to an optical transmitter.
- Intrinsic sensor - An optical fibre sensor that measures strain and other quantities by modifying a fibre so that the quantity to be measured modulates the wavelength or transit time of light in the fibre.
- Modulation - The process of varying one or more properties of a periodic waveform with a modulating signal.

Applications

Fibre optic sensors can be used in various SM applications as presented in Table 2.8.

Table 2.8: Types of material characteristics that can be measured with fibre optics

Material characteristic/parameter	Measured parameter of optical signal
Strain	Transmission of optical signal
Displacement	Wavelength
Vibration	Phase
Acceleration	Time of flight
Force	Brillouin scattering
Pressure	Brillouin scattering
Temperature	Fluorescence

Source: Daum (2013).

Key features

Table 2.9 below summarises the benefits and limitations of fibre optic sensors.

Table 2.9: Fibre optic sensor attributes

Benefits	Limitations
Excellent resolution	High cost, but the greater the number of sensors required, the more competitive they are as installation times are much quicker
Immunity to electromagnetic/radio frequency interference	
Excellent stability over time: as they are passive sensors, they have zero drift and can be used for many years without recalibration	
Possible to multiplex (have multiple sensors within the same fibre)	
Measure absolute strain	
Not affected by temperature	
Electrical interrogation units can be sited far from the sensing location as optical fibres are very efficient signal carriers	
Much smaller than conventional sensors so many sensors can be applied to a structure with little to no intrusion	
FBG sensors are very useful for localised strain measurement but area of interest must be known	
Brillouin fibre optic sensors are very useful for large applications where specific areas of interest are unknown	
Fabry-Perot strain gauges are insensitive to transverse strains	
Intrinsically safe as they do not require any power	

Specifications

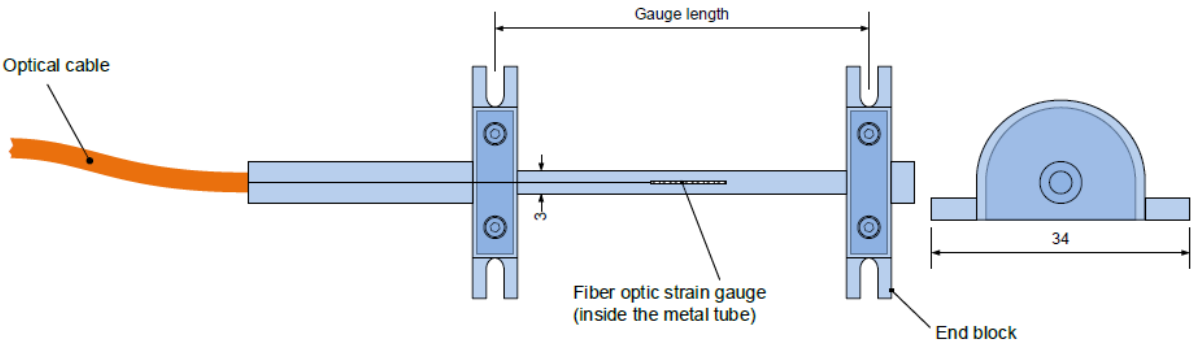
Table 2.10 lists specifications for various fibre optic strain gauges from selected vendors.

Table 2.10: Specifications for various fibre optic strain gauges from selected vendors

Vendor	HBM FiberSensing	Opsens	Opsens	Opsens	Smart Fibres
Model Number	**FS6200**	**OSP-A**	**OSP-B**	**OSP-C**	**SmartPatch**
Active gauge length (mm)	25-107	50 (can be varied)	50 (can be varied)	50 (can be varied)	6 (can be varied)
Range (με)	+/- 2500	+/- 1000	+/- 2500	+/- 5000	+/- 5000
Resolution (με)	0.6	0.15	0.15	0.15	0.4
Gauge factor accuracy (% FS)	-	+/- 3	+/- 5	+/- 10	-
Operation temperature (°C)	-20 to 80		-40 to 85		-30 to 60

Figure 2.9 illustrates an Opsens surface-mounted fibre optic strain sensor.

Figure 2.9: Opsens surface mountable fibre optic strain sensor



Spécifications

Measuring range[1]	± 1000 με	± 1500 με	± 2000 με	± 3000 με
Resolution	0.15 με	0.2 με	0.25 με	0.3 με
Precision[2]	± 1 με	± 1.5 με	± 2 με	± 3 με
Gauge length[3]	50 mm			
Operating temperature	Standard : -40 °C à +85 °C HT : -40 °C à +250 °C			
Housing material [4]	Stainless steel : AISI 306; AFNOR Z6 CND 17-11			
Optical cable	Polyurethane outer jacket reinforced with aramid yarn ($\varnothing_{ext}$ = 4 mm)			

[1] Other ranges available upon request
[2] Sensors individually calibrated
[3] Other lengths available upon request
[4] Other alloys available

Source: <http://www.opsens.com/pdf/products/OSP-A%20Rev%201.5.pdf>.

Selection criteria

When selecting a particular type of fibre optic strain gauge, careful consideration should be given to the locations at which strain measurements are required, the dynamic strain range of the fibre optic strain gauge and the costs involved in such a system.

- Fibre Bragg Grating strain gauges are most suitable for localised strain measurements; however, for their efficient use it is important that the specific areas of interest are known.
- Brillouin scattering optical fibre strain gauges are most suitable for applications with total lengths in excess of ten metres. Distributed Brillouin strain gauges can be used for much broader coverage and can locate fault points not known prior to installation of the gauges.
- As fibre optic strain gauges are impervious to electromagnetic or microwave interferences, they are suitable for structures located near electrical transfer stations or radio towers. Conventional foil strain gauges depend on electrical currents and would be affected by electromagnetic noise near transfer stations, etc.
- Optical fibres are efficient signal carriers which means that they would be well suited to isolated structures which are many kilometres away from SM software.

The operating temperature ranges of the fibre optic strain gauges listed in Table 2.10 indicate that the majority of fibre optic strain gauges have operating temperatures ranges that are outside the maximum highs and lows recorded. Therefore, fibre optic gauges need not be selected based on their operating temperature range.

Mating gauges to the readout unit:

- For the proper use of the gauges, the fibre optic connector must be kept clean and free of dust at all times in order to ensure that the light travelling through the optical fibre is not disrupted. Dust can also reduce the signal-to-noise ratio to an unusable level.

Permissible voltage:

- As fibre optic strain gauges require no electricity, the permissible voltage need not be considered.

Suggested vendors

- Opsens
- FiberSensing
- FBGS Technologies
- MTI Instruments
- Scaime.

2.4.5 iMETRUM

The iMETRUM system uses the output from high-resolution, high-speed black and white (280 grey scales) video cameras used to record high-speed video of selected targets on a structure. The video is then processed using specialised pattern recognition software (Video Gauge™) to obtain real-time displacement of the selected targets. Infrared lighting can be used for monitoring at night.

The Video Gauge™ pattern recognition technology works on rivets, bolts, beams, masonry, concrete staining – almost all typical bridge material, without the need to fit targets.

The software uses pattern recognition and sub-pixel interpolation to make measurements to identify the exact location of a user-defined target in the image. It tracks the pattern at user-defined locations frame by frame, outputting the corresponding measurement data in real time.

It should be noted that, unlike photogrammetry, iMETRUM uses only one video camera.

An iMETRUM system includes the following components:

- High resolution digital video camera with different lenses
- Controller box with Video Gauge software installed, storage capacity, export data to USB/hard drive in csv format, 1 GB per minute, running on 12 V battery
- Software to post-process the recorded video, developed by University of Bristol
- Lighting/tripod
- Rugged case for storage and transportation including spray paints for applying speckle patterns.

Figure 2.10: iMETRUM system

Source: iMETRUM, viewed on 15 January 2015, <http://www.imetrum.co.uk/how-it-works/>.

Applications

iMETRUM can be used to measure the following:

- position (displacement)
- strain (expansion and contraction)
- rotation (twist, tilt and bending)
- continuous dynamic monitoring.

Key features

Table 2.11 below summarises the benefits and limitations of the iMETRUM system.

Table 2.11: iMETRUM attributes

Benefits	Limitations
Can be set up at a distance from the structure, with no disruption to traffic and safer working environment	Requires an external trigger
Installation of targets/sensors on structure not required	Set to Greenwich Mean Time (GMT)
Uncompressed black-and-white video from any video camera can be processed using the software	Lower resolution than conventional strain gauges (5 $\mu\varepsilon$ versus 1 $\mu\varepsilon$)
Measure up to 250 points per camera field of view	Position (displacement) with a resolution of 0.1 mm
Up to 1600 measurements per second (e.g. sample 100 points at 16 Hz or 8 points at 200 Hz)	Security of equipment for continuous monitoring application
Reusable	Stability of camera
	Capability of technology to measure strain in SM application requires further assessment. iMETRUM and vendor have committed to trial of technology for upcoming monitoring of Dawson's Creek bridge.

Suggested vendors

iMETRUM.

2.5 Acceleration and Vibration

Application of moving loads on structures causes acceleration of structural components. Conversely, ground accelerations, caused by seismic loads for instance, result in the dynamic loading of structural components. The combination of the frequency of the response as well as the amplitude of the response to these dynamic excitations is called the modal response. Although structures are designed to withstand these accelerations, SM can be used to determine exactly how a structure is responding to these accelerations and the resulting loads via determination of the modal response parameters. Furthermore, changes in support conditions or material properties may alter the modal response and, in certain situations, an SM system may be able use these changes to identify damage or deterioration.

Applications

- structure modal analysis
- vehicle dynamics
- structure vibration testing and monitoring
- ideal for cable force measurements.

Accelerations are commonly measured using a class of sensors called accelerometers of which there are three main technologies:

- Piezoelectric (PE) accelerometers – offer a very wide measurement frequency range (a few Hz to 30 kHz) and are available in a range of sensitivities, weights, sizes, and shapes. They are appropriate for both shock and vibration measurements.
- Piezoresistive (PR) accelerometers – generally have low sensitivity making them desirable for shock measurements and less useful for vibration measurements. They are also used extensively in transportation crash tests. PR accelerometers generally have a wide bandwidth (from a few hundred Hz to >130 kHz) and the frequency response goes down to 0 Hz (often called 'DC responding') or steady state, so they can measure long-duration transients.
- Variable capacitance (VC) – among the newer accelerometer technologies. Like piezoresistive accelerometers, VC accelerometers are DC responding. They have high sensitivities, a narrow bandwidth (from 15 Hz to 3000 Hz), and outstanding temperature stability. Thermal zero and sensitivity shifts can be as low as 1.5% over a temperature range of 180 °C. These devices are suited for measuring low-frequency vibration, motion, and steady-state acceleration.

For SM applications covered in this guide, the vibration category is of most interest. Piezoelectric accelerometers are the first choice for most vibration measurements since they have a wide frequency response, good sensitivity and resolution, and are easy to install. There are two types of piezoelectric accelerometers: the basic charge-mode accelerometer and the voltage-mode internal electronic piezoelectric (IEPE) accelerometer. The latter type incorporate built-in signal conditioning electronics, making them ideal for use in the field unless expected maximum temperatures exceed 120 ^{o}C. Variable capacitance accelerometers should also be considered where low frequencies are of interest.

In addition to the above, fibre optic accelerometers are also available that utilise a fibre optic sensor to measure wavelength shifts as a result of applied forces. These sensors operate between 0-1 kHz and, as for other fibre optic sensors, have a wide operating temperature range and are intrinsically safe.

An alternative sensor type to accelerometers is the geophone which measures ground velocity as opposed to ground acceleration. A traditional geophone comprises a mass (surrounded by coiled wire) suspended from a spring. A magnet encloses the hanging mass and coiled wire and, when the magnet moves due to movement of the ground/structure, voltage is generated in the coiled wire. Geophones are widely used in the mining industry and geotechnical applications (e.g. ground movement) due to their low-cost and excellent reliability when compared to accelerometers. They are not, however, as precise or offer as much resolution as accelerometers and their use for measuring the response of structures has, to date, been limited (noting they are specified for measurement of vibration in tunnel roofs).

Selection criteria

General considerations specific to selection of accelerometers for bridge monitoring include:

- Amplitude range – the amplitude range of the accelerometers has to be defined with respect to vibration levels of the structure.
- Axes – how many directions of movement are required to be measured
- Cabling – cabling and length of cable runs are an important consideration. The choice of cable, shielding and connectors will have a direct impact on the durability and reliability of the system. Long cable runs can affect frequency response and introduce noise/distortion.
- Frequency response – the frequencies to be measured should be within the linear frequency response band of the sensor. The high frequency response of the sensor will be governed by the mechanical characteristics of the sensor and the method of attachment to the structure (see Mounting, below). For low-frequency applications, VC accelerometers should be considered, as they allow for the measurement of low-level, low frequency vibration with a high output level. They also provide a high degree of stability over a broad temperature range.
- Ground isolation – ground isolation for piezoelectric accelerometers becomes important when dealing with steel structures. A difference in ground voltage levels between the electronic instrumentation and the accelerometer may cause a ground loop, resulting in erroneous data. Accelerometers are available with ground isolation or with the ground connected to the accelerometer case. Accelerometers with ground isolation usually have an isolated mounting base and, where applicable, an isolated mounting screw. In some cases the entire accelerometer case is ground isolated.
- Mass loading – the dynamic response of a structure is a function of its mass, damping and stiffness. Vibration of a structure will be dampened if the mass of the accelerometer has a significant contribution to the overall mass of the system. In most structure monitoring applications this is unlikely to be an issue, except where the response of lightweight components is being monitored.
- Mounting
  - In many cases, the accelerometer mounting location will be dictated by the reason for measuring the vibration; however, the accelerometer should be mounted with its main sensitivity axis aligned with the desired measurement direction.
  - The mounting location should provide a short and rigid vibration transmission path to the vibration source, which avoids any compliance and damping elements present in the structure.

- — Mounting techniques influence the frequency range and dynamic performance of accelerometers.
  - ♦ Stud mounting provides optimum accelerometer performance and should be used wherever possible, as it does not limit the temperature range of the accelerometer and allows operation at very high vibration levels.
  - ♦ Wax mounting is a quick and easy mounting option and provides a resonance frequency only slightly lower than that for stud mounting; however, it does impose a temperature limitation as low as 40 °C.
  - ♦ Magnet mounting, like wax mounting, is a very rapid mounting method that provides high acceleration capability; however, the surface of the test object must be ferromagnetic and absolute repeatability cannot be guaranteed.
  - ♦ Given the mounting techniques available and that most bridges in Queensland have been built using concrete, stud mounting would appear to be the most suitable.
- Sensitivity – accelerometers with higher sensitivity are less susceptible to electromagnetic interference. However the weight of the sensor increases with sensitivity, lowering its resonant frequency. Providing the resonant frequency is outside the frequency range of interest and the addition of mass to the structure (mass loading) is negligible, then higher sensitivity sensors should be selected.

Environmental factors should also be considered, including temperature, maximum acceleration levels and humidity. The operating temperature range for most accelerometers will exceed those typically experienced; however, this should be confirmed.

Suggested vendors

- BDI
- PCB
- MicronOptics.

2.6 Displacement

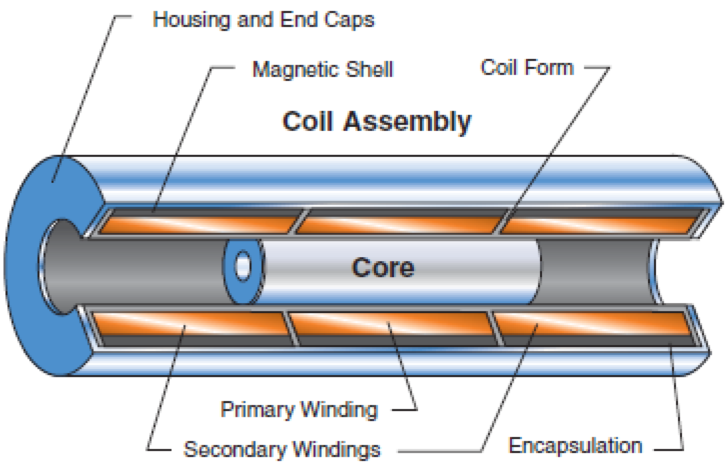
Various displacement sensors are available for measuring live load (dynamic) responses and crackmeters for long-term monitoring. Sensor types include:

- Linear variable differential transducers
- displacement fibre optic sensor
- string potentiometers
- vibrating wire crackmeters
- proximity sensors
- rod extensometers
- interferometric radar
- iMETRUM.

2.6.1 Linear Variable Differential Transducers (LVDT)

LVDT, also known as linear variable differential transformers, are essentially small transformers that have one primary and two symmetrically wound secondary coils and an armature core that is free to move along the linear axis. A push rod connects the armature core to the monitored component. If the armature core is moved off-centre, an electromagnetic force is produced that creates a differential between the transformation efficiency of the secondary coils resulting in a positive or negative output voltage. This output voltage is then correlated to the displacement of the monitored component. Figure 2.11 describes the componentry of a typical LVDT.

Figure 2.11: Componentry of a typical LVDT



Source: *Position Sensing* Solutions, Bestech, viewed on 20 March 2015, <http://www.bestech.com.au/wp-content/uploads/brochures/lvdt_Products_Catalogue.pdf>.

LVDTs are rugged and self-contained units that are ideal for recording displacements on structural members due to live loads and/or temperature variations.

Applications

LVDTs can be used for the following SM applications:

- displacement
- deflection of beams and other structural components
- expansion joint movement
- concrete crack monitoring
- moveable structure testing.

Key features

Table 2.12 below summarises the benefits and limitations of LVDTs.

Table 2.12: LVDT attributes

Benefits	Limitations
Suitable for high-temperature applications when compared with other displacement technologies, e.g. off-the-shelf LVDT have an operating temperature range of –60 °C and 200 °C and use of different materials increases that range to –200°C to 500 °C	Many LVDTs required fixed anchor points for proper operation, making the use of LVDTs difficult for bridges with tall piers or abutments because a frame would have to be installed for anchorage of the LVDTs
Virtually 'noise-free' and displaying extreme resistance to the effects of vibration, rotation and electrical interference	
Even in the most unfavourable industrial surroundings, calibration remains stable for years of operation	
Can handle extreme pressure	

Benefits	Limitations
Close to infinite resolution due to its being able to detect infinitesimally small changes in core position	
Close to unlimited mechanical life as the core does not rub against any wiring, which means that no mechanical components wear out	
As there is no friction, the LVDT responds very quickly to changes in core position	
Absolute output device as opposed to an incremental output device	

Specifications

Table 2.13 lists specifications for various LVDTs from selected vendors:

Table 2.13: Specifications for various LVDT sensors from selected vendors

Vendor	BDI	UniMeasure	Bestech	Stellar Technology	Smart Fibres
Model Number	**LVDT**	**HX Series**	**PR Series**	**LLU60X Series**	**SmartPatch**
Range (mm)	+/- 25 mm	0 - 50 mm to 0 – 80 m	+/- 0.63 mm to +/- 250 mm	+/- 12.5 mm to +/- 200 mm	+/- 6 (can be varied)
Maximum linearity error (%)	+/- 0.1	+/- 0.1	+/- 0.25	+/- 0.5	+/- 0.5

Selection criteria

The following considerations should be taken into account when selecting a LVDT:

- performance considerations - measuring range
- resolution - linearity, influence of thermal effects
- mechanical considerations - size, location access, mounting and fixing
- electrical considerations - output signal from the sensor, electrical termination (connector, integral cable), type of power supply per output, signal conditioning, set-up
- environmental considerations - operating temperature range, compensated temperature range, IP rating, hazardous environment, submersible
- special requirements - calibration, special approval/certifications, labelling, serviceability (maintenance).

Installation considerations

LVDT mounting

- As most LVDT housing is cylindrical, they can be installed with clamping blocks. Clamping forces must be controlled in order to avoid distortion of the LVDT housing as it could stress the internal component and damage them.
- Mounting arrangements involving set screws that press onto the surface of the housing must never be used as they could deform it and damage the internal components.

Maximum excitation voltage

- It is important that the LVDT has enough capacity to dissipate the input power without significant self-heating and without damaging the coils.

Electromagnetic considerations

- Most LVDTs have magnetic shielding around the coil assembly; however, this does not completely eliminate the effects of intense external magnetic fields. As a result, LVDTs should not be installed near devices that generate high electromagnetic fields.
- When two or more AC LVDTs are in close proximity to each other cross-talk can occur, which is when LVDTs are excited with slightly different frequencies. The leaked electromagnetic waves can penetrate other LVDTs, which induces very low AC voltages. Double shielding of AC LVDTs is desirable in this situation and shielding of cables is also important.

Suggested vendors

- BDI
- Measurement Computing
- UniMeasure
- Kyowa
- SpaceAge Control
- Stellar Technology.

2.6.2 Displacement Fibre Optic Sensors

Fibre optic sensors were described in detail in section 2.4.4. Displacement monitors utilise FBG technology.

Applications

Displacement fibre optic sensors are particularly suited for the following SM applications:

- crack monitoring
- continuous monitoring of construction joints and cracks in rock and structural members
- long term measurement of expansion joint movement.

Key features

Table 2.14 below summarises the benefits and limitations of displacement fibre optic sensors.

Table 2.14: Displacement fibre optic sensors attributes

Benefits	Limitations
Excellent resolution	High cost, but the greater the number of sensors required, the more competitive they are as installation times are much quicker
Immunity to electromagnetic/radio frequency interference	
Excellent stability over time; as they are passive sensors, they have zero drift and can be used for many years without recalibration	
Possible to multiplex (have multiple sensors within the same fibre)	
Measure absolute strain	
Not affected by temperature	
Electrical interrogation units can be sited far from the sensing location as optical fibres are very efficient signal carriers	
Much smaller than conventional sensors so many sensors can be applied to a structure with little to no intrusion	

Benefits	Limitations
Intrinsically safe as they do not require any power	
Most fibre optic displacement sensors have a second FBG incorporated into the housing which allows for temperature compensation	

Specifications

Table 2.15 lists specifications for various fibre optic displacement sensors from selected vendors:

Table 2.15: Specifications for various sensors from selected vendors

Vendor	Philtec	Scaime		Opsens		MicronOptics
Model Number	**D Series**	**OBDI**	**ODP**	**OS5000**	**OS5100**	**OS5500**
Range (mm)	0–76 mm	0–100 mm	0–25 mm	0–12 mm	0–50 mm	up to 450 mm
Resolution	0.15–1 µm	0.05 % E_{max}	25 µm	0.02 % E_{max}	0–.03 mm	0.02 % E_{max}
Temperature range °C	-	–20 to 50		–40 to 85		–40 to 80

Installation considerations

Fibre optic displacement sensors are typically supplied housed in robust weatherproof casings ready for fixing to the structure/component, using either screw fixings or adhesives.

Suggested vendors

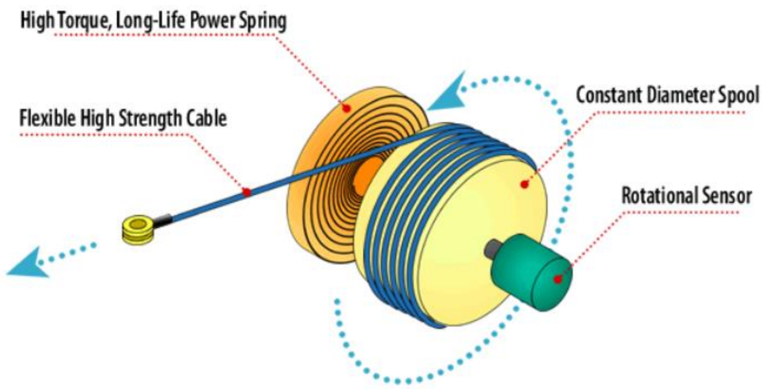
- SCAIME
- Philtec
- MicronOptics
- Opsens.

2.6.3 String Potentiometer Transducers

A string potentiometer transducer, also known as a ‘string pot’, ‘cable-extension transducer’, ‘draw wire sensor’ or ‘yo-yo sensor’, is a device using a flexible cable and spring-loaded spool to measure displacement. Each string potentiometer consists of four main parts: measuring cable, spool, spring and rotational sensor. Inside the potentiometer’s housing, a stainless steel cable is wound around a cylindrical spool that turns as the cable reels and unreels. Cable tension is maintained via a spring coupled to the spool. The spool is also connected to the shaft of a rotational sensor, which creates an electrical signal proportional to the cable’s linear extension.

Figure 2.12 below illustrates the general configuration of the componentry inside the main housing of a string potentiometer transducer.

Figure 2.12: General configuration of componentry inside potentiometer housing



Source: *Validyne Engineering*, viewed on 18 March 2015, <http://validyne.com/blog/connecting-usb2250-string-pot/>.

Applications

- Monitoring joints for unexpected movement to provide early warning of performance problems.
- Monitoring joints and cracks in structures that may be affected by nearby excavation and construction activities.

Specifications

Table 2.16 lists specifications for various string potentiometer transducers from selected vendors:

Table 2.16: Specifications for various string potentiometer transducers from selected vendors

Vendor	Celesco – SM series				BEI Sensors	Micro-Epsilon
Model Number	**SM 1-2**	**SM 1-7**	**SM 1-12**	**SM 1-25**	**LT25**	**MPM series**
Range (mm)	0–64	0–191	0–318	0–635	0–3175	0–50 to 0–250
Accuracy %FS	1	.25	.25	.25	-	0.25
Resolution	Essentially infinite					
Temperature range (°C)	–18 to 70				–25 to 90	–20 to 80

Key features

Table 2.17 below summarises the benefits and limitations of string potentiometer transducers

Table 2.17: String potentiometer attributes

Benefits	Limitations
Multi-axis capability - string potentiometers can be used to track linear, rotary, two-dimensional and three-dimensional displacements, which proves useful where size and mounting restrictions eliminate other choices	Catenary curve error effects - although the tension in the cable is relatively high, external forces such as wind or gravity can lead to curves in the cable which may result in measurement errors; however, these errors are generally very small (±0.0025%).
The flexible displacement cable inherent in string potentiometers allows for flexible mounting; the cable can be attached to the component being monitored via magnets, eyebolts or other threaded fasteners	Using non-backlash connections and threaded drums can offer accuracy exceeding ±0.025% of full scale; however, in some instances the use of non-backlash connections and threaded drums is not sufficient and LVDTs or laser-based devices should be used

Benefits	Limitations
Flexible mounting features combined with the broad tolerance for displacement cable misalignment allow for installation in less than two minutes	
Intrinsically safe as they do not require power source	
Small size relative to measurement range	
Rugged design allows potentiometer to perform reliably in harsh industrial, aerospace and outdoor environments including environments containing vibration, humidity, corrosion and moisture	
Broad operating temperatures ranging between –65 °C and 125 °C depending on whether analogue or digital potentiometers are used	
Cost effective when installation and lifetime costs are considered	
Can measure displacements ranging from a few millimetres up to 50 m	
Essentially infinite resolution	

Selection criteria

- String potentiometers have broad measurement ranges from a few millimetres up to 50 m. It is important that a potentiometer with a suitable range is chosen, as the larger the range, the larger the potentiometer. Preliminary calculations can be carried out to determine expected displacements.
- Raw accuracy may not be the most suitable selection criterion. Linearity, resolution and repeatability should be considered. If the level of accuracy provided is not required, costs will be high for capacity that is not utilised.

Suggested vendors

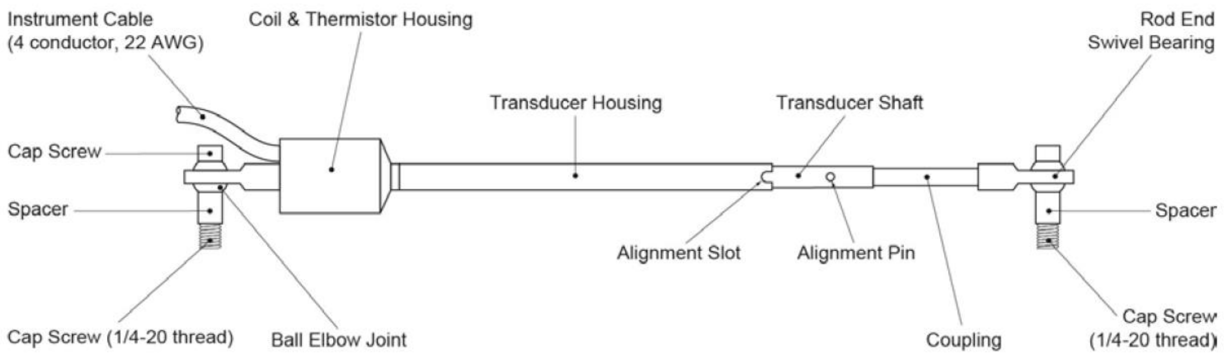
- Celesco - SM series of string potentiometers (range is 0–60 mm)
- BEI Sensors - LT25 series of string potentiometers (range is 0–3150 mm)
- Micro-Epsilon - WDS-50 MPM string potentiometer (range 0–50 mm).

2.6.4 Vibrating Wire Crackmeters

A vibrating wire (VW) crackmeter consists of a VW displacement transducer and a mounting kit. Anchors are installed on either side of a crack and the transducer is mounted across the anchors. A change in the distance across the crack causes a change in the frequency signal produced by the VW displacement transducer when excited by the readout or data logger. The readout device then processes the signal, applies calibration factors and displays a reading in millimetres or inches. Subsequent readings are then compared with the initial value.

Figure 2.13 below illustrates the general configuration of the Model 4420 vibrating wire crackmeter manufactured by Geokon.

Figure 2.13: Model 4420 crackmeter available from Geokon



Source: *Model 4420 VW Crackmeter,* Geokon, viewed on 20 March 2015, <http://www.geokon.com/content/manuals/4420_Crackmeter.pdf>

The following definitions are common for vibrating wire crackmeters:

- Setting distance: The distance between the two anchors suspending the crackmeter gauge.

Applications

- Monitoring joints for unexpected movement to provide early warning of performance problems.
- Monitoring joints and cracks in structures that may be affected by nearby excavation and construction activities.

Key features

Table 2.18 below summarises the benefits and limitations of vibrating wire crackmeters.

Table 2.18: Vibrating wire crackmeter attributes

Benefits	Limitations
Robust and corrosion-proof construction	
Easy installation and excellent long-term stability	
Fully waterproof	
Option for fitting thermistors enables the examination of temperature effects	
Options for manual or remote monitoring	
Good accuracy achievable with cable lengths in excess of 1000 m.	

Specifications

Table 2.19 lists specifications for various vibrating wire crackmeters from selected vendors.

Table 2.19: Specifications for various vibrating wire crackmeters sensors from selected vendors

Vendor	Slope Indicator	Geokon	Soil Instruments Ltd
Model Number	**VW Crackmeter**	**4420**	**J2 VW Crackmeter**
Range (mm)	60 or 100	12.5, 25 or 50	30, 50 or 100
Accuracy %FS	+/- 0.1	+/- 0.1	+/- 0.1
Resolution mm	0.15	0.025% FS	0.025% FS

Vendor	Slope Indicator	Geokon	Soil Instruments Ltd
Model Number	**VW Crackmeter**	**4420**	**J2 VW Crackmeter**
Temperature range (°C)	-	–20 to 80	–20 to 80

Installation considerations

Setting distance

- The manufacturer's specifications will indicate a setting distance suitable for the chosen crackmeter. Upon installation of the crackmeter, the reading should be checked with a portable readout and the position should then be checked by comparing the readout with the manufacturer's specifications.

Protection

- In order to prevent mechanical damage to the crackmeter, cover plates should be installed over the top and be anchored to the surface using resin anchors or, in the case of steel structures, regular bolts. The cover plates are best made from sheet steel.

Suggested vendors

- Slope Indicator
- Geokon
- Soil Instruments Ltd.

2.6.5 Proximity Sensors

A proximity sensor is a sensor that can detect the presence of nearby objects without any physical contact. Primarily, proximity sensors function by emitting an electromagnetic field or a beam of electromagnetic radiation and then looking for changes in the field or return signal. The objects being sensed, often referred to as the proximity sensors target, may demand different types of sensors. For example, a capacitive sensor might be suitable for a plastic target compared with an inductive sensor that requires a metal target.

Proximity sensor types come in many types including but not limited to:

- capacitive displacement sensors
- eddy-current sensors
- laser triangulation
- inductive sensors (work on similar principles to LVDT)
- ultrasonic sensors.

Applications

- analogue detection of linear movement
- bearing shake and concentricity monitoring
- absolute distance measurement
- crack measurement.

Key features

Table 2.20 below summarises the benefits and limitations of proximity sensors.

Table 2.20: Proximity sensor attributes

Benefits	Limitations
Non-contact design protects the integrity of the sensor	Capacitive sensors are not suited for dirty or wet environments (eddy-current sensors are more suited)
Some inductive sensors are inherently immune to magnetic field interaction making them useful where electromagnetic noise is likely	Eddy-current, capacitive and inductive sensors are not suited for large gaps (>80 mm) between sensor and target
Ultrasonic sensors are suitable for targets in a solid, liquid, granular or powder state	
High positioning accuracy	
High sensing range	
No mechanical parts	

Specifications

Table 2.21 lists typical parameters for various proximity sensors.

Table 2.21: Operating parameters for various proximity sensor types

Sensor type	Capacitive displacement	Eddy-current	Laser triangulation	Inductive	Ultrasonic
Range (mm)	0.05–10	0.4–80	0.5–3 000	up to 630	50-6 000
Linearity %FS	0.2	0.2	0.2	0.2	+/- 1
Resolution (%FS)	0.03	0.005	0.05	0.03	0.1 mm

Selection criteria

General considerations specific to the selection of accelerometers for proximity sensors include:

- measurement range
- required resolution
- environment
- setting distance (between sensor and target).

Suggested vendors

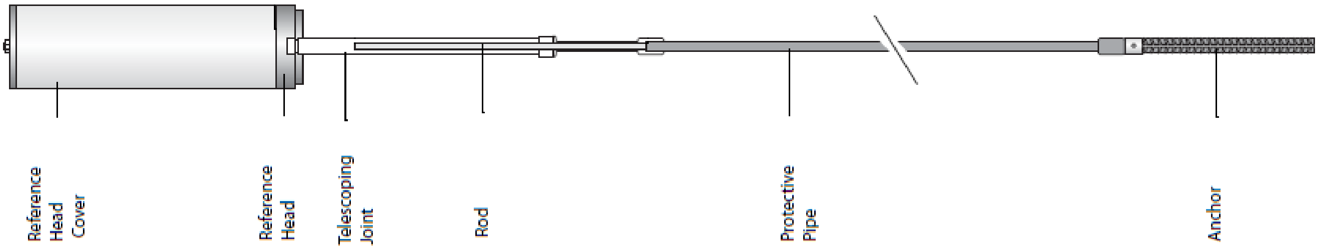
- SICK
- Contrinex
- Bestech
- Omron.

2.6.6 Rod Extensometers

Rod extensometers are relatively common instruments used to monitor small displacements in soil, rock and concrete along a single axis.

The rod extensometer comprises a reference head, anchors, rods and a protective sleeve (refer Figure 2.14). Typically rod extensometers are either single point (measures displacement between one fixed point and a reference point) or multipoint (uses multiple rods allowing measurements between several fixed points and the reference point).

Figure 2.14: Typical components of a rod extensometer



Source: *Rod Extensometer,* Slope Indicator, viewed on 15 January 2015, <http://www.slopeindicator.com/pdf/manuals/rod-extensometer.pdf>.

Displacement measurements between fixed point(s) and the reference point are taken at the head of the extensometer, either manually via micrometer gauge or electronically via a displacement sensor (typically vibrating wire or potentiometer).

Applications

Rod extensometers are particularly suited for the following SM applications:

- monitoring tunnel stability
- monitoring displacement of retaining structures
- monitoring subsidence
- monitoring settlement or heave in batters/embankments.

Key features

Table 2.22 below summarises the benefits and limitations of rod extensometers.

Table 2.22: Rod extensometer attributes

Benefits	Limitations
Efficient means for monitoring displacement along a single axis in boreholes	Limited range of movement (typically up to 10 mm or 150 mm)
Accurate and precise measurements	Displacement measurements are based on an assumed fixed point (the anchor at the base of the bore hole) and, if the anchor is not truly fixed, then measured displacements are relative, and not absolute values
Adjustable rods to suit project requirements	

Suggested vendors

- HMA Geotechnical.

2.6.7 Interferometric Radar

The IBIS-S system marketed by PCTE utilises microwave interferometric radar to remotely measure displacements of structure components at frequencies of up to 50 Hz. As for the iMETRUM system, the instrument can operate remotely (up to 1 km), with no contact/targets required on the area being monitored.

The system comprises a sensor module, a control PC and power supply. The sensor module is a coherent radar generator that transmits and receives the electromagnetic signals. The sensor module is installed on a tripod equipped with a rotating head, allowing the sensor to be orientated in the desired direction.

IDS Australasia have indicated a willingness to undertake trials of their IBIS-S system in order to demonstrate its effectiveness.

Applications

The IBIS-S system can be used to measure the following:

- position (displacement)
- vibration sampling
- static monitoring
- dynamic monitoring.

Key features

Table 2.23 below summarises the benefits and limitations of the IBIS-S system.

Table 2.23: IBIS-S attributes

Benefits	Limitations
Can be set up at a distance from the structure, with no disruption to traffic and a safer working environment	Requires an external trigger
Installation of targets/sensors on structure not required	Security of equipment for continuous monitoring application
Position (displacement) accuracy of 0.01 mm	Stability of equipment
Structure vibration sampling and analysis up to 200 Hz	
Operates day/night in all weather conditions	

Suggested vendors

- PCTE
- IDS Australiasia

2.6.8 iMETRUM

The iMETRUM system is described in detail in section 2.4.5.

2.7 Tilt and Rotation

Tiltmeters are used for measuring short-term and long-term rotation due to live loads, dead loads and, for concrete structures, creep and shrinkage-induced rotations as a result of prestress. Tiltmeters using different technologies are available including, but not limited to, the following:

- Electronic level (EL) tiltmeter
- Vibrating wire (VW) tiltmeter
- Micro-electro-mechanical sensor (MEMS) tiltmeter.

EL tiltmeters consist of an electrolytic tilt sensor housed in a compact, weatherproof enclosure. The tilt sensor is a precision bubble level that is sensed electronically as a resistance bridge. The bridge circuit outputs a voltage that is then correlated with an angular displacement.

VW tiltmeters work on similar principles to VW strain gauges and crackmeters in that an external movement changes the frequency of the internal vibrating wire. While at rest in a vertical configuration, a pendulous mass inside the sensor of the tiltmeter, under the force of gravity, attempts to swing beneath the elastic hinge on which it is supported but is restrained by the vibrating wire. As the tilt changes, the mass attempts to rotate beneath the hinge point and the tension in the vibrating wire changes, altering its vibrational frequency. This change in vibrational frequency is then correlated to an angular displacement.

MEMS tiltmeters are based on capacitive technology and have not traditionally been used in the monitoring of civil structures.

Applications

Tiltmeters are suitable for monitoring:

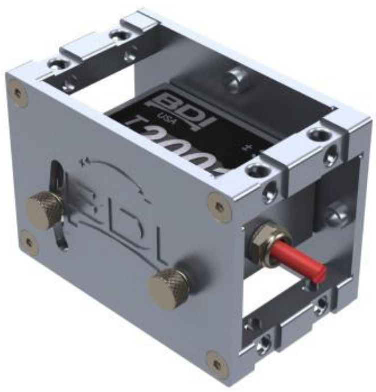
- stabilisation measures such as pressure grouting and underpinning
- structures for the effects of tunnelling and excavating (both as early warning of potential structural damage and for documenting the effects of nearby excavations)
- behaviour of structures under load
- deflection and deformation of retaining walls
- rotation of retaining walls, piers and piles
- convergence and other movements in tunnels.

Key features

Key features of tiltmeters include:

- high resolution capable of detecting changes in tilt as small as one second of an arc
- high accuracy and repeatability
- measurement ranges of ±0.5° to ±60° available
- robust and reliable due to no moving parts and a weatherproof enclosure
- easy to install due to versatile brackets and easy placement of the sensors
- reconfigurable to suit site requirements, e.g. a tiltmeter can be reconfigured to act as a beam sensor at a subsequent site
- cost-effective.

Figure 2.15: BDI tiltmeter



Source: BDI Bridge Diagnostics Inc. viewed on 12 May 2015, <http://bridgetest.com/products/bdi-tiltmeter/>.

Specifications

Table 2.24 below provides specifications of various tiltmeters from selected vendors.

Table 2.24: Specifications of various tiltmeters from selected vendors

Vendor	Slope Indicator	Geokon	Slope Indicator	RST Instruments	RST Instruments
Model Number	**EL Tilt Sensor 56802100**	**Model 6350 VW Tiltmeter**	**MEMS Tiltmeter 57803101**	**In-Place MEMS Tiltmeter (Analogue)**	**In-Place MEMS Tiltmeter (Digital)**
Range (°)	+/-0.67	+/-10	+/-10	+/-15	+/-15
Resolution (arc seconds)	1	8	9	+/-5	+/-2
Repeatability (arc seconds)	+/-3	-	+/-22	+/-12	+/-6
Accuracy (% FS)	-	+/-0.1	-	-	-
Adjustment range (°)	+/-4	-	+/-4	-	-

Selection criteria

Key selection criteria for tiltmeters will be the required measurement range and resolution. EL tiltmeters offer very high resolution but narrow-angle operating ranges (< +/- 1º). Wide-angle EL tiltmeters are available; however, resolution suffers (similar to VW and MEMS). VW and MEMS tiltmeters offer a much wider operating range, but lower resolution and lower repeatability.

While EL and VW tiltmeters are uniaxial, multiple units can be installed to allow biaxial monitoring.

All three technologies come in robust weatherproof casings suitable for mounting on structures.

Suggested vendors

- Geosense Ltd
- RST Instruments Ltd
- Slope Indicator
- Geokon.

2.8 Force/Load

The forces/loads applied to a structure can be measured directly using load cells or inferred through strains or other parameters measured using sensors discussed previously. Understanding the loads being applied to a structure is essential when trying to determine if the loads being applied are as expected or, in the case of load-restricted structures, if the structure is being subjected to greater (potentially damaging) loads. Direct measurement is achieved using load cells.

Load cells are available in many different configurations including, but not limited to:

- compression load cells
- S-beam load cells
- bending beam load cells
- canister load cells
- low-profile (pancake) load cells.

Load cell designs can be distinguished by the type of output signal generated (hydraulic, pneumatic or electric) and by the direction/type of loading (tension, compression, alternating tension and compression or bending). While hydraulic and pneumatic load cells are available, the increased accuracy, and lower unit cost and greater durability mean that strain gauge load cells lend themselves to monitoring applications.

Applications

Load cells are typically used for monitoring:

- anchored retaining walls
- strut loads
- rock bolts/soil nails
- on-board monitoring of vehicle loads
- weigh-in-motion systems.

Selection criteria

The choice of load cell will depend on the required application.

Compression load cells often have an integral button design and are ideal for mounting where space is restricted. They also offer long-term stability.

Tension load cells include S-beam load cells and canister tension cells.

Pancake load cells are suitable for both compression and tension applications.

Suggested vendors

- HBM Australia
- BDI
- ADM.

2.8.1 Weigh-in-motion Systems

Weigh-in-motion (WIM) systems estimate a moving vehicle’s gross weight and the portion of that weight that is carried by each wheel, axle, or axle group, or combination thereof, by measurement and analysis of its dynamic vehicle tire forces (ASTM 2009). WIM systems are placed in a static location and are not connected to any singular vehicle as is the case with on-board weighing systems.

There are two major types of WIM:

- low speed - WIM systems measuring vehicles at speed equal to or lower than 15 km/h
- high speed - WIM systems measuring vehicles at speeds above 15 km/h.

For highway structure monitoring applications, high speed types of WIM are adopted as they do not impact on road users.

The typical WIM system consists of four basic components (Austroads 2010):

- mass sensor
- vehicle classification and/or identification sensor
- processor and data storage unit

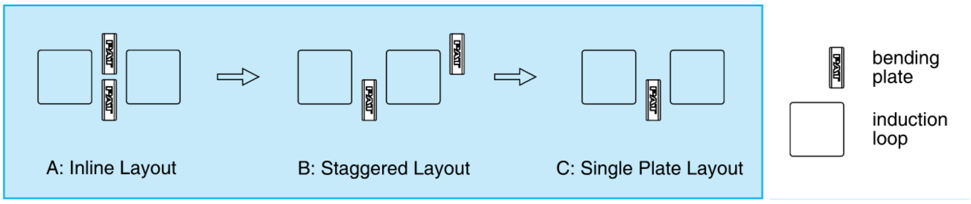
- user communication unit.

The mass sensor is the key component in the WIM system as it directly measures the dynamic axle weight. The vehicle classification/identification component of the system is used to identify the vehicle type and, where appropriate, take a photo of the vehicle. The processor, data storage and communication unit are used in the management of the information generated by the sensor and identification component.

There are four main types of mass sensor mechanisms used in Australia as identified by Austroads (2010): bending plate technology, capacitance pad, strain gauging existing structures and piezoelectric cabling. The accuracy of all sensor devices was documented as ±10% of gross vehicle mass to a 95% confidence level.

Bending plate technology utilises a plate with strain gauges bonded to the underside to measure induced strain from dynamic wheel actions. The system is installed perpendicular to the direction of travel with induction loops upstream and downstream to identify when vehicles are approaching the plates, which is common to most permanent high-speed WIM systems. The system can be installed in multiple configurations as shown in Figure 2.16.

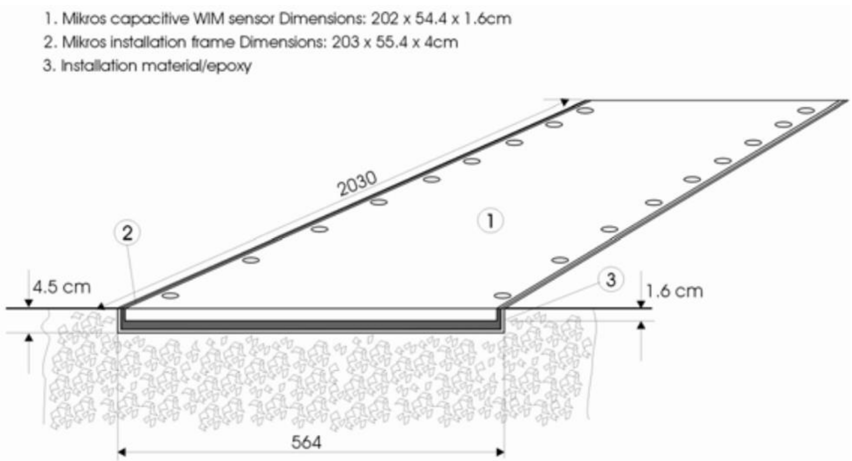
Figure 2.16: Example of installation configurations for bending plate WIM technology



Source: IRD (2010)

Capacitance pads (mats) consist of two metal sheets separated by a dielectric material (Austroads 2010). The two metal sheets have a voltage applied between them and, when unloaded, are separated by a known distance. When dynamic wheel actions are applied to the top pad, the deflection of the pad results in a change in the circuit created by the voltage applied, which can be measured (the capacitance). A view of the capacitance pads installation plans can be seen in Figure 2.17.

Figure 2.17: Illustration of installed capacitance sensor for WIM purposes

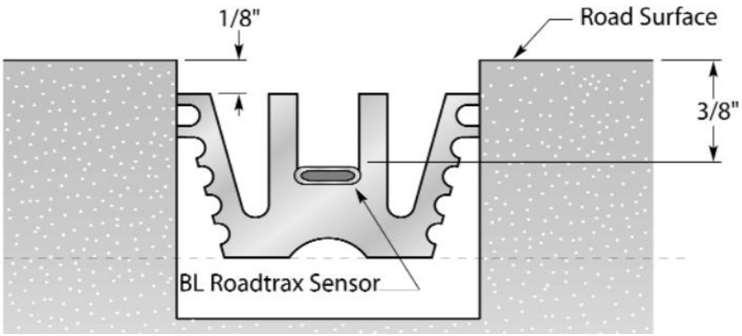


Source: Mikros Systems (2008)

Piezoelectric WIM systems utilise piezo technology to convert the force applied by dynamic wheel actions into a change in voltage, which reflects the magnitude of the action applied (FHWA 2007).

The system may or may not be encapsulated in an epoxy-filled metal channel. The installed device is typically no wider than 50 mm, measured along the roadway and flush with the roadway surface as illustrated in Figure 2.18.

Figure 2.18: Cross section of RoadTrax BL piezoelectric WIM sensor



Note: Dimensions in inches.

Source: RoadTrax BL (2010).

Strain gauging of existing structures is a method to create a high-speed WIM site where an existing structure allows. A common example of this in the Australian context is Culway, a system designed by MRWA that uses strain gauges fitted to the underside of an existing culvert. Ideal culvert sizes are between 1.2 m and 1.5 m, which allows isolation of a singular axle. This system is also in use in Queensland.

The output from sensors is not just a function of the type of sensor and correct installation of the instrument, but also a function of the site conditions at the installation location. Consideration for horizontal and longitudinal alignment, cross slope, lane width and surface smoothness can all affect the quality of the results. The ASTM standard's performance criterion requires that minimum standards be achieved for these variables in order to ensure appropriate quality of the outputs. These criteria will assist in improving the accuracy of the static axle load measurement derived from the dynamic axle load measurement from the sensor.

The main factors affecting the accuracy of the WIM system are (Austroads 2010):

- pavement quality, specifically evenness, error up to 100%
- vehicle condition, specifically tyres and suspension, error up to 30%
- driver behaviour, specifically braking and accelerating, error up to 50%
- equipment used, errors up to 2%.

These main factors are addressed in the calibration period specific to the sensor, system used and correct site selection. An important component to ensure the ongoing integrity of the data produced from the WIM system is the regular and planned inspection of the site to ensure defects affecting accuracy are known, accounted for and repaired.

One of the key potential uses of the WIM technology in bridge asset management is using the actual recorded vehicle numbers and axle masses to develop a traffic profile of the road network in a given area. Furthermore, this can be used at a specific site to identify the load envelope for the structure, which can be compared to the loads used in design and assessment of the structure. This usage may be further extended to the fatigue assessment of structures to identify how many loading cycles have occurred during the measurement period.

Data captured at specific sites can be used to develop site-specific probabilistic loading models to use in bridge assessments/rating.

2.9 Temperature

Cycles of heating and cooling can cause damage to structures through repeated cycles of deformation or thermally-induced loads. Including temperature measurement in a SM application can assist with understanding how temperature changes influence a structure. Furthermore, some sensors are sensitive to temperature changes and, where internal temperature compensation is not provided, it is necessary to monitor temperature to account for its effect.

When monitoring temperature, either the surface (or internal) temperature of a component or the ambient temperature is measured. For understanding the influence of thermally induced stresses and deformations, the surface temperature of components is of interest as the components own thermal mass is such that the temperature gradients will not directly follow the ambient temperature.

Sensor types most commonly used for temperature measurement include:

- thermocouples
- resistance temperature detectors (RTD)
- thermistors
- fibre optic (Fibre Bragg Grating).

Applications

As noted above, temperature sensors are used for monitoring:

- ambient temperatures (for compensation of temperature-sensitive sensors or for operational/event indication)
- temperature of structural components where thermal induced effects are of interest.

Selection criteria

Most sensors based on the above technologies will have operating ranges far in excess of that typically required for structure monitoring applications and selection should rather be based on accuracy, repeatability, durability and other relevant performance characteristics.

Thermocouples are the most commonly used temperature sensors because they are relatively inexpensive yet accurate sensors that can operate over a wide range of temperatures. A thermocouple is created by the junction of two dissimilar metals, which produces a small open-circuit voltage that varies as a function of temperature. Thermocouples are inexpensive and have a response time of fractions of a second (not particularly relevant for structure monitoring applications). They are not suitable for use where very small temperature differences need to be measured with the highest accuracy.

RTD’s rely on the principle that the electrical resistance of a metal varies as a function of temperature increases (thermal resistivity). RTDs are popular because of their excellent stability, very linear output, and high accuracy particularly over a wide temperature range; however, they are also generally more expensive than alternative sensors.

Thermistors are semiconductor devices that also rely on the principle that electrical resistance of a material varies with temperature. Thermistors are inexpensive, have fast response times and also demonstrate high accuracy and stability.

Fibre optic sensors use the changes in wavelength of reflected light as a result of expansion and contraction of the FBG sensor to measure temperature. Fibre optic sensors offer the advantages over electrical systems as previously noted. They are immune to electromagnetic interference and allow distributed sensing.

Suggested vendors

- BDI
- Campbell Scientific
- National Instruments.

2.10 Vehicle Detection

As discussed previously, for continuous monitoring applications, thresholds should be set to reduce the data storage requirements and post-processing time. In many instances, the passage of a vehicle across a predetermined point will be the appropriate trigger to commence instrumentation recording. The following is a very brief summary of vehicle detection technologies (FHWA 2007):

Sensors used for vehicle detection and surveillance typically comprise the following three components:

- transducer – detects passage of a vehicle or its axles
- signal processing module – converts transducer output into electrical signal
- data processing module – converts signal into required parameters, e.g. vehicle presence, count, speed, type, etc.

2.10.1 In-roadway Sensors

In-roadway sensors are either:

- embedded in the pavement of the roadway
- embedded in the subgrade of the roadway
- taped or otherwise attached to the surface of the roadway.

Examples of in-roadway sensors include:

- inductive loop detectors – require saw cuts in the pavement
- weigh-in-motion sensors – embedded in the pavement
- magnetometers – embedded or placed beneath a paved roadway or bridge structure
- tape switches, microloops, pneumatic road tubes or piezoelectric cables – mounted on the roadway surface.

All of the above sensor types have been in use for many years and are well understood.

The main disadvantage with in-roadway sensors include traffic disruption (installation and repair), failures associated with installations in poor road surfaces and poor installation methods. Resurfacing and utility repairs can also result in a need to reinstall these sensors.

2.10.2 Over-roadway Sensors

Over-roadway sensors are mounted above the surface of the roadway either:

- above the roadway
- alongside the roadway, offset from the nearest traffic lane by some distance.

Examples of over-roadway sensors are:

- video image processors – video cameras mounted on poles adjacent to the roadway, on structures that span the roadway, or on traffic signal mast arms over the roadway

- microwave radar sensors – mounted adjacent to the roadway or over the lanes to be monitored
- ultrasonic, passive infra-red or laser radar sensors – typically mounted over the lanes to be monitored (some passive infra-red models can be mounted adjacent to the roadway)
- passive acoustic sensors – mounted adjacent to the roadway.

In addition, some emerging applications for wide area surveillance envision over-roadway sensors mounted on tall buildings and radio towers near the roadway and on aerial platforms.

2.10.3 Comparison of Technologies

Table 2.25 compares the strengths and weaknesses of the sensor technologies that will be discussed in the following chapters with respect to installation, parameters measured, performance in inclement weather and variable lighting conditions, and suitability for wireless operation.

Most over-roadway sensors are compact and not roadway invasive, making installation and maintenance relatively easy. Some installation and maintenance applications may require the closing of the roadway to normal traffic to ensure the safety of the installer and motorists. All the sensors discussed operate under day and night conditions, although video-image processors may show improved performance at night when some street lighting is available.

Table 2.25: Comparison of vehicle detection technologies

Sensor type	Advantages	Disadvantages
Pneumatic road tube	▪ Quick installation ▪ Low power usage ▪ Low-cost ▪ Simple maintenance	▪ Inaccurate axle counting when truck/bus volumes are high ▪ Sensitive to temperature ▪ Prone to damage/vandalism
Inductive loop	▪ Flexible design to satisfy large variety of applications ▪ Mature, well understood technology ▪ Large experience base ▪ Provides basic traffic parameters (e.g. volume, presence, occupancy, speed, headway, and gap) ▪ Insensitive to inclement weather such as rain and fog ▪ Provides best accuracy for count data as compared with other commonly used techniques ▪ Common standard for obtaining accurate occupancy measurements ▪ High-frequency excitation models provide classification data	▪ Installation requires pavement cut ▪ Decreases pavement life ▪ Installation and maintenance require lane closure ▪ Wire loops subject to stresses of traffic and temperature ▪ Multiple detectors usually required to monitor a location ▪ Detection accuracy may decrease when design requires detection of a large variety of vehicle classes
Magnetometer (two-axis fluxgate magnetometer)	▪ Less susceptible than loops to stresses of traffic ▪ Insensitive to inclement weather such as rain and fog ▪ Some models transmit data over wireless RF link	▪ Installation requires pavement cut ▪ Decreases pavement life ▪ Installation and maintenance require lane closure ▪ Models with small detection zones require multiple units for full lane detection
Magnetic (induction or search coil magnetometer)	▪ Can be used where loops are not feasible (e.g. bridge decks) ▪ Some models are installed under roadway without need for pavement cuts; however, boring under roadway is required ▪ Insensitive to inclement weather such as rain and fog ▪ Less susceptible than loops to stresses of traffic	▪ Installation requires pavement cut or boring under roadway ▪ Cannot detect stopped vehicles unless special sensor layouts and signal-processing software are used

Sensor type	Advantages	Disadvantages
Microwave radar	▪ Typically insensitive to inclement weather at the relatively short ranges encountered in traffic management applications ▪ Direct measurement of speed ▪ Multiple-lane operation available	▪ CW Doppler sensors cannot detect stopped vehicles
Active infrared (laser radar)	▪ Transmits multiple beams for accurate measurement of vehicle position, speed, and class ▪ Multiple-lane operation available	▪ Operation may be affected by fog when visibility is less than 6 m ▪ Installation and maintenance, including periodic lens cleaning, require lane closure
Passive infra-red	▪ Multizone passive sensors measure speed	▪ May have reduced sensitivity to vehicles in heavy rain and dense fog ▪ Some models not recommended for presence detection
Ultrasonic	▪ Multiple-lane operation available ▪ Capable of overheight vehicle detection ▪ Large Japanese experience base	▪ Environmental conditions such as temperature change and extreme air turbulence can affect performance; temperature compensation is built into some models ▪ Large pulse repetition periods may degrade occupancy measurement on freeways with vehicles traveling at moderate to high speeds
Acoustic	▪ Passive detection ▪ Insensitive to precipitation ▪ Multiple-lane operation available in some models	▪ Cold temperatures may affect vehicle count accuracy ▪ Specific models are not recommended with slow-moving vehicles in stop-and-go traffic
Video image processor	▪ Monitors multiple lanes and multiple detection zones/lane ▪ Easy to add and modify detection zones ▪ Rich array of data available ▪ Provides wide-area detection when information gathered at one camera location can be linked to another	▪ Installation and maintenance, including periodic lens cleaning, require lane closure when camera is mounted over roadway (lane closure may not be required when camera is mounted at side of roadway) ▪ Performance affected by: inclement weather (such as fog and rain) vehicle shadows sun glint vehicle projection into adjacent lanes occlusion day-to-night transition vehicle/road contrast dirt on camera lens ▪ Requires 9-15 m camera mounting height (in a side-mounting configuration) for optimum presence detection and speed measurement ▪ Some models susceptible to camera motion caused by strong winds or vibration of camera mounting structure ▪ Generally cost-effective when many detection zones within the field of view of the camera or specialized data are required ▪ Reliable night-time signal actuation requires street lighting

Source: FHWA (2007)

Table 2.26 lists the parameters typically available from each sensor type. Several sensor types are capable of supporting multiple lane, multiple detection zone applications with one or a limited number of units. These devices may be cost-effective when larger numbers of detection zones are needed to implement the traffic management strategy.

Table 2.26: Comparison of parameters captured from vehicle detection technologies

Sensor type	Parameter					
	Count	Presence	Speed	Occupancy	Vehicle classification	Multiple lane/zone data
Pneumatic road tube	Yes	Yes	Yes [1]	No	Yes	No
Inductive Loop	Yes	Yes	Yes [1]	Yes	Yes [2]	No
Magnetometer (Two-axis fluxgate magnetometer)	Yes	Yes	Yes [1]	Yes	No	No
Magnetic (Induction or search coil magnetometer)	Yes	Yes [3]	Yes [1]	Yes	No	No
Microwave Radar	Yes	Yes [4]	Yes	Yes [4]	Yes [4]	Yes [4]
Active Infrared (Laser radar)	Yes	Yes	Yes [5]	Yes	Yes	Yes
Passive Infrared	Yes	Yes	Yes [5]	Yes	No	No
Ultrasonic	Yes	Yes	No	Yes	No	No
Acoustic	Yes	Yes	Yes	Yes	No	Yes [6]
Video Image Processor	Yes	Yes	Yes	Yes	Yes	Yes

Notes:

[1] Speed can be measured by using two sensors a known distance apart or estimated from one sensor and the effective detection zone and vehicle lengths

[2] With specialised electronics unit containing embedded firmware that classifies vehicles

[3] With special sensor layouts and signal-processing software

[4] With microwave radar sensors that transmit the proper waveform and have appropriate signal processing

[5] With multi-detection zone passive or active mode infra-red sensors

[6] With models that contain appropriate beamforming and signal processing

Source: FHWA (2007)

2.11 Acoustic Emission

Acoustic emissions (AE) monitoring is the use of a highly sensitive listening device to detect elastic wave propagation in a material caused by changes in the material, typically cracking. The elastic waves are created from the release of stored strain energy which is consumed by nucleating new cracks (Ohtsu 2008). The elastic wave is detected by the AE sensor as illustrated in Figure 2.19.

Bohse (2013) identified the fundamental characteristics of the AE method are:

- passive detection system that monitors the dynamic response
- allows detection of active sources and degradation only
- allows global monitoring of the whole structure and is capable of locating a growing defect in the structure under test with sufficient number of sensors
- offers a dynamic real-time monitoring of any discontinuity that grows under the applied stress.

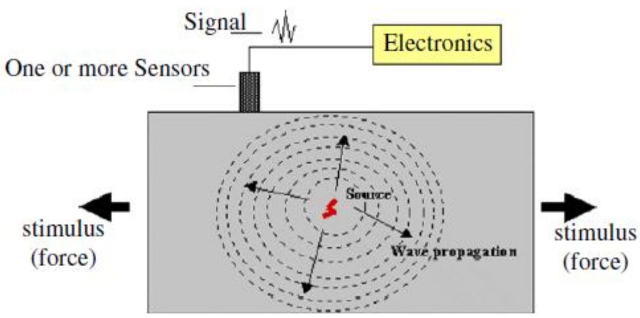
AE monitoring can be either global (useful for assessing an entire structure's integrity) or local (to address an area of specific concern). In this instance, local monitoring would be the appropriate approach.

Interpretation of AE signals is fundamental to the application of AE monitoring as, without a thorough understanding of wave modes and how they propagate through various materials/components, locating the source of an emission accurately becomes very difficult. In addition, it is essential to understand other factors affecting the AE such as background noise, sensor sensitivity and the materials being monitored.

While source detection and location algorithms are continually improving, standardised methodologies are still not available for practical application to most structures and, for real-time applications in particular, extensive calibration testing is required along with experienced personnel to interpret the results (Nair & Cai 2010)Importantly AE monitoring can only detect defects if they occur (initiate or propagate) during the monitoring process. AE monitoring technology cannot retrospectively identify defects that have occurred but are inactive during the monitoring period.

The sensor that detects the elastic waves contains a piezoelectric transducer that converts the energy form the wave into an electric response. The information that comes from the sensor is then amplified, conditioned, filtered and assessed for AE signal features. These signal features can be used to locate the original of the AE signal.

Figure 2.19: Acoustic emission detection of a crack propagating



Source: Nair A. & Cai C. 2010

The technology has been developed alongside techniques which allow for the inspection of concrete structures. Research has identified valuable relationships that can assist in the interpretation of AE results. Rossi et al (1994) noted in their research that into creep of concrete using AE that there is a strong correlation between the basic creep of concrete and the creation of micro cracks in the material, which were recorded as AE events. Ohtsu (2008b) observed that the variation in amplitude distribution under cycling loading may indicate the degree of fatigue that has occurred in the concrete.

Whilst AE is typically used for monitoring, a damage assessment model has been developed and standardised (NDIS 2421:2000). The assessment models is based on two core observations, that AE activity is very low in a stable structure and that stable structures AE activity is rarely observed during the unloading process.

Given that AE is not specific to a material type the monitoring for AE may offer value for timber structures. A wide range of research is being performed in the area and is well documented by Landis (2008). Much of the research focuses on mechanical failure mechanisms and AE relationships and exploring the properties of timber and AE behaviour, especially moisture content.

Applications

- monitoring of fracture critical steel components and connections
- possible monitoring applications for timber structures

- crack initiation and growth
- damage assessment.

Suggested vendors

- ALS Global
- Advanced Technology Testing and Research (ATTAR)
- Physical Acoustics

3 LOAD TESTING AND MONITORING

3.1 Introduction

Load testing is an effective method of evaluating the performance and structural capacity of a highway structure. Where actual structural actions (strains, deflections, etc.) are measured to accurately determine the response of the bridge and its components to the applied loads, the results can be taken into consideration in the determination of the rating of the bridge. The results of load testing, however, can only be applied to structures of similar form, taking into consideration material properties and conditions (AS 5100.7-2004).

Load testing involves static or dynamic load testing, or a combination of both, depending on the testing purpose. Dynamic load testing may be used to provide information on the vehicles using a bridge, as well as information on the performance of the structure.

Various structural components can be examined during a load testing exercise under known loads using various sensors, instruments and the data acquisition system discussed in Section 2. The sensors and instruments are installed at predetermined locations of critical components to confirm characteristic performance as predicted by theoretical analysis, in accordance with a predefined instrumentation plan. Loads are then applied on the structure to create load effects. Test data will be recorded by the data acquisition system and later processed to obtain information/data of interest.

3.2 Static Load Tests

3.2.1 Applications

Static load tests involve placing static loads (vehicles, known weights, etc.) on the structure components and measuring the structural behaviour of the components in question. These tests include performance and proof load tests (see Section 1.5.1) for virtually all types of structure (such as simply supported, continuous, beam-and-slab bridges and major culverts) and materials (such as concrete, timber, steel, and composite). The applications of these static load tests are specified in AS 5100.7-2004 as follows:

Static performance load testing

Static performance load testing is a serviceability limit state test. Static performance load testing involves monitoring a structure using normal loaded road or railway traffic, or specific vehicles loaded to predetermined weights to determine specific responses (such as vertical and horizontal forces, deflection and strains) to assist in assessing load distribution, to identify weak or failed components and to understand the structural performance. Static performance load testing may also be repeated over time to monitor degradation of structural performance and assist in detecting defective components, particularly for complex redundant structures.

Static proof load testing

Static proof load testing involves monitoring a structure while progressively loading it to induce stresses approaching the elastic limit at one or more critical locations. This form of testing is usually undertaken with vehicles loaded beyond legal limits. This approach makes it possible to load the structure at multiple locations longitudinally and transversely with a pattern similar to regular traffic loading.

The proof load on a bridge is the maximum load that can be applied to the structure without inducing nonlinear behaviour. Theoretical analyses are used to estimate the proof load and this value is known as the target proof load. The bridge is carefully and incrementally loaded to a predetermined target proof load or until the bridge approaches its elastic limit, whichever occurs first. The effects of these loads on critical members of the bridge is measured by gauging these members and monitoring them in real time, to ensure that the structure is still acting in a linearly elastic manner at all stages of loading. The bridge foundations are gauged to monitor movements during testing and the magnitude of permanent set, if any, of these foundations.

3.2.2 Test Outputs

The processed data that can be obtained from static load tests include strains, deflections, relative movements, crack width, etc. Interpretation of these data can provide the following information:

- deformations, displacements, rotations, relative deformations and force values (strains, stresses, axial forces, bending moments)
- stiffness of components, as well as the load distribution between components
- effects of a component with repair/damage, etc. on other components and general behaviour of the bridge
- load-carrying capacity of a bridge including flexural bending capacity, shear capacity, axial capacity of individual components
- load rating
- relative movements
- evidence of torsion
- crack opening/development.

3.2.3 Likely Test Duration

A static load test is usually a one-off event or may be periodically repeated to monitor deterioration.

3.2.4 Test Vehicles/Load Application

Various methods for load application for static load testing of bridges include test vehicles, known weights, load frames, etc. A good loading system applicable to various types of static load testing should preferably have the following characteristics (ISIS 2001):

- It should be representative of actual vehicular loads on the bridge.
- It should be easy to manoeuvre so that it can be brought on and off a bridge quickly.
- It should be easily transportable.
- Its load should be adjustable so that it can be increased or decreased conveniently.
- After it has been placed on the bridge, its weight distribution should be repeatable and capable of quick stabilisation.
- For proof testing, it should be capable of being moved by remote control as well as manually.

Test vehicles

Designated test vehicles with known loads are most commonly used in performance and proof load tests. Test vehicles are selected depending on the purpose of the test and route types. For example, for a B-double and Road Train route, test vehicles may include heavy cranes, high mass limit (HML) semi-trailers, and HML road trains. Factors that should be taken into consideration when selecting test vehicles include vehicle type, axle spacing, axle mass, and suspension type, etc. Vehicle mass can be obtained by gravel, dump trucks, tipper trucks, water tanks, metal blocks, etc. It is important to obtain weighbridge certificates for the test vehicles including detailed axle masses and axle spacing.

Known weights

Known weights such as water tanks, concrete blocks, load frame and ground anchors can be used for static load tests.

Load limit and load application

For performance load tests, the test loads are usually kept at or below the maximum service loads or the legally permitted maximum loads. For proof load tests, in order to protect the bridge and the testing personnel, AS 5100.7-2004 specifies that the test loadings shall be applied incrementally from a base load of 50% of the theoretical ultimate capacity, and load responses shall be continuously monitored to ensure that the bridge is behaving in an elastic manner. Testing shall be terminated when nonlinear behaviour is observed.

For static load testing of bridges, depending on the test purpose, the test vehicles can be positioned on the bridge in transverse and longitudinal direction in accordance with relevant TMR guidelines, such as *Heavy Load Assessment project brief* (TMR 2011).

3.2.5 Triggers/Limitations

Limits on measured data should be determined theoretically, and should be monitored during the load tests to ensure all bridge components are within the elastic range at all times.

3.3 Dynamic Load Tests

3.3.1 Applications

Dynamic load tests involve applying impact loads (running vehicles, hammers, etc.) to the structure and measuring the structural response of critical components. The dynamic response of the structure depends upon a combination of many factors including vehicle speed, mass, configuration, suspension type and condition, the road or rail profile on the structure and approaches, in addition to the structure type, configuration and existing condition.

It should be noted that modal impact testing is a form of dynamic load test that provides information on natural frequencies, modal shape and damping, etc. of the structure.

Dynamic load tests can be conducted for:

- all bridge materials and types (concrete, timber, steel beam-and-slab, simply supported, continuous)
- cable-stayed and suspension bridges
- monitoring vibrations/dynamic movements in superstructure and substructure.

3.3.2 Test Outputs

Determination of the following from test output:

- all of those from 3.2.2
- dynamic performance of the bridge
- fundamental frequency, damping characteristics, dynamic modulus, and other dynamic materials characteristics (modal analysis)
- vibration and movements of structural elements (multi-directional, individual and relative)
- quantification of dynamic amplification of loads
- wind loading.

3.3.3 Likely Test Duration

Depending on the purpose, dynamic load testing can be one-off or periodic.

3.3.4 Vehicles/Load Application

Designated (i.e. known loads) test vehicles (usually the same test vehicles used for the static performance load test) are used for dynamic load tests; but with dynamic effects, i.e. test vehicles traverse the bridge at critical transverse locations at various speeds ranging from a crawling speed (approximately 5 km/h) to the speed limit. Speed bumps are used in some cases to increase the dynamic effects.

Ambient traffic, i.e. random vehicles traversing the bridge at random speeds, can also be used for dynamic load tests to investigate the bridge's dynamic response under the service condition.

For impact instrumentation (for modal analysis), forced impacts can be applied by, for example, a 6 kg hammer (as used in the load testing of Canal Creek Bridge).

3.3.5 Triggers/Limitations

For dynamic load tests using test vehicles, the limits of measured data should be determined in the same way as for the static load tests, which can be theoretically determined. These limits should be monitored during the load testing.

Sampling rates should also be determined for dynamic load tests. Typically 200-250 Hz is the desired sampling rate.

3.4 Continuous Monitoring

3.4.1 Applications

Continuous monitoring can be used in various circumstances for all bridge materials and types (concrete, timber, steel beam-and-slab, simply supported, continuous). It involves the following:

- monitoring through ambient vibrations - the health of a structure can be diagnosed based on the changes in dynamic characteristics of the structure such as natural frequencies, and modal shapes, etc. Vibration-based damage detection techniques can be used based on monitoring data
- monitoring through testing under random traffic
- monitoring of crack growth.

3.4.2 Test Outputs

Determination of the following from test output:

- all of those from 3.2.2
- dynamic performance of the bridge
- fundamental frequency, damping characteristics, dynamic modulus, and other dynamic materials characteristics (modal analysis)
- vibration and movements of structural elements (multi-directional, individual and relative)
- quantification of dynamic amplification of loads
- wind loading.

3.4.3 Likely Test Duration

Depending on the purpose, continuous monitoring may range from several days to months, with the data acquisition system staying on site during the monitoring period. It also possible to install a permanent monitoring system to monitor the structure during its service life.

3.4.4 Vehicles/Load Application

Continuous monitoring usually involves in-service conditions such as ambient traffic (i.e. random vehicles traversing the bridge at random speeds), and other external loadings such as floods, water current, wind.

3.4.5 Triggers/Limitations

For continuous monitoring of the structure under ambient traffic, thresholds should be set to reduce the data storage requirements and post-processing time. Any event causing a measured value lower than the threshold will not be recorded.

The data acquisition system should be able to automatically start/stop recording.

For example:

- passage of vehicle trigger to commence instrumentation recording
- load limit event to trigger recording (for ambient traffic conditions, continuous monitoring).

3.5 Post-processing and Data Manipulation

3.5.1 Post-processing and Interpretation

The following should be taken into account for the post-processing of test data:

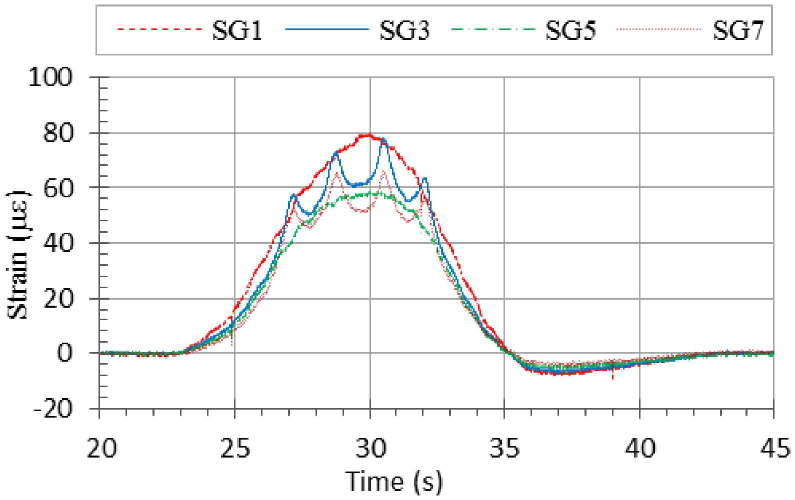
- TMR output requirements
- filtering of data required to predetermined limits, removal of data noise, extraneous data
- calculation/conversion of data (i.e. load distribution, dynamic increment, bending capacity)
- presentation of data using waveforms, histogram plots, and scatter plots.

The most common types of data presentation and interpretation are described below.

Waveforms

Waveforms are excellent graphical presentations of test data. Important information can be extracted from waveforms including peak values, critical positions of test loads, and response frequencies. Figure 3.1 shows an example of the waveforms of the strains at four different locations recorded when a test vehicle traverses the test bridge. The maximum strain incurred in this test is 80 $\mu\varepsilon$.

Figure 3.1: Sample waveform of measured strains

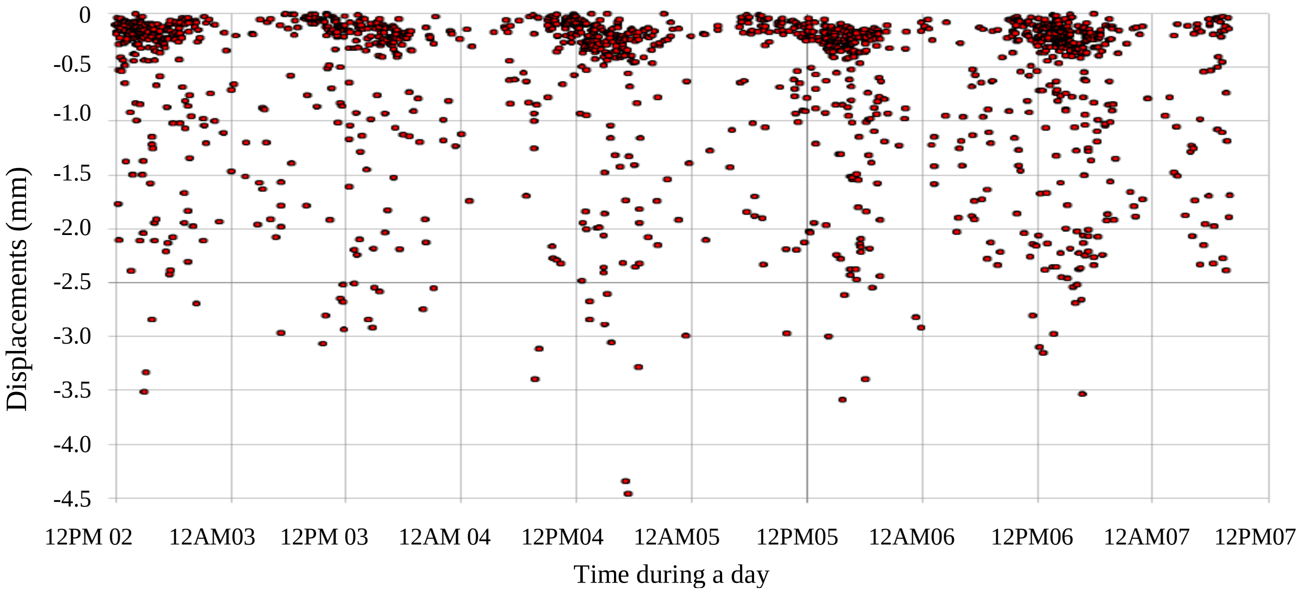


Source: TMR 2015, *BIS 7703 Canal Creek Bridge: Load Test and In-service Monitoring* (Contract report for TMR)

Scatter plots

Scatter plots can be used to determine the number of events that induced the measurement values exceeding certain limits. Figure 3.2 shows an example of the scatter plot of the displacement recorded at one location during a day of monitoring under random traffic. There are a couple of events causing a displacement exceeding 4 mm.

Figure 3.2: Sample scatter plot

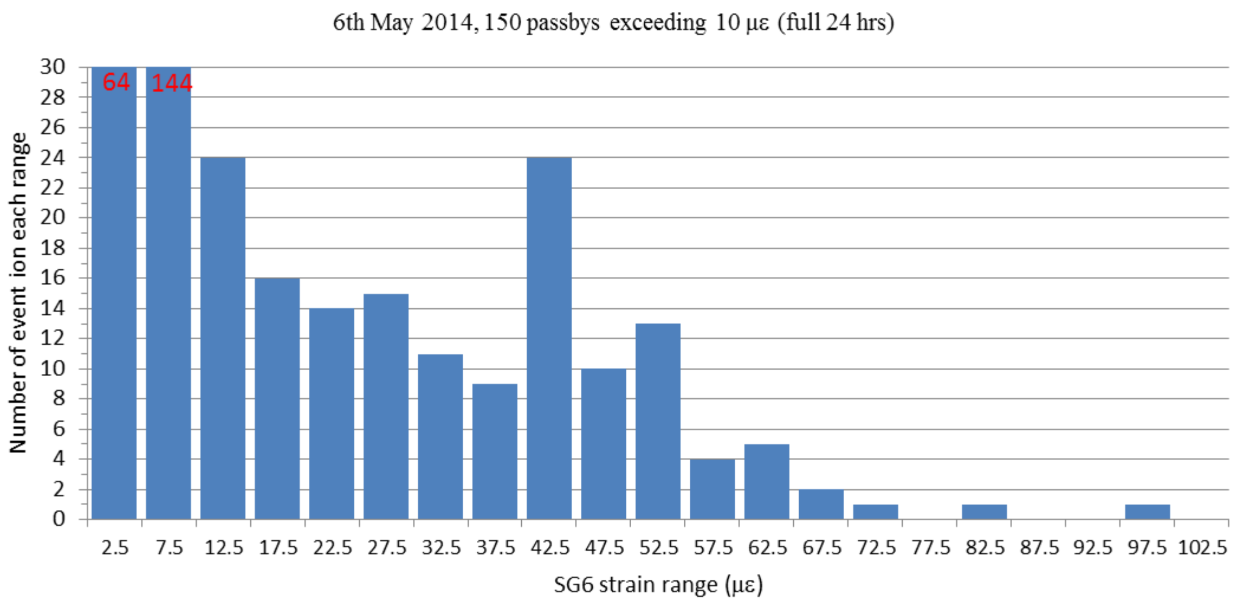


Source: TMR 2015, *BIS 7703 Canal Creek Bridge: Load Test and In-service Monitoring* (Contract report for TMR)

Histogram plots

Histogram plots are useful, especially for continuous monitoring. The graphs present the number of events against the measurement values in which the measurement values are binned into predefined lots. For example, 5 $\mu\varepsilon$ lots can be used to display the number of events that induce strains in different ranges. It can be derived from Figure 3.3 that 150 events induced a strain value exceeding 10 $\mu\varepsilon$.

Figure 3.3: Sample histogram plot



Source: TMR 2015, *BIS 7703 Canal Creek Bridge: Load Test and In-service Monitoring* (Contract report for TMR)

3.5.2 Data Storage and Transmission Requirements

- Anticipated quantity of data required for storage (100GB, 20TB, multiple servers, etc.) is dependent on post-processing, presence of triggers, number of sensors

3.6 Sample Projects

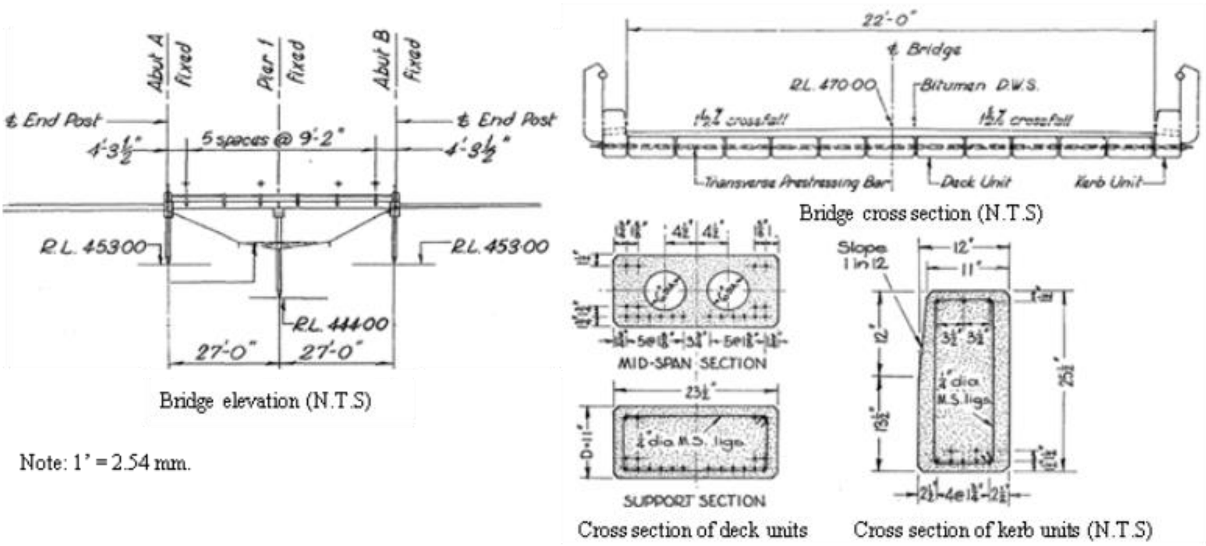
3.6.1 Canal Creek Bridge

Description

Canal Creek Bridge on Flinders Highway, Queensland, was selected for field load testings and health monitoring over a period of time under controlled and in-service traffic. The bridge comprises precast prestressed deck units featuring transverse post-tensioned tendons and stiff upright kerb units that also act as bridge kerbs. This bridge is representative of the typical short span deck unit type structures and also represents a family of deck unit bridges on the Flinders Highway which is a key freight route and subject to permit restrictions. With a carriageway width of 6.7 m, the bridge has two 27' (8.23 m) spans comprising 13 precast, prestressed concrete deck units transversely post-tensioned. Both abutments and the central pier comprise a cast-in situ concrete headstock and four driven precast concrete piles (Figure 3.4).

The testing program includes an impact modal test, static and dynamic load testing under known vehicle loads, and continuous monitoring under random traffic for a week. These tests provide inputs to the research projects for studying the dynamic response of the bridge under vehicle impacts and calibrating computer models used in the assessment of this bridge type.

Figure 3.4: Bridge profile and beams cross-sections



Source: TMR drawing plan no. 98570 and standard drawing No. S926.

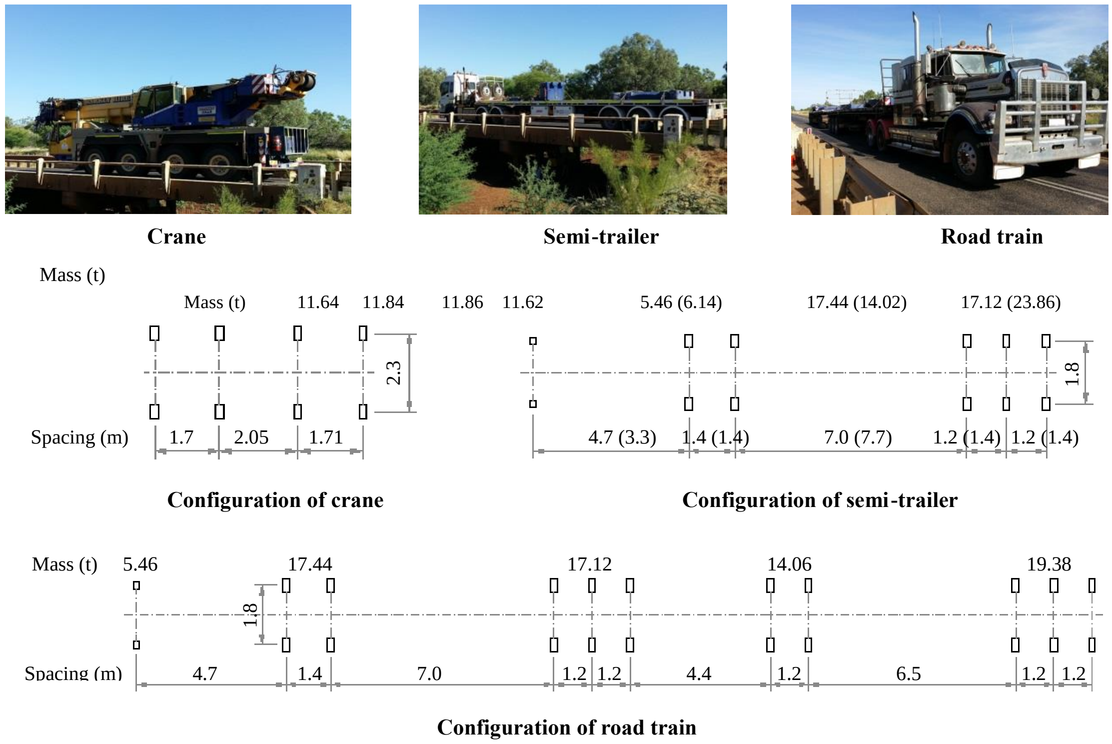
Test vehicles

Four test vehicles were selected for the controlled load test, including:

- a 4-axle 48 t all-terrain pneumatic crane (CR)
- a steel-leaf suspension articulated general mass limit (GML) semi-trailer of 1-2-3 axle configuration (ST1)
- an air-bag suspension articulated high mass limit (HML) semi-trailer of 1-2-3 axle configuration (ST2)
- a steel-leaf suspension GML road train with two trailers (RT).

The details of each vehicle are shown in Figure 3.5. Minor differences in actual measured mass and dimensions were encountered; however, these differences were inconsequential.

Figure 3.5: Test vehicles



Note: the numbers in parenthesis () are used for the semi-trailer ST2 (air-suspension).

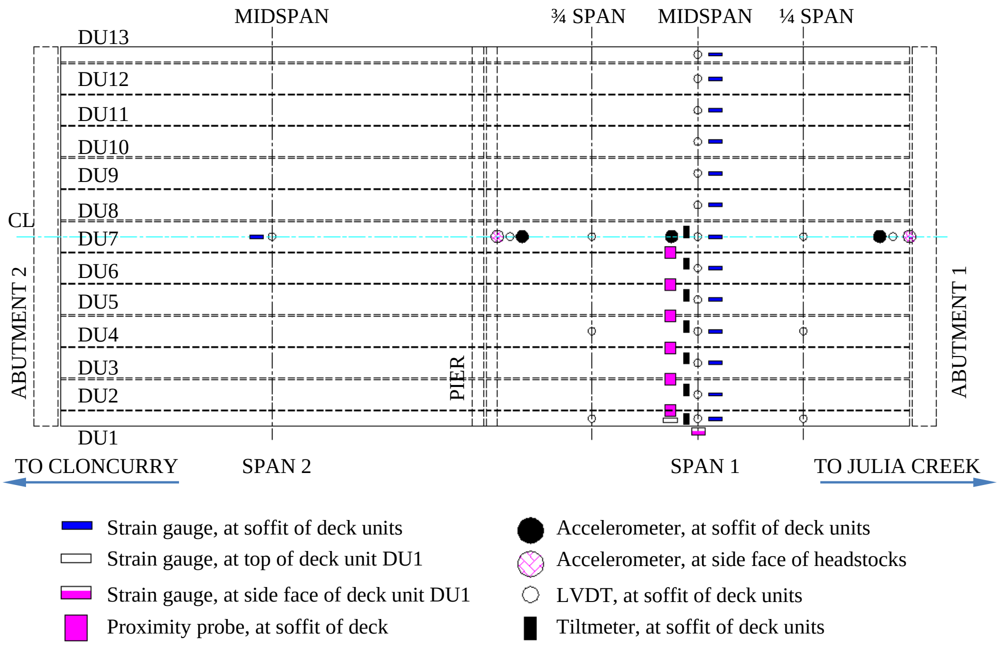
Instrumentation plan

Priorities for data capture were determined in the development of the load test program as shown in Table 3.1, in which span 1 was instrumented. The installation of one LVDT and one strain gauge in span 2 was included to compare the performance between the two spans. The instrumentation layout is shown in Figure 3.6.

Table 3.1: Data capture requirements

What	Where	Instrument used
Deflections	Midspan of every deck unit (span 1) Quarter span for deck units DU1, DU3, DU5 and DU7 (span 1) Either end of the centre deck unit DU7 (span 1) Midspan of DU7 (span 2)	Linear variable displacement transducers (LVDT1 – LVDT24)
Bending strains	Midspan of every deck unit (span 1) Top and side face of the kerb DU1 (at midspan, span 1) Midspan of DU7 (span 2)	Foil strain gauges (SG1-SG15)
Dynamic response of deck	Midspan and either end of DU7 (span 1) Headstock of abutment 1 and pier 1	Accelerometers (3D on pier and abutment headstock) (A1-A9)
Gap opening between deck units	Midspan, between deck units DU1 – DU7 (span 1)	Proximity probes (PS1-PS6)
Rotation of deck units	Midspan, at soffit of deck units DU1 – DU6 (span 1)	Tiltmeters (TM1-TM6)

Figure 3.6: Instrumentation locations



Data acquisition system

The DAQ system used in Canal Creek Bridge load test includes the following components:

IOtech WaveBook 516e (ethernet-based portable high speed waveform acquisition – Figure 3.7 (a) connected to field laptop (hardware driven by DASYLab 9.0 software) was used to record acceleration (9 accelerometers), tilt (7 tiltmeters) and strain (16 gauges).

MSC DT9834 (Figure 3.7 (b)) was used to record vertical displacement (24 LVDTs) and lateral opening between channels (6 proximity probes).

Figure 3.7: IOtech WaveBook 516e (Measurement Computing) and DT9834 (DataTranslation)

(a) IOtech WaveBook 516e (b) DT9834

UniMeasure JX-PA linear position transducers with analogue output were used with a measurement range of 50 mm. The LVDTs were bolted to an aluminium plate that, in turn, was glued (Araldite) to the deck units. A braided, non-stretching fishing line was used to connect the transducer to a peg driven into the ground.

Slope Indicator's DGSI single axis tiltmeters were used. The nominal resolution is 1 arc second (or 0.000277º). The tiltmeters were oriented to measure tilt along the axis parallel with the road. A positive tilt value indicates a slope that points up towards the edge of the bridge and down towards the centre of the bridge. The tiltmeters were bolted to angles that in turn, were glued to the deck units.

Inductive proximity probes model IMA12 (manufacturer SICK) were used. The nominal resolution is less than 1 micrometer. The proximity probes were mounted on angles using tow locknuts. The angles, in turn, were glued to the edge of the deck units to measure any transverse gap opening between adjacent deck units. In the employed configuration, the proximity probes were vertically offset 25 mm from the deck unit's lower surface.

Uniaxial Kyowa prewired strain gauges were used with a foil length of 30 mm (KFG-30-120-C1-11 L1M3R). The gauges were pre-installed on strips of thin aluminium and coated in silicon for protection. The aluminium strips (with the gauges) were glued to the deck units with a two-part epoxy glue. All strain gauges were oriented in parallel with the direction of traffic.

The following accelerometers were used:

- triaxial accelerometers - PCB model 356A32 (sensitivity of 10 mV/m/s/s).
- single-axis accelerometers - Wilcoxon model 786A (sensitivity of 10 mV/m/s/s).

The accelerometers were magnet mounted to a washer that had been glued to the bridge. The accelerometer at the Julia Creek abutment location was glued to the abutment in its watertight enclosure.

Other projects underway at the time of preparing this guide include:

- Macrossan Bridge
- Dawson Bridge
- Neerkol Bridge

TMR contact for the above projects – Faisal Mir (07) 3066 1056.

4 EVENT RESPONSE

4.1 Introduction

While a risk-based program of visual inspection is the most practical way of monitoring the condition of structures, for such a program to be effective where structures are known to be at risk of deterioration/damage as a consequence of discrete events, it is necessary for:

- the discrete event to have occurred prior to the inspection
- visible deterioration/damage to have occurred as a consequence.

The above is partially addressed by the requirement to undertake inspections immediately following events above certain thresholds (e.g. flooding). However, given the potentially large number of structures affected in a single event, limited resources and/or the possible impact on public safety during such events, the ability to be able to remotely identify potential damage as it occurs in structures noted as being of concern, is invaluable in order to ensure a prompt and informed response.

For such event-based applications, sensor signals are only collected during the event of interest. The event of interest can include:

- construction activities
- heavy load movements
- an accident
- abnormal environmental conditions or a natural hazard such as flooding, earthquake or fire.

Installing a monitoring system at sites of interest to continuously monitor for events and/or structural response beyond a predetermined trigger level(s) is a means of providing early warning of the event, damage or an abnormal change in structure behaviour occurring and allows real-time management of problem structures.

4.2 Intervention Levels/Trigger Points

Key to the success of continuous monitoring systems of this nature is the identification of appropriate intervention levels/trigger points.

These will differ depending on application and site characteristics but it is recommended that a hierarchical approach, similar in nature to that outlined in Section 9 of the Department's *Design Guide for Bridges and Other Structures* (TMR 2012), be developed with an increasing level of response implemented as each trigger level is initiated. For example, in most instances a three-level traffic-light strategy as described below would probably be appropriate:

Trigger Level	Description	Response
Green	Below lower intervention level	No action required
Amber	Between lower and upper intervention level	Inspection required, structure remains open
Red	Above upper intervention level	Close structure; immediate inspection required

For any event-based monitoring system it will be necessary to develop an appropriate alert and response plan. This plan provides the alarm and reporting procedure in the event of the specified thresholds being exceeded. Example systems discussed below utilise automated messaging systems whereby the monitoring software will automatically generate an email and/or SMS message to the appropriate/responsible people.

The alert-and-response plan shall specify the contact chain in case of an alarm being triggered.

Any changes to the agreed alert-and-response plan must be approved by the Deputy Chief Engineer, Structures.

4.3 Flood and Scour Events

4.3.1 Application

Structures identified as being at risk during flood events can include those with:

- superstructures at risk of uplift during a flood event (i.e. overtopping of bridge)
- critical substructure elements at risk of undermining during a flood event
- waterway profiles susceptible to global changes in bed profile such degradation, aggradation or lateral erosion.

Scour is a major cause, in many instances, of damage to piers and abutments and is the leading cause of bridge failures. In most cases, scour is not easily noticeable in underwater conditions.

At scour or flood-prone sites, monitoring can be carried out in 'real time' using various sensors to either monitor the waterway or detect the onset of unwanted structural behaviour. The use of these devices enables continuous monitoring to determine long-term trends, provide information on bed movements during flood events and early warning of damage.

A typical fixed scour monitoring system includes sensors, data loggers and a data transfer system. The selection of sensors is based on parameters such as measurement method (direct/indirect or continuous/discrete), measurement type (current water level, scour depth, displacement and/or rotation) and mounting location (in river bed or on bridge structure).

While it is not possible to predict certain events such as earthquakes, flood and fire hazards can be identified in advance. Monitoring of non-structural variables should be considered when developing an alert and response plan. For example, severe weather conditions can be identified and tracked, based on data supplied by established agencies. Intervention and trigger points should make provision for notification of these events, once the severity levels reach predetermined thresholds.

4.3.2 Intervention Levels/Trigger Points

Intervention levels will be site/application specific but would typically relate to:

- weather forecasts for severe storm events/cyclones/fire conditions
- river levels – structures prone to overtopping/uplift
- bed levels – sites susceptible to scour
- structure displacement/rotation – structures prone to undermining (settlement of substructure) or overtopping (uplift).

4.3.3 Suggested Solutions

Examples of flood and scour monitoring systems include:

Sonar scour monitor

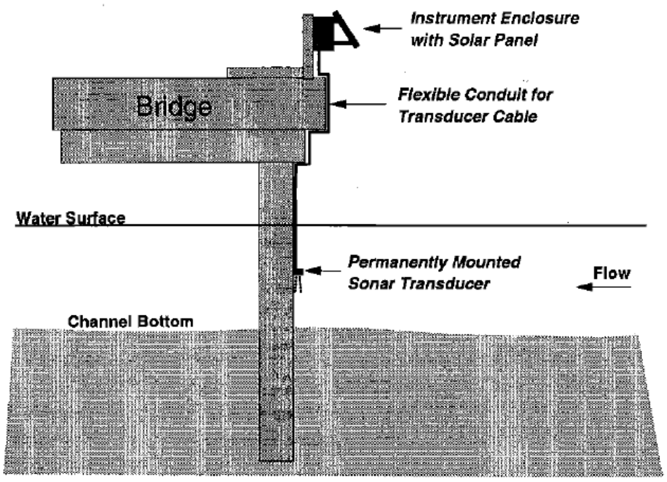
The sonar scour monitor is a conventional sonar instrument connected to a data logger that can provide continuous records of scour depth by measuring the distance based on the travel time of a soundwave through water (NCHRP Report 397a).

Sonar monitoring uses a low-cost, commercially available sonic fathometer pointed at the locations of anticipated scour or critical failure. The sonar probe is typically mounted to the substructure of a bridge and connected to a data logger placed on the bridge deck. The technique can measure an aggrading or degrading bed.

This system can track both scour and refill processes and can be mounted in a variety of elevations out of the way of debris and at various angles of inclination without affecting function. Measurements are, however, affected by aerated flow and bed load.

An example of a sonar scour monitoring system is shown in Figure 4.1.

Figure 4.1: Sonar scour monitoring with permanently mounted transducer



Source: NCHRP Report 397a (1997).

Magnetic sliding collar monitor

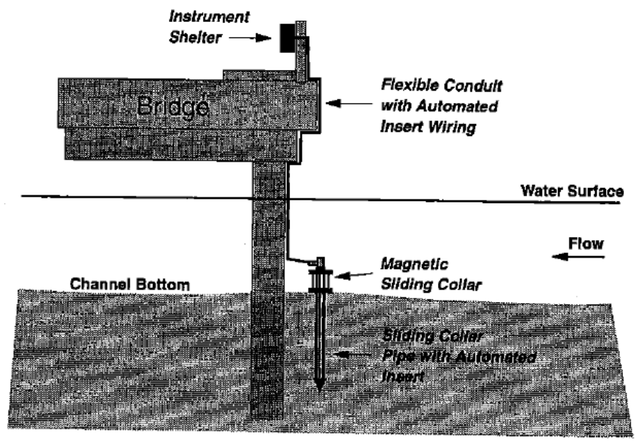
Magnetic sliding collars are collars that slide down a rod driven into the streambed. The collar sits on the riverbed, and as the local bed erodes, the collar follows the bed. This method of monitoring only measures maximum scour depth. The system may be automated or manually read. With the automated set-up, magnetic switches inside the driven rod locate the collar and a data logger records the collar's location. In the manual set-up, a magnetic switch is lowered until it is triggered by the collar (NCHRP Report 397b). This system is affected by debris preventing the collar from moving up and down the pipe and also by an aggrading bed burying the collar. An example of the magnetic sliding collar monitoring system set-up is shown in Figure 4.2.

Float-out devices

Float-out devices are buried at appropriate points near the bridge. They are activated when scour exposes the sensor. The sensor floats to the stream surface and an on-board transmitter is activated and transmits the float-out device's digital identification number to a data logger.

Float-out scour monitoring systems only provide a measurement if the scour has progressed past a datum. Float-outs can be installed at increasing depths to provide hierarchical intervention points. There is a power requirement, but it is minimal. However, the device cannot be checked to verify operational capability and the on-board power must be reliable for long periods without use. By its nature, the interface with the data logger is wireless.

Figure 4.2: Automatic magnetic sliding scour monitoring



Source: NCHRP Report 397b (1997).

Sounding rods

Sounding-rod or falling-rod instruments are manual or automated gravity-based physical probes. As the streambed scours, the rod, with its foot resting on the streambed, follows the streambed and causes the system counter to record the change. The foot must be of sufficient size to prevent penetration of the streambed due to gravity and/or the vibration of the rod from flowing water. This is a major limitation for sand bed channels.

Time domain reflectometry

Time domain reflectometry operates by sending an electromagnetic pulse down a rod buried vertically in the streambed. When the pulse runs into a change in the boundary conditions, such as the soil-water interface, a portion of the pulse's energy is reflected back to the source from the boundary. The remainder of the pulse's energy propagates through the boundary until another boundary condition (or the end of the probe) causes part or all of the energy to be reflected back to the source. By monitoring the round trip travel time of a pulse in real time, the distance to the respective boundaries can be calculated. This provides information on any changes in streambed elevation.

Tiltmeter arrays

Tiltmeter arrays can be used to measure movement and rotation of the structure. Tiltmeters installed on the bridge pier(s) of concern and superstructure above allow monitoring of the bridge position. In order to monitor all potential ranges of movement, the optimal installation will include sensors installed on pier faces parallel and perpendicular to the direction of travel as well as to the superstructure directly above the pier(s). A system of this nature allows for the monitoring of a structure's stability not only due to scour but for other events, including earthquakes, long-term settlement, impact, construction adjacent to the structure and the effects of 'locked' bearings.

For all of the systems suggested above, it is important to recognise that they will be required to operate reliably during periods of high river levels and potential overtopping of structures. Design of the system must therefore consider a reliable power supply and ensure that sensors, along with any associated cabling/componentry, are installed in such a manner, and are sufficiently durable, to minimise the potential for damage/malfunction due to inundation, submersion and impact from debris.

4.3.4 Example Projects

There are presently no flood or scour monitoring projects being undertaken by TMR.

4.4 Vibration, Ground Movement and Settlement

4.4.1 Application

Monitoring of event-triggered vibration, ground movement and/or settlement include the following scenarios:

- Monitoring impact of new construction/development on adjacent structures.
- Monitoring of structures and/or embankments where settlement has historically occurred or continues to occur (including scour/erosion).

Vibration, ground movement and/or settlement due to construction activities or any other external trigger can result in damage that can affect durability, alter load distribution within the structure and affect stability. While construction-induced damage will typically be monitored through the use of dilapidation surveys, monitoring systems will typically be required for critical infrastructure.

Specific monitoring criteria for construction activities adjacent to existing tunnels are outlined in TMR (2012). Similar principles can be employed for existing structures where concerns over ground stability exist.

The use of such systems enables continuous monitoring throughout construction or otherwise in order to determine long-term trends and provide early warning of potential damage.

Monitoring of slope stability, specifically at-risk/key retaining walls (failure of which would have significant impact on the road) should be included. Events which could cause damage include earthquakes, but the most likely event would be heavy rainfall that would have an impact on ground conditions, which could cause reduction of factors of safety.

4.4.2 Intervention Levels/Trigger Points

Intervention levels will be site/application specific but would typically relate to:

- vibration – piling activities adjacent to existing structures
- structure displacement/rotation – ground movement/settlement
- load – monitoring anchor loads in tied retaining structures/abutments
- crack widths – ground movement/settlement.

Monitoring of crack widths is discussed in Section 5 and hence is not considered in this section.

4.4.3 Suggested Solutions

Examples of solutions for monitoring systems include:

Vibration

The *Design Criteria for Bridges and Other Structures* (TMR 2012) specifies the use of triaxial geophones for monitoring of vibration in tunnel roofs caused by phenomenon such as blasting, piling, ground compaction or traffic.

The developer is required to install vibration monitoring equipment utilising triaxial geophones (4.5 Hz) to capture vibration prior to commencement of any demolition, excavation or construction work. The devices should be calibrated against a traceable event and must be installed as per manufacturer’s installation guidelines. The output result should also include waveforms of extreme events.

A suitable measurement frequency is to be specified by the instrumentation designer, such that all events are captured, to avoid the two scenarios - low and high measurement frequencies. The first will lead to data overflow and the second will miss the critical event.

Background monitoring and baseline reading should determine and correct external influences on monitoring results e.g. temperature, traffic and atmospheric pressure, which can lead to errors in reported data. Hence a two-month baseline reading regime is required to be undertaken prior to commencement of works to establish base level conditions and must continue for a minimum of three months following completion of works.

System reliability is important as a lack of monitoring may result in limitations on works or even suspension of construction operations. Where the consequences of monitoring system failure are unacceptable to a project, there should be sufficient redundancy built into the system so that losses of discrete elements do not cause loss of the entire monitoring system.

Monitoring systems require routine checks and maintenance. Most monitoring systems require some access for maintenance. The monitoring designer must consider how this can be achieved. A log of maintenance undertaken on the system is recommended. This log should record the date, nature of the work and who undertook it. This is useful for error tracing and a change in control procedures.

Trigger and alarm limits are specified as follows:

- A peak component particle velocity (PCPV) threshold of 1.5 mm/sec is to be set in the data logger.
- A warning trigger level between 1.5 mm/sec to 5 mm/sec is to be set in the logger.
- The alarm to close the tunnel to traffic and immediately cease all excavation work is to be set at a PCPV exceeding 5 mm/sec.

Table 4.1 below summarises the recommended intervention levels.

Table 4.1: Intervention levels for ground vibration in tunnel roof

Trigger Levels	Tunnel Lining Vibration Monitoring	Responses
Green	PCPV < 1.5 mm/s	Proceed
Amber	1.5 mm/s < PCPV < 5 mm/s	Notify Supervising Engineer and TMR. Review monitoring frequency and construction procedures.
Red	PCPV > 5 mm/s	Stop all buses from using tunnel. Place hold on excavation. Notify Supervising Engineer and TMR. Release for works to be provided by TMR.

Structure displacement/rotation

A suggested solution for monitoring of structures for displacement/rotation was discussed in Section 2.7.

The Department's *Design Criteria for Bridges and Other Structures* (TMR 2012) specifies the following two requirements for monitoring ground movement adjacent to tunnels.

Tiltmeters (inclinometers)

Install three inclinometers at 10 m intervals at a depth equal to the mid-height of the adjacent tunnel between the existing tunnel and the proposed excavation. The decision to increase/decrease the number of sensors based on the proximity of the excavation adjacent to the tunnel and the length of excavation is at the discretion of the TMR representatives.

The inclinometer must be monitored daily during basement excavation and weekly until three months after completion of construction. The developer's consultant requires collection and review of all inclinometer data during the excavation stage, as well as the construction stage. Reports are to be compiled and submitted to TMR.

Trigger and alarm limits for inclinometer movements are to be agreed prior to commencement of any demolition, excavation or construction work.

The alert-and-response plan to inclinometer movement shall spell out the contact chain in case of alarm.

Rod extensometers (for monitoring secondary lining on driven tunnels)

The contractor must install rod extensometers in the tunnel to determine movement of the ground adjacent to the tunnel primary layer resulting from excavation associated with the new development.

The trigger levels for rod extensometer movement are to be agreed prior to commencement of excavation.

The alert-and-response plan for rod extensometer movement shall spell out the contact chain in case of alarm. In addition to submitting all alarm trigger reports, the developer is required to submit to TMR, at monthly intervals, the monitoring reports for evaluation and assessment.

Table 4.2 below summarises the recommended intervention levels.

Table 4.2: Intervention levels for ground displacement adjacent to tunnels

Trigger Levels	Ground Deformation Adjacent to Tunnel (Extensometers)	Responses
Green	Ground displacement <1 mm	Proceed.
Amber	Ground displacement between 1 mm and 2 mm	Notify Supervising Engineer and TMR. Review monitoring frequency and construction procedures.
Red	Ground displacement >2 mm	Stop all buses from using tunnel. Place hold on excavation. Notify Supervising Engineer and TMR. Release for works to be provided by TMR.

4.4.4 *Example Projects*

The following are two recent construction projects where automated monitoring systems have been utilised to protect key infrastructure:

- TransLink Busway – Vulture Street Tunnel. TMR contact - Mohamed Nooru (07) 3066 6374
- Anne Street/George Street Flyover – abutment monitoring. TMR contact - Mohamed Nooru (07) 3066 6374.

4.5 Impact Damage (Low Bridges)

4.5.1 *Application*

The state highway network includes numerous structures over the highway (rail or road underpasses) as well as bridges crossing over local roads. Many of these structures are susceptible to accidental impact damage from over-height vehicles. The consequences of an overhead strike include:

- safety of road users

- delay and disruption to the rail, highway and/or local road networks (immediately following the impact, pending emergency inspection and until any subsequent repairs are completed)
- structural damage.

In addition, many ‘minor’ bridge strikes may go unreported.

While the overhead clearances of all overpasses are typically clearly signed, incidents still occur on a regular basis (e.g. in excess of 330 rail bridge strikes were recorded to the South East Queensland Rail Network for the period 2000–2010).

Traditional control measures include advance warning signage, coupled with alternative route advice and/or sacrificial structures in advance of the low bridge (usually along the lines of a beam spanning the carriageway with or without suspended chains).

Monitoring systems can be used to assist with the management of bridge strikes, either as an advance warning tool or as a detection tool to capture a bridge strike occurring. The latter is of benefit for ‘minor’ bridge strikes (i.e. where minimal contact is made with the structure and the vehicle is able to continue).

Over-height vehicle strikes are also a risk in the case of tunnels. Where over-height vehicles enter tunnels, substantial damage may result due to the number of overhead systems involved, e.g. lighting, signage, deluge and video surveillance. Any incident in a tunnel will cause major traffic disruption with associated costs.

4.5.2 Intervention Levels/Trigger Points

Intervention levels will be site/application specific but would typically relate to the following parameters:

- vertical clearance – appropriate trigger/intervention level would be the available clearance (less an appropriate safety margin) with no need for a hierarchical response (a vehicle is over-height or not).
- vibration – detect impact damage.

4.5.3 Suggested Solutions

Examples of monitoring systems for the prevention and detection of bridge impacts include:

Prevention

Prevention of bridge strikes requires a means of detecting over-height loads and notifying the driver that they may exceed the available bridge clearance.

A typical system will comprise height sensors (e.g. active infra-red, ultrasonic or overhead laser) mounted adjacent to the carriageway coupled with visual (flashing lights, variable message signs) and audible warnings which are activated once sensors are triggered.

The detection system needs to be installed sufficiently in advance of the bridge to allow the vehicle time to pull over in a safe manner or divert onto an alternative route.

Detection

A system for detection of bridge strikes will usually entail installing sensors on the leading edge(s) of the superstructure, or other component likely to be struck. For example, uniaxial accelerometers installed at midspan (positioned to avoid damage from vehicle impact) can detect lateral impact on the superstructure.

Both the prevention and detection components of any system should also consider the inclusion of CCTV monitoring of the site for compliance and prosecution purposes.

4.5.4 Example Projects

Queensland Rail (QR) introduced a trial Bridge Impact Detection System (BIDS) in 2011 at two problem low bridge sites in Corinda and Indooroopilly.

The system comprises the following:

- laser detection of over-height vehicles on a bridge approach road
- CCTV images of the bridge recorded continuously and remotely accessible
- impact detection through sensors attached to the bridge
- remote alarms and bridge strike force indications
- visual warning to drivers through high visibility LED signs and lamps on the bridge.

The BIDS uses a camera and recording arrangement identical to the level crossing CCTV system and permits remote access in the same way.

Functions of the system include:

- automatic email notification of bridge impact
- platform independent user interface providing information on:
  - alarm notification
  - BIDS last impact records as well as over-height readings and maximum accelerometer readings
  - sensor details.

4.6 Overloading/Weight-restricted Bridges

4.6.1 Application

With an aging bridge stock and an increasing drive to improve productivity through increased vehicle mass, it is inevitable that the number of structures on the network with an assessed load restriction will increase.

Section 3 of this document discusses various methods of load testing as an effective means of evaluating the performance and structural capacity of a highway structure. Where actual structural actions (strains, deflections, etc.) are measured to accurately determine the response of the bridge and its components to the applied loads, the results can be taken into consideration in determining a more realistic load rating for the bridge. Section 5 of this document also discusses methods of detecting and monitoring cracks in structures. These principles can be used, in conjunction with other approaches, to determine the final load rating of a bridge in accordance with the methodology outlined in AS 5100.7-2015 (draft).

In addition, the instrumentation methods discussed in Section 3 and Section 5 can also be used to detect instances of overstress as a consequence of overloading and inform the need for:

- inspection to confirm if damage has occurred
- increased enforcement on site.

The use of CCTV technology, in conjunction with the applications discussed in Section 3 and Section 5, at problem sites can be used as a means of enforcing compliance.

Further to the above, weigh-in-motion systems offer benefits in relation to bridge management by allowing asset managers to:

- determine route/structure specific live load models for selected bridge sites/routes to inform the load rating process and/or determine the likely impact of load restrictions
- identify ‘problem’ routes, i.e. those where overloads are routinely occurring.

This section discusses the application of WIM technologies to achieve the above.

4.6.2 Intervention Levels/Trigger Points

Intervention levels will be site/application specific but would typically relate to:

- axle mass – recorded mass of individual axles compared with maximum permitted axle mass
- gross mass – recorded mass of groups of axles or overall vehicle mass compared with maximum permitted gross mass.

Given that Section 3 and Section 5 discuss approaches for monitoring/detecting instances of overstress in structural components, only intervention levels/trigger points for WIM systems are considered in this section.

4.6.3 Suggested Solutions

In most instances, except for compliance and live load case development purposes on critical structures, it is unlikely that WIM systems will be installed at individual bridge sites unless as part of a bridge weigh-in-motion system (BWIM) where the structure itself is instrumented to act as a WIM site. Examples of this latter approach include the Culway system and the SiWIM system (see example projects below).

As described in Section 2.8.1, the standard components of a WIM will comprise:

- mass sensor
- vehicle classification/identification module
- processor and data storage module
- user communication module.

For traditional WIM applications, installation of the mass sensor will typically involve disruption to road users and cutting of the pavement wearing surface.

BWIM applications involve attaching strain gauges/transducers to the soffit of existing structures and is therefore not as intrusive (although it should be noted that the Culway system requires installation of non-drainage box culverts at each measurement site).

The vehicle classification/identification component of a WIM application is usually a constituent component of the mass sensor for WIM applications. For BWIM applications, detection and classification of the vehicle can either be through pavement-installed components (e.g. piezoelectric sensors) or infra-red sensors installed adjacent to the carriageways. ‘Nothing on the road’ (NOR) or ‘free-of-axle detector’ (FAD) systems employing additional strain transducers and post-processing to determine vehicle velocity and derive the number of axles and axle spacing as used in the SiWIM system, are also an option with BWIM systems.

The advantages of a BWIM system attached to an existing bridge is that the system:

- is portable (i.e. it can be moved from one bridge site to another)
- is quicker to set up

- provides the true behaviour of a bridge under in-service loading (for feedback into the assessment process), including the dynamic impact factor and lateral load distribution.

As discussed in Section 2.8.1 the main factors affecting the accuracy of the WIM system are (Austroads 2010):

- pavement quality, specifically evenness, error up to 100%
- vehicle condition, specifically tyres and suspension, error up to 30%
- driver behaviour, specifically braking and accelerating, error up to 50%
- equipment used, errors up to 2%.

These main factors are addressed in the calibration period specific to the sensor, system used and correct site selection. An important component of any WIM application is to ensure the ongoing integrity of the data produced is the regular inspection and maintenance of the site to ensure defects affecting accuracy are known, accounted for and repaired.

While high-speed WIM (pavement or bridge-mounted) are not sufficiently accurate for enforcement purposes, systems should ideally have configurable output triggers for use with VMS, cameras or CCTV. The system may then be used for driver education and operation in conjunction with low-speed WIM sites for enforcement purposes (e.g. a BWIM site with trigger-enabled CCTV could be used as a means of selecting vehicles for testing at low-speed WIM sites).

4.6.4 Example Projects

Examples of BWIM projects identified through research of technologies for this guide include:

- Express-Weigh WIM – pavement installed system capable of capturing vehicle volume, speed, classification and axle mass data: ARRB Group, Systems.
- ViperWIM – a pavement-installed system capable of capturing vehicle volume, speed, classification and axle mass data: Contact details and further information at http://www.appliedtraffic.co.uk/.
- Culway 3G – next generation Culway system capable of capturing vehicle volume, speed, classification and axle mass data: ARRB Group, Systems.

SiWIM – BWIM system based on simple strain gauges, precise amplifiers, fast signal converters and a reliable computer, the SiWIM system is a set of basic components, which combined form a high-tech, advanced, reliable and scalable system for use in a wide range of different situations, both in the areas of WIM as well as for the analysis of bridge structures: Contact details and further information at http://www.cestel.eu/.

5 CRACK MONITORING

5.1 Introduction

The intent of this section is to review applications for monitoring cracks observed in concrete and steel structures, as well as applications for monitoring ground stability. This assumes the cracks have already been detected through normal Level 2 or requested Level 3 inspections.

Detection of cracks initiating in a structure is feasible through the use of acoustic emission (AE) technologies; however, these have not been explored further in this revision of the guide.

5.1.1 Concrete

Cracks in concrete structures can develop for a number of reasons through the life of a structure and, if wide enough, may lead to durability or strength issues affecting the performance of the structure.

Depending on the characteristics, cracks in concrete structures can be classified as follows:

- Structural cracks – these may occur due to overload, structural deficiency, vehicle impact, settlement or some other unanticipated structural actions. The three main types of structural cracks are flexure, shear and torsion cracks.
- Non-structural cracks – these may occur during the plastic state (settlement, shrinkage or early thermal cracks) or through the life of the structure (drying shrinkage, corrosion induced, ASR/AAR, etc.).

While some cracks cease to develop further after the initial instigation (passive), others may follow a hysteresis cycle or continue to grow (active). Where there is concern regarding the cause and stability of cracks in concrete structures, a crack monitoring system is useful to monitor the evolution or progression of the monitored cracks in order to determine their root cause and the extent to which they influence the performance of the structure.

5.1.2 Structural Steel

Fatigue failure is the most common cause of cracking in structural steelwork and can lead to fracture of the components. Poor workmanship can also lead to cracking in welded connections.

Once fatigue cracks have initiated, they will continue to develop until brittle failure occurs or the component is strengthened/replaced.

5.1.3 Ground stability

Instability in embankments, batter protection and rock slopes have the potential to impact on road users. Ground instability will often be evidenced by the development of tension cracking in the slope surface. As movement continues, the cracks widen and, through monitoring, it is possible to determine the rate of movement. Where slip failure is evident, monitoring of crack widths should be combined with monitoring of surface movement (i.e. heaving of slope toe) well as changes in material properties due to water ingress (pore pressure changes) as discussed in Section 4.4.

5.2 Application

Crack monitoring applications include:

- Monitoring the impact of new construction/development on existing cracks in adjacent structures.
- Investigating the causes and status (passive or active) of cracking observed in concrete structures (including monitoring activities).
- Estimating residual service life of structures.
- Monitoring fatigue cracks in structural steelwork.

- Monitoring stability of slopes.

5.3 Likely Test Duration

With the exception of crack monitoring undertaken as part of one-off load tests, most crack monitoring applications will be continuous in nature.

5.4 Intervention Levels/Trigger Points

Intervention levels will be site/application specific but will be related to the measured width of the cracks being monitored.

Example intervention levels for cracks in tunnel linings are provided in Section 5.5 below.

5.5 Suggested Solutions

5.5.1 Impact of New Construction/Development on Existing Cracks in Adjacent Structures

Where new construction or development is proposed adjacent to existing structures, it is a common requirement to undertake dilapidation surveys to establish pre-existing condition/defects and monitor the impact of any construction activities on the existing structure(s). For critical infrastructure, crack monitoring is a useful tool for monitoring the impact of construction activities.

The *Design Criteria for Bridges and Other Structures* (TMR 2012) specifies the following requirements for monitoring of existing cracks in the crown of driven tunnels adjacent to proposed developments.

The developer is required to install crack monitoring devices in the tunnel crown before the start of any demolition, excavation or construction. Suitable crackmeters with accuracy and reliability are to record the crack growth inside the tunnel. The location and the number of devices to be installed for crack monitoring are to be identified after the dilapidation survey.

Responses to trigger levels of tunnel lining crack monitoring shall comply with those listed in Table 5.1.

Table 5.1: Monitoring Alarm Limits and Responses, Tunnel Lining Cracks

Trigger Levels	Tunnel Lining Cracks (Crack Monitoring)	Responses
Green	Existing cracks open < 0.5 mm. New cracks open <0.2 mm.	Proceed.
Amber	Existing cracks open between 0.5 mm and 1.0 mm. New cracks open >0.2 mm and < 0.5 mm.	Notify Supervising Engineer and TMR. Review monitoring frequency and construction procedures.
Red	Existing cracks open > 1.0 mm. New cracks open > 0.5 mm.	Stop all buses from using tunnel. Place hold on excavation. Notify Supervising Engineer and TMR. Release for works to be provided by TMR.

The alert-and-response plan shall spell out the contact chain in case of alarm.

5.5.2 General Considerations

Irrespective of the application, the choice of sensor will depend on the anticipated range of movement and the required resolution and accuracy to achieve the desired output from the monitoring application.

Refer to Section 2.6 for guidance on the various sensors available for monitoring crack widths such as Linear Variable Differential Transducers, Displacement Fibre Optic Sensors, Vibrating Wire Crackmeters and Proximity Sensors

In addition to monitoring crack widths, it is important to ensure that all other additional parameters required to investigate potential causes for the observed cracks are monitored.

5.6 Example Projects

Refer to Section 4.4.4.

6 COMPLEX STRUCTURES

6.1 Introduction

This section discusses options for the monitoring for monitoring complex structures. For the purposes of this section, a complex structure is considered to be:

- a structure with low redundancy/difficult to access components (e.g. cables, hangers, pot bearings, half-joints etc.)
- a structure strengthened with fibre reinforced polymer (FRP) strips.

6.1.1 Low Redundancy/Difficult to Access Components

For those structures with low redundancy/difficult to access components, continuous monitoring can be used as a means to trigger detailed engineering inspections with appropriate specialist access where:

- existing/known defects continue to deteriorate
- previously unknown defects occur.

For existing/known defects and instances where development of unknown defects can be directly measured (e.g. bearing movement), the principles discussed in the other sections of this guide apply. The only additional consideration is access requirements for installation and maintenance of the system components.

Unknown defects where initiation cannot be directly measured would typically be detected through the normal inspection regime; however, due to the low redundancy and difficult access associated with said components, some means of indirect monitoring would be beneficial for components deemed to be of high risk. A technology briefly discussed in Section 2, with potential future applications, is acoustic emission (AE) monitoring.

6.1.2 FRP-Strengthened Structures

FRP materials are increasingly being used to strengthen highway structures, most commonly through the bonding of FRP panels to concrete members in order to enhance shear or flexural capacity. Of greatest concern with any bonded FRP strengthening is the potential for delamination/debonding of the panels. In addition, understanding the actual influence of the strengthening on the behaviour of the structure is also beneficial (Wu et al. 2006).

6.2 Application

For low redundancy/difficult to access components, AE monitoring offers the ability to detect defects at a very early stage and monitor their progression.

Monitoring of FRP-strengthened structures offers the following benefits:

- evaluation of the effects of strengthening
- monitoring performance of a strengthened structure (short and long term)
- detection of any delamination or debonding of strengthening systems.

6.3 Likely Test Duration

For both of the applications/problems discussed in Section 6.1, monitoring applications will most likely be continuous in nature.

6.4 Suggested Solutions

6.4.1 AE Monitoring of Low Redundancy/Difficult to Access Components

AE monitoring involves the installation of acoustic sensors to detect emissions generated by the rapid release of energy as a member deteriorates. Essentially, flaws developing within a component emit bursts of energy in the form of high-frequency soundwaves (acoustic emissions) that propagate within the material and are received by sensors. The acoustic emissions can be primary (originating from the material of interest) or secondary (all other emissions originating from external sources).

6.4.2 Monitoring of FRP-Strengthened Structures

Monitoring systems utilising distributed fibre optic strain sensors (embedded or surface-mounted) to monitor global and local strain are yielding positive results for the real-time monitoring of FRP-strengthened members. In theory they offer the ability to monitor for premature peeling or debonding of the FRP laminates as well as evaluating the performance of the strengthened member.

The key benefits offered by fibre optic sensors is their small size (compared to other strain sensors), which allows them to be embedded between FRP layers, and their ability to measure strains locally with high resolution and accuracy.

Systems using both Fibre Bragg Grating and Brillouin back-scattering have been developed and successfully used to monitor the performance of FRP-strengthened concrete girders as well as evaluate the effectiveness of different FRP materials (laminates and adhesives) and methods of application/construction (Lau et al. 2001)

The benefits and potential application of these systems in monitoring the performance and effectiveness of FRP-strengthened structures will be explored further in the 2015/16 NACOE program.

6.5 Example Projects

The following is a list of referenced projects associated with the monitoring of complex structures that were reviewed during the preparation of this guide:

- Wu et al. (2006)
- Nair and Cai (2010)
- Lau et al. (2001)

Ayoub and Mehrani (2005)

7 STRUCTURES INFLUENCED BY THERMAL EFFECTS

7.1 Introduction

The intent of this section is to review applications for monitoring components and structures that are suspected of being unduly influenced by temperature variation.

All highway bridges continuously exchange heat with the environment and are subject to daily and seasonal temperature fluctuations that affect the mean temperature of the structure. Further to fluctuations in mean temperature over time, temperature gradients through the cross-section of the structure are possible at any given time. A uniform temperature gradient will typically exist around sunrise as the air temperature will have remained constant for a few hours. The temperature of the deck increases as the sun rises and a positive temperature gradient develops, increasing to a maximum around mid-afternoon. A negative gradient occurs when the top surface of the bridge is rapidly cooled (e.g. rain, high wind or rapid drop in air temperature). Steel components respond quickly to temperature changes and their temperature is usually uniform and equal to air temperature. Concrete components, however, have a low thermal conductivity and large temperature gradients can develop.

When an unrestrained homogeneous body undergoes a uniform temperature change, all points within the body move radially from the point of zero movement in proportion to their distance from this point. When there is a variation in temperature throughout the body, the warmer parts tend to expand more than the cooler parts. This thermal bending contributes a second-order effect to overall movements. If thermal deformations are even partially restrained, large forces can develop. Because neither free movement nor complete restraint conditions exist in bridge structures, a combination of both thermal stress and thermal strain generally prevails (Tindal & Yoo 2003).

While low skew bridges with low width/span ratios typically experience very few problems, thermal bending can be significant in acutely skewed or curved spans. For continuous structures, thermal bending may cause significant redistribution of support reactions in both the horizontal and vertical planes. Nonlinear temperature gradients that arise in concrete bridges can also induce high tensile stresses frequently associated with deck cracking.

Issues associated with in-service bridges attributable to thermal effects include:

- spalling of concrete around bearings
- deformed/failed anchor bolts
- locked expansion joints/premature failure of expansion joints
- ‘lift-off’ of curved/highly skewed spans
- cracking in concrete components due to secondary effects not anticipated in design.

7.2 Application

Applications for monitoring thermal effects on highway structures include determining the influence of daily, seasonal and temperature gradients on:

- displacement range of bridge/spans
- in-service performance of bearings
- cracks in concrete components
- strains in concrete components
- width/behaviour of cracks.

7.3 Likely Test Duration

As any investigation into thermal effects will need to include seasonal effects monitoring, applications will typically be continuous in nature.

7.4 Intervention Levels/Trigger Points

As the purpose of any application will be to explore the influence of thermal effects on component/structure behaviour, intervention levels and trigger points are not necessarily applicable. Obvious exceptions would be where observed effects exceed acceptable limits. These would need to be determined on a case-by-case basis.

7.5 Suggested Solutions

The key point of any SM application established to explore thermal influence on behaviour is the capture of relevant temperature data. As discussed in Section 2.9, it is important to establish what/where temperature readings are required. Ambient temperature will be required to establish the daily and seasonal fluctuations to which the structure in question is subjected. Furthermore, the surface (or internal) temperature of the components of interest will also be required, along with any supplementary surface temperatures to establish the thermal gradient.

Once the required temperature locations have been established, monitoring of the parameter of interest will be as discussed in earlier sections of the report. For instance:

- Displacement range of bridge/spans – displacement sensors at free ends of span(s) to monitor horizontal distance between superstructure and substructure/target.
- In-service performance of bearings – displacement sensors and tiltmeters to monitor bearing movement. Axial strain sensors to monitor anchor bolts (for uplift bearings). Tiltmeters installed on pier columns to detect locked bearings.
- Locked expansion joints/premature failure of expansion joints – displacement sensors to establish if movement is occurring and that range of movement is within specification for the joint assembly.
- ‘Lift-off’ of curved/highly skewed spans – displacement sensors to monitor vertical distance between superstructure and substructure/target.
- Cracking in concrete components – crackmeters and/or strain gauges at areas of interest.

7.6 Example Projects

The following is a list of referenced projects associated with the monitoring of thermal effects that were reviewed during the preparation of this guide:

- Tindal and Yoo (2003)

8 BURIED CORRUGATED METAL CULVERTS

8.1 Introduction/Overview

The intent of this section is to review potential applications for monitoring buried corrugated metal culverts, deemed to be at risk of failure through distortion, deflection or settlement due to poor construction, overloading, corrosion of steelwork or other contributory cause.

Corrugated metal culverts can fail in a number of ways, including (TMR 2013):

- Collapse of the culvert due to buckling or crushing of the corrugated metal as a result of factors such as overloading, section loss/perforation due to corrosion, soil loss from behind the culvert wall or softening of the soil due to increased moisture content.
- Loss of fill material around the culvert during wet periods resulting in pavement failure. Loss of fill material may be a consequence of overtopping, failure of headwalls/end protection or erosion of fill through perforations in the culvert.
- Inadequate hydraulic capacity.
- Combinations of the above.

The consequences of failure can be severe and can include:

- Loss of life, injury and damage to vehicles as a consequence of pavement depressions or chasms, complete loss of fill material across the road, and structural collapse.
- Closure of the road and diversion of traffic for the period of the closure.
- Emergency works that can include:

    Construction of a side track and/or an emergency repair, possibly during a wet period in a location where construction equipment may not be readily available. The construction and maintenance of a side track during wet periods could be costly with safety requiring careful consideration.

    Design and construction of a permanent replacement structure.

    Impact on the TMR budget as works may not be programmed.

Any situation where corrosion of the culvert is a cause for concern or where loss of fill material is suspected to be occurring should be prioritised for appropriate remedial works (e.g. invert lining, slip lining, etc.) based on the extent of corrosion/perforation present and in accordance with the recommendations for risk assessment and treatment outlined in Austroads (2011). **The application of structural monitoring technologies in this instance is not considered appropriate.**

Where ongoing deflection, distortion or settlement of the culvert barrel due to causes not attributable to corrosion or loss of fill is suspected, then displacement monitoring techniques may be of use.

Similarly, where softening of the fill material is possible due to high water levels, then monitoring of water levels can be applied as an indirect method of establishing the likelihood of this occurring.

While other factors affecting hydraulic performance such as reduced waterway area (due to silt build-up or blockages) could be monitored, the Level 1 and Level 2 inspection regimes (including inspection after significant flooding events) are best suited for this scenario.

8.2 Application

Monitoring applications for buried corrugated metal culverts include:

- monitoring culvert barrel for ongoing deflection/distortion

- monitoring culvert barrel for settlement.

8.3 Likely Test Duration

Culvert monitoring applications described above will, by their nature, be continuous.

8.4 Intervention Levels/Trigger Points

Intervention levels will be site/application specific but will be related to the expected rate and range of movement for displacement-based monitoring.

8.5 Suggested Solutions

Monitoring culvert barrel for ongoing deflection/distortion

Monitoring of culvert barrels for ongoing deflection/distortion essentially involves monitoring the barrel shape of the culvert through measurement of the barrel diameter. As the barrel distorts, the measured diameter will change (increase/decrease depending on the distorted shape and where the diameter is being measured). For example, if the culvert barrel is deflecting vertically downwards, this has the effect of decreasing the vertical diameter and increasing the horizontal diameter.

The installation of displacement sensors within the barrel would require a technique that does not impede the flow of water through the culvert and with sufficient range to measure the barrel diameter. The only sensors discussed in Section 2.6 that meet this criteria would be laser triangulation or ultrasonic proximity sensors. However, installation of sensors within the culvert barrel for the purpose of monitoring for changes in diameter is flawed for the following reasons:

- Any sensor installed within the barrel will be susceptible to damage from debris carried through the barrel along with potential periods of prolonged submersion.
- Accurate monitoring of vertical diameter will not be reliable due to the deposition of silt/debris on the culvert invert.

Due to the reasons cited above, permanent monitoring of barrel shape through installed sensors is not considered practical at this point in time.

The iMETRUM and interferometric radar systems discussed in Section 2.6 offer a potential solution, as does photogrammetry, but could not be employed in a continuous monitoring role as both methods will require line of sight through the barrel. This would require placement of the camera/radar sensor within the waterway and at risk of impact damage or submersion.

On the above basis, a more practical and cost-effective means of monitoring culvert barrel deflection would be scheduled periodic readings by inspectors (potentially as part of the Level 1 inspection program).

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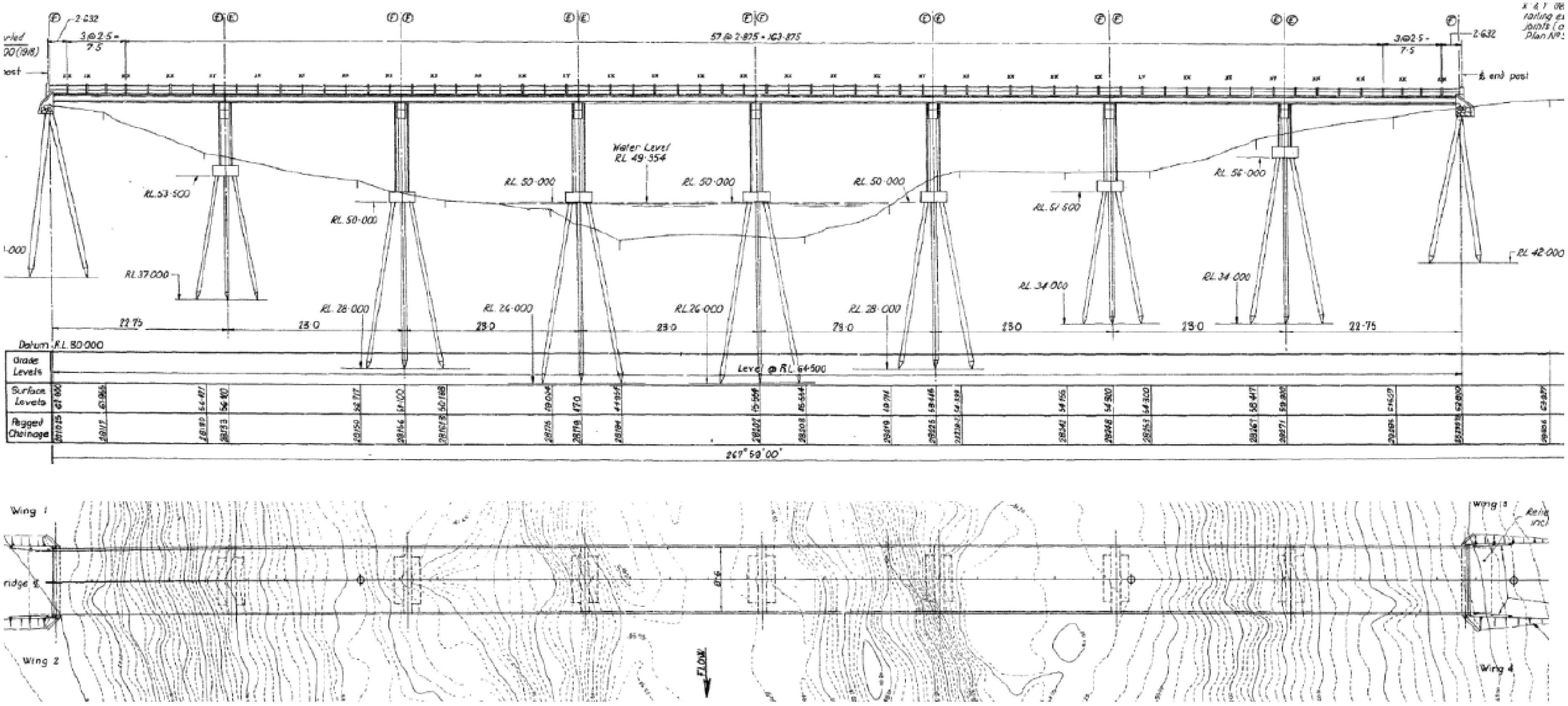
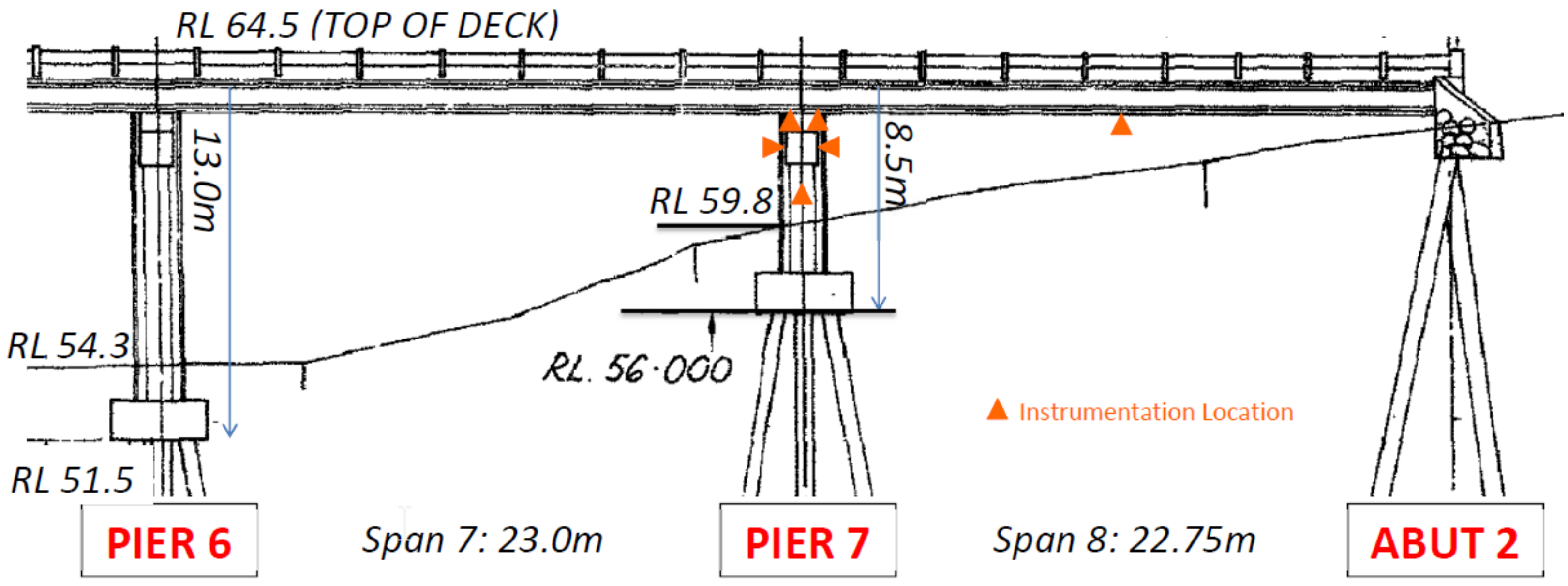
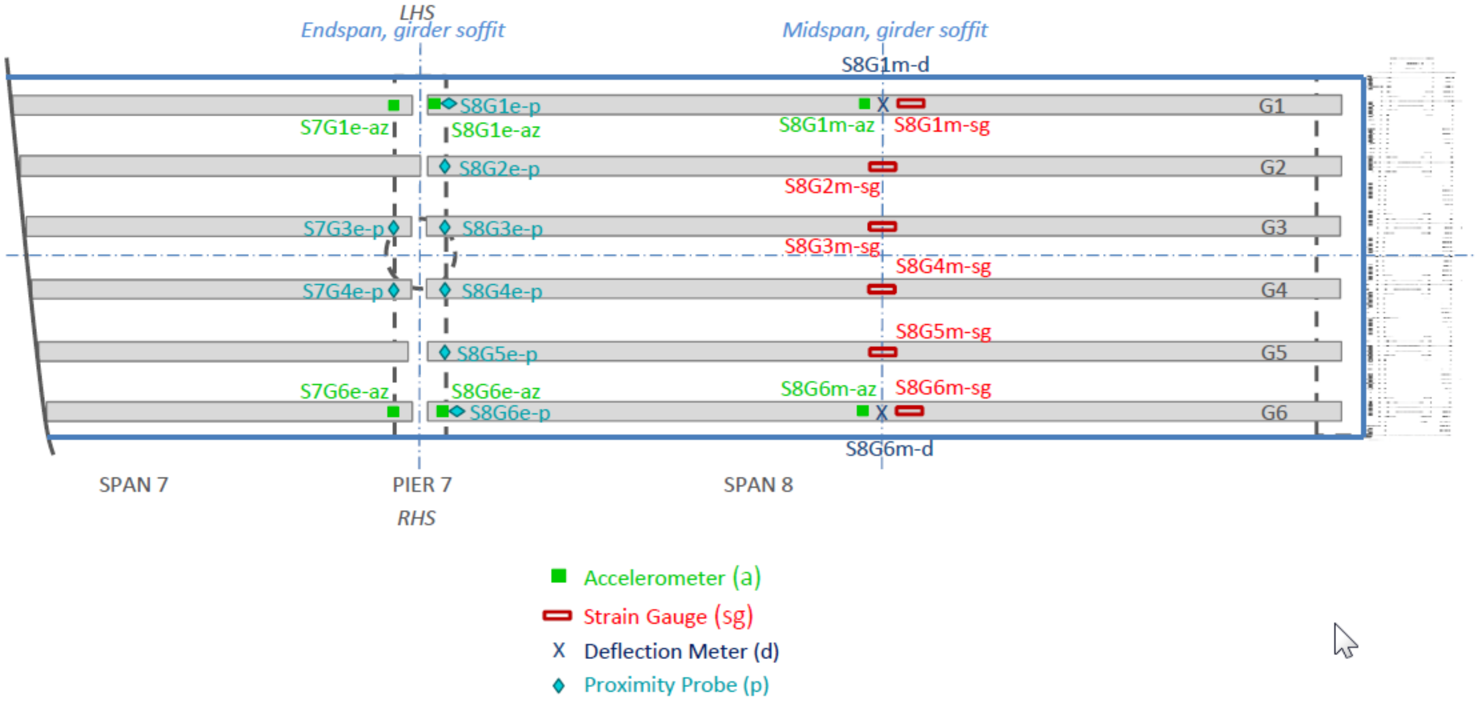
APPENDIX A SAMPLE INSTRUMENTATION PLAN

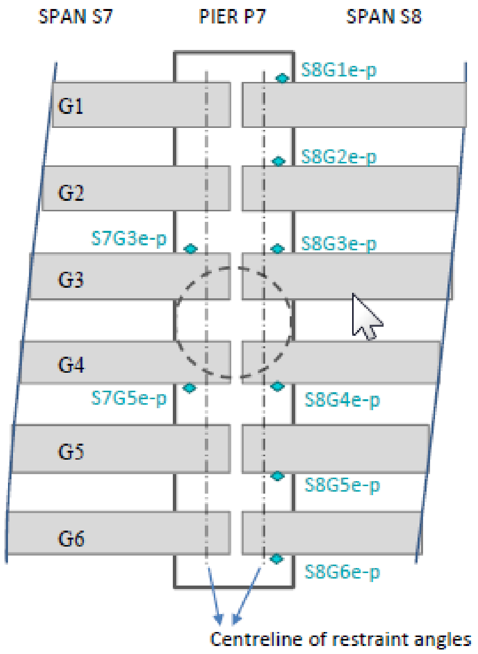
Dawson River Bridge




RL 64.5 (TOP OF DECK)
13.0m
8.5m
RL 59.8
RL 54.3
RL. 56·000
RL 51.5
Instrumentation Location
PIER 6
Span 7: 23.0m
PIER 7
Span 8: 22.75m
ABUT 2

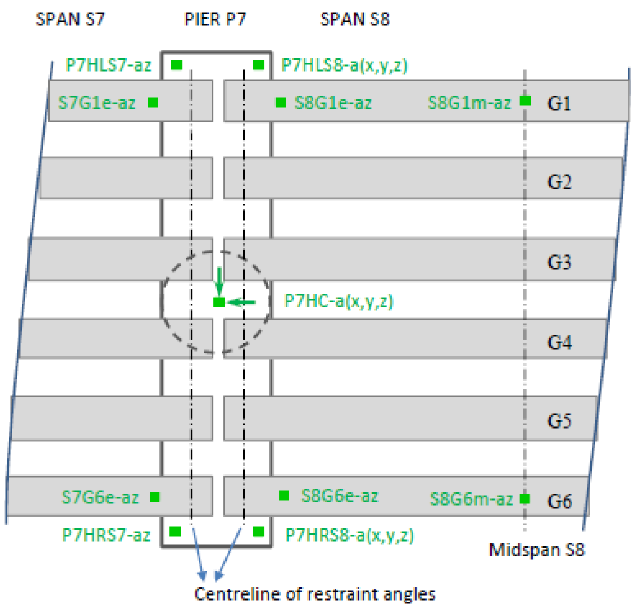

LHS
Endspan, girder soffit
Midspan, girder soffit
S8G1m-d
S8G1e-p
S7G1e-az
S8G1e-az
S8G1m-az
S8G1m-sg
G1
S8G2e-p
S8G2m-sg
G2
S7G3e-p
S8G3e-p
G3
S8G3m-sg
S8G4m-sg
S7G4e-p
S8G4e-p
G4
S8G5m-sg
S8G5e-p
G5
S7G6e-az
S8G6e-az
S8G6m-az
S8G6m-sg
S8G6e-p
G6
S8G6m-d
SPAN 7
PIER 7
SPAN 8
RHS
Accelerometer (a)
Strain Gauge (sg)
Deflection Meter (d)
Proximity Probe (p)

Dawson River Bridge: Installation plan of proximity probes

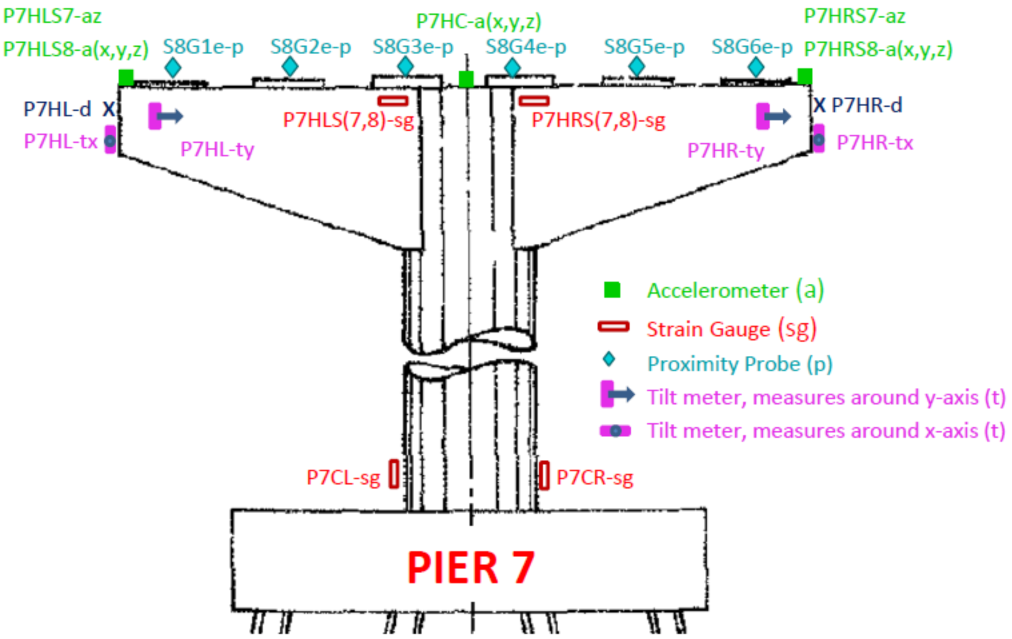


Note: Proximity probes were installed at the side of girders.

Dawson River Bridge: Installation plan of accelerometers



Notes: 1. Girders' accelerometers were installed at the soffit of girders and in upward direction
2. Headstock's accelerometers were installed on top surface of the headstock. The vertical accelerometers were in upward direction.


P7HLS7-az
P7HLS8-a(x,y,z)
S8G1e-p
S8G2e-p
P7HC-a(x,y,z)
S8G3e-p
S8G4e-p
S8G5e-p
S8G6e-p
P7HRS7-az
P7HRS8-a(x,y,z)
P7HL-d X
P7HL-tx
P7HL-ty
P7HLS(7,8)-sg
P7HRS(7,8)-sg
P7HR-ty
X P7HR-d
P7HR-tx
Accelerometer (a)
Strain Gauge (sg)
Proximity Probe (p)
Tilt meter, measures around y-axis (t)
Tilt meter, measures around x-axis (t)
P7CL-sg
P7CR-sg
PIER 7