First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

Abstract of Paper No: 16

Approach for the life-cycle management of structures including durability analysis, shm and maintenance planning

Peter Furtner
VCE – Vienna Consulting Engineers, Austria

Robert Veit-Egerer
VCE – Vienna Consulting Engineers, Austria

A tailor-made model was developed, which utilizes state-of-the-art information from literature as well VCE's experience gained in the course of performing bridge monitoring and bridge inspection worldwide. This knowledge has been incorporated into the assessment procedure that is described in the paper. Probabilistic methods are used for the service life calculations of the whole structure as well as for individual items. The reason is to cover occurring uncertainties which have to be also implemented into the established maintenance plan in terms of lower & upper bound of life expectancy. The starting point of the bridge's service life – in terms of the safety level – is according to the initial over design and depends on the applied design code and certain safety consideration in the course of the static calculations. For existing structures it is important to consider following variables:

- initial static calculation
- schedule of maintenance and rehabilitation measures
- loading history (historical traffic data)
- material tests
- historical data about environmental exposure
- judgment / rating from bridge inspections
- performed monitoring campaigns

A strong emphasis is to be put on in-situ investigations, especially full-scale monitoring, which turned out to reflect structural resistance and load bearing capacity in a most suitable manner. A monitoring concept for the full service life time is presented.

Based on the assessment procedure and its results maintenance instructions are worked out to guarantee the design life and to preserve the structures functions. Besides cost optimization the main focus is on the minimization of traffic impediment. The paper describes the approach on the example of an urban highway extension project with more than 100 existing and new bridges.

Corresponding author's email: furtner@vce.at

First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

Approach for the life-cycle management of structures including durability analysis, shm and maintenance planning

Peter Furtner[1], Robert Veit-Egerer[2]

[1] VCE – Vienna Consulting Engineers, Austria
[2] VCE – Vienna Consulting Engineers, Austria

ABSTRACT: A tailor-made model was developed, which utilizes state-of-the-art information from literature as well as VCE's experience gained in the course of performing bridge monitoring and bridge inspection worldwide. This knowledge has been incorporated into the assessment procedure that is described in this paper. Probabilistic methods are used for the service life calculations of the whole structure as well as for individual structural members. The reason is to cover occurring uncertainties which have to be also implemented into the established maintenance plan in terms of lower & upper bounds of life expectancy. The starting point of the bridge's service life – in terms of the safety level – is according to the initial over design and depends on the applied design code and certain safety consideration in the course of the static calculations. This paper describes the developed methodology using the example of an urban highway extension project with more than 100 existing and new bridges.

1 INTRODUCTION

The A15 highway is the main connection of the Rotterdam seaport with the industrial area in the Netherlands. At present the A15 suffers from considerable accessibility and safety problems. A major upgrade and extension project has been planned to increase the number of traffic lanes and to switch to a safer and more efficient road design.

The project is implemented by means of a PPP (=Private-Public-Partnership) model, where the design, execution, maintenance, operation and financing are placed into the hands of a market party (contractor) for more than 25 years including a construction time of 5 years. The payments to the contractor are conditional on compliance with and verification of the road availability.

The project section of the highway has a length of 37 km and includes more than 100 bridges, viaducts and tunnels. All construction and maintenance works have to be executed under traffic with as little traffic impediment as possible.

As the payment of the contractor is dependent on the availability and the traffic impediment, a well elaborated maintenance concept is of major interest. A Management Information System (MIS) shall be developed and implemented for the optimisation of the condition assessment and the maintenance planning of all engineering structures as well as the road pavement over the whole availability period. This MIS shall collect and analyse all relevant data from visual inspection, structural health monitoring, maintenance measures and the traffic management system. The results will be interpreted and lead to an as-precise-as possible maintenance planning. A continuously working, dynamic updating procedure for the maintenance plan shall be implemented.

2 APPLIED METHODOLOGIES

With the introduction of lifecycle aspects it became even more important to create a time depending deteriorations model represented by a condition index. Numerous models have been developed already that describe the transition of a variety of condition states which are mainly based on a linear deterioration where the deterioration rate can be expressed in terms of condition rating loss per year. Actually most of the existing Bridge Management Systems (BMS) use the Markov chain approach to model condition deterioration. A direct connection to budget planning and most effective use of means is under development.

Monitoring and non-destructive testing has a long history in Europe. The ideas and principles were developed already 40 years ago. They did not succeed due to the insufficient tools available at that time. Since 15 years monitoring and assessment has successfully entered the field of bridge management. Due to the complexity of the issue there is still difficulty in application. Development has been too focused on scientific issues and forgot to transport the message that only clear objectives make a monitoring campaign valuable. The motivation has been too curiosity driven rather than pragmatic. Nevertheless it has been understood that only a useful combination of visual inspection, based on the existing well proven systems, and the quantitative results of a shm campaign will bring the required precise results in condition ratings. Nevertheless some main topics to be solved in the near future are: How to deal with the measuring errors, uncertainties and noise in relation to the different sensors and measurement techniques and how to integrate the data from the point of time of measurement into the assessment of the condition rating. A respective example is provided below showing the authors approach.

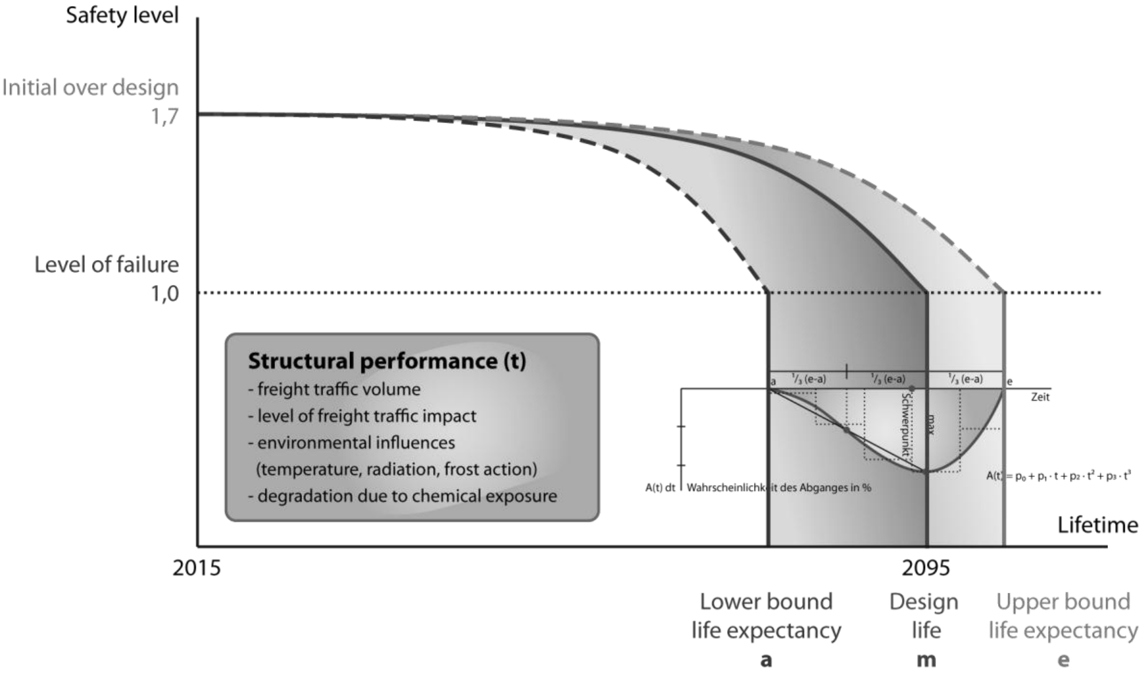


Figure 1. Expected (analytical) lifetime of new structures

2.1 *The determination/estimation of the design life of new structures*

A tailor-made model was developed, which utilizes state-of-the-art information from literature (European, American & Asian) as well as VCE's experience gained in the course of performing bridge monitoring and bridge inspection worldwide. This knowledge has been incorporated into the assessment procedure that is briefly described in the following.

Probabilistic methods are used for the service life calculations of the individual items. The reason is to cover occurring uncertainties which have to be also implemented into the established maintenance plan in terms of lower & upper bounds of life expectancy.

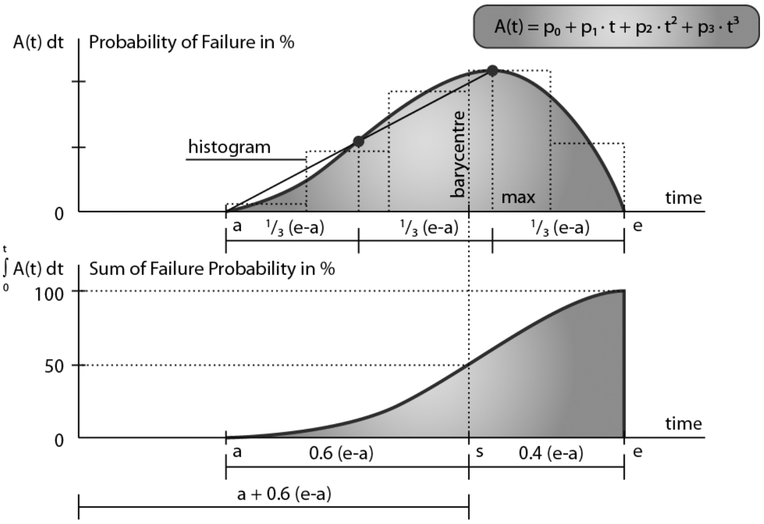


Figure 2. Failure probability and sum of the failure

The starting point of the bridge's service life – in terms of the safety level – is according to the initial over-design and depends on the applied design code and certain safety considerations in the course of the static calculations. To estimate the range of lifetime in the first step, statistic analyses using probability density functions are applied – covering the operational lifetime depending on the following parameters:

- cross section design
- static system
- material
- year of construction

Exemplified for the primary load bearing structure:

$$\text{Average design life} = a' + 0.6 * (e' - a') \qquad (1)$$

where

$$a' = a \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \text{....adapted lower bound life expectancy} \qquad (2)$$

$$e' = e \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \text{....adapted upper bound life expectancy} \qquad (3)$$

a=45 years……lower bound life expectancy

e= 120 years….upper bound life expectancy

k_1, k_2, k_3, k_4 ….factors for influence parameters (see also table 1)

Table 1. Parameters which influence the lifetime of a bridge

Year of construction	**k_1**	**Static system**	**k_3**
<1970	0,667	Vault	1,2
1971-1985	0,9	Frames and arches	1,05
>1986	1	Girder/beam, slab, other	1
Cross section design	**k_2**	**Material**	**k_4**
Solid cross section	1,05	Stone	1,2
Box girder	1	Concrete and reinforced concrete	1,1
T-beam, composite section etc.	0,95	Prestressed concrete, steel-concrete composite	1
Corrugated profile	0,8	Wood	0,8

To guarantee these stated ranges of theoretical design life of new structures the following aspects have to be considered:

- concrete cover
- concrete quality (concrete grade)
- environmental influences
- regular maintenance
- bridge monitoring

To address the deterioration process properly, the following sources of impact affecting the Structural Performance (t) are to be considered in detail:

- freight traffic volume
- level of freight traffic impact
- environmental influences (temperature, radiation, frost action)
- degradation due to chemical exposure

For demonstration purposes, a well established approach (suggested by A. Miyamoto (Japan) and D. Frangopol (USA)) [1,2] is described briefly, which covers all the major sources of deterioration impact. For the present demands these suggestions will necessarily have to be broadened and refined due to each of the listed major issues.

The task of chloride induced corrosion – covered with the CUR Guideline “Sustainability of constructional concrete in relation to chloride-initiated reinforcement corrosion” is to be highlighted in the current project.

Soundness (vertical axis) $h_n(t)$ - initial consideration (NEW Structures):

$$h_n(t) = b_n - a_n(t-t_n)^c \tag{4}$$

Where:

t: is the year of service life ending

n: the number of times a remedial action was taken by year t (Index)

a_n: the slope of the deterioration curve at the time the nth remedial action has been taken

b_n: the soundness of the existing bridge at the time the nth remedial action has been taken, which changes according to the effectiveness of the remedial action taken

c: is the power exponent of the deterioration equation

Updating consideration (Existing structures):

The parameters a and b are updated every time repair or strengthening is carried out by using the following equations:

$$b_n = h_n(t_n) \;=\; h_n-1(t_n)+R*\rho \tag{5}$$

$$R=(h_n-1(t_n-1)-h_n-1(t_n)) \tag{6}$$

$$a_n=a_0*\eta_n \tag{7}$$

Where:

ρ: parameter for reducing soundness recovery

a_0: the slope of the initial deterioration curve

η: parameter for increasing the rate of deterioration.

2.2 The determination/estimation of the design life of existing structures

Basically the same methodology and the same sources of impact are utilized for primary load bearing members as well as for secondary load bearing members. What makes the difference for the analysis itself is the fact that design assumptions are replaced as well as possible by everything, supporting a deeper understanding of the previous lifeline of the investigated structure:

- initial static calculation
- schedule of maintenance and rehabilitation measures
- loading history (historical traffic data)
- material tests (chloride penetration, carbonatisation, material strength, …)
- historical data about environmental exposure
- judgement / rating from bridge inspections
- performed monitoring campaigns

				Initial design safety level (acc. to comparison of γ_F old/new)						
				1	2	3	4	5		
			Weighting function	1,625	1,485	1,345	1,205	1,07		
		Weighting function		1,7-1,56	1,55-1,42	1,41-1,28	1,27-1,14		Rating	
Bridge inspection	1	1,625	1,7-1,56	1,625	1,553	1,478	1,399	1,319	≥1,56	1
	2	1,485	1,55-1,42	1,553	1,485	1,413	1,338	1,261	≥1,42	2
	3	1,345	1,41-1,28	1,478	1,413	1,345	1,273	1,200	≥1,28	3
	4	1,205	1,27-1,14	1,399	1,338	1,273	1,205	1,135	≥1,14	4
	5	1,07	1,13-1	1,319	1,261	1,200	1,135	1,070	<1,14	5

Figure 3. Maintenance condition matrix

Each of these variables can strongly affect the current maintenance condition and determine the offset between the initial safety level in the year of construction and the present date of judgment.

The continuative progression is derived in a similar way to new structure – but of course depends on the former impact. The use of the established maintenance condition matrix supports the individual determination of the current remaining structural resistance and the present risk level by means of a comprehensive weighting function.

2.3 Assessment criteria whether the real degradation process (determined by bridge monitoring) corresponds to the values in the life cycle model, in order to take corrective measures in case of an accelerated degradation

The approach is necessarily completely the same as shown in the previous section 2, as even designed new structures are becoming existing structures.

To cover this certain demand, a strong emphasis is to be put on in-situ investigations, especially full-scale dynamic monitoring, which turned out to reflect structural resistance and load bearing capacity in a most suitable manner.

Structural health monitoring (SHM) is the implementation of damage identification strategies to the civil engineering structures such as bridges. Damage is defined as changes to the material and / or geometric properties of the structures, including changes to the boundary conditions (e.g. settlements) and system connectivity. Appropriate SHM by measuring the structural behaviour with various kinds of sensors allows an objective assessment of the structures condition and actual performance. This is the basis for reliable damage detection, the prediction of the future performance and precise maintenance planning. SHM allows increasing the regular visual inspection intervals for bridges and therefore a reduction of inspection caused traffic impediment.

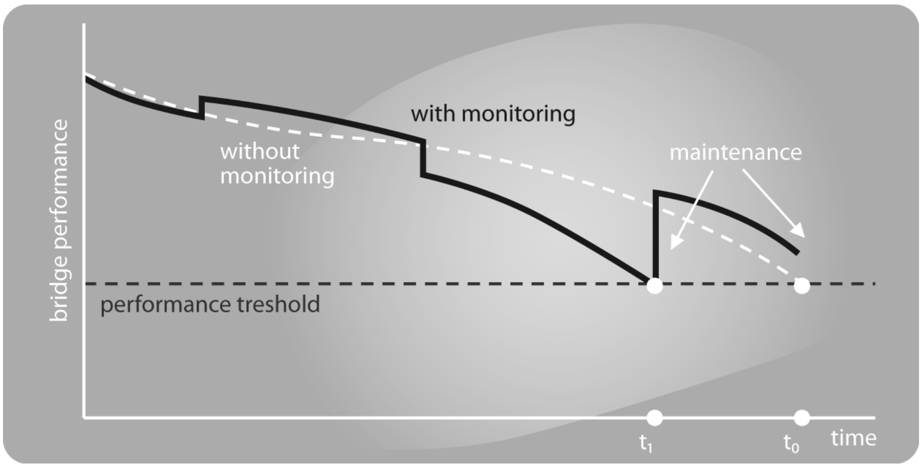


Figure 4. Bridge performance (soundness) over the time

The BRIMOS® concept (suggested by H. Wenzel (Austria)) [3,4] knows different levels of investigation depths. The appropriate investigation type has to be chosen for each bridge individually according to its size, age, condition, building type, load level and accessibility for a suitable investigation concept. SHM helps to avoid unnecessary repair works and to minimize maintenance caused traffic impediment. In general the BRIMOS® concept knows 3 levels of investigations:

1) Spot Observation

A spot observation shall comprise a very quick measurement campaign with only one or a few sensors, which are simple to handle. It brings information on the general condition of a bridge in direct comparison with the initial investigation. Spot observation shall be always scheduled within the routine maintenance procedures. The measurements can always be done on the cap or at the emergency lane without any traffic impediment.

2) Periodic Monitoring

Periodic assessment means a detailed measurement campaign on the bridges, which is repeated every 6 years to detected damages and to generate information on the performance over time. Periodic assessment allows performing the necessary measurements on the cap or on the emergency lane without traffic disturbance.

3) Permanent Monitoring

Permanent online monitoring means to apply various appropriate sensors in critical positions to the bridges and to record and analyse the measurement signals continuously. The results of the permanent data analysis will be transferred to a central user-interface. This allows an almost real-time condition monitoring for the bridges. In case the measurement results exceeds preset threshold values (e.g. in case of damages) visual alarms will be triggered on the user interface.

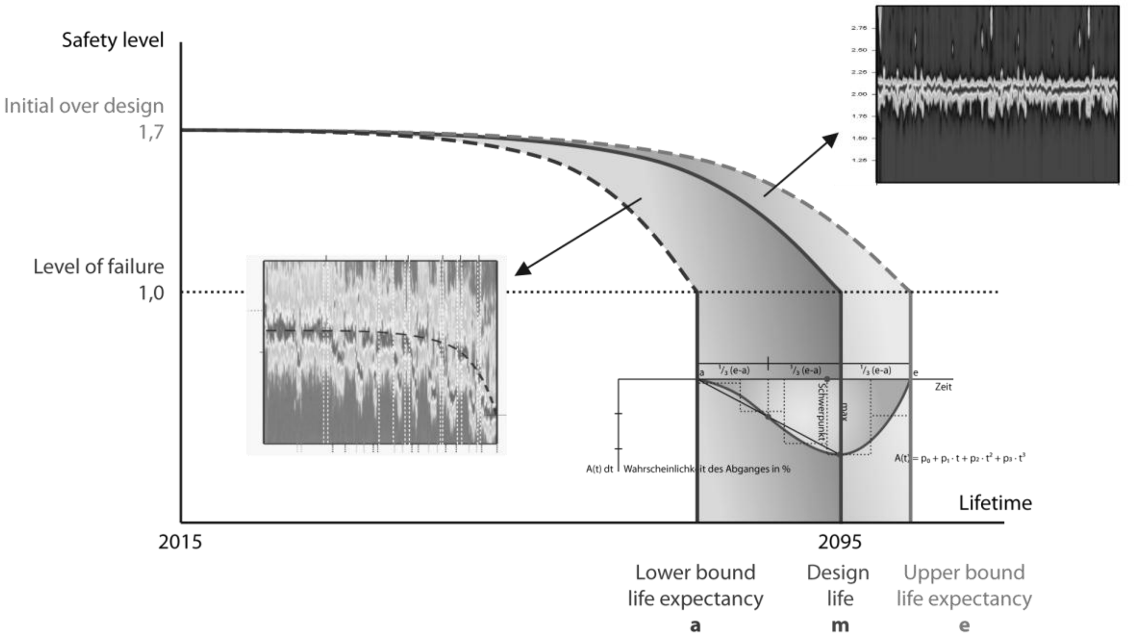


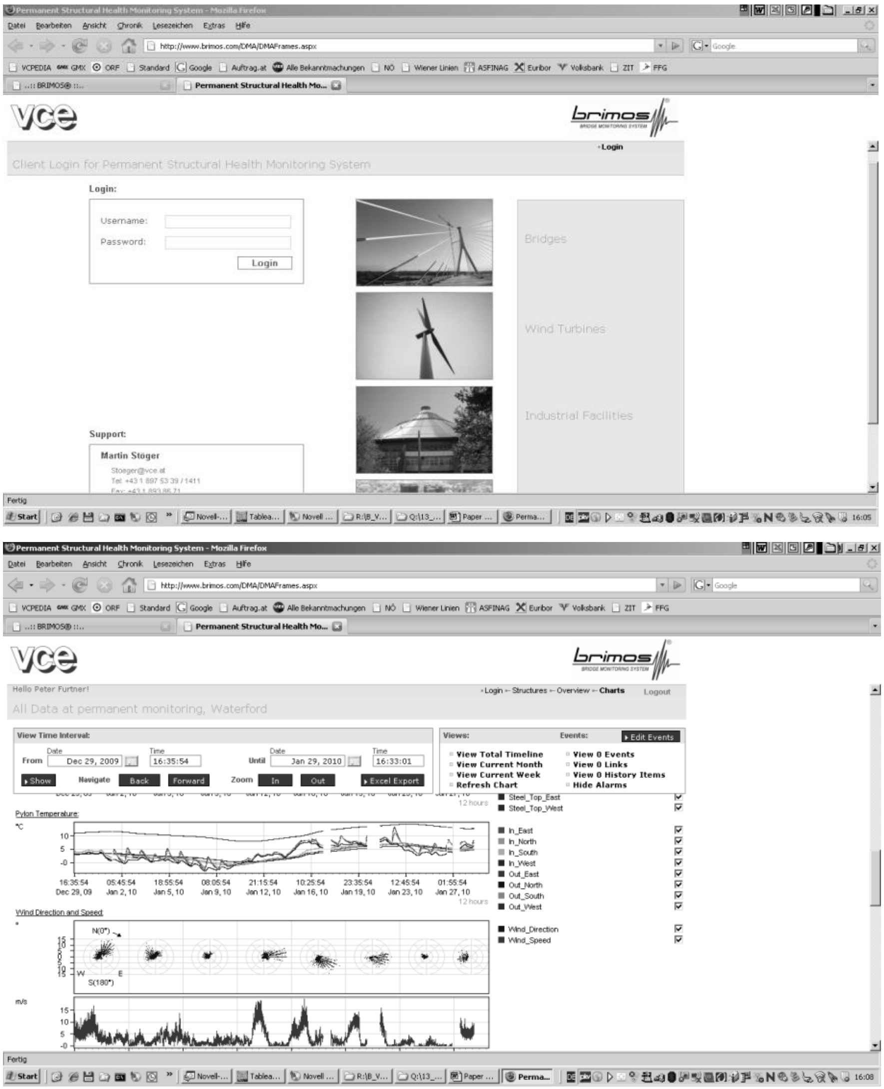
Figure 5. Expected (analytical) lifeline of structure, validated with BRIMOS® bridge inspection

Additionally to the user-interface a so-called "monitoring web-interface" will be implemented. Via UMTS or GPRS network the most important monitoring results together with status information on the monitoring systems will be directly transferred to the internet.

The web-interface will also be used for the maintenance of the permanent monitoring systems by the contractor. Function control, software updates and a support service are other main features of this web-interface.

The most important feature is the implementation of a Management Information System (MIS), where all maintenance relevant information is collected. At this terminal the results of the different monitoring levels will find together with information from visual inspections, pavement monitoring, weather stations and others.

This database and the analysis of its data will be used for performance prediction and an integrated maintenance planning. The MIS will provide periodic performance and maintenance reports in intervals agreed with the contracting authority or on demand. The main goal is to have only one management information system (MIS) which covers all maintenance features for the whole infrastructure. This is to provide easy handling and to avoid mistakes.



Permanent Structural Health Monitoring System - Mozilla Firefox

http://www.brimos.com/DMA/DMAFrames.aspx

Client Login for Permanent Structural Health Monitoring System

Login:

Username:
Password:

Support:

Martin Stöger
Stoeger@vce.at
Tel: +43 1 897 53 39 / 1411

Hello Peter Furtner!

All Data at permanent monitoring, Waterford

View Time Interval:

From Date Dec 29, 2009 Time 16:35:54
Until Date Jan 29, 2010 Time 16:33:01

Figure 6. BRIMOS® web-interface

Thus BRIMOS® offers a well-defined rating system for investigated structures. This classification allows a fast identification on the structure's integrity as well as the corresponding risk level based on measured dynamic parameters, visual inspection, Finite Element Model-update and reference data (BRIMOS® Database). By merging these sources of information the major task of determining the exact present position of the analysed structure on its lifeline is covered. Furthermore the result is a classification which is related to a predefined risk level. The experience of about 1000 investigated structures worldwide has been incorporated into the assessment procedure.

3 CONCEPT ELABORATED FOR THE A15 PROJECT

For the A15 project a maintenance plan was elabroated, which delivers all necessary measures for each single bridge under consideration of the individual service life of the different bridge elements over the whole contract period. Subsequently categorisation, which is coherent with the bridge inspection reports and the “DISK mainte-nance plans”, was prepared:

- superstructure / main structure
- substructure, foundation
- expansion joints
- asphalt/pavement
- drainage
- bearings
- edge beam
- guard rail
- railing

These basic maintenance intervals are adjusted using functions of the failure probability), considering the general conditions and sources of impact during the operating phase, which can be variable over the years, such as:

- heavy traffic volume and level of freight traffic impact
- environmental influences (temperature, radiation, frost action)
- degradation due to chemical exposure (a main factor in these considerations is the chloride initiated reinforcement corrosion)
- inspections (assessment/rating) and structural health monitoring.

As a result of the developed methodology the upper and the lower bounds of the life expectancy of the single bridge elements are determined, which supports the operator’s decision process in the course of maintenance planning.

4 CONCLUSIONS

In times of shringking budgets at public authoritities big infrastructure projects are put into the hands of private bodys in form of PPP models for a long period. As the payments to the private contractor depend on the availability of the infrastructure, either directly by tolls or indirectly by periodic payments from the authorities, a well elaborated maintenance concept is of major interest for the contractor. Appropriate condition assessment and condition monitoring of the infrastrucutre as well as life-cycle analysis and prediction are the basic tools for maintencance planing. The tools of strucutral health monitoring are perfectly suited for this purpose.

5 REFERENCES

Bondini, F. and Frangopol, D.M., 2008. Life-Cycle Civil Engineering. CRC Press Taylor and Frances Group, Lon-don. ISBN: 978-0-415-46857-2 (hbk)

Cruz, P.J.S, Frangopol, D.M., Neves, L.C., eds. 2006. Bridge Maintainence, Safety, Management, Life-Cycle Perform-ance and Cost. Taylor & Fracis, London. ISBN: 0415403154

Wenzel, H., 2008. Health Monitoring of Bridges, J. Wiley and Sons Ltd, ISBN0470031735; Chichester England.

Wenzel, H., Pichler, D., 2005. Ambient Vibration Monitoring, J. Wiley and Sons Ltd, ISBN 0470024305; Chichester England.