Vibration Monitoring of the Hong Kong Stonecutters Bridge

E. Dascotte
Dynamic Design Solutions (DDS) NV, Leuven, Belgium

ABSTRACT: A custom-developed software system for vibration monitoring of the Stonecutters Bridge in Hong Kong is described. This is a cable-stayed bridge with a main span of 1 km that was opened to traffic in December 2009. The vibration monitoring system is a part of the bridge's Wind and Structural Health Monitoring System (WASHMS) that monitors the response of the bridge to wind loading, temperature loading, highway loading and seismic loading. For this purpose, the bridge is equipped with an impressive array of structural and environmental sensors to measure displacements, strain, acceleration, temperature and wind conditions.
A vibration monitoring system, combined with a structural health evaluation system, enhances safety by allowing better planning of inspections and maintenance work. The system consists of the following components:
(a) Operational modal analysis from acceleration time histories. Modal extraction is automated and is used for model updating, and monitoring of modal parameters.
(b) Displacement monitoring using GPS receivers. The displacement data serves as input for stress recovery at any location using a finite element model of the bridge. The stresses are used for accumulated fatigue monitoring.
(c) Correlation of stress, force and moments with environmental conditions (wind, temperature).
The concepts, development and initial results obtained with the vibration monitoring software system are described.

1 INTRODUCTION

1.1 Stonecutters Bridge

Stonecutters Bridge in Hong Kong is a high-level cable-stayed bridge, with two towers located in the back-up areas of the busy Kwai Chung Container Port which is frequented by the world’s largest container ships.

It has a steel main span of 1018 meters across the Rambler Channel and a total length, including the backspans, of some 1.6 km. The vertical clearance is 73.5 meters over the navigation channel. The deck is supported by two 290 meters tall concrete and stainless steel towers. It is 53 meters wide and split into two streamlined boxes connected by ross girders.

The bridge deck was completed on 7 April 2009 and opened to traffic on 20 December 2009. Stonecutters is the second longest cable-stayed span in the world, and one of only two cable-stayed bridges with a span in excess of 1 km.

1.2 Wind and Structural Health Monitoring System

A wind and structural health monitoring system (WASHMS) is deployed by Hong Kong Highways Department to monitor the structural performance of Stonecutters Bridge under its designated performance criteria at serviceability limit state and to evaluate possible defects and structural safety when these are exceeded (Wong 2010, Ni 2010). For this purpose a wide array of 1,700+ sensors are deployed, including structural and environmental sensors to measure displacements, strain, acceleration, temperature and wind conditions (Fig. 1). This makes Stonecutters Bridge the most heavily instrumented bridge in the world.

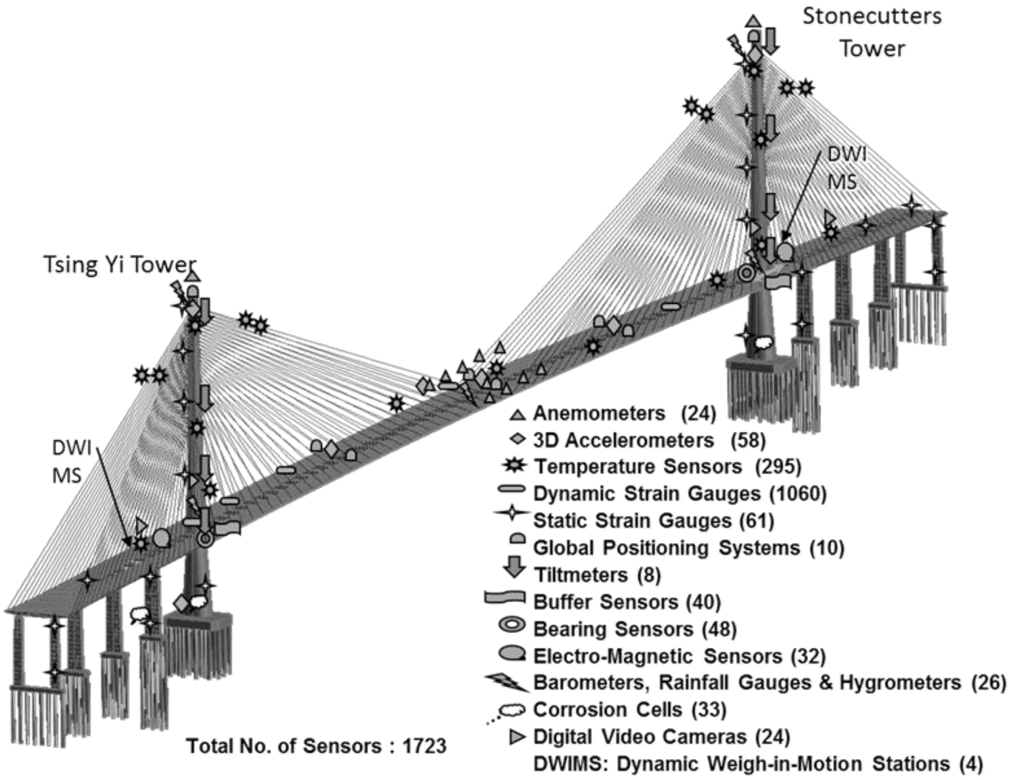

Figure 1 : Layout of sensory systems on Stonecutters Bridge.

Safety requirements have increased the focus on vibration monitoring using acceleration signals and displacements using GPS receivers. The acceleration signals are primarily used for operational modal analysis (OMA) to obtain reference values for validation and updating the finite element models of the bridge (Dascotte 2007). The measured displacements and updated finite element models are used in a hybrid method to compute the strains, stresses, forces and moments at any location of the bridge. Vibration monitoring, combined with a structural health evaluation system and fatigue assessment, enhances safety by allowing better planning of inspections and maintenance work.

The various sensory systems of Stonecutters Bridge are connected to 8 PC-based data acquisition units (DAU-1, DAU-2,…, DAU-8) that are installed at different locations on the bridge deck and in the towers. Each DAU is equipped with a GPS time synchronizer and is connected to an optical fiber backbone to an off-site control building that contains the data processing systems and a control room. In addition to the fixed installations, portable data acquisition systems for temporary accelerometer installations are connected by a wireless system.

This paper focuses on the dynamic features monitoring and geometrical configuration monitoring, respectively using OMA and GPS-based displacement analysis. Customized data processing and analysis programs that were developed by DDS are in operation since 2011. All custom-developments were made using the FEMtools software system (www.femtools.com).

2 OPERATIONAL MODAL ANALYSIS

2.1 Processing Acceleration Data

Collection and processing of the dynamic signals received from fast sampling rate (≧50 Hz) sensors, such as accelerometers and dynamic strains gauges, is by 24-bits and simultaneous data acquisition boards (Dewesoft Dewe-Orion-1624). All data are stored in an SQL database system that is accessible by the various data processing software packages.

Dynamic features monitoring refers to the use of accelerometers to extract the global modal parameters of the bridge such as modal frequencies, mode shapes, and modal damping ratios by means of operational modal analysis (OMA). These modal parameters form the bases for subsequent dynamic analyses of wind, highway and seismic load effects, for updating and refinement of the finite element models, and for supplying data to the structural health monitoring and evaluation systems. A high level of automation is required for continuous operational modal analysis with only minimal human intervention.

The data processing system for OMA is shown in Fig.2. Raw acceleration time histories are extracted from the SQL database by an acceleration data reader. Information on the sensors, the measurement channels and the test model are stored in separate tables for easy reconfiguration. The data reader can perform signal processing operations like filtering, decimation, de-trending and averaging before exporting the processed time histories to a graphical viewer or to internal or external OMA programs. The extracted modal parameters are further processed depending on the application or exported to a database for archiving.

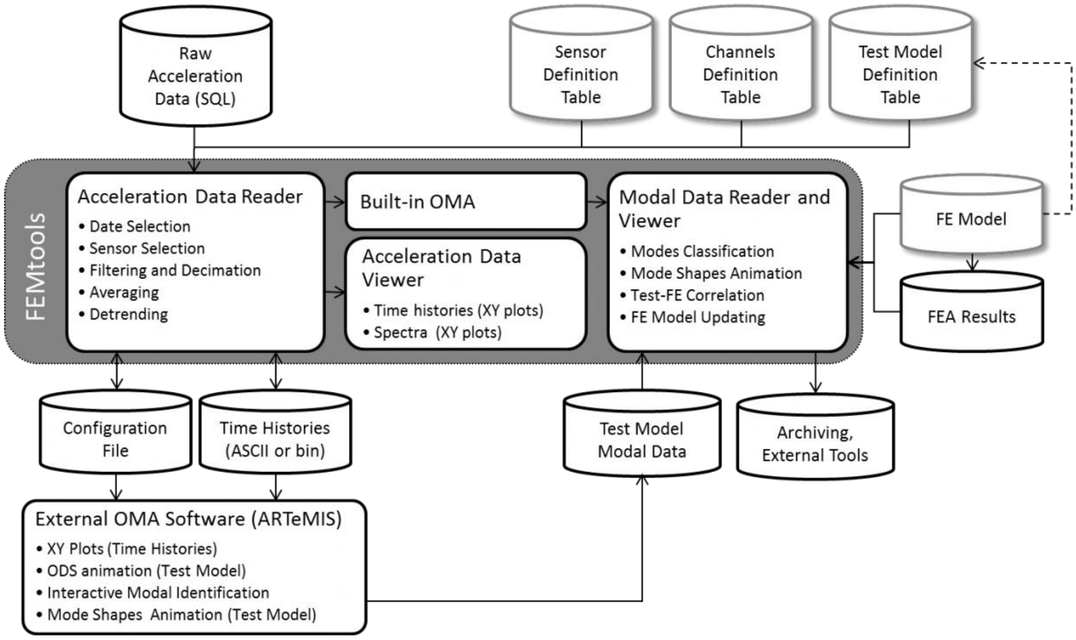

Figure 2 : Processing of acceleration data.

2.2 Modal Parameters Extraction

Modal parameters extraction is done using two industry-standard OMA methods: (i) Stochastic Subspace Identification (SSI) with an external standalone program (ref. ARTeMIS; www.svibs.com) and (ii) Polyreference Least Squares Complex Frequency-Domain Estimator (pLSCF) with a module of the FEMtools program (ref. www.femtools.com).

The SSI method fits a mathematical model directly to the acceleration times series data by adjusting a set of parameters of the model to minimize the deviation between a predicted system response of the model and the measured system response.

The pLSCF method is a polyreference version of the well-known LSCF estimator that estimates a so-called common-denominator transfer function. The advantages of using multiple references is that also participation factors are available to construct the stabilization diagram and that closely spaced poles can be separated. The pLSCF method extracts the modal parameters in two separate steps: (a) extraction of the poles with frequencies, damping and modal participation factors and (b) estimation of the mode shapes and upper and lower residuals. Working with output-only data, the extractor is fed with cross power spectra between the responses and a number of carefully selected reference channels.

For a more comprehensive description of these methods reference is made to literature on the subject (Guillaume et al. 2003, Van Overschee et al. 1996, Verboven 2002). Both methods produce very clear stabilization diagrams and are therefore suitable for automation of the pole selection process (Fig. 3). For the Stonecutters Bridge WASHMS, the external OMA software is mainly used for thorough data inspection and interactive processing. The built-in OMA is more suitable for automatic processing as it enables a smooth data flow between the acceleration data reader and the tools that make use of mode shapes.

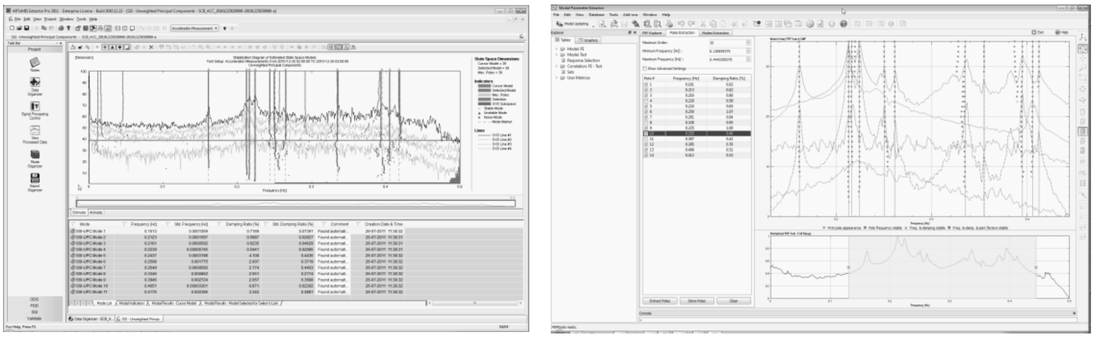

Figure 3 : Stabilization diagrams for SSI (left) and pLSCF (right) methods.

2.3 Example using Global Modes Extraction

A comparison was made between the results obtained with pLSCF, SSI and different finite element analysis (Table 1). The acceleration data was recorded on 25 December 2010 from 2 am to 3 am; 50 Hz sampling decimated by order 50 so that frequencies up to 0.5 Hz are extracted. Data from only 6 sensors was used (on both sides of the deck at 1/4 and 3/4 span and on each tower top). This was a night with strong winds (mean 43 km/h, ENE) and temperature of 12 degrees Celsius.

Considering the challenging conditions (the sensors at mid-span were unavailable; noisy data), the results obtained with the pLSCF and SSI methods are almost identical. This consistency between results obtained with two different OMA methods, one time-domain and another frequency-domain, inspires trust in the obtained mode shapes.

The HKP results refer to a recent ANSYS model of Stonecutters Bridge (Hong Kong Polytechnic 2010), ARUP are the results obtained with a NASTRAN model by Arup consulting engineers and HYD are the results provided by Hong Kong Highways Dpt. using a preliminary coarse NASTRAN model. It is to be noted that only the HKP team had access to experimental modal data at the time of modeling and therefore only their FE model can be considered as an updated model. As a result, correspondence between the OMA and HKP results is very good. Mode 5 appears in the OMA results as 2 distinct modes. Modes 6 and 10 obtained by the FE models could not be extracted with the given acceleration data.

Table 1 : Frequency comparison between different OMA methods and FEA.

Mode	pLSCF (Hz)	SSI (Hz)	HKP (Hz)	ARUP (Hz)	HYD (Hz)	Mode Description
1	0.1612	0.1613	0.1609	0.1536	0.1515	1st symmetric, lateral, bridge deck
2	0.2128	0.2123	0.2121	0.2048	0.3470	1st symmetric, vertical, bridge deck
3	0.2164	0.2161	0.2124	0.1858	0.1884	1st asymmetric, lateral, towers
4	0.2240	0.2239	0.2185	0.1906	0.1873	1st symmetric, lateral, towers
5	0.2498	0.2508	0.2605	0.2580	0.4053	1st asymmetric, vertical, bridge deck
	0.2613	0.2649				
6	-	-	0.3274	0.3251	0.4625	Long. back spans and towers; vertical deck
7	0.3358	0.3346	0.3314	0.3289	0.5678	2nd symmetric, vertical, bridge deck
8	0.3951	0.3946	0.3910	0.4066	-	2nd asymmetric, vertical, bridge deck
9	0.4055	0.4051	0.3993	0.3871	0.3891	1st asymmetric, lateral, bridge deck
10	-	-	0.4501	0.4496	0.6078	1st torsion bridge deck; lateral back spans

To study the influence of recording length on the OMA results, data recorded on an average summer day with light winds and morning traffic was used (2 August 2010, from 8 am to 11 am; mean wind speed 14 km/h SW; 32 degrees Celsius). Table 2 shows that at least one hour recording length is needed under these conditions. With three hours recording the same number of mode shapes can be obtained as with one hour recording on a day with strong winds (Table 1). The values between brackets are weak poles.

Table 2 : Frequencies obtained using different recording times with pLSCF method.

Mode	30′ (Hz)	45′ (Hz)	60′ (Hz)	120′ (Hz)	180′ (Hz)	Mode Description
1	0.159	0.160	0.160	0.160	0.161	1st symmetric, lateral, bridge deck
2	0.210	0.210	0.210	0.210	0.211	1st symmetric, vertical, bridge deck
3	-	-	-	-	(0.216)	1st asymmetric, lateral, towers
4	-	-	0.223	0.223	0.223	1st symmetric, lateral, towers
5	-	-	(0.248)	(0.248)	0.248	1st asymmetric, vertical, bridge deck
6	-	-	-	-	(0.326)	2nd symmetric, vertical, bridge deck
7	-	-	-	(0.390)	(0.395)	2nd asymmetric, vertical, bridge deck
8	-	0.405	0.405	0.404	0.405	1st asymmetric, lateral, bridge deck

To study the influence of the time of day, the recordings of Monday 2 August 2010 were used to also extract modal parameters during 24 hours. The pLSCF method was used with one hour recordings. Based on previous experience, only up to 5 modes could be expected. The curves in Fig. 4 show that only during heavy traffic hours 5 modes can be extracted. Frequencies remain very stable throughout the day while modal damping increases and varies significantly during heavy traffic hours. During the night, with very light winds and less traffic, extraction either fails or less than 5 modes are found. There was no data available at noon, and during several hours in the evening and night.

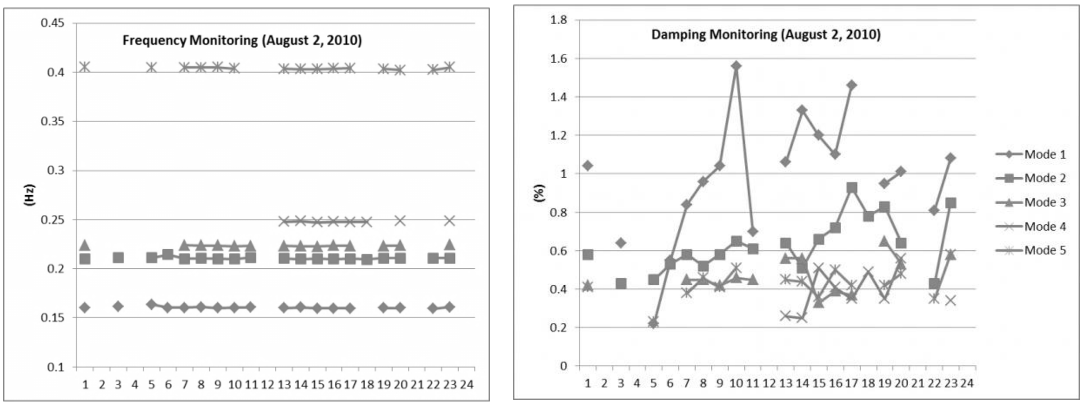

Figure 4 : Frequency and damping tracking during 24 hours.

2.4 Example using Extraction per Mode Type

To improve the condition of the acceleration signals and to better separate the different types of mode shapes, the acceleration time series A_i at both sides of the deck (Fig. 5) are averaged using the following expressions:

$$Lateral\ acceleration\ of\ deck = \frac{A_2 + A_5}{2}$$

$$Vertical\ acceleration\ of\ deck = \frac{A_3 + A_6}{2}$$

$$Longitudinal\ acceleration\ of\ deck = \frac{A_1 + A_4}{2}$$

$$Torsional\ acceleration\ of\ deck = \frac{A_3 - A_6}{B}$$

Together with the accelerometers at the top of the towers this results in 6 types of time series. Each type is separately used for OMA and the resulting modes are labelled, combined and sorted by increasing frequency. The following mode shape types are obtained: (1) Vertical Flexural Mode of Bridge Deck; (2) Lateral Flexural Mode of Bridge Deck; (3) Torsional Mode of Bridge Deck; (4) Longitudinal Flexural Mode of Bridge Deck; (5) Longitudinal Flexural Mode of Bridge Towers; and (6) Lateral Flexural Mode of Bridge Towers. The torsional and vertical modes of the towers are not considered. The entire procedure is automated as part of the built-in OMA tool (Fig 2.).

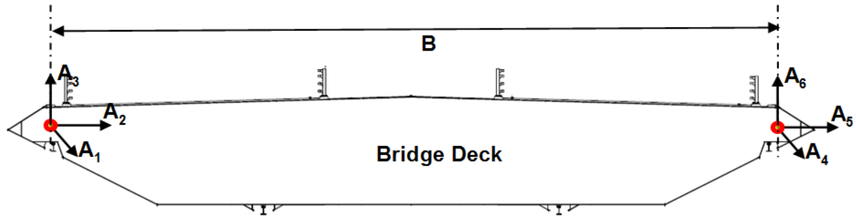

Figure 5 : Layout of the accelerometers on the bridge deck.

Table 3 shows the resulting frequencies and damping compared to the results obtained with the global approach. One hour recording on 2 August 2010 from 8 am to 9 am was used. The results demonstrate that using this approach, the same number of modes can be extracted as with a one hour recording on a day with strong winds or using three hour recordings on a day with light winds.

Table 3 : Modal extraction per mode type versus global extraction using 1 hour recording.

Mode	Per Type		Global		Mode Description
	Freq. (Hz)	Damping(%)	Freq. (Hz)	Damping (%)	
1	0.160	1.09	0.160	1.04	1st symmetric, lateral, bridge deck
2	0.210	0.54	0.210	0.58	1st symmetric, vertical, bridge deck
3	0.210	0.68	-	-	1st asymmetric, lateral, towers
4	0.228	0.87	0.223	0.51	1st symmetric, lateral, towers
5	0.249	0.54	-	-	1st asymmetric, vertical, bridge deck
	0.260	0.51			
6	0.335	0.44	-	-	2nd symmetric, vertical, bridge deck
7	0.395	0.65	-	-	2nd asymmetric, vertical, bridge deck
8	0.405	0.81	0.405	0.46	1st asymmetric, lateral, bridge deck

3 DISPLACEMENT AND STRESS MONITORING

3.1 Processing of Displacement Data

Using custom-developed data processing tools that are similar to what is shown in Fig. 2, displacements of GPS receivers are retrieved from an SQL database for further processing by a program for displacement and stress monitoring (Fig 6). The GPS system converts the raw GPS signals (longitude, latitude and height) to displacements of the GPS receivers in the bridge coordinate system prior to storage in the SQL database.

There are 10 GPS receivers planned of which 8 were available at the time of testing (Feb. 2011). Like the accelerometers used in the previous section, they are located at the tower tops, and at both sides of the bridge deck at 1/4, 1/2 and 3/4 span. The displacements obtained by the GPS system (Leica) are said to be accurate to +/- 2 cm. This is achieved by using an error correction signal emitted by a reference transmitter on the ground with an exactly known position. The sampling rate is 20 Hz. The atmospheric conditions in Hong Kong are in general suitable for the proper functioning of the GPS system. However, during passing of heavy clouds the performance of the system may be negatively influenced. During the test period it was observed that GPS signals sometimes show spurious behavior or become temporarily unavailable. Appropriate signal processing is therefore mandatory to condition the data (i.e. removal of outliers, interpolation of missed measurements,…).

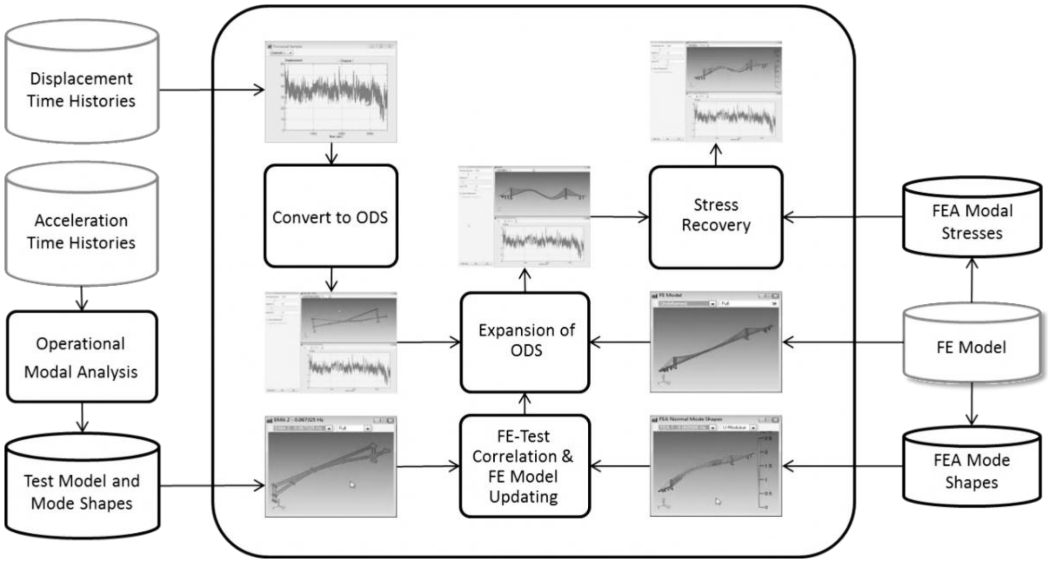

Figure 6 : Processing of the displacement and stress data.

3.2 Expansion of Displacements and Stress Recovery

Using an updated finite element model, the sparse set of displacements measured at the GPS receiver locations can be expanded using a modal-based method to obtain displacements at all FE node locations. The transformation matrix that is used by this expansion process can also be applied to obtain forces, moments, strain, or stress at any location in the bridge. This is a very efficient process that can be performed on real-time or historical GPS data and requires only minimal data storage capacity and computational effort.

Consider the following expression that relates the unknown transient element forces with modal element forces:

$$\{ef(t)\} = \sum_{i=1}^{nmode} q_i\,(t)\,\{EF_i\} \tag{1}$$

where $\{ef(t)\}$ are the transient element forces vector at given time step t, $q_i\,(t)$ are the modal participation factors at given time step t, $\{EF_i\}$ are the modal element forces for mode i and *nmode* is the number of modes taken into account. Note that element forces in Eq. (1) can be substituted by any modal type of data that can obtained by finite element analysis like displacement, strain, or stress.

For any given time step t, the modal participation factors are obtained by solving the following system:

$$\begin{bmatrix} U_{1,1} & \cdots & U_{1,nmode} \\ \vdots & \cdots & \vdots \\ U_{nd,1} & \cdots & U_{nd,nmode} \end{bmatrix} \begin{Bmatrix} q_1(t) \\ \vdots \\ q_{nmode}(t) \end{Bmatrix} = \begin{Bmatrix} u_1(t) \\ \vdots \\ u_{nd}(t) \end{Bmatrix} \tag{2}$$

where $\{u(t)\}$ are the transient displacements (measured) at given time step t, U_i are the modal displacements for mode i and *nd* is the number of measured displacements. Practical implementation is shown in Fig. 6.

The validity of the process depends on the refinement of the finite element model, the proper choice of sensor locations and a sufficient number of mode shapes:

The finite element model will have to be continuously updated to account for any structural changes in the bridge during its lifetime. Different transformation matrices can be used depending on the displacement amplitudes as a way to consider nonlinear behavior of the bridge.

The type of sensors to construct Eq. 2 are GPS receivers but could also include strain gauges. The number and position of the GPS receivers is fixed in this case and currently no strain gauges are used.

The mode shapes, and corresponding modal element forces or other modal results, form a basis of vectors that is used by the expansion procedure. The required number of modes is to be determined but is a priori limited to the modes that can be validated by operational modal analysis. More modes can be used if such modes are considered needed. Additional vectors like static deformed shapes can be added if deemed necessary to improve the quality of the expansion procedure.

Verification of the selected configuration was done by comparing the forces and moments time histories obtained by the expansion procedure with the results obtained by simulation.

Knowing the stresses resulting from the actual deformation of the bridge during its service life is desirable as they provide input to an accumulated fatigue monitoring procedure. This will allow to adjust the 120-years design life time. In practice, the information on the actual loading that the bridge was subjected to is mainly used to support decision-making about the inspection and maintenance intervals.

Although stresses will also be computed using various updated finite element models of the bridge, and using statistical and probabilistic load information obtained by the WASHMS sensors (more specifically wind, temperature, traffic and seismic), the GPS system with stress recovery provides an alternative by recording and monitoring the actual deformation of the bridge at all times. This is especially true for incidental loading situations like vessel collisions or extreme transient loading like during typhoons or earthquakes.

The strain and stress data obtained by the recovery process can be used as an alternative to strain recording using strain gauges. During the initial service life, the recorded strain data will remain the primary source for fatigue monitoring and serve as references for finite element model validation and updating. The economies that can be realized with the GPS-based approach are, however, significant and therefore it is expected that with time, as confidence in the process builds up, the need for continuous strain recording may be re-evaluated.

3.3 Correlation with Wind and Temperature Data

Large cable-stayed bridges like Stonecutters Bridge are subject to varying environmental conditions such as temperature and wind. These environmental effects cause changes in displacements and modal properties, which may mask the changes caused by structural damage.

Additional data readers have been developed to retrieve recorded environmental data from the central database. This includes wind speed, direction, power spectrum and temperatures at different locations on the bridge. They are used for correlation against modal parameters, maximal displacements of the deck and towers, and tower base forces and moments.

Postprocessing of the results includes producing scatter plots and histograms, computing various statistical quantities or performing regression analysis. This information helps bridge engineers to gain understanding of the variability of monitoring parameters which is needed by the subsequent structural health rating and evaluation systems.

4 CONCLUSIONS

Initial results obtained with a custom-developed vibration monitoring software system for Stonecutters Bridge have been presented. State of the art techniques for operational modal analysis and a hybrid method for displacement and stress recovery using data from GPS receivers and an updated finite element model of the bridge have been successfully deployed and integrated in the bridge wind and structural health monitoring system. Operational modal analysis under different conditions were evaluated and compared to determine optimal configurations for automated monitoring of modal parameters. Substantial economies can be realized with a GPS-based displacement and stress monitoring system as an alternative or complement to experimental strain gauge monitoring.

5 REFERENCES

Dascotte, E. 2007. Model Updating for Structural Dynamics: Past, Present and Future Outlook. *Proc. Int. Conference on Engineering Dynamics (ICED 2007)*, Carvoeiro, Algarve, Portugal.

Guillaume P., Verboven P., Vanlanduit S., Van Der Auweraer H. and Peeters B. 2003. A Poly-Reference Implementation of the Least-Squares Complex Frequency-Domain Estimator. *Proc. International Modal Analysis Conference (IMAC 21)*, Kissimmee (FL), USA.

Hong Kong Polytechnic. 2010. *Development of Structural Health Prognosis Tools for Evaluation of Stonecutters Bridge under In-Service Conditions*. Research Report, Department of Civil and Structural Engineering, December 2010.

Ni, Y.Q. 2010. Structural Health Monitoring for Civil Infrastructure: From Research to Application. *Proc. 5th European Workshop on Structural Health Monitoring*, Sorrento, Italy.

Van Overschee, P. and De Moor, B. 1996. *Subspace identification for linear systems: Theory, implementation, applications*. Kluwer Academic Publishers.

Verboven, P. 2002. *Frequency-domain System Identification for Modal Analysis*, PhD Thesis Vrije Universiteit Brussel, Brussels.

Wong, K-Y. 2010. *Wind and Structural Health Monitoring System for Stonecutters Bridge*, Technical Note, Bridges & Structures Division, Highways Department, The Government of Hong Kong Special Administrative Region.