STRUCTURAL CONTROL AND HEALTH MONITORING
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香港众多桥梁的监控
非常漂亮的测试图片
欧进萍在土木学报上的文
章其实是跟风

Instrumentation and health monitoring of cable-supported bridges

Kai-Yuen Wong*,†

TMCA Division, Highways Department, The Government of Hong Kong Special Administrative Region, The Administration Building, North-West Tsing Yi Interchange, Tsing Yi Island, New Territories, Hong Kong

SUMMARY

Instrumentation and health monitoring of cable-supported bridges in Hong Kong involve the integration of instrumentation, analytical and information technologies with knowledge and experiences in design, construction, operation and maintenance of cable-supported bridges for continuous monitoring of performance throughout their life-span. A bridge health monitoring system, called the WASHMS (wind and structural health monitoring system) has been devised and operated by Highways Department to monitor the structure conditions of the Tsing Ma (suspension) Bridge, the Kap Shui Mun (cable-stayed) Bridge and the Ting Kau (cable-stayed) Bridge. The main objective of instrumentation and health monitoring is to detect and evaluate any symptoms of operational anomalies and/or deterioration or damage that may induce adverse effects on service or safety reliability through the processing and analysis of data collected from transducers and sensors. This WASHMS is composed of six modules, namely, the sensory system, the data acquisition and transmission system, the data processing and control system, the bridge health evaluation system, the portable data acquisition system and the portable inspection and maintenance system. The monitoring items are in general classified into three categories, namely, the loading sources (or input parameters) which include: wind, temperature, traffic (highway and railway) and seismic loadings; system characteristics (or system parameters) which include: static influence coefficients and global dynamic characteristics; and bridge responses (or output parameters) which include: variation in geometric configuration (or displacements of the bridges), stress/strain distribution, cable forces and fatigue stress estimation. This paper introduces the system architecture of the WASHMS with a brief functional description of each module. Categorization of the monitoring parameters and corresponding monitoring procedures are also outlined. The applications of the monitoring results are illustrated by some typical graphical plots such as wind-rose diagrams, spectral analysis, bogie loading and remaining fatigue life assessment. For successful design and operation of a bridge health monitoring system, conclusions are drawn with reference to the integration of knowledge and experience in four aspects: (i) design, construction, operation and maintenance of long-span bridges; (ii) instrumentation technologies for collection and processing of data; (iii) graphical CAD and numerical analytical technologies for modeling and analysis; and (iv) information technologies for transmission, processing and visualization of data. Copyright © 2004 John Wiley & Sons, Ltd.

传感器系统
数据获取系统
传输系统
数据过程
控制系统

KEY WORDS: instrumentation; health monitoring; cable-supported bridges; sensory system; data acquisition units; data transmission; data processing and analysis; structural health evaluation

*Correspondence to: Kai-Yuen Wong, TMCA Division, Highways Department, The Government of Hong Kong Special Administrative Region, The Administration Building, North-West Tsing Yi Interchange, Tsing Yi Island, New Territories, Hong Kong.
† E-mail: sebh.tmca@hyd.gov.hk

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1. INTRODUCTION

The importance of bridge health monitoring and management has been recognized by authorities of long-span bridges throughout the world in securing proper operation of their important lifetime infrastructures and in protecting the vast investments made in road and rail transportation network systems. Long-span bridges, particularly cable-supported bridges, are expensive to inspect, maintain or rehabilitate, and frequently pose complex technical problems. The process of elaborating instrumentation, measurement and analysis of dynamic response data, supplemented by *ad hoc* or routine inspection, maintenance and rehabilitation programs can be considered as a health monitoring and diagnostic operation. The measured and analyzed data obtained from proper instrumentation systems are valuable in enhancing the state of knowledge in structural performance of long-span bridges under environmental and applied loads. Such knowledge is essential for diagnosis and prognosis of structure conditions.

2. BRIDGE HEALTH MONITORING SYSTEMS IN HONG KONG

The long-span cable-supported bridges so far constructed in Hong Kong are the Tsing Ma Bridge (TMB) [1], the Kap Shui Mun Bridge (KSMB) [2], and the Ting Kau Bridge (TKB) [3]. In the coming four years, two cable-stayed bridges will be constructed in Hong Kong. The first is the cable-stayed bridge in Shenzhen Western Corridor (CSB-SWC) [4]; its construction will be completed by 2005. The second bridge is the Stonecutters Bridge [5] (SCB); its construction will be completed by 2007. Table I provides some information of the five bridges regarding type of bridge, type of traffic loading and major structural features. Figure 1 shows the locations of these five bridges in Hong Kong. Photos of the bridges are shown in Figures 2–6. All the bridges have been or will be equipped with a bridge health monitoring system, called the WASHMS [6], which is devised and operated by Highways Department. The design and installation of WASHMS for TMB, KSMB and TKB has been completed and is currently in operation; whereas the design of the WASHMS for CSB-SWC and SCB has been completed and is currently out to tender for supply and installation.

深圳西部通道

3. SYSTEM ARCHITECTURE

The system architecture of WASHMS is configured in six integrating modules comprising the sensory system (SS); data acquisition and transmission system (DA&TS); data processing and control system (DP&SC); structural health evaluation system (SHES); portable data acquisition system (PDAS); and portable inspection and maintenance system (PIMS). Each module is capable of stand-alone operation under normal and abnormal conditions irrespective of whether they are inter-connected together, i.e. failure of an individual module will have no detrimental effect on the remaining parts of the system. The WASHMS is in general split into four levels of operation. The first level refers to the collection and delivery of signals from SS to DA&TS. The second level refers to the conversion of the collected signals into digital data and transmission of the data to DP&S through fibre optic cabling network. The third level refers to the computer system which carries out the overall control of post-processing, archiving, display and data storage. The fourth level refers to the high-performance computer system which carries out the

Table I. Major structural features of cable-supported bridges in Hong Kong.

Bridge (year of completion)	Type	Traffic loading	Major Structural Features
Tsing Ma Bridge (1997)	Suspension bridge (double deck traffic)	6 Lanes of highway traffic on upper deck 2 Lanes of emergency highway traffic on lower deck 2 Lines of railway (passenger) traffic on lower deck	Span configuration: 63 + 76 + 355.5 m + 1377 + 4 × 72 (= 2159.5 m) Bridge-deck structure: (i) a continuous structure throughout the whole bridge length of 2159.5 m; (ii) streamlined box-shaped continuous steel truss girder deck with central air at main and MA Wan side spans; (iii) continuous steel truss girder at Tsing Yi side span 2 Concrete (H-portal type) pylons
Kap Shui Mun Bridge (1997)	Cable-stayed bridge (double deck traffic)	6 Lanes of highway traffic on upper deck 2 Lanes of emergency highway traffic on lower deck 2 Lines of railway (passenger) traffic on lower deck	Span configuration: 70 + 2 × 80 + 430 + 2 × 80 (= 820 m) Bridge-deck structure: (i) side spans: concrete deck; (ii) main span: composite truss girder deck with central air gap 2 Concrete (H-shape) pylons, each pylon with 2 (fan-type) cable planes
Ting Kau Bridge (1998)	Cable-stayed bridge (single deck traffic)	6 Lanes of highway traffic 2 Hard shoulders for emergency highway traffic	Span configuration: 127 + 448 + 475 + 127 (= 1177 m) Bridge-deck structure: (i) a continuous floating deck structure throughout the whole length of 1177 m; (ii) composite plate-girder deck with central air gap 4-span structure supported by 3 single-leg concrete towers, each with 4 (fan-type) cable planes
Shenzhen Western Corridor (2005)	Cable-stayed bridge (single deck traffic)	6 Lanes of highway traffic 2 Hard shoulders for emergency highway traffic	Span configuration: 74.585 + 74.585 + 99 + 210 (= 458.17 m) Bridge-deck structure: (i) non-streamlined continuous steel box girder deck throughout the whole bridge length of 458.17 m; (ii) monolithic deck and tower connection; (iii) wide bridge-deck (38.6 m)

Table I *Continued*.

Bridge (year of completion)	Type	Traffic loading	Major Structural Features
			Asymmetric single-cable plane (fan-type) Inclined single-leg concrete tower
Stonecutters Bridge (2007)	Cable-stayed bridge (single deck traffic)	6 Lanes of highway traffic 2 Hard shoulders for emergency highway traffic	Span configuration: $69.25 + 2 \times 70 + 79.75 + 1018 + 79.75 + 2 \times 70 + 69.25$ ($= 1596$ m) Bridge-deck structure: (i) Side spans: concrete deck; (ii) Main span: steel deck with separated streamlined continuous twin box girder deck; (iii) Monolithic connections between deck and piers 2 Single-leg composite towers, each with 2 cable planes (fan-type)

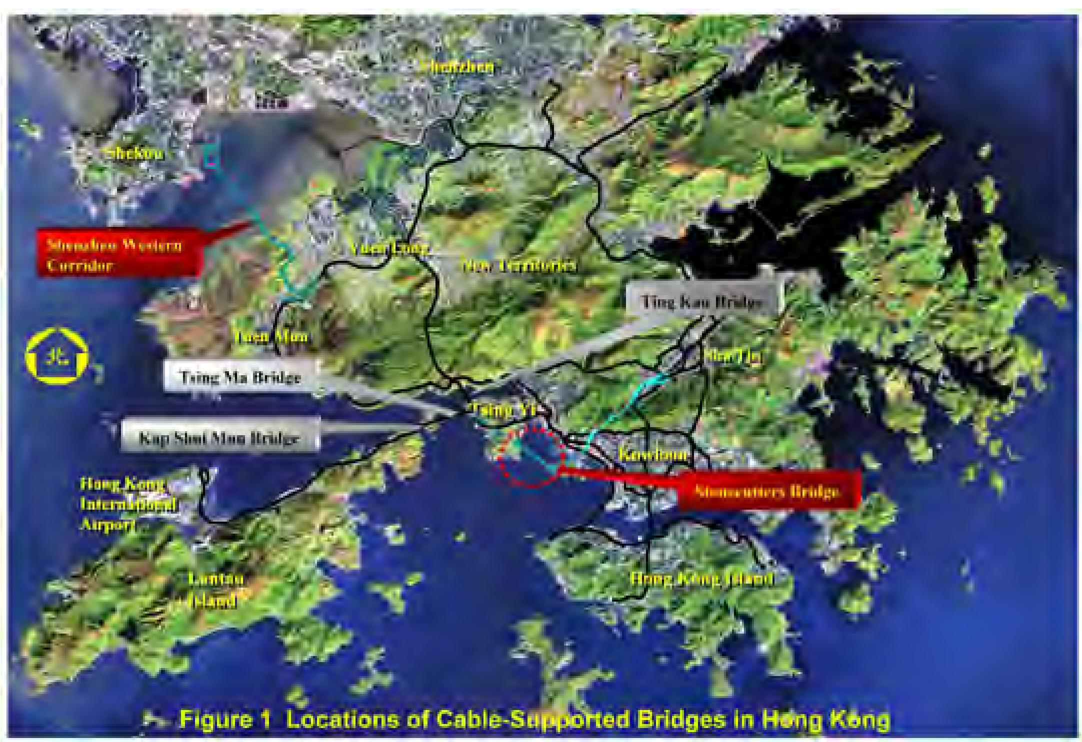

Figure 1. Locations of cable-supported bridges in Hong Kong.

Figure 2. Tsing Ma Bridge.

Figure 3. Kap Shui Mun Bridge.

Figure 4. Ting Kau Bridge.

Figure 5. Shenzhen Western Corridor (artist's impression).

Figure 6. Stonecutters Bridge (artist's impression).

bridge heath evaluation works and the generation of monitoring reports. In the event of failure of any hardware at any level, the hardware at all other levels will continue normal operation. In the case of power failure in an individual unit, the operation of other units will not be affected. This is because the buffer memory of each data acquisition unit in DA&TS is able to collect data continuously for a period of at least 12 h. On power restoration, the WASHMS is capable of arranging an orderly staging up of each lower level unit, and obtaining status reports from each data acquisition unit such that no data overloading will occur. A brief functional description of these six modules is given in the following sections.

3.1. Sensory system (SS)

The SS is comprises nine types of sensor: anemometers, temperature sensors, servo-type accelerometers, dynamic weigh-in-motion sensors, global positioning systems (GPS), level sensing stations, displacement transducers, weldable strain gauges and CCTV video cameras. These sensors collect the signals and deliver them to the PC-based data acquisition units through category 5 unshielded twisted-pair (UTP) cables. Tables II–V show the summary of information for the sensory system used in TMB, KSMB, TKB and PDAS. The global layouts of the sensory systems and data acquisition systems in TMB, KSMB and TKB are shown in Figures 7–9 respectively. The details of the sensors are shown in Figures 10–27 and the brief functional descriptions of these figures are given as follows:

(i) Figures 10 and 11 illustrate the three-dimensional and two-dimensional wind measurements in Tsing Ma Bridge by ultrasonic and propeller types of anemometers.
(ii) Figures 12–17 illustrate the types of temperature measurements in structural steel, air, steel cladding, asphalt pavement and main suspension cables.
(iii) Figures 18 and 19 illustrate the measurements of highway loading.
(iv) Figures 20 and 21 illustrate the measurements of global dynamic characteristics of bridge deck sections and main suspension cables.
(v) Figures 22 and 23 illustrate the measurements of the variation of geometric configuration by GPS. Figure 22 shows the GPS and data-logger for base reference in a stationary location, whereas Figure 23 shows the GPS and the data-logger for measurement of movements at deck levels in the Tsing Ma Bridge and the Ting Kau Bridge and main suspension cable in the Tsing Ma Bridge.

Table II. Summary of information for sensory system (excluding GPS and CCTV cameras) installed in TMB and KSMB.

Data type	Sensor type	Signal type	Sensor	Channel	Sampling rate per sensor (Hz)	Total raw data** archived per hour (MB)
Wind	Ultrasonic anemometer	Digital	8	24	02.56	0.98
	Propeller anemometer	Analog	4	10		
Temperature	TMA1 (steel bolt)	Digital	86	10	0.07	0.25
	TMA2 (steel-adhesive)	Digital	45			
	TMA3 (air)	Digital	15			
	TMA4 (steel cladding)	Digital	2			
	TMA5 (concrete)	Digital	160			
	TMA6 (asphalt)	Digital	8			
	TMC (cable)	Digital	23	1		
Traffic	Bending plate	Digital	7	2		0.22
Displacement	Longitudinal movement	Digital	1	1	02.56	0.11
	Lateral movement	Analog	3	3		
Leveling	Level-sensing station	Digital	14	56	02.56	1.99
	Level-sensing datum	Digital	4	16		
Acceleration (fixed)	Uniaxial accelerometer	Analog	9	9	25.6*	7.23
	Biaxial accelerometer	Analog	12	24		
	Triaxial accelerometer	Analog	2	6		
Strain	Single strain gauge	Analog	60	60	25.6, 51.2 for transient	52.68
	Pair strain gauge	Analog	68	68		
	Rosette strain gauge	Analog	12	36		
Total			543	326		63.46

*The sampling rate will be increased to 51.2 Hz during filed vibration measurements and typhoons.
**Data in binary format.

Table III. Summary of information for sensory system (excluding GPS and CCTV Cameras) installed in TKB.

Data type	Sensor type	Signal type	Sensor	Channel	Sampling rate per sensor (Hz)	Total raw data** archived per hour (MB)
Wind	Ultrasonic Anemometer	Digital	4	12	2.56	0.61
	Propeller Anemometer	Analog	3	9		
Temperature	TMA1 (steel bolt)	Digital	15	8	0.07	0.02
	TMA3 (air)	Digital	12			
	TMA5 (concrete)	Digital	48			
	TMA6 (asphalt)	Digital	8			
Traffic	Bending plate	Digital	6	2		0.35
Displacement	Longitudinal movement	Digital	2	2	2.56	0.06
Acceleration (fixed)	Uniaxial accelerometer	Analog	24	24	25.6*	12.42
	Biaxial accelerometer	Analog	20	40		
	Triaxial accelerometer	Analog	1	3		
Strain	Single strain gauge	Analog	66	66	25.6, 51.2	42.41
	Rosette strain gauge	Analog	22	66		
Total			231	227		55.87

*The sampling rate will be increased to 51.2 Hz during filed vibration measurements and typhoons.
**Data in binary format.

Table IV. Summary of information for GPS and CCTV cameras installed in TMB, KSMB and TKB.

Data type	Sensor type	Signal type	Sensor	Channel	Sampling rate per sensor (Hz)	Total raw data archived per hour (MB)
GPS	Rover station	Digital	27	27	10	157*
	Reference station	Digital	2	2		
IMS	CCTV video cameras	Video	16†	16	2.5	1811**
Total			45	45		1968

*Data in text format.
**Data in audio video interleaved format.
†There are 97 CCTV cameras installed in TMCA for traffic operation, but for bridge health monitoring, only any 16 of them can be displayed simultaneously.

Table V. Summary of Information for Portable Sensory System used by PDAS.

Data type	Sensor type	Signal type	Sensor	Channel	Sampling rate per sensor (Hz)	Total raw data archived per hour (MB)
Acceleration (removable)	Uniaxial accelerometer	Analog	24	48	51.2	9.44
	Biaxial accelerometer	Analog	5	5		
Total			29	Max. 32*		9.44

*For simultaneously data acquisition.

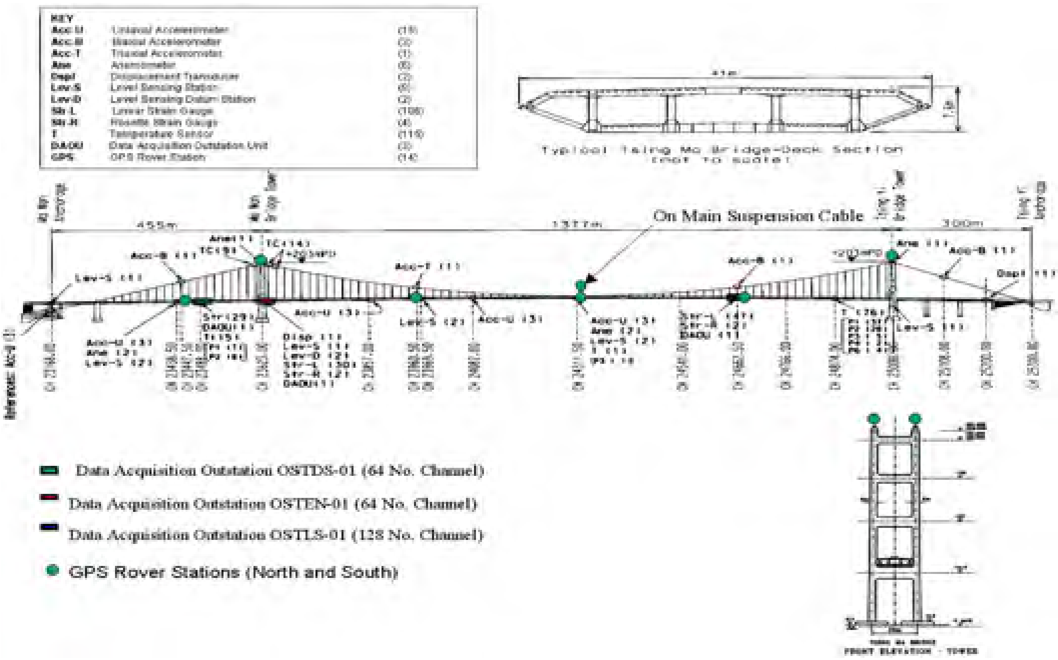

Figure 7. Layout of sensory system and data acquisition outstations, Tsing Ma Bridge.

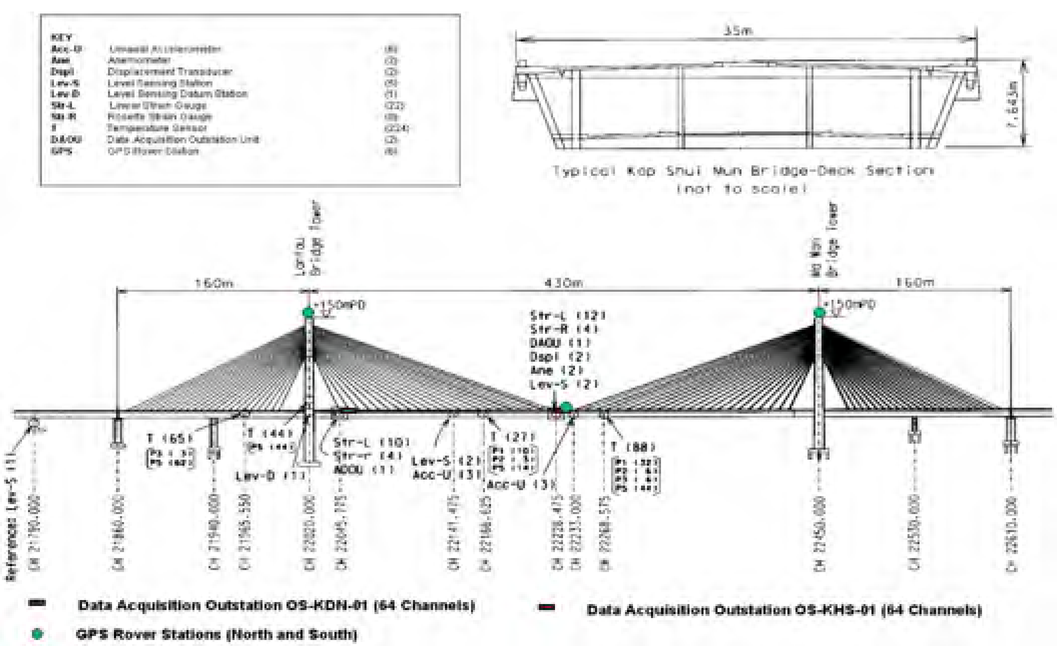

Figure 8. Layout of sensory system and data acquisition outstations, Kap Shui Mun Bridge.

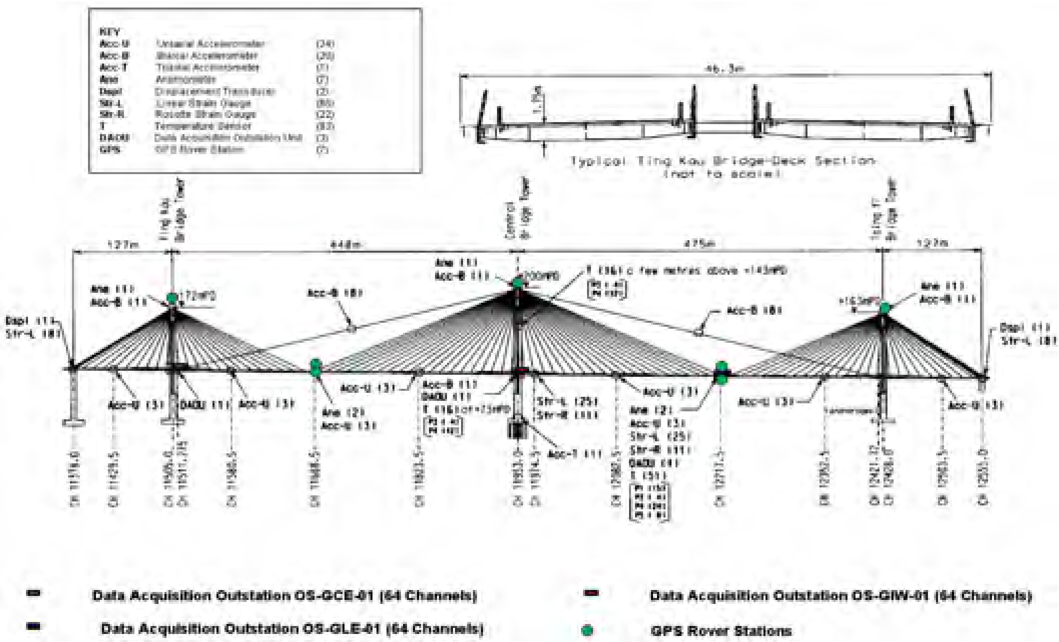

Figure 9. Layout of sensory system and data acquisition outstations, Ting Kau Bridge.

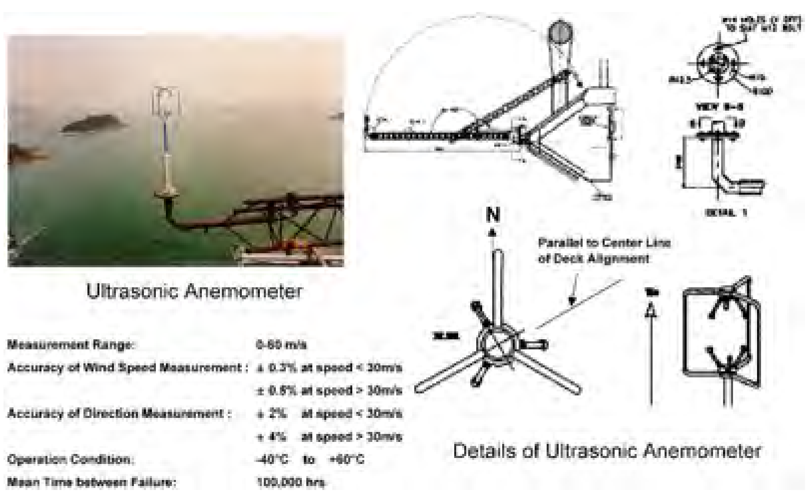

Figure 10. Ultrasonic anemometer at deck level, Tsing Ma Bridge.

(vi) Figure 24 illustrates the measurements of longitudinal deck movement in the Ting Kau Bridge.
(vii) Figures 25–27 illustrate the measurements of strains in truss and cross-frame members of the Tsing Ma Bridge and in rocker bearings of the Ting Kau Bridge.

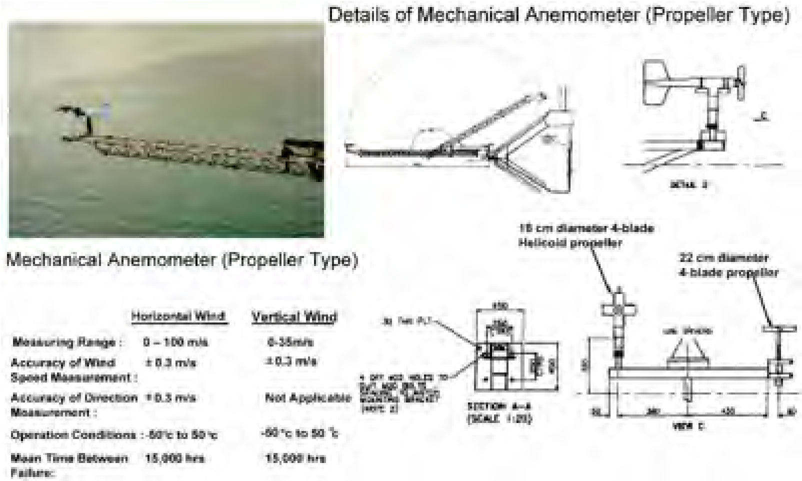

Figure 11. Propeller anemometer at deck level, Tsing Ma Bridge.

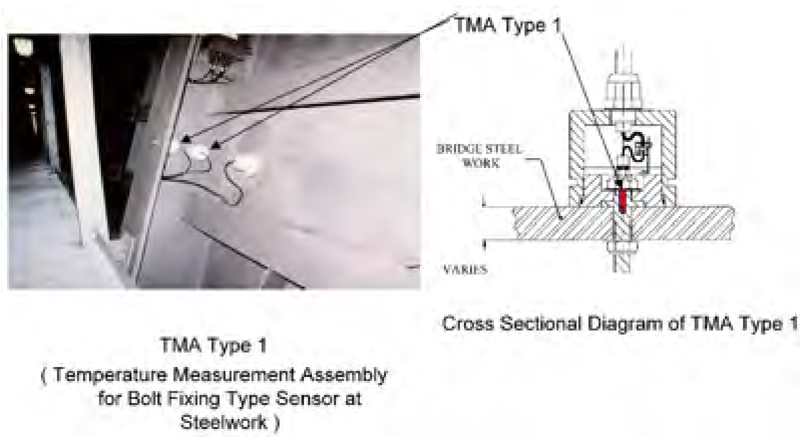

Figure 12. Temperature measurement assembly type 1, South cross-frame, Kap Shui Mun Bridge.

3.2. Data acquisition and transmission system (DA&TS)

The DA&TS are PC-based data acquisition units (DAUs) connected by fibre optic network. The architecture of the fibre optic network is either the token ring system used in TMB, KSMB and TKB or the 100/1000 Mbps Ethernet system to be adopted for CSB-SWC and SCB. One DAU usually controls 64–128 high-speed data channels. The number of DAU is usually dependent upon the number of high-speed data channels while its location is dependent on the location of analog-type sensors with low resistance, low sensitivity and nonlinear output characteristics, such as weldable or foiled-type strain gauges. In WASHMS, there are 6 DAUs (which control 326 data channels) in TMB and KSMB and 3 DAUs (which control 227 data channels) in TKB. Figure 28 shows the typical connection among sensors, DAU and fibre optic network. Figure 29 shows the token ring system layout for TMB, KSMB and TKB.

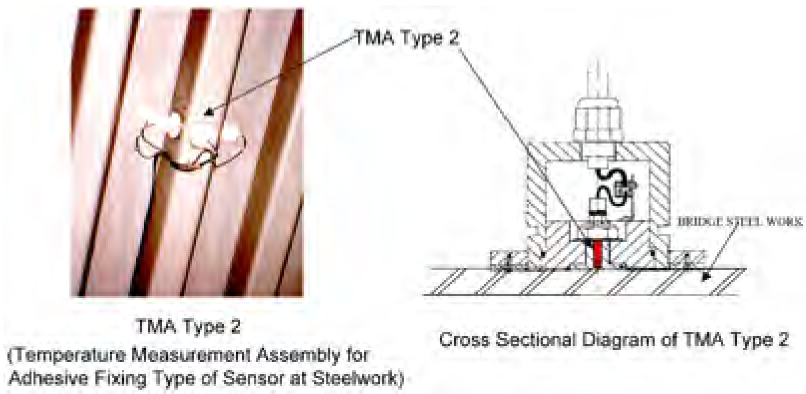

Figure 13. Temperature measurement assembly type 2, at South upper deck trough plate, Tsing Ma Bridge.

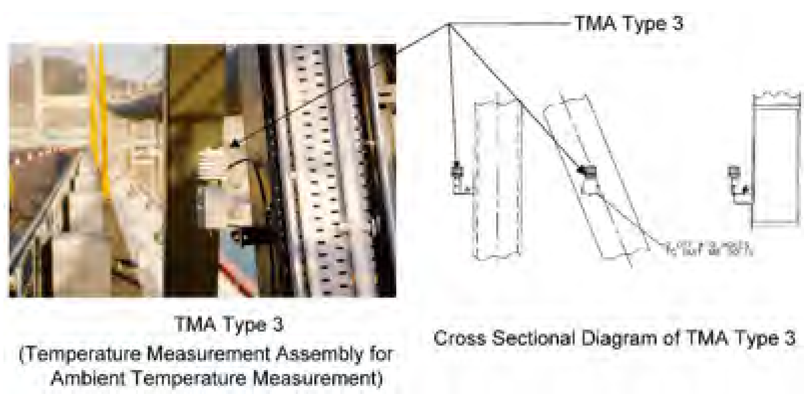

Figure 14. Temperature measurement assembly type 3, upper deck, Tsing Ma Bridge.

3.3. Data processing and control system (DP&CS)

The DP&CS in WASHMS comprises two UNIX-based 64-bit Alpha Servers and two 32-bit SGI Intel-based (Quad-CPU) Visual Workstations. The DP&SC carries out the overall control of data acquisition, processing, transmission, filing, archiving, backup, display and operation. The current application software systems for WASHMS are customized MATLAB, customized GPS software and MATLAB data analysis suite. In addition to MATLAB data analysis suite, LABVIEW software will be used in the WASHMS for respective CSB-SWC and SCB. This is because the hardware of the DAUs are based on a PXI real-time controller which is best compatible with LABVIEW software for data acquisition and associated work. All data processing and analysis tools are required to have the capabilities of deriving or computing the required functions in amplitude domain, time domain, frequency domain and frequency count, as shown in Figure 30.

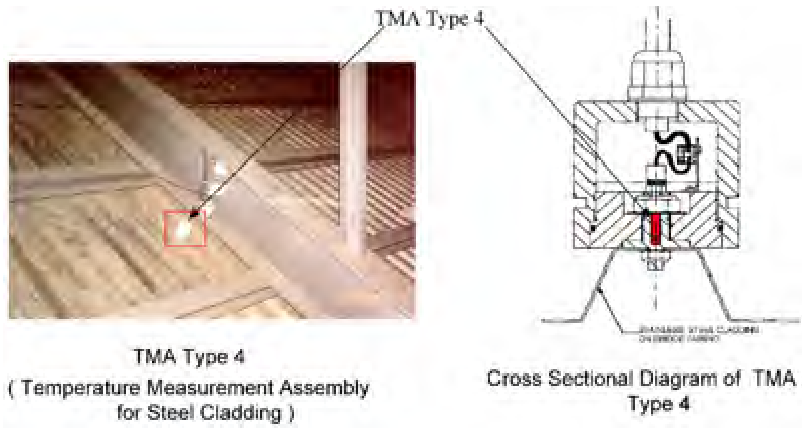

Figure 15. Temperature measurement assembly type 4, South side fairing, lower deck Tsing Ma Bridge.

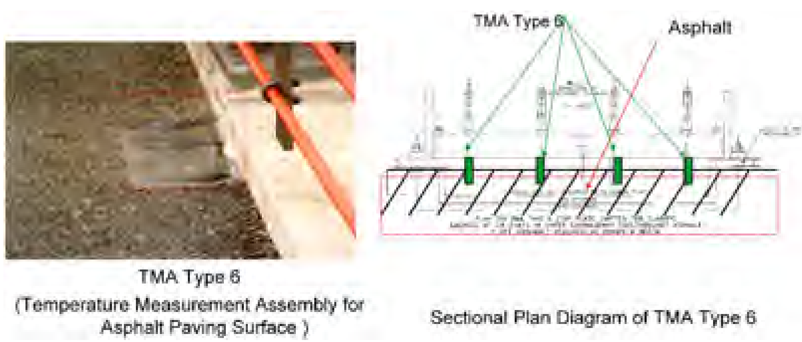

Figure 16. Temperature measurement assembly type 6, South carriageway (edge), Kap Shui Mun Bridge.

3.4. Structural health evaluation system (SHES)

The SHES in WASHMS comprises one UNIX-based 64-bit (Quad-CPU) Alpha server and one 64-bit UNIX-based Alpha workstation. The Sever is used for structural health evaluation works based on a customized bridge rating system, together with advanced finite element solvers such as MSC/NASTRAN, ANSYS/Mulitiphysics, ANSYS/LS-DYNA, ANSYS/FE-SAFE, and MATLAB's data analysis suite. The workstation is used for the preparation and display of graphical input and output files based on advanced graphical Input/Output tools such as MSC/PATRAN and ANSYS/7.1. The functional applications of those commercial finite element and numerical software systems are briefly outlined as follows:

(i) the MSC/NASTRAN, which works with the graphic interface MSC/PATRAN, has been the WASHMS's basic finite element software packages for local and global structural evaluation of the cable-supported bridges under environmental and applied loads such as wind, seismic, temperature, highway and railway loadings since 1993;

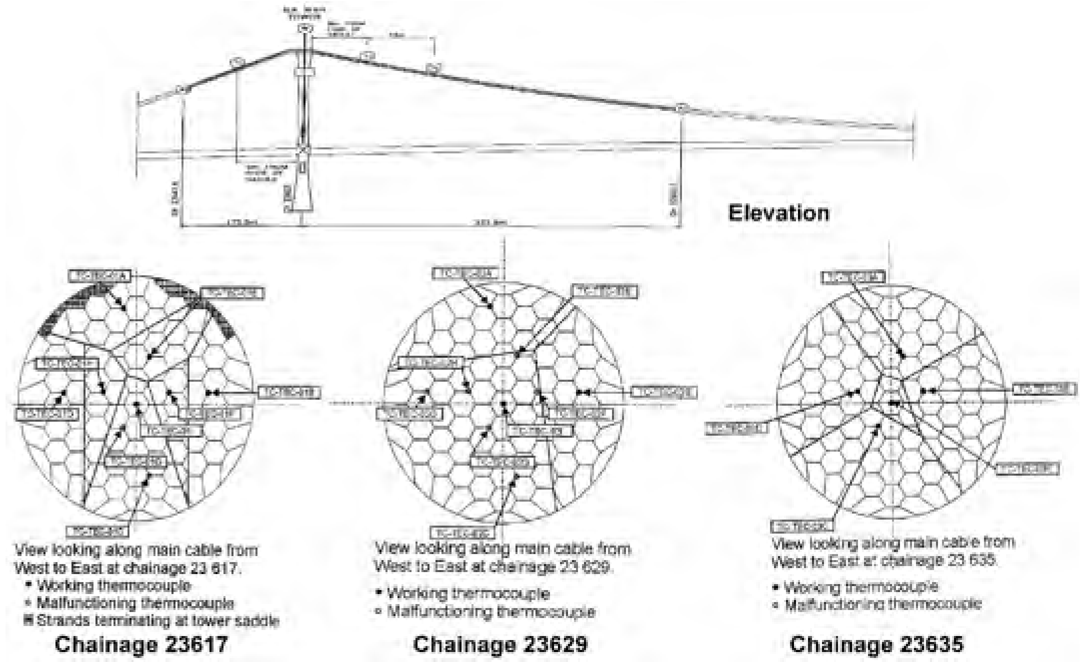

Figure 17. Thermocouple positions in main suspension cable, Tsing Ma Bridge.

(ii) the ANSYS/Multiphysics, which works with the graphic interface ANSYS/7.1, is intended to supplement or take up the work of MSC/NASTRAN and MSC/PATRAN because after 2002, both updated versions of MSC/NASTRAN and MSC/PATRAN are no longer supported in operation under UNIX-based Alpha servers and workstations;

(iii) the ANSYS/LS-DYNA, which works with the graphic interface ANSYS/7.1, is used to carry out impacting analysis such as a ship impacting tower/pier or a car impacting parapets;

(iv) the ANSYS/FE-SAFE is used to carry out fatigue analysis;

(v) the MATLAB data analysis suite is used to carry out data processing and analysis work such as identification of the bridge's global dynamic characteristics from the acceleration data.

3.5. Portable data acquisition system (PDAS)

The PDAS in WASHMS comprises a 32-channel PC-based data-logger, 24 portable biaxial servo-type accelerometers, 5 portable uniaxial servo-type accelerometers and 16 cable drums (each drum 100 m in length) of category 5 UTP cables and equipped with a customized LABVIEW software system for acquisition, processing, archiving, storage and display. It is used to measure the tensile forces in cables and to assist the fixed servo-type accelerometers to identify the global dynamic characteristics of the bridges. The collected data will be directly transferred to the DP&SC or SHES for spectrum analysis.

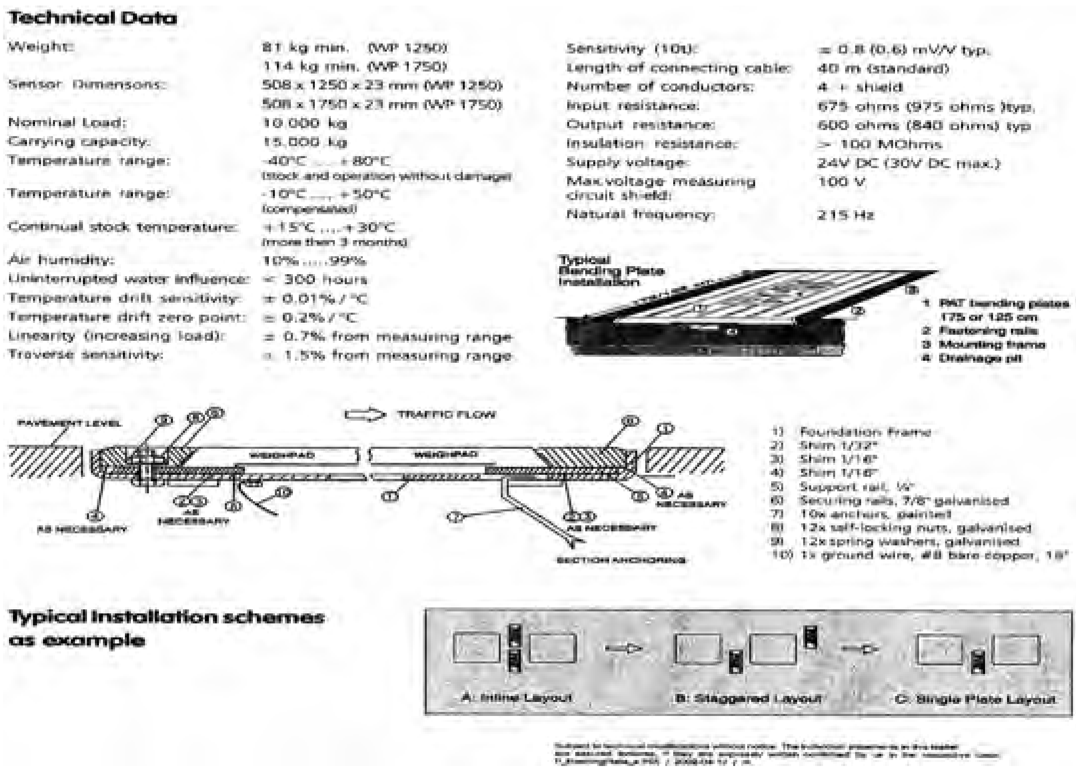

Figure 18. Dynamic weigh-in-motion sensors, installation details on carriageway.

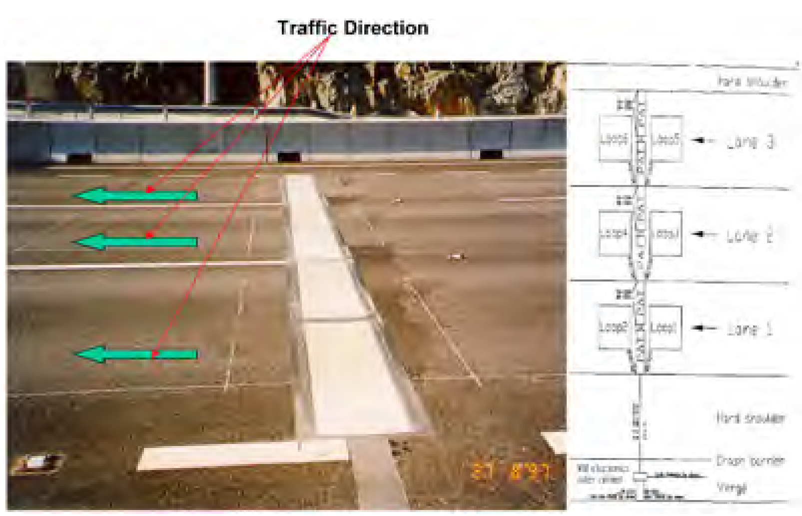

Figure 19. Dynamic weigh-in-motion sensors for Lantau fixed crossing.

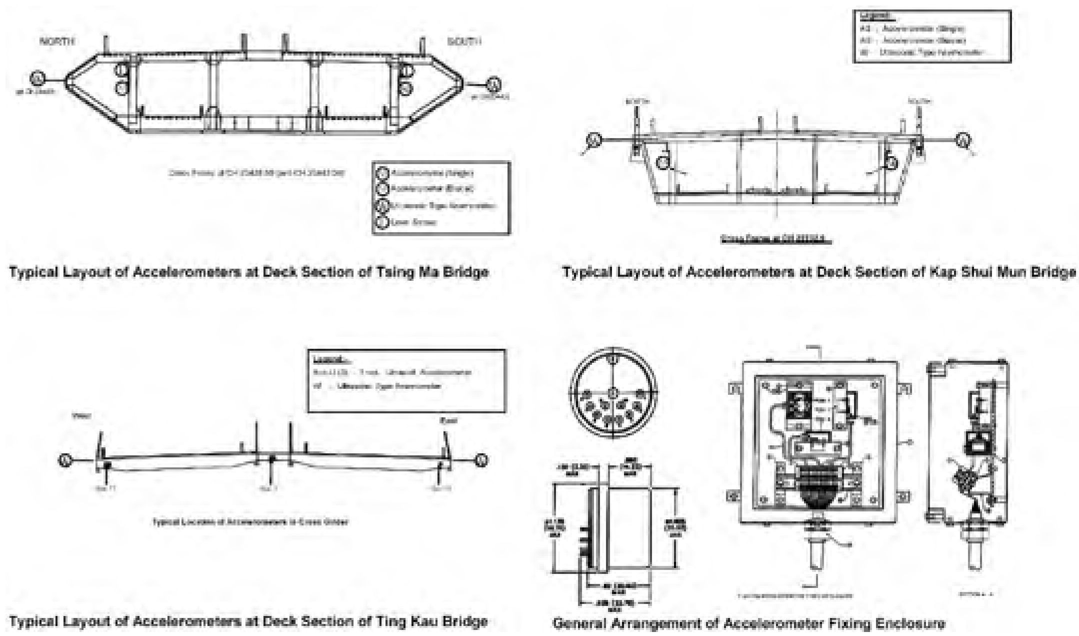

Figure 20. Typical layout of accelerometers in bridge decks.

3.6. Portable inspection and maintenance system (PIMS)

The PIMS in WASHMS comprises three portable notebook (Intel-based) computers. They are used to carry out the inspection and maintenance work on the DA&TS and SS. Another major function of the PIMS is to facilitate the system inspection and maintenance by storing and updating all the system design information including all drawings and all operation and maintenance manuals.

4. CATEGORIZATION AND PROCEDURES OF MONITORING

In the WASHMS for TMB, KSMB and TKB, the monitoring parameters can be categorized into three groups: the loading sources (or input parameters) which include wind, temperature, traffic (highway and railway) and seismic loadings, the system characteristics (or system parameters) which include static influence coefficients and global dynamic characteristics, and the bridge responses (or output parameters) which include geometric configuration (or displacements of the bridge), cable forces, stress/strain distribution and fatigue stress estimation. Table VI provides a list of required sensors and major parameters in each group. The functional descriptions of these parameters are given in the following sections.

4.1. Wind loading

Wind loading is always of great importance in the structural design of long-span cable-supported bridges. It usually consists of time-averaged wind forces and some contribution of the

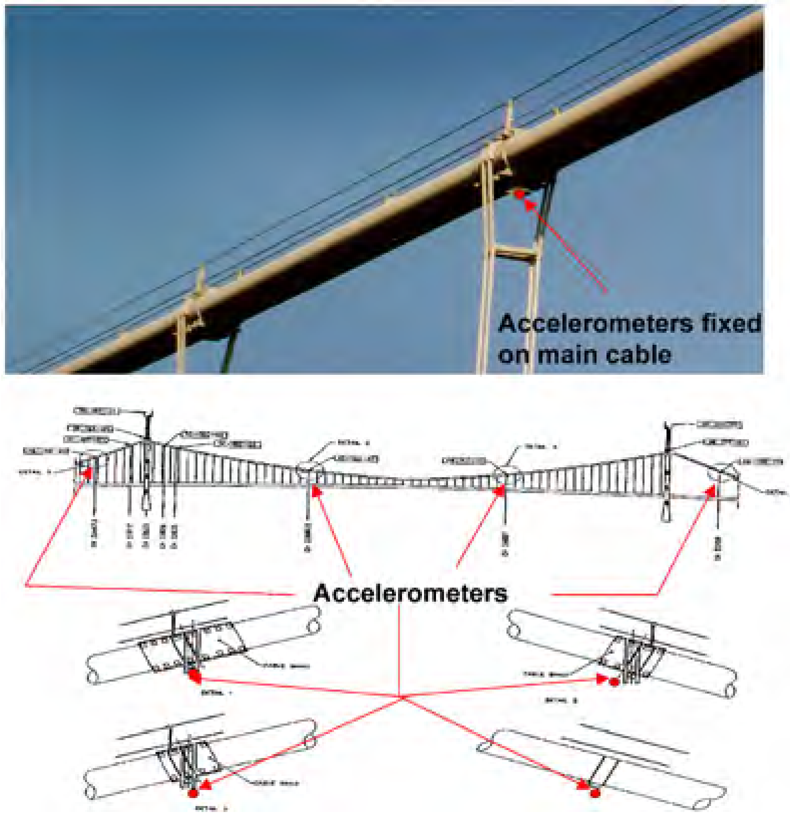

Figure 21. Accelerometers on main cable, Tsing Ma Bridge.

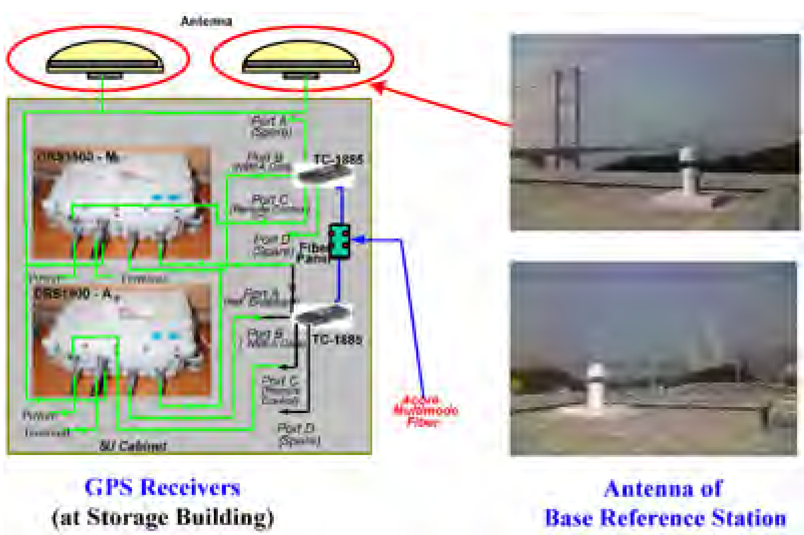

Figure 22. GPS base reference station roof of storage building near Tsing Ma Bridge.

Figure 23. Typical GPS sensory system: GPS rover station at upper deck level and main suspension cables.

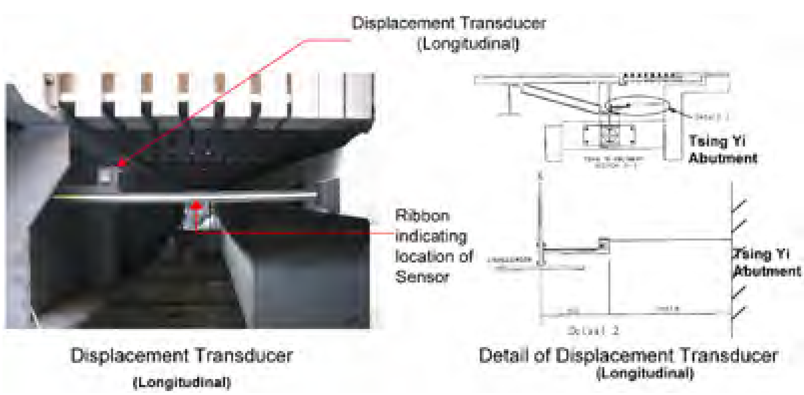

Figure 24. Displacement transducer (longitudinal), at Tsing Yi abutment, Ting Kau Bridge.

dynamic response due to the wind fluctuation, but there still remain uncertainties in the expression of the wind characteristics for defining the accuracy and reliability of wind loading. In order to overcome these uncertainties, it is essential to compile information on the wind at the bridge site with the design parameters and assumptions. In this regard, the wind load effect monitoring in WASHMS involves the monitoring of typhoons, monsoons and high winds (i.e. any wind with a mean speed greater than 5 m/s) which includes: (1) to record/archive the time-history data of wind speeds in three orthogonal directions u, v and w from ultrasonic-type anemometers at deck levels and the time-history data of wind speeds and directions in the horizontal plane at the tower tops from propeller-type anemometers; (2) to draw wind-rose diagrams of mean and gust winds, plot wind incidences against wind speeds and derive/plot the

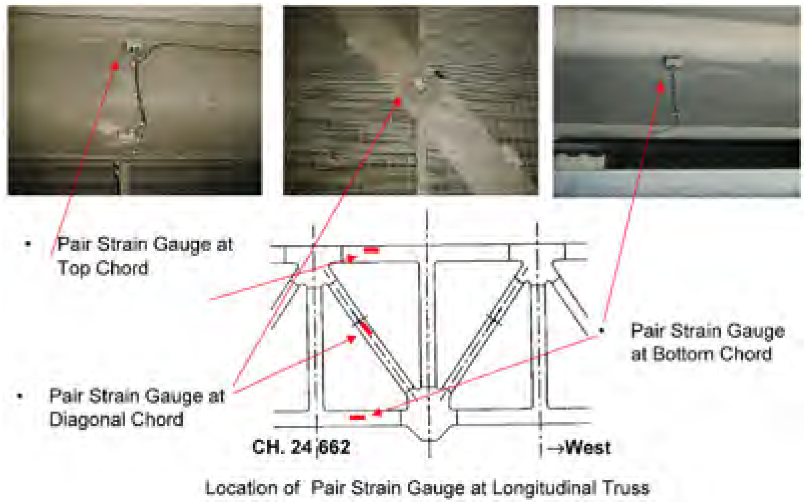

Figure 25. Strain gauges installed at longitudinal truss of Tsing Ma Bridge.

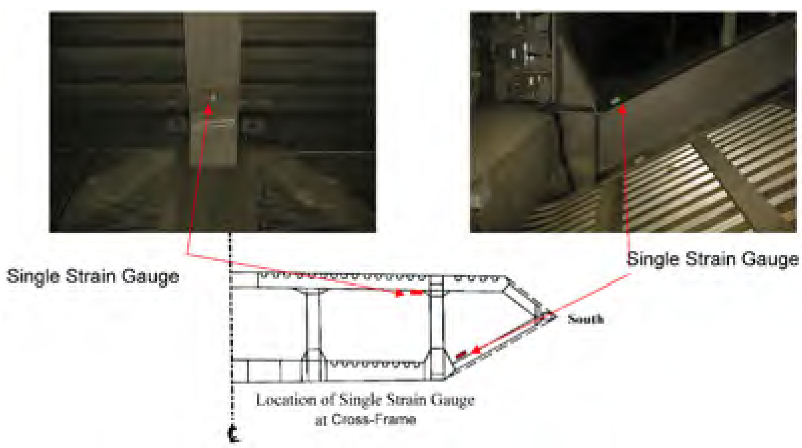

Figure 26. Single strain gauge at cross-frame of Tsing Ma Bridge.

gradient and gust wind speed profiles; (3) to compute the wind turbulent intensities, time and length scales, spectra, co-spectra and coherences, if any; (4) to plot the bridge responses against wind speeds for bridge components installed with accelerometers, displacement transducers, GPS and strain gauges (which are used for comparison with results obtained from wind tunnel testing of the bridges during design and construction stages); and (5) to plot stress demand ratio diagrams in wind bracing members installed with strain gauges. Upon obtaining sufficient wind data/results, extreme value analysis will be carried out to predict the extreme wind conditions under the respective serviceability limit state and ultimate limit state. Figures 31–33 are illustrations of wind loading monitoring.

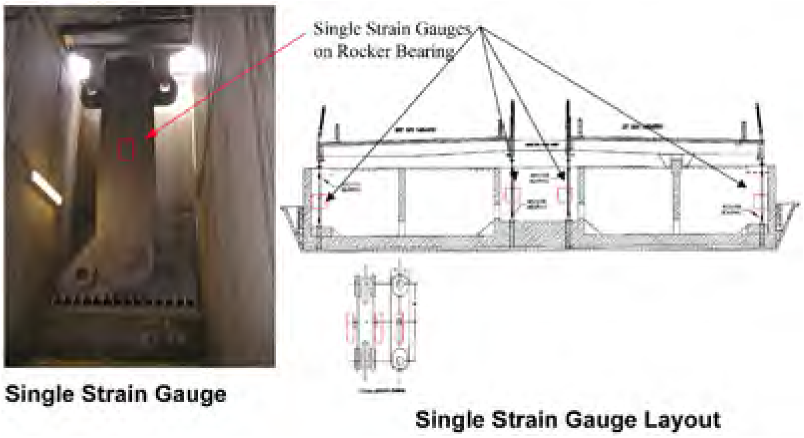

Figure 27. Single strain guage on rocker bearing at Tsing Yi abutment, Ting Kau Bridge.

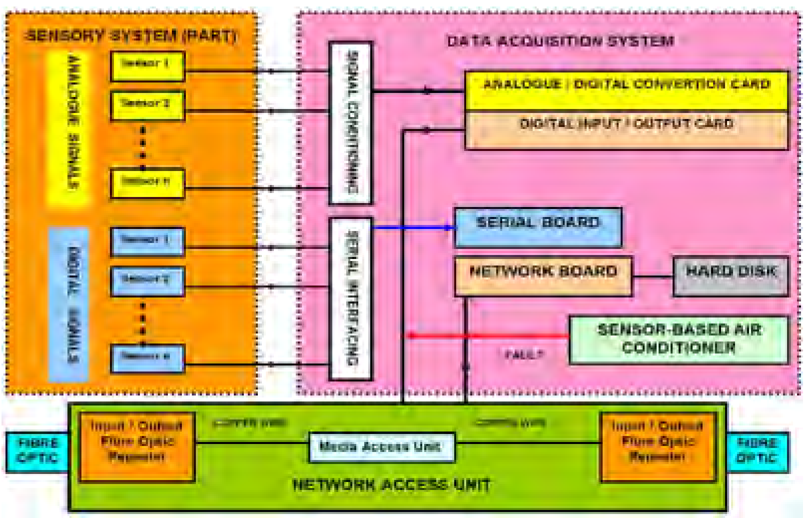

Figure 28. System layout of typical data acquisition system.

4.2. Temperature loading

The thermal response of the bridge is affected by ambient temperature, wind speed fluctuations, material properties, surface characteristics and section geometry. The temperature or thermal load effect monitoring in WASHMS is divided into four steps: (1) to measure the temperatures in air, asphalt pavement, stainless steel and plotting of the variation of temperatures vs time (hourly, daily, monthly and annually); (2) to derive or compute the effective bridge temperatures (EBT) and the differential temperatures (DT) from measurement points in representative or critical sections of bridge decks, towers and cables and to plot the derived or computed results vs

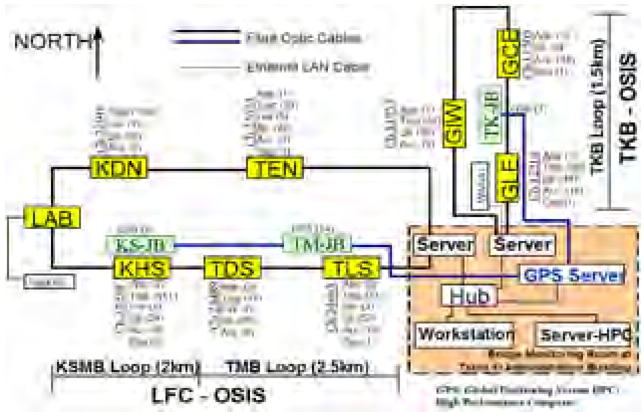

Figure 29. Network layout of LFC-OSIS and TKB-OSIS.

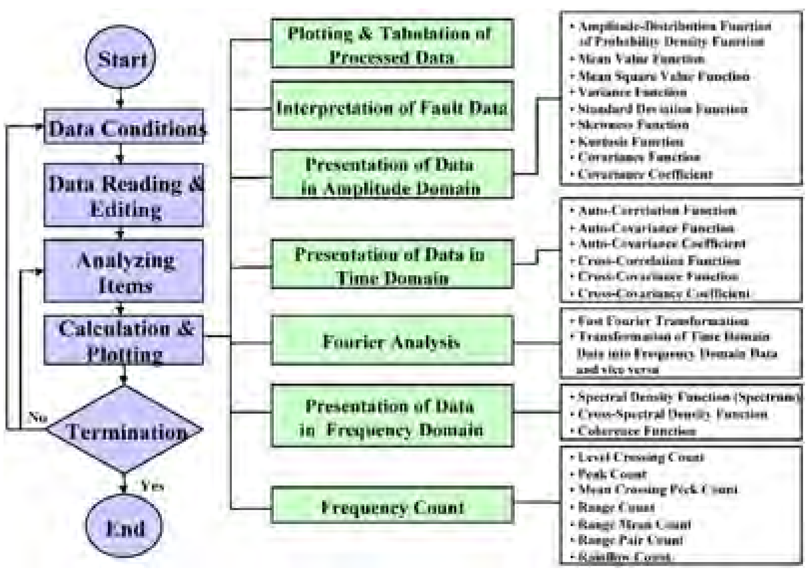

Figure 30. WASHMS flow chart for random data processing and analysis.

time (hourly, daily, monthly and annually) for EBT and the distribution of maximum and minimum temperatures throughout the sectional depth for DT; (3) to estimate/calculate the stress levels induced in the bridge superstructure by the measured thermal gradient; and (4) to plot the thermal movements of deck against temperature at critical locations such as middle of main span for vertical movements and at movement joints for longitudinal movements. The measured results will be used for comparison with the design values. The sensors for this category of monitoring are all temperature sensors, displacement transducers, strain gauges and GPS. Figures 34 and 35 are illustrations of temperature loading monitoring.

4.3. Highway loading

For long-span bridges, a traffic jam is the major design assumption in deriving the required intensity of highway loading. The intensity of highway loading relies on the traffic-loaded length. This traffic-loaded length is based on: (1) the number of traffic jams formed daily; (2) the positions, the duration and the pattern of vehicular distribution of the traffic jams; (3) the

Table VI. List of sensors and major monitoring parameters.

Monitoring category	Monitoring items	Required types of sensor	Major monitoring parameters
Loading sources	Wind loading	Ultrasonic anemometers (usually at deck levels)	Mean and gust wind-rose diagrams
		Propeller anemometers (usually at tower-tops)	Gradient and gust wind speed profiles
		Barometers*	Wind incidences
		Rainfall gauges*	Wind turbulence intensities
			Time and length scales of turbulent winds
			Turbulent wind spectra
			Horizontal and vertical coherences[1]
	Temperature loading	Platinum RTD type for measuring the temperatures in structural steel, concrete, asphalt pavement and air	Effective bridge temperatures
		Thermocouplers for cables	Different temperatures
			Air temperatures
			Asphalt pavement temperatures
	Highway loading	Dynamic weigh-in-motion sensors (bending-plate type)	Gross vehicular weight per vehicle
			Axle-load distributions
		Weldable strain gauges	HA lane factor
		CCTV video cameras	Traffic patterns
			Bridge deflection under traffic jams
			Highway loading spectrum
			Strain/stress distribution in truss/girder
	Railway loading	Weldable strain gauges	Bogie loads each train line on
		CCTV video cameras	Train loading spectrum
			Strain/stress distribution in truss/girder
	Seismic loading	Servo-type accelerometers	Acceleration spectra near tower and anchorage
			Deck and tower response spectra
	Corrosion status†	Corrosion sensors*	Ingress rate of deleterious substances migrating into concrete such as chlorides and carbon-dioxide (concrete towers)
		Hygrometers*	
System characteristics	Static influence coefficients	Level sensing stations†	Influence lines for train loading

Table VI *Continued.*

Monitoring category	Monitoring items	Required types of sensor	Major monitoring parameters
		Global positioning systems	Influence lines for highway loading
		Weldable strain gauges	Influence surfaces for deck plates
	Global dynamic characteristics	Servo-type accelerometers	Modal frequencies
		Weldable strain gauges	Mode shapes
			Modal damping ratios
			Mass participation factors
Bridge responses	Tensile forces in cables	Servo-type accelerometers	Tensile force in individual cable (including main cables, suspenders and stay cables)
	Geometric configuration	Global positioning system	Thermal movements of cables and deck
		Level-sensing stations†	Wind-induced movements in cables, deck and towers
		Displacement transducers	Seismic-induced movements in deck
		Servo-type accelerometers	Highway-induced movement in deck and cables‡
		Anemometers	Railway-induced movement in deck and cables‡
		Temperature sensors	Creep and shrinkage effects in concrete towers
		Vibrating-wire strain gauges*	
	Strain/stress distribution	Weldable strain gauges	Stress/force distributions in rocker bearings
			Stress/force distribution in horizontal bracing members for wind monitoring
		Vibrating-wire strain gauges*	Stress/force distribution in truss/girder members
			Stress/force demand ratios in key components
	Fatigue stress estimation	Weldable strain gauges	Rainflow count of cycles at different stress levels

*For Stonecutters Bridge and the cable-stayed bridge in Shenzhen Western Corridor only.
†For Tsing Ma Bridge and Kap Shui Mun Bridge only.
‡For Tsing Ma Bridge only.

assumptions adopted for the traffic flow in traffic jams. Highway loading effect monitoring in WASHMS involves two steps: (1) to measure the traffic flow and traffic loads by the dynamic weigh-in-motion sensors installed in the carriageways, which are used to identify the different types of axle-loads and different categories of vehicles passing through the bridges, and (2) to establish the highway loading spectrum basing on strain/stress results for fatigue damage assessment in key structural components (such as deck trough sections). The types of sensors for this category of monitoring are dynamic weigh-in-motion sensors, strain gauges, level-sensing stations, GPS and CCTV cameras. Figures 36 and 37 are some illustrations of highway loading monitoring.

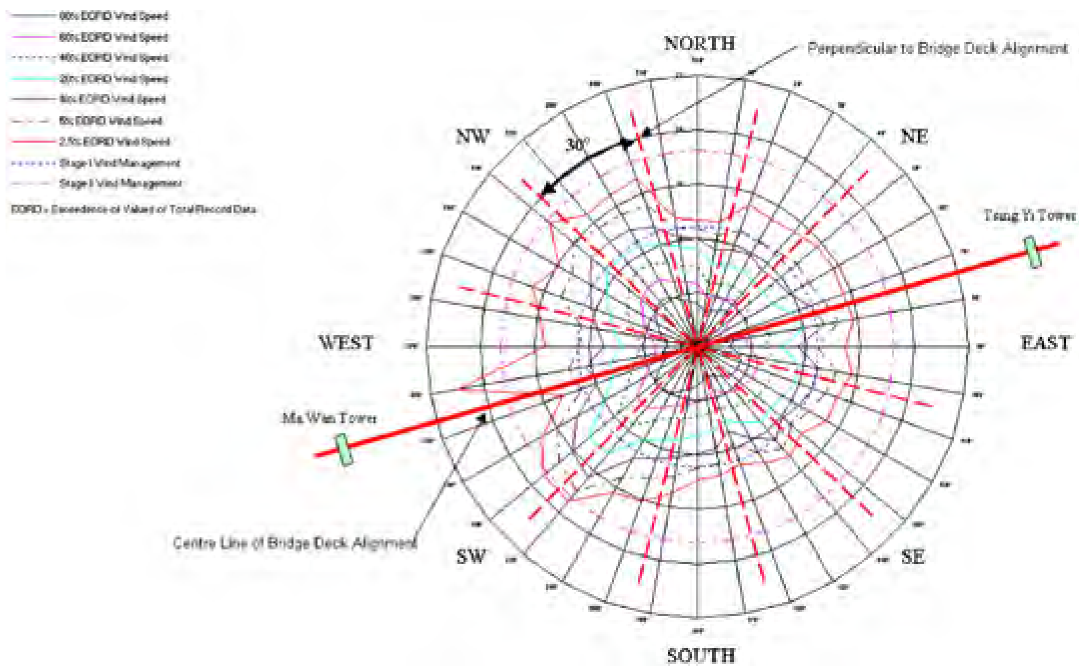

Figure 31. Deck level wind-rose diagram (3-second wind speed) at mid-central span (wind data July 1997–December 2002).

4.4. Railway loading

The railway loading on TMB and KSMB is another major parameter for traffic load design. The railway trackform of TMB and KSMB are supported by longitudinal I-girders at the soffit of the stiffening deck sections. Railway load is therefore distributed to the stiffening deck sections through the longitudinal I-girders. As there is no sensor to measure the dynamic loading exerted by trains to the bridge, railway loading monitoring is carried out indirectly by using strain gauges installed in the longitudinal I-girders. The strain and displacement results are processed to establish the influence lines (force and displacement) for each set of bogie loads. The influence line for a line of train (which consists of 14 sets of bogie loads for a 7-car train) is obtained by superposition of the 14 sets of influence lines. The strain results are also processed to develop a railway loading spectrum for fatigue loading assessment. The types of sensors involved in this category of monitoring are weldable strain gauges, GPS and level sensing stations. Figure 38 is the plot of train loading monitoring.

4.5. Seismic loading

The monitoring of seismic loading is the measurement of the acceleration spectra at tower base and anchorage base and also the corresponding deck and tower response spectra during seismic events. The type of sensor for this monitoring is accelerometers. Since the recorded peak ground acceleration at tower and anchorage bases are 0.0031 and 0.0041 g, respectively, which are considered negligible in comparison with the design value of 0.07 g. Therefore, until now, not much work has been done on this monitoring, and no typical results can be presented.

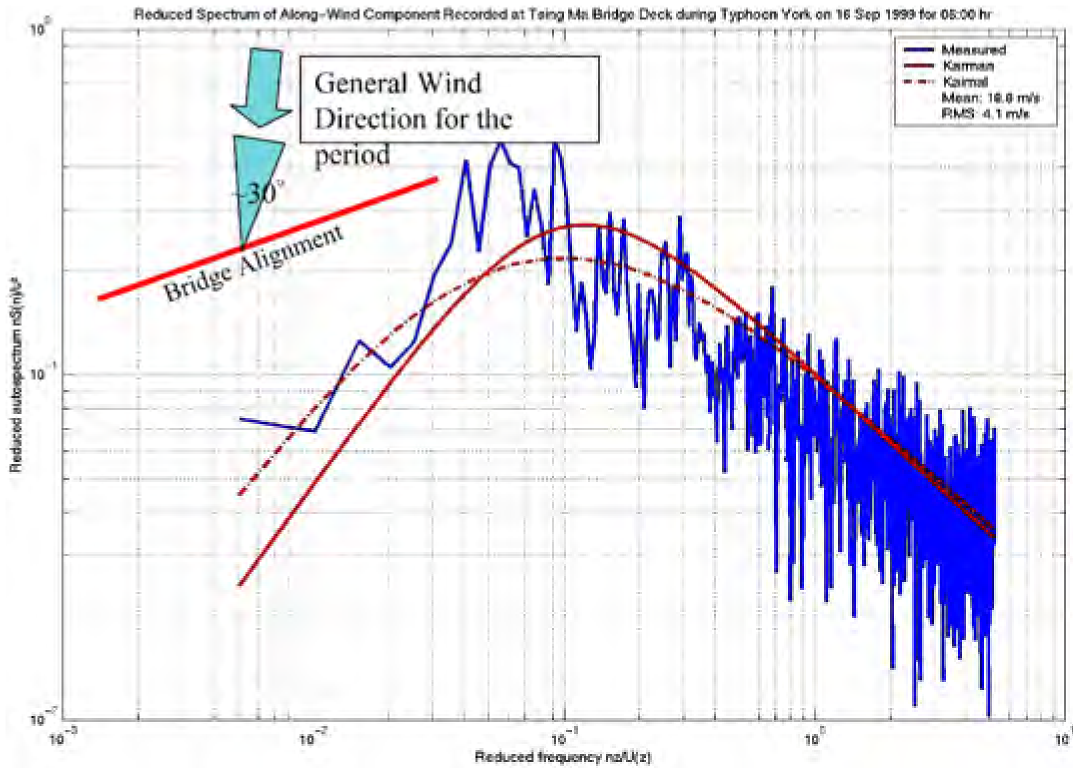

Figure 32. Along-wind turbulence spectra at deck level of Tsing Ma Bridge during Typhoon York, 16 September 1999.

4.6. Static influence coefficients

The monitoring of static influence coefficients is to measure/derive the static influence lines and/or surfaces at selected locations and to compare/update/calibrate the analytical values. The updated/calibrated results are then applied to the study of multi-load effects. The locations for the development of influence coefficients are mostly in the deck sections at mid-span, at quarter-span and at pylons. The types of sensors involved in this category of monitoring are GPS, level-sensing stations, accelerometers and weldable strain gauges. Figure 39 is an illustration of the comparison between measured and analyzed influence lines in the bridge deck (truss members) of the Tsing Ma Bridge.

4.7. Global dynamic characteristics

The monitoring of global dynamic characteristics refers to the measurement of modal frequencies, vibration mode shapes, modal damping ratios and modal mass participation factors, which are extracted from the time-history acceleration data through spectra analysis, as shown in Figure 40. In fact this type of monitoring is an essential part of monitoring in WASHMS because the measured/extracted modal frequencies, mode shapes, modal damping

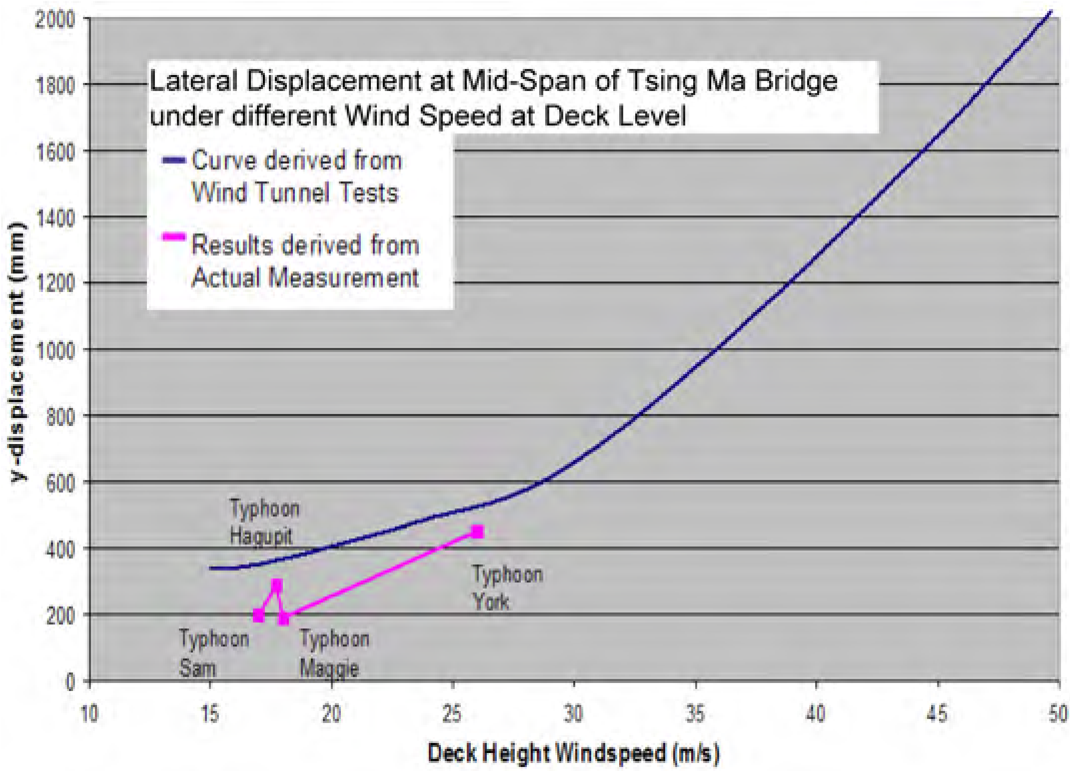

Figure 33. Lateral displacement comparison of measured lateral displacement and wind tunnel test values.

ratios and mass participation factors are then used to calibrate the finite element bridge model which forms the basis in the prediction of structure conditions of the bridge. This category of monitoring is also used to evaluate the structural integrity of the bridge through the comparison of measured frequencies and various time intervals. Accelerometers are the major sensors used in this monitoring category. Typical monitoring results for the Tsing Ma Bridge, Kap Shui Mun Bridge and Ting Kau Bridge are given elsewhere [7,8]. The global dynamic characteristics of the Tsing Ma Bridge, Kap Shui Mun Bridge and Ting Kau Bridge determined by their respective calibrated finite element models (of MSC-PATRAN + MSC-NATRAN) are given in Figure 41 for the first three vibration mode shapes.

4.8. Geometric configuration

The geometric configurations of the main cable profile in suspension bridges and the deck profile in cable-stayed bridge are major items in estimating the loading conditions of the bridge. Any deviation of the cable/deck profile implies a change of force condition in the whole bridge. Such deviation can be monitored through continuous measurement and comparison of the cable/deck profiles. This approach is used to monitor the long-term load effects due to dead plus live loads on cable/deck structures. For the monitoring of short-term load effects due to typhoons, passage

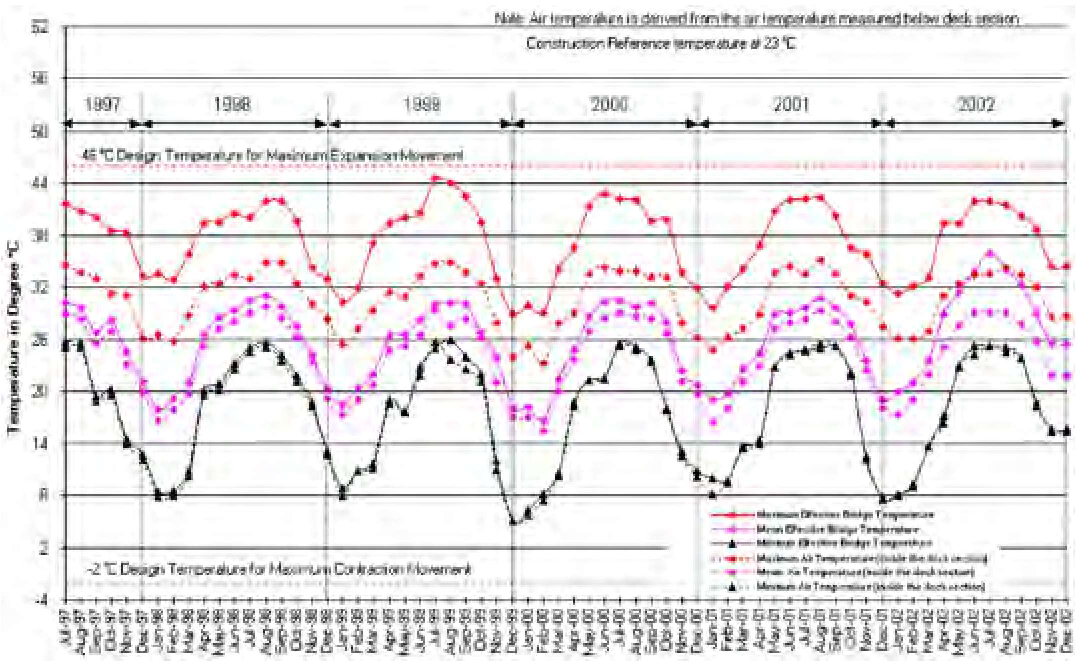

Figure 34. Historical variation of effective bridge deck and air temperature for Tsing Ma Bridge deck.

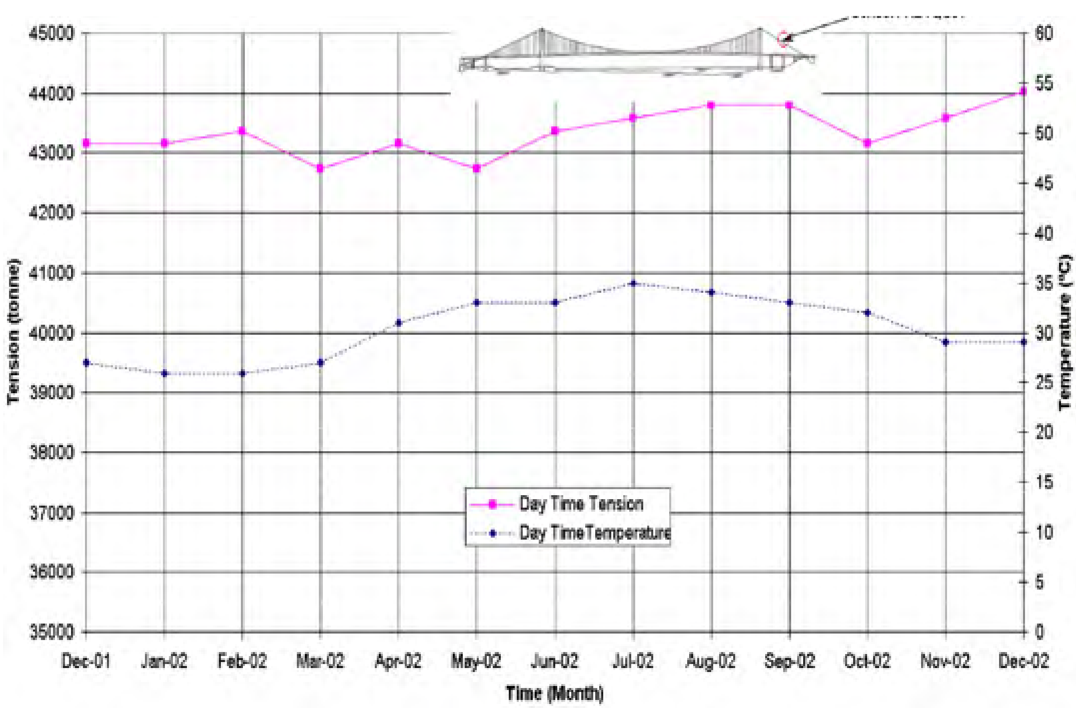

Figure 35. Variation of tension and monthly mean temperature of Tsing Ma Bridge main cable.

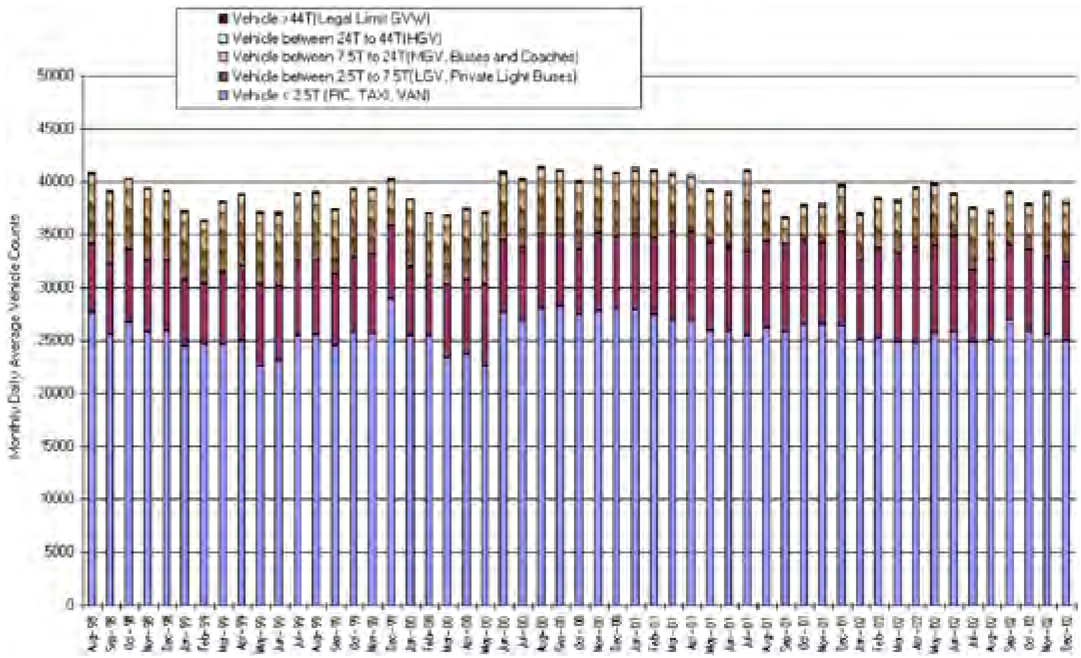

Figure 36. Monthly daily average vehicular count on Lantau fixed crossing.

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Figure 37. Variation of monthly daily percentage of goods vehicle, on Lantau fixed crossing.

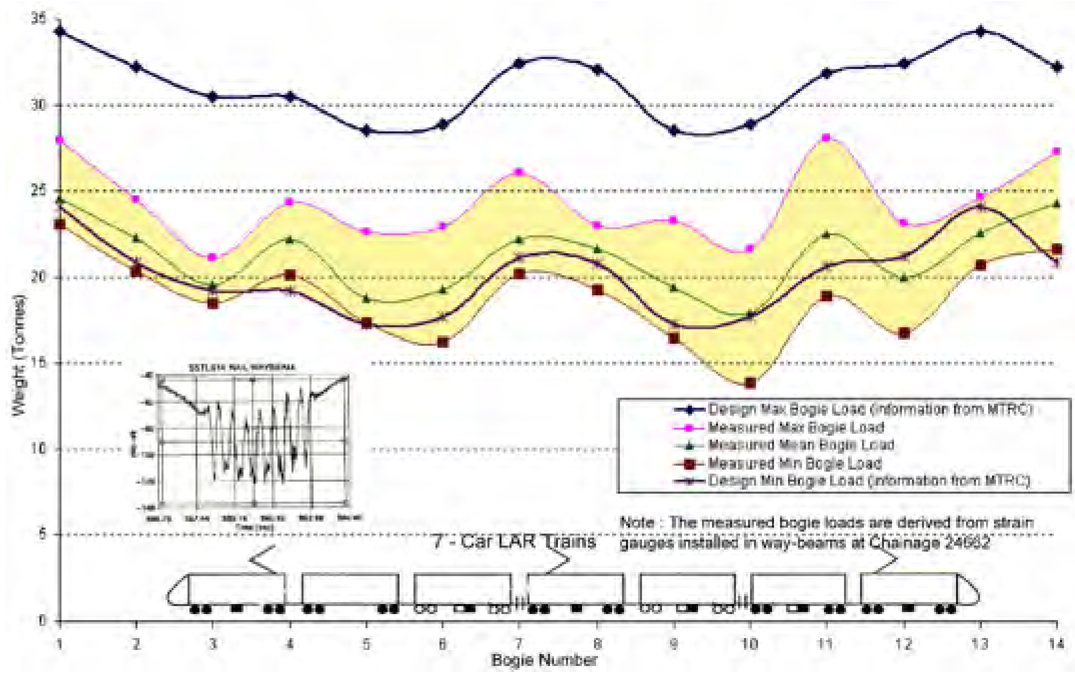

Figure 38. Comparison of measured and design Bogie loads on Tsing Ma Bridge.

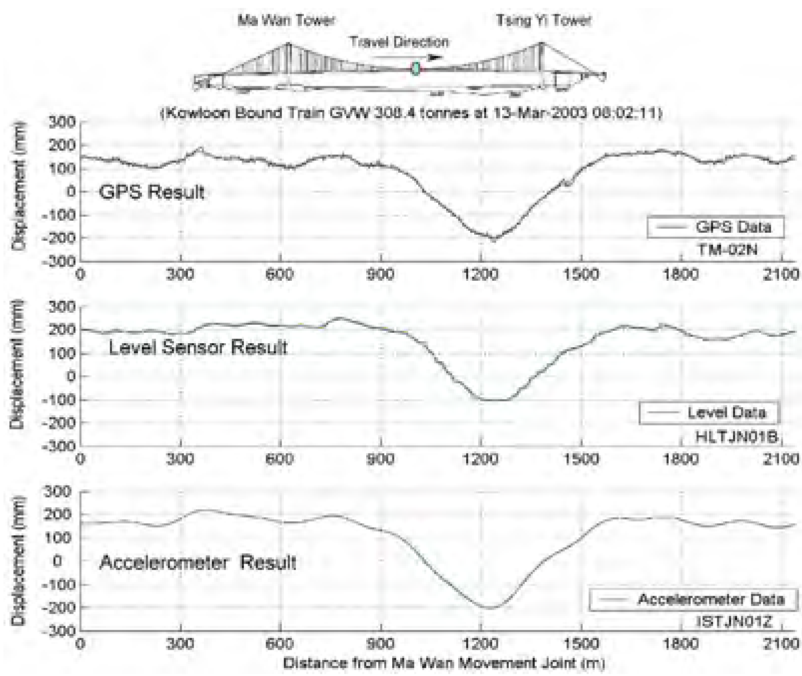

Figure 39. Displacement influence line at mid-span of Tsing Ma Bridge (comparison of results derived from GPS, level sensor and accelerometers).

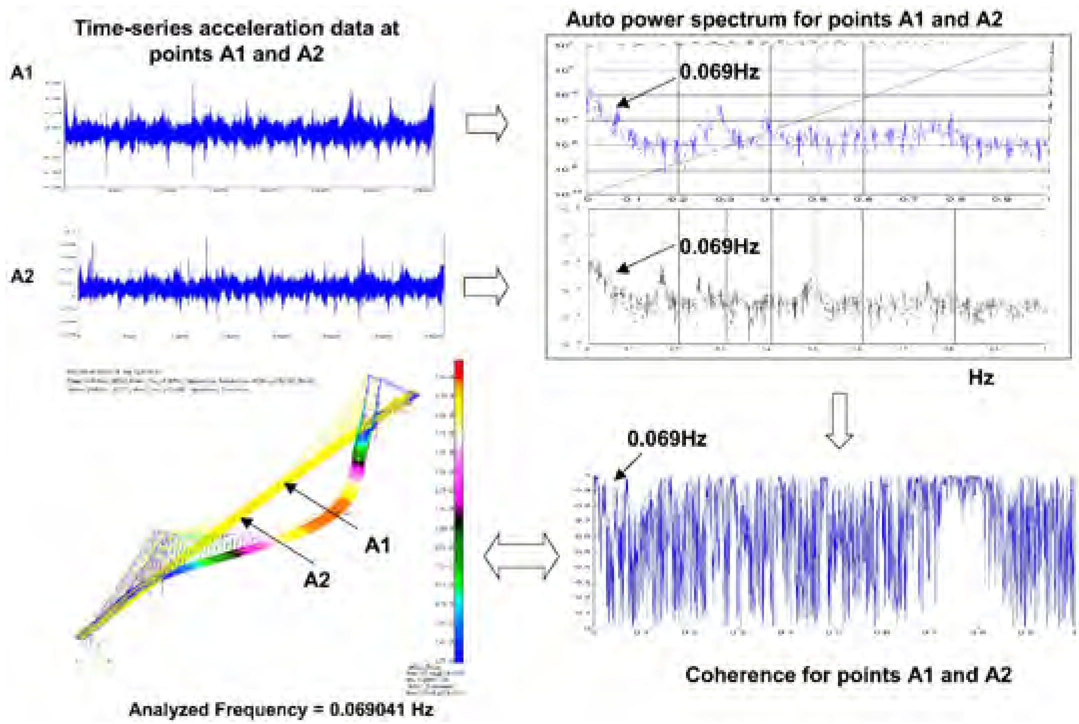

Figure 40. Modal analysis of measured and theoretical modal frequencies of Tsing Ma Bridge.

of abnormal load vehicles, etc., the stress/force conditions at critical locations such as the pylon sections at bases, the deck sections at the center of the main span and at pylons are estimated from the measured displacements of the cables, the stiffening deck and the pylons at control points through the usage of the calibrated finite element bridge model. The types of sensor involved in this category of monitoring are GPS, level-sensing stations and displacement transducers. Figure 42 is an illustration of geometric configuration monitoring.

4.9. *Cable forces*

In cable-supported bridges, the cable system is the key component for load resistance, particularly for vertical loads. In WASHMS, cable force monitoring is carried out by the accelerometers, level-sensing stations and GPS. Through the extraction of frequencies from time-history acceleration data of ambient vibrations (during the night with mean wind speed less than 5 m/s), the current tensile force (due to dead loads) in each cable can be determined. In cable-stayed bridges, the amount of vertical and horizontal forces (induced by cable vibrations) acting on the bridge deck and pylons respectively can also be estimated through the monitoring of the vibration amplitudes of stay cables. The level-sensing stations and GPS can also be used to evaluate the cable force due to live loads by converting the measured net displacements in cables. The calculated cable forces are then compared with their design values at both

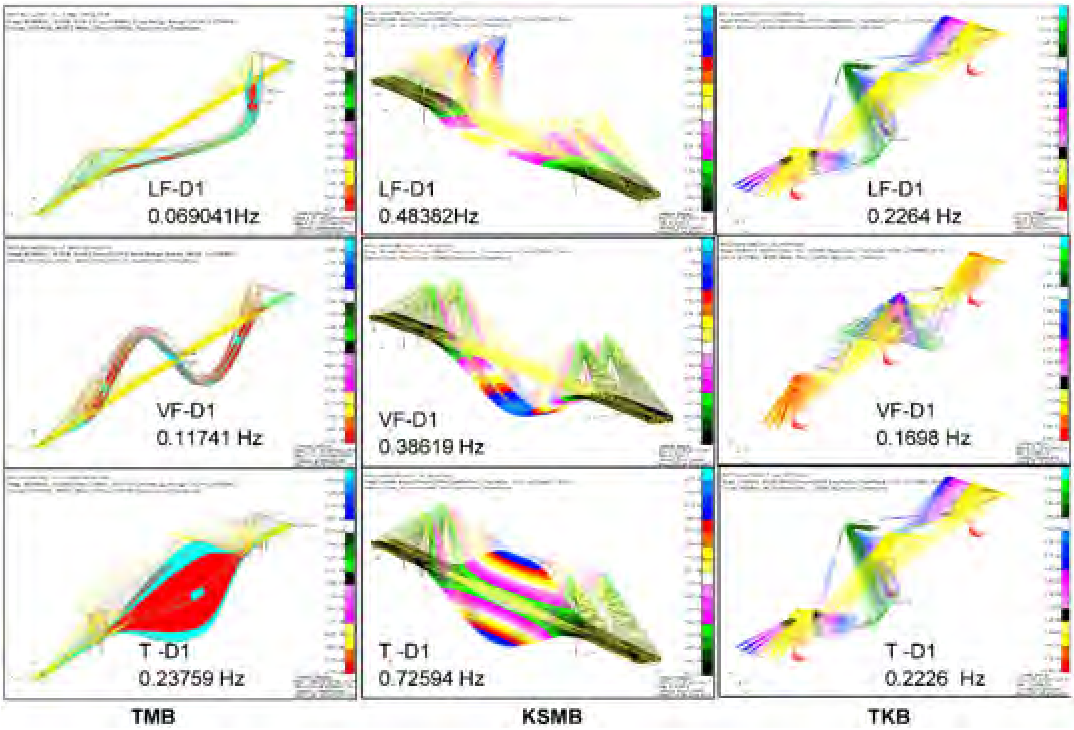

Figure 41. Fundamental mode shapes and frequencies of Tsing Ma Bridge, Kap Shul Mun Bridge and Ting Kau Bridge.

serviceability and ultimate limit states. Figure 43 show, plots for results of cable force monitoring in the suspenders of TMB.

4.10. Strain/stress distribution

Strain/stress distribution monitoring in WASHMS is the monitoring of the fluctuation of stresses due to live loads in: (i) truss/girder members at maximum stress locations; (ii) horizontal wind bracing members; and (iii) rocker bearings. The type of sensor involved in this monitoring category is the weldable strain gauge. The monitoring is carried out by use of stress demand ratio plots, an example of which is illustrated in Figure 44.

4.11. Fatigue stress estimation

In fatigue stress estimation, the technique of rainflow count is used to count the cycles at different stress levels of measured output from strain gauges installed at fatigue-sensitive and especially fracture-critical details, elements and connections. Figure 45 is an example of rainflow count application. The method first determines a peak at a reversal in slope by a simple algorithm. Initially, at the beginning of each data set, the algorithm assumes no particular slope. Once the slope is established the minimum or maximum peak (depending on the slope) is

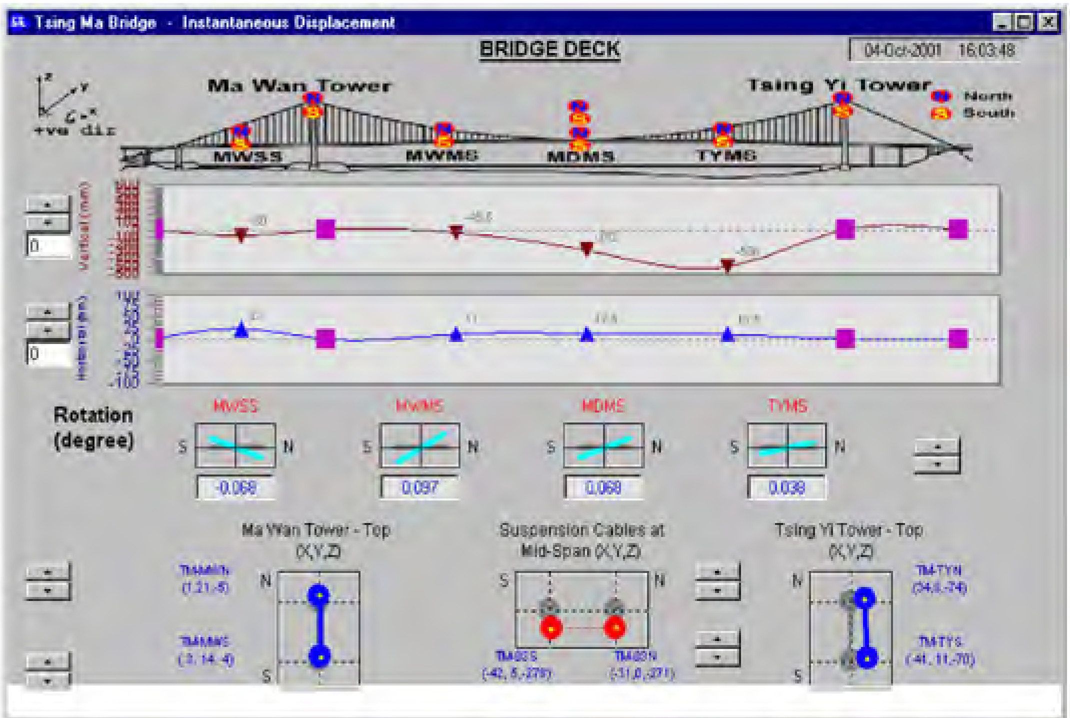

Figure 42. Screen display of instantaneous displacement for Tsing Ma Bridge: bridge deck, suspension cables and tower tops.

updated with each new value. The reversal in slope is detected if the difference between the current peak and the new value meets the hysteresis conditions. The reversal in slope uses hysteresis to determine a true reversal and not a noise change. The peak is then passed to the rainflow algorithm where it is stored to be reviewed later or is matched with a previous peak to generate a difference which is used to increment a bin, which is of 4 micro-strain. The rainflow alogorithm has three stages: (i) the initial setting is done before each data set; (ii) the actual algorithm finds peaks and passes them through the rainflow process; and (iii) the clean-up flushes out any peaks still in the peak buffer.

5. CONCLUSIONS

The design and operation of a bridge health monitoring system requires the input of experiences and/or technologies in four aspects: (i) design, construction, operation and maintenance of long-span bridges, for the identification of appropriate locations, types and ranges of monitoring parameters and interpretation of measured and analyzed results; (ii) instrumentation technologies for measurement and processing of signals or data; (iii) graphical CAD and numerical analytical technologies for input/output, analysis and interpretation of data; and (iv) information technologies for transmission, processing and visualization of data.

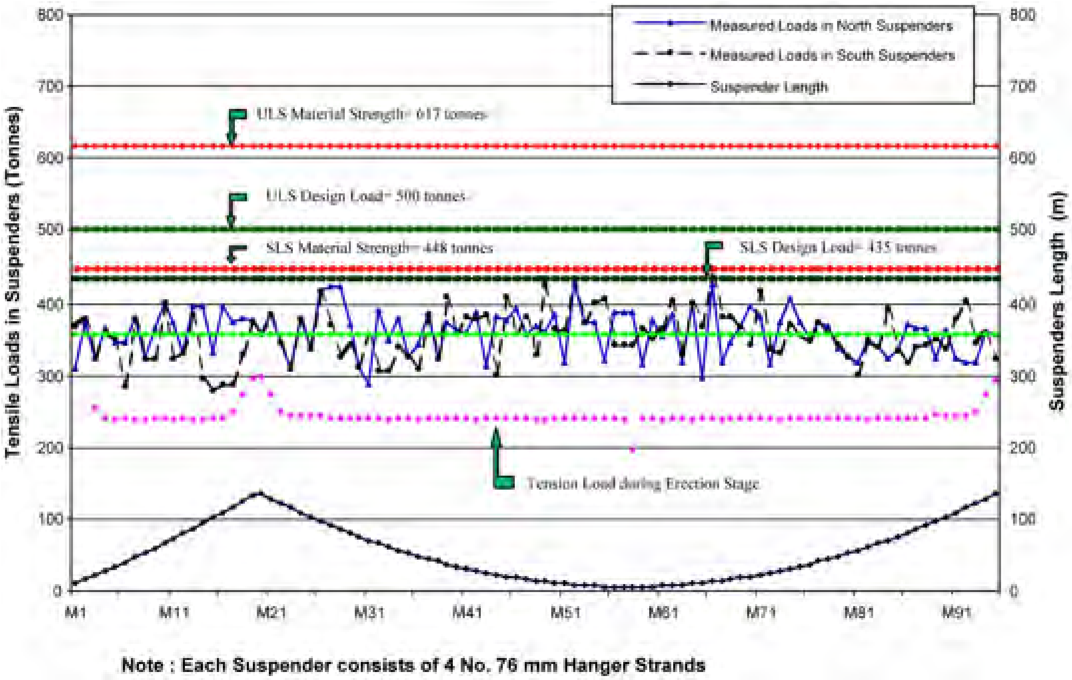

Figure 43. Comparison of measured and designed tensile forces in suspenders of Tsing Ma Bridge.

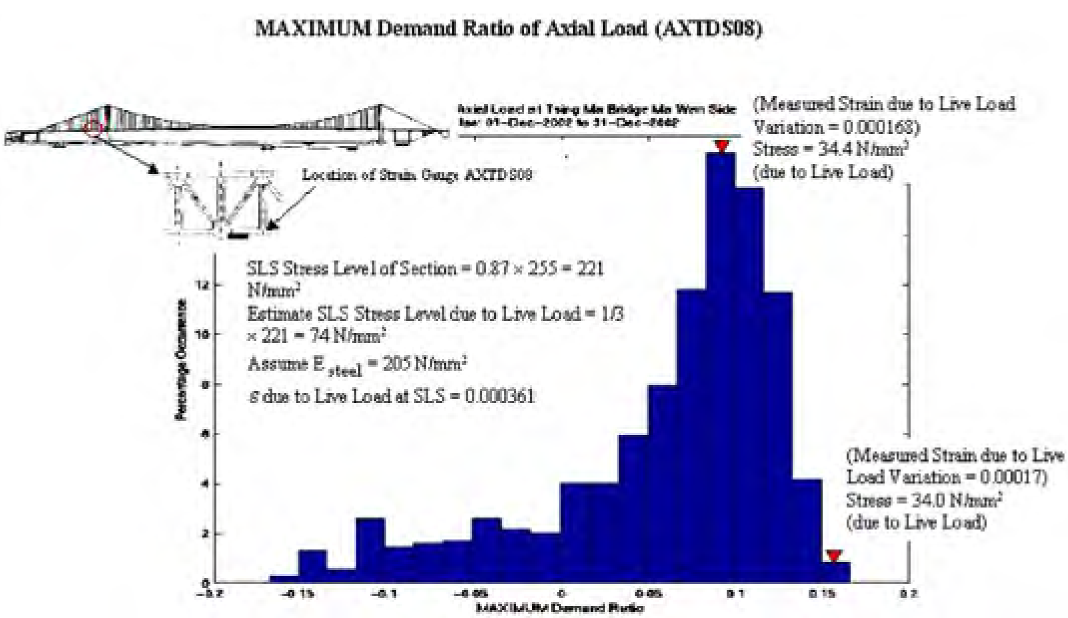

Figure 44. Demand ratios of inner longitudinal trusses near Ma Wan Tower at bottom chord of Tsing Ma Bridge.

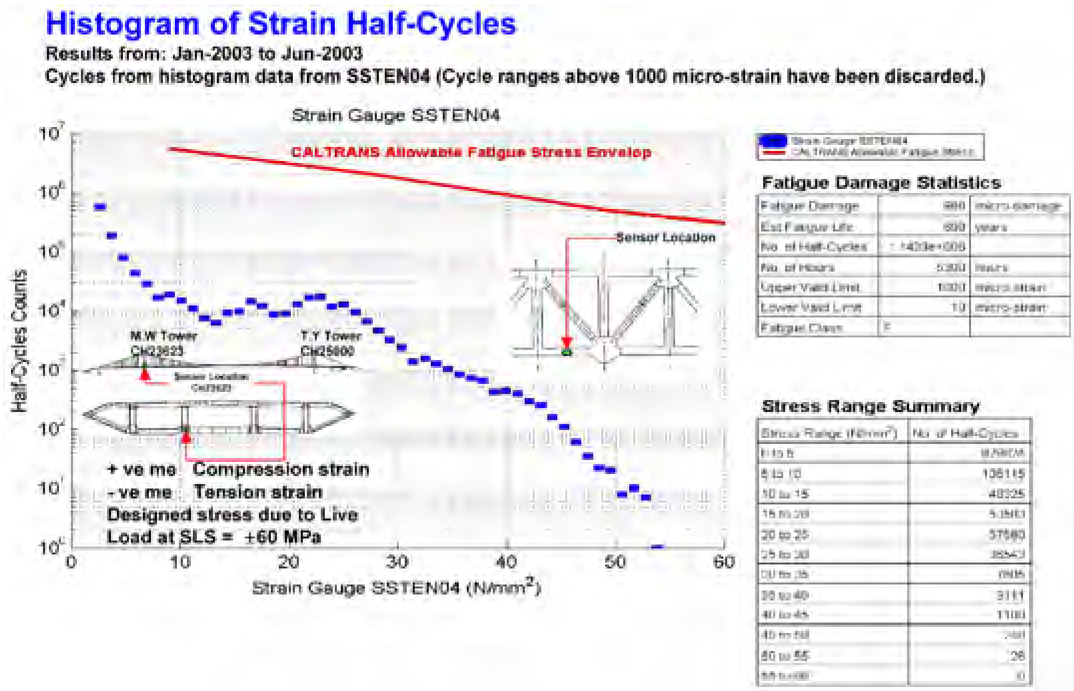

Figure 45. Fatigue damage statistics—stress/strain half-cycles count in bottom chord of longitudinal truss of Tsing Ma Bridge.

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