Brodagen 2009:
Stonecutters Bridge
WASHMS:
Wind and Structural Health Monitoring System,
2005-2008
Stonecutters Bridge, Hong Kong S.A.R.
Tsing Ma Control Area
- central circular tower
- twin deck with curved soffit
- upper part of tower in steel
- two cable planes

Winning Design
Stonecutters Bridge - Involved Parties

Client:
- Highways Department, Hong Kong S.A.R.

Designer:
- Ove Arup & Partners, Ltd. Approach Bridges
- COWI A/S. Cable Stayed Bridge

Contractor:
- MHYH JV (Maeda - Hitachi - Yokogawa - Hsin Chong Joint Venture)
Stonecutters Bridge - Typhoons

Max. hourly wind speed: 150 km/h
Max. gust wind speed: 230 km/h
Stonecutters Bridge - Wind Studies

Typhoon York, North Wind
WASHMS - Wind and Structural Health Monitoring System

- Sensory System (SS)
- Data Acquisition and Transmission System (DATS)
- Portable Data Acquisition System (PDAS)
- Data Processing and Control System (DPCS)
- Structural Health Evaluation System (SHES)
- Portable Inspection and Maintenance System (PIMS)

Diagram:
- Measurement of Loads & Environments
  - Actual Bridge Loads and Environments
  - Bridge Structural System: e.g. Stonecutters Bridge
- Measurement of Bridge Responses & Characteristics
- Detection of Anomalous Signals?
  - Yes
  - No
- Data Interrogation
  - Loads
  - Environments
  - Bridge Characteristics
  - Bridge Responses
  - Any adverse structural effects?
    - Yes
    - No
- Structural Health Evaluation Process
- Notification to Bridge Maintenance Team for follow-up actions!
- Updating, display & storage of analyzed data
- Review of Monitoring Criteria
- Production of Monthly Monitoring Report
Loads & Responses

- Environments and status.
  - Wind monitoring.
  - Temperature monitoring.
  - Seismic monitoring.
  - Corrosion status monitoring.
- Traffic loads.
  - Highway traffic monitoring.
- Bridge characteristics.
  - Static influence coefficients monitoring.
  - Global dynamic characteristics monitoring.

- Bridge responses.
  - Cable forces monitoring.
  - Geometric configuration monitoring.
  - Strain/Stress distribution monitoring.
  - Fatigue stress monitoring.
  - Articulation monitoring.
Sonic anemometers
Stonecutters Bridge
Composite Upper Tower
Corrosion monitoring
Stonecutters Bridge
Fiber optic sensors
Stonecutters Bridge - Bearings & Dampers
Stonecutters Bridge
Feb. 2009
Data Acquisition and Transmission System (DATS)
Data Processing and Control System (DPCS)

Measurement of Loads & Environments

- Actual Bridge Loads and Environments
  - Bridge Structural System: e.g. Stonecutters Bridge
  - Measurement of Bridge Responses & Characteristics

Detection of Anomalous Signals?

Data Interrogation

- Loads
- Environments
- Bridge Characteristics
- Bridge Responses

Detection of any Exceedance of Design Performance Criteria?

Structural Health Evaluation Process

- Yes
- No

Updating, display & storage of analyzed data

Review of Monitoring Criteria

Production of Monthly Monitoring Report

Anomalous Data Monitoring

- Issue of Fault Report to System Maintenance Team
- Investigation of Anomalous Data
- Fault Rectification & Clearance Checked by System Maintenance Team

Has normal operation resumed within 1 month?

- Yes
- No

Fault Report Closed & Filed

Notification to Bridge Maintenance Team for follow-up actions!

- Yes
- No

Any adverse structural effects?

- Yes
- No
## Data Processing

<table>
<thead>
<tr>
<th>Names and Requirements of Parameters or Plots for Monitoring</th>
<th>Duration</th>
<th>Presentation Formats</th>
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<th>Duration</th>
<th>Presentation Formats</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Global Dynamic Characteristics</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>- Measurement and Tabulation of Modal Frequencies, Mode Shapes, Modal Damping Ratios and Modal Mas Participation Factors</td>
<td>For each frequency extraction, at least 8 hours of stationary and ergodic data are required. Only at manual trig</td>
<td>X X</td>
<td>Spectra Plots</td>
<td>For extreme events such as heavy traffic flow, monsoons and typhoons, etc.</td>
<td>Duration of the whole event</td>
</tr>
<tr>
<td>- Plots of Measured Mode Shapes for all Measured Modal Frequencies</td>
<td></td>
<td></td>
<td>- Acceleration, velocity and displacement spectra at bridge-deck</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Correlating the measured/extracted results to those Design/Theoretical Values</td>
<td></td>
<td></td>
<td>- Acceleration, velocity and displacement spectra at tower-tops</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Calibration of Analytical Model for the bridge</td>
<td></td>
<td></td>
<td>- Acceleration, velocity and displacement spectra at instrumented stay cables</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tensile Forces in Stay Cables</strong></td>
<td>Same as above.</td>
<td>X X</td>
<td>Displacement Demand Ratio Plots</td>
<td>Plots of the ratio of the measured maximum displacement at instrumented location to the design values at SLS and ULS respectively</td>
<td>Monthly and Annually</td>
</tr>
<tr>
<td>- Measurement and Tabulation of Modal Frequencies, hence the Tensile Force in each Stay Cable</td>
<td></td>
<td></td>
<td>- Correlating with corresponding requirements for inspection and maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Plotting the measured frequency of stay cables along bridge-deck alignment and comparing with the first few lower frequencies (measured) of deck and tower for parametric effect validation</td>
<td></td>
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</tr>
<tr>
<td>- Comparing the measured/extracted force results with those Design Values at SLS &amp; ULS</td>
<td></td>
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</tr>
<tr>
<td>- Assessing the vertical and horizontal forces induced in deck and towers as a result of cable vibration</td>
<td></td>
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</tr>
</tbody>
</table>

**Notes:**

1. AD = Amplitude Domain, TD = Time Domain, FD = Frequency Domain and FC = Frequency Count.
2. ‘X’ denotes format required.
Bridge Rating System

Initiation by SHMP

Monitoring of Bridge Characteristics & Responses

Monitoring of Environments & Loads

Correlation Analysis & Features* Extraction
- Measurement-to-Measurement Correlation
- Analysis-to-Analysis Correlation
- Measurement-to-Analysis/Design Correlation

Estimation of Future Environments & Loads on Bridge

Structural Health Diagnosis & Prognosis
- Identification of Overstressed or Defective Components
- Evaluation of Bridge Performance with Identified Overstressed or Defective Components
- Assessing Scope of Remedial Works, where necessary
- Predict future environments and loads on bridge
- Predict bridge performance under predicted environments and loads

Examples of Features* Extraction
- Vibration Frequencies
- Temporal Moments
- Equivalent Plastic Strain
- Load Path Distribution
- Peak Accelerations
- Peak Stresses
- Energy Flows

Annual and Special Reports* of Bridge Health Conditions
- Report of any identified overstressed or defective components
- Report of Bridge Performance with overstressed or defective components
- Estimation of remaining service life, time to failure & time to maintenance, if overstressed or defective components are reported
- Rating current structural health condition of bridge with recommendations for further Inspection or Maintenance

Annual and Special Reports*
- Annual Report – Prepared at the end of each year
- Special Report – Prepared after the occurrence of extreme events such as strong typhoons

Take action, update Bridge Monitoring Criteria and continue the Process

Structural Health Evaluation System (SHES)
Software

- Software A – Customized LabVIEW or MATLAB Software for Data Acquisition and Processing or products having equivalent functions or performance
- Software B – Customized LabVIEW or MATLAB Software for Data Transmission and Filing Control or products having equivalent functions or performance
- Software C – Customized LabVIEW or MATLAB Software for Data Archiving and Backup or products having equivalent functions or performance
- Software D – Customized LabVIEW or MATLAB Software for Display, Operation and Control or products having equivalent functions or performance
- Software E – NI Developer Suite Professional Control Edition or products having equivalent functions or performance
- Software F – NI DIAdem Powerful Analysis and Report Generation Software or products having equivalent functions or performance
- Software G – MS Office Professional for 32-bit and 64-bit MS Windows or products having equivalent functions or performance
- Software H – Adobe Design Collection or products having equivalent functions or performance
- Software I – Adobe Digital Video Collection or products having equivalent functions or performance
- Software J – Adobe Publishing Collection or products having equivalent functions or performance
- Software K – NI VI Logger or products having equivalent functions or performance
- Software L – MATLAB “Data Analysis Suite” or products having equivalent functions or performance
- Software M – MSC.PATRAN or products having equivalent functions or performance
- Software N – MSC.Marc or products having equivalent functions or performance
- Software O – MSC.Fatigue or products having equivalent functions or performance
- Software P - ANSYS Physics Verticals Whole Package or products having equivalent functions or performance
- Software Q – GPS Monitoring Software
- Software R – CAD Software for viewing and editing of drawing files
- Software S – FEvis Finite Element Results Visualization Publisher for Windows with FEvis Viewer or products having equivalent functions or performance
- Software T – Customized Traffic Jam Recording Software
Tsing Ma Bridge Wind Actions
Tsing Ma Bridge tower estimated wind loading on tower from: 01 Sep 2010 to 08 Sep 2010

NOTE: SPECIMEN ONLY - VALUES ARE ARBITRARY
Fatigue

Histogram of Strain / Stress Half-Cycles for Fatigue Damage Assessment
Fatigue Damage deduced from Traffic Flow Conditions
– Fatigue Cycles from histogram data recorded at Longitudinal Girders of Stonecutters Bridge

![Histogram of Strain / Stress Half-Cycles for Fatigue Damage Assessment](image)

**Fatigue Damage Statistics**
- Fatigue Damage: 365 micro-str
- Est Fatigue Life: 1027 years
- No. of Half-Cycles: 97167e+006
- No. of Hours: 3287 hours
- Upper Valid Limit: 1000 micro-str
- Lower Valid Limit: 10 micro-str
- Fatigue Class: F

**Stress Range Summary**

<table>
<thead>
<tr>
<th>Stress Range (N/mm²)</th>
<th>No. of Half-Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 5</td>
<td>5.40748e+006</td>
</tr>
<tr>
<td>5 to 10</td>
<td>955456</td>
</tr>
<tr>
<td>10 to 15</td>
<td>429015</td>
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<tr>
<td>15 to 20</td>
<td>135682</td>
</tr>
<tr>
<td>20 to 25</td>
<td>36976</td>
</tr>
<tr>
<td>25 to 30</td>
<td>7374</td>
</tr>
<tr>
<td>30 to 35</td>
<td>709</td>
</tr>
<tr>
<td>35 to 40</td>
<td>44</td>
</tr>
<tr>
<td>40 to 45</td>
<td>2</td>
</tr>
<tr>
<td>45 to 50</td>
<td>1</td>
</tr>
<tr>
<td>50 to 55</td>
<td>0</td>
</tr>
<tr>
<td>55 to 60</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 33-35 Example Plot of Fatigue Damage Assessment
GPS Monitoring Console – 4 in 1
Display of Selected Monitoring Regimes

a) Animated Motion Display of Real-Time GPS Monitoring Data Illustrating Global Bridge Movements
b) Similar Display for Horizontal Monitoring Data
Damage Detection

Date/Time: 01-Jan-2003
00:00:00

Perspective View

East Quarter Span
East One-Third Span
Mid-span
West One-Third Span
West Quarter Span
Inspection & Point Ranking

Inspection and Monitoring Program

- Inspection and Monitoring Planning
  - Superficial Inspection
  - WASHMS
  - Principal Inspection
  - Special Inspection and Technical Investigation
  - Maintenance Inspection

Conversion of WASHMS data to be used in Rating

Modelling, e.g.: establishment of thresholds

Rating of Components based on Models

Corrective Maintenance of Components
- Procedures
- Instructions

Preventive Maintenance of Components
- Procedures
- Instructions
WASHMS Status March 2009

- Sensory system: Basically, the installation for embedded sensory system is completed, but not for the associated cabling work. Installation for the other sensory systems are outstanding at the moment.

- The Global Cabling Network System is completed.

- Data Acquisition Units - The FAT for DAU 5 to 8 was conducted in mid February and the others (DAU 1 to 4) will be carried out around end of March 2009. The DAU 5 to 8 will be delivered to site in March and DAU 1 and 4 will be delivered to site in around April 2009.

- Computer servers - the hardware proposal are now under review and will be finalized in this month. Servers would be delivered to site around May 2009.

- Software development - Most of the development for customized software, such as Software A, B, C, D, Q, T, and the Historical Database is on-going. In term of percentage, it should be around 50-60% completed.
Stonecutters SHMS compared to other major bridges

- **Stonecutters Bridge.**
  WASHMS, 80 mill DKK, **3.2%** of construction cost (2.500 mill DKK)

- **Sutong Bridge.**
  SHMS, 23 mill DKK, **0.5%** of construction cost (4.500 mill DKK)

- **Naini Bridge.**
  SHMS, 6 mill DKK, **1.2%** of construction cost (500 mill DKK)