List of SAMCO Reference Projects

No.	Submitted by			Project		
	Name	Institute	Country	Name	City	Country
1	Rohrmann	BAM, Berlin	DE	Westend-Bridge	Berlin	Germany
2	Rohrmann	BAM, Berlin	DE	Putlitz- Bridge	Berlin	Germany
3	Rohrmann	BAM, Berlin	DE	Zittau-Viaduct	Zittau	Germany
4	Helmerich	BAM, Berlin	DE	Lehrter Bahnhof	Berlin	Germany
5	Aktan	Univ. Drexel	USA	Commodore Barry Bridge	Chester	USA
6	Huth	EMPA, Dübendorf	CH	RAMA IX - Bridge	Bangkok	Thailand
7	De Stefano	Politecnico di Torino	IT	Holy shroud chapel	Turin	Italy
8	Brownjohn	Univ. Sheffield	UK	Republic Plaza	Singapore	Singapore
9	Brownjohn	Univ. Sheffield	UK	Tuas Second Link	Singapore	Singapore
10	Brownjohn	Univ. Sheffield	UK	Pasir Panjang Semi Expressway	Singapore	Singapore
11	Brownjohn	Univ. Sheffield	UK	Pioneer Bridge	Singapore	Singapore
12	Lesoille	LPCP, Paris	F	Saint-Jean Bridge	Bordeaux	France
13	Mentes	Acad. of Science, Sopron	H	Szechenyi Bridge	Györ	Hungary
14	Rosell	Swedish National Road Administration	S	Källösund Bridge	Gothenburg	Sweden
15	Inaudi	Smartec	CH	Bolshoj Moskvoretsky Bridge	Moskau	USSR
16	Inaudi	Smartec	CH	Versoix Bridge	Versoix	Switzerland
17	Inaudi	Smartec	CH	Punggol EC26	Singapore	Singapore
18	Teughels	KUL	B	Z24 Bridge	Koppingen	Switzerland
19	Geier	Arsenal	A	Florido Tower	Vienna	Austria
20	Geier	Arsenal	A	Talübergang Haag	Haag	Austria
21	Geier	Arsenal	A	Warth Bridge	Vienna	Austria
22	Geier	Arsenal	A	PORR Bridge	Vienna	Austria
23	Geier	Arsenal	A	Railway Bridge Heugasse	Vienna	Austria
24	Geier	Arsenal	A	Melk Bridge	Melk	Austria
25	Geier	Arsenal	A	Hospital Leoben	Leoben	Austria
26	Huth	EMPA, Dübendorf	CH	Bridge BE 109/21	Bützberg	Switzerland
27	Wenzel	VCE	A	Europa-Brücke	Innsbruck	Austria
28	Viberg	KTH	S	New Arsta Bridge	Stockholm	Sweden

29	Karoumi	KTH	S/N	New Swinesund Bridge	Svinesund	Sweden - N
30	Peeters	LMS	B	Oeresund Bridge	Oeresund	Denmark - S
31	Cheng	TNO TPD	B	Tsing Ma Bridge	Hong Kong	Hongkong
32	Frenz	TU Braunschweig	DE	Highway Bridge BW91	Braunschweig	Germany
33	Hariri	TU Braunschweig	DE	Herrenbrücke Bridge Lübeck	Braunschweig	Germany
34	Wenzel	VCE	A	St.Marx Bridge	Vienna	Austria
35	Wenzel	VCE	A	Taichung Bridge	Taiwan	China
36	Woodward	TRL	UK	Huntingdon Railway Bridge	Huntingdon	UK
37	Bolle	Infokom	DE	ESK 551	Bad Bevensen	Germany
38	Fritzen	Uni Siegen	DE	I40 Bridge	New Mexico	USA
39	Fritzen	Uni Siegen	DE	Steelquake Stucture	JRC	Italy
40	Bourquin	LPCP, Paris	F	Roberval Bridge	Senlis	France
41	Ortega	Geosica	SP	Titulcia Steel Bridge	Madrid	Spain
42	Ortega	Geosica	SP	Condamine floating dock	Monaco	Monaco
43	Goltermann	Ramboll	DK	Skovdiget Bridge superstructure	Copenhagen	Denmark
44	Goltermann	Ramboll	DK	Skovdiget Bridge columns	Copenhagen	Denmark
45	Ko	Hong Kong Polytechnic University	China	Ting Kau Bridge	Hong Kong	China

List of SAMCO Reference Projects

No.	Submitted by			Project		
	Name	Institute	Country	Name	City	Country
1	Rohrmann	BAM, Berlin	DE	Westend-Bridge	Berlin	Germany
2	Rohrmann	BAM, Berlin	DE	Putlitz- Bridge	Berlin	Germany
3	Rohrmann	BAM, Berlin	DE	Zittau-Viaduct	Zittau	Germany
4	Helmerich	BAM, Berlin	DE	Lehrter Bahnhof	Berlin	Germany
5	Aktan	Univ. Drexel	USA	Commodore Barry Bridge	Chester	USA
6	Huth	EMPA, Dübendorf	CH	RAMA IX - Bridge	Bangkok	Thailand
7	De Stefano	Politecnico di Torino	IT	Holy shroud chapel	Turin	Italy
8	Brownjohn	Univ. Sheffield	UK	Republic Plaza	Singapore	Singapore
9	Brownjohn	Univ. Sheffield	UK	Tuas Second Link	Singapore	Singapore
10	Brownjohn	Univ. Sheffield	UK	Pasir Panjang Semi Expressway	Singapore	Singapore
11	Brownjohn	Univ. Sheffield	UK	Pioneer Bridge	Singapore	Singapore
12	Lesoille	LPCP, Paris	F	Saint-Jean Bridge	Bordeaux	France
13	Mentes	Acad. of Science, Sopron	H	Szechenyi Bridge	Györ	Hungary
14	Rosell	Swedish National Road Administration	S	Källösund Bridge	Gothenburg	Sweden
15	Inaudi	Smartec	CH	Bolshoj Moskvoretsky Bridge	Moskau	USSR
16	Inaudi	Smartec	CH	Versoix Bridge	Versoix	Switzerland
17	Inaudi	Smartec	CH	Punggol EC26	Singapore	Singapore
18	Teughels	KUL	B	Z24 Bridge	Koppingen	Switzerland
19	Geier	Arsenal	A	Florido Tower	Vienna	Austria
20	Geier	Arsenal	A	Talübergang Haag	Haag	Austria
21	Geier	Arsenal	A	Warth Bridge	Vienna	Austria
22	Geier	Arsenal	A	PORR Bridge	Vienna	Austria
23	Geier	Arsenal	A	Railway Bridge Heugasse	Vienna	Austria
24	Geier	Arsenal	A	Melk Bridge	Melk	Austria
25	Geier	Arsenal	A	Hospital Leoben	Leoben	Austria
26	Huth	EMPA, Dübendorf	CH	Bridge BE 109/21	Bützberg	Switzerland
27	Wenzel	VCE	A	Europa-Brücke	Innsbruck	Austria
28	Viberg	KTH	S	New Arsta Bridge	Stockholm	Sweden

29	Karoumi	KTH	S/N	New Swinesund Bridge	Svinesund	Sweden - N
30	Peeters	LMS	B	Oeresund Bridge	Oeresund	Denmark - S
31	Cheng	TNO TPD	B	Tsing Ma Bridge	Hong Kong	Hongkong
32	Frenz	TU Braunschweig	DE	Highway Bridge BW91	Braunschweig	Germany
33	Hariri	TU Braunschweig	DE	Herrenbrücke Bridge Lübeck	Braunschweig	Germany
34	Wenzel	VCE	A	St.Marx Bridge	Vienna	Austria
35	Wenzel	VCE	A	Taichung Bridge	Taiwan	China
36	Woodward	TRL	UK	Huntingdon Railway Bridge	Huntingdon	UK
37	Bolle	Infokom	DE	ESK 551	Bad Bevensen	Germany
38	Fritzen	Uni Siegen	DE	I40 Bridge	New Mexico	USA
39	Fritzen	Uni Siegen	DE	Steelquake Stucture	JRC	Italy
40	Bourquin	LPCP, Paris	F	Roberval Bridge	Senlis	France
41	Ortega	Geosica	SP	Titulcia Steel Bridge	Madrid	Spain
42	Ortega	Geosica	SP	Condamine floating dock	Monaco	Monaco
43	Goltermann	Ramboll	DK	Skovdiget Bridge superstructure	Copenhagen	Denmark
44	Goltermann	Ramboll	DK	Skovdiget Bridge columns	Copenhagen	Denmark
45	Ko	Hong Kong Polytechnic University	China	Ting Kau Bridge	Hong Kong	China

+

Westend Bridge - Germany

Project Description:

The Westend bridge is part of the Berlin city highway that connects downtown Berlin with the airport in the north. The 38 years old structures is a pre-stressed concrete bridge. In the past the bridge had to be strengthened multiple times due to cracks and open connecting joints within the floor slab. After the reunification of Berlin the commercial traffic into the city increased considerably and, hence, doubts arose whether the bridge would sustain this new loading.

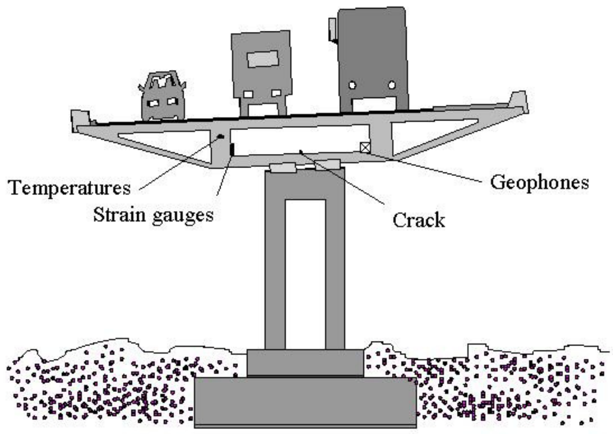
Westend bridge Berlin, Germany

Quick Facts:

- **Name and Location:** Westend Bridge, Berlin, Germany
- **Owner:** City of Berlin, Germany
- **Structure category:** medium span bridge
- **Spans:** 8 spans: 25.0/ 36.3/ 37.5/ 31.1/ 38.1/ 38.0/ 31.6/ 5.0 m
- **Structural system:** Pre-stressed concrete box girder and reinforced concrete columns
- **Start of SHM:** January, 1994
- **Number of sensors installed:** 36
- **Instrumentation design by:** BAM, Buildings and Structures Division, Germany

Description of Structure:

The 243 m long superstructure is continuous and consists of a three-cell box girder with a maximum width of 14 m. It is supported by 7 reinforced concrete columns with a hollow cylindrical cross section. The column in the middle of the bridge which is fixed at both ends takes the horizontal loads. All the remaining columns are pin-ended. The whole bridge is built on foundation slabs. The two bridge abutments are formed by RC-walls.



Cross section and sensor distribution within the superstructure

Purpose of Inspection:

The purpose of the inspection of the Westend bridge was to assess their condition with respect to the presence of multiple cracks within the girder. The inspection was performed by using a monitoring system that records permanently the current traffic loads, stresses and the structure's health. Since 1994 this systems is working till now and has, with an increasing number of measurement channels, supplied continuously bridge data.

Sensor Details*:

Type	Number	Location
Strain gauges	4	all sensors are fixed within the box girder of span 2 and 3 except the temperature sensors which are attached at the web of one the girders
Velocity transducers	20	
Accelerometers	3	
Crack sensors	1	
Inclinometers	2	
Position Sensitive Detectors	1	
PT100	5	

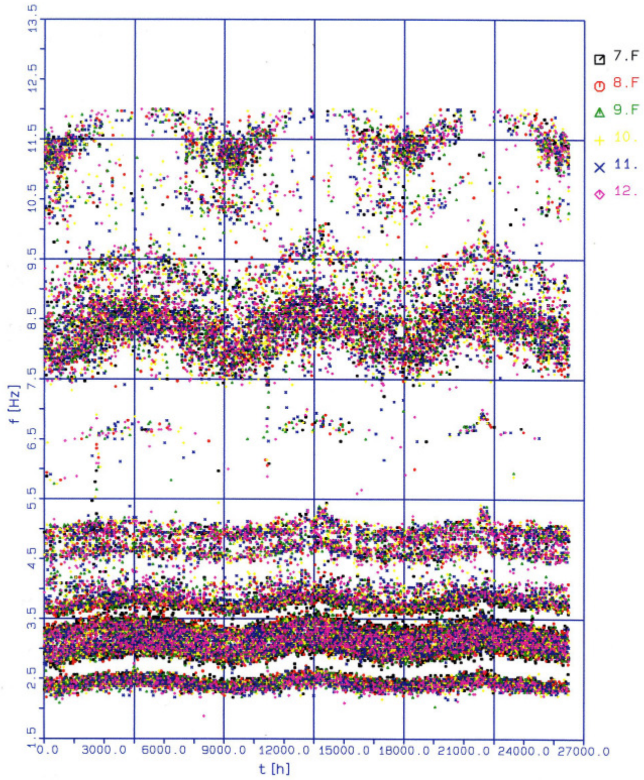
Examples of Outcomes:

It could be found out, that in general the dynamic loads acting on a bridge are dependent on the weight of their vehicles. In case of the Westendbridge it could be shown, that the increasing dynamic loads are correlated to the quality of the road surface.

Analyzing the traffic data obtained by load monitoring, changes in the load spectra could be observed and the increasing number of heavy load vehicles and their weight could be quantified.

Performing global condition monitoring it could be found out, that the natural frequencies of the bridge are varying with respect to changes of the structural temperature (see figure), what means that changes of the bearing capacity can be assumed.

Local condition monitoring proves a strong temperature dependent but reversible behavior of the cracks in the slab of the girder.



Observed natural frequencies, duration 3 years

Benefits of Using SHM Technologies in the Project:

The Westend bridge is that structure where BAM has performed all over the time a lot of investigations to develop dynamic approaches for the inspection of bridges (see references) including SHM. Many of the questions bridge owners have, like actual acting static traffic loads, dynamic amplification factors or combined loadings due to traffic and temperature or condition monitoring and the automatic detection of damage cannot be answered without SMH.

References:

Rücker, W. F., Said, S.; Rohrmann, R. G.; Schmid, W., "Load and Condition Monitoring of a Highway Bridge in a Continuous Manner", Proc. IABSE Symposium. Extending the Lifespan of Structures, San Francisco, 1995

Rohrmann, R. G., Said, S., Schmid, W., Rücker, W. F., "Results of the automatic monitoring of the Westend bridge in Berlin", Research report A, B and C, BAM Berlin 1996 till 1998 (in German).

Link, M.; Rohrmann, R. G.; Pietrzko, S., "Experience with the automated procedure for adjusting the finite element model of a complex highway bridge to experimental model data", Proc. of the 14th IMAC, Dearborn, 1996

Rohrmann, R.G., Baessler,M., Said,S., Wolfgang Schmid,W., Ruecker, W.F., "Structural causes of temperature affected modal data of civil structures obtained by long time monitoring", Proc. of the 18th IMAC, San Antonio, 2000

Submitted by:

Federal Institute for Materials Research and Testing (BAM)
Division Buildings and Structures
D-12200 Berlin, Germany
87 Unter den Eichen
Phone: +49(30) 8104-3293
Fax: +49(30) 8104-1727
Email: rolf.rohrmann@bam.de
werner.ruecker@bam.de
samir.said@bam.de

Putlitz Bridge - Germany

Project Description:

The Putlitz Bridge in Berlin, Germany, opened in 1977, is part of a main route for urban traffic which is also used for heavy loads. Currently the bridge is stressed by the transport of heavy gas turbines with maximum loads of 500 t, which is much more than the design loads. To ensure the bearing capacity experimental investigations including SHM have to be carried out.

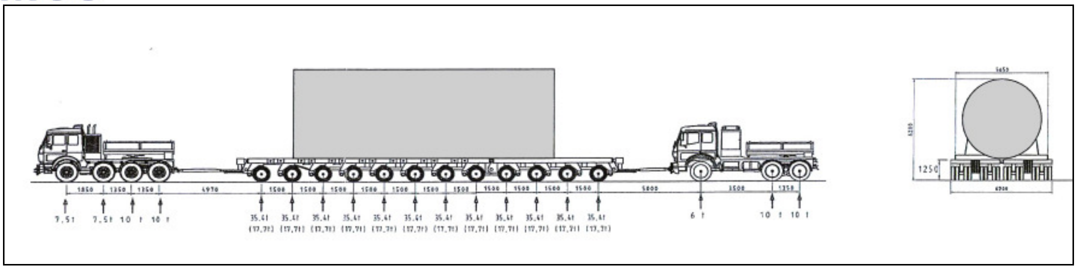
Putlitz Bridge, Berlin, Germany

Quick Facts:

- **Name and Location:** Putlitz Bridge, Berlin, Germany
- **Owner:** City of Berlin, Germany
- **Structure category:** medium span bridge
- **Spans:** 9 spans: 25.1/ 34.7/ 31.5/ 30.2/ 32.6/ 30.1/ 30.2/ 30.4/ 29.2 m
- **Structural system:** Steel box girder with orthotropic deck and steel columns
- **Start of SHM:** September, 2001
- **Number of sensors installed:** 21
- **Instrumentation design by:** BAM, Division Buildings and Structures, Berlin,Germany

Description of Structure:

The superstructure comprises of two steel box girders and an orthotropic deck plate. The bridge with a total length of 270 m consists of two parts, separated by a lengthways joint. A roadway is led with two lanes of traffic each on every bridge part. Every bridge part is 14 m wide. For the heavy load transports the western part is of use for the bridge.



Heavy load transport 490 t

Purpose of Inspection:

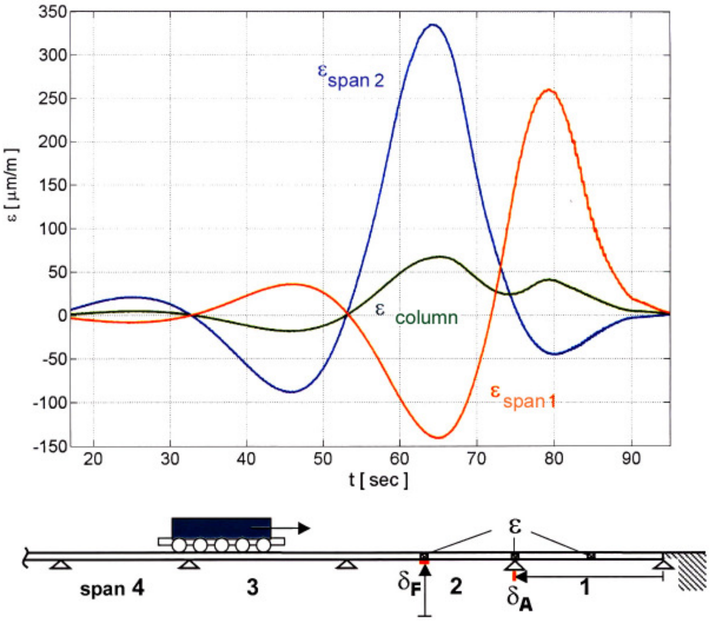
Static calculations show that the ultimate limit state of the bridge is reached under those heavy loads. These results have to be verified by experimental investigations measuring continuously maximum strains due to heavy loads und temperature. Additional fatigue stresses at endangered points of the bridge are of interest. Furthermore it is important to know the real static and dynamic loads which can be calculated from the results of the available stain measurements.

Sensor Details*:

Type	Number	Location
Strain gauges	11	at the main girders and the orthotropic bridge deck
Velocity transducers	4	
Position Sensitive Detectors	2	all sensors are fixed at the main girders
LVDT	2	
PT100	2	

Examples of Outcomes:

It could be affirmed that the dynamic loads, as assumed for the static calculations, can be neglected. Within the time of observation no exceeding of the limit state could be noted. The global condition state of the bridge is not yet affected.



Strain distribution at a main girder during the crossing of a heavy load vehicle measured by SHM

Benefits of using SHM Technologies in the Project:

All data from stress measurements due to normal and heavy traffic loads as well as temperature loads is available so that the exceeding of limit states and the occurrence of damage can be detected immediately.

References:

R.G. Rohrmann, S. Said, W. Schmid, "Load and condition monitoring of the Putlitz Bridge in Berlin-Moabit", Proc. Symposium Topics from civil and bridge engineering, BAM, Berlin 2003 (in German)

Submitted by:

Federal Institute for Materials Research and Testing (BAM)
Division Buildings and Structures
D-12200 Berlin, Germany
87 Unter den Eichen
Phone: +49(30) 8104-3293
Fax: +49(30) 8104-1727
Email: rolf.rohrmann@bam.de
werner.ruecker@bam.de
samir.said@bam.de

Zittau Viaduct - Germany

Project Description:

The railway viaduct was built in 1859. It crosses the Polish-German border nearby the town of Zittau. A spacious lowering of the groundwater level led to a pier foundation settling and that caused in wide cracks, appearing at the superstructure above the piers.

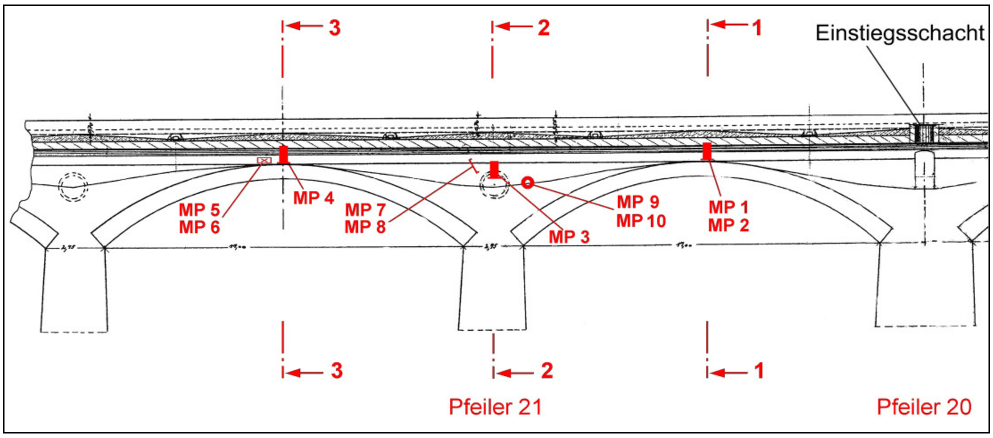
Railway viaduct Zittau, Germany

Quick Facts:

- **Name and Location:** Neisse viaduct, Zittau, Germany/Poland
- **Owner:** German Rail
- **Structure category:** Masonry arch bridge
- **Spans:** 34 archs: each between 17 and 23 m
- **Structural system:** Arch bridge on masonry piers
- **Start of SHM:** November, 2000
- **Number of sensors installed:** 12
- **Instrumentation design by:** BAM, Division Buildings and Structures, Germany

Description of Structure:

The Neisse viaduct is a natural stone masonry arc bridge. It is 750 m long and between 3 and 25 m high. The width of the superstructure is 8 m. The bridge is used for public railway transport. The structure was strengthened in the past by a concrete construction.



Distribution of sensors within the superstructure

Purpose of Inspection:

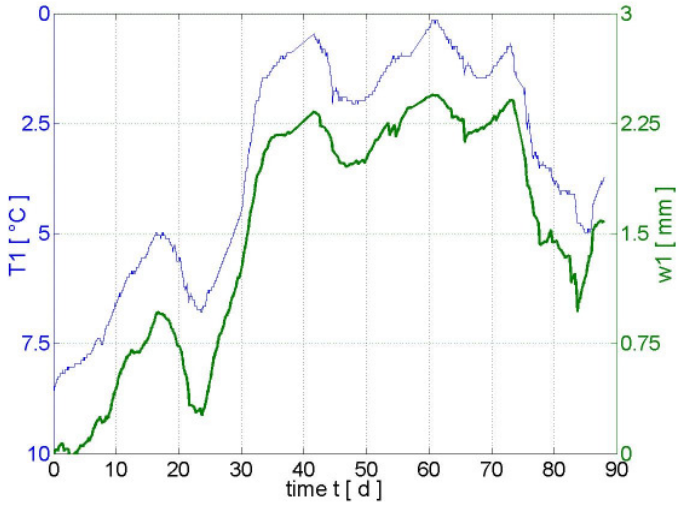
It was observed by visual inspection, that the existing cracks still opened. Through structural health monitoring the cause for the additional crack movement ought to be found out and it was also intended to assess, in which degree the bearing capacity of the structure was affected.

Sensor Details*:

Type	Number	Location
Velocity transducers	4	all sensors are fixed at the superstructure of the bridge (see figure above)
Crack sensors	2	
Strain gauges	2	
Pt 100	2	

Examples of Outcomes:

The long-term monitoring of the crack width together with other monitored parameters showed that the whole cross section of the superstructure was cracked. The crack widths change with the temperature course of structure (see results). The progressive foundation settlings as much as the traffic have obviously no irreversible influence on the crack evolution.



Crack width via structural temperature measured by SHM

Benefits of using SHM technologies in the project:

Only because of the simultaneous measurement of the different crack movement influencing parameters over a long period a cause and effect relation could be found. The effect of the cracks on the bearing capacity of the structure is determined by the measurement of strain and of dynamic parameters.

References:

W. Ruecker, R.G.Rohrmann, S.Said, W. Schmid, "Dynamic approaches used for the safety observation of bridges, Proc. Symposium Actual problems in the dynamic behaviour of bridges, D-A-CH, Zurich, 2003 (in German)

Submitted by:

Federal Institute for Materials Research and Testing (BAM)
Division Buildings and Structures
D-12200 Berlin, Germany
87 Unter den Eichen
Phone: +49(30) 8104-3293
Fax: +49(30) 8104-1727
Email: rolf.rohrmann@bam.de
werner.ruecker@bam.de
samir.said@bam.de

Berlin Main Station, Lehrter Bahnhof - Germany

Project Description:

The Lehrter Bahnhof in Berlin, Germany, has been under construction since 2000 and will be finally opened in 2006. The station is the mayor project for a high speed train crossing of the main European railway routes connecting North-South, East-West. The East-West-viaduct carries the steel-glass roof, which is sensitive to vertical movement in the level of its bearings, especially during construction work on site. Since the East-West tracks have been taken into service in May 2002, BAM operates a Longterm-Monitoring-System to control settlements as well as surface strains of prestressed concrete bridges, influenced by construction processes at the station. To ensure the longterm stability of new sensors enhanced at BAM, experimental investigations on model beams have been carried out in the laboratory and under environmental conditions.

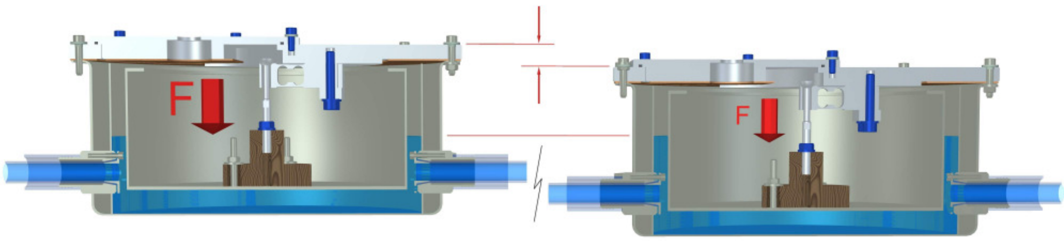
Main Station, Lehrter Bahnhof, Berlin, Germany

Quick Facts:

- **Name and Location:** Lehrter Bahnhof, Berlin, Germany
- **Owner:** German railways, DB AG, Germany
- **Structure category:** short and medium span bridges
- **Spans:** RC bridge viaduct with spans between 8 and 29 m, prestressed concrete bridges: 18-21-18 m;
- **Structural system:** Steel box girder with orthotropic deck and steel columns
- **Start of SHM:** May 2002
- **Number of sensors installed:** 128
- **Instrumentation design by:** BAM, Divisions Sensores and Measurement Systems; Structural Stress Analysis and Buildings and Structures, Berlin, Germany

Description of Structure:

The East-West-superstructure consists of 4 parallel track viaducts, partially covered by a steel glass roof. The viaducts in the middle are for two tracks.
The outer bridges have one track each, loading the viaducts symmetrically. They are additionally loaded by torsional load resulting from the steel-glass roof. The middle bridges of all four viaducts are prestressed concrete structures



Hydrostatic leveling system “Kohlhoff”, developed and patented at BAM

Purpose of Inspection:

As result of static calculation the vertical movement of the bearings for the steel-glass roof was limited by the railway authorities (EBA). The bearings of the glass roof are located on the top of the outer bridges of the East-West-Tracks. The roof is loading the track bridges with a torsional load additional to the symmetrical traffic load

Sensor Details*:

Type of sensors	Number	Location
Strain gauges	40	Bridge 12 an 15
Strain gauge rosettes	16(+16)	Columns under bridge 12 + 15
Hydrostatic leveling sensors	30(+4)	North and south viaduct
Laser sensors	10	Bridge 12 and 15
Inclination sensors	10	North and south viaduct
Temperature sensors	12	North and south viaduct

Measurement Equipment and Data Management:

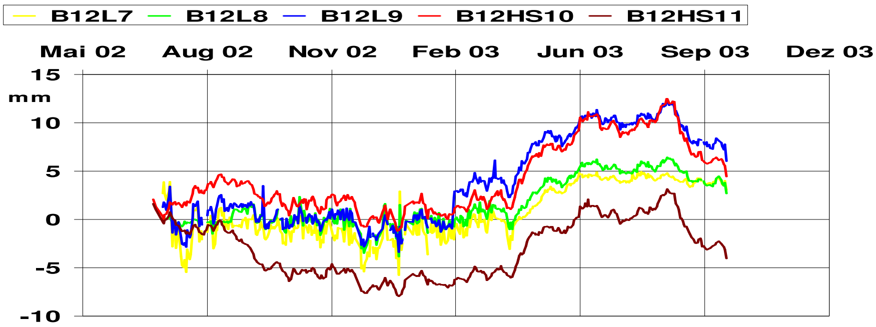
Type of system	Data Management	CMS
PC and internet-based measurement system	▪ data pre-analysis on BAM-external server ▪ main analysis, graphical presentation and documentation in office ▪ data transfer via web ▪ long term data base	

Data Analysis Procedures:

Type of analysis	Software	Additional features
damage indicators; influence of settlements and Temperature	self made software by BAM	▪ no expert system

Examples of Outcomes:

During the building process monitoring showed, that limit values for vertical displacements were not exceeded. The global condition state of the bridge and of the glass roof did not suffer from a critical loading situation.



Strains, continuously measured at prestressed outer bridges since mid of 2002

Benefits of Using SHM Technologies in the Project:

All data from vertical displacement and strain measurements during building processes as well as from traffic and temperature loads are measured and presented via web. Exceeding of limit values can be detected immediately via web.

References:

Helmerich, R.; Kohlhoff, H.; Niemann, J.; Werner, K.-D.;
Structural Condition Monitoring of a high-speed train station
Proc. IABSE Symposium Antwerpen 2003, Structures for High-Speed Railway Transportation, August 27-29, 2003

Submitted by:

Federal Institute for Materials Research and Testing (BAM)
Division Measurement and Testing Technology, Sensors
Division Buildings and Structures
D-12200 Berlin, Germany
87 Unter den Eichen
Phone: +49(30) 8104-3623
Fax: +49(30) 8104-1917
Email: joachim.niemann@bam.de
falk.hille@bam.de

COMMODORE BARRY BRIDGE - USA

Project Description:

The Commodore John Barry Bridge (CBB) spans the Delaware River between Chester, Pennsylvania and Bridgeport, New Jersey. The bridge has five traffic lanes and currently serves more than six million vehicles annually, a significant percentage of which is heavy truck traffic. It was opened to traffic in 1974.

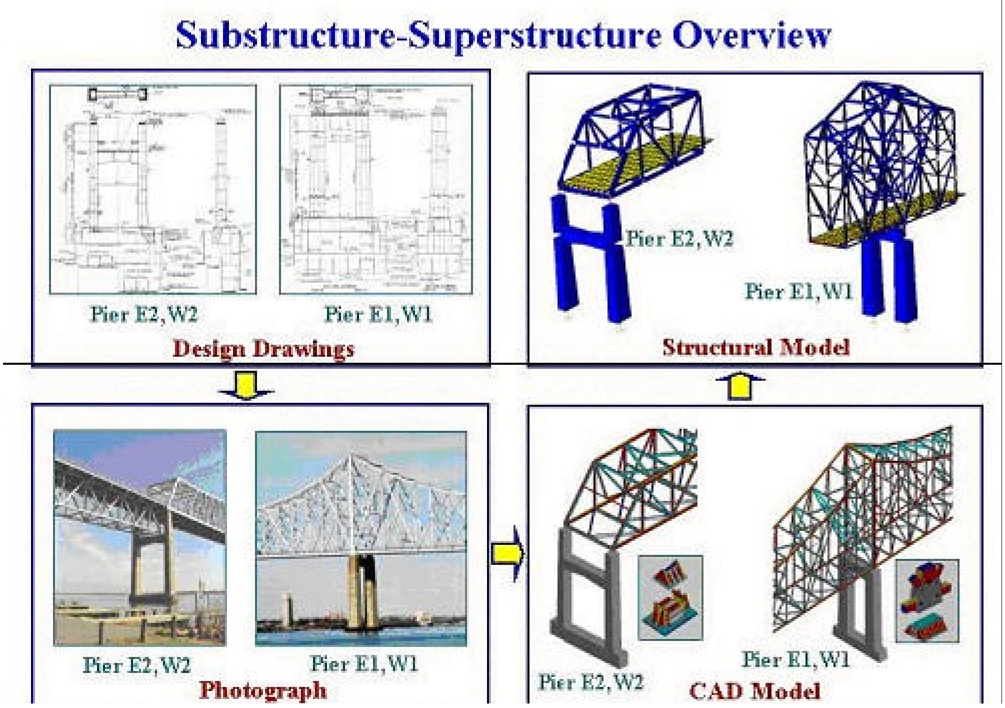
Commodore Barry Bridge Through-Truss Structure

Quick Facts:

- **Name and location:** Commodore John Barry Bridge (CBB) spans the Delaware River between Chester, Pennsylvania and Bridgeport, New Jersey, USA.
- **Owner:** Delaware River Port Authority (DRPA) of Pennsylvania and N. J., USA
- **Structure category:** Long-span steel truss bridge
- **Spans:** 3 spans; 822 ft / 1,644 ft / 822 ft.
- **Structural system:** Steel truss bridge
- **Start of SHM:** 1998
- **Number of sensors installed:** 97 sensors
- **Instrumentation design by:** Drexel Intelligent Infrastructure Institute

Description of Structure:

The total length of the bridge is 13,912 feet. The study focuses on the long span through truss section of the bridge which is 3,288 ft. long. The sub-structures of the through-truss, comprised of four reinforced concrete piers, were constructed on pile foundations in the riverbed. The main truss has 73 panel points spaced at 45.7 feet intervals. The two principal trusses of the through-truss are spaced 72.5 feet apart. The floor system of the bridge is an 8-inch thick lightweight reinforced concrete deck that is composite with 9 steel beams laterally spaced at 6.9 feet.



Substructure-Superstructure Overview

Purpose of Instrumentation:

The purpose of monitoring the truss bridge is to evaluate the following:

- the actual stresses of the critical elements that govern the structural safety performance such as the hangers, stringers and the truss members that were constructed with an electro-slag welding process;
- ambient environmental conditions at the bridge;
- performance of the primary movement systems;
- performance of the truss hangers and the auxiliary support system that was added as a retrofit;
- the effectiveness and condition of approximately 1,000 vibration dampers

Sensor Details*:

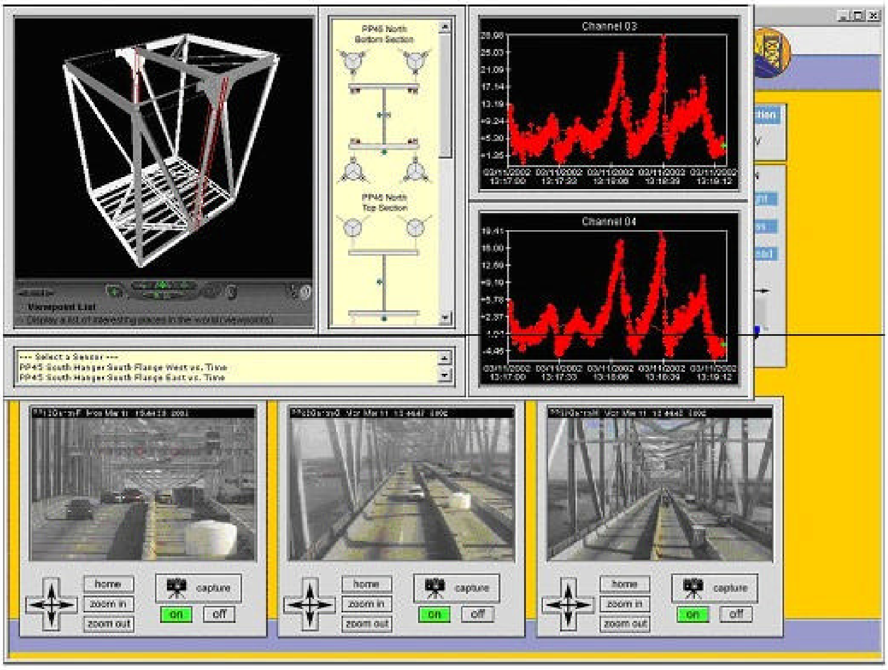
Type	Number	Location
ultrasonic wind sensors	4	on tower and at midspan
strain gages, tiltmeters, and crackmeters	231	on the truss members, hangers and auxiliary support system, floor system, and piers
accelerometers	16	for the vibration dampers

Examples of Outcomes:

The layout of the information systems that was designed in conjunction with the monitors for this project provides a user-friendly, intuitive and secure interface. The basic building blocks of the health and performance monitoring system can be summarized as follows:

- Sensing, data acquisition and control;
- Data processing and information management;
- Human and organizational interfacing for adoption as a management tool.

The data and information processing challenges are influenced by the necessity of providing proper training for the human operators, which is, in fact, the key to organizational acceptance and adoption. The latter is naturally the true measure of success for any technological innovation.



Real Time Synchronized Hanger Strain Data and Live Load Imaging

Benefits of using SHM Technologies in the Project:

Monitoring the Commodore Barry Bridge shows the following:

- The damper should have a useful life of at least 50 years if controlled by the durability of neoprene.
- No changes were observed in the conditions of any of the defects that were identified a decade ago.
- A closer scrutiny of the measured strain and temperature histograms indicated that the hanger intrinsic strains were affected by the complex movement and force-release systems at and in the vicinity of these members. A distinctly unsymmetrical behavior at the long-term strains of the two-instrumented hangers was attributed to a difference in the behavior of the movement systems at their respective boundaries on the North and the South trusses. In addition, an out of plane behavior was noted in the hangers that were expected to be concentrically loaded due to radiation and temperature changes.

References:

1- F.N.Catbas, S.K.Ciloglu, K.Grimmelsman, Q.Pan, M.Pervizpour and A.E.Aktan “Limitations in the Structural Identification of Long-Span Bridges” Proceedings of the International Workshop on Structural Health Monitoring of Bridges/ Colloquium on Bridge Vibration‘ 03, September 1-2, 2003.

2- A. Emin Aktan, F.Necati Catbas, Kirk A. Grimmelsman, and Mesut Pervizpour “Development of a Model Health Monitoring Guide for Major Bridges” Technical report submitted to Federal Highway Administration Research and Development, Drexel Intelligent Infrastructure and Transportation Safety Institute, Drexel, USA, September 2002.

Submitted by:
Dr. A. Emin Aktan
Drexel Intelligent Infrastructure and Transportation Safety Institute
Mezzanine Level, Suite 50
3101 Market Street, One Drexel Plaza
Philadelphia, PA 19104
USA
Email: aaktan@drexel.edu
Phone: + 1 (215) 895 - 6135
Fax: + 1 (215) 895 - 6131

RAMA IX Bridge - Thailand

Project Description:

The RAMA IX Bridge in Bangkok, Thailand was opened in 1987. The bridge is part of Metropolitan Bangkok's Expressway. The bridge represents a crucial connection between Bangkok and Thonburi, across the Chao Phraya River. As part of a regular 15 years inspection, all 68 stay cables of the bridge were subjected to Non Destructive Evaluation in order to assess their conditions.

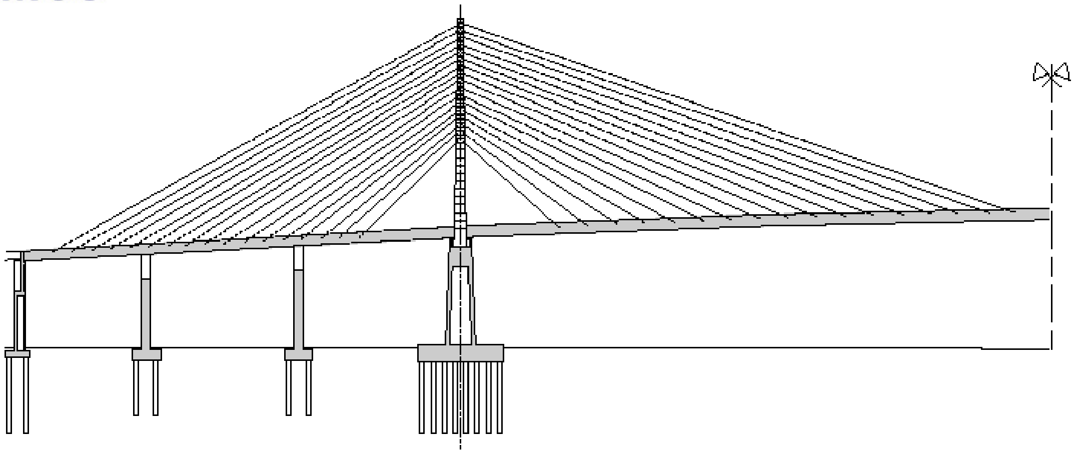
RAMA IX Bridge, Bangkok, Thailand (Photo by Katrin Janberg, www.structurae.net)

Quick Facts:

- **Name and Location:** RAMA IX Bridge - Bangkok, Thailand
- **Owner:** Expressway and Rapid Transit Authority of Thailand (ETA), Bangkok, Thailand
- **Structure category:** Medium span (cable stayed bridge)
- **Spans:** Main span: 450 m Back spans: 61.20 m - 57.60 m - 46.80 m
- **Structural system:** Steel box girder with orthotropic deck and steel pylons, supported on concrete piers and pile foundations.
- **Start of SHM:** July, 2001
- **Number of sensors installed:** N/A
- **Instrumentation design by:** EMPA, Structural Engineering Research Laboratory, Switzerland

Description of Structure:

The Rama IX is a single plane cable stayed bridge with steel box girder and orthotropic deck and steel pylons. It is comprised of a main span (450 m) and two back spans (61.2m+57.6m+46.8m). The bridge carries 6 lanes of traffic. A total of 68 locked coil cables (121mm≤Ø≤168mm) are divided in 4 groups of 17 (1 group on each back span and 2 groups on the main span of the bridge).



Longitudinal-section of the RAMA IX Bridge

Purpose of Inspection:

The purpose of the inspection of the RAMA IX Stay cables was to assess their condition with respect to the presence of fractured wires and possibly of corrosion in the cross-section of the free length of the cables. The inspection was performed using the magnetic flux leakage (MFL) method. The MFL method is non-destructive inspection method.

Due to the importance of the link for the city's traffic system, the inspection had to be carried out without interrupting the service of the bridge. This condition together with practical considerations ruled out the use of radiation based methods for the inspection.

Sensor Details*:

Type	Number	Location
Global MFL sensor	1	In the MFL device, on the
circumference of the cable		
Circumference resolved MFL Sensors		≤26
the circumference of the cable		

Measurement Equipment and Data Management:

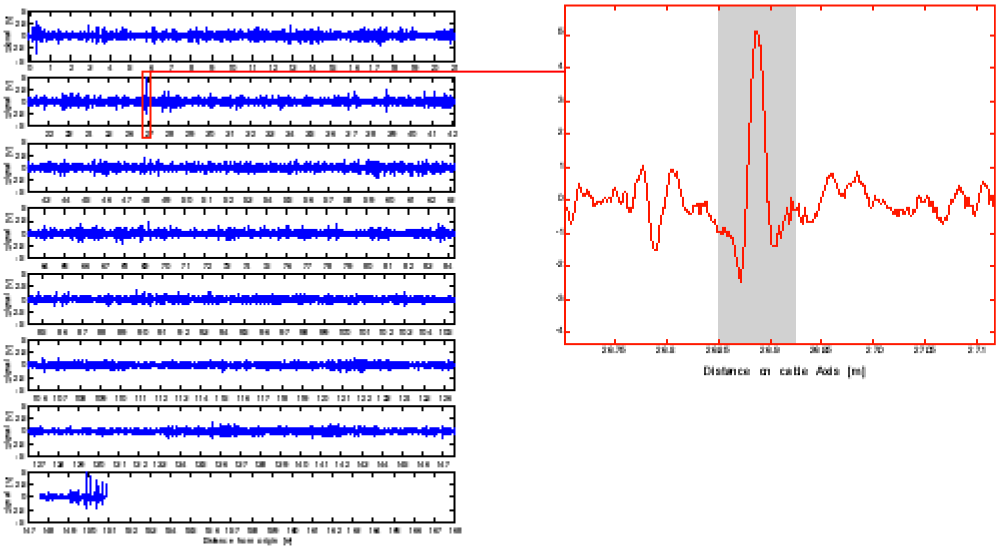
Type of system	Data Management	CMS
PC based measurement system	▪ data pre-view (overview of unfiltered signal) on site ▪ main analysis, graphical presentation and documentation in office ▪ data backed up on CDs on site	N/A

Data Analysis Procedures:

Type of analysis	Software	Additional features
Data post-processing (filtering of speed related effects) Flaw recognition and localization	Software developed in-house	New developments after RAMA IX: • 3D localization of the flaws for multi-strand cables • ANN based recognition of flaws

Examples of Outcomes:

100% of the free length of the cables was inspected. The output from the global MFL sensor yielded overall information about the presence of fractures within the cable cross-section as a function of the distance along the cable axis, as shown in figure below:



In the case of locked coil cables, such as the ones installed on RAMA IX Bridge, and parallel wire bundles, the information obtained from the circumference resolved MFL sensors, is not used to localize the position of flaws within the cross-section of the cable but as a second set of sensors for backup measurement. For multi-strand systems, the mapping of the magnetic flux leakage maps on the surface of the cable can be used to localize the position of flaws within the cross-section of a cable. The identification of signals indicating the presence of flaws has now been automated to a large extent.

Benefits of Using SHM Technologies in the Project:

The application of the MFL technique was at the time of its deployment the only commercially viable solution for the inspection of the cables installed on the bridge for a total length of approximately 8.5 km.
To present no alternatives to the application of magnetic methods to the inspection of large diameter steel cables has been found.
In addition to making use of a nondestructive method, the inspection procedure used on RAMA IX did not require any interruption of the traffic on the bridge.

References:

R. K. Stanley, "Simple explanation of the theory of the total magnetic-flux method for the measurement of ferromagnetic cross-sections", Materials Evaluation, **53** (1), 72-75 (1995)

A. Bergamini, "Nondestructive Testing of Stay Cables - Field Experience in South East Asia", Proc. 3WCSC, Como, Italy, Wiley, 2002 (in print)

A. Bergamini, R. Christen "A Simple Approach to the Localization of Flaws in Large Diameter Steel Cables" SPIE's 8th Annual international Symposium on NDE for Health Monitoring and Diagnostics, 2003, to be published

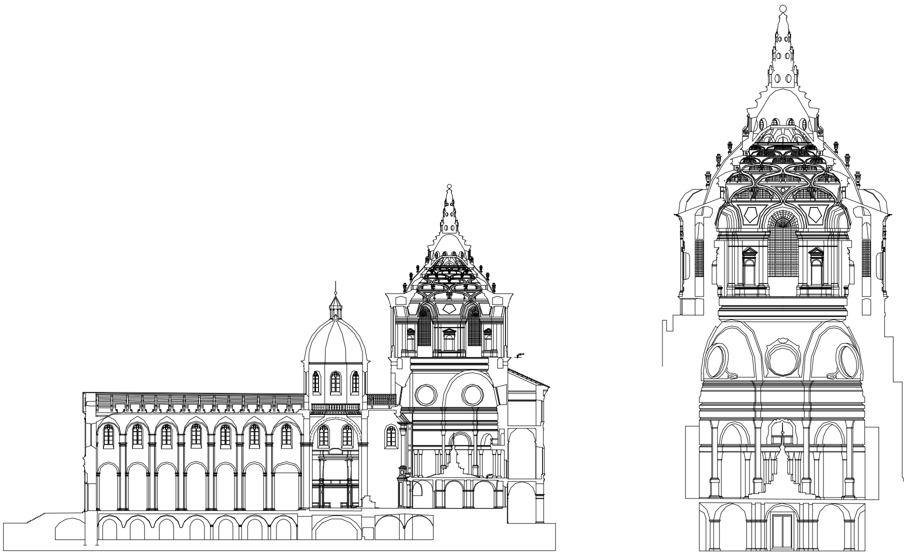
Submitted by:

Swiss Federal Institute for Materials Testing and Research (EMPA)
Structural Engineering Research Laboratory
CH-8600 Dübendorf, Switzerland
129-133, Ueberlandstrasse
Phone: +41 1 823 4424
Fax: +41 1 823 4455
Email: andrea.bergamini@empa.ch

Holy-Shroud Chapel, Torino, Italy

Project Description:

- Designed by Guarino Guarini, built from 1667 to 1694
- Heavily damaged by fire in 1997
- Governmental contract with Politecnico di Torino to provide a project for a general experimental campaign on materials and structure (P. Napoli) and a dynamic test programme (A. De Stefano)
- Governmental contract with Politecnico di Torino (A. De Stefano) and University of Kassel (Link) to provide a numerical model refinement and model updating



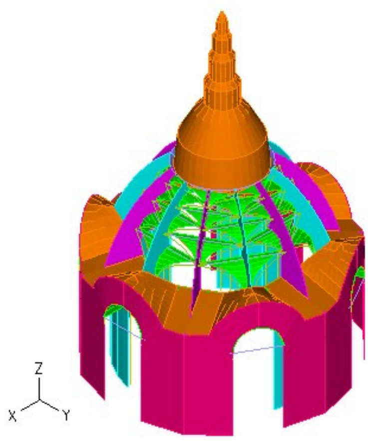
Holy shroud chapel

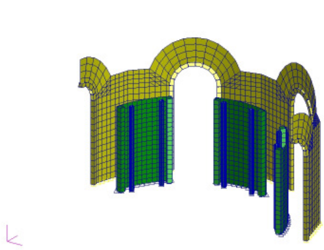
Quick Facts:

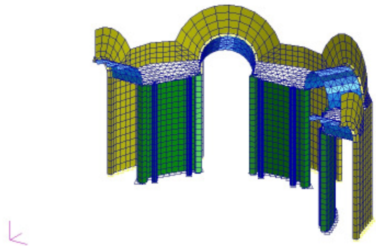
- **Name and Location:** Holy-Shroud Chapel, Turin, Italy
- **Owner:** Italian Government
- **Structure category:** Monumental building: high-valued architectural treasure built in XVIIth century
- **Height:** about 80 m.
- **Structural system:** clay-brick masonry, decorated stone internal layer, iron confining belts. unknown interaction between brick masonry and stone layer
- **SHM:** planned but not yet executed (except for preliminary ambient vibration tests)
- **Number of tests and sensors:**
    - 10 destructive lab tests
    - 73 flat jack tests on site
    - 41 inclinometers
    - 34 temperature sensors
    - 16 strain sensors
    - 14 three-axial accelerometers
- **Instrumentation design by:** Department of structural and Geotechnical Engineering, Politecnico di Torino, Turin, Italy

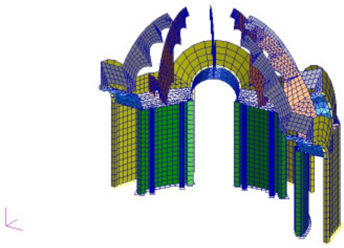
Description of Structure:

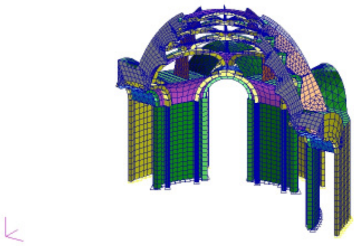
The architecture of the chapel is highly scenic, the structure, in clay bricks, is fully hidden. It seems that the structural shape is less rigorously organized and less regular than the architectural organization allows imagining. A redundancy in internal restrains compensates, somehow, the lack of regularity. The structural complexity is high and can be illustrated by the structural FE model.

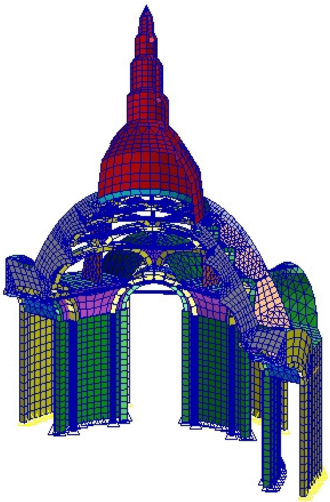


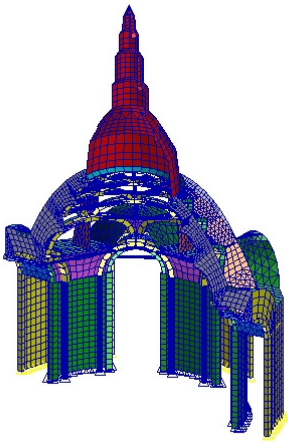


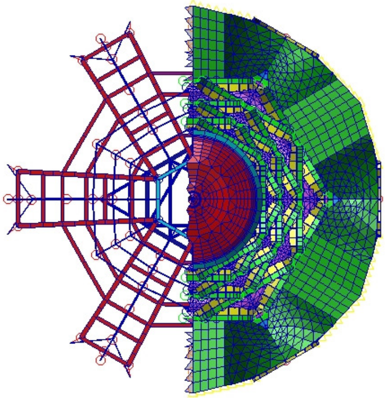


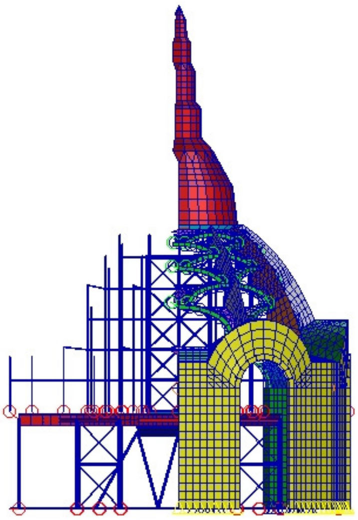


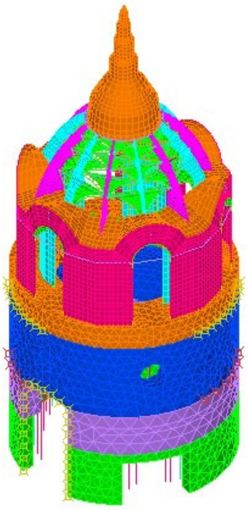












Purpose of Inspection:

After the fire induced damages it was necessary to design a retrofitting intervention. To help to select the most reliable choice it was recognized the needing of a well assessed model, able to reduce the uncertainty level. The experimental campaign was object of a contest among a number of invited companies. The whole test campaign will included ambient vibration tests and vibration tests under impulsive excitations, caused by a mass falling on a pile head in the near field.

The model includes the scaffold to keep into account the interaction between it and the structure.

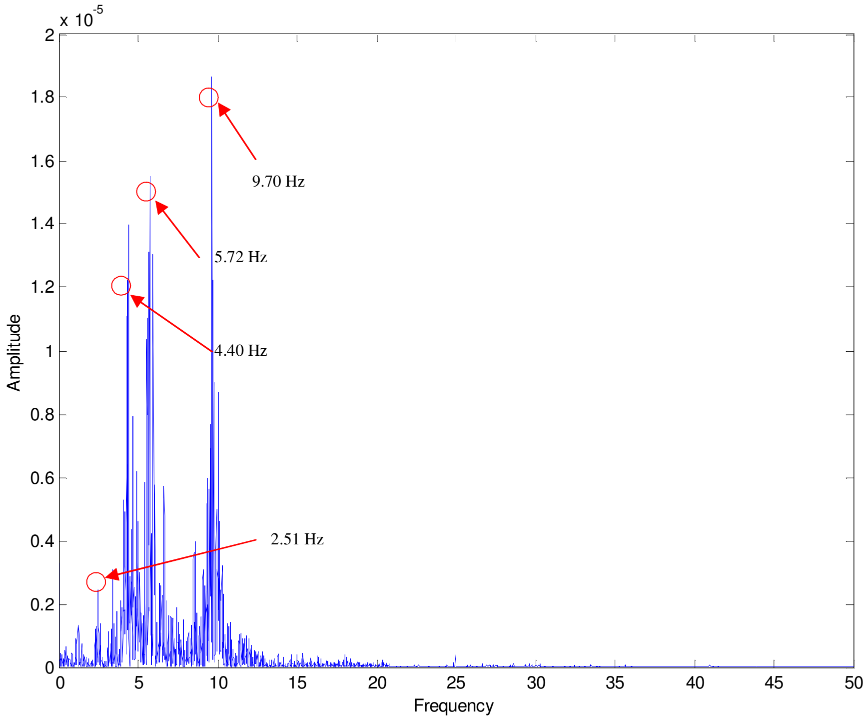
Tests and Sensor: Details*:

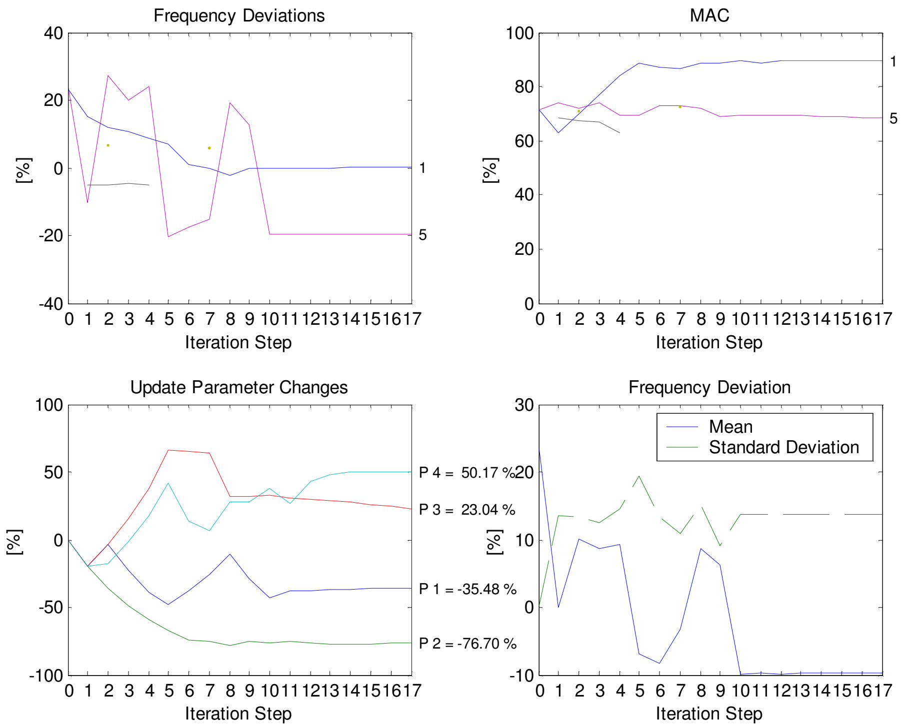
Type	Number
Cylindrical foundation and soil samples: extraction and test	# 10
Flat jack tests:	# 73
inclinometers	# 41
Temperature and heat flow sensors:	# 34
Strain sensors:	n. 16
3 axial accelerometers:	n. 14

Examples of Outcomes:

An upgradeable model was built-up by Politecnico and Kassel University and preliminary updated on the base of a reduced initial set of ambient vibration tests. Those tests were conduced under the excitation produced by the turbulence generated by the rotor of a fire police helicopter.

The recorded data were enough to identify reliably the first and fifth modes.





An upgradeable model was built-up by Politecnico and Kassel University and preliminary updated on the base of a reduced initial set of ambient vibration tests. Those tests were conduced under the excitation produced by the turbulence generated by the rotor of a fire police helicopter.

The recorded data were enough to identify reliably the first and fifth modes.

Benefits of Using SHM Technologies in the Project:

The whole test campaign will included ambient vibration tests and vibration tests under impulsive excitations, caused by a mass falling on a pile head in the near field.

Submitted by:
Alessandro De Stefano
Politecnico di Torino, Turin, Italy

Republic Plaza - Singapore

Project Description:

Republic Plaza is one of the three tallest buildings in Singapore, at 280m. Monitoring, for the purpose of tracking wind and seismic loads and developing an understanding of the structural and loading mechanisms at work in such a structure, has included

- manual readings of stress and strain during and after construction,
- periodic measurements of natural frequencies during construction,
- recording of level 65 (building top) vibrations,
- addition of wind sensors and basement accelerometers,
- development of data logger for collecting response characteristics and capturing the small number of high quality waveforms,
- installation of synchronised dual-rover GPS system
- comprehensive ambient vibration survey
- finite element model (FEM) updating

Republic Plaza, Singapore

Quick Facts:

- **Name and Location:** Republic Plaza, Singapore
- **Owner:** City Developments Limited
- **Structure category:** Tall building
- **Height:** 280m
- **Structural system:** RC shear core, ring of concrete filled steel columns and horizontal framing system for vertical loads
- **Start of SHM:** September, 1994
- **Number of sensors installed:** 56 static +14 dynamic +2 GPS
- **Instrumentation design by:** NTU Singapore. Leica, SysEng (S) Pte Ltd.

Description of Structure:

A RC core of variable thickness extends from basement 1 (B1) the full building height. A horizontal steel framing system is simply supported at the core and spans to a perimeter of steel tubes (filled with concrete up to level 49) that transfer vertical loads to the deep caisson foundation. Outriggers are installed at two M&E levels to control wind-induced drift. A cladding system was installed with a storey lag behind the main structure.

Purpose of Monitoring:

Static monitoring was installed to track the load sharing between structural components and to identify creep. Dynamic monitoring was installed to monitor the wind loading and effects, and proved highly capable of recording earthquakes originating from hundreds of thousands of km distant. Recently a GPS system has been installed to identify the relative contributions of static and dynamic wind-induced response. Hence the focus has been more on using the building as a wind and earthquake 'super-sensor'.

Sensor Details:

Type of sensors	Number	Location
Strain gauges	46	At levels 18 to 19 in core, columns and beams
Stress gauges	10	In core wall and columns
Accelerometers	4	At B1 and level 65
Anemometers	2	At roof top on east and west corners
GPS rovers	2	At roof top on east and west corners

Measurement Equipment and Data Management:

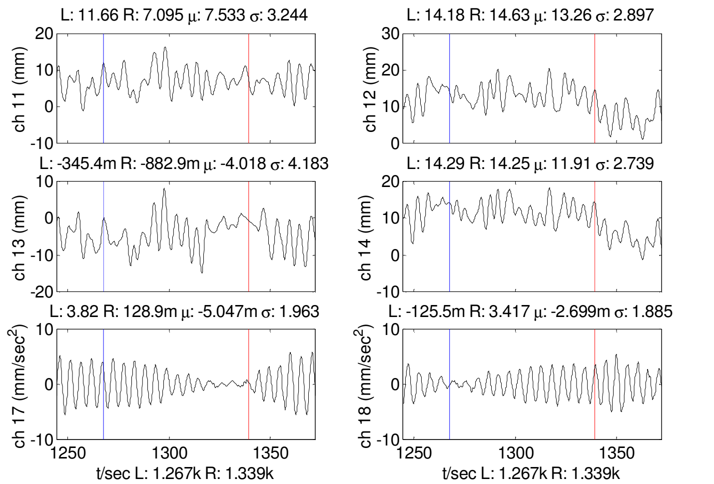
Type of system	Data Management
DOS based 16-channel data acquisition system	▪ Computes statistics and in-band RMS of 512-second segments ▪ Event triggering based on broad- and narrow-band RMS and level threshold, with LTA algorithm. Trigger signal sent to separate GPS system. System control and data download via modem with independent system reset line.\
Ruggedised PC for controlling dual-rover GPS system	▪ Continuous collection to ring buffer at 1Hz ▪ NMEA conversion to analog form for acquisition in DOS based system ▪ Leased line for base station correction Dial up line for data download

Data Analysis Procedures:

Type of analysis	Software	Additional features
Range of correlations, Gumbel plots, modal parameter tracking etc.	Self made software	▪ Unique system for monitoring loading and response

Examples of Outcomes:

Static monitoring over ten years has shown distinct load transfer and creep tendencies in the structural system. After steady changes of modal parameters during construction, minor changes were observed during installation of cladding, water tanks and interior fittings. Subsequently, frequencies have slowly dropped. Effects of distance tremors have been captured and compared with those due to strong winds. It has been shown that seismic load is the dominant effect for medium to tall buildings in Singapore. When the GPS system has been able to identify the relative effects of mean and turbulent components of wind it is likely that (attitudes of authorities permitting), there could be impact on local diesn against lateral loads, possibly via design codes or guides.



Comparison of building acceleration and displacement recorded by accelerometers and GPS

Benefits of Using SHM Technologies in the Project:

Identification of structural mechanisms, loading effects and slow changes in building performance over time.

References:

Brownjohn J M W, Pan T C, 'Response of a tall building to long distance earthquakes' Earthquake Engineering and Structural Dynamics **30**, 2001, p709-729.

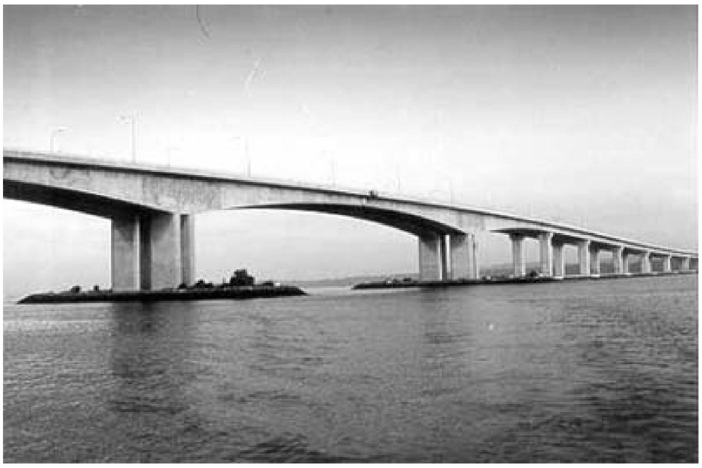
Submitted by:

School of Engineering
University of Plymouth
Drake Circus
Plymouth PL4 8AA United Kingdom
Email: james.brownjohn@plymouth.ac.uk

Tuas Second Link - Singapore

Project Description:

The ‘Second Link’, completed in 1997, is the second road access between Singapore and Peninsular Malaysia.



Second Link, Singapore/Malaysia

Quick Facts:

- **Name and Location:** Second Link, Singapore
- **Owner:** Govts. of Singapore, Malysia
- **Structure category:** multiple medium span bridge
- **Spans:** 27 spans totalling 1.9km, 2 spans in Singapore, max 92m
- **Structural system:** Cast in-situ dual RC box with expansion joints either end of bridge
- **Start of SHM:** March, 1997
- **Number of sensors installed:** 75
- **Instrumentation design by:** Gage Technique UK, SysEng (S) Pte Ltd, Infratech Australia

Description of Structure:

All but 170m of the 1.9km bridge are in Malaysian territory. Visually similar, Singapore side uses internal post-tensioning, Malaysia side external post-tensioning. On the Singapore side, spans were balanced-cantilever segmental cast in-situ for the parallel carriageways that are joined only at foundation level. Of note are the slender piers and the use of only two expansion joints, one at each end.

Purpose of Monitoring:

A case of an opportunity available: consultant requirement for ‘instrumentation’ was directed to NTU and converted to a monitoring installation based on systems implemented by Waldron et al in 1980s. Arrays of thermocouples were installed, also stress cells, and the aim was to track performance and learn about behaviour, particularly thermal effects.

Sensor Details:

Type of sensors	Number	Location
VWG Strain gauges	12	at corners of box
VWG stress cells	12	In line with strain gauges
Thermistors	48	with strain stress/strain gauges, through depth of webs and in tarmac
Triaxial accelerometer	1x3	midspan

Measurement Equipment and Data Management:

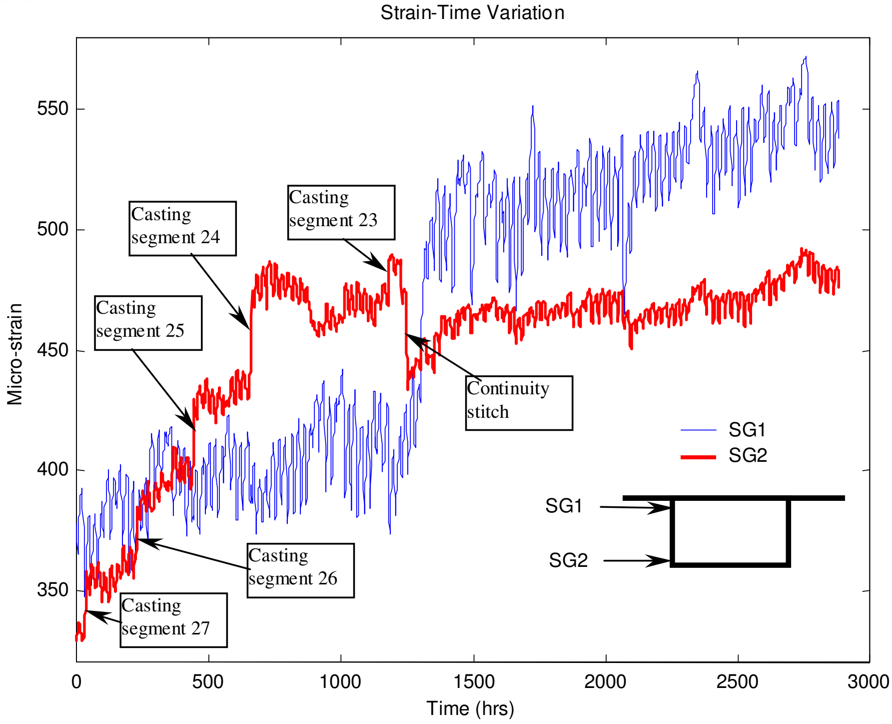
Type of system	Data Management
Local data loggers operated by local PC	▪ Logging to logger memory cards (VWGs) ▪ Logging to RMX logger (accelerations) ▪ Logger control by PC ▪ Data download via modem using PCAnywhere, data analysis offline

Data Analysis Procedures:

Type of analysis	Software	Additional features
Statistics, correlations, PCA, intervention analysis, anomaly detection, ARX	Self made software	▪ Learning platform for SHM algorithms

Examples of Outcomes:

Monitoring during construction provided training for ‘pattern recognition’ systems for SHM, as well as providing basic data on structural performance and some calibration of thermal loading (design) codes.



Strain variation in segment 31 (close to pier) during construction

Benefits of Using SHM Technologies in the Project:

The project has been a great opportunity to develop strategies for recovering information fro response data. In particular the experience during construction has led to insights in recognizing signatures of performance during service. We have not found great use for the acceleration data.

References:

Moyo P, Brownjohn JMW, 'Application of Box-Jenkins models for assessing the impact of unusual events recorded by structural health monitoring systems', International Journal of Structural Health Monitoring **1**(2), 2002, 149-160.

Brownjohn J M W, Moyo P 'Monitoring of Malaysia-Singapore Second Link during construction', 2nd International Conference on Experimental Mechanics, Singapore, 29/11-1/12/2000, p528-533.

Submitted by:

School of Engineering
University of Plymouth
Drake Circus
Plymouth PL4 8AA United Kingdom
Email: james.brownjohn@plymouth.ac.uk

Pasir Panjang Semi Expressway - Singapore

Project Description:

Pasir Panjang Semi-Expressway, still under construction.

Pasir Panjang Semi-Expressway

Quick Facts:

- **Name and Location:** Pasir Panjang Semi-Expressway Singapore
- **Owner:** Land Transport Authority
- **Structure category:** Multiple short span dual carriageway viaduct
- **Spans:** multiple, varying length, typical span 38m
- **Structural system:** Pre-cast segmental concrete box, internal post-tensioning
- **Start of SHM:** 2003
- **Number of sensors installed:** 60
- **Instrumentation design by:** SysEng (S) Pte Ltd, NTU Singapore

Description of Structure:

Segments of the same shape but different web dimensions are cast in West Singapore and added using balanced cantilever method, 4 segments at a time. Closure strips are added at a much later date. The spans are arranged in 'bridges' of about five spans between expansion joints. The expressway was built to carry heavy goods vehicles, principally containers in transit between two container terminals.

Purpose of Monitoring:

As well as also serve to validate the original design through performance evaluation, the original aim of the monitoring was to evaluate the design of a comprehensive bridge SHM system. By instrumenting span segments in one span of each bridge, the aim was to capture the performance and interaction of a lrge stretch of the viaduct. Modal testing has been used to validate FEM of substructures during construction for extrapolating to a complete bridge. Via a validated FEM the aim is to interpret the static response data in terms of structural events that can be simulated and characterized by FEM.

A further aim was to evaluate the performance of FBG systems for SHM of such bridges.

Sensor Details:

Type of sensors	Number	Location
VWG Strain gauges	40	In segment near pier of five spans as well as in piers
VWG Stress cells	4	In two segments of one span
Fibre Bragg Grating	22	On deck soffit in two spans

Measurement Equipment and Data Management:

Type of system	Data Management
Local static loggers with wireless modem	▪ Off-line correlation and statistical analysis
Dynamic data acquisition	▪ Offline modal analysis and FEM updating

Data Analysis Procedures:

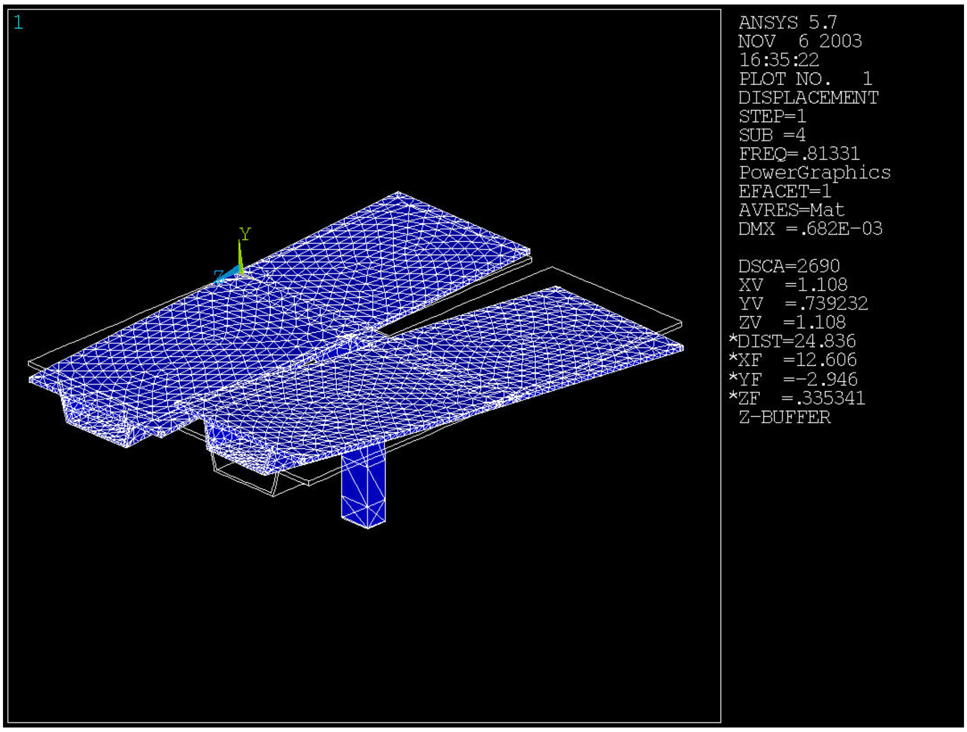
Type of analysis	Software	Additional features
For static data: Statistics, Correlations	Excel/MATLAB	
For modal test data: modal analysis	MATLAB GUI: MODAL	Ambient vibration test using human shakers

Examples of Outcomes:

So far it has been possible to create and validate FEM (see below) that will be used to simulate load and structural anomalies as training for diagnosis via performance monitoring. As the bridge is constructed and spans joined, the strain/stress increments will be used for similar purposes, i.e. SHM system training.

FBG arrays have been installed on deck soffits and will be used to monitor performance during proof testing

The exercise so far has shown the utility of remote data collection via wireless modem, from these data, traditional temperature-induced trends and stress-strain correlations have been observed.



Strain distribution at a main girder during the crossing of a heavy load vehicle measured by SHM

Benefits of Using SHM Technologies in the Project:

There is no other way to assess the as-built structure and to monitor performance under the possibly excessive loading of HGVs. Hence the aim is to feed back to LTA not only on the effectiveness of the design but on the assessment of the loads. Further, the bridge is being used as a tested for relatively advanced SHM systems via automated wireless data downloads and fibre optic sensors.

References:

Brownjohn JMW. Sensor and data management technology for structural health monitoring of civil structures. First International Conference on Structural Health Monitoring and Intelligent Infrastructure, Tokyo, November 2003.

Submitted by:

School of Engineering
University of Plymouth
Drake Circus
Plymouth PL4 8AA United Kingdom
Email: james.brownjohn@plymouth.ac.uk

Pioneer Bridge - Singapore

Project Description:

Pioneer Bridge, Singapore, was completed in 1970 and upgraded by Land Transport Authority Singapore in 2000/2001. It carries heavy industrial traffic to and from Jurong Port and is rated to carry vehicles of 44 tonnes. Modal testing and short term strain/vibration monitoring was conducted before and after the upgrade to test the need for and effect of the upgrade.

Pioneer Bridge, Singapore

Quick Facts:

- **Name and Location:** Pioneer Bridge, Singapore
- **Owner:** Land Transport Authority (LTA), Singapore
- **Structure category:** short span bridge
- **Spans:** 1 span: 18m
- **Structural system:** Steel box girder with orthotropic deck and steel columns
- **Start of SHM:** October 2000
- **Number of sensors installed:** 8 for monitoring, up to 16 for vibration test
- **Instrumentation design by:** Infratech, Australia (monitoring system), modal test system designed by J Brownjohn (at NTU Singapore).

Description of Structure:

37 pre-cast pre-tensioned inverted T-beams tied together by 25 lateral tensioning cables set in a cast in-situ transverse diaphragm. The T-beams carry a deck slab having thickness that varies from 152mm to 305mm. Bearings formerly simply supported, now built in. Bridge was upgraded in line with LTA island wide program, and carries occasional extra heavy loads:

Heavy load (bridge segment)

Purpose of Monitoring:

The program of two modal tests and two short term live response monitoring exercises was aimed at validating analytical models (via modal testing and FE model updating) then using the validated models together with live strain statistical properties to identify the load capacity before and after the upgrade. The exercise was also aimed at evaluating the procedures for doing this.

Sensor Details:

Type of sensors	Number	Location
Strain gauges	4	At midspan on soffit
Accelerometers	4	Near strain gauges
Modal test accelerometers	16	According to test grid
Shaker	1	1/3rd span, footpath

Measurement Equipment and Data Management:

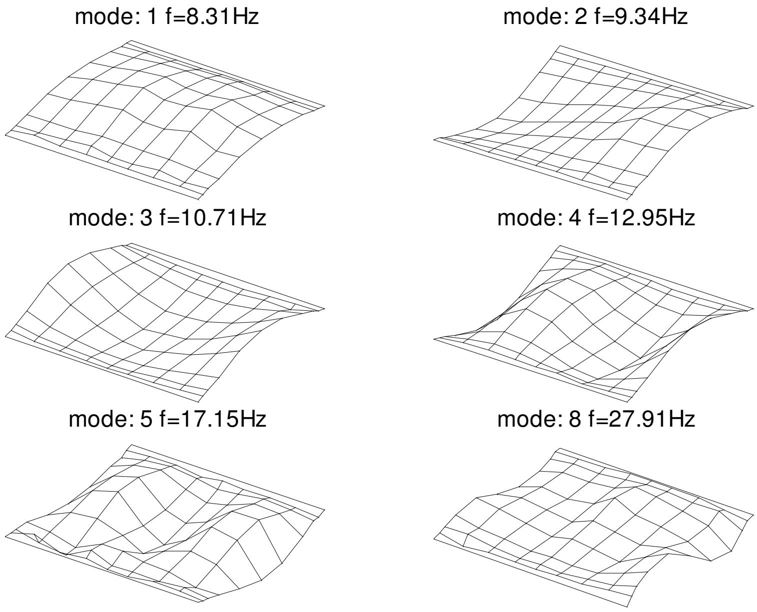
Type of system	Data Management
HMX data logger	▪ Waveform logging ▪ Peak value recording
Modal test system	• Acceleration recording

Data Analysis Procedures:

Type of analysis	Software	Additional features
Statistics, Gumbel plot, independent storm	Self made software	
Modal analysis and FEM updating	SDTools, purpose-developed MATLAB GUI: MODAL	Forced and ambient vibration test analysis software

Examples of Outcomes:

The mode shapes shown below, identified from post-upgrade forced vibration testing, prove the effectiveness of the upgrade through finite element model (FEM) updating, showing clearly the rotational stiffness imposed at the bearings. The FEM has been used to estimate load carrying capacity.



Mode shapes of bridge after upgrade:
effect of bearing fixity is visible in mode shapes and increased frequencies

Benefits of Using SHM Technologies in the Project:

It was possible to show that the bridge was already in good shape and that n-year return period strains were a smaller % of capacity after upgrade.

References:

Moyo P, Brownjohn JMW, Omenzetter P, ‘Bridge live load assessment and load carrying capacity estimation using health monitoring system and dynamic testing. 3rd International conference on current and future Trends in Bridge Design, construction and Maintenance. Shanghai, September 2003

Submitted by:

School of Engineering
University of Plymouth
Drake Circus
Plymouth PL4 8AA United Kingdom
Email: james.brownjohn@plymouth.ac.uk

Saint-Jean Bridge – Bordeaux, France

Project Description:

The Saint-Jean Bridge is located in Bordeaux, France. Opened in 1965, it was built to release Pierre Bridge. Like most prestressed concrete bridges built at that time when thermo-mechanical behaviours were not taken into account, it is not sufficiently prestressed. To determine whether prestress reinforcement works have to be carried out or not and to validate calculations, Bordeaux Urban Community ordered experimental investigations including SHM.

Saint-Jean Bridge, Bordeaux, France

Quick Facts:

- **Name and Location:** Saint-Jean Bridge, Bordeaux, France
- **Owner:** City of Bordeaux, France
- **Structure category:** medium span bridge
- **Spans: 8 spans:** 15.4m-67.76 m - 4 x 77.00 m – 67.76m-15.4m
- **Structural system:** triple box-girder prestressed concrete bridge
- **Start of SHM :** 2000. SHM described here : November 2003
- **Number of sensors installed:** 26
- **Instrumentation design by :** Public Works Laboratory in Bordeaux (laboratoire régional des Ponts et Chaussée à Bordeaux)

Description of Structure:

The Saint-Jean bridge is located in the city of Bordeaux. It is a triple-girder bridge with a total length of 474 m. It consists of 8 spans, the four intermediate are 77m long surrounded by two 67.76m long spans and 15.4m long spans. As the first and last spans are much shorter than their neighbour (0.23 time smaller), it required special disposal to prevent rising of the span.
Bridge girder is 3.3m deep.

Purpose of Inspection:

The purpose of this inspection is twofold.

First, it is to monitor the thermo-mechanical behavior of the bridge. More precisely, two specific box-girder joints are monitored. The most-open joint (noticed during inspection and expected so by calculations) located in the third span, and one thin joint located in the fourth span, that inspection hesitated to qualify. Measurements are done with standard sensors, namely LVDT and strain gauges.

The second purpose is to evaluate the influence of sensor length over its accuracy and even its relevance. As a result, sensors with length ranging from 10cm to 400cm were installed at different places were deformations are either large (first 77m-span) or small (thin junction on the second 77m-span). Two types of very-long-length-sensors are compared to traditional sensors: optical fiber sensors (OFS) and vibrating wire sensors (VWS). Those sensors measure strains due temperature, on a day-night-cycles and also on winter-summer cycles: every season (starting in Nov. 2003), measurements are carried out during three weeks.

Sensor Details*:

Type of sensors	Number	Location
Thermal Gauges	6	
LVDT	2 (10cm long)	first 77m-span, on an open-joint
Optical Fiber Sensor (OFS)	2 (60cm, 200cm)	
LVDT	1	
Vibrating Wire Sensor (VWS)	1 (50cm)	second 77m-span, thin joint
OFS	2 (200cm, 50cm)	
LVDT	2	
VWS	4 (2*50cm 2*250cm)	second 77m-span, open-joint
OFS	2 (50cm, 400cm)	
Strain Gauges	1	
LVDT	1 (10cm)	Plain concrete
VWS	1 (50cm)	
OFS	1 (25cm)	

Measurement Equipment and Data Management:

Type of system	Data Management
PC based measurement system	• data pre-analysis on site • main analysis, graphical presentation and documentation in office

Data Analysis Procedures:

Type of analysis	Software
	• self made software

Benefits of Using SHM Technologies in the Project:

After visual inspections revealed problems, calculations were made on the basis of original documents, sometime missing or incomplete. Structural Health Monitoring technologies allow validating those calculations. It is economically important as prestressed reinforcement works will depend on those calculations.
We also benefit from the presence of standard instrumentation (strain gauges and LVDT) to study different types of sensors, to compare their relevance and accuracy as a function of the sensor length.

Submitted by:

P. Barras, J. Dumoulin, Y. Gautier
CETE du Sud Ouest, Laboratoire Régional des Ponts et Chaussées,
24 rue Carton, BP 58, 33019 Bordeaux cedex, France
c.dumoulin@bouygues-construction.com
&
S. Lesoille
Laboratoire Central des Ponts et Chaussées
Division for Metrology and instrumentation 58 bld Lefebvre, 75 732 Paris cedex 15, France
Sylvie.Lesoille@lcpc.fr

Széchenyi Bridge - Hungary

Project Description:

The Szécheny Bridge in Győr, Hungary, opened in 1976, is a part of a main route crossing River Small-Danube between two towns, Győr and Vámosszabadi. Therefore it is used for heavy loads.

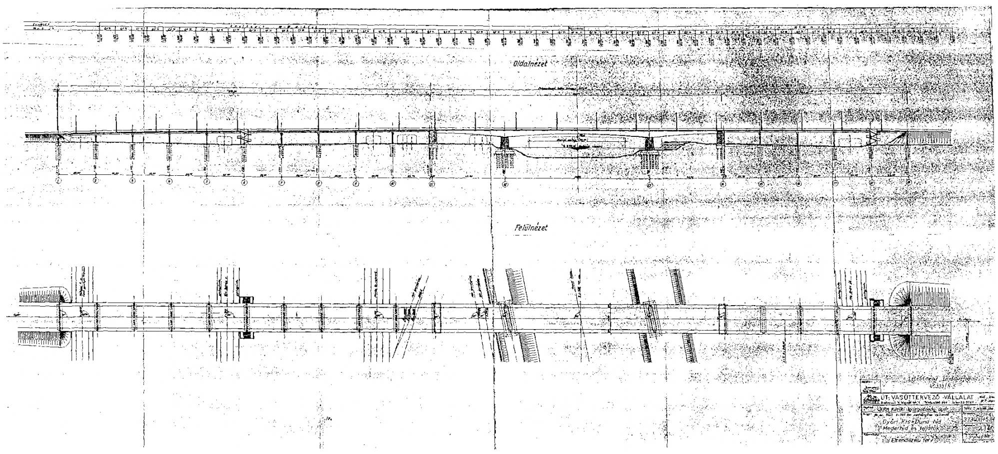
Széchenyi Bridge, Győr, Hungary

Quick Facts:

- **Name and Location:** Széchenyi Bridge, Győr, Hungary
- **Owner:** Hungarian State
- **Structure category:** concrete bridge
- **Spans:** 18 spans: 23.00/ 23.00/ 23.00/ 23.00/ 23.00/ 23.00/ 23.00/ 23.00/ 23.00/22.70/45.00/90.00/45.00/22.70/23.00/23.00/23.00/23.00 m
- **Structural system:** concrete
- **Start of SHM**: 09.10.2003
- **Number of sensors installed:** one three component velocity sensor on 7 places successively
- **Instrumentation design by:** Kinemetrics

Description of Structure:

The bridge has a total length of 527.2 m. The bridge consists of a road with two lanes in both directions for vehicles. The road is 14 m wide. On each side of the bridge there is a pavement 2.10 m wide.



Purpose of Inspection:

replacement of the visual inspection and load test by a new, reliable method

Sensor Details*:

Instruments	Number	Sensitivity
Recorder: Kinemetrics SSR1 seismometer	1	150 V/m/s if Gain=100
Sensor: SS1	3 (1 vertical sensor, 2 horizontal,)	

date of measurements: Oct. 9th 2003
measurements were carried out by Tibor Czifra and Gyula Mentes

Description of the data files measured on the bridge:

File Name	Place of the Sensors	Gain of Sensor Components			Duration [min]
		X	Y	Z	
Győr1	on the middle of the bridge above of the bed of the river	100	100	100	20
Győr2	on the middle of the bridge above of the bed of the river	10	10	10	10
Győr3	on the middle of the bridge above of the bed of the river	10	10	1	10
Győr4	Direct on the middle of pillar 13	10	10	1	10
Győr5	In the middle between pillars 13 and 14 in direction Révfalu	10	10	10	
Győr6	In the middle between pillars 14 and 15 in direction Révfalu	10	10	10	
Győr7	In the middle between pillars 10 and 11 in direction Győr	10	10	10	

Measurement Equipment and Data Management:

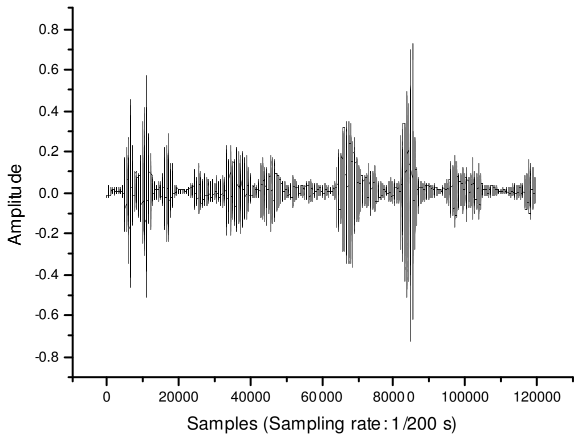
Type of system	Data Management	CMS
PC based measurement system	▪ Data control (vibration diagram) on site ▪ main analysis, graphical presentation and documentation in office ▪ data transfer via modem ▪ long term data base	y

Data Analysis Procedures:

Type of analysis	Software	Additional features
Fourier-analyses	ORIGIN 6.0	

Examples of Outcomes:

Only one measurement was carried out and therefore there was not a possible to compare different vibration records made in different times.



Benefits of Using Vibration Measurement Techniques in the Project:

All data series from vibration measurements are available so that the occurrence of damage can be detected immediately.

Submitted by:

Geodetic and Geophysical Research Institute of the
Hungarian Academy of Sciences
Csatkai E. u. 6-8.
H-9400 Sopron, Hungary
Phone: +36-99-508 348
Fax: +36-99-508 355

Källösund Bridge - Sweden

Project Description:

The Källösund Bridge is a part of a road link to a group of islands north of Gothenburg on the Swedish west coast. The bridge was built in 1960 as a free cantilever box beam. When an assessment of the bearing capacity was made in the late 1990´s it was found that the capacity for sagging moment in the superstructure close to the abutments was to low. Special inspections showed that casting joints in those parts of the bridge were cracked but the cracks were closed. To maintain the bridge open for full traffic loads while awaiting strengthening to be designed and executed the bridge was monitored. The bridge will be strengthened during 2004.

Quick Facts:

- **Name and Location:** Källösundsbron, 50 km north of Gothenburg.
- **Owner:** Swedish National Road Administration
- **Structure category:** posttensioned concrete bridge built by the free cantilever method.
- **Spans:** 4 spans: 50 / 107 / 107 / 50 m
- **Structural system:** Concrete box girder and concrete box columns.
- **Start of SHM:** December, 2000
- **Number of sensors installed:** 72
- **Instrumentation design by:** NGI, P.O. Box 3930, Ullevaal Stadion, N-0806 Oslo, Norway

Description of Structure:

The superstructure comprises of a concrete box beam that was built by the free cantilever method and posttensioned in stages. The substructure comprises of abutments in a rock slope at the ends and box section concrete columns as intermediate supports.

Purpose of Inspection:

Static calculations show that the ultimate limit state of the bridge is reached under heavy loads. The bridge was not designed for a sagging moment as creep was not foreseen. When the bottom flange cracks under sagging moment there is not enough reinforcement to resist the moment but the bending moment can be redistributed to the support section of the beam. The instrumentation was used both for calibration of calculations and for monitoring of those sections.

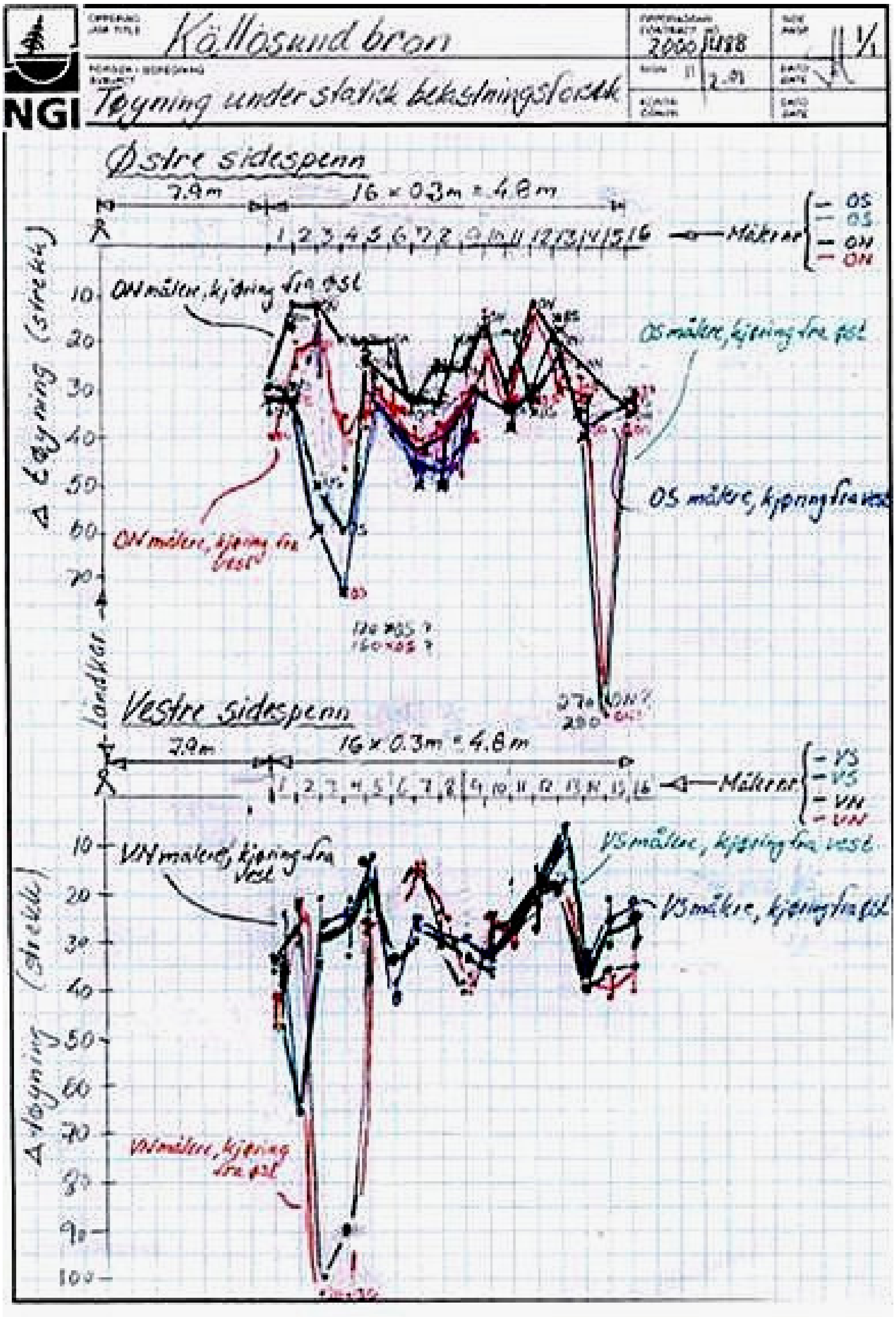
Sensor Details*:

Type of sensors	Number	Location
Strain gauges	72	on the bottom flange and on the webs of the main girder
Temperature gauges	2	for calibartion of strain gauges

Measurement Equipement and Data Management:

Type of system	Data Management	CMS
PC based measurement system	1) calibration of calculations was done with a load test. 2) monitoring of the strains in the crack. A larm limit was set to give an automatic alarm when crack width reaches 0,1 mm. The alarm was placed at the "Traffic Information Center" of SNRA in Gothenburg. This center is manned around the clock.	?

Examples of Outcomes:



Strain distribution in the bottom of the main beam during the load test with a heavy vehicle. The test showed a mean strain of 40 microstrain and the calculated value was 50 microstrain. The peak values of up to 280 microstrain are at the cracked joints.

Benefits of Using SHM Technologies in the Project:

The monitoring verified the assessment calculations. The “full time inspection” given by monitoring with set alarm limits made it possible to keep the bridge open for heavy traffic while waiting for strengthening.

References:

"Resultater av databehandling och tolkning för hela perioden Februari 2000 - September 2002" Frank Myrvoll and Per Sparrevik, NGI, 2002-12-03. (In Swedish)

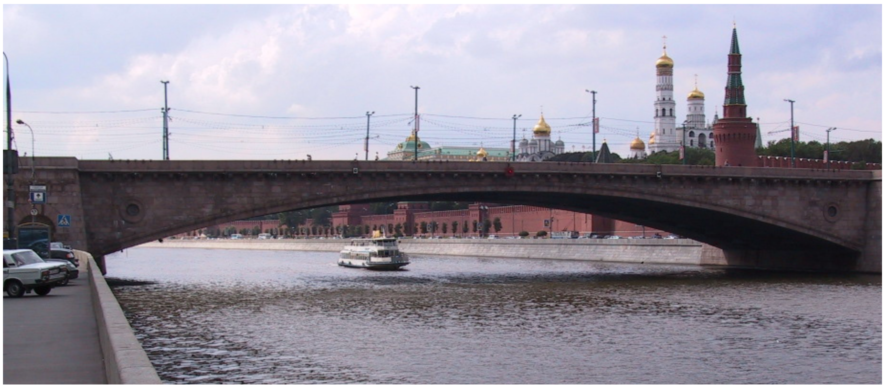
Submitted by:

Swedish National Road Administration
Section Bridge and Tunnel Technology
S-781 87 Borlänge
Sweden
Phone: +46 243 75000
Email: ebbe.rosell@vv.se

Bolshoj Moskvoretsky Bridge

Project Description:

Bolshoj Moskvoretsky Bridge over the Moskva-river was built in 1936-37 by a famous Soviet architect A. Shjusev. It is situated in the historical centre of Moscow, next to the Kremlin, and leads one of the main traffic lines of the city to the Red Square. The bridge has a status of "functioning architectural heritage" protected by the state.



Bolshoj Moskvoretsky Bridge, Moscow, Russia

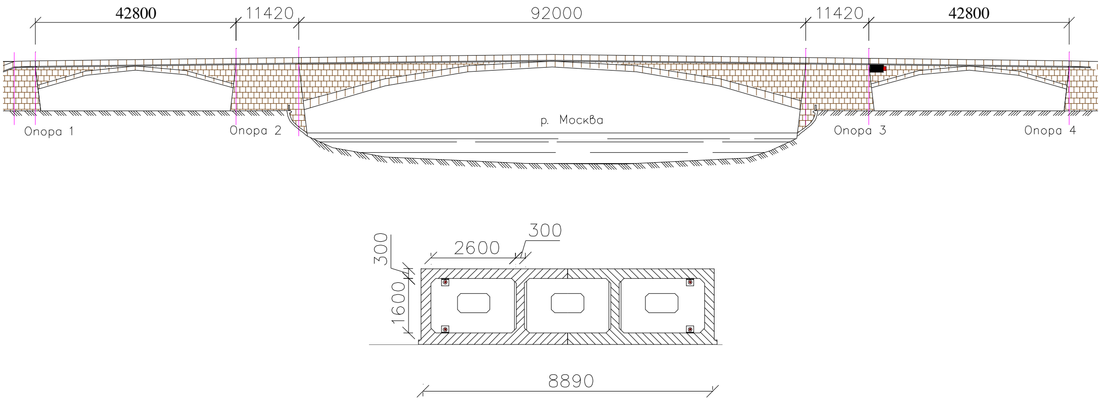
Quick Facts:

- **Name and Location:** Bolshoj Moskvoretsky Bridge, Moscow, Russia
- **Owner:** The Government of Moscow
- **Structure category:** Reinforced concrete arched box girder bridge with a decorative external facing of natural stone. Total length of the bridge is about 250 m
- **Spans:** Three spans (43/92/43 m)
- **Structural System:** The bridge consists of three parallel arches. The cross-section of each arch contains three boxes separated by partitions 350-450 mm thick (along the axis of the bridge) and diaphragms with openings for maintenance purposes (transverse to the bridge axis). The superstructure consists of the bridge deck supported by columns that rest on the above-mentioned separating partitions.
- **Start of SHM:** July 2003
- **Number of sensors installed:** 22
- **Instrumentation design by:** "Smartec SA", Switzerland; ZAO "Triada-Holding", Ru

Description of Structure:

The bridge has eight vehicle lanes and two sidewalks separated from them by curbs. Two types of degradation are noticed on the bridge: settlement of an abutment provoking cracking of the stone lining as well as the structural elements and chlorides penetration into the structures leading to reinforcement corrosion.

These signs of degradation on the bridge after nearly 70 years of operation and its functional and historical importance led the authorities to decide to monitor structural behavior of the bridge on the continuous basis.



Geometry of the structure

Purpose of Instrumentation:

The aim of monitoring is to increase the knowledge concerning structural behavior. Standard SOFO sensors have been installed to continuously monitor average strain along the arch, curvature in both horizontal and vertical direction. Thermocouples have been installed to distinguish thermal influences.

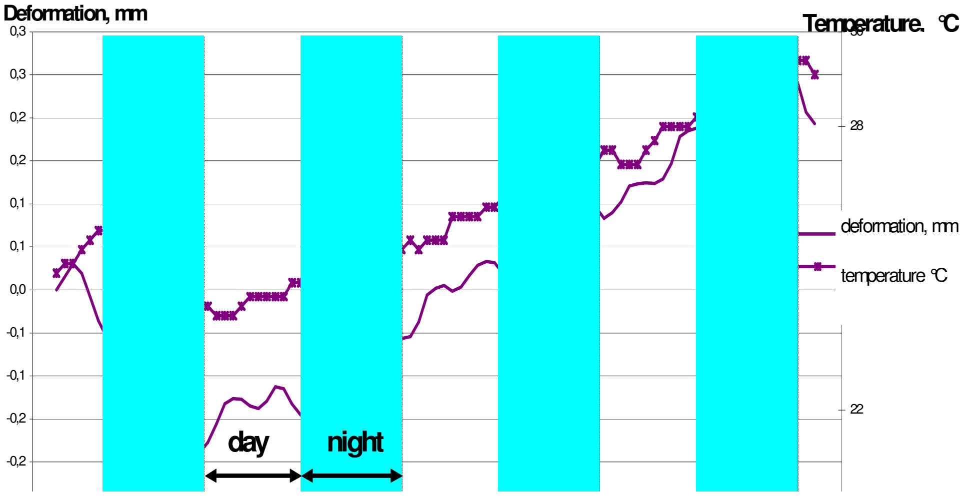
Sensor Details*:

Type	Number	Location
Standard SOFO Sensors	16	In the central arch (see
Thermocouples	6	the cross-section)

Example of defects: cracks on structural elements and external facing

Examples of Outcomes:

The installation of the SOFO System was finished in July 2003. The long-term monitoring started.



At the moment data is being accumulated for further interpretation and analysis.

Benefits of Using SHM Technologies in the Project:

- Data acquisition for better knowledge concerning the structural behavior to increase safety and to reduce maintenance costs
- Continuous remote monitoring
- Innovative system (part of which is a sophisticated software for data interpretation) allows to get a comprehensive information on bridge behavior

Submitted by:

Dr. Daniele Inaudi
CTO
SMARTEC SA
Via Pobiette 11, CH-6928 Manno, Switzerland
Phone: +41 91 610 18 00
Fax: +41 91 610 18 01
Email: inaudi@smartec.ch

Versoix Bridge - Switzerland

Project Description:

The Versoix Bridge is located near to the city of Versoix, crossing the river with the same name. It lies on the A1 highway between Lausanne and Geneva, Switzerland making an important connection between two major Swiss cities (60'000 vehicles per day). 1996 – 1998, the bridge was refurbished and enlarged to accommodate an additional security lane in both directions. Since an important amount of new concrete was added asymmetrically to an existing structure, the issues of differential shrinkage could occur and decrease the structural performance.

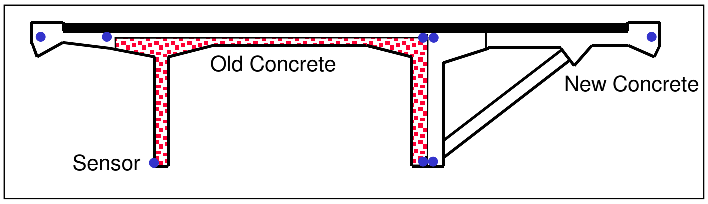
Versoix Bridge – Versoix, Geneva, Switzerland

Quick Facts:

- **Name and Location:** Versoix Bridge - Versoix, GE, Switzerland
- **Owner:** Canton of Geneva
- **Structure category:** Short and medium span bridges (36 m to 56 m)
- **Spans:** 2 border spans of 36 m and four central spans of 56 m
- **Structural system:** twin bridges, two prestressed continuous girders stiffened by diaphragms supports along with steel beams cantilevered deck
- **Start of SHM:** 1996
- **Number of sensors installed:** 120
- **Instrumentation design by:** IMAC-EPFL, Swiss Federal Institute of Technology, Lausanne

Description of Structure:

The old Versoix Bridge consisted of six spans twin concrete bridges. The deck of each bridge was laid on two continuous girders stiffened by diaphragms. Both bridges are refurbished and widened. The girders are reinforced with new prestressed concrete, while the decks are cantilevered at the external side and supported by inclined steel beams.



Cross-section of the Versoix Bridge and position of the SOFO sensors

Purpose of Instrumentation:

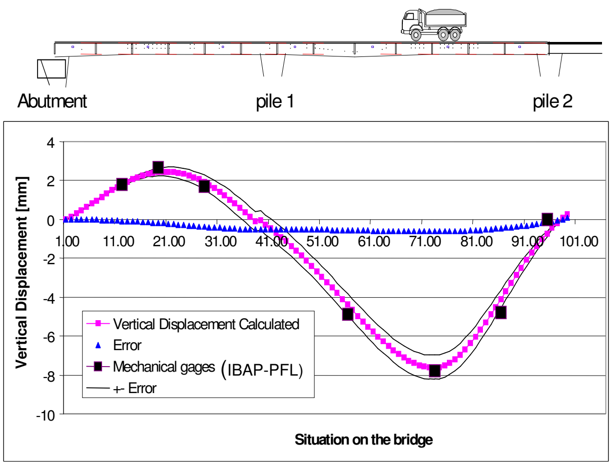
The aim of instrumentation of the Versoix Bridge is to monitor long-term performance with particular care to the consequences of interaction between the existing and new part of the structure. Thus, the following parameters were monitored: average strain in concrete including early and very early age, old-new concrete interaction, and average curvature analysis in both horizontal and vertical plan, detection of torsion and distribution of both horizontal and vertical displacements. Fiber optic sensors of type SOFO were used and, long-term automatic and remote monitoring was performed. Thermocouples of type “K” were used in order to distinguish thermal strain and load cells at abutments to control the force.

Sensor Details:

Type	Number	Location
SOFO fibre optic sensors	104	Span No. 1 –2
“K” thermocouples	12	Span No.1 – 2
Load cells	4	Abutments

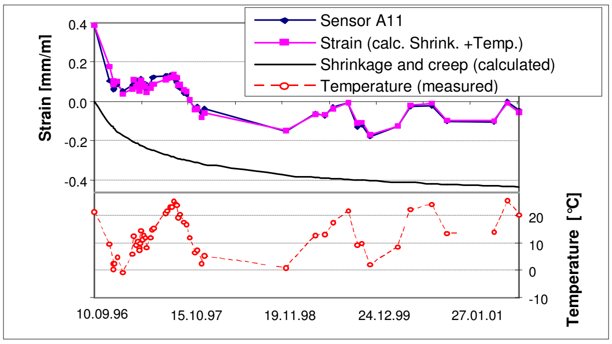
Examples of Outcomes:

The early age measurements allowed the prediction of cracking long before it became visible, and the optimization of the concrete mix for successive pours. The sensor pairs at interface confirmed the excellent adherence between the old and new concrete. The vertical displacement was measured during the load test by double integration of the curvatures.



vertical displacement during the load test

Horizontal bending of the bridge due to asymmetrically added new concrete was successfully observed and measured. The single sensors were used to follow the long-term shrinkage of concrete and the seasonal deformations due to temperature changes.



five years measurement of single sensor and evaluation of rheologic strain

Benefits of Using SHM Technologies in the Project:

The SHM technology in case of the Versoix Bridge provided the following benefits:

- Long-term data collecting concerning the structural behavior of the bridge
- Improvement of concrete mix composition after the first pouring was done
- Possibility to verify the interaction between the existing and new concrete

After seven years of monitoring the following conclusions are carried out:

- The structure is perfectly monolithic and no delaminating is detected
- The evolution of concrete performances is in range of model prediction

References:

Vurpillot, S., Casanova, N., Inaudi, D., Kronenberg, P., *Bridge spatial deformation monitoring with 100 fiber optic deformation sensors*, SPIE 5th Annual Meeting on Smart Structures and Materials, San Diego, USA, Vol 3043, p 51 - 57, 1997.

Inaudi, D., Casanova, N., Vurpillot, S., Glisic, B., Kronenberg, P., Lloret S., *Deformation monitoring during bridge refurbishment under traffic,* 16th Congress of IABSE, Luzern, Switzerland, on CD, 2000.

Glisic, B., Inaudi, D., *Structural Monitoring of Concrete Bridges during Whole Lifespan,* 82nd Annual Meeting of the Transportation Research Board (TRB), January 12-16, 2003, Washington DC, USA, on CD paper no. 03-3012.

Submitted by:

Dr. Daniele Inaudi
CTO
SMARTEC SA
Via Pobiette 11, CH-6928 Manno, Switzerland
Phone: +41 91 610 18 00
Fax: +41 91 610 18 01
Email: inaudi@smartec.ch

Punggol EC26, Block 166A - Singapore

Project Description:

The Housing and Development Board (HDB), as Singapore's public housing authority, has an impressive record of providing a high standard of public housing for Singaporeans through a comprehensive building program. As part of quality assurance of new Housing and Development Board (HDB) residential buildings, it embarked on a project to perform long-term structural health monitoring of its new development at Punggol East Contract 26. The monitoring is to be performed during its whole lifespan of the building, from construction stage to occupancy. Thus, for the first time the sensors are used in large-scale life cycle monitoring of high-rise buildings.

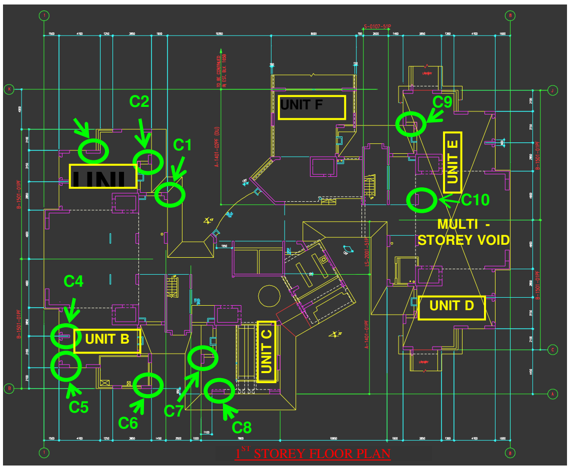
Punggol EC26, Block 166A

Quick Facts:

- **Name and Location:** Punggol EC26 - Singapore
- **Owner:** Housing and Development Board (HDB)
- **Structure category:** Residential Building
- **Spans:** 19 storeys
- **Structural system:** Reinforced Concrete Structure
- **Start of SHM:** 2001
- **Number of sensors installed:** 10 sensors x 6 block = 60 sensors
- **Instrumentation design by:** HDB, Singapore & SMARTEC SA, Switzerland

Description of Structure:

Punggol EC26 project consists of six blocks founded on piles, and each block is a nineteen-storeys tall building, consisting of 6 Units and supported on more than 50 columns at ground level. A block called 166A has been selected for monitoring. Its construction started on December 2000 and was completed in July 2003.



Position of the columns at ground level equipped with sensors.

Purpose of Instrumentation:

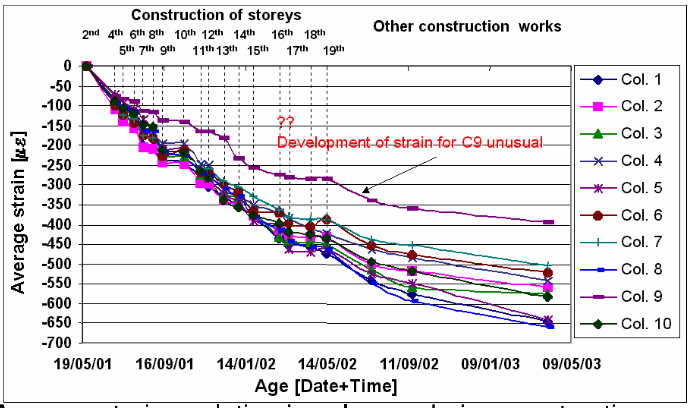
This monitoring project is considered as a pilot project with two aims: to develop a monitoring strategy for column-supported tall building structures and to collect data related to the stress behavior of this building providing rich information concerning their 'health' conditions.

Sensor Details:

Type	Number	Location
SOFO fiber optic sensors	10	1st Story

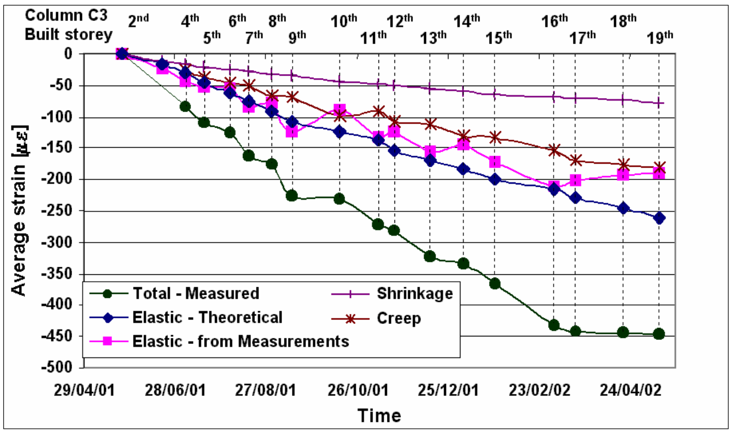
Examples of Outcomes:

Measurements were recorded during the construction of the 19-storey residential building. To decrease the costs of monitoring in this phase, only periodical readings were taken. One round of readings was taken for all the sensors after a new storey was completed. The aim of these measurements was to increase the knowledge concerning the real behavior of the columns during construction and to control the construction process.



Average strain evolution in columns during construction works.

The theoretical elastic strain evolution has been calculated using known theoretical values for loads. The different shrinkage and creep components of strain were calculated for each column using CEB-FIP Model Code 1990. The elastic strain is obtained from monitoring in an indirect way, subtracting the creep and shrinkage from the total monitored strain. Influence of temperature variations to the strain was neglected.



Separation of different types of strain and comparison with theoretical predictions.

Benefits of Using SHM Technologies in the Project:

The SHM technology in this pilot project provided the following benefits:

- Long-term structural data collection including during construction phase
- Verification and improvement of numerical models
- Control of construction process

After two years of monitoring the following conclusions were arrived:

- Readings obtained reflect the predicted theoretical behaviors of building
- The shrinkage, creep and elastic component of strain were observed in the order of 20% and 40%, and 40% of total strain after all the 19 stories were constructed
- Measured strain within acceptable design limits – no overstress in each column, no instability of structure detected

References:

Glisic, B., Inaudi, D., Hoong, K. C., Lau, J. M., *Monitoring of building columns during construction,* 5th Asia Pacific Structural Engineering & Construction Conference, Pages 593-606, 26-28 August 2003, Johor Bahru, Malaysia.

Submitted by:

Er. Hoong Kee Ching
Principal Structural Engineer
Structural Engineering Department, Housing & Development Board (HDB)
HDB Hub 480 Lorong 6 Toa Payoh, Singapore 310480
Phone: +65 64902507
Fax: +65 64902601
Email: hkc1@hdb.gov.sg

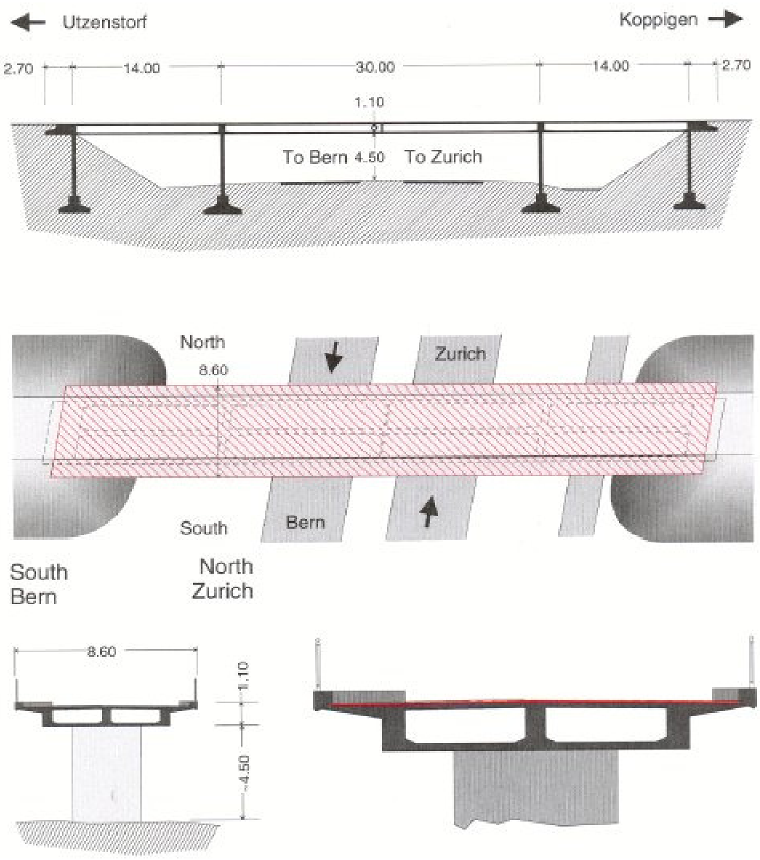
Bridge Z24 - Switzerland

Project Description:

The Z24 bridge, built between 1961 and 1963, spanned the A1 Bern-Zurich motorway and linked Koppigen with Utzenstorf. The three-span structure with spans of approximately 14, 30 and 14 m crossed the A1 at a slightly oblique angle. The superstructure consisted of a two-cell closed box girder with tendons in the three webs. The condition of the bridge was relatively good but the bridge had to be demolished to allow the construction of new railway tracks.

Within the SIMCES project the influence of the environment on the dynamic characteristics (natural frequencies and mode shapes) was investigated as well as the changes of the dynamic characteristics due to progressive damage tests (PDT).

It was the aim to provide an experimental basis for a feasibility proof of the SHM method. Vibration measurements prior to and after a damage scenario should allow conclusions to be drawn about the possibility of identifying damage from changes in dynamic characteristics.



Z24 Bridge, Switzerland


Z24 Bridge, Koppigen-Utzenstorf, Switzerland

Quick Facts:

- **Name and Location:** Z24 Bridge, Koppigen-Utzenstorf, Switzerland
- **Owner:** Road department of the canton of Bern
- **Structure category:** medium span bridge
- **Spans:** 3 spans: 14 / 30 / 14 m
- **Structural system:** Prestressed concrete, with two-cell closed box girder, two concrete diaphragms as main piers and concrete columns at abutments
- **Start of SHM:** August and September, 1998
- **Number of sensors installed:** (15+2) x 9 setups + 3 reference channels
- **Instrumentation design by:** EMPA

Description of Structure:

The three-span structure had a total length of 58 m, subdivided in three spans of 14, 30 and 14 m, respectively. It crossed the A1 at a slightly oblique angle. The superstructure consisted of a two-cell closed box girder with tendons in the three webs. More tendons were allocated over the main piers than in the middle of the spans.
Both main piers were built as concrete diaphragms, fully connected with the superstructure. The three abutment columns were pinned at both ends.
To protect the anchor heads, both ends of the bridge deck were extended.

Purpose of Inspection:

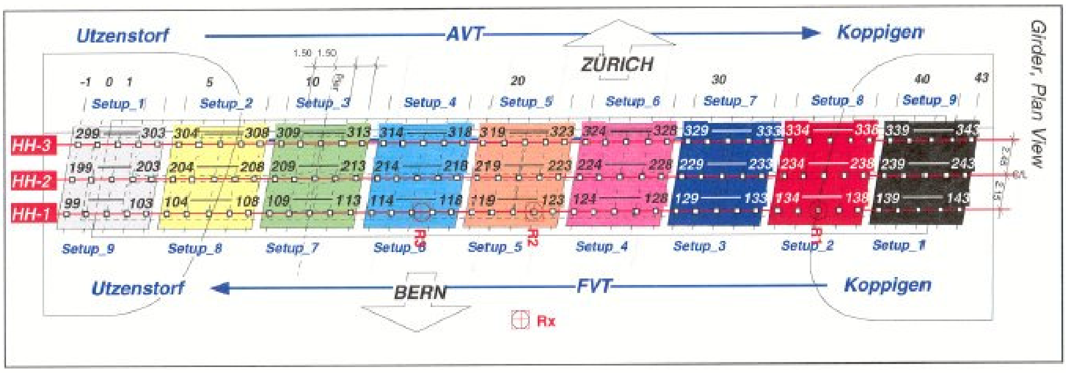
The purpose of the SIMCES project was to prove the feasibility of assessing the integrity of civil structures by means of evaluating their vibration. Several damage scenarios were applied and the resulting changes in dynamic characteristics were recorded and used to detect and identify the corresponding structural damage. Full-scale ambient (AVT) as well as forced vibrations (FVT) were carried out.
More information on http://www.kuleuven.ac.be/bwm/SIMCES.htm
One way to solve the inverse problem is by Finite Element model updating. As an example, the damage scenario consisting in the lowering of the main pier at the right-hand side over 95 mm, which induced cracks in the main girder above this pier, is investigated. It was the aim to identify the stiffness reduction of the girder by updating the FE model using the experimental dynamic characteristics. Only the AVT results were used in the updating process.

Sensor Details (AVT tests):

Type of sensors, Number and Location

Accelerometers:

15 (on the bridge deck)
+ 2 (on a pier)
+ 3 reference channels } X 9 setups



Measurement grid on bridge deck

Measurement Equipment and Data Management:

Type of system	Data Management
PC based measurement system	▪ data pre-analysis (data reduction and frequency analysis) on site ▪ raw data: available on http://www.kuleuven.ac.be/bwm/IMAC/index.html ▪ main analysis: performed by different partners of SIMCES project. KUL results: available in office. ▪ graphical presentation and documentation on http://www.kuleuven.ac.be/bwm/SIMCES.htm and http://www.kuleuven.ac.be/bwm/Z24/index.html

Data Analysis Procedures:

Type of analysis	Software	Additional features
Dynamics, experimental modal analysis, damage indicators	*System identification*: Stochastic Subspace Identification technique [1] *FE model updating*: Own developed software (in Matlab) [2]	▪ output-only system identification in time domain ▪ natural frequencies and mode shapes are used

Examples of Outcomes:

The box bridge is modeled by a beam model with equivalent stiffness properties. The damage is represented by a reduction in bending and torsional stiffness of the constituting beam elements.

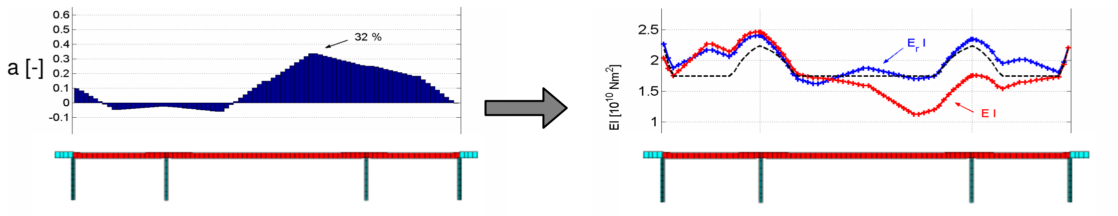
A globally realistic damage pattern is identified for the bending and the torsional stiffness with the FE model updating method. A good correlation between the experimental and the updated numerical modal data is obtained.

Reduction factor of bending stiffness

$$a = (E_rI - EI)/ E_rI$$

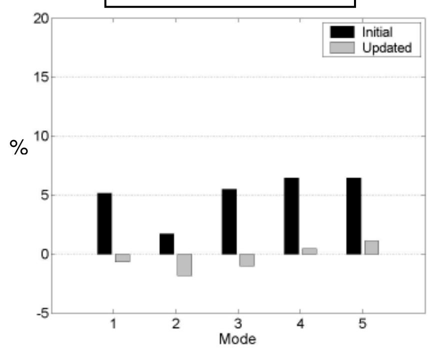
Identified bending stiffness

$$EI = E_rI\ (1 - a)$$

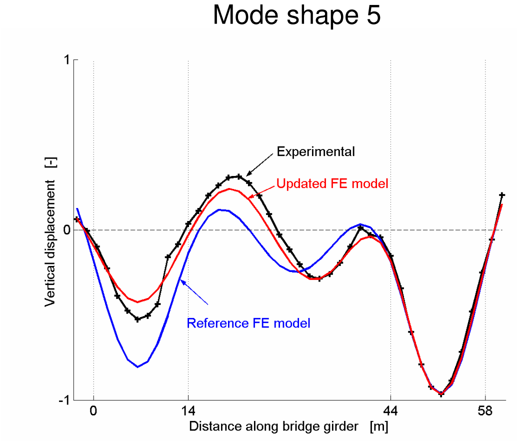


Eigenfrequency differences

$$(f_{FE} - f_{exp}) / f_{FE}$$



Mode shape 5



Top: Identified relative reduction and resulting bending stiffness of main girder
Bottom: Discrepancies between numerical and experimental modal data

Benefits of Using SHM Technologies in the Project:

Based on the experimental modal characteristics of the bridge, the applied damage pattern could be identified through an inverse analysis. The realistic result proves the performance of the nondestructive vibration-based damage identification method.

References:

[1] Peeters B. and De Roeck G., Reference-based stochastic subspace identification for output-only modal analysis. *Mechanical Systems and Signal Processing*, **6**(3), 855-878, 1999.

[2] Teughels A. and De Roeck G., Structural damage identification of the highway bridge Z24 by FE model updating. *Journal of Sound and Vibration*, accepted for publication, 2003, http://www.kuleuven.ac.be/bwm/pub_pap.htm

[3] EMPA work package, *Brite-Euram Project SIMCES, Tasks A1 and A2: Long term Monitoring and Bridge Tests*. Technical report, Dübendorf, Switzerland, 1999.

Submitted by:

Katholieke Universiteit Leuven
Division of Structural Mechanics
Department of Civil Engineering
Kasteelpark Arenberg 40
B- 3001 Heverlee (Leuven)
Belgium
Phone: +32 16 32 16 66
Fax: +32 16 32 19 88
Email: Guido.DeRoeck@bwk.kuleuven.ac.be

Floridotower Highrise Building - Austria

Project Description:

In the 21st district of Vienna a high-sophisticated high-rise project was developed and realized by A. Porr Aktiengesellschaft and UBM Realitätenentwicklung AG during the last years. The office center is directly located in the heart of Vienna's dynamic, new high-rise district. The tower is presenting an outstanding sign of the new part of the district development.

Floridotower, Vienna, Austria

Quick Facts:

- **Name and Location:** Floridotower Highrise Building, Vienna, Austria
- **Owner:** Real I. S. Project and UBM Realitätenentwicklung AG
- **Structure category:** High-rise building
- **Height:** 113 m
- **Structural system:** Composite Structure
- **Start of SHM:** August 2001
- **Number of measurement points:** 62 (each floor 2x)
- **Instrumentation design by:** arsenal research, Business Area Transport Route Engineering, Vienna, Austria, VCE Holding GmbH., Vienna, Austria

Description of Structure:

The Florido high-rise building consists in total of 31 floors with a total floor space of approximately 36.000 m². The height of the building is 113, 00 m. In addition a joint shopping and food mall and 3 floors parking with 600 lots are included. The tower is presenting one of the advanced office buildings in Vienna recently.

Geometry of the structure

Purpose of Inspection:

In the scope of the comprehensive investigations of the Floridotower in Vienna, the registration and determination of the dynamic characteristic of the structure was major task. Moreover an assessment of the vibration response as well as the proneness of vibration in case of seismic events should be performed. The investigation was additionally focused to determination of the serviceability stage and user comfort in operation.

Sensor Details*:

Type of sensors	Number	Location
Acceleration Sensors	3	2 reference sensors and 1 moving sensor
Reaction Mass Exciter "VICTORIA"	1	Located on ground level
PT100 (Temperature)	1	Measurement inside and outside of structure

Measurement Equipment and Data Management:

Type of system	Data Management	CMS
Mobile measurement system based upon Ambient + Forced Vibration Technology	▪ data pre-analysis (natural frequencies) on site in order to check the obtained data quality ▪ main analysis, graphical presentation and documentation in office ▪ data transfer by data cables to main station ▪ Forced Testing by Reaction Mass Exciter VICTORIA	

Data Analysis Procedures:

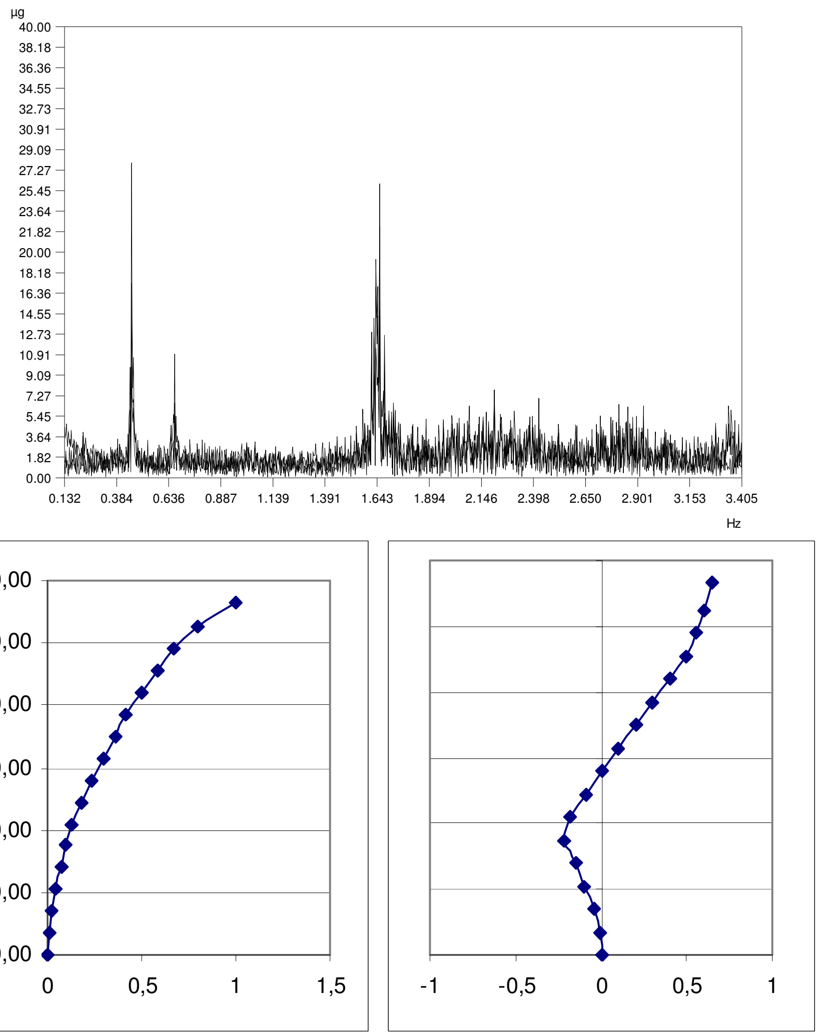
Type of analysis	Software	Additional features
Identification of modal parameters by System Identification	Stochastic Subspace Identification (MACEC)	▪ Comparison to current wind velocity from meteorological station ▪ Identification of ground response by Reaction Mass Exciter VICTORIA

Examples of Outcomes:

The modes in transversal and longitudinal direction are clearly separated for the forced and ambient vibration tests. The structure represents a well developed dynamic response in the observed frequency range. Due to the high number of measurement points in each floor the first three modes of vibration could be clearly determined in transverse and longitudinal direction.

Longitudinal Direction: f_1 = 0,38 Hz, f_2 = 1,79 Hz

Transversal Direction: f_1 = 0,46 Hz, f_2 = 0,66 Hz, f_3 = 1,64 Hz



Frequency Spectrum in transverse direction (top) mode shapes (below)

Benefits of Using SHM Technologies in the Project:

Based upon the analysis of the ambient and forced vibration tests carried out on the Florido high-rise building the structural behavior was clearly identified. Due to the interpretation of the measurements as well as a prospective comparison to a finite element simulation conclusions concerning the vibration response and the proneness of vibration could be derived. An assessment concerning resonance effects in case of ground induced motions in case of an earthquake was possible. Moreover structural health monitoring is feasible by comparison of the results from the initial investigation to future measurements.

References:

Report concerning the dynamic response of the Floridotower high rise building, submitted to the A. PORR AG

Submitted by:

Arsenal Research GmbH.
Business Area Transport Route Engineering
A-1030 Vienna, Austria
Faradaygasse 3
Phone: +43 (0) 50-550-6319
Fax: +43 (0) 50-550-6599
Email: rainer.flesch@arsenal.ac.at or roman.geier@arsenal.ac.at

Talübergang Haag - Austria

Project Description:

In the framework of an Austrian research project focused to noise emission and vibration transmission a work package was related to the global and local vibration behavior of railway bridges. In order to study the dynamic characteristic of the structure accurately a combined approach consisting of forced and ambient vibration testing was designed. In parallel a finite element simulation was prepared to compare the results from numerical and experimental testing.

TÜG Haag, Haag, Austria

Quick Facts:

- **Name and Location:** TÜG Haag, Haag, Lower Austria, Austria
- **Owner:** HL AG (Hochleistungsstrecken AG), Austria
- **Structure category:** short span post tensioned box girder
- **Spans:** 5 span: 40,0 m, Total Length 200,00 m
- **Structural system:** post tensioned box girder, single supported structures
- **Start of SHM:** April, 2001
- **Number of measurement points:** 46
- **Instrumentation design by:** arsenal research, Business Area Transport Route Engineering, Vienna, Austria

Description of Structure:

The bridge, erected in the year 2000, is an integral part of the track upgrade of Austrian Federal Railways. The design and realization of the project was done by the Austrian HL AG. The bridge consists of a chain of 5 single supported structures, each having a span of 40,0 m. The total length of the structure is 200,0 m. The deck width is sufficient to bear to parallel tracks for the high speed railway traffic. Each single supported structure completely is equipped with internal prestressing, where the main part of tendons is located in the massive 80 cm thick concrete webs.

Reaction Mass Exciter VICTORIA

Purpose of Inspection:

Main purpose of monitoring in this context was to establish a initial measurement of the structure, which could be the base for future implemented monitoring concepts. Moreover the sound emission of a post tensioned concrete bridge should be compared to numerical simulations as well as to other bridge types within the research project. In addition a comparison between the results of ambient and forced vibration testing was performed in order to point out the advantages and disadvantages for both systems in practical testing.

Sensor Details*:

Type of sensors	Number	Location
Acceleration Sensors	8	Aligned on both sides of the carriageway
Displacement Sensors	2	Mid-span
Reaction Mass Exciter	1	Close to each pile of the structure
Load Cell	1	Integral Part of VICTORIA
PT100 (Temperature)	1	Inside box girder

Measurement Equipment and Data Management:

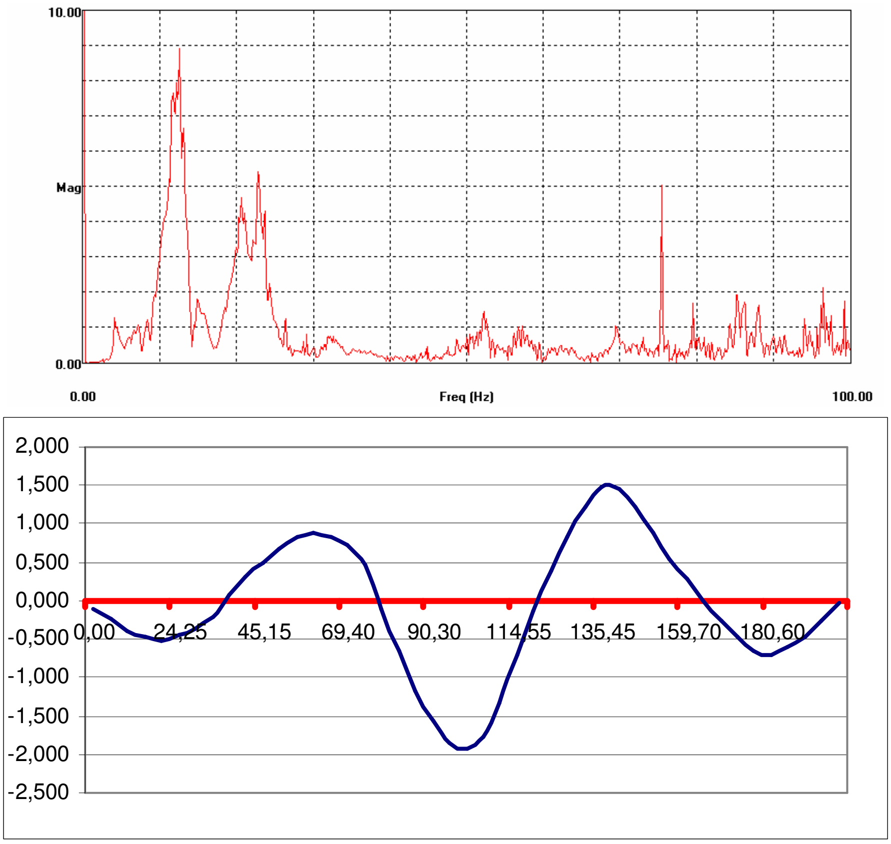
Type of system	Data Management	CMS
Mobile measurement system based upon Ambient and Forced Vibration Technology	▪ data pre-analysis (natural frequencies) on site in order to check the obtained data quality ▪ main analysis, graphical presentation and documentation in office ▪ data transfer by data cables to main station ▪ Use of Reaction Mass Exciter VICTORIA in order to excite all relevant modes of vibration	

Data Analysis Procedures:

Type of analysis	Software	Additional features
Identification of modal parameters by System Identification, Additional Forced Vibration Testing	Stochastic Subspace Identification (MACEC)	▪ Application of the Reaction Mass Exciter VICTORIA and additional measurement of sound emission during train passage.

Examples of Outcomes:

Ambient testing of the structure results in a first frequency of 2,7 Hz which represents the first vertical bending mode. The second bending mode was identified at 3,39 Hz. The corresponding mode shapes are very well developed and do not show any unsuspected shapes. Due to the fact, that almost no excitation was available during testing (no wind, no ground excitation) the Reaction Mass Exciter was required for successful System Identification. It was observed recently, that especially for railway bridges with low ambient excitation the identification of the dynamic response is hardly possible.



Frequency Spectrum (top) and mode shape for the first bending mode (below)

Benefits of Using SHM Technologies in the Project:

By performing these global and local vibration tests, a initial measurement of the structure was established which could be used for further monitoring activities.

Moreover a finite element model was created which was updated to the experimental results. Based upon both data sources (measurement and simulation) a reliable monitoring concept could be applied for the structure. Moreover it turned out, that the sound emission of massive concrete bridges is much lower compared to modern steel or composite structures.

References:

„Final Report Work-package 2c of the national Research Project LEO – Lärm und erschütterungsarmer Oberbau“ by R. Flesch and Partners of the Consortium

Submitted by:

Arsenal Research GmbH.
Business Area Transport Route Engineering
A-1030 Vienna, Austria
Faradaygasse 3
Phone: +43 (0) 50-550-6319
Fax: +43 (0) 50-550-6599
Email: rainer.flesch@arsenal.ac.at or roman.geier@arsenal.ac.at

Warth Bridge - Austria

Project Description:

To convince the engineering community that vibration monitoring is a valuable technique for structural assessment a proof of significance is essential. Therefore it is of paramount importance that existing bridges are going to be tested. In the framework of an European research project SIMCES several bridges were one bridge was extensively instrumented to setup a long term test for quantifying the degree of variance due to environmental influences and also due to differences induced by the parameter choice of the selected system identification methods. In addition some initial measurements were carried out, in order to present the capabilities of System Identification Techniques. Moreover the intention was to create a initial measurement of the structure, which might be used for future monitoring and maintenance concepts.

Warth Bridge, Lower Austria, Austria

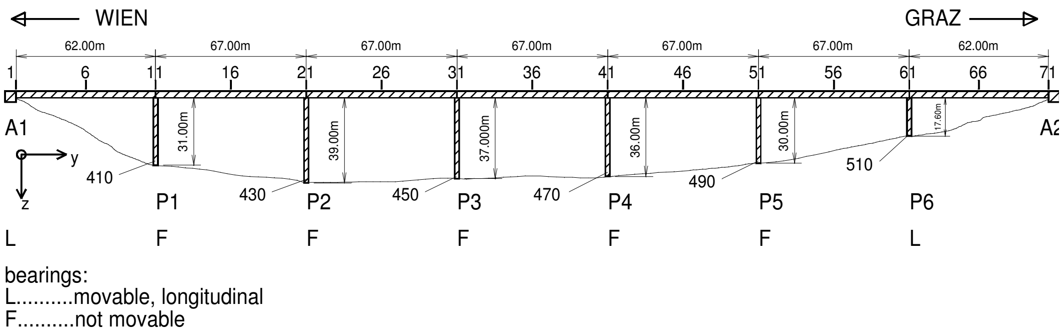
Quick Facts:

- **Name and Location:** Warth Bridge, A2, 63 km south of Vienna
- **Owner:** Municipal Authorities of Lower Austria, Austria
- **Structure category: multi-span post tensioned structure**
- **Spans:** 7 spans, 62,0 m + 5x67,0 m + 62,0 m = 459,0 m
- **Structural system:** Post tensioned box girder
- **Start of SHM:** April 1999
- **Number of measurement points:**
- **Instrumentation design by:** arsenal research, Business Area Transport Route Engineering, Vienna, Austria in the Framework of the European SIMCES project

Description of Structure:

Talübergang Warth is located on motorway A2, 63km south of Vienna. One of the non coupled twin bridges (direction to Graz) was tested. The bridge has 7 spans and a total length of 459m. The continuous cross section of the bridge does have a width of the carriageway of 14,0m. The height of the regular cross section is

5,0m. The box girder bottom width is 6,2m which is extended to 8,0m under the carriageway.



Geometry of the structure

Purpose of Inspection:

Service loads, environmental and accidental actions may cause damage to constructions. Regular inspection and condition assessment of engineering structures are necessary so that early detection and localisation allows maintenance and repair works to be properly programmed, thereby minimising costs. Vibration monitoring of civil engineering structures (e.g. bridges, buildings, dams) has gained a lot of interest over the past few years, due to the relative ease of instrumentation and the development of new powerful system identification techniques. The first goal was to demonstrate the high capability of measurements using swept sinusoidal force excitation. The experiments have been carried out under operational conditions The second goal for the measurement campaign was to compare the results obtained by forced vibration and by ambient vibration testing.

Sensor Details*:

Type of sensors	Number	Location
Velocity Transducer Hottinger SMU 30A	8	Multiple setups along the bridge axis to identify mode shapes
Acceleration Sensors	4	Expansion Joints
Displacement Sensors	2	Expansion Joints
Temperature Sensors	1	Air Temperature
Load Cell	1	Reaction Mass Exciter

Measurement Equipment and Data Management:

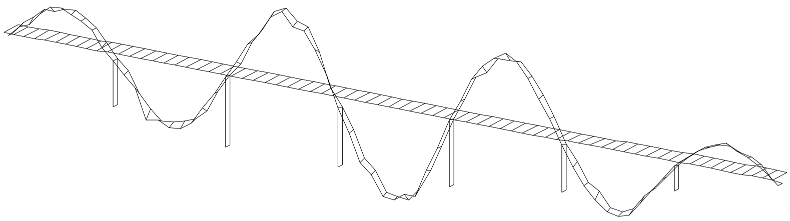
Type of system	Data Management	CMS
Mobile measurement system based upon Ambient and Forced Vibration Technology	▪ data pre-analysis (natural frequencies) on site in order to check the obtained data quality ▪ main analysis, graphical presentation and documentation in office ▪ data transfer by data cables to main station ▪ Reaction Mass Exciter	

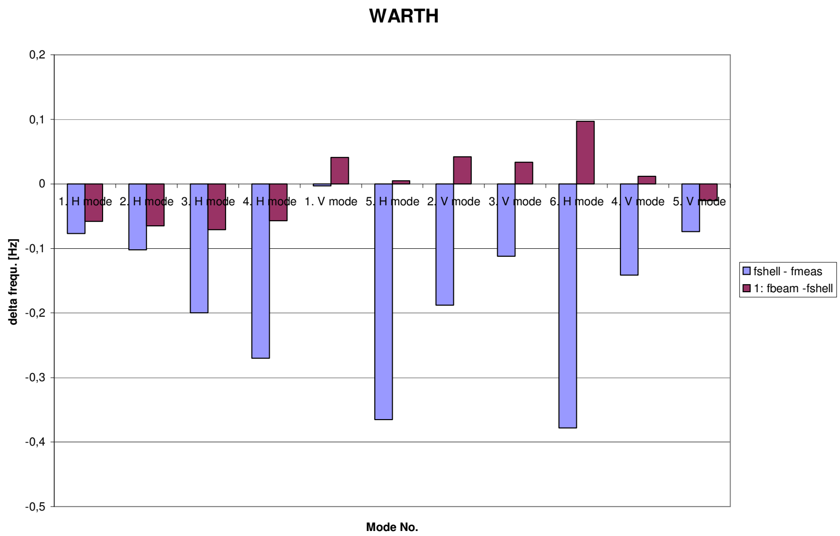
Data Analysis Procedures:

Type of analysis	Software	Additional features
Identification of modal parameters by System Identification	Simple Peak Picking Approach to identify the modal parameters. MACEC for ambient testing	▪ Additional Forced Vibration Testing of the structure ▪ Comparison of data quality from forced and ambient vibration tests

Examples of Outcomes:

The modal properties can be identified by forced vibration under traffic disturbance quite well. Due to the large number of sweeps, the traffic disturbances can be filtered out at least to a great extent. The higher modes (in this case torsional + mixed modes), which could be very important for model updating, are not excited by traffic sometimes in the case of ambient testing. This is plausible, because trucks are mainly using the rightmost lane (the closed lane is only for emergency stops) which is almost above the center of gravity. Hence they are also not disturbed when measuring under traffic and forced vibration is the only possibility to excite also these modes. Also the transverse modes could be identified quite well. In general comparable results have been obtained by ambient and forced vibration testing.





Frequency differences between shell model and measurement and between beam model and shell model

Benefits of Using SHM Technologies in the Project:

Within the project modal updating was performed in order to adapt the numerical results to the real vibration behavior obtained. Thus, a realistic simulation does exist, which might be used for future monitoring concepts. Moreover an initial measurement was established which could be very important for damage detection if required. From the results it was derived, that ambient vibration testing employing an advanced System Identification Technique is a powerful tool in civil engineering practice. The use of an additional reaction mass exciter is particular important if higher order modes must be determined by vibration testing.

References:

FLESCH R.G., STEBERNJAK B., FREYTAG B.: Dynamic insitu testing and FE – modelling of bridge WARTH / Austria. ISMA 23, Leuven– Belgium, Sept. 1998.

Submitted by:

Arsenal Research GmbH.
Business Area Transport Route Engineering
A-1030 Vienna, Austria
Faradaygasse 3
Phone: +43 (0) 50-550-6319
Fax: +43 (0) 50-550-6599
Email: rainer.flesch@arsenal.ac.at or roman.geier@arsenal.ac.at

PORR Bridge - Austria

Project Description:

In 1975 a bridge structure in segment-construction was erected by the A. PORR AG for research purposes. The bridge crossing a major road in Vienna consists of single segments which are glued and stressed together. The single supported box girder with a span of 44,0 m consists of 18 prefabricated parts. In the framework of a research project it was possible to introduce artificial damages and study the changes of the dynamic behavior of the structure.

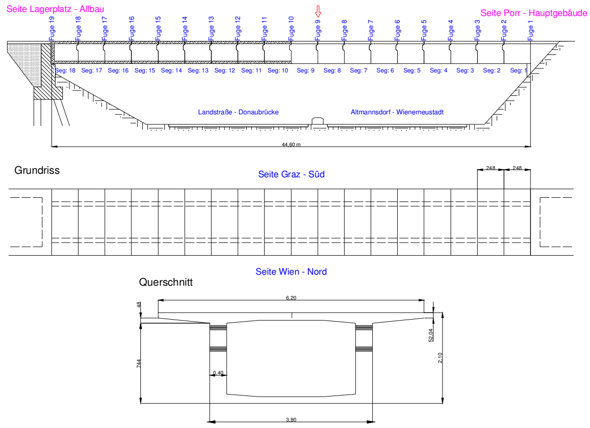

Porr Bridge, Vienna, Austria

Quick Facts:

- **Name and Location:** Porr Bridge, Vienna, Austria
- **Owner:** PORR AG, Austria
- **Structure category:** short span post tensioned box girder
- **Spans:** 1 span: 44,0 m
- **Structural system:** post tensioned box girder, segment construction
- **Start of SHM:** October, 2002
- **Number of measurement points:** 36
- **Instrumentation design by:** arsenal research, Business Area Transport Route Engineering, Vienna, Austria, VCE Holding GmbH, TU Wien – Institut für Massivbau

Description of Structure:

The structure was designed as precast segmental bridge with glued joints. The single supported structure (appr. 380 t weight) with a span of 44,0 m and a free length of 43,5 m offers a total width of 6,2 m. The width of the carriageway was 4,8 m. The monocellular box girder was designed with a constant web width of 40 cm and a construction height of 2,10 m. The width of the box girder was 3,80 m, thus the cantilever arm had a length of 1,20 m on both sides.



Geometry of the structure

Purpose of Inspection:

The main target of the investigation was to evaluate and determine the changes of the dynamic properties of the structure caused by artificial damages. These damages have been applied to the concrete itself as well as to selected prestressing tendons. In particular it was from main interest, how the dynamic properties (frequencies, modes and damping coefficients) are changing due to loss in prestressing forces. An other question was to assess, if vibration testing technologies may be used as early diagnosis tool for failure of single tendons.

Sensor Details*:

Type of sensors	Number	Location
Acceleration Sensors	6	Aligned on both sides of the carriageway
Displacement Sensors	2	Mid-span
Displacement Sensors	8	Measuring crack widths
Strain Gauges	8	Attached to the tendons
PT100 (Temperature)	1	Inside box girder

Measurement Equipment and Data Management:

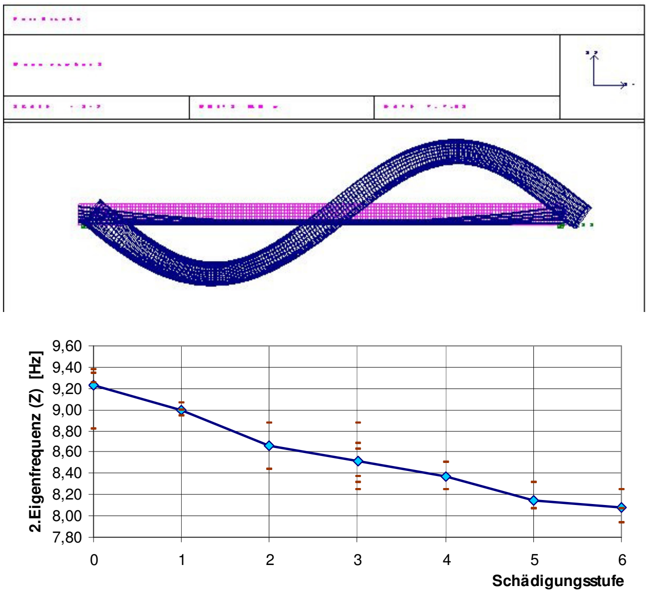
Type of system	Data Management	CMS
Mobile measurement system based upon Ambient Vibration Technology	▪ data pre-analysis (natural frequencies) on site in order to check the obtained data quality ▪ main analysis, graphical presentation and documentation in office ▪ data transfer by data cables to main station ▪ 24-h measurement	

Data Analysis Procedures:

Type of analysis	Software	Additional features
Identification of modal parameters by System Identification, Correlation to damage state	Stochastic Subspace Identification (MACEC)	▪ correlation of the results to the current damage stage and the applied load

Examples of Outcomes:

The first two modes have been identified reliable by the ambient vibration method. Both frequencies were reduced with increasing damage stage in the loaded condition. In the unloaded stage the frequency of the first mode is below the loaded one, this effect is mainly caused by the stiffness coming from the stressing construction. An important damage indicator is the mode shape, which is in particular sensitive for smaller damages. In addition the higher order modes are relevant if local damages should be reliable detected. Focusing only to the basic modes is not sufficient.



Correlation of damage stage (below) to second bending mode (top)

Benefits of Using SHM Technologies in the Project:

It was shown within this project, that structural health monitoring and modal updating could be a powerful tool for assessing the condition of a structure. Moreover an important outcome of the investigation was that focusing to basic modes is not sufficient for damage detection and localization. The difference in the dynamic response between the loaded and unloaded stage for post-tensioned structures is important to consider.

References:

"Dynamische Untersuchungen einer Segmentbrücke" by Geier, R.; Benko, V.; Ralbovsky, M., Proceedings of the D-A-CH Tagung 2003, 18.-19. September 2003, Zürich, Switzerland

Submitted by:

Arsenal Research GmbH.
Business Area Transport Route Engineering
A-1030 Vienna, Austria
Faradaygasse 3
Phone: +43 (0) 50-550-6319
Fax: +43 (0) 50-550-6599
Email: rainer.flesch@arsenal.ac.at or roman.geier@arsenal.ac.at

Railway Bridge Heugasse - Austria

Project Description:

For the railway bridge Heugasse, located at the track Vienna – Spielfeld a simple approach for identifying the dynamic response of the structure in operational conditions should be evaluated. In particular the eigenfrequencies and modes in ambient and loaded condition are desired, moreover estimates for the deflection caused by the traffic-load as well as damping coefficients should be derived. This measurements are contributing to a pilot project for future monitoring concepts. Therefore several measurement points and different sensing technologies have been used in order to identify the equipment which is suited best for fast and reliable testing under operational conditions.

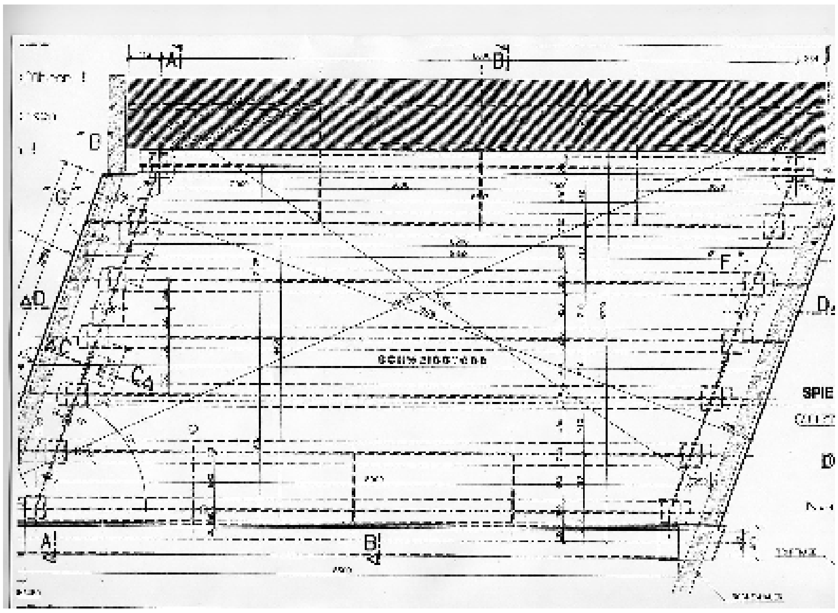
Railway Bridge Heugasse, Vienna, Austria

Quick Facts:

- **Name and Location:** Railway Bridge Heugasse, Vienna, Austria
- **Owner:** ÖBB, Austrian Federal Railways, Austria
- **Structure category:** short span composite structure
- **Spans:** 1 span: 8,0 m
- **Structural system:** Composite structure
- **Start of SHM:** October, 2003
- **Number of measurement points:** 5
- **Instrumentation design by:** arsenal research, Business Area Transport Route Engineering, Vienna, Austria

Description of Structure:

The railway bridge Heugasse is a composite, simple supported structure with a main span of 8,0 m. For each tracks of the railway line a single bridge is available with a widt of 5,72 m. The total width of the bridge is 11,44 m. Each structure is supported by 7 parallel steel beams with a heigth of 540 mm. The bridge is supported by elastomere bearings.



Geometry of the structure

Purpose of Inspection:

Dynamic aspects are getting more importance nowadays. There are several reasons for this development. On one hand all structures are getting slender due to optimized design methods, new construction technologies and advanced materials. Thus, usually the proneness to vibration is increasing. The assessment of the serviceability of railway structures is done under operational conditions and no interruption of the track is required compared to static load tests. Moreover the results are representing the real behavior of the structure in operation. Therefore a pilot project was performed, presenting the powerful approach of dynamic testing of structures.

Sensor Details*:

Type of sensors	Number	Location
Acceleration Sensors	3	Mid-span and at bearings
Velocity Sensors	1	Mid-span
Laser-Doppler Vibrometer (Displacement Sensor)	1	Mid-span
PT100 (Temperature)	1	Air Temperature

Measurement Equipement and Data Management:

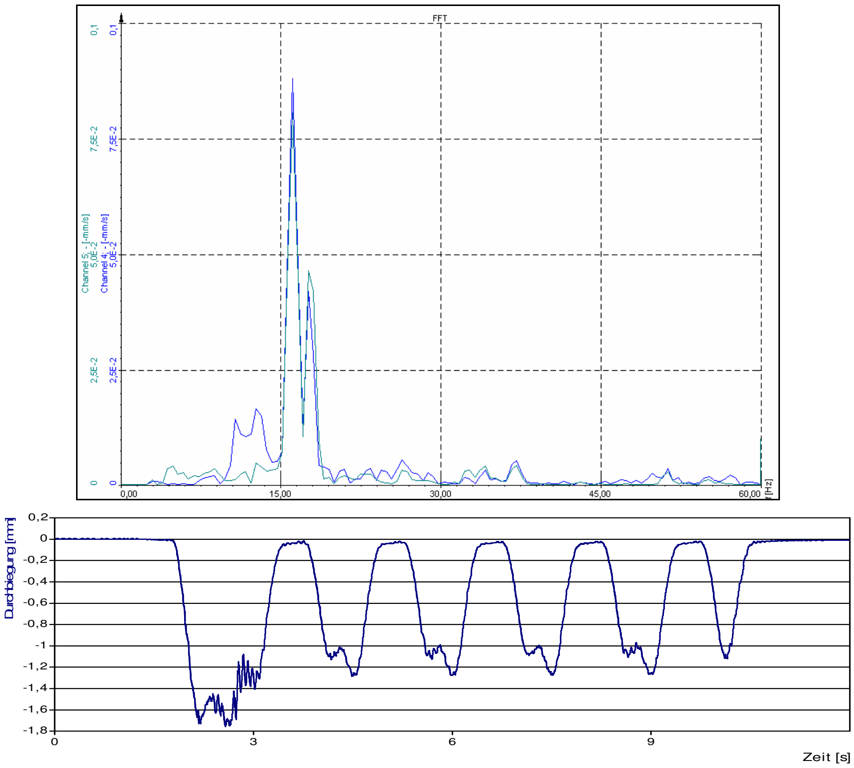
Type of system	Data Management	CMS
Mobile measurement system based upon Ambient Vibration Technology	▪ data pre-analysis (natural frequencies) on site in order to check the obtained data quality ▪ main analysis, graphical presentation and documentation in office ▪ data transfer by data cables to main station ▪ Correlation of Laser-Results to Acceleration Response	

Data Analysis Procedures:

Type of analysis	Software	Additional features
Identification of modal parameters by System Identification	Stochastic Subspace Identification (MACEC)	▪ Determination of the structural response in operational conditions

Examples of Outcomes:

Some results are available on-site, which is the eigenfrequency, the maximum vertical deflection as well as the maximum acceleration level induced by the train passage. For ambient vibration conditions a basic frequency was identified about f = 16,1 Hz. Due to the additional load during the train passage the frequency of the first bending mode is reduced to f = 13,2 Hz. The free decay of the structure after train passage results in a damping of 2,4 %. A maximum acceleration level of 9,2 m/s² have been identified during train passage, the maximum vertical deflection of the structure in mid-span equals 1,2 mm (excluding rigid body movements).



Identified frequency spectrum (top) and deflection during train passage (below)

Benefits of Using SHM Technologies in the Project:

The results obtained by operational testing of the structure have shown that measuring the structural response under operational conditions by means of dynamic methods is a powerful tool in order to check the structure. Complicated and costly static load tests are therefore not compulsory required. Moreover the results are corresponding much better to the structural characteristics due to measurement of realistic acting loads.

References:

Report submitted to the Austrian Federal Railways ÖBB – Measurement Results of the Railway Bridge Heugasse.

"Simulation of Bridge Vibrations Induced by High Speed Train Passages" by R. Flesch, IMAC-XXII Conference & Exposition on Structural Dynamics „Linking Test to Design", January 2004, Dearborn, USA

Submitted by:

Arsenal Research GmbH.
Business Area Transport Route Engineering
A-1030 Vienna, Austria
Faradaygasse 3
Phone: +43 (0) 50-550-6319
Fax: +43 (0) 50-550-6599
Email: rainer.flesch@arsenal.ac.at or roman.geier@arsenal.ac.at

Melkbridge M6 - Austria

Project Description:

In the framework of an Austrian research project focused to noise emission and vibration transmission a work package was related to the global and local vibration behavior of railway bridges to study the sound emission radiated by steel structures. A detailed monitoring concept was implemented, consisting of ambient and forced vibration testing of the global structure, testing of the steel webs and measurement of the related noise emission. Using this data, an extensive comparison between the noise radiation of steel and concrete bridges was performed.

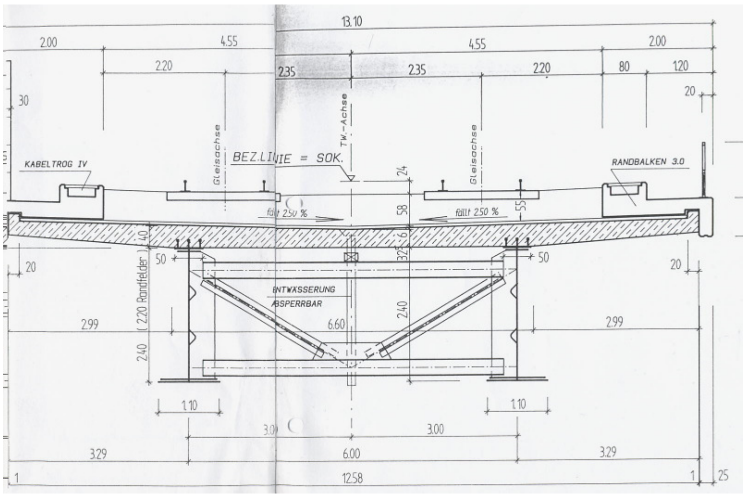
Melkbridge M6, Melk, Austria

Quick Facts:

- **Name and Location:** Melkbridge M6, Melk, Lower Austria, Austria
- **Owner:** HL AG (Hochleistungsstrecken AG), Austria
- **Structure category:** large span composite bridge
- **Spans:** 5 span: 53,0 + 53,0 + 79,0 + 53,0 + 36,0 m Total Length 274,00 m
- **Structural system:** composite bridge, steel main girder, concrete slab deck
- **Start of SHM:** July, 2001
- **Number of measurement points:** 40
- **Instrumentation design by:** arsenal research, Business Area Transport Route Engineering, Vienna, Austria

Description of Structure:

The bridge, erected in the year 2000, is an integral part of the track upgrade of Austrian Federal Railways. The design and realization of the project was done by the Austrian HL AG. The bridge consists of a continuous composite beam with 5 spans. The total length of the structure is 274,0 m. The deck width is sufficient to bear to parallel tracks for the high speed railway traffic. The bridge plan view is slightly curved; therefore the bridge must bear high transversal loads. The high design speed of the track requires dynamic investigations for the structure.



Cross section of the bridge

Purpose of Inspection:

Main purpose of the investigation performed in this case was the check and further development of the technology to assess the noise emission. Therefore the noise emission was measured during a train passage. This measurement was compared to the frequency response of the girder webs. From the investigation it was shown, that the vibration of the web is mainly responsible for the noise emission (sound speaker effect). Moreover an initial dynamic investigation was performed to assess the global response of the structure. This measurement could serve as base for future implemented monitoring concepts, modal updating for damage assessment and localization and for upgrading the noise emission from the structure.

Sensor Details*:

Type of sensors	Number	Location
Acceleration Sensors	8	Aligned on bottom flange and girder web of the structure
Reaction Mass Exciter	1	Close to each pile of the structure
Load Cell	1	Integral Part of VICTORIA
PT100 (Temperature)	1	Surface Temperature

Measurement Equipment and Data Management:

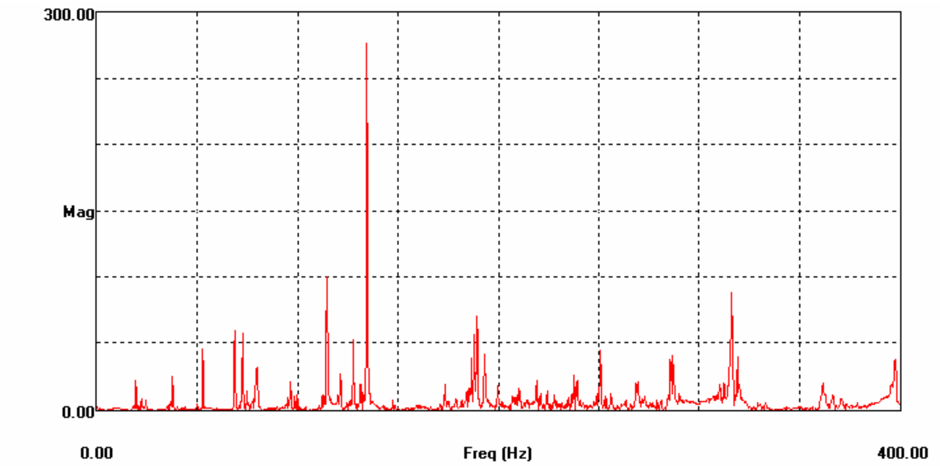
Type of system	Data Management	CMS
Mobile measurement system based upon Ambient and Forced Vibration Technology	▪ data pre-analysis (natural frequencies) on site in order to check the obtained data quality ▪ main analysis, graphical presentation and documentation in office ▪ data transfer by data cables to main station ▪ Use of Reaction Mass Exciter VICTORIA in order to excite all relevant modes of vibration	

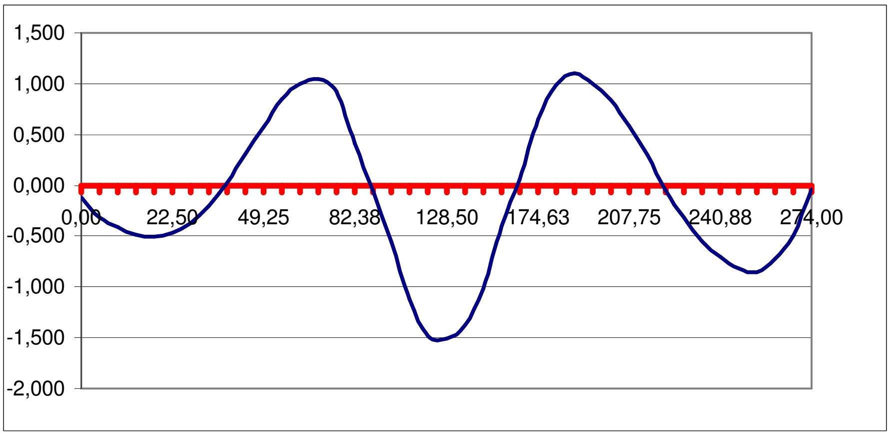
Data Analysis Procedures:

Type of analysis	Software	Additional features
Identification of modal parameters by System Identification, Additional Forced Vibration Testing	Stochastic Subspace Identification (MACEC)	▪ Application of the Reaction Mass Exciter VICTORIA and additional measurement of sound emission during train passage.

Examples of Outcomes:

The comparison between ambient and forced vibration testing has shown very good correspondence. The frequency of the first vertical mode is f = 1,86 Hz. The second vertical mode was identified at f = 3,31 Hz representing typical vibration shapes. Due to the curved shape of the structure, all modes have a major transversal and torsion component. The analysis of the web elements have shown frequencies in the range of 19,27 Hz, 21,91 Hz and 24, 22 Hz. Main energy is represented by the first mode of the web. The modes of the web elements have been identified by a detailed finite element model.





Response of a web element and first vertical bending mode of the bridge (below)

Benefits of Using SHM Technologies in the Project:

By performing these global and local vibration tests, a initial measurement of the structure was established which could be used for further monitoring activities. Moreover a finite element model was created which was updated to the experimental results. Based upon both data sources (measurement and simulation) a reliable monitoring concept could be applied for the structure. Moreover it turned out, that the sound emission of steel structures mainly comes from the local vibration behavior of the girder webs.

References:

„Final Report Work-package 2c of the national Research Project LEO – Lärm und erschütterungsarmer Oberbau“ by R. Flesch and Partners of the Consortium

Submitted by:

Arsenal Research GmbH.
Business Area Transport Route Engineering
A-1030 Vienna, Austria
Faradaygasse 3
Phone: +43 (0) 50-550-6319
Fax: +43 (0) 50-550-6599
Email: rainer.flesch@arsenal.ac.at or roman.geier@arsenal.ac.at

Seismic Vulnerability of Hospitals - Austria

Project Description:

During the design procedure of new buildings usually seismic effects are taken into account, resulting in high safety values for these structures. New design codes are already in line with the European EC8 which is describing a detailed calculation procedure. Main problem in context of seismic events is the effect to existing structures, which are always designed according the current standards. Thus it is clear, that the main part of human and economic losses appear for these old structures, which are not appropriate designed. An assessment and improvement of all existing structures which are subjected to excessive seismic loads is not feasible, but the improvement of major structures which must fulfill their function after a seismic event is an economic approach. In particular this fact is important for hospitals.

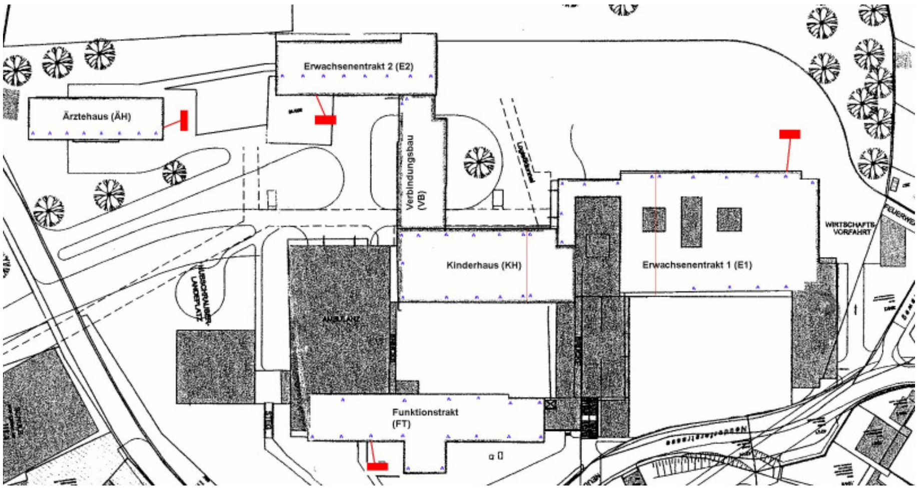
Hospital Leoben, Styria, Austria

Quick Facts:

- **Name and Location:** Hosptial Leoben, Leoben, Styria, Austria
- **Owner:** Stmk. Krankenanstalten GesmbH
- **Structure category:** Hospital
- **Height:** consisting of several buildings between 1 and 6 floors
- **Structural system:** Reinforced Concrete, Masonry Structure
- **Start of SHM:** July 2003
- **Number of measurement points:**
- **Instrumentation design by:** arsenal research, Business Area Transport Route Engineering, Vienna, Austria

Description of Structure:

The hospital Leoben is consisting of several buildings, which are different in case of structural system, construction material, number of floors and age. During the evaluation of the project it turned out, that some single structures are more important because of their structural system, height or condition. From this assessment it was decided to investigate the following structures, also indicated in the plan view of the hospital area: “Ärztehaus”, “Erwachsenentrakt” number 1 and 2, “Funktionstrakt” and “Kinderhaus”. The location of each building as well as the location of the reaction mass exciter is indicated in the plan view of the hospital area.



View of the hospital area

Purpose of Inspection:

First step of the investigation was related to the measurement of the vibration response of major structures. The determined natural frequencies and mode shapes are representative for the current undamaged condition of the buildings. During the next step a numerical analysis was performed for the structures, reaching from simple MDOF systems to advanced finite element models. Consequently, these models are fitted to the measured data (modal updating). These models are used for seismic calculations by the response spectra or the quasi-static method. The capacity of the structures was evaluated in accordance to the Austrian code B 4015, which was described by the “GPR” index. Secondary risks were also considered (GSR-index). Both indices are contributing to the risk index, which was presented by a risk-mapping technique. Main outcome are measures which should be implemented in order to increase seismic safety for identified areas of the structure. In addition a further investigation can be performed after an earthquake in order to assess the structural integrity after such event.

Sensor Details*:

Type of sensors	Number	Location
Dewetron Port 2000 incl. DASYLAB	1	Mobile Acquisition Unit
Oros OR38 Multichannel Analyzer	1	Data Analyzer (mobile)
Geosig Velocity Sensors	6	Each floor of investigated structure
Seismic Sensors	4	Identification of ground response at selected locations
HBM Sensors SMU 30A	6	Each floor of investigated structure

Measurement Equipment and Data Management:

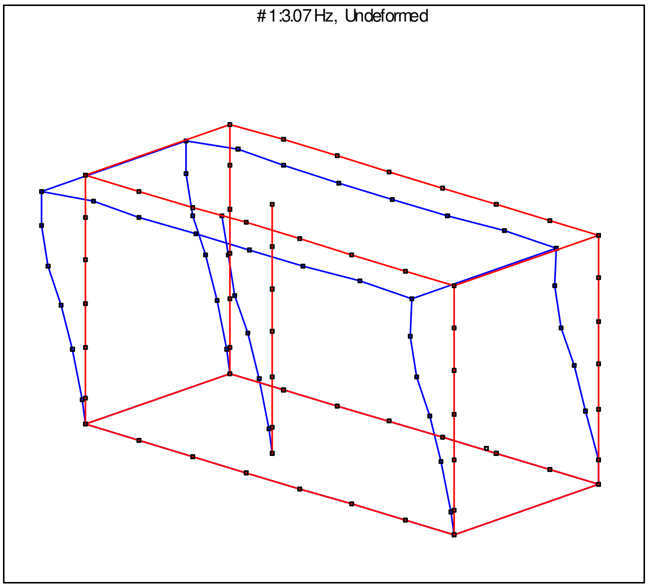
Type of system	Data Management	CMS
Mobile measurement system based upon Ambient + Forced Vibration Technology	▪ data pre-analysis (natural frequencies) on site in order to check the obtained data quality ▪ main analysis, graphical presentation and documentation in office ▪ data transfer by data cables to main station ▪ Forced Testing by Reaction Mass Exciter VICTORIA connected by a chain	

Data Analysis Procedures:

Type of analysis	Software	Additional features
Identification of modal parameters by System Identification	Stochastic Subspace Identification (MACEC)	▪ Identification of ground response by Reaction Mass Exciter VICTORIA ▪ Modal updating of major structures

Examples of Outcomes:

The investigation of the structure results in several results. On one hand the modal parameter of each building were identified by measurements, which have been compared to the results of the finite element analysis. The modal parameters were identified by ambient measurement and by forced vibration testing employing the reaction mass exciter VICTORIA. The exciter was attached to the structure by a stiff chain. Thus, results in sufficient excitation level. On the other hand the ground response was identified, using the exciter as well. A conventional risk study was additionally applied for each structure. By combining all results, a detailed impression from the structures could derived, which is base for seismic upgrading and future monitoring concepts.



Calculated Mode Shape of the Hospital

Benefits of Using SHM Technologies in the Project:

Major benefit of this project is to determine structures or areas which are subjected to a higher risk of failure or structural damages. For these problems adequate counter-measures could be performed. Moreover an initial measurement was established, which will be used for further assessment of the structure in case of an earthquake by comparing initial and new vibration data. The updated finite element mode is relevant to estimate the capacity of a structure and to enable damage detection based upon the comparison of measured and simulated data. The identification of critical areas within the structure enables a target-oriented inspection after the next earthquake. Thus, the remaining load carrying capacity could be evaluated, quickly. Application of a permanent monitoring system to the identified areas would be a appropriate solution for very sensitive structures.

References:

Final Report "Earthquake Investigation of Austrian Hospitals" (submitted in German) to the responsible authority (Stmk. Krankenanstalten GesmbH), Graz, Austria

Submitted by:

Arsenal Research GmbH.
Business Area Transport Route Engineering
A-1030 Vienna, Austria
Faradaygasse 3
Phone: +43 (0) 50-550-6319
Fax: +43 (0) 50-550-6599
Email: rainer.flesch@arsenal.ac.at or roman.geier@arsenal.ac.at

Bridge BE 109/21- Switzerland

Project Description:

The Bridge BE 109/21 in Bützberg/BE, Switzerland, was built in 1970 as a part of the railway route between Bern and Zürich. Recently the bridge was demolished because of changes in SBB the railway routing (Bahn 2000). As a part of the SBB initiated research program "ZEBRA" the load capacity of the bearings will be investigated within labor experiments. In order to collect data about the behavior of the bearings dependent on temperature influences, two monitoring periods measuring the deformations of the bearings and the temperature of the superstructure during the summer- and winter time were performed.

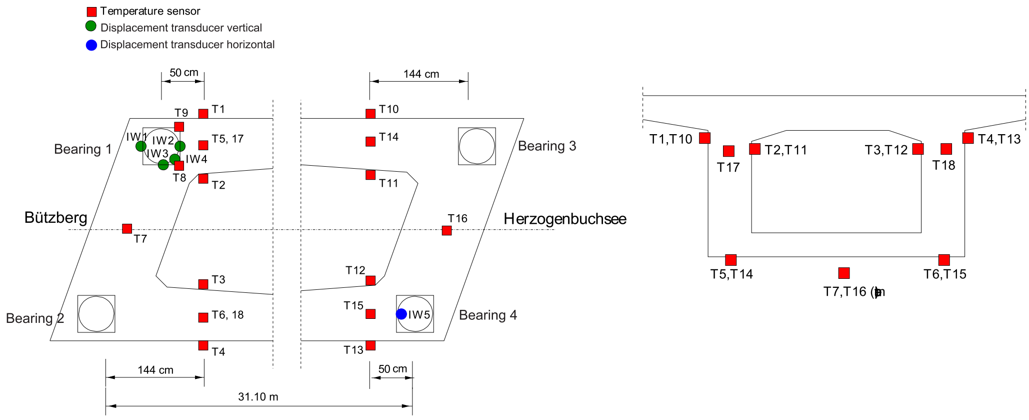
Bridge BE 109/21, Bützberg/BE, Switzerland

Quick Facts:

- **Name and Location:** Bridge BE 109/21, Bützberg/BE, Switzerland
- **Owner:** Swiss Federal Railways (SBB), Switzerland
- **Structure category:** medium span bridge
- **Spans:** one span: 31.10 m
- **Structural system:** Posttensioned concrete box girder bridge
- **2 Periods of SHM:** 29.8.-4.9.2002; 13.1.-15.1.2003
- **Number of sensors installed:** 21
- **Instrumentation designed by:** EMPA, Structural Engineering Research Laboratory, Switzerland

Description of Structure:

The railway bridge BE 109 existing of two single bridges: BE 109/21 and BE 109/22. Each of them was built as a concrete box girder and an orthotropic deck plate of a total length of 31.10 m. Each bridge was constructed for one lane of railway lane.



Temperature sensors and displacement transducers on the bridge BE 109/21 (schematically)

Purpose of Inspection:

For many railway bridges this special type of bearings has been used. The bridge owner (SBB) is especially interested on life expectation messages for this kind of bearings. After demolishing the bridge BE 109 the bearings will be dismantled and tested within labor experiments by fatigue loads and in a later state up to failure loads. The temperature influences and the deformations caused by traffic have been observed within two monitoring periods.

Sensor Details*:

Type of sensors	Number	Location
Temperature sensors	16	within and outside the box girder
Displacement transducers	5	all sensors fixed at two bridge bearings

Measurement Equipment and Data Management:

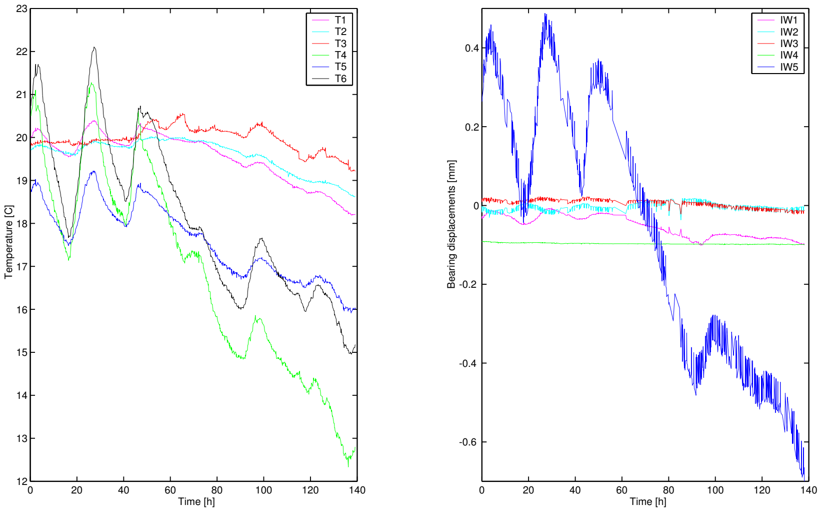
Type of system	Data Management	CMS
PC based measurement system	▪ main analysis, graphical presentation and documentation in laboratory ▪ long term data base	

Data Analysis Procedures:

Type of analysis	Software	Additional features
Analysis of time series analysis	Self made software Cadman Matlab	▪ adjustable trigger levels for different alert phases

Examples of Outcomes:

The deformations of the bearings according to temperature influence and traffic loads were observed. No particular deformation scenario was found. The bearings were working well and were in good general condition.



Measured temperature on T1-T6 (left-side) according bearing deformations on location IW1-IW5 (right-side) during the summer monitoring period

Benefits of Using SHM Technologies in the Project:

The measurements of temperature and bearing deformations caused by traffic loads and temperature effects give an idea of the long term behavior of bearings. Together with a well known load history (time tables of SBB) during the bridge life, the load-deformation history of the bearings life can be reconstructed. Temperature effects can also be taken into account. An enforced load history within labor experiments up to failure loads show the life expectation of this special kind of bearings.

References:

Huth, O., "Forschungsprojekt ZEBRA: Topflageruntersuchungen am BE 109 in Bützberg", EMPA-Report, Nr. 202’902/1, Dübendorf 3/2003 (in German)

Submitted by:

Olaf Huth
EMPA, Swiss Federal Laboratories for Materials Testing and Research
Structural Engineering Research Laboratory
CH-8600 Dübendorf, Switzerland
129-133 Ueberlandstrasse
Phone: +41(1) 823-4791
Fax: +41(1) 823-4455
Email: olaf.huth@empa.ch

Europabrücke - Austria

Project Description:

Bridges are ageing and traffic is growing, which creates a demand for accurate fatigue life assessment. The Europabrücke – a well known Austrian steel bridge near Innsbruck, opened in 1963 - is one of the main alpine north-south routes for urban and freight traffic. A long-term preoccupation of VCE with BRIMOS® (BRIdge MOnitoring System) on the Europabrücke (since 1997) and the assessed prevailing vibration intensities with regard to fatigue problems and possible damage led to the installation of a permanent measuring system in 2003. Today's monitoring abilities enable us to measure performance precisely. High-precision sensor data of accelerations, velocities, displacements in dependence of separately registered wind and temperature data and their implementation into analytical calculation provide the possibility to realize lifetime considerations, which are of eminent importance for bridge operators.

Europabrücke, Innsbruck, Austria

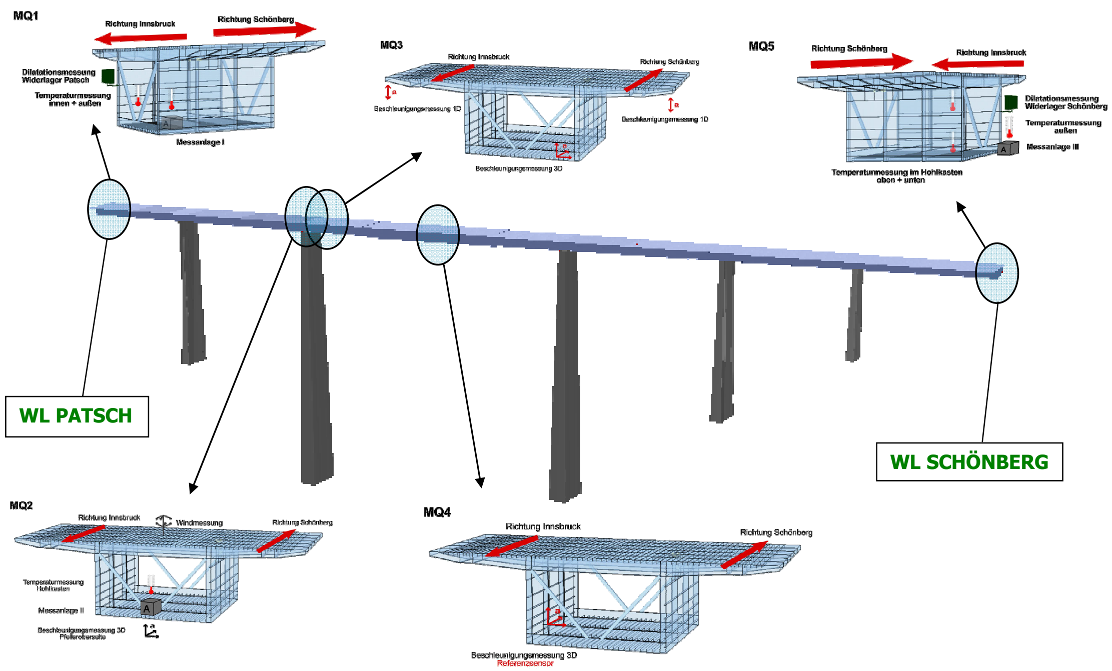
Description of Structure & Monitoring System

Previous measurements at the Europabrücke matched very well with the comparative analytical calculations, but they also exhibited the remarkable loading impact. Currently the bridge is stressed by more than 30000 motor vehicles per day (approximately 20% freight traffic). The superstructure is represented by a steel box girder (width = 10m; variable height along the bridge-length 4,70 – 7,70 m) and an orthotropic deck and bottom plate. This motorway bridge with six spans differing in their length (longest span 198m, supported by piers with an elevation of 190m) and a total length of 657 m comprises six lanes, three for each direction distributed on a width of almost 25 meters.

Quick Facts:

- **Name and Location:** Europabrücke, Innsbruck, Austria
- **Operator:** ASAG (Alpenstrassen AG), Austria
- **Structure category:** large span bridge
- **Spans:** 6 spans: 81/ 108/ 198/ 108/ 81/ 81 m
- **Structural system:** Steel box girder with orthotropic deck and concrete columns
- **Start of SHM:** May, 1998
- **Number of sensors installed:** 24
- **Instrumentation design by:** VCE, Vienna Consulting Engineers, Austria

The monitoring system itself consists of 24 measuring channels (sampling rate 100 Hz) representing the main span's, the pier's and the cantilever's accelerations, the abutment's dilatation, wind speed and direction, and temperatures at several locations.



Purpose of Inspection:

The superior goal is to determine the relation between the randomly induced traffic loads (vehicles per day) and the ***fatigue***-relevant, dynamic response of the structure. As life-time predictions in modern standards depend on lots of assumptions, the emphasis is to replace all these guesstimates by measurements. In that context it is going to be focused on three ranges:

- Global behavior in dependence of all relevant loading cases
- Cross-sectional behavior under special consideration of the cantilever regions
- Local systems analyzing the interaction between tires and the beam-slab connections

In each of these levels of analysis the consumption of the structure's overall-capacity per year is to be determined.

Additionally to fatigue assessment, new compensation methods for ***assessment & compensation of environmental conditions*** (temperature, additional mass loading,…) in frequency analyses are developed. This opens new possibilities for structural management and lifetime prediction as well as for more accurate damage detection.

Sensor Details:

Type of sensors	Number	Location
Displacement sensors	2	at both abutments
1D-acceleration transducers	3	at the cross section's cantilevers
3D-acceleration transducers	3	orthotropic bottom plate
Wind sensors	1	5m above the road surface
Temperature sensors	7	inside & outside the box girder

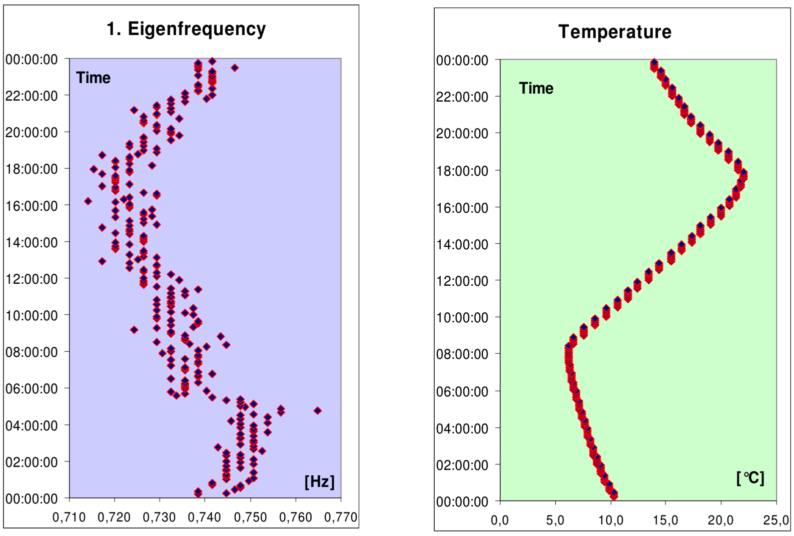
Measurement Equipment and Data Management:

Type of system	Data Management
PC & remote access - based measuring system	▪ automatic report generating at the end of each week ▪ Storage in a long term data base on site ▪ More detailed analysis (statistics, frequency analysis…) and graphical presentation and documentation in office ▪ notification via modem about the successful operation of the measuring system

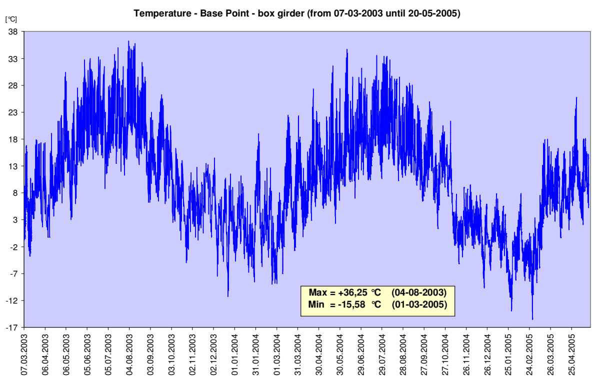
Data Analysis Procedures:

Type of analysis	Software	Additional features
Ambient vibration monitoring, Fatigue assessment based on rainflow analysis & statistics, assessment & compensation of environmental conditions, damage detection and lifetime calculations	Self made software, RFEM	▪ no expert system

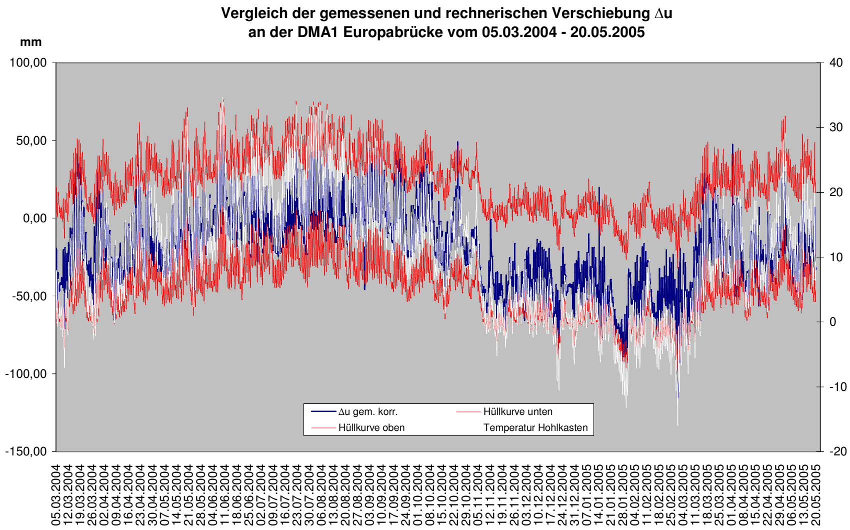
Examples of Outcomes
- Assessment & Compensation of Environmental Conditions



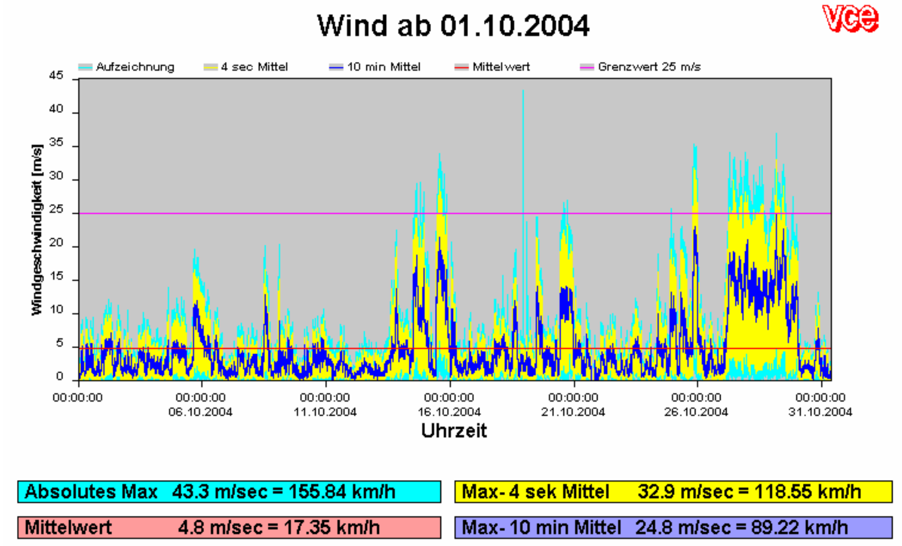
Pattern of the main span's stiffness and its obvious dependency on temperature (daily cycle)



Pattern of temperature at the bridge's basing point (assessment period 2 ½ years)

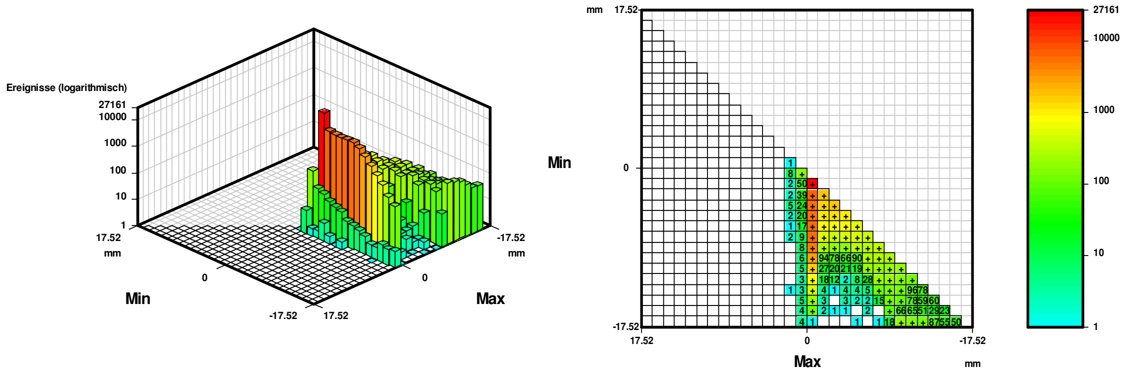


Comparison of assessed & expected horizontal bridge deformations in dependence of temperature

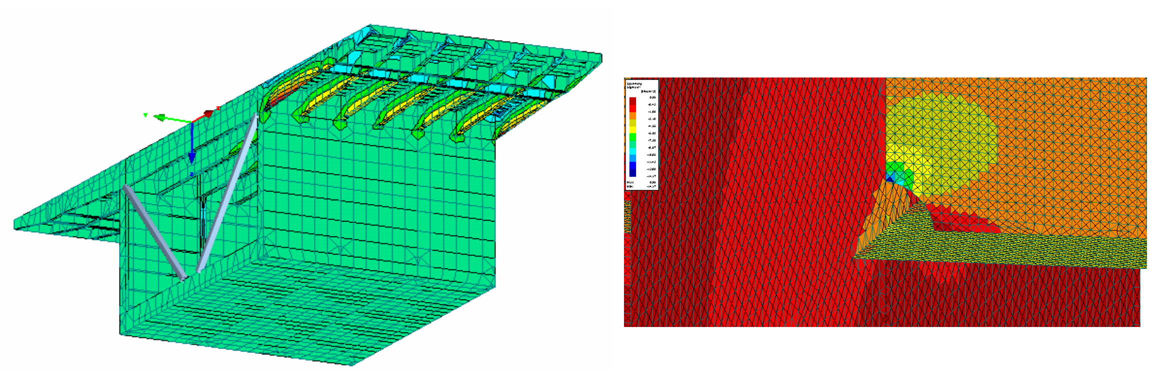


Wind velocity-analysis for a certain month

In each of the already described levels of **fatigue analysis** performed by means of Rainflow-Counting, damage-accumulation, global and local Finite Element Analysis & statistical consideration. The detailed knowledge about the progression of the prevailing traffic from the very beginning up to these days and the implementation of published future trend studies for the next ten years can be used for an extrapolation of the measured impact for the whole lifetime.



Rainflow Matrices for counting of recurring fatigue-relavant impact cycles



Damage assessment via implementation of measurements into Finite Element-Models

References

1. Wenzel, H., and D. Pichler. 2005. “Ambient Vibration Monitoring,” *J. Wiley and Sons Ltd.,* Chichester - England, ISBN 0470024305
2. Veit R., H. Wenzel and J. Fink. 2005. “Measurement data based lifetime-estimation of the Europabrücke due to traffic loading - a three level approach”, In International Conference of the International Institute of Welding. Prague.
3. H. Wenzel, R. Veit, H. Tanaka.: “Damage detection after condition compensation in frequency analyses” in “Proceedings of the 5th International Workshop on Structural Health Monitoring”, Stanford, September 2005

Submitted by:

Vienna Consulting Engineers (VCE)
A-1140 Vienna, Austria
60 Hadikgasse
Phone: +43(1) 8975339-1420
Fax: +43(1) 8975339-2420
Email: veit@vce.at

The New Årsta Railway Bridge - Sweden

Project Description:

The New Årsta Railway Bridge in Stockholm, Sweden, which is under construction at this very moment, will be opened for traffic in 2006. The bridge is part of the overall upgrading to four tracks, compared to today's two tracks on the old bridge, between Stockholm South and a new station called Årstaberg. The purpose of the extension is to increase track capacity. The structure is a very slender and complex prestressed concrete bridge without any ballast. Therefore, the Swedish National Railway Administration (Banverket) has initiated a measuring program to follow up and evaluate/verify stresses and deformations during construction and operation. Static and dynamic measurements/analyses are being conducted.

Data animation of the New Årsta Railway Bridge

Quick Facts:

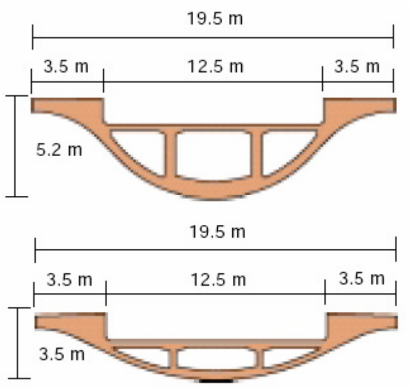
- **Name and Location:** The New Årsta Railway Bridge, Stockholm, Sweden
- **Owner:** The Swedish National Railway Administration (Banverket)
- **Structure category:** long span bridge
- **Spans:** 11 spans: 48/ 78/ 78/ 78/ 78/ 78/ 78/ 78/ 78/ 78/ 65 m
- **Structural system:** continuous prestressed concrete troughed-beam bridge
- **Start of SHM:** January, 2003
- **Number of sensors installed:** 86
- **Instrumentation design by:**
  - **Strain gauges:** Royal Institute of Technology (KTH), Department of Civil and Architectural Engineering, Division of Structural Design and Bridges
  - **Fibre optic sensors (SOFO system):** SMARTEC
- **Installations:** Most of the installation work was carried out by The Royal Institute of Technology (KTH) , Department of Civil and Architectural

Engineering, Division of Structural Design and Bridges

Description of Structure:

The bridge is 833 m long, 19,5 m wide and has ten piers with an elliptical cross-

section measuring 7 x 2,5 m. The pier height varies from 9 to 25 m. The rail carriageway is embedded in a trough with 1,2 m high parapets. Running along the left-hand side of the bridge is a pedestrian and cycle way, and on the eastern side there is a road for service and rescue vehicles. In order to reduce the weight of the bridge structure and to distribute forces the beam height is decreased by eliminating the ballast and embedding the rail fasteners directly in the concrete structure. The superstructure is built in two different ways. On the north side, the curved section of the bridge, use is made of conventional fixed scaffolding, whereas from the south, the straight section of the bridge, launching formwork is used and gradually advanced as each span is completed. The design was first produced by Foster/Aarup, but reworked twice. The final design was done by the Danish consult COWI A/S.



The slender design of the superstructure is thickest above the piers (upper figure) and tapers of towards the center of the span (lower figure)

Purpose of Inspection:

The aim is to verify uncertainties in the structure during construction and 10 years of service, leading to knowledge and perhaps updated codes, especially concerning dynamic effects. This will, in turn, give economical and safe solutions concerning similar structures in the future.

Static measuring:

- Verify that maximum strains and stresses are kept within permissible limits
- Check that no cracking occurs in critical sections, according to design
- Study changes in strain, both during construction and in service
- Compare results from fibre optic sensors with results from strain gauges

Dynamic measuring:

- Evaluate fundamental frequencies, mode shapes and damping ratios
- Evaluate dynamic effects of trains crossing the bridge, especially train/bridge interaction and effects of track irregularities
- Evaluate long-term changes in the bridge's dynamic properties

Sensor Details:

Type of sensors	Number	Location
Strain gauges	24	The figure below describes the locations
Accelerometers	6	
LVDT	1	
Fibre optic sensors	46	
Thermocouples	9	

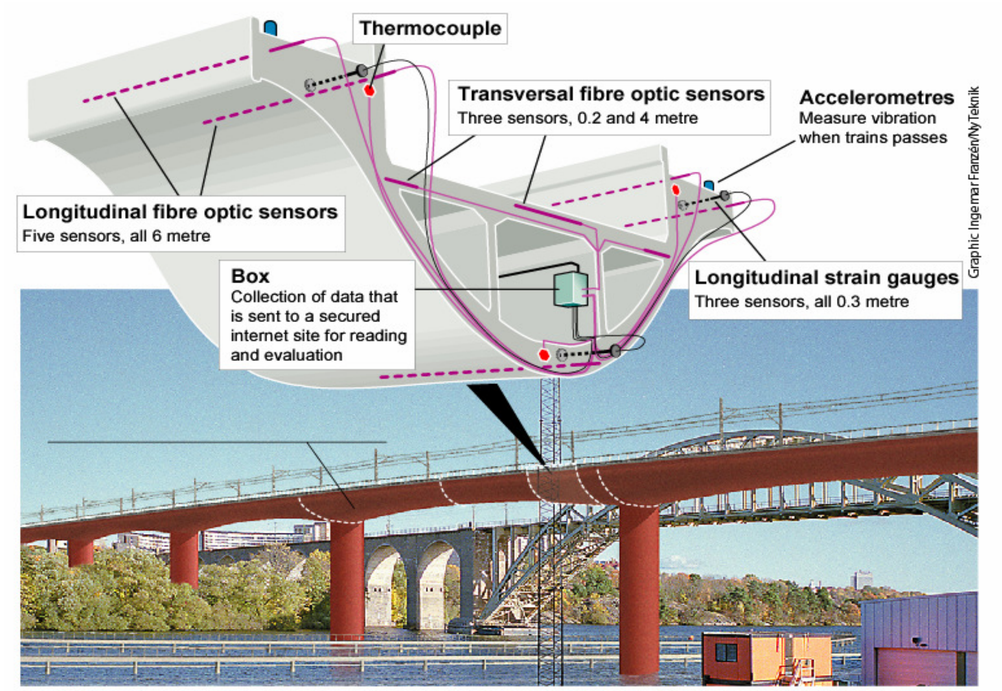


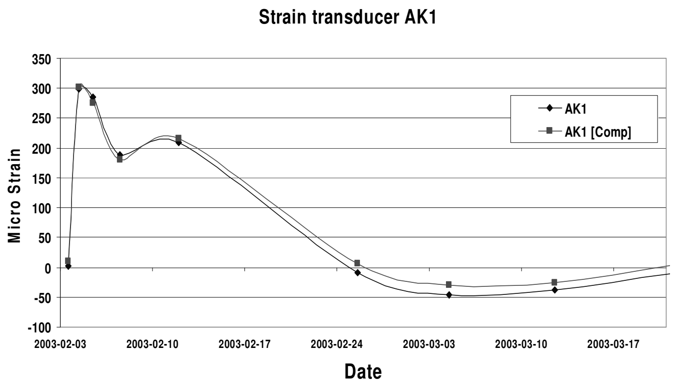
Illustration of one specific cross-section with sensors measuring strain, temperature and acceleration

Measurement Equipment and Data Management:

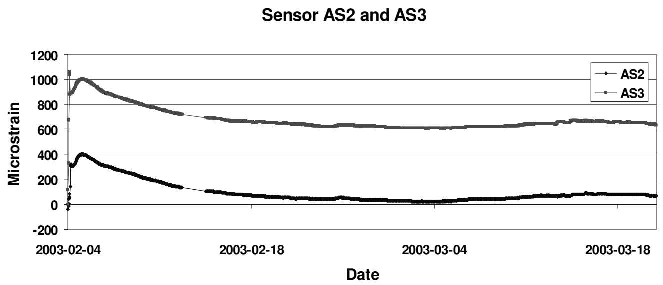
Type of system	Data Management	CMS
PC based measurement system	▪ data pre-analysis (statistics) on site ▪ main analysis, graphical presentation and documentation in office ▪ data transfer via broadband ▪ long term data base	?

Examples of Outcomes:

Only some early results are presented here and much more will be presented in a short time since more data acquisition and analysis work in the office has to be carried out before any further conclusions can be drawn.



Typical results from strain transducers during construction (casting).
One of the curves is temperature compensated.



Results from two different fibre optic sensors in a very early stage.

Benefits of Using SHM Technologies in the Project:

Since measurements are planned for the first 10 years of service it will be possible to, for example, detect long-term changes in the bridge's dynamic properties.

References:

M. Enckell-El Jemli, R. Karoumi, J. Wiberg, "Structural health monitoring for an optimised prestressed concrete bridge", Proceedings of **SHMII 2003**, Nov 13-15, 2003, Tokyo, Japan

M. Enckell-El Jemli, R. Karoumi, F. Lanaro, "Monitoring of the New Årsta Railway Bridge using traditional and fibre optic sensors", SPIE's Symposium on Smart Structures and Materials, NDE for Health Monitoring & Diagnostics, March 2-6, 2003, San Diego, California, USA

Swedish National Railway Administrator (Banverket), Eastern Track Region, "The new Årsta Bridge – a new railway bridge in Stockholm"

Ny Teknik, "Ingjutna sensorer håller koll på ny järnvägsbro" (In Swedish), May, 2003

Submitted by:

Ph.D. Student Johan Wiberg
Royal Institute of Technology (KTH)
Department of Civil and Architectural Engineering
Division of Structural Design and Bridges
100 44 Stockholm, Sweden
Phone: +46 8 790 64 93
Fax: +46 8 21 69 49
E-mail: johan.wiberg@byv.kth.se

The New Svinesund Bridge - Sweden

Project Description:

The world's largest bridge with a single arch is being built across the Ide Fjord at Svinesund. The bridge will form a part of the European highway, E6, which is the main route for all road traffic between Gothenburg and Oslo. The bridge is an elegant but structurally complicated bridge as it combines a very slender construction with a special structural form. Due to the uniqueness of design and the importance of the bridge a monitoring project was initiated by the Swedish National Road Administration (Vägverket). The monitoring project, including measurements during the construction phase, the testing phase, and the first 5 years of operation, is coordinated by The Royal Institute of Technology (KTH).
For more information, see the monitoring project homepage at http://www.byv.kth.se/svinesund/

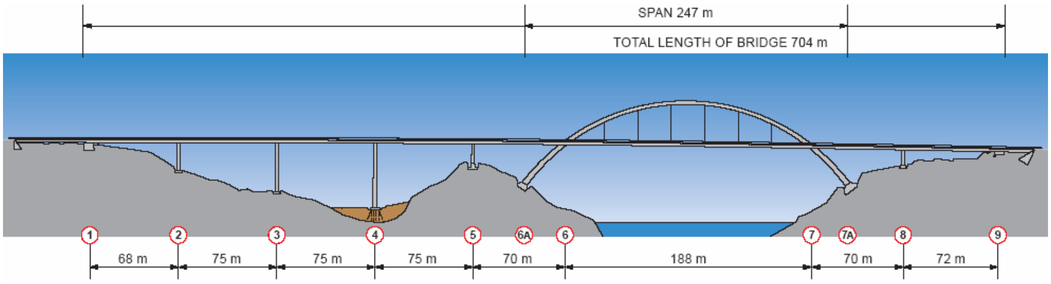
The New Svinesund Bridge - Sweden

Quick Facts:

- **Name and Location:** The New Svinesund Bridge, joining Sweden and Norway
- **Owner:** The Swedish National Road Administration (Vägverket)
- **Structure category:** Arch bridge
- **Spans:** main arch span of 247 m
- **Structural system:** 2 steel box girders suspended from a single concrete arch
- **Start of SHM:** June, 2003
- **Number of sensors installed:** 58 (68 when the bridge is completed)
- **Instrumentation design by:** KTH, division of structural design and bridges, Stockholm, Sweden

Description of Structure:

The New Svinesund Bridge is a highway bridge across the Ide fjord joining Sweden and Norway. The total length of the bridge is 704 m and consists of a substructure in ordinary reinforced concrete together with a steel box-girder superstructure. The main span of the bridge between abutments is approximately 247 m and consists of a single ordinary reinforced concrete arch which carries two steel box-girder bridge decks, one on either side of the arch. The level of the top of the arch and the bridge deck are +91.7 m and +61 m, respectively. Over the part of the bridge where the arch rises above the level of the bridge decking, the two bridge decks are joined by traverse beams positioned at 25.5 m centres. The traverse beams are in turn supported by hangers to the concrete arch.



Sketch of the New Svinesund Bridge in its entirety, showing grid-line numbering and approximate dimensions.

Purpose of Inspection:

The primary objective of the monitoring programme is to check that the bridge is built as designed and to learn more about the as-built structure. This will be achieved by comparing the measured structural behaviour of the bridge with that predicted by theory.

Sensor Details*:

Type of sensors	Number	Location
Vibrating-wire strain gauges	16	4 at arch base and 4 just below the bridge deck, Norwegian and Swedish side.
Resistance strain gauges	8	2 at arch base, 2 in a segment just below bridge deck, and 4 at the crown.
Linear servo accelerometers on concrete arch	4	installed pair-wise and are moved to new arch segments as construction of the arch progresses. When the arch is completed, 2 accelerometers will be moved to the arch mid point and 2 to the arch's Swedish quarter point.
linear servo accelerometers on bridge deck	6	3 at mid point and 3 at quarter point.
Temperature gauges	28	at the same sections as the strain gauges.
outside air temperature gauge	1	at arch base on Swedish side.
3-directional ultrasonic anemometer	1	for measuring wind speed and direction at deck level close to the first support on the Swedish side.
Load cells	2	monitor the forces in the first hanger pairs on the Swedish side.
LVDT	2	monitor transverse movement of the bridge deck at the first bridge pier supports on both sides of the arch.

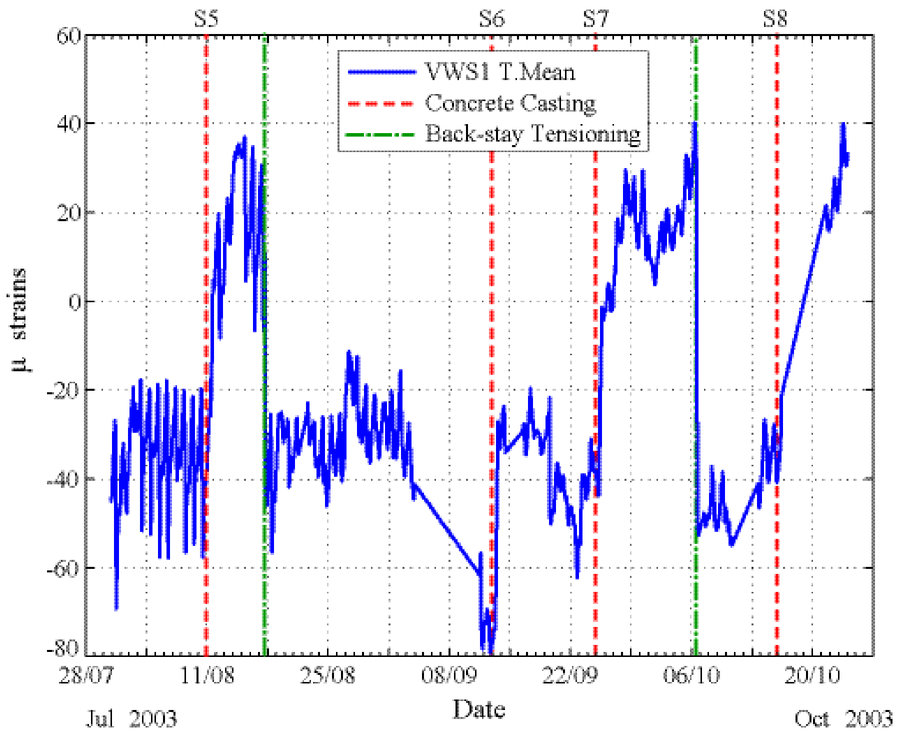
Measurement Equipment and Data Management:

The data acquisition system consists of two separate data sub-control units built up of basic MGC Digital Frontend modules from HBM (Hottinger Baldwin Messtechnik). The units are located at the base of the arch on respectively the Norwegian and Swedish side. The sub-control system on the Swedish side contains the central rack-mounted industrial computer and is connected with ISDN telephone link for data transmittal to the computer facilities at KTH for further analysis and presentation of data. The logged data on the Norwegian side is transmitted to the central computer on the Swedish side via a radio Ethernet link.

The selected logging procedure provides sampling of all sensors continuously at 50 Hz with the exception of the temperature sensors which have a sampling of once per 20 seconds or 1/20 Hz. At the end of each 10 minutes sampling period, statistical data such as mean, maximum, minimum and standard deviation are calculated for each sensor and stored in a statistical data file having a file name that identifies the date and time period when the data was recorded. Raw data, taken during a 10 minutes period, is stored in a buffer if the “trigger” value for calculated standard deviation for acceleration is exceeded.

Examples of Outcomes:

The figure below show the strains measured at the roof of a segment close to the arch base on the Swedish side. The casting of each subsequent segment causes an elongation of the reinforcement bars. This is to be expected as the arch behaves as a cantilever and the extra weight at the end of the structure caused by the newly cast arch segments will cause tension in the top of the section at the base of the arch. In a similar manner, tensioning the support cables, represented by the green dot-dashed lines, causes a contraction of the same reinforcement bars.



This figure show how the work on site is mirrored by the measured strains. The casting dates for segments are represented by dotted red lines. Segment numbers are shown at the top of the figure. The dates when tensioning of support cables occurred are shown in green.

Benefits of Using SHM Technologies in the Project:

See purpose of inspection.

References:

Gerard James and Raid Karoumi, "Monitoring of the New Svinesund Bridge, Report1: Instrumentation of the arch and preliminary results from the construction phase", TRITA-BKN. Rapport 74, Brobyggnad 2003, ISSN 1103-4289, ISRN KTH/BKN/R--74--SE, Royal Institute of Technology (KTH), Stockholm.

This report will soon be available on the monitoring project homepage at http://www.byv.kth.se/svinesund/

Submitted by:

Dr. Raid Karoumi
Royal Institute of Technology (KTH)
Divison of Structural Design and Bridges
SE-100 44 Stockholm, Sweden
Phone int.: +46 8 7909084
Fax int.: +46 8 216949
Email: raid.karoumi@byv.kth.se

Øresund Bridge – Denmark / Sweden

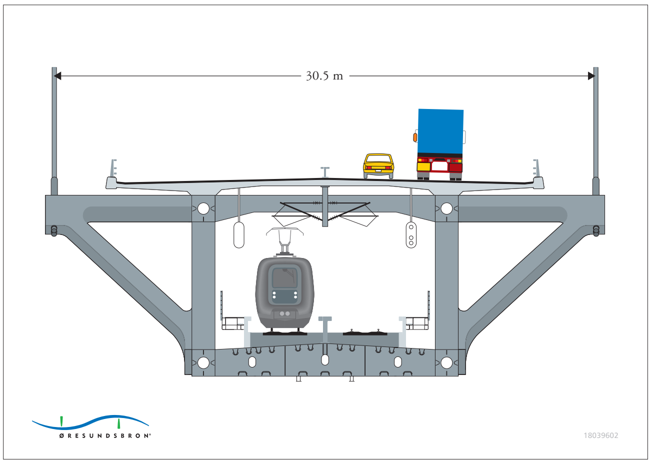
Project Description:

The Øresund Bridge opened in July 2000. It is the most striking part of the fixed link across the Øresund connecting Copenhagen (Denmark) and Malmø (Sweden), which further includes a tunnel and an artificial island. The bridge owner was concerned about the stay cable oscillations under heavy wind conditions, as well as the deformation of the bridge when trains or heavy trucks are passing.

Quick Facts:

- **Name and Location:** Øresund Bridge – Denmark/Sweden
- **Owner:** Øresundsbro Konsortiet (www.oeresundsbron.com)
- **Structure category:** cable-stayed bridge
- **Spans:** 49 approach spans (7 spans of 120 m, 42 spans of 140 m) and a cable-stayed component with 2 side spans at each side (160 m and 141 m) and a main span of 490 m over the navigational channel
- **Structural system:** The bridge has a quite unique two-level design, with a four-lane motorway placed above a two-track railway. 10 Pairs of cables at each side are connecting the pylons of the two H-shaped towers with the bridge deck.
- **Start of SHM:** July 2000
- **Number of sensors installed:** 55
- **Instrumentation design by:** GeoSIG, Zürich, Switzerland

Description of Structure:



Purpose of Inspection:

The bridge owner was concerned about the stay cable oscillations under heavy wind conditions, as well as the deformation of the bridge when trains or heavy trucks are passing. On a daily basis, the monitoring system is mainly used to record events and archive the data. As research cooperation In the frame of the SAMCO network, the dynamic cable data was used to identify the cable tension forces and the deck/tower vibrations were used to identify the structural modal parameters of the bridge.

Sensor Details*:

Type of sensors	Number	Location
Strain gauges LV3400VS0	19	Twelve strain gauges are mounted on 3 steel outriggers of the cables, one on each side. Two are mounted on the rail level in the concrete and five are mounted on the lower side of the bridge. These sensors are mainly observing torsions due to heavy wind and railway traffic.
Triaxial force balance accelerometers AC-53	22	Most of these accelerometers (16) are mounted on the stay cables to measure the cable vibrations. The 2 tops of the east pylons are also equipped with accelerometers, as well as 4 locations along the deck. These sensors allow monitoring the cable vibrations under heavy wind load and the bridge response to railway and road traffic.
Thermometers Pt100	12	mounted on different locations, but mostly at the pylons. These sensors are measuring temperatures, which are correlated with the strain gauge measurements.
Weather stations	2	measuring wind speed, wind direction (1172T), air humidity and air temperature (RHA1). One is mounted on the top of a pylon, the

other at road level. The wind measurements serve as a reference for the stay cable vibrations. The air humidity and temperature complete the meteorological information.

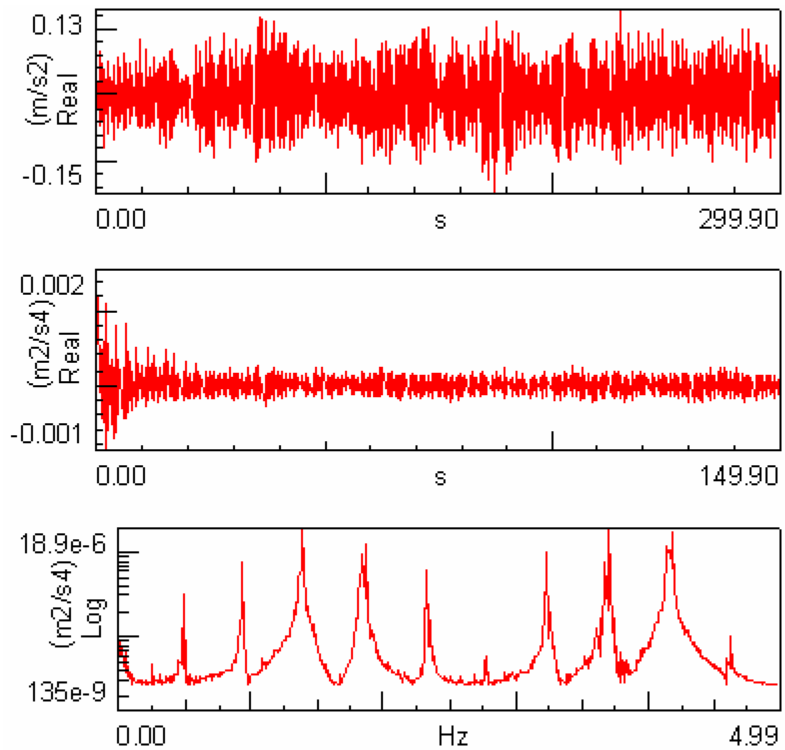
Measurement Equipment and Data Management:

Type of system	Data Management	CMS
PC based measurement system	• SEISLOG controls the CR-4 system and acquires data from the DSP boards. • CENTRAL provides the interface for remote access to the CR-4 systems. • CMS (Civil Monitoring System) processes the static data acquired by the system.	y

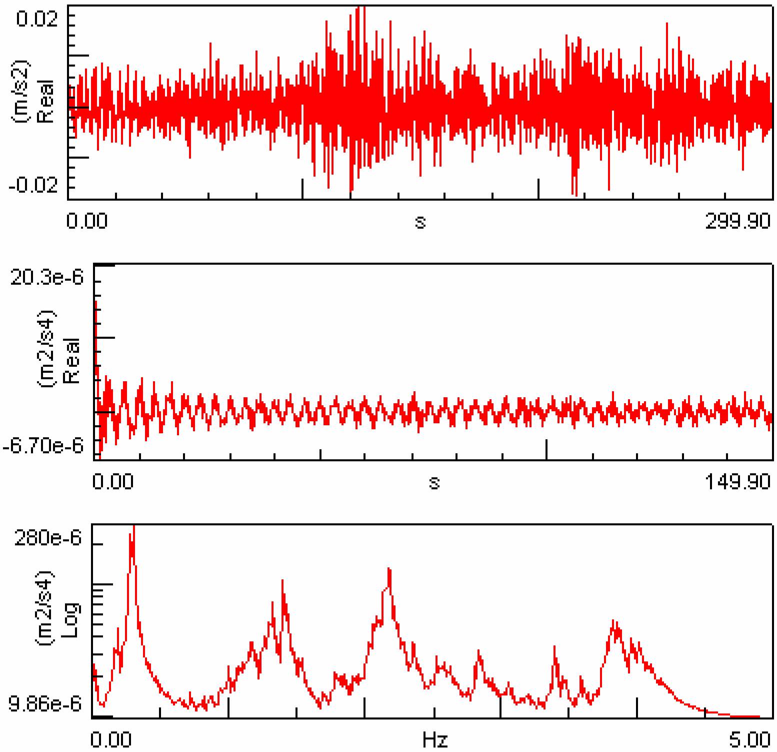
Data Analysis Procedures:

Type of analysis	Software	Additional features
Current status, statistics, alarm if out of range.	GeoSIG software	
Operational Modal Analysis	LMS International software	

Examples of Outcomes:



Dynamic data analysis of cable vibrations: Time history, auto-correlations, auto spectrum.



Dynamic data analysis of tower vibrations: Time history, auto-correlations, auto spectrum

References:

PEETERS B., COUVREUR G., RAZINKOV O., KÜNDIG C., VAN DER AUWERAER H., AND DE ROECK G. Continuous monitoring of the Øresund Bridge: system and data analysis. In *Proceedings of IMAC 21*, Kissimmee (FL), USA, February 2003.

Submitted by:

Bart Peeters
LMS International
Interleuvenlaan 68
B-3001 Leuven
Tel: +32 16/384 200
Fax: +32 16/384 350
E-mail: bart.peeters@lms.be

Tsing Ma Bridge – Hong Kong (PRC)

Project Description:

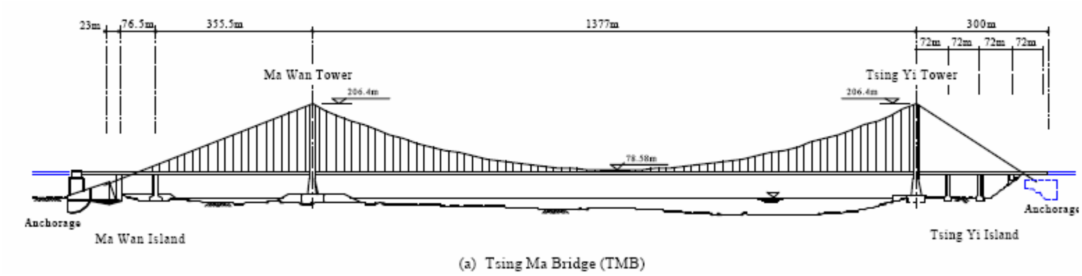
The Tsing Ma Bridge (TMB) is the longest suspension bridge (2.2 km) in the world for carrying both vehicle and railway traffic. The TMB is a double deck bridge. The upper deck has two three-lane highways for vehicle traffic. The sheltered lower deck includes two railway tracks and two single-lane emergency roadways for maintenance and ensuring uninterrupted traffic from/to the Hong Kong International Airport during typhoons when wind speed is still within acceptable level. Besides the existing conventional sensors, Fiber Bragg Grating sensors are installed by the Photonics Research Centre of the Hong Kong Polytechnic University to measure vibration, strain distribution and suspension cable tension.

Quick Facts:

- **Name and Location:**, Tsing Ma Bridge, Hong Kong, China
- **Structure category:** Suspension bridge (two main suspension cables)
- **Main span:** 1377 mm (two high-strength concrete towers)
- **Overall length:** 2.2 km
- **Main cable:** 1.1 m in diameter
- **Shipping clearance:** 62 m
- **Number of sensors:** > 350

Description of Structure:

The Tsing Ma Bridge is a double deck suspension bridge having a fully suspended main span supported by two portal-braced, reinforced-concrete towers. The bridge deck is suspended from two main cables passing over the main towers and secured into massive concrete anchorages at each end. The bridge deck section, 41 m wide and 7.5m high, is a hybrid arrangement combining both longitudinal trusses and cross-frames. The main span deck and the Ma Wan side span deck are suspended at 18m intervals by hangers to the main cables, while the Tsing Yi side span deck is supported by three concrete piers spaced at 72m.



Tsing Ma Bridge (TMB)

Purpose of Inspection:

The sensors are the early warning system for the TMB and provide the essential information that help the Hong Kong Highways Department to accurately monitor the general health conditions of the bridge, in terms of structural durability, reliability and integrity. The sensors include strain gauges, GPS position sensors, accelerometers, level sensors, temperature sensors and weight-in-motion sensors.

This project is focused on the application of Fiber Bragg Grating for strain measurement and the comparison with conventional strain gauges.

Sensor Details:

Type of sensors	Number	Location
FBG strain sensor	10	Metal structure of Section 23
FBG temperature sensor	1	Metal structure of Section 23
FBG strain sensor	9	Rocker bearing on tower
FBG temperature sensor	1	Rocker bearing on tower
FBG strain sensor	1	Suspension cable

Measurement Equipment and Data Management:

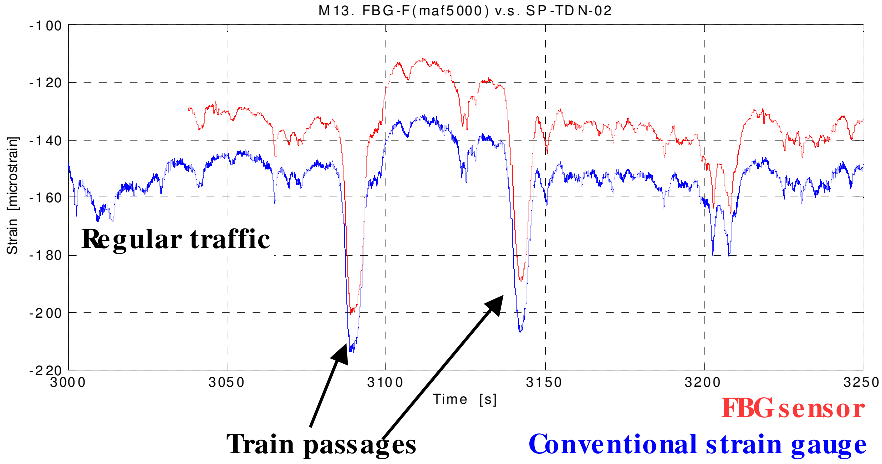
Type of system	Data Management
TNO high-speed dense-channel demultiplexing / interrogation system for FBG sensor array	▪ Data logging ▪ Main analysis (statistic, frequency analysis), graphical presentation and documentation in office

Data Analysis Procedures:

Type of analysis	Software
Statistics, frequency analysis	Self made software

Examples of Outcomes:

The results of the FBG sensor are compared with that of the existing strain gauge. Although the sensors are not located at exactly the same location, great resemblance in the results has been found. Train passages and heavy traffics can clearly be measured.



Comparison of strain measurement between FBG sensor and existing strain gauge.
An artificial off-set is applied to the FBG sensor signal.

Benefits of Using SHM Technologies in the Project:

- Providing information to determine distribution of strains/stresses in critical bridge components
- Documenting abnormal loading incidents such as typhoons, earthquakes, traffic overloads and ship collisions with bridge piers
- Detecting damage or accumulated damage in critical bridge components
- Providing information for a cost-effective maintenance program

References:

CHENG L.K. ET AL., "DYNAMIC LOAD MONITORING OF THE TSING-MA BRIDGE USING A HIGH-SPEED FBG SENSOR SYSTEM", SUBMITTED TO THE 2ND EUROPEAN WORKSHOP ON STRUCTURAL HEALTH MONITORING.

Submitted by:

L.K. Cheng
TNO TPD
Division Optical Instrumentation
Stieltjesweg 1
2628 CK Delft
The Netherlands
Phone : +31 15 269 2000
Fax : +31 15 269 2111
Email : cheng@tpd.tno.nl

Highway Bridge BW 91, Germany

Project Description:

The highway-bridge BW91 is part of the highway A2 between Hannover and Berlin, Germany. The bridge crosses the Mittellandkanal near Braunschweig. It was opened in 2003 as a three-lane-bridge.

BW91 near Braunschweig, Germany

Quick Facts:

- **Name and Location:** BW91 (highway-bridge) near Braunschweig, Germany
- **Owner:** Bundesrepublik Deutschland
- **Structure category:** composite bridge
- **Spans:** 1 span: 56,26m
- **Structural system:** Steel box girder with deck as an composite construction
- **Start of SHM:** January 2003
- **Number of sensors installed:** 15
- **Instrumentation design by:** University of Technology CAROLO WILHELMINA at Braunschweig, Institute of Steel Structures, Braunschweig, Germany

Description of Structure:

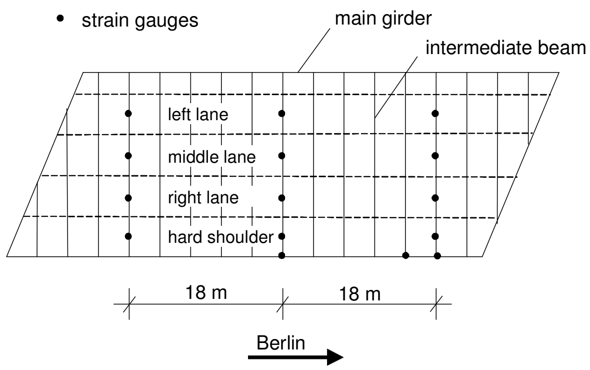
The superstructure comprises of two steel box girders and a deck as an composite construction. The intermediate beams of the composite construction have a spacing of 3.60 m, the width of the bridge is 20 m.
There are two units of this bridge, one for each direction.

Purpose of Inspection:

Due to the central position of the bridge BW91 the validity area of the measured weights of the vehicles and their distribution in the flow of traffic covers a large number of other bridges of the Highway A2. Beside this, the measurements are carried out to obtain the strains at critical details. The measurements are carried out within the collaborative research center SFB 477 ´Life Cycle Assessment of Structures via Innovative Monitoring´ (www.sfb477.tu-braunschweig.de).

Sensor Details:

Type of sensors	Number	Location
Strain gauges	15	at 3 intermediate beams (spacing: 18 m) underneath each lane including the hard shoulder



Measurement Equipment and Data Management:

Type of system	Data Management	CMS
PC based measurement system	▪ data pre-analysis (statistics) on site ▪ main analysis, graphical presentation and documentation in office ▪ long term data base due to permanent monitoring	

Data Analysis Procedures:

Type of analysis	Software	Additional features
WIM, statistics, rain flow analysis, changes in traffic density	Self made software	▪

Example of Outcome:

The calibration of the sensors was carried out by use of a 30 to truck. According to the specification of the COST 323 - Project the measuring system has an accuracy class of D+(20).

Benefits of Using SHM Technologies in the Project:

Due to permanent monitoring long-term changes in the flow of traffic can be observed.

References:

Peil, U., Frenz, M.: Lebensdauervorhersage von ermüdungsbeanspruchten Bauwerken durch Monitoring und begleitende Versuche *Arbeitsbericht 2000-2003 des SFB 477, Beitrag TP B3, Schriftenreihe des SFB 477, 2003, S. 37-60* (in German)

Submitted by:

Institute of Steel Structures
Prof. Dr.-Ing. Udo Peil
Dipl.-Ing. Matthias Frenz
University of Technology at Braunschweig
Beethovenstraße 51
D-38106 Braunschweig, Germany
Phone: +49(531) 391-3373
Fax: +49(531) 391-4592
Email: m.frenz@tu-bs.de

Herrenbrücke Bridge Lübeck - Germany

Project Description:

The Herrenbrücke crossing the river Trave (see Fig. 1) was built between 1962 and 1964. A new building, a tunnel, is under construction, and will be finished 2006. The Herrenbrücke bridge should remain in service up to that time. The highways department of the city Lübeck assigned a consultant engineer for a statement, which has to assess the life cycle of the bridge up to the year 2006.

Herrenbrücke Bridge, Lübeck, Germany

Quick Facts:

- **Name and Location:** Herrenbrücke Bridge, Lübeck, Germany
- **Owner:** City of Lübeck, Germany
- **Structure category:** bascule bridge with 2 medium span foreland bridges
- **Spans:** 18 spans 19.4 m
- **Structural system:** prestressed concrete orthotropic deck, reinforced columns, steel bascule
- **Start of SHM:** October, 2000
- **Number of sensors installed:** 34
- **Instrumentation design by:** TU Braunschweig, Institute for Building Materials, Structural Concrete and Fire Protection,Germany

Description of Structure:

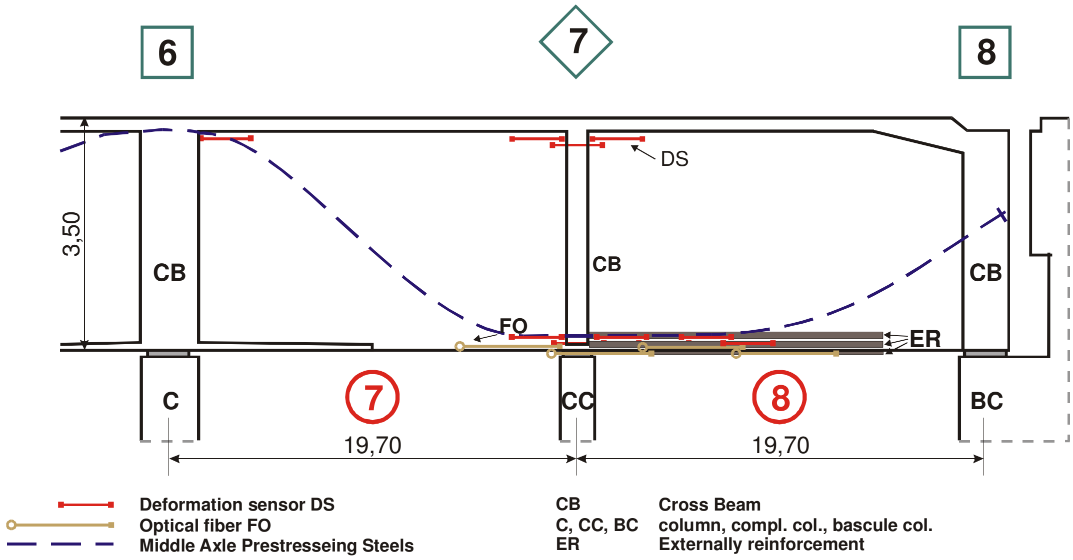
It consists of two side spans made from prestressed concrete (approx. 153 m and approx. 311 m long) as well as a balance bridge made from steel (approx. 86 m long). The bridge shows signs of corrosion damage, which is attributed to poor working quality in grouting the tendons. Tendon failure is assumed to account for up to 45%. Repair measures were executed thereupon.

Purpose of Inspection:

From the point of view of the consultant engineer, a life cycle assessment of this bridge is not yet possible on the basis of today's level of knowledge regarding its state of condition only. Therefore SHM systems had to be installed to monitor displacements and deformations of the bridge

Sensor Details*:

Type of sensors	Number	Location
LDVT	29	
Fibre Optic sensors	5	Foreland bridge
PT 100	15	



Instrumentation plan

Measurement Equipment and Data Management:

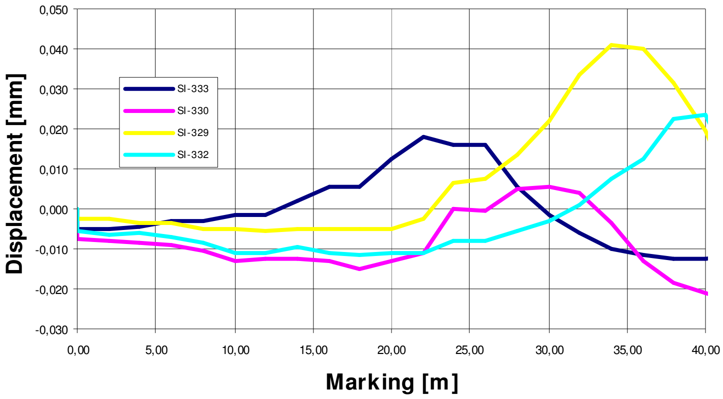
Type of system	Data Management	CMS
PC based measurement system	▪ data pre-analysis (statistics,frequency analysis) on site ▪ main analysis, graphical presentation and documentation in office ▪ data transfer via modem ▪ long term data base	

Data Analysis Procedures:

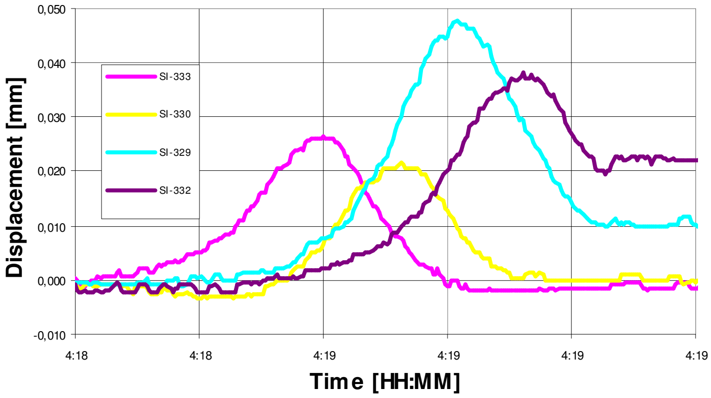
Type of analysis	Software	Additional features
Statistics, ambient analysis,	Self made software + MATLAB	▪

Examples of Outcomes:

Static as well as dynamic measurements are possible.



static measurement



dynamic measurement

Benefits of Using SHM Technologies in the Project:

The available measurement data allow the definition of threshold values regarding maximum traffic within a defined temperature range in order to assess the crack risk due to tendon failure.

References:

Karim Hariri, Harald Budelmann: Monitoring of the Bridge Herrenbrücke in Lübeck: Motivation, Procedures, Results and Data Evaluation in 2nd European Workshop on Structural Health Monitoring, July 7-9, 2004, Munich, Germany

Submitted by:

TU Braunschweig, Institute for Building Materials, Structural Concrete and Fire Protection,Germany
D-38106 Braunschweig, Germany
Beethovenstraße 52
Phone: +49(531) 391-5487
Fax: +49(531) 391-8179
Email: K.Hariri@tu-bs.de

St. Marx Bridge - Vienna

Project Description:

The St. Marx Bridge in Vienna, Austria, built from 1973 to 1978, is located between the Danube-Canal and the Traffic Node Landstrasse. The bridge is counted among one of the most frequented partitions of the A23-South-East-Highway. The total traffic volume averages about 240,000 motor vehicles per day, whereas an increase of the ratio of heavy loads is detected as well. This leads to an enormous loading of the bridge structure. As a consequence thereof the serviceability of the expansion joints and the bridge bearings is affected. Thus, in order to detect the passing heavy loads, which cause damage, a structural health-monitoring system in combination with a video control system have been installed in 1998. Furthermore, the remaining structural service life can be predicted as well.

St. Marx Bridge, Vienna, Austria

Quick Facts:

- **Name and Location:** St. Marx Bridge, Vienna, Austria
- **Operator:** MA 29 (Bridge Maintenance by Magistrate of City Vienna)
- **Structure category:** multiple span bridge; total length L = 2.70 km
- **Spans:** 54 column sets und 24 expansion joints between single bridge girders
- **Structural system:** prestressed and reinforced concrete box girder
- **Start of SHM:** November 1998
- **Number of sensors installed:** 4×accelerometer, 1×temperature sensor
- **Instrumentation design by:** VCE – Vienna Consulting Engineers, Austria

Description of Structure:

The substructures of consideration, namely TW4 respectively TW5, with a total length of 205.10m represent a 7-spans continuous beam with 29.30m span length respectively. The cross section, however, comprises three lines which with a width of 3.25m, whereas the total width is 12.88m. The construction type is prestressed concrete box girder with dimensions 1.96×4.50m.

Purpose of Inspection:

On the basis of a permanent analysis of the dynamic structural behavior possible issues to be considered are as follows:

- Determination of passing heavy loads causing structural damage;

- Verification respectively update of the existing numerical load models;
- Determination of the overall load configurations and vibration coefficients, whereas wind and temperature effects are considered optionally;
- Consideration of long-term trends with respect to the life loads by means of statistics;
- Monitoring of the structural loading capacity and serviceability by means of structural identification.

Sensor Details:

Type of sensors	Number	Location
Accelerometers	4 channels at 2 sensors per substructure	At the box girders of the spans 1 and 2 (at $0.6 \times L_{Span}$ from the span beginning)
PT100	1 at substructure TW5	At the box girder of the first span (at the beginning)

Measurement Equipment and Data Management:

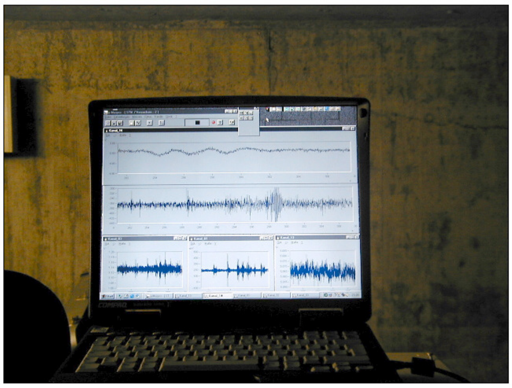
Type of system	Data Management	CMS
PC based measurement system	• Data pre-analysis (statistics, system identification) • Main analysis, graphical presentation and documentation in office • Data transfer via modem • Long term data base	y

Data Analysis Procedures:

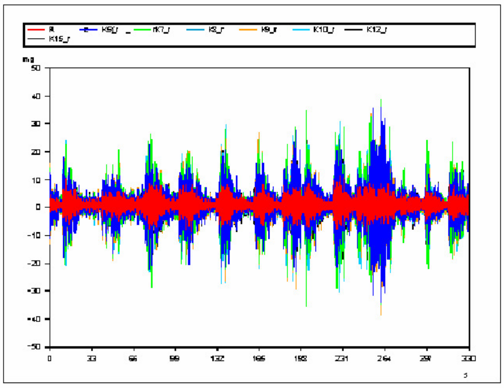
Type of analysis	Software	Additional Features
Time domain and frequency domain SI, statistics, damage detection, FEM – update, life time prediction	Self made software, Octave 2.1.50, RSTAB 5.13.042, ANSYS 5.3	No expert system

Examples of Outcomes:

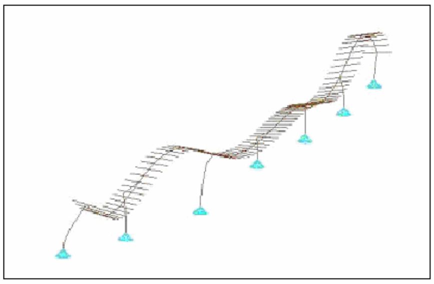
Using the obtained accelerations time-history data system identification is carried out by time domain as well as frequency domain methods. In general the observed bridge structure is characterized by a distinct dynamic behavior. Therefore a long-term Structural Health Monitoring is very well applicable. The implemented statistic analysis showed a relevant influence of the heavy loads. Environmental effects, e.g. wind induced vibrations and temperature influence, are recognized as well. Additionally, in order to simulate the structure numerically and to detect damage Finite Element Model Update is applied.



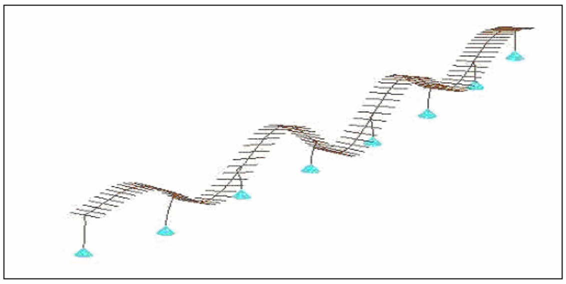
Deformation and acceleration signals during test phase



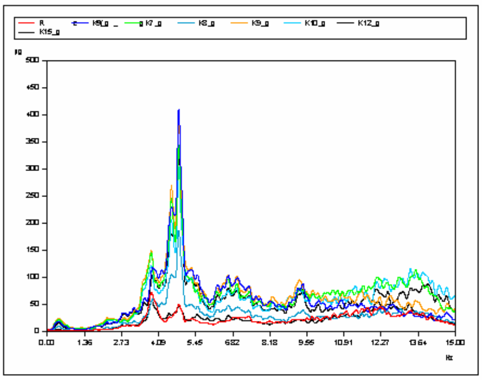
Vertical acceleration signal: all sensors



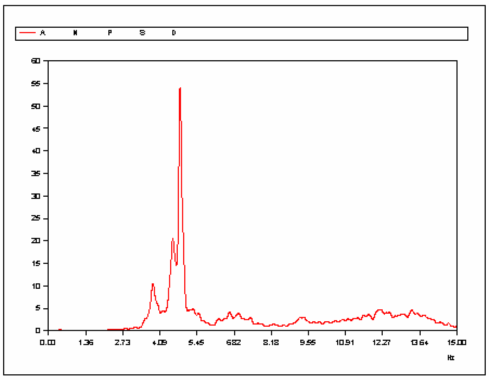
First vertical mode shape of TW4



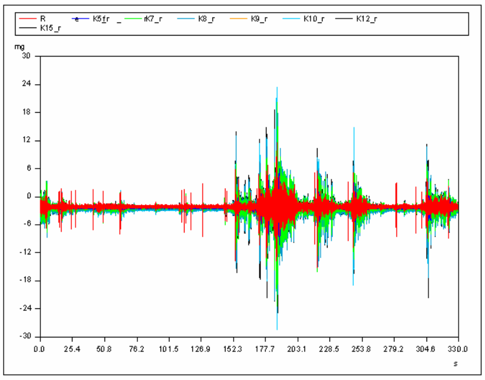
First vertical mode shape of TW5



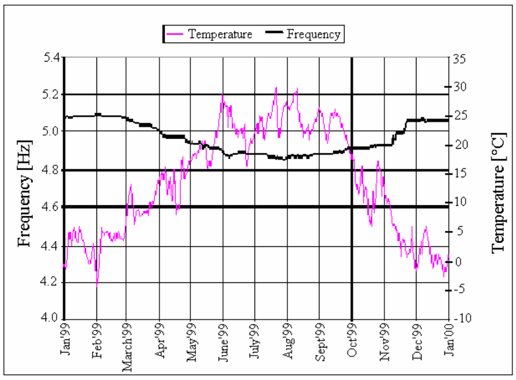
Spectral analysis: all sensors



ANPSD



Vertical acceleration due to crossing at time instant 150 sec



Temperature – frequency relationship vehicle over 1999

Benefits of Using SHM Technologies in the Project:

The Structural Health Monitoring allows the real-time observation and the life time prediction of civil engineering structures. Therefore, using the SHM technique is linked with enormous cost effectiveness for the structural maintenance.

Submitted by:

Vienna Consulting Engineers (VCE)
A-1140 Wien
Hadikgasse 60
Phone: +43(1) 8975339
Fax: +43(1) 8938671
Email: vce@atnet.at

Taichung Bridge - Taiwan

Project Description:

The Taichung Bridge, opened in 2003, is a Cable stayed bridge for urban traffic located in Taichung in the middle of Taiwan. Due to the requirement to assess the cable forces, the global state of the structure and the dynamic behavior of the pylon base a Permanent Monitoring System have been installed in 2003.

Taichung Bridge, Taiwan

Quick Facts:

- **Name and Location:** Taichung Bridge; Taichung, Taiwan
- **Operator:** BPI Taiwan
- **Structure category:** Cable stayed bridge
- **Cables:** 44
- **Spans:** 2 spans: 89.5 / 89.5 m
- **Height of the Pylon:** 80 m
- **Structural system:** Steel girder with orthotropic deck
- **Start of SHM:** November, 2003
- **Number of sensors installed:** 15
- **Instrumentation design by:** VCE - Vienna Consulting Engineers, Austria

Description of Structure:

The Taichung Bridge is a Stay Cable Bridge with 44 cables and a total length of 189 m which comprises four lanes and two small lanes for pedestrians and bicycles. The superstructure is represented by steel girders and an orthotropic deck.

Wind Sensor at Taichung Bridge, Taiwan

Purpose of Inspection:

The Permanent Monitoring System gives an overview about the global behavior of the bridge structure and supplies the actual cable forces. The system consists of following parts, which are monitored:

- Dynamic determination of the cable forces of 8 selected cables
- Measuring of temperature, wind speed and wind direction
- Dynamic measurement of the main girders and the pylon top
- 3-dimensional measurement of the pylon base

Sensor Details:

Type of sensors	Number	Location
Acceleration transducers	8	at 1 cable each
Velocity transducers	3	at the main girders
3 dimensional Acceleration transducer	1	at pylon base
Wind sensor	1	5m above the road surface
Temperature sensors	2	inside & outside the box girder

Measurement Equipment and Data Management:

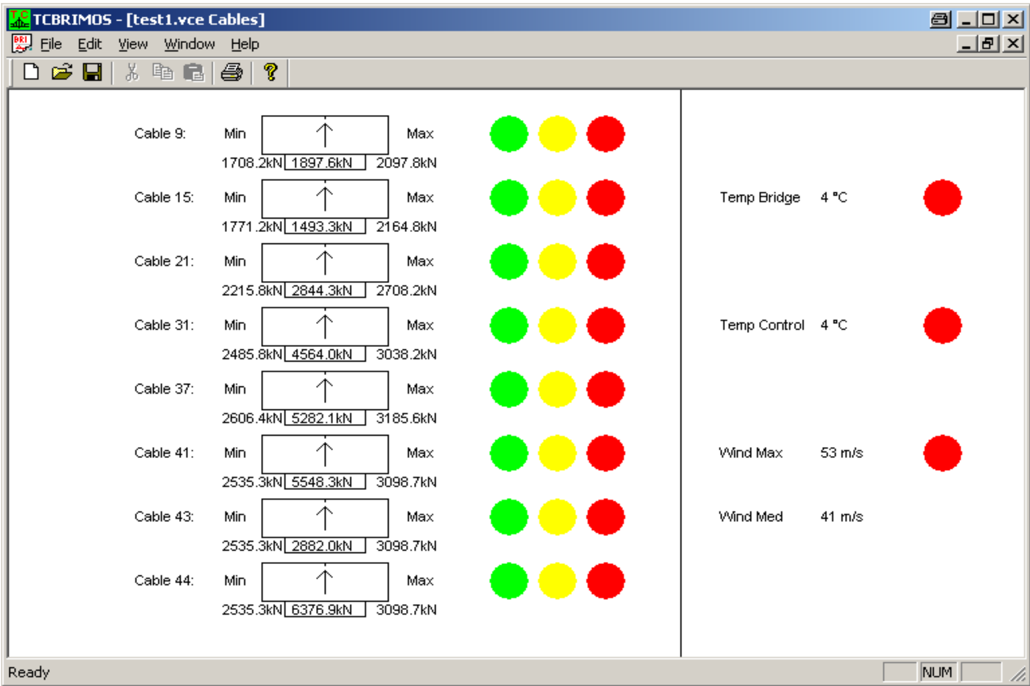
Type of system	Data Management
PC & stand alone - based measuring system	▪ Storage in a long term data base on site ▪ Analysis (statistics, frequency analysis…) and graphical presentation and documentation in office ▪ controlling of the successful operation of the measuring system via modem

Data Analysis Procedures:

Type of analysis	Software	Additional features
Ambient analysis, calculation of cable forces and lifetime calculations	Self made software	▪ no expert system

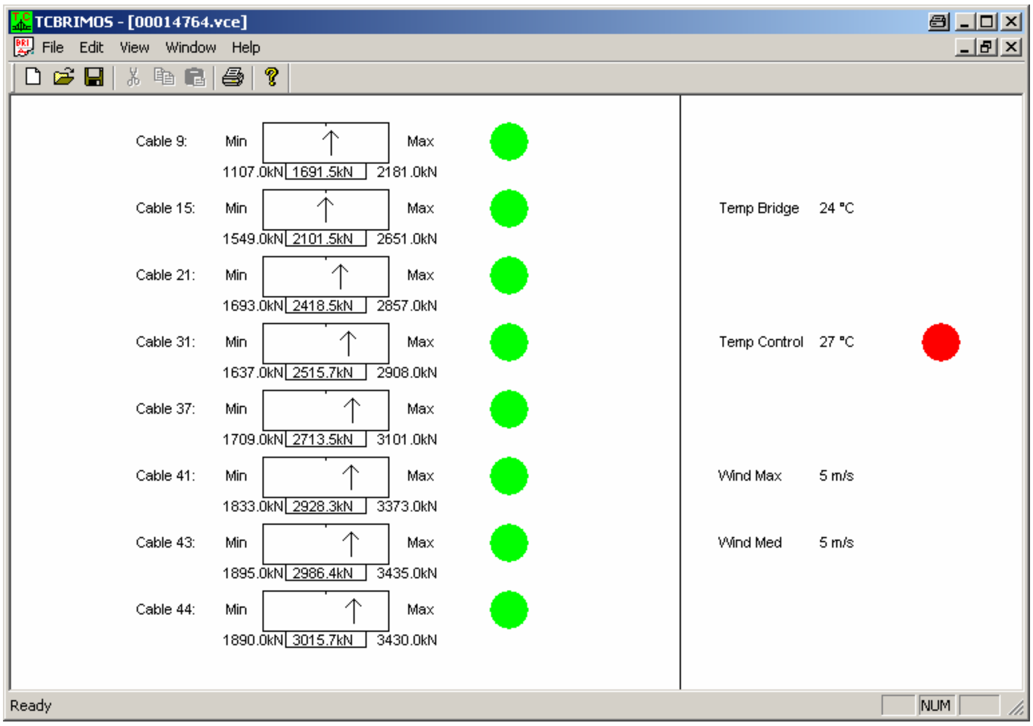
Examples of Outcomes:

The Permanent Monitoring System at Taichung Bridge measures vibration, temperature and wind. The self-made software supplies the cable forces of 8 selected cables in the way that the client can easily check the status of the cable forces in the form of a light.



Theoretical output of the Monitoring System

The green light shows immediately that all cable forces are all right.



Real Output of the Permanent Monitoring System

Benefits of Using Permanent Measuring System in the Project:

The ability to merge high-precision sensor data of accelerations and velocities in dependence of separately registered wind and temperature data provides the possibility to realize lifetime considerations, which are of highest importance for bridge operators.

Submitted by:

Vienna Consulting Engineers (VCE)
A-1140 Vienna, Austria
Hadikgasse 60
Phone: +43(1) 8975339
Fax: +43(1) 89386071
Email: vce@atnet.at

A14 Huntingdon Railway Viaduct

Project Description:

The A14 Huntingdon Railway Viaduct is part of the Cambridge to Kettering section of the A14 dual carriageway. The structure has been the subject of a Special Inspection that indicated the presence of voids, water and chlorides in the tendon ducts, but no significant corrosion of the strands. A SoundPrint® acoustic monitoring system, designed by Pure Technologies Ltd of Canada was installed to monitor tendon wire break activity in one of the cantilevers.

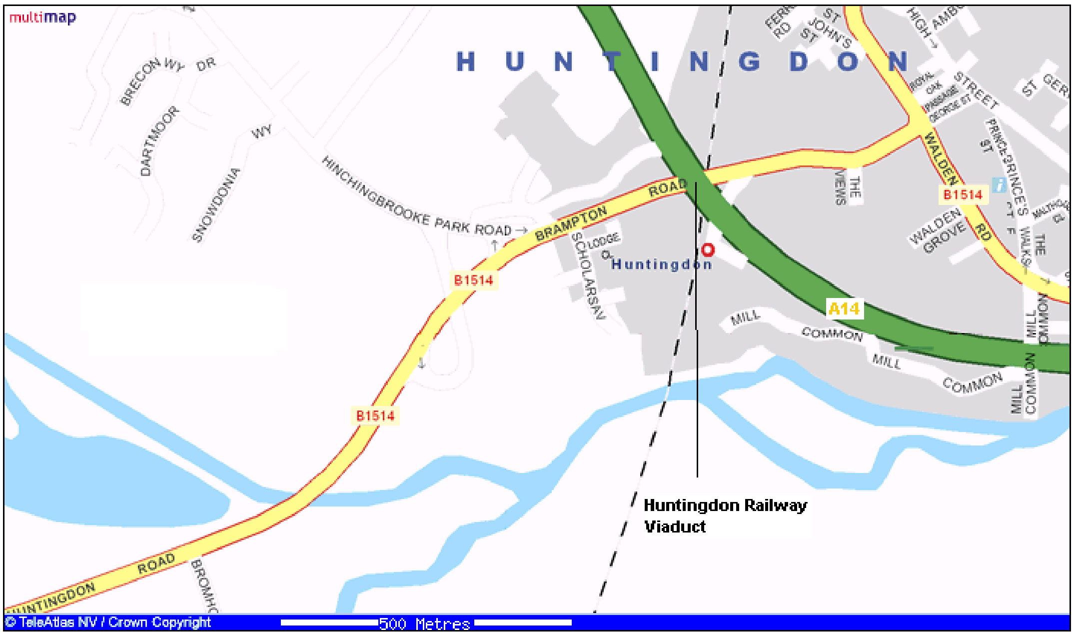
Huntingdon Railway Viaduct, England

Quick Facts:

- **Name and Location:** Huntingdon Railway Viaduct, Cambridgeshire, England
- **Owner:** Highways Agency, England
- **Structure category:** Medium span bridge
- **Spans:** 6 spans: 32.3/ 32.3 / 32.3/ 64.3/ 32.3/ 32.3m
- **Structural system:** Six span structure of which span 4 consist of two 16.15m cantilever sections and a 32.0m suspended span.
- **Start of SHM:** Mid 1998
- **Number of sensors installed:** 36
- **Instrumentation design by:** Pure Technologies Ltd, Calgary, Canada

Description of Structure:

The structure has six spans; the main span consists of a 32m long suspended span sat on half joints formed at the end of two 16m long cantilevers extending from the adjacent piers. The viaduct spans the B1514, the East Coast Main Line and part of Huntingdon railway station.



Location of Huntingdon Railway Viaduct

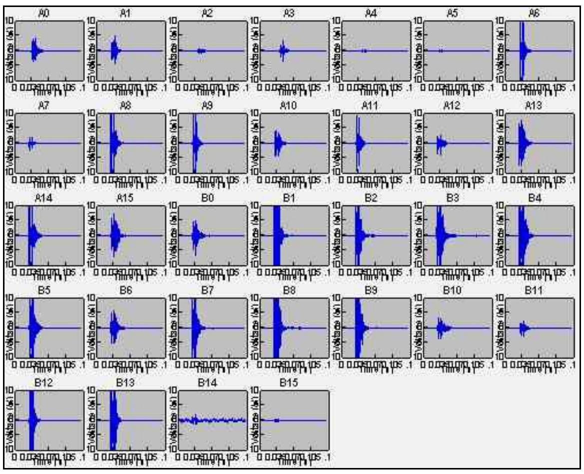
Purpose of Inspection:

Special Inspection indicated the presence of voids, water and chlorides in the tendon ducts. The SoundPrint® acoustic monitoring system has been installed to monitor tendon wire break activity in one of the cantilevers. The structure possessed further features that made it a good candidate for acoustic monitoring.

- Additional structural investigations were in progress. This would be enhanced by a clear indication of the presence or absence of actively fracturing wires.
- The structure contained features that lent themselves to monitoring, such as difficult to inspect half joints.
- The structure occupies a strategic position on the network and carried a high volume of HGV traffic.

Examples of Outcomes:

The probability of a tendon wire break occurring in the structure is very low so an external wire break device was installed on the structure to check the operation of the monitoring system.



Typical acoustic response from externally mounted wire break device

Benefits of Using SHM Technologies in the Project:

The SoundPrint® acoustic monitoring system at Huntingdon has been in operation since mid 1998. It has provided an excellent opportunity for confronting challenges in detecting and locating post-tensioned wire breaks in noisy environments, and establishing the protocols needed to ensure the success of long-term, continuous, unattended monitoring. The viaduct has not experienced any naturally-occurring wire breaks during monitoring, although the conditions for corrosion are present. To test the monitoring system, external wire breaks have been artificially created and detected in blind trials.

References:

Cullington D W, MacNeil D, Paulson P and Elliot J (1999). Continuous acoustic monitoring of grouted post-tensioned concrete bridges. A paper presented at the 8th International Structural Faults and Repair Conference, London, 13th June 1999.

Submitted by:

TRL Limited
Old Wokingham Road
Crowthorne
Berkshire
RG45 6AU
England
Phone: +44(1344) 773131
Fax: +44(1344) 770356
Email: enquiries@trl.co.uk

ESK551 Bridge – Bad Bevensen / Germany

Project Description:

The bridge 551 of the country road 232 Bad Bevensen – Altenmedingen leads across the Elbe – Seiten – Canal and was built in the beginning of the 1970s. It is a threebay prestressed concrete bridge with bearing distances of 32,05 – 66,40 – 32,05 m; as a result of manufacturing defects it has relatively severe flexures. Considering only the loading condition of dead load, the structure already shows bending cracks in the midspan.

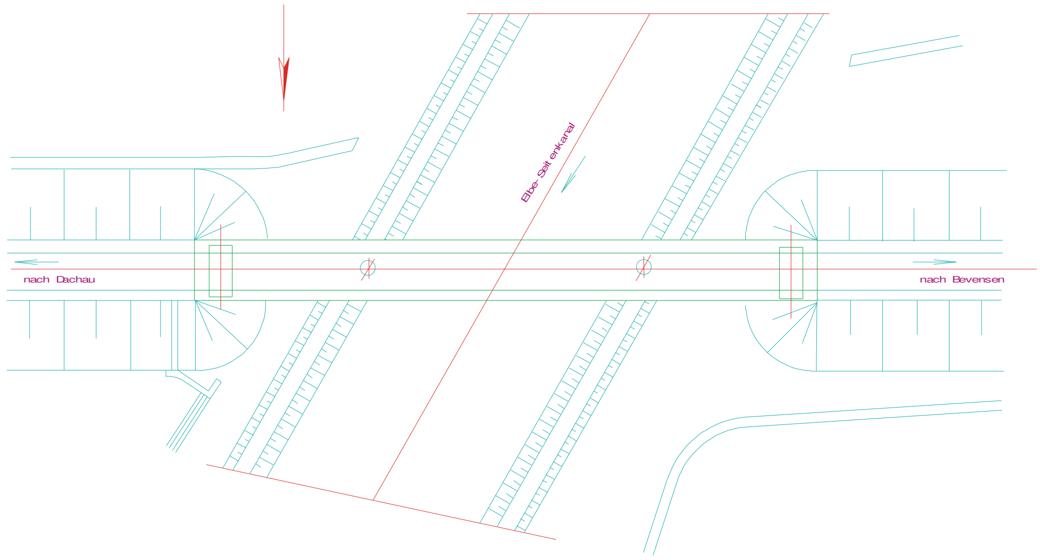
ESK 551 Bridge, Bad Bevensen, Germany

Quick Facts:

- **Name and Location:** ESK 551 Bridge, Bad Bevensen, Germany
- **Owner:** Bundesamt für Wasserbau, Germany
- **Structure category:** prestressed concrete bridge
- **Spans:** 3 spans: 32,05 / 66,40 / 32,05 m
- **Start of SHM:** 1996 / 1999
- **Number of sensors installed:** 21
- **Instrumentation design by:** BAW Karlsruhe; Bauhaus University Weimar, Infokom GmbH Neubrandenburg, Germany

Description of Structure:

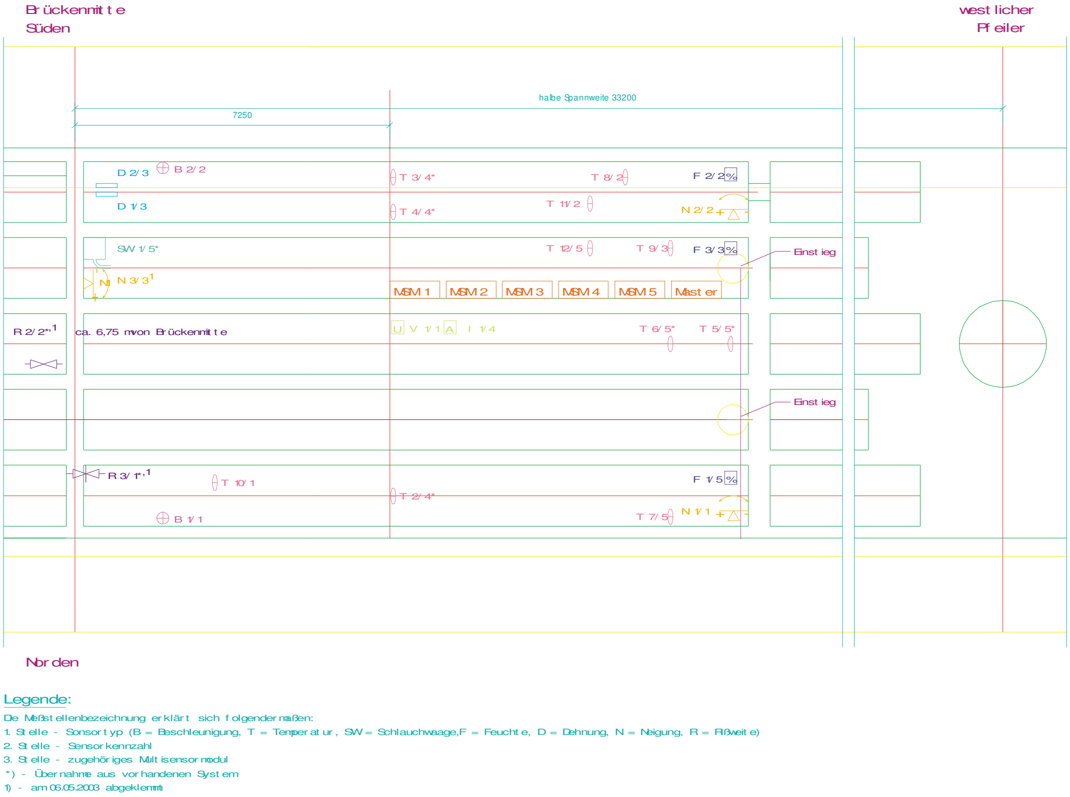
see above



site drawing

Purpose of Inspection:

Monitoring of the structural deformation as a result of general climatic variations as well as the individual deformation during vehicle crossings.



plan of measurement locations

Sensor Details*:

Type of sensors	Number	Location
electronically scanned hydrostatic tube balance	1	see plan of measurement locations
inductive displacement transducers (crack width)	2	
inductive displacement transducers (expansion)	2	
humidity pickup sensors	2	
PT100	6	
acceleration sensors	2	
inclination sensors	2	

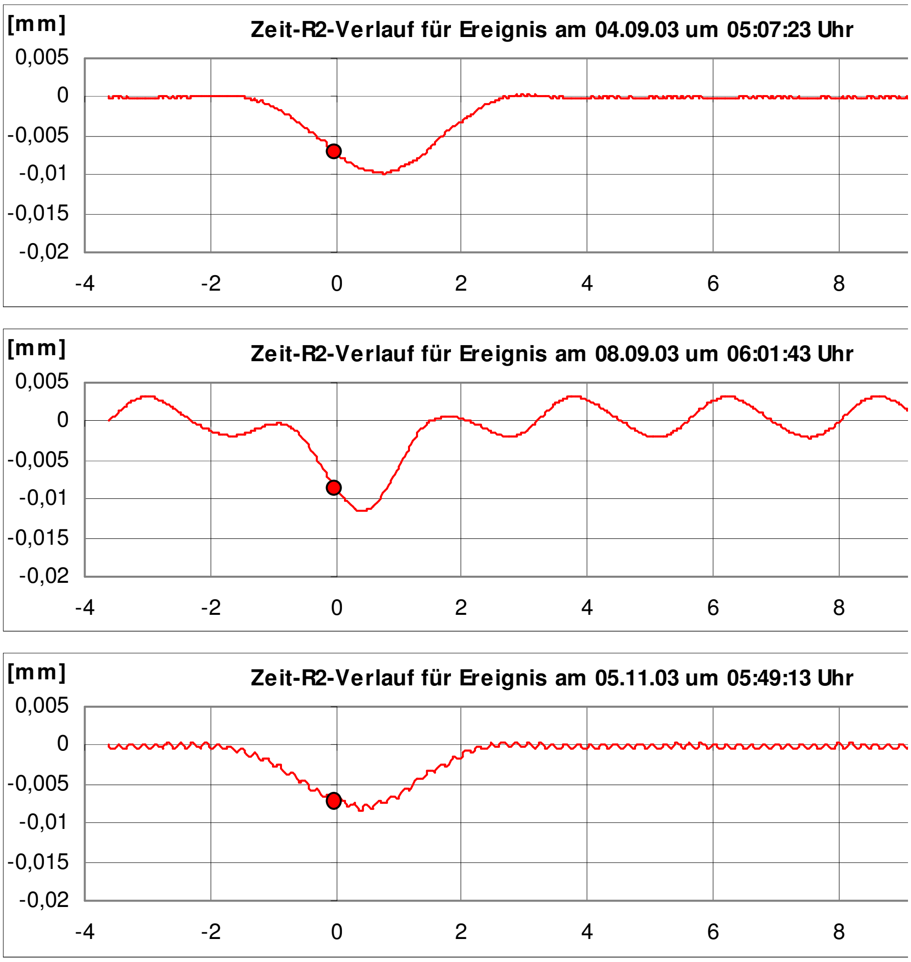
Measurement Equipment and Data Management:

Type of system	Data Management	CMS
mikrocontroller based stand-alone measurement system	▪ main analysis, graphical presentation and documentation in office ▪ data transfer via modem ▪ long term data base	

Data Analysis Procedures:

Type of analysis	Software	Additional features
statistics, general monitoring of the reformation after an incident	self made software	▪ adjustable trigger levels for different alert phases ▪ no expert system

Examples of Outcomes:



dynamical incidents at the same displacement transducers

Benefits of Using SHM Technologies in the Project:

- Solar power supply continuously showed to be problematic during the winter months. Measurement was just occasionally possible. By means of spontaneous shutoffs of the solar collector calibrations and measurement data were partly corrupted.
- The system works extensively stable. Failures were only noticed at some components.
- All along several years reproducable as well as comparable deformations of the load-bearing structure were located. Therefore the system was temporary closed down at the end of 2003 and reopened in 2005.

Submitted by:

Infokom GmbH
17034 Neubrandenburg, Germany
8 Johannesstraße
Phone: +49(395) 430-52-34
Fax: +49(395) 430-52-49
Email: TBolle@infokom.de

I40-Bridge, New Mexico, USA

Project Description:

The I40-Bridge over the Rio Grande was part of the Highway "Interstate 40" in New Mexico. In the 1960's and 1970's over 2500 bridges were built in the U.S. with a design similar to this on Interstate 40. These bridges were built without structural redundancy and typically had only two plate girders carrying the loads. Failure of either girder was assumed to produce catastrophic failure of the bridge; hence these bridges were referred to as fracture-critical bridges. The US-Federal Highway Administration (FHWA) and the National Science Foundation (NSF) have provided funds for evaluation and testing of the existing fracture critical bridges over the Rio Grande. The investigation was conducted by the structural dynamics group around Dr. C.R. Farrar of the Los Alamos National Laboratories.

After a modal analysis of the undamaged bridge, it has been damaged artificially in different states where all scenarios have been chosen to reproduce observed damage in the field. The test data has been made available for the scientific community and so the bridge tests could be used as benchmark for testing structural damage assessment methods at a full scale structure.

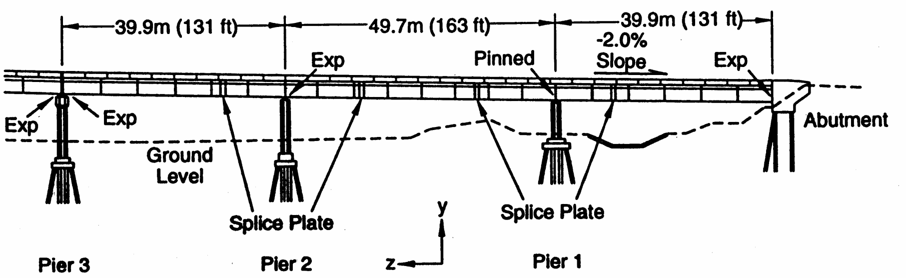
I40-Bridge, New Mexico, USA

Quick Facts:

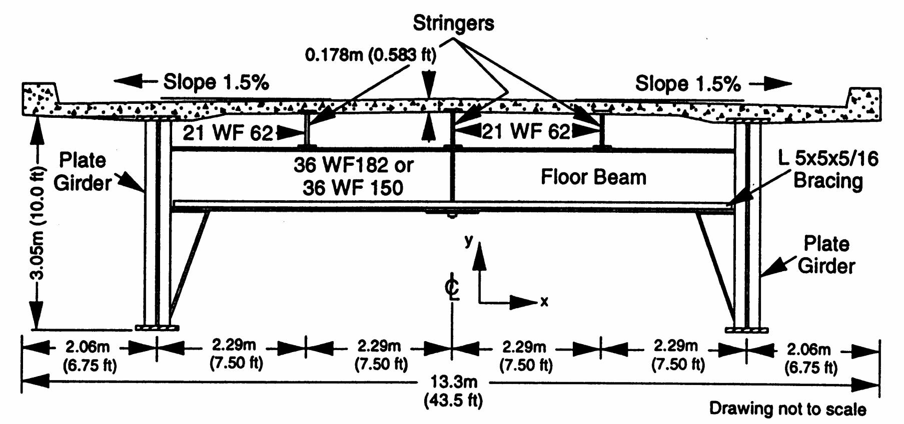
- **Name and Location:** I40-Bridge, Rio Grande, New Mexico, USA
- **Owner:** State of New Mexico
- **Structure category:** large span bridge
- **Spans:** 9 spans: 39.9/ 49.7/ 39.9/ 39.9/ 49.7/ 39.9/ 39.9/ 49.7/ 39.9 m
- **Structural system:** Steel box girder with concrete deck and concrete columns
- **Start of SHM:** September, 2001
- **Number of sensors installed:** 26
- **Instrumentation design by:** Los Alamos National Institute, USA

Description of Structure:

The I40-bridge consisted of two separate spans for each traffic direction divided in three identical, structural nearly independent sections, respectively. Each section was made up of three spans, see Fig. “Elevation view” which shows one section. The bridge was made up of a concrete deck supported by two plate girders and three steel stringers. The loads from the stringers were transmitted to the plate girders by floor beams, see Fig. “Cross section of the bridge”.



Elevation view of the bridge



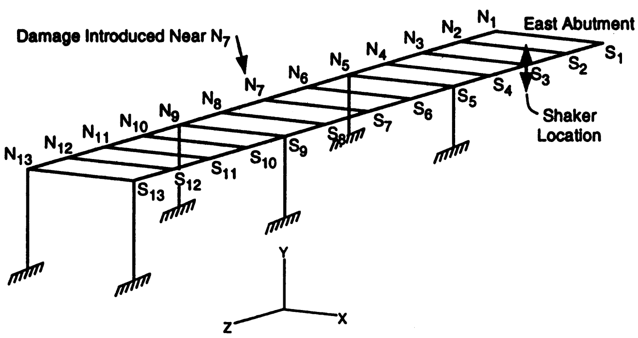
Cross section of the bridge

Purpose of Inspection:

The purpose of the measurement was to detect the applied damage based on measured modal data and model based damage detection algorithms.

Sensor Details:

Type of sensors	Number	Location
Acceleration	26	N1-S13, see Figure below
Force	1	Shaker, see Fig. below

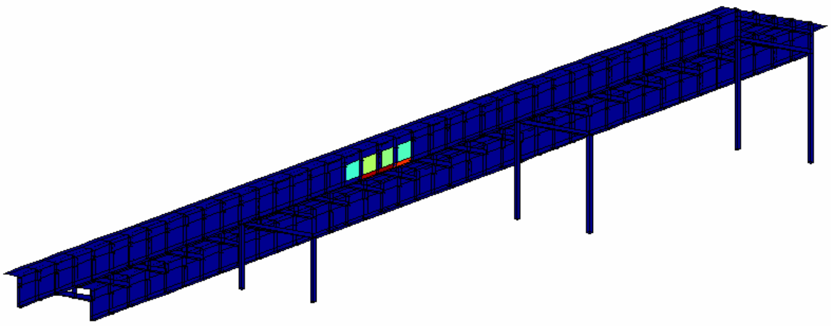


Data Analysis Procedures:

Type of analysis	Software	Additional features
Modal Analysis by means of FRFs, Excitation by shaker		

Examples of Outcomes:

The damage could be detected, localized and quantified by means of an inverse eigensensitivity approach and Frequency Response Function (FRF) approach (alternatively) combined with parameter selection and regularization techniques.



Benefits of Using SHM Technologies in the Project:

The occurrence of damage can be detected immediately. A lot of lessons learned lead to optimized model updating and damage detection algorithms.

References:

Fritzen, C.-P., Bohle, K., "Model-Based Health Monitoring of Structures – Application to the I40-Highway-Bridge", Proc. Identification in Engineering Systems IES99, Swansea, UK, 1999, pp. 492-505.

Fritzen, C.-P.; Bohle, K.: "Identification of Damage in Large Scale Structures by Means of Measured FRFs - Procedure and Application to the I40-Highway-Bridge", Key Engineering Materials Vols. 167-168, 1999. pp. 310-319.

Farrar, C.R. et al., "Dynamic Characterization and Damage Detection in the I40-Bridge Over the Rio Grande", Los Alamos National Laboratory, Report No. LA-12767-MS, 1994.

Submitted by:

Institute of Mechanics and Automation Control-Mechatronics
University of Siegen
D-57068 Siegen
Paul-Bonatz-Str. 9-11
Phone +49(271)740-4621
Fax: +49(271)740-2769
Email: fritzen@imr.mb.uni-siegen.de

Steelquake Structure – JRC, Ispra, Italy

Project Description:

The “Steelquake” structure corresponds to a two-story frame as depicted in the figure below. It was investigated during the European COST F3 action as benchmark example to compare different damage identification algorithms at the European Joint Research Center JRC in Ispra, Italy. The main dimensions are 8m x 3m x 9m. The stories are a composite of corrugated steel sheets supporting a concrete slab having orthotropic elastic characteristics. The stories are connected by welded vertical steel columns and horizontal steel beams. The structure can be interpreted as a module of a high-rise building, which has been loaded via shakers to simulate an earthquake-like loading. During this loading, damage (cracks) occurred at several locations which had to be detected.

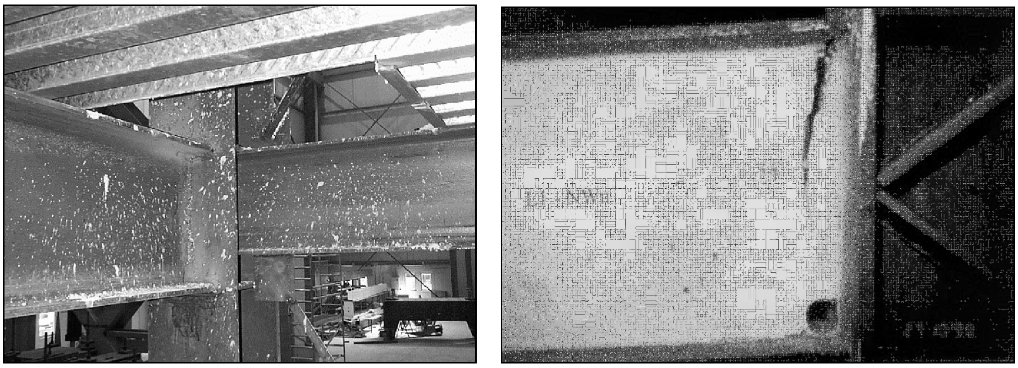
Steelquake Structure, European JRC, Ispra, Italy

Quick Facts:

- **Name and Location:** Steelquake Structure
- **Owner:** JRC, Ispra, Italy
- **Structure category:** two story frame building
- **Dimensions:** 8x3x9 m
- **Structural system:** Steel frame with stories made of concrete slabs
- **Start of SHM:** 1998
- **Number of sensors installed:** 15
- **Instrumentation design by:** JRC, Ispra, Italy

Description of Structure:

The main dimensions are 8m x 3m x 9m. The stories are made of corrugated sheets supporting a concrete slab, forming a composite with orthotropic elastic characteristics, and are connected by welded vertical and horizontal steel girders. The vertical steel girders were stiffened up by cross bracings in the plane parallel to the wall. In the background the reaction wall can be observed which supports the 4 pistons (not present in the photo) that will deform the structure (on each frame, on each story). There are several standard profiles of steel girders in use. The columns consist of HE300B, the stories of IPE400 on the long side and IPE300 on the short side. Bracings are made of L60x30x5 profiles.



Details (left) and crack after “steelquake”

Purpose of Inspection:

The benchmark was performed for testing and further enhancement of damage detection algorithms in the frame of the European COST F3 Action.

Sensor Details*:

Type of sensors	Number	Location
Accelerometers	15	at the main girders and the orthotropic concrete slab
Force	1	Hammer test

Measurement Equipement and Data Management:

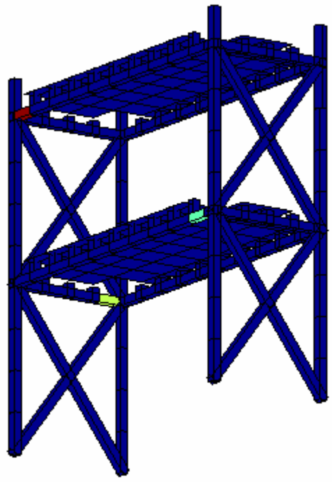
Type of system	Data Management	CMS
Workstation-based measurement system		

Data Analysis Procedures:

Type of analysis	Software	Additional features
Modal Analysis based on hammer excitation and acceleration data		

Examples of Outcomes:

The damage could be detected, localized and quantified by means of an inverse eigensensitivity approach combined with parameter preselection and regularization techniques.



Detected damage along the structure (dark locations)

Benefits of Using SHM Technologies in the Project:

The benchmark could be used to test and to modify different approaches for damage identification along the European research community.

References:

Fritzen, C.-P., Bohle, K., Stepping, A.: “Damage Detection in Structures with Multiple Cracks Using Computational Models“. Ed.: Güemes, J.A. : Proc. European COST F3 Conf. on System Identification & Structural Health Monitoring, Spain, 2000, S. 191 – 200

Submitted by:

Institute of Mechanics and Automation Control, Mechatronics
University of Siegen
D-57068 Siegen
Paul-Bonatz-Str. 9-11
Phone +49(271)740-4621
Fax: +49(271)740-2769
Email: fritzen@imr.mb.uni-siegen.de

Roberval Bridge - France

Project Description:

The Roberval bridge is located on the Lille-Paris motorway (A1). This bridge is submitted to heavy traffic loading which is of interest for bridge design codes.

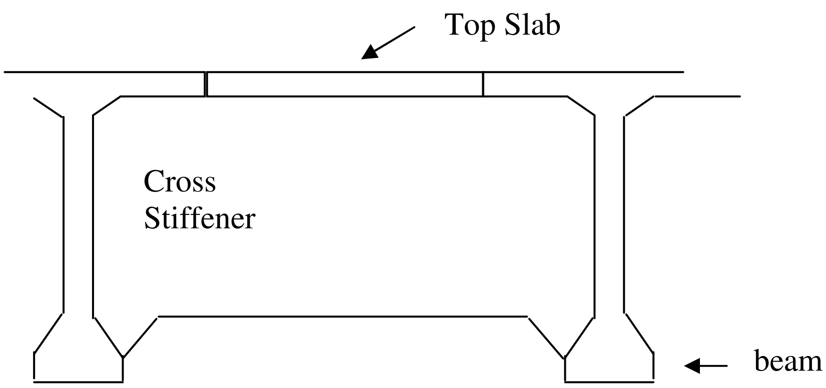
Roberval Bridge, motorway A1 (Lille - Paris), District de Senlis, France

Quick Facts:

- **Name and Location:** Roberval Bridge on the motorway A1 (Lille-Paris) near Senlis, France
- **Owner:** SANEF (Société des Autoroutes du Nord et de l'Est de la France) District de Senlis
- **Structure category:** medium span bridge
- **Spans:** 16 spans - 33m long
- **Structural system:** Girder bridge with independent spans, post-tensioned concrete girders cross braced, concrete top slab
- **Start of SHM:** September, 2001
- **Number of sensors installed:** 33
- **Instrumentation design by:** LCPC, Division for structures behaviour and durability, Division for metrology and instrumentation

Description of Structure:

The instrumented span is a one way, three traffic lanes (Lille-Paris), 34m long and 13.9m large with 5 braced I-shaped prestressed beams.



Part of the cross section

Purpose of Inspection:

The aim of the instrumentation is to record the loads and the effects of the heavy traffic. Database (WIM data - peak strain values) for calibration of bridge loading codes.

Sensor Details*:

Type of sensors	Number	Location
Strain gauges	31	at the prestressed main beams and at the top slab
WIM system	two lanes	
Temperature sensors	2	
Complementary instrumentation: accelerometers for modal analysis in ambient conditions	6	at the prestressed main beams

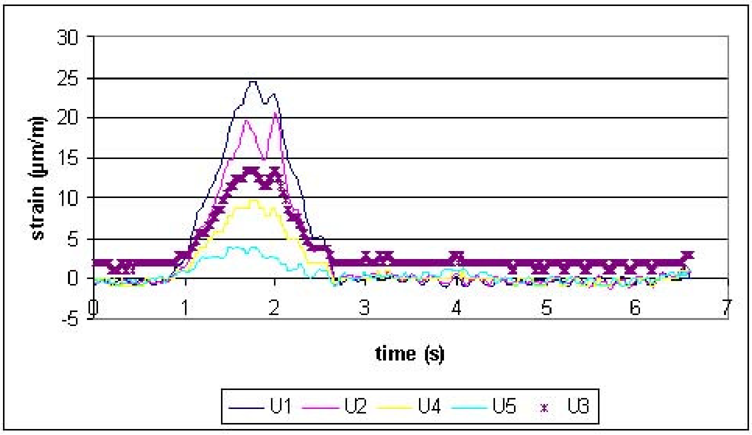
Measurement Equipment and Data Management:

Type of system	Data Management
PC based measurement system	▪ data pre-analysis (peak analysis on site ▪ main analysis, graphical presentation and documentation in office ▪ data transfer via modem ▪ long term data base

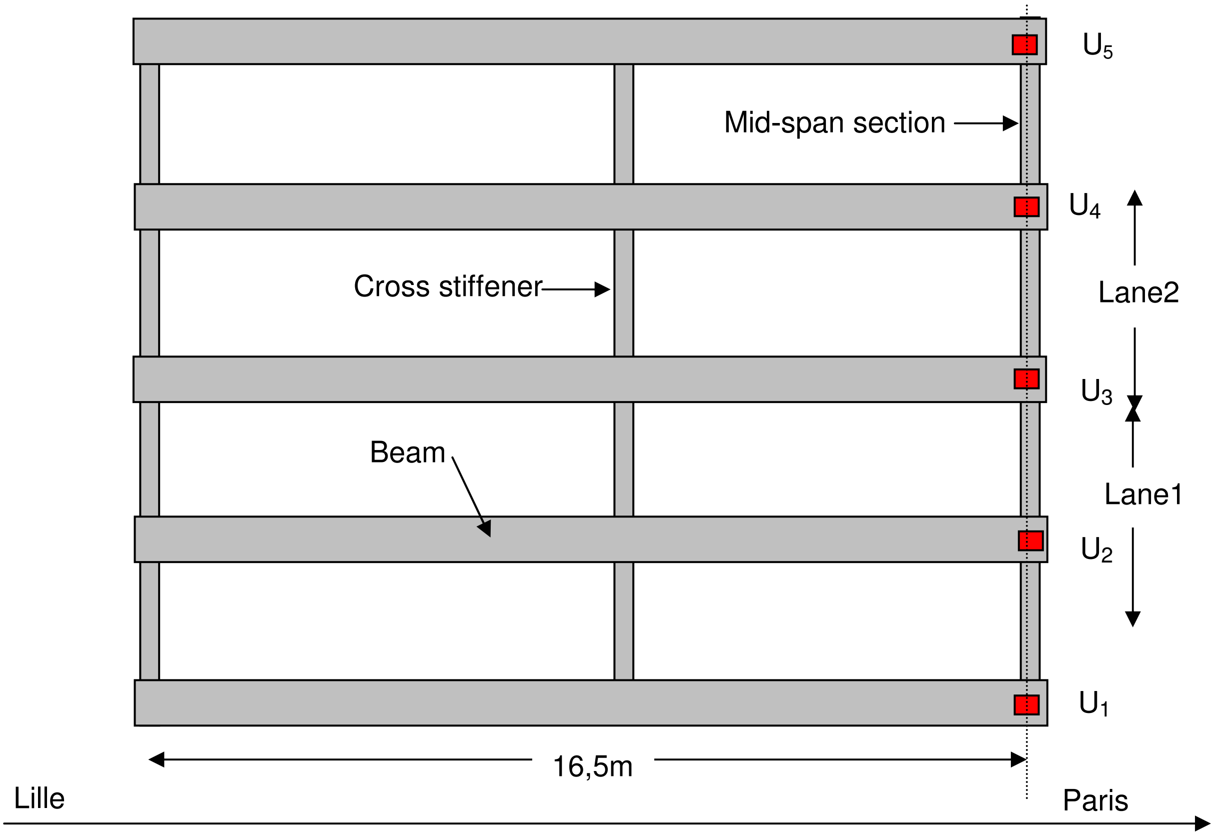
Data Analysis Procedures:

Type of analysis	Software	Additional features
Statistics, rain flow analysis, peak analysis, modal analysis from ambient vibrations	Self made software (REVE) and Catman 4.0 (HBM software)	

Examples of Outcomes:



Bending strain distribution during the crossing of one heavy load vehicle on lane 1



Bending strain gages location at mid span

Benefits of Using SHM Technologies in the Project:

Evaluation of the effects of traffic loading (extreme values – dynamic amplification factors).

References:

J. Carracilli (2000): Coefficients de majoration dynamique des charges routières sur les ouvrages d'art, calcul et extrapolation, application au pont de Bruneseau, Bulletin des laboratoires des ponts et chausses – 229 – novembre – décembre 2000 – Ref. 4343 – pp.71-82 (in french).

Submitted by:

Laboratoire Central des Ponts et Chaussées (LCPC)
Division for structures behaviour and durability, Division for metrology and instrumentation
58, Boulevard Lefebvre
75 732 Paris cedex 15
Tel: 33 (0)140 43 53 14
Fax: 33(0)1 40 43 54 99
Email: dominique.siegert@lcpc.fr

Titulcia Steel Bridge – Madrid / Spain

Project Description:

The Titulcia Steel Bridge dates from the XIX century, specifically from the year 1894. It was designed by Enrique Cardenal.

Titulcia steel truss bridge

Quick Facts:

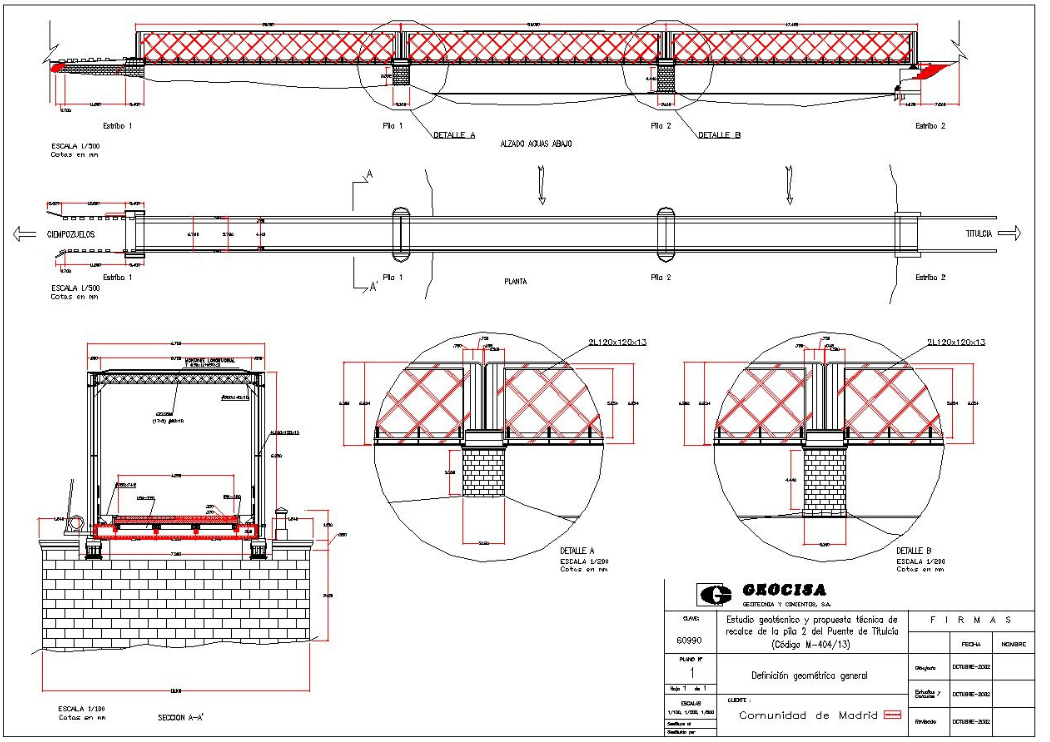
- **Name and Location:** Titulcia Steel Bridge, Madrid (Spain)
- **Owner:** Madrid Community
- **Structure category:** Bridge
- **Dimensions:** 147.45 m long, 6.72 m wide and 6.35 m high.
- **Structural system:** Steel truss
- **Start of SHM:** 31 July 2003
- **Number of sensors installed:** 16 (topographic references)
- **Instrumentation design by:** GEOCISA, Madrid, Spain

Description of Structure:

The structure is an isostatic three span truss bridge. Each span is 50 meters long, except the third one which has 47.45 meters long (because it was rebuilt after being blown up during the Spanish Civil War). Abutments and piles are made of masonry and they are founded on the river bed.

The total length of the bridge is 147.45 m, its width is 6.72 m and its height is 6.35 meters.

It supports road traffic and passes over the Jarama river.



Bridge geometry

Purpose of Inspection:

This bridge is integrated in a Bridge Management System implemented in the Madrid Community and it is periodically inspected.

In 1998 a scour problem was detected in a periodical inspection. In 1999 a sub aquatic inspection was carried out, confirming the scour problem.
From 2000 to 2003 periodical inspections have been carried out. In 2003 it is decided to implement a topographic control on the structure, to monitor the scour movements of pile 2.

In 2004 a repair work was decided due to the evolution of measured settlements. The topographic measurements were continued during the repair process to control its effectiveness.

Sensor Details*:

Magnitude controlled	Type of sensors	Number	Location	Frequency of measurements
Vertical movements	Topographic reference	16	Both sides of the bridge: abutments, piles and mid-span	Initially every 3 months, finally twice a week

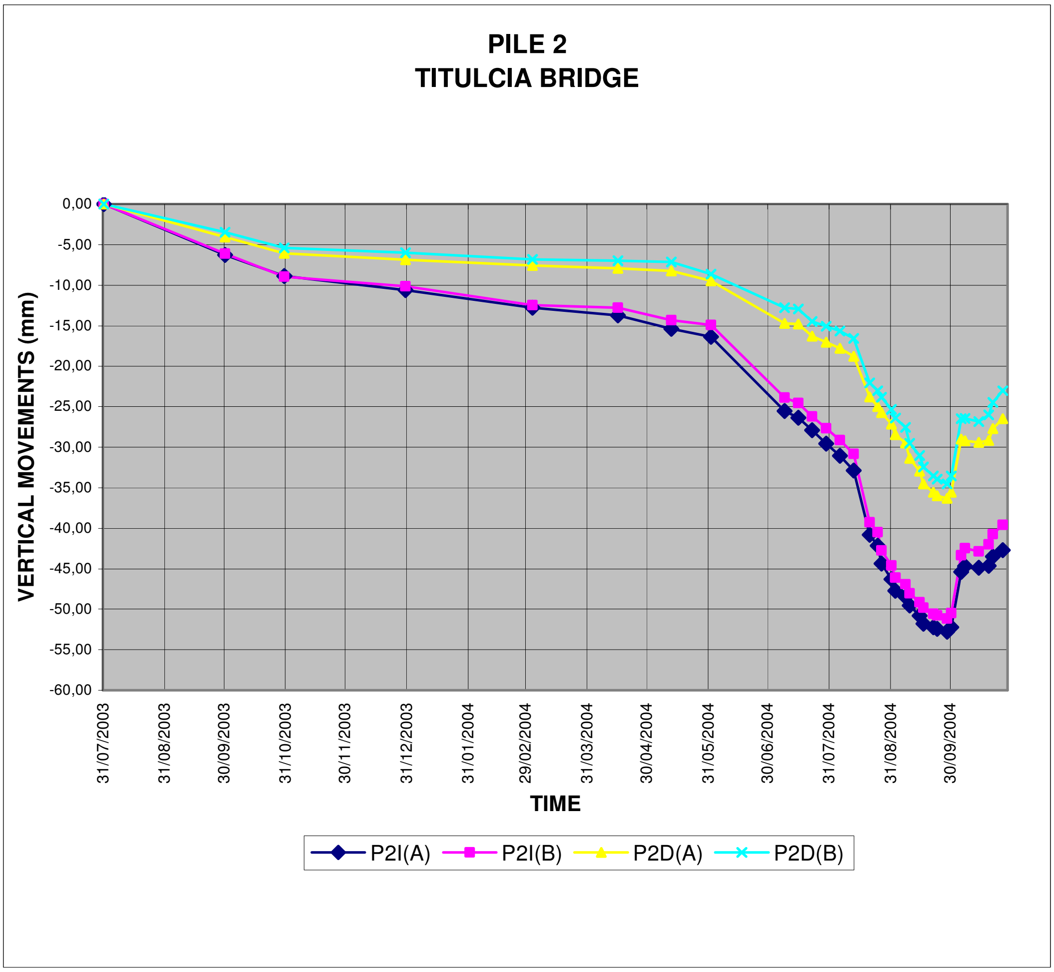
Measurement Equipment and Data Management:

Type of system	Data Management
Periodical topographic measures (manual)	▪ Analysis of every reading. ▪ Predefined control parameters related with the evolution of the movements.

Data Analysis Procedures:

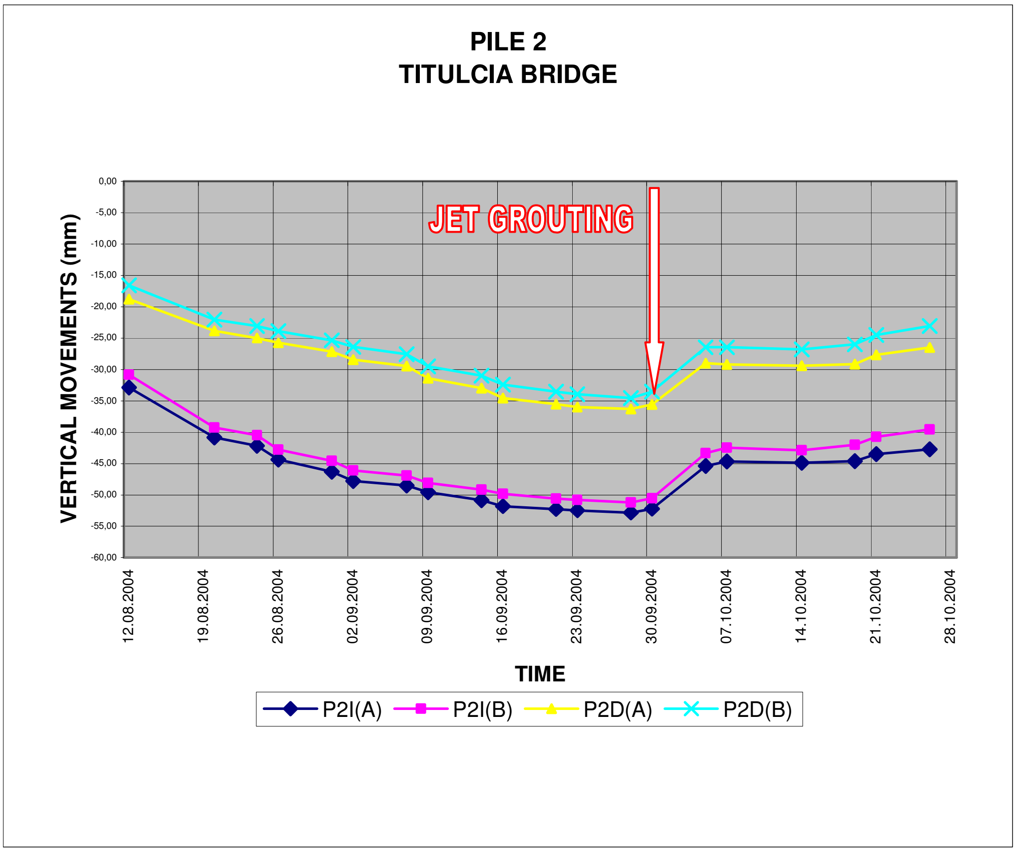
Type of analysis	Software	Additional features
Direct analysis of the data	No software needed	Periodicity of the measurements and need of action were depending on movements evolution

Examples of Outcomes:



evolution of the pile 2 (4 topographic references)

Examples of Outcomes (cont.):



evolution of the pile 2: repair works detail

Benefits of Using SHM Technologies in the Project:

These simple measurements performed during a long period of time have permitted to:

- Control the evolution of the scour process in the structure
- Adopt the decision of repair
- Control the effectiveness of repair works while and after development

References:

Andrés, Carmen: “Historical Bridges in the Madrid Community” Madrid 1989 (in Spanish).

Submitted by:

GEOCISA
Los Llanos de Jerez 10-12
28820 Coslada
Madrid
Spain
Phone: +34 91 660 30 00
Fax: +34 91 671 64 60
Email: dgr-geocisa-madrid@dragados.com

The Condamine Floating Dock – Spain / Monaco

Project Description:

The Condamine Marina in Monaco enlarged its surface area in 60.000 m². This enlargement was achieved by means of a floating caisson 352.72 m which was built in a dry dock prepared for this purpose in Algeciras Bay (Cádiz - Spain) and towed to Monaco in August 2002.

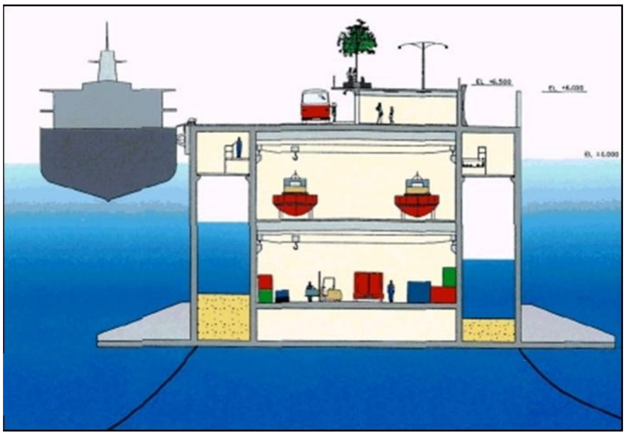
Floating Dock, Mónaco, during transport

Quick Facts:

- **Name and Location:** La Condamine floating dock, Monaco
- **Owner:** Principality of Monaco
- **Structure category:** semi floating box girder
- **Dimensions:** 352.72 m long, 28 m wide and 19 m high.
- **Structural system:** Prestressed concrete box girder
- **Start of SHM:** 10 June 2002
- **Number of sensors installed:** 97
- **Instrumentation design by:** GEOCISA, Madrid, Spain

Description of Structure:

The floating dock is a double hull structure, connected to the land abutment through a ball joint (hinge) and with displacements limited at the opposite end by means of anchored chains. It is 352.72 m long, 28 m wide (44 m at the bottom slab level) and 19 m high (24,5 m with building superstructures included). In the first 192 m of the dock there is a four level car park with a capacity of 380 vehicles. The next 136 m will be used for storing cargo and small boats in a building with two stories, each 6m high.



Transversal section of the floating dock

Purpose of Inspection:

The owner required the contractor to assure that bending moments induced by sea action during the whole transport process do not surpass the maximum values foreseen in the design. Besides that, for safety reasons during transport the contractor wished to control the water level inside the liquid ballast tanks and the owner consulting engineering was also interested in controlling the hydrodynamic pressure applied by sea waves.

Sensor Details*:

Magnitude controlled	Type of sensors	Number	Location	Sampling rate (samples/sec)
Strains	Fibre optic	39	Transversal sections A, B, C	10
Rotations	Servoclinometers	6		
Temperature	PT100	16		
Water level in ballast tanks	Pressure	12	Ballast tanks	1
Draught	Pressure	6	Corners and mid section	
Hydrodynamic pressures	Hydrodynamic pressure sensors	18	External surface	10

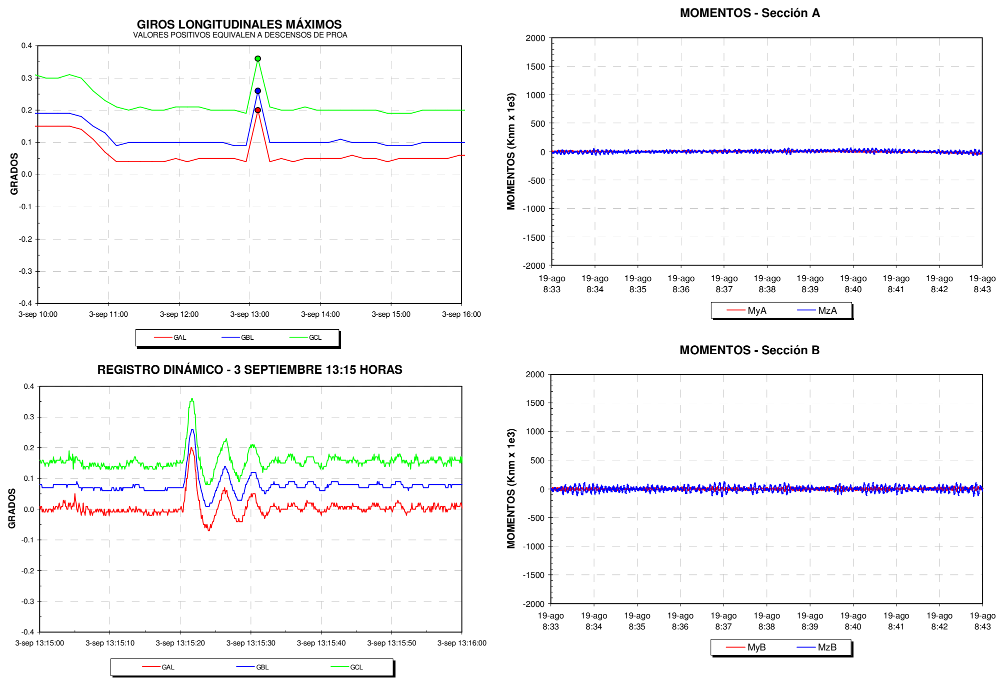
Measurement Equipment and Data Management:

Type of system	Data Management
PC based measurement system installed on the dock	▪ data pre-analysis (statistics) and graphical presentation on site ▪ main analysis (calculus of bending moments) in office ▪ data transfer during trasnport via radio to the second computer in the auxiliary tug

Data Analysis Procedures:

Type of analysis	Software	Additional features
Records measured data every 10´. Display measured data and visual signals if values surpass a pre-fixed threshold	Self made software	Calculates and records: ▪ bending moments in each instrumented sections estimated from measured strains ▪ statistical parameters (max, min, mean value, standard deviation) for each channel every 10´.

Examples of Outcomes:



left-top: Maximum tilts every 10´ during hinge coupling operation showing a sudden peak
left-bottom: detail of the dynamic record in the 10´period of that peak
right: evolution of bending moments in sections A/B during 10' period on August 19th 2002

Benefits of Using SHM Technologies in the Project:

The complete history of controlled magnitudes during transport is available, with records every 10 minutes of the time evolution of each sensor at the sampling rate applied, as well as the evolution of statistical paremeter . Analysis of the maximum moments during transport proved that they were well below the design values foreseen in the design.

References:

Peset, L.; Barceló, J.; López, D.; Hue, F.; Vázquez, A. and Ortega, L.: "Singular elements in the Monaco dock", ACHE - Journal “Hormigón y Acero” No. 223-226, pgs. 67-117, Madrid 2002 (in Spanish).

Ortega, L.: “Monitoring of the Semi-Floating Dock of La Condamine Harbour – Monaco”. SAMCO Newsletter, Issue 8, January 2003

Submitted by:

GEOCISA
Los Llanos de Jerez 10-12
28820 Coslada
Madrid
Spain
Phone: +34 91 660 30 00
Fax: +34 91 671 64 60
Email: lob-geocisa-madrid@dragados.com

Skovdiget Bridge Superstructure - Denmark

Project Description:

The Skovdiget bridge north of Copenhagen, Denmark opened in 1965 and is part of a main route for urban traffic, which is also used for heavy loads. The bridge carries the busiest highway in Denmark with app. 60000 daily passengers over the S-train line with app. 6000 daily passengers. The superstructure in the western bridge is severely deteriorated in critical positions, while at the same time facing an increased traffic load. The main girders are therefore under surveillance in order to follow the effect of the replacement of the water protection and drainage, while at the same time following the corrosion rates in the critical parts of the structure. The variations of the strains are at the same time logged, in order to generate a realistic statistic of the load variations and frequencies as well as provide a control of the FEM-modelling.

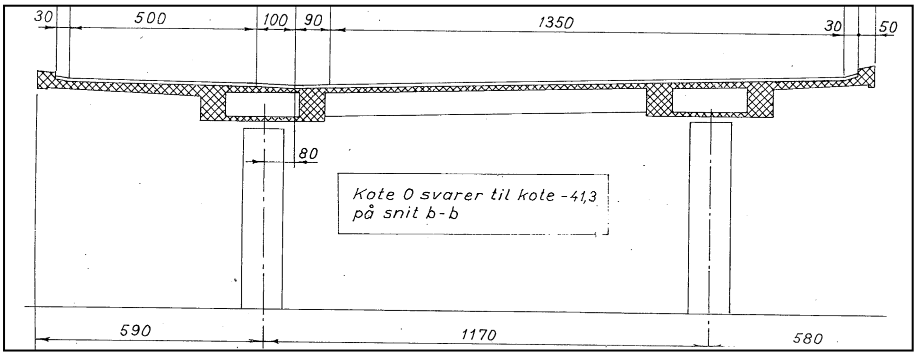
Skovdiget Bridge, Copenhagen, Denmark.

Quick Facts:

- **Name and Location:** Skovdiget Bridge, Copenhagen, Denmark
- **Owner:** Danish Road Directorate
- **Structure category:** medium span bridge
- **Spans:** 11 spans: 9.4/17.2/20.2/20.1x6/24.3/14.5 m
- **Structural system:** Prestessed concrete bridge, with hollow core girders and cross-beams, supported on concrete columns
- **Start of SHM:** 2000, updated in 2003.
- **Number of sensors installed:** 63 in superstructure.
- **Instrumentation design by:** RAMBØLL, Denmark.

Description of Structure:

The superstructure comprises of two pre-stressed concrete girders with a hollow core, with a number of closed cells. The bridge deck is in each bridge supported by two main girders and by 111 pre-stressed cross-beams. The superstructures are supported by a number of columns, placed under each of the main girders. The bridge with a total length of 220 m consists of two separate, parallel bridges, of which the eastern received a major renovation in 1975, whereas the western bridge received only minor repairs and renovation of the water protection. The western bridge has therefore been under surveillance since 1975.



cross-section of the bridge

Purpose of Inspection:

Initial inspection has shown severe damages in parts of the structure and the ingress of chloride and variations of humidity and corrosion potentials have been followed since 2000. It has been found necessary to determine the condition of the reinforcement in the most deteriorated parts of the main girder as well as to determine the corrosion rate. This leads to the conclusion that the traffic loads must be logged in order to generate an overview of the actual variations of the traffic loadings in the bridge.

Sensor Details*:

Type of sensors	Number	Location
Strain-sensors (based on fibre optics)	7	3+2 on the two main girders plus 2 on two cross-beams
Corrosion rate sensors (CorroEye)	10	The cell over the railway and another, equally deteriorated cell over the parking area
Humidity sensors (HUM)	10	
Corrosion risk sensors (ERS)	1	
Corrosion risk sensors (CorroRisk)	12	
Humidity sensors (HUM)	7	The edge beams, main girders and some of the cross-beams.
Humidity sensors (MRE)	7	
Temperature sensors (PT 100)	4	
Chloride sensors (CHL)	5	

Measurement Equipment and Data Management:

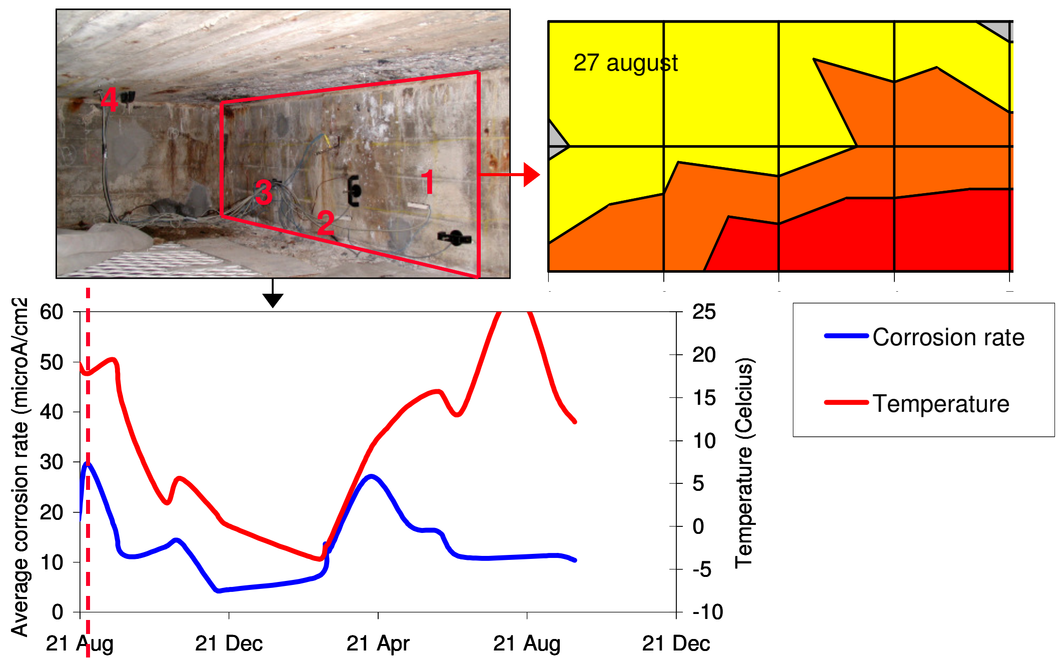
Type of system	Data Management	CMS
PC- based measurement system for strains. Manual system for reading CorroEye. Datalogger(s) for additional sensors.	▪ data pre-analysis (evaluating, averaging and identification of extreme load, leading to storage of data) on site ▪ main analysis, graphical presentation and documentation in office ▪ data transfer via modem ▪ long term data base in SMART light	y

Data Analysis Procedures:

Type of analysis	Software	Additional features
Transformation of strains into loading, speed and position on bridge. Transformation of corrosion current into corrosion rates.	SMART Light and Excel	▪ SMART Light has a number of traditional Bridge Management facilities built-in.

Examples of Outcomes:

The corrosion rates have been determined several times by means of NDT-methods, using the Galvapulse equipment. This verified, that the apparent corrosion rate would limit the service-life of the structure, despite the recent renovation of the water-proofing.

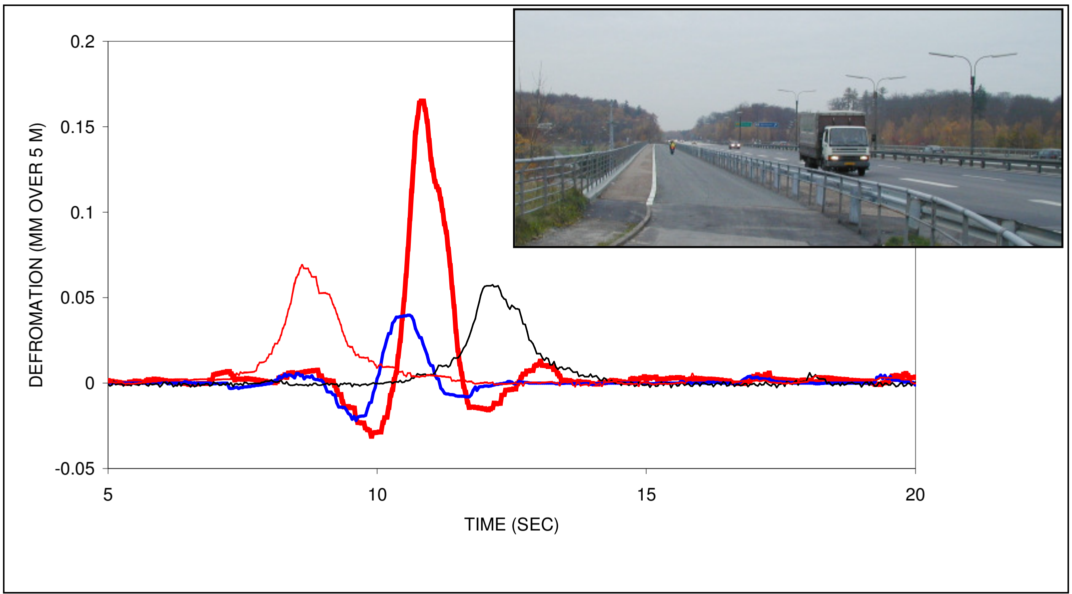


NDT-Mapping of corrosion rates in a cell during August 27th 2003 and corresponding logging of average corrosion rates by CorroEye sensors

The NDT-mapping requires, however, regulation of the traffic on the electrically powered railway line and was therefore combined with installation of corrosion rate sensors, which enable monitoring of corrosion rates without traffic regulations.

The inspection, the FEM-calculations and the monitored corrosion rates indicate, that the structure within 10 years will have a insufficient load-carrying capacity and will require strengthening, replacement or a more detailed assessment of the traffic loadings.

The deformations has since 2000 been monitored continuously with sensors based on fiber optics, which allow measurements to be carried out app. 25 times pr. second. These deformations are averaged over each hour. Passage of a heavy vehicle will be detected by the system and the variations of the strains from app. 10 s before to 10 s after the passage will be kept in the records. This allows essentially a logging of the number of heavy vehicles, their loads, position on the road and their speed.



logging of strain variations during passage of a heavy truck

Benefits of Using SHM Technologies in the Project:

The monitoring of deterioration parameters (chloride, humidity, temperature and corrosion potentials) as well as the visual inspection have identified the need for monitoring. The use of corrosion rate monitoring provides a record of the actual corrosion rates in the critical structural parts without traffic regulations.
The combination of NDT-mapping and monitoring with sensors provides both a general mapping of large areas of the structures and a recording of the variation in time.

The logging of the passages of the heavy trucks generates an improved load model, which will be useful in the next probalistic assessment of the structures safety and will add some years to the structures service life.

References:

P. Goltermann: “Managing large bridge structures in Scandinavia”, SAMCO Summer School, July 14-18 2003, Cambridge, UK.

Klinghoffer, O.; Goltermann, P. and Bässler, R.: “Smart Structures: Embeddable sensors for use in the integrated monitoring systems of concrete structures”, Proc. IABMAS 02, July 2002, Barcelona, Spain.

Goltermann, P. et al: “SMART STRUCTURES Integrated Monitoring Systems for Durability Assessment of Concrete Structures. Project Report”, February 2002, available for downloading at http://smart.ramboll.dk/smart_eu/index.htm

Elsener, B. et al:”Assessment of reinforcement corrosion by means of galvanostatic pulse technique”, Proc. Int. Conf. “Repair of Concrete Structures”, Svolvær, Norway, 1997.

Frølund, T. and Klinghoffer, O.: “Comparison of half-cell potentials and corrosion rate measurements – A field experience with evaluation of reinforcement corrosion”, Proc EUROCORR 2004, Nice, France, 2004.

Goltermann, P. et al.: ”SMART STRUCTURES. Integrated Monitoring Systems for Durability Assessment of Concrete Structures, Subtask 3.2 On-site Testing of Portable Systems. Extensive Testing of Portable Systems”, February 2002.

Luping, T. “Calibration of the Electrochemical Methods for the Corrosion Rate Measurement of Steel in Concrete. NORDTEST Project No. 1531-01”, SP REPORT 2002:25.

Suppliers information on the CorroEye-sensor available at http://www.germann.org/

Bjerrum, J.; F. Jensen, J. and Enevoldsen, I.: "The owners perspective in probability-based bridge management", Proc. IABMAS02, Barcelona, Spain, July 2002.

Jensen, F.; Knudsen, A. and Enevoldsen, I.: "Probalistic-based Bridge Management Implemented at Skovdiget West Bridge" in Fourth International Conference on Bridge Management, 16-19 April, 2000, University of Surrey, UK.

Mondrup, A. J.; Frederiksen, J. O. and Christensen, H. H.: "Load Testing as an Assessment Method", IABSE symposium "Durability of Structures", 1989.

Submitted by:

RAMBØLL
Bridge Maintenance and Material Technology
Bredevej 2
D-2830 Virum
Denmark
Phone: +45 4598 6726
Fax: +45 4598 6302
Email: peg@ramboll.dk

Skovdiget Bridge Columns - Denmark

Project Description:

The Skovdiget bridge north of Copenhagen, Denmark opened in 1965 and is part of a main route for urban traffic, which is also used for heavy loads. The bridge carries the busiest highway in Denmark with app. 60000 daily passengers over the S-train line with app. 6000 daily passengers. Currently the columns under the western bridge are much deteriorated, just as the foundations used are of the same type, which have previously failed at the Fiskebæk bridge. The columns are therefore under surveillance in order to secure their performance in the future.

Skovdiget Bridge, Copenhagen, Denmark.

Quick Facts:

- **Name and Location:** Skovdiget Bridge, Copenhagen, Denmark
- **Owner:** Danish Road Directorate
- **Structure category:** medium span bridge
- **Spans:** 11 spans: 9.4/17.2/20.2/20.1x6/24.3/14.5 m
- **Structural system:** Prestessed concrete bridge, with hollow core girders and cross-beams, supported on concrete columns
- **Start of SHM:** 1975 and summer 2000
- **Number of sensors installed:** 47 in columns
- **Instrumentation design by:** RAMBØLL, Denmark.

Description of Structure:

The superstructure comprises of two pre-stressed concrete girders with a hollow core, with a number of closed cells. The bridge deck is in each bridge supported by two main girders and by 111 pre-stressed cross-beams. The superstructures are supported by a number of columns, placed under each of the main girders. The bridge with a total length of 220 m consists of two separate, parallel bridges, of which the eastern received a major renovation in 1975, whereas the western bridge received only minor repairs and renovation of the water protection. The western bridge has therefore been under surveillance since 1975.

Purpose of Inspection:

It is necessary to verify that the foundations have no unexpected settlements, that the columns remain in position and that the supports work properly.

It is also necessary to check the deterioration of the columns, especially so that the corrosion will not lead to an unacceptable decrease of the load-carrying capacity due to corrosion of the reinforcement.

Sensor Details*:

Type of sensors	Number	Location
Positions for inklinometers	40	2 on each column
Corrosion risk sensors (ERS)	5	Sensors are installed in the columns in heights from 0.1 to 2.0 m above the ground. The additional sensors in the superstructure are not included in this list.
Corrosion risk sensors (CorroRisk)	20	
Humidity sensors (HUM)	3	
Humidity sensors (MRE)	3	
Temperature sensors (PT 100)	3	
Temperature sensors (others)	3	
Chloride sensors (CHL)	10	

Measurement Equipment and Data Management:

Type of system	Data Management	CMS
Datalogger based measurement system. Manual system for reading inclinometers	▪ data pre-analysis (noise filters) on site ▪ main analysis, graphical presentation and documentation in office ▪ data transfer via modem ▪ long term data base in SMART light	y

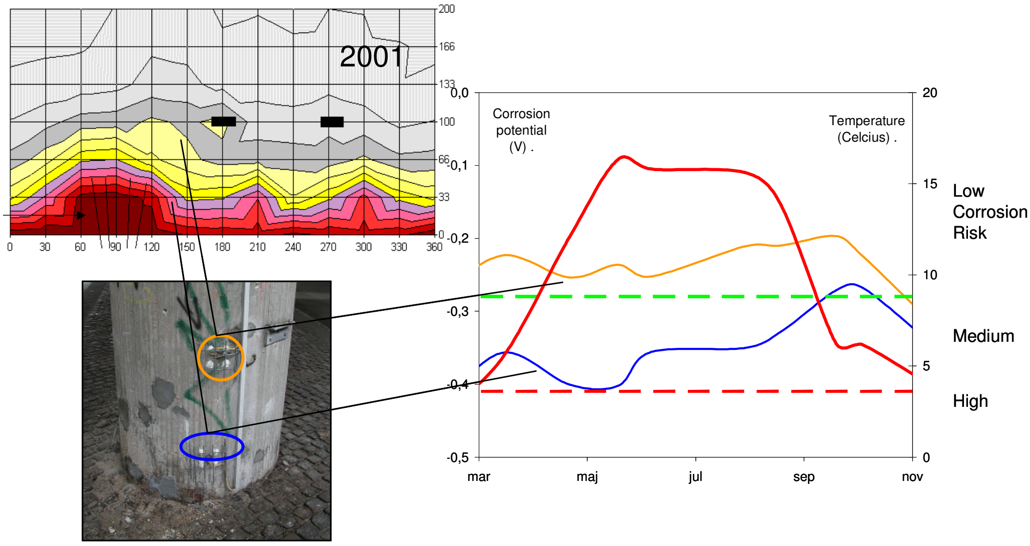
Data Analysis Procedures:

Type of analysis	Software	Additional features
Averaging and additional noise filtering	SMART Light and Excel	▪ no expert system

Examples of Outcomes:

It has been shown that the columns and foundations has performed well so far, as very little variations in the positions of the supports on top of the columns (beyond those variations due to temperature variations) have been observed. The inclinometer measurements over 30 years have also shown that the columns remain vertical.

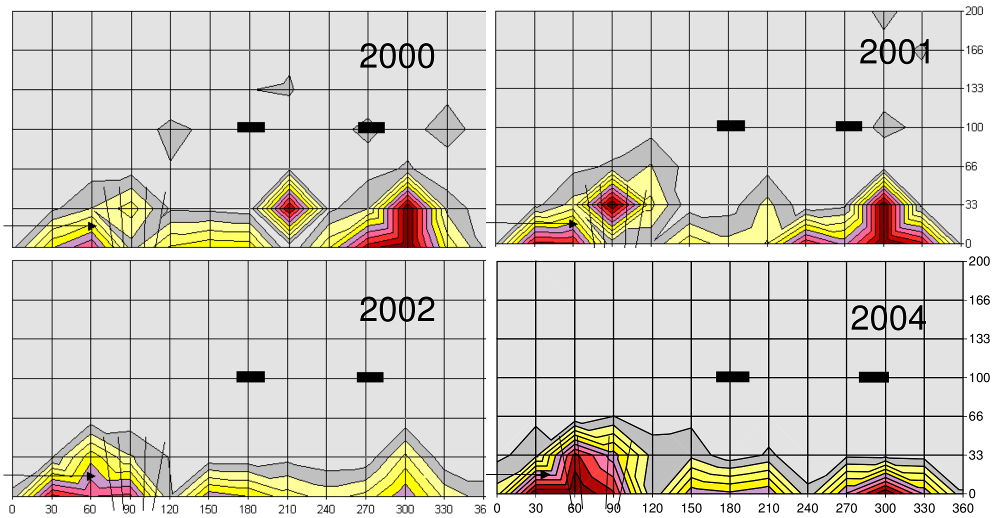
The continuous monitoring has been combined with the NDT-mapping of resistance and corrosion potential and verifies that the NDT-inspections during the autumn period tend to provide a conservative measurement of the corrosion potentials (and thus corrosion risk). NDT and monitoring corresponds well (See below) and provide in combination both an overall mapping of the variations and a recording of the variation in time.



NDT-mapping of corrosion potential compared with logging of corrosion potentials measured with CorroRisk sensors.

The NDT-mapping of corrosion potentials are correlated with the reinforcement's actual condition, and provide thus a good assessment of the reinforcement's condition and the risk of future corrosion. The evaluation shows that there is a high corrosion risk in some areas of the columns and that corrosion rates must be checked.

The checking of corrosion rates is carried out annually with NDT-equipment during the autumn on selected columns in the most exposed positions and reveals a large variation over time. The mapped corrosion rates verifies, however, that the corrosion rates observed will not lead to serious loss of reinforcement at the current corrosion rate levels.



NDT-Mapping of corrosion rates in a column during the autumn 2000 to 2004

Benefits of Using SHM Technologies in the Project:

The performance of the columns and foundation is checked and verifies that this bridge has no problems with the supports and foundations. The combination of NDT-mapping and continuous monitoring of corrosion risk identifies the critical positions, the correct inspection periods and the variations with time of the corrosion risk.

The combination leads also to a conservative assessment of the corrosion rate, which still verifies, that the loss of reinforcement area is no immediate treat to the safety of the columns.

The selected sensors have over a 5 years period been found work well in existing concrete structures and provide a good recording of the conditions in the existing concrete and of the corrosion risk of the reinforcement.

The sensors have been found to be suitable for installation in existing structures, where the NDT-mapping can identify the relevant monitoring positions.

References:

P. Goltermann: "Managing large bridge structures in Scandinavia", SAMCO Summer School, July 14-18 2003, Cambridge, UK.

Klinghoffer, O.; Goltermann, P. and Bässler, R.: "Smart Structures: Embeddable sensors for use in the integrated monitoring systems of concrete structures", Proc. IABMAS 02, July 2002, Barcelona, Spain.

Goltermann, P. et al: "SMART STRUCTURES Integrated Monitoring Systems for Durability Assessment of Concrete Structures. Project Report", February 2002, available for downloading at http://smart.ramboll.dk/smart_eu/index.htm

Elsener, B. et al:"Assessment of reinforcement corrosion by means of galvanostatic pulse technique", Proc. Int. Conf. "Repair of Concrete Structures", Svolvær, Norway, 1997.

Frølund, T. and Klinghoffer, O.: "Comparison of half-cell potentials and corrosion rate measurements – A field experience with evaluation of reinforcement corrosion", Proc EUROCORR 2004, Nice, France, 2004.

Goltermann, P. et al.: "SMART STRUCTURES. Integrated Monitoring Systems for Durability Assessment of Concrete Structures, Subtask 3.2 On-site Testing of Portable Systems. Extensive Testing of Portable Systems", February 2002.

Luping, T. "Calibration of the Electrochemical Methods for the Corrosion Rate Measurement of Steel in Concrete. NORDTEST Project No. 1531-01", SP REPORT 2002:25.

Submitted by:

RAMBØLL
Bridge Maintenance and Material Technology
Bredevej 2
D-2830 Virum
Denmark
Phone: +45 4598 6726
Fax: +45 4598 6302
Email: peg@ramboll.dk

Ting Kau Bridge – Hong Kong, China

Project Description:

The 1,177m long Ting Kau Bridge is a three-tower cable-stayed bridge carrying a dual three-lane carriageway over Rambler Channel in Hong Kong. It provides important access connecting Hong Kong Island, Kowloon, and the New Territories and the mainland of China to the new Chek Lap Kok Airport. After 44 months in design and construction, the bridge opened to public traffic in May, 1998.

Ting Kau Bridge – Hong Kong, China

Quick Facts:

- **Name and Location:** Ting Kau Bridge – Hong Kong, China
- **Owner:** Highway Department, the Hong Kong SAR Government
- **Structure category:** Cable-stayed bridge
- **Spans:** 4 spans with main spans of 475m and 448m, side span 127m each
- **Structural system:** 3 single-leg towers strengthened by stabilizing cables, 384 stay cables in 4 planes support the two separate decks
- **Start of SHM:** November, 1998
- **Number of sensors installed:** 236 with 7 different types
- **Instrumentation design by:** Fugro Geotechnical Service (Hong Kong) Ltd.

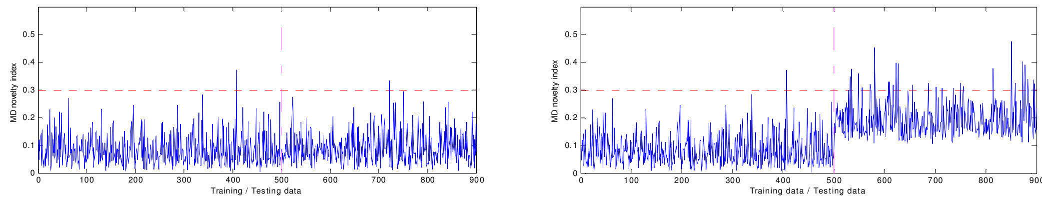
Description of Structure:

The bridge is one of the limited instances of using multi-span cable-stayed bridges in practice. It comprises two main spans of 448 m and 475 m respectively, and two side spans of 127 m each. A unique feature of this bridge is the use of slender single-leg towers that are strengthened by transverse and longitudinal stabilizing cables. The two carriageways, with a central air gap of 5.2 m, are linked at 13.5 m intervals by I-shape main cross girders. Each carriageway grillage consists of two longitudinal steel girders along the deck edges with steel cross girders at 4.5 m intervals, and a composite deck panel on top. The deck is supported by 384 stay cables in four cable planes.

Development of Damage Detection Methodology:

Since the majority of vibration-based damage detection methods need a refined or validated analytical model as baseline reference, a 3D finite element (FE) model comprising over 5500 elements has been developed for the Ting Kau Bridge. The model provides a base in simulating any member-level damage, detecting damage-sensitive features and checking the feasibility of damage detection methods.

A neural network based hierarchical identification strategy has been proposed for structural damage detection in accordance with the instrumented sensors on the bridge. This multi-stage diagnosis strategy aims at successive detection of the occurrence, location, type and extent of the structural damage. Following figures illustrate the performance of a proposed novelty index to detect damage occurrence. By using global eigenfrequencies and local modal components, multi-novelty indices are able to locate the damage region. The feasibility study indicates that using only measured natural frequencies, the novelty detector is able to signal the damage occurrence even the damage-caused frequency change level is less than the corrupted noise level.



(a) Intact structure (b) Damaged structure

Performance of novelty index

Purpose of Instrumentation:

A sophisticated long-term monitoring system, called Wind And Structural Health Monitoring System (WASHMS) has been devised by the Highways Department of the Hong Kong SAR Government to monitor the structural health and performance under in-service condition of three long-span cable-supported bridges in Hong Kong, namely the Tsing Ma suspension bridge, the Kap Shui Mun cable-stayed bridge and the Ting Kau cable-stayed bridge. This on-line monitoring system consists of about 800 permanently installed sensors of various types. The main objectives of devising this system are: (i) to monitor the structural health (safety) conditions of the three bridges; (ii) to provide information for facilitating the planning of inspection and maintenance activities; and (iii) to verify design assumptions and parameters for future construction of cable supported bridges.

Sensor Details*:

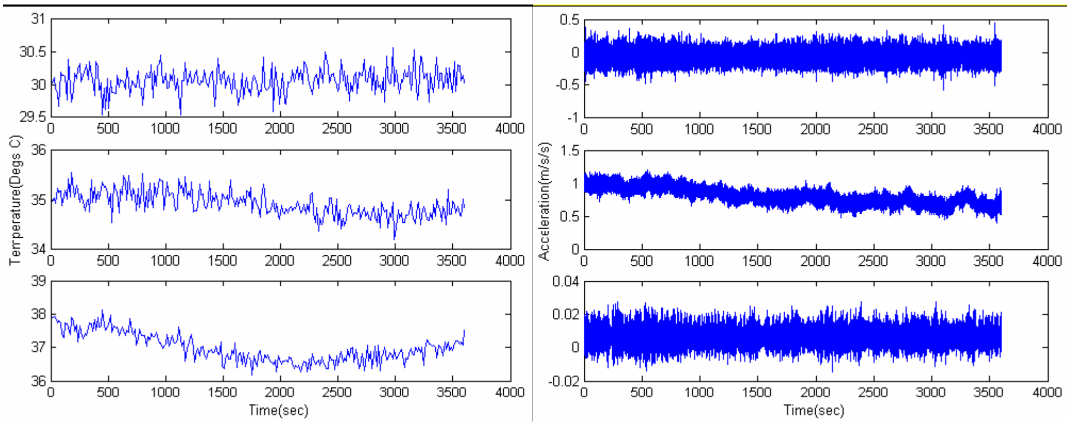
Type of sensors	Number	Type of sensors	Number
Anemometer	7	Displacement transducer	2
Temperature Sensor	83	Weight-in-motion sensor	6
Accelerometer	45	Global positioning system (GPS)	5
Strain Gauge	88		

*detailed information may refer to the website: http://158.132.127.210:8080/bridge_data/index.htm.

Examples of Outcomes:

The online system accomplishes continuous 24-hour monitoring per day for all sensors.

The acquired raw data are accumulated at a rate about 56.0 MB per hour in binary format for the Ting Kau Bridge. Measured data are archived and backed up in the form of one hour record and each item containing data from one channel. Based on one-year data, a data management system has been developed. Examples of measured data are shown in time-plot below.

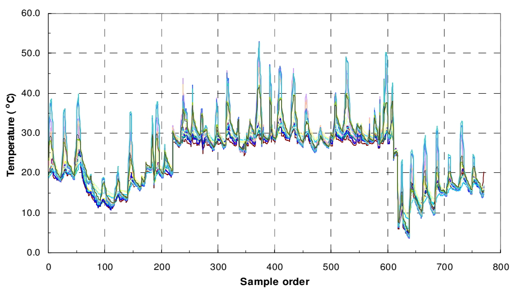


(a) temperature (b) acceleration

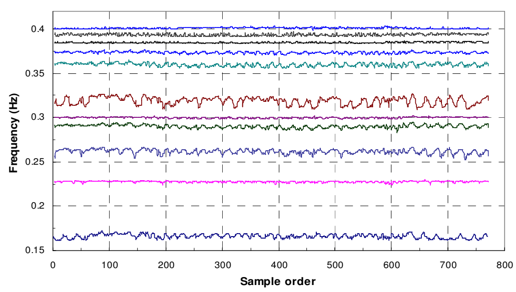
Examples of measurements

The influence of operational and environmental factors on modal characteristics of the bridge has been investigated. For this purpose, a total of 770-hour data covering measurements in February, March, June, July, August and December of 1999 were selected. The left below figure plots the average temperatures in one-hour duration for 20 selected sensors. The right one shows the identified modal frequencies. The statistical computation indicates that the standard deviation of measured frequencies can reach 4.3×10–3. The variation of frequencies is attributed to the varying operational and environmental conditions. Such a variation level may mask the changes caused by actual structural damage.

Therefore, for the reliable performance of damage detection methods, it is of paramount importance to discriminate abnormal changes in dynamic features due to structural damage from normal changes due to the natural variability.



Variation in measured temperatures



Variation in identified frequencies

Benefits of Using SHM Technologies in the Project:

Using SHM technologies on the Ting Kau Bridge provides following benefits:

- the ability to collect information of real loading effects and bridge responses, which are valuable in evaluating design parameters and assumptions

- the ability to provide data useful in validating and updating damage-oriented structural model and in identifying damage sensitive features
- the opportunity to provide data in verifying the feasibility and reliability of damage detection methods
- the ability to help in maintenance and rehabilitation planning, and to give the prediction of the deterioration when combining with the analytical model

References:

Wong, K.Y, Lau, C.K., and Flint, A.R. Planning and implementation of the structural health monitoring system for cable supported bridges in Hong Kong. Nondestructive Evaluation of Highways, Utilities, and Pipelines IV, A.E. Aktan and S.R. Gosselin (eds.), SPIE Vol. 3995, 2000, 266-275.

Ko, J.M., Ni, Y.Q., Zhou, X.T., and Wang, J.Y. Structural damage alarming in Ting Kau Bridge using auto-associative neural networks. Advances in Structural Dynamics, J.M. Ko & Y.L. Xu (eds.), Elsevier Science Ltd., Oxford, UK, 1021-1028.

Wang, J.Y., Ni, Y.Q., Ko, J.M., and Chan, T.H.T. Damage detection of long-span cablesupported bridges. Structural Health Monitoring Workshop, SHM ISIS 2002, A.A. Mufti (ed), September 2002, Winnipeg, Canada, 299-308.

Ko, J.M., Wang, J.Y., Ni, Y.Q. and Chak, K.K. Observation on Environmental Variability of Modal Properties of a Cable-stayed Bridge from One-year Monitoring Data. Structural Health Monitoring 2003: From Diagnostics & Prognostics to Structural Health Management, F.-K. Chang (ed.), DEStech Publications, Lancaster, Pennsylvania, USA, 467-474.

Report, Data management of three cable-supported bridges in Hong Kong including one-year monitoring data, Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, July, 2003.

Submitted by:

Prof. J. M. Ko
Vice President
The Hong Kong Polytechnic University
Hung Hom, Kowloon, Hong Kong
Phone: (852) 2766 5036
Fax: (852) 2356 2682
Email: cejmko@inet.polyu.edu.hk