eBook of the 1st Workshop Meeting
Geneva, September 21st – 22nd 2015

Editors: Jose C. Matos, Joan R. Casas, Eleni N. Chatzi, Niels P. Høj, Alfred Strauss, Irina Stipanovic, Rade Hajdin

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Opening Note from the Chair

COST Action TU1406 aims to address the European economic and societal needs by standardizing the condition assessment and maintenance level of roadway bridges. Currently, bridge quality control plans vary from country to country and, in some cases, within the same country. This therefore urges the establishment of a European guideline to surpass the lack of a standard methodology to assess bridge condition and to define quality control plans for roadway bridges.

Such a guideline will comprise specific recommendations for assessing performance indicators as well as for the definition of performance goals, bringing together different stakeholders (e.g. universities, institutes, operators, consultants and owners) from various scientific disciplines (e.g. on-site testing, visual inspection, structural engineering, sustainability, etc.) in order to establish a common transnational language.

COST Action TU1406 Workshops aim to facilitate the exchange of ideas and experiences between active researchers and practitioners as well as to stimulate discussions on new and emerging issues in line with the conference topics. This first Workshop essentially focuses on WG1 issues, namely, intends to address performance indicators, how these are assessed (e.g. visual inspection, non-destructive tests and monitoring systems), with what frequency and what values are generally obtained. The main outcomes, given in this eBook, were really important, not only for WG1 developments, but also for all the other WGs and for the Action itself.

Jose C. Matos
Chair COST Action TU1406
Note from the Vice Chair

The meeting of COST Action TU1406 in Geneva has been the first one where presentations and discussions related to the different working groups in the Action took place. Due to the relevance for the success of the first part of the Action, the main work was devoted to the state-of-the-art and the different approaches along Europe on the performance indicators used by the different owners and operators to meet the quality expectations of the users.

Apart from oral presentations, 25 posters were delivered with a very high quality which served as the initial seed for the main task that Working Groups 1 to 3 are facing. This is the construction of a large European-wide data base containing the performance indicators and performance goals used in the countries participating in the Action. This data base will be the milestone from where the standardization and homogenization of the condition assessment and maintenance level of roadway bridges in Europe can be finally build up. The bases for the elaboration of this data base have been settled in this first meeting in Geneva.

The large number of participants in the Action as well as the excellent attendance in this meeting show the interest around Europe in the objectives of the Action. As pointed out several times during the presentations and discussions in this first WG meeting, it is of paramount importance the involvement of academics as well as professionals working in the field of highway bridge assessment and management. The meeting in Geneva has been a key point to start the collaborative work between both parts. In summary, looking to the success of this kick-off WGs meeting, we may be confident on the achievement of the required standardization of the quality specifications for highway bridges in Europe.
Note from the Local Organizers

As general secretariat and member of the Local Organizing committee, it has been a pleasure to host the 1st Workshop of the COST TU1406 Action in Geneva, Switzerland. The principal aim of the COST Action is to facilitate the identification of maintenance needs within the roadway bridge management process, and to provide performance indicators which enable the enforcement of this scheme in a uniform and repeatable, i.e., standardized manner.

The value of this Action therefore lies beyond its obvious academic merit, delivering a framework which is at this point in time urgently needed by practitioners worldwide. This first workshop essentially framed the overarching goals, processes and eventual deliverables of this COST action and defined the foundations of the joint effort to follow.

The COST Action TU1406 comprises members from nearly all European Countries, as well as countries outside Europe. Wide participation is an important feature of these actions, whose scope is to form a European research area across borders and interlink high-quality research and practice communities in Europe and worldwide.

Within the context of the COST Mission and with the goal of improving cooperation within the COST countries and beyond, we cannot think of a better place to meet than the city of Geneva. Geneva is a global city, a worldwide centre for diplomacy and hosts many international organizations including the headquarters of many of the agencies of the United Nations. Geneva also comprises a high-tech city, well known for organisations like CERN (European Organization for Nuclear Research).

With these words: It is a pleasure to welcome the first Workshop of the COST TU1406 Action in Geneva!

Prof. Eleni Chatzi

Mr. Niels Peter Høj
Acknowledgment

The editors would like to thankfully acknowledge the contribution of those who supported the execution of this event:

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Sérgio Fernandes, Technical Support of COST Action TU1406

Henar Martín-Sanz, PhD candidate, Department of Civil, Environmental and Geomatic Engineering, ETH Zürich
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**COST ACTION TU1406**

**SLIDE 8**
WG1: Performance indicators for road bridges

Preface

Life-cycle analyses methods are used for the assessment of new and existing bridges, as well as for the evaluation of maintenance strategies. Management systems, capturing different degradation processes, are very often used in relation to such life-cycle analyses methods. Such systems, developed for a structural condition assessment, are usually based on deterministic performance prediction models which describe the future condition by a functional correlation between structural condition attributes, such as the structural age, and the mechanical, chemical and thermal loading processes.

Each construction, during its life cycle, will face with deterioration depending on several factors such as the environmental condition, the natural aging, the quality of the material, the execution of works and the planned maintenance. Therefore, several design procedures based on the prediction of the deterioration that will likely act on the structure will be developed in the framework of the international research. In addition, performance Indicators for the present and future structural conditions on deterministic and probabilistic level will be defined and determined. It is known that management systems are supported in QC plans which in turn are supported by performance indicators. Therefore, it is extremely important to analyze such indicators in terms of used assessment frameworks (e.g. what kind of equipment and software is being used), and in terms of the quantification procedure itself. In this particular work package, the objectives will be the collection and analysis of practical and research based performance indicators.
First results of TU1406 – Technical Survey on Performance Indicators

Working Group 1

TG 1.1: KPIs for Load-bearing Capacity and Serviceability
TG 1.2: KPIs for System Behaviour and Inspection
TG 1.3: KPIs for Conservation of Structures
TG 1.4: Environmental and Other Sustainable KPIs

National expert panels for identification and definition of KPIs

International research panels for identification and definition of KPIs

Structuring of the KPIs database
Life Cycle Framework
Life Cycle Framework

DATABASE
- Design File: special conservation strategy
- As-Built Documentation: Birth-Certificate document
- Service Life File: finaly conservation strategy
- Service Life File: inspection/monitoring data
- Service Life File: intervention data

INTERVENTION PLAN
Life Cycle Framework

DATABASE

Design File special conservation strategy
As-Built Documentation Birth-Certificate document
Service Life File finally conservation strategy
Service Life File intervention data

INTERVENTION PLAN

Birth Certificate

COMPONENT P-Indicators P-Goals

Main Girder
Slab
....
Cantilever

DEGRADATION P-Indicators P-Thresholds

Chlorides
Carbonisation
Freeze Thaw
Alkali-aggregate
Chemical Attack
Fatigue
Mechan. Property Shear
Life Cycle Framework

DATABASE
- Design File (special conservation strategy)
- As-Built Documentation (Birth-Certificate document)
- Service Life File (finaly conservation strategy)
- Service Life File (inspection/monitoring data)
- Service Life File (intervention data)

DATABASE

INTERVENTION PLAN
- Birth Certificate

COMPONENT
- P-Indicators
- P-Goals
- Main Girder
- Slab
- ....
- Cantilever

DEGRADATION
- P-Indicators
- P-Thresholds
- Chlorides
- Carbonisation
- Freeze Thaw
- Alkali-aggregate
- Chemical Attack
- Fatigue
- Mechn. Property Shear

INTERVENTIONS

COSTS
First results of TU1406 – Technical Survey on Performance Indicators

**Life Cycle Framework**

- **DATABASE**
  - Design File
  - As-Built Documentation
  - Service Life File
  - Service Life File Data

- **INTERVENTION PLAN**
  - Birth Certificate

- **COMPONENT P-Indicators P-Goals**
  - Main Girder
  - Slab
  - Cantilever
  - ....

- **DEGRADATION P-Indicators P-Thresholds**
  - Chlorides
  - Carbonisation
  - Freeze Thaw
  - Alkali-aggregate
  - Chemical Attack
  - Fatigue
  - Mechan. Property Shear

- **INFRASTRUCTURE SYSTEM**
  - P-Indicators
  - P-Goals

- **STRUCTURAL SYSTEM**
  - P-Indicators
  - P-Goals

- **INTERVENTIONS**

- **COSTS**
Documents uploaded

15 Countries

15 Countries

more than 100 documents

Austria
Czech Republic
Denmark
Germany
Hungary
Luxembourg
Netherlands
Portugal
Serbia
Slovakia
Slovenia
Spain
Sweden
Switzerland
United Kingdom
Challenges
Different types of documents
Applied/operator associated documents
Research associated documents
Contact to operators
Providing documents (legal situation)
Languages

Nomination of MC contact persons
Nomination of country responsible persons
Call for research specific documents
First results of TU1406 – Technical Survey on Performance Indicators

**Roadmap WG1**

**I**nspetion, **E** valuation, **B** ackground

- Nomination of **MC members** for:
  - contacting owners and operators of roadway bridges asking for
  - uploading I-DOC, E-DOC, B-DOC

- Nomination of **operating persons** per country for:
  - processing national documents according to **guidelines**
  - screening I-DOC, E-DOC, B-DOC

- **Core group WG1**
  - processed documents
  - transferring to Access Database

- **Core group WG1 - 3**

- **Analyzing PI - Database**

- **Geneva**
  - publishing official COST e-Book WG1 activities

- **January**
  - Preparation of WG1 activity and endreport

- **Belgrade**
First results of TU1406 – Technical Survey on Performance Indicators

**Roadmap WG1**

**I Inspection, E Evaluation, B Background**

**Nomination of MC members for:**
- contacting owners and operators of roadway bridges asking for
- uploading I-DOC, E-DOC, B-DOC

**Nomination of operating persons per country for:**
- processing national documents according to guidelines
- screening I-DOC, E-DOC, B-DOC

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**Geneva**
- publishing official COST e-Book WG1 activities

**January**
- Preparation of WG1 activity and endreport

**Belgrade**
- contacting owners and operators of roadway bridges asking for
- uploading I-DOC, E-DOC, B-DOC

**Call to researcher for:**
- uploading Performance associated documents

**Transferring documents to Access Database**
- analyzing PI - Database
Screening procedure - **Inspection** documents

**SURVEY DATABASE**

- Screening of documents

- **Applied documents**
  - Inspection documents *national mandatory*
  - Background documents
  - Case Studies

- **Evaluation documents** *national mandatory*
  - Advanced recommendations

- **Breaking down**
  - PI indexing
  - PI method
  - Performance goals/thresholds
  - Lower/upper limit range

**Importing PI in Applied Database**
## Screening procedure - **Inspection** documents

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<th>Title</th>
<th>Country</th>
<th>Type</th>
<th>Year, Author</th>
<th>Up-loader</th>
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<th>WG</th>
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<th>Threshold</th>
<th>Goal</th>
<th>Criteria</th>
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Screening procedure - Evaluation documents

A: Basics of document
Title: ONR24008
Country: Austria
Type: Evaluation
Issue year: 2012
Author: AS
Nom. Operator: Ivan Zambon

B: Structuring the document
Break down document into chapters
Discard chapters not of relevance
Assign WGs to chapters

C: Indexing chapters
Performance index
Performance level
Performance method

D: Condition assessment and decision making
Evaluation Component/system
Threshold Upper/lower limit
Goal E.g. reliability level
Criteria Min- maximizing

E: Possible attachments
Flow diagrams
Figures
Case Studies
Short explanations
Tables

ACCESS database
Screening procedure - Research documents

A: Basics of document
Up-loader: Alfred Strauss .. responsible for DB

B: Structuring the document
Break down document into chapters
Discard chapters not of relevance
Assign WGs to chapters

C: Indexing
Performance
Performance level
Performance method
Others

D: Condition assessment
Evaluation Component/system
Threshold Upper/lower limit
Goal E.g. reliability level
Criteria Min- maximizing

E: Possible attachments
Equations
Flow diagrams
Figures
Case studies
Short explanations
Tables

ACCESS database
Processed by uploader
First results of TU1406 – Technical Survey on Performance Indicators

Interaction between WGs DB

WG1 Performance indicators

**Chair: Strauss**

WG2 Performance goals

**Chair: Stipanovic**

WG3 QC plans

**Chair: Hajdin**

---

**Applied Documents**

- DB - Inspection
- DB - Evaluation
- DB - Background

**Research Documents**

- DB - Inspection
- DB - Evaluation
- DB - Background

---

**C: Indexing chapters**

- index
- level
- method

**D: Condition assessment**

- Evaluation
- Threshold
- Goal
- Criteria

**E: Possible attachments**

- Flow diagrams
- Figures
- Case Studies
- Short explanations
- Tables

**ACCESS database**
Interaction between WGs
IABMAS 2016 8th International Conference on. Bridge Maintenance, Safety and Management June 26 - 30, 2016 | Foz do Iguaçu | Brazil. Call for Abstracts
MS6: Novel techniques regarding the assessment and monitoring of bridges
SS3: Assessment and decision-making procedures for the life-cycle management of existing concrete bridges

IALCCE 2016: The Fifth International Symposium on Life-Cycle Civil Engineering, to be held in Delft, the Netherlands, from October 16 to 19, 2016. Call for Abstracts
SS13: System capacity and robustness for new and existing structures
MS13: Integrative monitoring for the life-cycle performance of engineering structures

IABSE 2015: Conference on Structural Engineering, providing solutions to global challenges:
BT-03: Nonlinear structural analyses tools and safety formats

Hans Beushaus:

IABSE WC 1: Structural Performance, Safety and Analysis

Fib COM 3: Existing concrete structures, T3.1 Reliability and safety evaluation, T3.2 Modeling of structural performance of existing structures, T3.3 Assessment/evaluation procedures for existing structures, T3.4 Selection and implementation of interventions

IASSAR, SHMii, cost 1402, JCSS, IABSE and others, (c) findings of expert panels…
Performance Indicators for Bridges: Results Based on the ASCE-SEI Technical Council on Life-Cycle Performance, Safety, Reliability and Risk of Structural Systems

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2 ATLSS Center, Lehigh University, Bethlehem, PA, USA
3 Politecnico di Milano, Milan, Italy
ABSTRACT

Over the last three decades, the implementation of reliability methods for assessing the safety and evaluating the performance of structures and infrastructure systems has gained wide-spread acceptance in the structural engineering community. An increasing number of researchers are applying reliability methods directly for evaluating the safety of specific projects and structural systems. But, more importantly, reliability-based design specifications have been adopted for different types of structural systems, including bridges. As the use of structural reliability methods expands to new applications, a review of the performance indicators and criteria recently utilized, and those upon which existing specifications are based need to be investigated to help engineers to assess the adaptability of current approaches to new situations, such as aging and deterioration processes, maintenance actions and repair interventions, abnormal loads and accidental actions, emergency response to natural and man-made hazards, among others. To this purpose, a huge work has been carried out to review the formulation and implementation in practice of probabilistic performance indicators within the ASCE-SEI Technical Council on Life-Cycle Performance, Safety, Reliability and Risk of Structural Systems. The Technical Council was created in 2008, replacing the former ASCE-SEI Technical Administrative Committee on Structural Safety and Reliability and its associated Technical Committees (Buildings, Bridges, Offshore Structures, Fatigue and Fracture) with a new Council with revised and updated objectives and scope. The Technical Council provides a forum for reviewing, developing, and promoting the principles and methods of life-cycle performance, safety, reliability, and risk of structural systems in the analysis, design, construction, assessment, inspection, maintenance, operation, monitoring, repair, rehabilitation, and optimal management of civil infrastructure systems under uncertainty. To achieve these objectives, three Task Groups have been formed. This presentation will specifically report on the findings and recommendations made by Task Group 2 during the review of the literature related to the application of reliability-based structural system performance indicators, both in European and non-European countries, with emphasis on bridges.
Output-only data normalization for bridge damage indicators

G. De Roeck, E. Reynders, G. Lombaert
Department of Civil Engineering, KU Leuven, Kasteelpark Arenberg 40, B-3001 Leuven
Overview

• Introduction: modal properties = bridge performance indicators
• Vibration-based performance (damage) identification
• Operational Modal Analysis (OMA)
• Elimination of environmental influences (= data normalization)
• Conclusions
Vibration-based performance identification

Environmental influences (temperature, …)

Initial structure → Damaging influences on structure → Damaged structure

Traffic

Temperature

Earthquakes

Corrosion of steel

\[ f_i^0, \phi_i^0, \xi_i^0 \]
\[ i = 1, n \]

\[ f_i^1, \phi_i^1, \xi_i^1 \]
\[ i = 1, n \]

1. Is the structure damaged?
2. / 3. Location and intensity of the damage?
4. Remaining life time?

Is the structure damaged?

2. / 3. Location and intensity of the damage?

4. Remaining life time?
Operational Vibration Monitoring versus Static Load Test

- **Operational Vibration Monitoring**
  - load not to be measured
  - traffic not interrupted
  - fast
  - cheap
  - continuous
  - ....

- **Static Load Test:**
  - [see left: the opposite]
  - more correlated to remaining strength
  - ....
Operational Modal Analysis (OMA)

- Output-only or operational modal analysis became very popular as no artificial vibration source is needed which is anyhow impossible in many cases. Powerful time domain system identification algorithms like Stochastic Subspace Iteration (SSI) have replaced the obsolete “peak-picking” method.
- Although theoretically a white noise (unmeasured) excitation is assumed, in practice these algorithms provide accurate lower modes and good damping estimates, even in case of (moderately) “colored” excitation.
- To cope with the quite distinct vibration levels during operational and ambient loading, a large dynamic range of the sensors is required and a 24 bits resolution for the A/D conversion is advised.
- Main disadvantage is the dependence on the temporal and spatial characteristics of the unmeasured ambient loads, exciting a limited number of the lowest modes.
- Operational modal analysis can be used for a permanent monitoring installation.
Output-only data normalization for bridge damage indicators / G. De Roeck, E. Reynders, G. Lombaert
OMA: Wireless nodes (Jalon viaduct)

Wind

Free vibration
• Type of sensors:
  - Uniaxial ↔ triaxial
  - Wired ↔ wireless
  - Accelerometers ↔ displacement transducers ↔ strain sensors
- **Number of sensors:**
  - Permanent monitoring ↔ baseline/periodic measurement
  - Number of vibration modes (frequency interval of excitation!)
  - Avoid spatial aliasing
  - In case of available number of sensors < preferred number: multiple setups
Output-only data normalization for bridge damage indicators / G. De Roeck, E. Reynders, G. Lombaert

The measurement nodes (located at the bottom flange of the box girder)
OMA: Wireless nodes (Jalon viaduct)

OMA of the ambient data (MACEC)

Vertical accelerations under ambient excitations at one of the reference nodes.

Representative stabilization diagram.
OMA: Wireless nodes (Jalon viaduct)

Lateral bending modes

Mode 1 (0.648 Hz, 0.75%)

Mode 2 (1.238 Hz, 0.491%)
OMA: Wireless nodes (Jalon viaduct)

Vertical bending modes

Mode 4 (3.279 Hz, 0.42%)
Mode 6 (3.758 Hz, 0.54%)
OMA: Increase the number of excited modes

Measured (Forced: shaker, pneumatic muscle, drop weight, impact hammer, ..)
Elimination of environmental influences

- Environmental changes like temperature variations may have an important influence on features of the modal characteristics such as natural frequencies. So they may mask the influence of damage completely. A second cause of inherent variance is due to estimation errors while applying system identification algorithms to the measured response data.
- So far the influence of the environment on mode shapes and modal strains is less understood.
- To connect changes of dynamic features, e.g. natural frequencies, mode shapes and/or modal strains, to damage, it is of paramount importance to account for this environmental variability. Therefore, global prediction models should be derived from measurements over a long time span, preferentially covering the complete range of possible environmental parameter values.
Elimination of environmental influences

• A possible approach for constructing the global prediction model is measuring the environmental factors that influence the damage-sensitive features, and identifying a black-box model with these environmental factors as inputs and the corresponding features as outputs. However, a major difficulty with this input-output approach is to determine which environmental (or even operational) influences should be measured, and where the corresponding sensors should be placed.

• This can be overcome by employing output-only system identification methods, for which measurement of the environmental parameters is not necessary.
Elimination of environmental influences: output-only prediction model

- In a first (training) step the available data are split in time sequences that are short compared to the parameter variations, and damage-sensitive features are estimated for each individual sequence.
- Then the second step consists in identifying a nonlinear prediction model, where the time-varying features of the first step are considered as outputs.
- The validity of this model can be checked by applying it to new data of the still intact structure.
- Then, the structure can be monitored by continuously repeating the first step. The features found in this way are compared with the ones predicted by the model of the second step. When the discrepancy becomes large, the model alone insufficiently explains the evolution of the features, so the structure may be damaged.

Elimination of environmental influences: output-only prediction model

- An improved output-only technique for constructing a nonlinear prediction model is developed and validated on real-life monitoring data. It is based on Gaussian kernel PCA, where the two parameters of the model are automatically determined.
- The first parameter, which represents the standard deviation of the Gaussian (or radial basis function) kernel is chosen in such a way that the matrix of mapped output correlations is maximally informative, as measured by Shannon’s information entropy.
- The second parameter, which equals the number of principal components in the mapped feature space, is chosen in such a way that the retained principal components amount for nearly all normal environmental and operational variability.

Elimination of environmental influences: output-only prediction model (Z24 bridge)

Output-only data normalization for bridge damage indicators / G. De Roeck, E. Reynders, G. Lombaert
Elimination of environmental influences: output-only prediction model (724 bridge)

Date | Scenario
--- | ---
04.08 | Undamaged condition
09.08 | Installation of pier settlement system
10.08 | Lowering of pier, 20 mm
12.08 | Lowering of pier, 40 mm
17.08 | Lowering of pier, 80 mm
18.08 | Lowering of pier, 95 mm
19.08 | Lifting of pier, tilt of foundation
20.08 | New reference condition
25.08 | Spalling of concrete at soffit, 12 m²
26.08 | Spalling of concrete at soffit, 24 m²
27.08 | Landslide of 1 m at abutment
31.08 | Failure of concrete hinge
02.09 | Failure of 2 anchor heads
03.09 | Failure of 4 anchor heads
07.09 | Rupture of 2 out of 16 tendons
08.09 | Rupture of 4 out of 16 tendons
09.09 | Rupture of 6 out of 16 tendons
Elimination of environmental influences: output-only prediction model (Z24)

- The Z24 data are used for to apply both linear and kernel PCA. Selection of the modal parameters from the stabilization diagram was done in an automated way. The first four natural frequencies are taken as damage-sensitive features. They correspond with a vertical bending mode around 4 Hz, a lateral bending mode around 5 Hz, and two modes combining vertical bending and torsion around 10 and 11 Hz.

- A total of $n_t = 3000$ data points, which amounts to about 50% of the number of data points available, are used for training the model. The other data points are used for monitoring.

- For the kernel PCA, the parameter in the radial basis function kernel is determined by maximizing the information entropy. Next, the number of retained principal components $n_u$ is determined based on the criterion that $n_u$ should account for at least a certain fraction (e.g. 99%) of the normal variability.
Elimination of environmental influences: output-only prediction model (Z24)

Z24 bridge, misfit of the **linear** output-only model constructed with 3000 data points. **Blue**: training data. **Green**: monitoring data in undamaged condition. **Red**: monitoring data in damaged condition.
Elimination of environmental influences: output-only prediction model

Z24 bridge, misfit of the \textit{nonlinear} output-only model constructed with 3000 data points. \textcolor{blue}{Blue}: training data. \textcolor{green}{Green}: monitoring data in undamaged condition. \textcolor{red}{Red}: monitoring data in damaged condition.
Elimination of environmental influences: input-output prediction model

- As an alternative, a nonlinear prediction model, that takes the measured temperatures as inputs and the estimated modal characteristics (e.g. the natural frequencies) as outputs, can be constructed. This influence is in general nonlinear and it affects different modal characteristics in a different way, so nonlinear system identification techniques are required.

- The nonlinear system model is identified using modal characteristics that have been obtained during a reference period in which the structure is undamaged. During the subsequent monitoring period, the values that are predicted by this model (using the measured environmental variables such as temperatures as inputs) are compared with the modal characteristics that are actually observed.

E. Reynders, G. De Roeck. Robust structural health monitoring in changing environmental conditions with uncertain data. ICOSSAR 2013, June 16-20, New York.
Elimination of environmental influences: input-output prediction model

An efficient method for the identification of a nonlinear input-output environmental model is proposed. The output of the model is a sequence of vectors \( m_k \in \mathbb{R}^{nm} \) containing modal characteristics that have been estimated from short-term acceleration data. The input is a vector sequence of corresponding environmental variables \( u_k \in \mathbb{R}^{nu} \). Only the first \( n_t \) input-output samples (out of a total of \( n_s \) samples) are used as training data for identifying the model. After removal of the DC input component, this model reads

\[
m_k = W^T \varphi(u_k) + b + e_k,
\]

where \( u_k \in \mathbb{R}^{nu} \) is the vector with known inputs and \( e_k \) an error term that accounts for the misfit between the data and the model. The term \( b \) is the DC component of the output. \( \varphi \) represents a nonlinear mapping of \( u_k \) onto a possibly very high-dimensional or even infinite-dimensional mapped feature space \( G \).

\[
\varphi : \mathbb{R}^{nu} \rightarrow G, \quad u_k \rightarrow \varphi(u_k)
\]

E. Reynders, G. De Roeck. Robust structural health monitoring in changing environmental conditions with uncertain data. *ICOSSAR 2013, June 16-20, New York.*
Elimination of environmental influences: input-output prediction model

- The model is identified by LS-SVM in a least-squares sense under the additional constraint that the regression should be smooth.
- Once an environmental model is identified, the considered structure can be monitored by regular experimental determination of a modal characteristics vector $m_k$ and comparing it with the corresponding environmental model prediction $m_k^\text{^}.$
- An unwanted change causes the system to behave differently as in the period during which the environmental model was trained, so that the misfit $e_k$ grows.

In a stochastic analysis, the misfit is a random variable. Since both $m_k$ and $m_k^\text{^}$ are normally distributed, the misfit, which is the difference between both, is also normally distributed. A probabilistic damage indicator can now be adopted. One possibility is to use the Mahalanobis distance between the misfit and zero as damage indicator.
Elimination of environmental influences: input-output prediction model (Z24)

- The data of the Z24 bridge are used to investigate the performance of LS-SVM in solving the monitoring problem.

- The lowest two monitored natural frequencies, corresponding to the first vertical and first lateral mode, are taken as outputs and a subset of nine measured temperatures as inputs for the environmental model.

- A total of $n_t = 2664$ data points were used for training the model; in this way a large portion of the temperature range is covered by the training data. The other data points were used for monitoring. There are approximately as many monitoring data in undamaged condition as there are monitoring data in damaged condition.
Elimination of environmental influences: input-output prediction model (Z24)

Z24 bridge, Mahalanobis distance of the prediction error from zero.

Blue: training data. Green: monitoring data in undamaged condition.
Red: monitoring data in damaged condition.
Conclusions

Modal properties (obtained by OMA) are good performance indicators if …

• **Enough modes** can be identified with good accuracy. This is dependent on:
  – The frequency interval of excitation;
  – The number, the type and the sensitivity of the sensors.

• **Environmental influences** are eliminated (data normalization) with output-only or input-output methods.

• For the discovery of small local damage, a **distributed strain sensor network** with Bragg grating technology (FBGs), able to cope with the very low strain intensities during ambient excitation, can be developed. This will provide **modal strains**.
On the Modeling of Vulnerability, Robustness and Resilience of Infrastructure

Michael H. Faber, DTU Civil Engineering
Contents

- Context for decision making for infrastructures
- Rationale for decision optimization
- Challenges of system representation
- Framework for systems modeling and assessment
- Concluding remarks
Context of Engineering Decision Making

• What are we up against?

Corrosion

Fatigue
Context of Engineering Decision Making

- What are we up against?

Tornados and strong winds
Context of Engineering Decision Making

- What are we up against?

Earthquakes
Context of Engineering Decision Making

- What are we up against?

Earth slide
Rock fall
Context of Engineering Decision Making

- What are we up against?

Fires

Explosions
Context of Engineering Decision Making

• What are we up against?

Over load

Design error
Context of Engineering Decision Making

- What are we up against?

Bombs

Airplane impacts
Context of Engineering Decision Making

What are we up against?

Deepwater Horizon
April 20, 2010

11 fatalities
17 injured
Oil spill > 5 million barrels
Health effects?
Eco. imp. > 10 billion $US
BP response – 14 billion $US
22000 lost jobs
What are we up against?

Hurricane Katrina
August 23, 2005

> 1800 fatalities

Eco. imp. > 80 billion $US
Context of Engineering Decision Making

What are we up against?

**Fukushima Nuclear Event**
March 11, 2011

No fatalities ..?

Eco. imp. > 75 billion $US
Context of Engineering Decision Making

- What is needed?
  - Framework
  - Methods
  - Tools

which facilitate ranking of decision alternatives regarding

- Design
- Operation
- Maintenance, repair and renewal
- Decommissioning

of infrastructure systems
Rationale for Decision Optimization

- **Optimization**

![Diagram showing optimization process with Utility on the y-axis and Decision alternative on the x-axis. The diagram illustrates feasible decisions, optimal decision, and decisions related to vulnerability, robustness, and resilience of infrastructure.](image-url)
The SWTP criterion can be visualized with the following equation:

\[
dC_y(p) \geq -\frac{g}{q} C_x N_{PE} k dm(p)
\]

\[
\frac{C_y(p)q}{C_x N_{PE} k g}
\]

The diagram illustrates the relationship between the maximum acceptable failure rate, acceptable decisions, and the decision variable \( p \). The area defined by these parameters helps in visualizing the constraints and the decision optimization rationale.
Challenges of Systems Representation

Intergenerational risk management

- Decisions
- Criteria
- Collection of Information
- Actions

Facility

Facility boundary

World

Present

Future

Transfer of benefit, cost and reduced resources
Challenges of Systems Representation

Life Cycle Management – Individual projects

- Safety of personnel
- Safety of environment
- Economic feasibility

Best practices
- State of the art
- Codes
- Standards
- Regulations
- Procedures
- Involved people
- Involved organizations

Life time????
Non-ergodic phenomena??
Adaptation/options????
Challenges of Systems Representation

Life Cycle Management – Portfolios of projects

Best Practices

- Codes
- Regulations
- Standards

State of the art

Procedures

Economy-Safety-Environment

Life time??
Non-ergodic phenomena??
Adaptation/options???
Challenges of Systems Representation

Socio-economic framework - sustainability

Sustainable developments:

Meets the needs of the present without compromising the ability of future generations to meet their own needs

- Individual activities (projects)
- Portfolios of activities (portfolios/codes/standards)

Challenges of Systems Representation

Decision situations and measures of risk management

Time of impact of hazard on system

Before the hazard event  After the hazard event

Barrier 1
Forecasting
- warning
- avoiding
- evacuating

Barrier 2
Vulnerability adaptation

Barrier 3
Loss reduction
- Assessing
- Saving
- Leading
- Repairing

Barrier 4
Robustness/resilience adaptation
Uncertain systems
Generally, we do not know the exact characteristics of the system we are dealing with – often competing models may be formulated
System Modeling and Assessment

Treatment of uncertainty

- Risk and reliability informed decision making

Actions  Models of real world  Real World

Risk reduction measures

Exposure
Vulnerability
Robustness
Indicators
System Modeling and Assessment

The system representation as proposed by the Joint Committee on Structural Safety (JCSS)

# System Modeling and Assessment

<table>
<thead>
<tr>
<th>Scenario representation</th>
<th>Physical characteristics</th>
<th>Indicators</th>
<th>Potential consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exposure</strong></td>
<td>Flood, Ship impact, Explosion/Fire, Earthquake, Vehicle impact, Wind loads, Traffic loads, Deicing salt, Water, Carbon dioxide</td>
<td>Use/functionality, Location, Environment, Design life, Societal importance</td>
<td><strong>Direct consequences</strong> Repair costs, Temporary loss or reduced functionality, Small number of injuries/fatalities, Minor socio-economic losses, Minor damages to environment</td>
</tr>
<tr>
<td><strong>Vulnerability</strong></td>
<td>Yielding, Rupture, Cracking, Fatigue, Wear, Spalling, Erosion, Corrosion</td>
<td>Design codes, Design target reliability, Age, Materials, Quality of workmanship, Condition, Protective measures</td>
<td><strong>Indirect consequences</strong> Repair costs, Temporary loss or reduced functionality, Mid to large number of injuries/fatalities, Moderate to major socio-economic losses, Moderate to major damages to environment</td>
</tr>
<tr>
<td><strong>Robustness</strong></td>
<td>Loss of functionality, partial collapse, full collapse</td>
<td>Ductility, Joint characteristics, Redundancy, Segmentation, Condition, control/monitoring, Emergency preparedness</td>
<td><strong>Indirect consequences</strong> Repair costs, Temporary loss or reduced functionality, Mid to large number of injuries/fatalities, Moderate to major socio-economic losses, Moderate to major damages to environment</td>
</tr>
</tbody>
</table>
Engineered systems exhibit generic characteristics

System Modeling and Assessment

On the Modeling of Vulnerability, Robustness and Resilience of Infrastructure

System 1: "Oil field"
- Oil & gas demand
- Hurricanes
- Earthquakes
...

System 2: "FPSO"
- Wave-loads
- Wind-loads
- Ship impacts
...

System 3: "Frame"
- Extreme environ. loads
- Corrosion
- Fatigue
...

Exposure:

Robustness

Vulnerability

Indirect consequences

Directed consequences

Failure to deliver oil & gas

Reduced capacity of the field

FPSO failure

Failure of the hull structure

Failure of the frame

Failure of the joint

$c_{ID2}(S_k, c_D(C))$ $c_{D1} C_i$

$c_{ID3}(S_k, c_D(C))$ $c_{D2} C_i$
System Modeling and Assessment

Engineered systems exhibit generic characteristics
System Modeling and Assessment

Aggregating risks

Exposure events

Constituent failure events and direct consequences

Indirect consequences

Aggregated direct (and indirect) risks

Vulnerability

Robustness

System Modeling and Assessment

Quantification of risks

Direct risks:

Indirect risks:

\[ R_D = \sum_{k=1}^{n_{\text{EXP}}} p(C_{ij} \mid EX_k) c_{D_k}(C_{ij}) p(EX_k) \]

\[ R_{ID} = \sum_{k=1}^{n_{\text{EXP}}} \sum_{l=1}^{n_{\text{STA}}} p(S_l \mid EX_k) c_{ID_l}(S_l, c_D(C)) p(EX_k) \]

System Modeling and Assessment

Updating risks

Bayesian updating
- spatial
- temporal

\[ P(C_{ij} | e) = \frac{P(e | C_{ij})P(C_{ij})}{P(e | C_{ij})P(C_{ij}) + P(e | \overline{C_{ij}})(1 - P(C_{ij}))} \]
System Modeling and Assessment

System characteristics

Index of vulnerability: \( I_V = \frac{R_D}{\sum_{i=1}^{n_c} \hat{a}_i c_{D_i}} \)

Index of robustness: \( I_R = \frac{R_D}{R_D + R_{ID}} \)

\[
I_R = E_{\text{EXP}} \left[ E_{D|\text{EXP}} \left[ E_{S|\text{EXP},D} \left[ \frac{c_D(D, \text{EXP})}{c_D(D, \text{EXP}) + c_{ID}(S, D, \text{EXP})} \right] \right] \right]
\]

System Modeling and Assessment

Resilience

\[ R_T = R_D + R_{ID} = R_D + \int_{t_H}^{T} (u(t) - u(t)) \, dt \]

System Modeling and Assessment

Resilience

Index of resilience

Conditional index of resilience

Concluding Remarks

Systems modeling and assessment is challenging

- System functionalities and consequences
- Dependencies of causal and statistical character
- Dependencies over time and space
- External and “internal” exposures
- Metrics of sustainability
- Analysis of systems

...
WG2: Performance goals

Preface

The main objective of this work package is to identify existing performance goals (where under the term goal is meant quantifiable requirement and/or threshold value) for the indicators previously identified in WG1. The performance goals will vary according to technical, environmental, economic and social factors, which are making the basis of WG 2 structure.

The main milestone for this working group is to develop recommendations which will specify the performance goals, linked to the Key Performance Indicators. The report should be finished by the end of year 2. Within this workshop in Geneva we have opened discussions related to different bridge assessment procedures and strategies, as well as different performance goal understandings. The outcome of the workshop will help us to develop further the scope and next steps of WG 2.
WG 2 Performance goals

Irina Stipanovic
University of Twente, Netherlands
Main objective of WG 2

- To provide an overview of existing performance goals for the indicators previously identified in WG1.
- These goals will vary according to technical, environmental, economic and social factors.
- To develop recommendations which will specify the performance goals, linked to the Key Performance Indicators.
Performance goals
- society / users related

- Technical PGs
  - Reliability and safety related goals
- Sustainable PGs
  - Environmental impact related goals
- Other PGs
  - Economic and social based goals
Where are we now?

- Application process is still running
- The WG 2 will be established in Geneva
- Currently 54 applicants,

<table>
<thead>
<tr>
<th>No</th>
<th>WG</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>WG 2</td>
</tr>
<tr>
<td>15</td>
<td>WG 1 + WG 2</td>
</tr>
<tr>
<td>2</td>
<td>WG 2 + WG 3</td>
</tr>
<tr>
<td>2</td>
<td>WG 2 + WG 4</td>
</tr>
<tr>
<td>28</td>
<td>≥ 3 GROUPS (incl. WG 2)</td>
</tr>
</tbody>
</table>

- For WG 2 only: 3 registered for Geneva Workshop
  - 3 oral presentations and 5 posters
Upcoming tasks

– Encourage the road authorities to submit both inspections and evaluation (decision support) documents
– Analysis of submitted documents

Tasks in 2016/2017

– Establishment and enhancement of the database (with WG 1)
– Establishment of causal relationship between Performance Indicators and Performance Goals (with WG3)
– Database validation at the workshop (IALCCE 2016, Sep 2016)
– Guideline (May 2017)
WG 2 Performance Goals | Stipanovic Irina

KPIs for load-bearing capacity and serviceability of structures
KPIs for system behaviour and inspection
KPIs for Conservation of Structures
Environmental and Other Sustainable KPIs

CONDITION ASSESSMENT

PERFORMANCE REQUIREMENTS

RISK / PERFORMANCE ASSESSMENT

Technical Performance Goals
Sustainable Performance Goals
Other Performance Goals (economic and social)
Proposal of the WG 2 structure

TG 2.1: Technical Performance Goals

TG 2.2: Sustainable Performance Goals

TG 2.3: Other Performance Goals

National expert panels for identification and definition of PGs

International research panels for identification and definition of PGs

Structuring of the PG database
# ROAD MAP

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Establishment of the group and means of communication</td>
<td>Q4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Screening of the documents (Budapest, Belgrade)</td>
<td></td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>3</td>
<td>Database draft</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>for Technical PGs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>for Sustainable PGs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>for Economic PGs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Workshop - database validation (Delft)</td>
<td></td>
<td>Q4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Draft of the Guideline</td>
<td></td>
<td></td>
<td>Q1</td>
</tr>
<tr>
<td>6</td>
<td>Guideline</td>
<td></td>
<td></td>
<td>Q2</td>
</tr>
</tbody>
</table>
RELIABILITY LEVELS FOR EVALUATION OF EXISTING BRIDGES

Peter Koteš - University of Žilina, Slovakia
Josef Vičan - University of Žilina, Slovakia

UNIVERSITY OF ŽILINA
Faculty of Civil Engineering
INTRODUCTION

• Transport infrastructure plays an important role from an economic and management point of view in every country.

• Bridges - inseparable and strategically very important part of the transportation infrastructure, - they should have such parameters not to become the limiting component of the communication capacity and traffic reliability).

• It is needed to distinguish between reliability of newly designed structures and existing ones.

• The presentation deals with the reliability-based evaluation and determination of the modified reliability levels for evaluation of existing bridges according to Eurocodes.
The reliability level for newly designed structures for total design lifetime $T_d$ ($T_d = 50$ years) - $P_{f,d} = 7.2 \cdot 10^{-5}$ ($\beta_d = 3.8$).

**Table 1. Reliability indexes and failure probabilities according to EN 1990**

<table>
<thead>
<tr>
<th>Reliability Class</th>
<th>Minimum value for reliability index $\beta_d$ and minimum value for failure probability $P_{f,d}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 year reference period</td>
</tr>
<tr>
<td></td>
<td>$\beta_d$</td>
</tr>
<tr>
<td>RC3</td>
<td>5.2</td>
</tr>
<tr>
<td>RC2</td>
<td>4.7</td>
</tr>
<tr>
<td>RC1</td>
<td>4.2</td>
</tr>
</tbody>
</table>
The design lifetime of bridges is $T_d = 100$ years.

<table>
<thead>
<tr>
<th>Design working life category</th>
<th>Indicative design working life (years)</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>Temporary structures 1)</td>
</tr>
<tr>
<td>2</td>
<td>10 - 25</td>
<td>Replaceable structural parts, e.g. gantry girders, bearings</td>
</tr>
<tr>
<td>3</td>
<td>15 - 30</td>
<td>Agricultural and similar structures</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>Building structures and other common structures</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>Monumental building structures, bridges, and other civil engineering structures</td>
</tr>
</tbody>
</table>

1) Structure or parts of structures that can be dismantled with a view to being re-used should not be considered as temporary.
The reliability level for newly designed bridges for total design lifetime $T_d$ ($T_d = 100$ years) - $P_{f,d} = 1.3 \cdot 10^{-4}$ ($\beta_d = 3.652$).

Table 3. Reliability indexes and failure probabilities for structures and bridges

<table>
<thead>
<tr>
<th>Structure / member</th>
<th>Consequences class / Reliability class</th>
<th>Minimum value for $\beta_d$ and Minimum value $P_{f,d}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 year reference period</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\beta_d$</td>
</tr>
<tr>
<td>building CC2 / RC2</td>
<td></td>
<td>4.7</td>
</tr>
<tr>
<td>bridges CC2 / RC2</td>
<td></td>
<td>4.7</td>
</tr>
</tbody>
</table>
RELIABILITY-BASED EVALUATION

• The reliability level for evaluation of existing bridges for remaining lifetime $t_r$ is not given in the Eurocodes.

• The existing bridge structure - new information concerning the actual bridge condition (unknown in the design phase).

• The extra information unknown in the design phase can be used not only for verification of the correct bridge performance or for detection of possible mistakes concerning the computational model assumptions or calculations but also helps to reduce some uncertainty related to the bridge member resistance and load parameters entering the evaluation process.
RELIABILITY ANALYSIS

It is assumed that:

• The reliability margin \( G \) is the basic parameter of the structural element reliability, and it is described by the equation

\[
G(t) = R(t) - E(t). \tag{1}
\]

• Bridge structural element was designed for total lifetime \( T_d \) with corresponding reliability index \( \beta \geq \beta_d = 3.652 \).

• The bridge inspection was performed at time \( t_{\text{insp}} < T \), during which the observed structural element was found to be without relevant failure due to overcrossing its limit states

\[
R(t_i) > \max (E(t_i)) \quad \text{for} \quad i = 1 \ldots N(t_{\text{insp}}). \tag{2}
\]
RELIABILITY ANALYSIS

- The load effects $E(t_i)$ are mutually independent normally distributed and occur in succession but randomly in time. $N(t)$ is considered as the random variable having Poisson distribution with parameter $\nu(t)$.

- The updated failure probability $P_{fu}$ of the observed structural element at the time period $(t_{insp}, T)$ should be obtained by means of the conditional probability according to the formula

$$P_{fu} = \left( P_f(T) - P_f(t_{insp}) \right) / \left( 1 - P_f(t_{insp}) \right)$$

$$\beta_u = -\Phi^{-1}(P_{fu})$$
RELIABILITY ANALYSIS

Failure probability $P_f(T)$, $P_f(t_{insp})$ can be obtained for normally distributed bridge element resistance $R(t_i)$ and normally distributed load effects $E(t_i)$ using the following formula for complete probability

$$P_f(T) = P\left[ \max(E(t_i)(i = 1...N(T)) > R(t_i) \right] =$$

$$= 1 - \int_{-\infty}^{\infty} F(x) \cdot \int_{0}^{t} \varphi \left( \frac{x - m_R(\tau)}{s_R(\tau)} \right) \cdot \frac{1}{s_R(\tau)} \cdot f(\tau) d\tau dx$$

Random variables $R(t_i)$ and $E(t_i)$ may have another type of probability distribution, so, the solution of the failure probability $P_f(T)$ could be generalised as the following equation

$$P_f(T) = \int_{-\infty}^{\infty} \left[ 1 - e^{-L(t)} \left( 1 - \int_{0}^{t} F_E(x, \tau) \cdot f(\tau) d\tau \right) \cdot \int_{0}^{t} f_R(x, \tau) \cdot f(\tau) d\tau dx \right]$$

where $f_R(x,t)$ is the probability density function of the random variable resistance $R(t_i)$,

$F_E(x,t)$ is the distribution function of the random variable load effects $E(t_i)$. 
Using the information (formula (2)), the updated reliability index $\beta_u$ can be greater than designed index $\beta_d$. Next, we are able to solve back the adjusted target failure probability $P_{ft}$ (target reliability index $\beta_t$) for which the element should be evaluated for remaining lifetime ($T - t_{insp}$) so that we can achieve the required value of the target failure probability $P_{ft}$ with minimal one inspection.

*Fig. 1. Updated reliability index $\beta_u(t)$ and the target reliability index $\beta_t(t)$ dependent on inspection time*
Planned remaining lifetime \( t_r \) - the total lifetime is not \( T = 100 \) years, but it is equal to sum \( t_{\text{insp}} + t_r \).

**Fig. 2.** Target reliability index \( \beta(t) \) in dependence on time of inspection and planned remaining lifetime.
Table 4. Reliability levels for existing bridge evaluation not respecting degradation

<table>
<thead>
<tr>
<th>Remaining Lifetime [years]</th>
<th>The age of the bridge [years]</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>95</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>β₁</td>
<td>β₁</td>
<td>β₁</td>
<td>β₁</td>
<td>β₁</td>
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<td>β₁</td>
<td>β₁</td>
<td>β₁</td>
<td>β₁</td>
<td>β₁</td>
</tr>
<tr>
<td>2</td>
<td>3.161</td>
<td>2.977</td>
<td>2.857</td>
<td>2.767</td>
<td>2.694</td>
<td>2.632</td>
<td>2.578</td>
<td>2.530</td>
<td>2.487</td>
<td>2.466</td>
<td></td>
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<tr>
<td>5</td>
<td>3.358</td>
<td>3.212</td>
<td>3.112</td>
<td>3.035</td>
<td>2.972</td>
<td>2.918</td>
<td>2.871</td>
<td>2.829</td>
<td>2.791</td>
<td>2.773</td>
<td></td>
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<tr>
<td>50</td>
<td>3.604</td>
<td>3.563</td>
<td>3.526</td>
<td>3.494</td>
<td>3.465</td>
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<td></td>
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<tr>
<td>60</td>
<td>3.611</td>
<td>3.575</td>
<td>3.543</td>
<td>3.515</td>
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<tr>
<td>70</td>
<td>3.617</td>
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</tr>
<tr>
<td>80</td>
<td>3.621</td>
<td>3.592</td>
<td></td>
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<td></td>
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<tr>
<td>90</td>
<td>3.624</td>
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</tr>
</tbody>
</table>
PARTIAL SAFETY FACTORS

FOR MATERIALS:
• Considering log-normally distributed random variable resistance

\[ \gamma_c = \frac{R_k}{R_d} \cdot \gamma_{\text{conv}} = e^{(-\beta_K \cdot v_x + \alpha_R \cdot \beta_i \cdot v_R)} \cdot \gamma_{\text{conv}}, \quad \gamma_s = \frac{R_k}{R_d} = e^{(-\beta_K \cdot v_x + \alpha_R \cdot \beta_i \cdot v_R)} \]

Where
- \( \gamma_R = 0.8 \) is the sensitivity coefficient,
- \( v_R = 0.166 \) is the coefficient of variation of material resistance - concrete,
- \( v_R = 0.069 \) is the coefficient of variation of material resistance - reinforcement,
- \( v_x = 0.150 \) is the coefficient of variation of material strength - concrete,
- \( v_x = 0.040 \) is the coefficient of variation of material strength - reinforcement,
- \( \gamma_{\text{conv}} = 1.15 \) is the coefficient of conversion for concrete,
- \( \gamma_t \) is the recommended target reliability index depending on the age of the bridge and on the planned remaining lifetime,
- \( \gamma_k = 1.645 \) is the reliability index corresponding to probability 5 % (valid for characteristic values),
## PARTIAL SAFETY FACTORS

### Table 5. Partial safety factor $\gamma_c$ for concrete strength valid for existing bridge evaluation

<table>
<thead>
<tr>
<th>Planned remaining lifetime $t_r$ [years]</th>
<th>$\gamma_c$ for bridge age [years]</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\leq 60$ years</td>
<td>$&gt; 60$ years</td>
<td></td>
</tr>
<tr>
<td>$\leq 5$</td>
<td>1.30</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>5 – 10</td>
<td>1.35</td>
<td>1.30</td>
<td></td>
</tr>
<tr>
<td>10 – 20</td>
<td>1.40</td>
<td>1.35</td>
<td></td>
</tr>
<tr>
<td>$&gt; 20$</td>
<td>1.45</td>
<td>1.40</td>
<td></td>
</tr>
</tbody>
</table>

### Table 6. Partial safety factor $\gamma_s$ for reinforcement valid for existing bridge evaluation

<table>
<thead>
<tr>
<th>Planned remaining lifetime $t_r$ [years]</th>
<th>$\gamma_s$ for bridge age [years]</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\leq 60$ years</td>
<td>$&gt; 60$ years</td>
<td></td>
</tr>
<tr>
<td>$\leq 5$</td>
<td>1.10</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>5 – 10</td>
<td>1.10</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>$&gt; 10$</td>
<td>1.15</td>
<td>1.10</td>
<td></td>
</tr>
</tbody>
</table>
PARTIAL SAFETY FACTORS FOR LOAD EFFECTS

PERMANENT LOADS:

- Considering normally distributed random variable permanent loads

\[ \gamma_{G,i} = \gamma_{sd} \cdot \frac{E_d}{E_k} = \gamma_{sd} \cdot \frac{\mu_{G,i} \cdot (1 + \alpha_E \cdot \beta_t \cdot v_G)}{\mu_{G,i}} = \gamma_{sd} \cdot (1 + \alpha_E \cdot \beta_t \cdot v_{G,i}) \]  \hspace{1cm} (9)

Where
\[ \gamma_E = 0.70 \] is the sensitivity coefficient of loads,
\[ E_d \] is the design value of loads,
\[ E_k \] is the characteristic value of loads,
\[ \gamma_{sd} = 1.05 \] is the partial safety factor of model uncertainties,
\[ v_{G,i} \] are the coefficients of variation of single permanent loads,
\[ v_{G,i} = 0.100 \] – for cast-in-place made produces,
\[ v_{G,i} = 0.050 \] – for factory-made produces and transported to construction,
PARTIAL SAFETY FACTORS FOR LOAD EFFECTS

Table 7. Partial safety factor $\gamma_{G,i}$ of permanent loads - cast-in-place made produces

<table>
<thead>
<tr>
<th>Planned remaining lifetime $t_r$ [years]</th>
<th>$\gamma_{G,i}$ for bridge age [years]</th>
<th>≤ 60 years</th>
<th>&gt; 60 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 5</td>
<td></td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>5 – 10</td>
<td></td>
<td>1.30</td>
<td>1.25</td>
</tr>
<tr>
<td>&gt; 10</td>
<td></td>
<td>1.30</td>
<td>1.30</td>
</tr>
</tbody>
</table>

Table 8. Partial safety factor $\gamma_{G,i}$ of permanent loads - factory-made produces and transported to construction

<table>
<thead>
<tr>
<th>Planned remaining lifetime $t_r$ [years]</th>
<th>$\gamma_{G,i}$ for bridge age [years]</th>
<th>≤ 60 years</th>
<th>&gt; 60 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 5</td>
<td></td>
<td>1.20</td>
<td>1.20</td>
</tr>
<tr>
<td>5 – 10</td>
<td></td>
<td>1.20</td>
<td>1.20</td>
</tr>
<tr>
<td>&gt; 10</td>
<td></td>
<td>1.25</td>
<td>1.20</td>
</tr>
</tbody>
</table>
PARTIAL SAFETY FACTORS FOR LOAD EFFECTS

VARIABLE LOADS DUE TO TRAFFIC:
• Considering Gumble distributed random variables

\[
\gamma_Q = \gamma_{sd} \frac{E_d}{E_k} = \gamma_{sd} \cdot \frac{\mu_Q \cdot \left\{1 - v_Q \left[0,449 + 0,778 \cdot \ln(-\ln\Phi(\alpha_E \cdot \beta_i))\right]\right\}}{\mu_Q \left\{1 - v_Q \left[0,449 + 0,778 \cdot \ln(-\ln(0,95))\right]\right\}}
\]

(10)

Where
\[\gamma_E = 0.70\] is the sensitivity coefficient of loads,
\[E_d\] is the design value of loads,
\[E_k\] is the characteristic value of loads,
\[\gamma_{sd} = 1.05\] is the partial safety factor of model uncertainties,
\[v_{Q,i}\] are the coefficients of variation of variable loads,
\[v_{Q,i} = 0.194\] – for loads on road bridges,
\[v_{Q,i} = 0.241\] – for loads on railway bridges,
### Partial Safety Factors for Load Effects

**Table 9. Partial safety factor $\gamma_{Q,i}$ of variable loads on road bridges**

<table>
<thead>
<tr>
<th>Planned remaining lifetime $t_r$ [years]</th>
<th>$\gamma_{Q,i}$ for bridge age [years]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\leq 60$ years</td>
<td>$&gt; 60$ years</td>
</tr>
<tr>
<td>$\leq 5$</td>
<td>1.15</td>
<td>1.10</td>
</tr>
<tr>
<td>5 – 10</td>
<td>1.25</td>
<td>1.20</td>
</tr>
<tr>
<td>$&gt; 10$</td>
<td>1.30</td>
<td>1.25</td>
</tr>
</tbody>
</table>

**Table 10. Partial safety factor $\gamma_{Q,i}$ of variable loads on railway bridges**

<table>
<thead>
<tr>
<th>Planned remaining lifetime $t_r$ [years]</th>
<th>$\gamma_{Q,i}$ for bridge age [years]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\leq 60$ years</td>
<td>$&gt; 60$ years</td>
</tr>
<tr>
<td>$&lt; 5$</td>
<td>1.20</td>
<td>1.15</td>
</tr>
<tr>
<td>5 – 10</td>
<td>1.30</td>
<td>1.25</td>
</tr>
<tr>
<td>$&gt; 10$</td>
<td>1.35</td>
<td>1.30</td>
</tr>
</tbody>
</table>
CONCLUSIONS

• The modified reliability levels for evaluation were determined according to Eurocodes and they depend on the bridge age and on planned remaining lifetime considering normally and log-normally distributed or Gumble distributed random variables.

• The values of the levels are valid for members in Ultimate Limit States (ULS).

• In the presentation, determined partial safety factors for concrete $\gamma_c$, partial safety factor for reinforcement $\gamma_s$ and partial safety factors for permanent loads $\gamma_{G,i}$ and variable loads $\gamma_{Q,i}$ are shown.

• It is possible to calculate values of partial safety factors also for another materials (steel, masonry) and also for another loads effects (wind, temperature and so on) using the approach presented herein.
Contact:

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URL http://svf.uniza.sk/.
SWISS STANDARDS: A BASIS FOR DEVELOPING PERFORMANCE CRITERIA FOR CONCRETE BRIDGES BASED ON DURABILITY INDICATORS

Roberto Torrent – Quali-TI-Mat Sagl, Argentina/Switzerland
Rui Neves - ESTBarreiro/IPS, Portugal
Objective

- To present the evolution of the Swiss Standards for Durability, from purely Prescriptive (2003) to the most advanced Performance-based Standards worldwide (2013)
- To show that it is possible to escape the “Prescriptive Trap”
Content

• Year 2003: Prescriptive EN-based Standards: “Theorecrete”
• Year 2008: Performance requirements on cast specimens:
  – “Labcrete”: Laboratory Durability Indicators as step forward
• Year 2013: Performance requirements on site concrete:
  – “Realcrete” vs “Labcrete”; Relevance of “Covercrete” for Durability
• Conclusions
Year 2003: Prescriptive Standard SN EN206-1

- In 2003 Switzerland adopted the European Standards for Concrete: EN 206-1 and Eurocode 2
- In particular, for Durability, the following were adopted:
  - Exposure Classes (slightly modified in 2008)
  - Prescriptive requirements in terms of \( w/c_{\text{max}} \) and \( C_{\text{min}} \), together with minimum strength classes for each Exposure Class, e.g.

<table>
<thead>
<tr>
<th>Damage</th>
<th>Carbonation-induced Corrosion</th>
<th>Chloride-induced Corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure Class</td>
<td>XC1</td>
<td>XC2</td>
</tr>
<tr>
<td>( w/c_{\text{max}} )</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>( C_{\text{min}} ) (kg/m(^3))</td>
<td>280</td>
<td>280</td>
</tr>
<tr>
<td>( f'c_{\text{min}} ) (MPa)</td>
<td>C25</td>
<td>C25</td>
</tr>
</tbody>
</table>
Prescriptive Standards: Shortcomings

• The w/c ratio is a poor durability indicator, because it regards constituents as commodities: same mix proportions = same performance
• The constraints to the mix proportions ($C_{\text{min}}$ and $w/c_{\text{max}}$) vary widely and are predominantly arbitrary
• Offer little room for innovation and adding value
• Limit the competitiveness of concrete as sustainable material
• Compliance almost impossible to be checked by purchaser/owner
Prescriptive Standards refer to “Theorecrete”

Prescriptive specifications refers to “Theorecrete”, based on expected (theoretical) assumptions seldom met in practice:

- **theoretical** performance based on the specified w/c ratio
- **theoretical** assumption that w/c ratio complies with prescribed limits (almost impossible to control on site)
- **theoretical** good construction practices (frequently not observed by contractors, e.g. the endemic “lack of curing”)
Year 2008: Theorecrete to Labcrete

In 2008, performance requirements were introduced in the Swiss Standards, coexisting with prescriptive ones. Concrete producers must show through regular testing on cast specimens ("Labcrete") that their concretes comply with limiting values for standard tests.

Frequency = f (Volume, experience) ≥ 4 samples/year
Swiss Standards P2P: Carbonation

### Exposure Class

<table>
<thead>
<tr>
<th>Exposure Class</th>
<th>XC1</th>
<th>XC2</th>
<th>XC3</th>
<th>XC4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strength Class</strong></td>
<td>25</td>
<td>25</td>
<td>30</td>
<td>37</td>
</tr>
<tr>
<td><strong>C_{min} (kg/m³)</strong></td>
<td>280</td>
<td>280</td>
<td>280</td>
<td>300</td>
</tr>
<tr>
<td><strong>w/c_{max}</strong></td>
<td>0.65</td>
<td>0.65</td>
<td>0.60</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>K_{N max} (mm/√y)</strong></td>
<td>---</td>
<td>---</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>50 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>K_{N max} (mm/√y)</strong></td>
<td>---</td>
<td>---</td>
<td>4.0</td>
<td>4.5</td>
</tr>
<tr>
<td>100 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Swiss Standards P2P: Chlorides

**Capillary Suction**

<table>
<thead>
<tr>
<th>Exposure Class</th>
<th>Chlorides</th>
<th>XD1</th>
<th>XD2a</th>
<th>XD2b</th>
<th>XD3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strength</strong></td>
<td><strong>Cube min</strong></td>
<td>30</td>
<td>30</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td><strong>C\text{min} (kg/m}^3\text{)</strong></td>
<td>300</td>
<td>300</td>
<td>320</td>
<td>320</td>
<td></td>
</tr>
<tr>
<td><strong>w/c\text{max}</strong></td>
<td>0.50</td>
<td>0.50</td>
<td>0.45</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td><strong>q\text{wmax} (g/m}^2\text{h)</strong></td>
<td>10</td>
<td>10</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td><strong>M\text{Cl max} (10^{-12} m}^2\text{s)</strong></td>
<td>---</td>
<td>---</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

**Chloride Migration**
"With regard to durability, the quality of the cover concrete is of particular importance"

"The ‘impermeability’ of the cover concrete shall be checked, by means of permeability tests (e.g. air permeability measurements), on the structure or on cores taken from the structure"
Labcrete vs Realcrete

Production

Sampling

Delivery

Placing & Compaction

Specimen Preparation

Curing ?

Moist Curing $T \sim 20^\circ C$

Natural Maturity

$\geq 28$ d.

$RH > 95%$

“Realcrete” is different, typically worse than “Labcrete”
Concept of “Covercrete”

Due to:
• Segregation
• Compaction
• Curing
• Bleeding
• Finishing
• Microcracking

Cast specimens, made and cured under standard conditions, DO NOT represent the quality of the vital “covercrete”
Site Air-Permeability Test Method (SIA 261/1:2013 Annex E)

Result: \( kT \ (10^{-16} \text{ m}^2) \)

2-Chamber Vacuum cell

Vacuum Pump

Valve 1

Valve 2

Touch-screen Computer

Pressure Regulator \( (P_e=P_i) \)

Soft rings

\( i \) : Inner chamber

\( e \) : External chamber

Concrete
Site Air-Permeability Test Method (SIA 261/1:2013 Annex E)

- Specification of $kT_s$ for different Exposure Classes
- Grouping and Sampling (Lot = 500 m² or 3 d.)
- 6 Tests at random within Lot
- Suitable age (28 - 90 days), Temperature ($\geq 10^\circ$C $\rightarrow$ 5°C?)
  and Surface moisture by impedance method ($\leq 5.5\%$)
- Conformity Rules
Relation of $kT$ with other Durability Indicators

- **Water Sorptivity**
  - 24-h Sorptivity ($g/m^2/s^{1/2}$)
  - $kT \times 10^{-16} m^2$

- **Water Penetration under Pressure (EN 12390-8)**
  - Max. Penetration (mm)
  - $kT \times 10^{-16} m^2$

- **ASTM C1202**
  - Coulombs
  - Water Sorptivity
  - High (+ Very High)
  - Low
  - Moderate
  - Very Low

- **Natural (lab) Carbonation Rate**
  - Carbonation Rate (mm/y^{1/2})
  - $28$-d. $kT \times 10^{-16} m^2$

**Data Sources**
- Imamoto et al (~3.5y)
- Torrent and Ebensperger (500 d)
- Torrent and Frenzer (2y)
### Specified Values function of Exposure Class (SIA 261/1:2013)

<table>
<thead>
<tr>
<th>Damage</th>
<th>Carbonation-induced Corrosion</th>
<th>Chloride-induced Corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>XC1</td>
<td>XC2</td>
</tr>
<tr>
<td>Exposure Class</td>
<td></td>
<td></td>
</tr>
<tr>
<td>w/C&lt;sub&gt;max&lt;/sub&gt;</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>C&lt;sub&gt;min&lt;/sub&gt; (kg/m³)</td>
<td>280</td>
<td>280</td>
</tr>
<tr>
<td>f'c&lt;sub&gt;min&lt;/sub&gt; (MPa)</td>
<td>C25</td>
<td>C25</td>
</tr>
<tr>
<td>KN&lt;sub&gt;max&lt;/sub&gt; (mm/y&lt;sup&gt;½&lt;/sup&gt;)</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>qw&lt;sub&gt;max&lt;/sub&gt; (g/m²/h)</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>MCl&lt;sub&gt;max&lt;/sub&gt; (10&lt;sup&gt;-12&lt;/sup&gt; m²/s)</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>kT&lt;sub&gt;s&lt;/sub&gt; (10&lt;sup&gt;-16&lt;/sup&gt; m²) site</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

kT<sub>s</sub> = upper «characteristic» value
Conformity Rules

1. Not more than 1 out of 6 \( kT_i \) values above \( kT_s \)
2. If just 2 out of 6 \( kT_i \) values are above \( kT_s \): Another series of 6 random tests are conducted within the Lot, again with not more than 1 out of 6 \( kT_i \) values above \( kT_s \);
Conclusions

1. Specifying the performance of the covercrete, measured on site, aims at controlling the end, as-built product.

2. By checking the end product, a performance-oriented mindset is created in all players, ensuring a fair competition for:
   - Contractors, who have to deliver the specified quality of the product to be tested.
   - Concrete Producers, who have to efficiently design, produce and deliver mixes capable of achieving the required performance.
   - Raw Materials Suppliers (cement, additions, admixtures) who have to design their products to achieve the best performance in concrete.
Conclusions

3. Discourages all too common bad practices such as:

- Accidental or deliberate transgressions of the specified w/cmax by concrete producers
- Uncontrolled addition of water to the ready-mixed concrete trucks after leaving the batching point
- Incorrect placing and compaction practices
- Poor finishing techniques of floors and pavements
- Insufficient or total absence of moist curing
Conclusions

4. Incentives innovation by encouraging the use of:
   - SCC, creating a more compact and uniform concrete
   - Permeable formwork liners
   - Efficient curing compounds, “self-curing” concrete and sealers
   - High Performance Concretes and UHP Composites
   - Low or no Shrinkage Concretes (ShCC)
   - More sustainable systems, currently precluded by prescriptive standards
Conclusions

5. It is expected that, in 5 years time, the requirements of minimum cement content will be eliminated and the requirements of maximum w/c ratio will be either relaxed or eliminated altogether.

Then, a 100% performance Swiss Standard for durability will have been established.
Conclusions

5. It is expected that, in 5 years time, the requirements of minimum cement content will be eliminated and the requirements of maximum w/c ratio will be either relaxed or eliminated altogether.

Then, a 100% performance Swiss Standard for durability will have been established.
Design service lives beyond 50-yr

- Panama Canal: 100 years
- Port of Miami Tunnel: 150 years
- HK-Z-M Link: 120 years
- 2nd Gateway Bridge, Brisbane: 300 years
USING RISK MANAGEMENT FOR SETTING PERFORMANCE GOALS

Yiannis Xenidis – Aristotle University of Thessaloniki, Greece
To define a set of goals for the indicators previously identified in WG1. These goals will vary according to technical, environmental, economic and social factors.

To provide specific recommendations, in order to ensure that the definition of such goals will be the most generalized as possible.

**PERFORMANCE GOALS FOR BRIDGES**

*Enable safe and reliable traffic* (req: traffic loads, transport models)

Require less maintenance

Have a longer expectancy

*Meet standards well into the future* (req: projections of future needs)

Have least possible impact on the environment
PERFORMANCE GOALS ➔ RISK ASSESSMENT

- KPIs for load-bearing capacity and serviceability of structures
- KPIs for system behaviour and inspection
- KPIs for Conservation of Structures
- Environmental and Other Sustainable KPIs

CONDITION ASSESSMENT

PERFORMANCE REQUIREMENTS

- Technical Performance Goals
- Sustainable Performance Goals
- Other Performance Goals (economic and social)
Performance measurement can be defined as:

- the process of quantifying the efficiency and effectiveness of action
- the comparison of results against expectations (pre-determined goals) with **the implied objective of learning to do better**

- Performance Management Systems (PMS) include inclusiveness, measurability, consistency, and universality. **They also include a sense of direction and purpose.**
CONTEXT: RISK MANAGEMENT PRINCIPLES

<table>
<thead>
<tr>
<th>Risk management</th>
<th>On the Objectives</th>
<th>On the Prerequisites</th>
<th>On the Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• creates and protects value</td>
<td>• takes human and cultural factors into account</td>
<td>• is transparent and inclusive</td>
</tr>
<tr>
<td></td>
<td>• is part of decision making</td>
<td>• is based on the best available information</td>
<td>• is dynamic, iterative and responsive to change</td>
</tr>
</tbody>
</table>

ISO 31000:2009 - Principles and Guidelines on Implementation
RISK’S CONNECTION TO PERFORMANCE

- Risk management utilizes the same data with performance management

- Risk attitudes (averse/desire) affect performance appraisal processes

- Risk thresholds constitute minimum performance goals

- Risk management contributes to the demonstrable achievement of objectives and improvement of performance (for example, in human health and safety, security, legal and regulatory compliance, public acceptance, environmental protection, efficiency in operations, etc.)

- Risks improperly managed are followed by decline in value
NEED

(Past) Performance  Risk

Which activities are critical and responsible for potential problems?
Known performance - Unknown risk
REACTIVE: From the effect to the cause

(Future) Performance  Risk

Which activities have an impact to performance?
Known risk - Unknown performance
PROACTIVE: From the cause to the effect
A shift from the minimum thresholds (value loss prevention) to the optimum thresholds (value creation)!

QUESTIONS:
Is this just an issue of levels of application?
Is this shift actually needed?
ADDED-VALUE

Risk Management

- Identify risks that pose threats to design
- Use specific information for specific risks
- Assess damage

Future Performance-based Risk Management

- Identify risks that pose threats to objectives
- Use all information for all risks
- Assess deviation from profit (variance analysis)
REQUIREMENTS TO SATISFY THE NEED

• Identify measures of performance

• Propose a way for risk metrics to incorporate performance issues

• Define risk-informed performance measures (indicators)

• Propose a method for integrating risk-informed performance measures (indicators)

• Suggest the use of risk-informed performance measures (indicators) towards goal setting
HOLISTIC RISK-BASED PERFORMANCE MANAGEMENT (HRPM): AN ERM-BASED APPROACH
EXPECTED BENEFITS

ERM benefits in business

- Reduce cost of capital
- Reduce earnings volatility, which results in enhancing shareholders’ value
- Gain competitive advantage through identifying those risks that can be exploited
- Enhance informed decision making ability
- Build confidence for investors

HRPM benefits in infrastructure

- Reduce cost of maintenance
- Increase life cycle earnings and sustainability
- Become critical infrastructure through managing those risks that can be exploited
- Enhance informed decision making ability
- Build confidence for society
ALLIGNMENT WITH TU-1406 OBJECTIVES

WG2 Objectives

- Require less maintenance
- Have a longer expectancy - Meet standards well into the future - Have least possible impact on the environment
- Enable safe and reliable traffic

HRPM benefits in infrastructure

- Reduce cost of maintenance
- Increase life cycle earnings and sustainability
- Become critical infrastructure through managing those risks that can be exploited
- Enhance informed decision making ability
- Build confidence for society

• Risk management creates and protects value
CONCLUSIONS - DISCUSSION

• Analyze the system’s - under study - operation at all levels by applying life cycle assessment.

• Move away from a silo based to a portfolio based system of performance management

• Formalize the links between risk and performance management towards HRPM.
Reference List


WG3: Establishment of a QC Plan

Preface

Based on the results of the WG 1 and 2 as well as on survey of existing approaches in practice the objective of this group to provide a guideline with detailed step-by-step explanations for establishment of QC plans for different types of bridges. The QC plans will address the dynamics and uncertainty of the processes that may significantly comprises the bridge performance.

The QC plan has to relate to performance goals, which are user / society related, e.g. traveling time, weight allowance and clearance, safety level, comfort / serviceability, etc. The quality means that the set of performance indicators satisfy certain criteria e.g. load carrying capacity ≥ 440 kN, failure probability (of some kind) ≤ 0.5•10-6, etc. These satisficing criteria are to be fulfilled at any time and define the latest time point for an intervention. Further performance goals are expressed as extremising criteria i.e. the corresponding performance indicators are to be maximized or minimized. The examples are for instance to minimize societal losses or maximizing availability. These criteria may define the point in time at which is the most beneficial to trigger an intervention. In the diagram on the next page, some performance goal and indicators are illustrated. The extremising criteria are presented in red.

The milestone for this WG is to prepare a report with detailed explanation of the steps towards the establishment of a QC plan for different types of bridges until the middle of year 3. This outcome will constitute the basis of WG5, being also used within the WG4.
**WG3: Establishment of a QC Plan**

**Performance indicators:**
- **Construction costs**
- **Serviceability** -> OK or accepted margin for possible scenarios
- **Safety** -> OK or accepted margin for possible scenarios

**Influence factors:**
- Structure type incl. hydraulic design
- Geometry
- Structural materials
- Loads
- Environment
- Soil characteristics

**Performance indicators:**
- **Intervention costs** -> long-term costs + user costs
- **Serviceability** -> nOK or unacceptable margin for possible scenarios
- **Safety** -> nOK or unacceptable margin for possible scenarios

**Influence factors:**
- Damages
- Material condition
- Loads

**Performance indicators:**
- **Inspection costs**
- **Serviceability** -> OK or accepted margin for possible scenarios
- **Safety** -> OK or accepted margin for possible scenarios

**Performance indicators:**
- **Intervention costs** -> minimum long-term costs + user costs
- **Serviceability** -> OK or acceptable margin for possible scenarios
- **Safety** -> OK or acceptable margin for possible scenarios

---

**Commissioning**

**Inspection**

**Intervention 1**

**Intervention 2**

**Durability?**

**Time**

**Today**
WG 3: Establishment of a QC Plan for Road Bridges

Rade Hajdin - University of Belgrade, Serbia
Based on the results of the WG 1 and 2 as well as on survey of existing approaches in practice the objective of this group is to provide a methodology with detailed step-by-step explanations for establishment of QC plans for different types of bridges. The QC plans will address the dynamics and uncertainty of the processes that may significantly comprises the bridge performance.

The QC plan has to relate to performance goals, which are user / society related, e.g.
- Traveling time
- Weight allowance and clearance
- Safety level
- Comfort / Serviceability

Implementation of common methodology across Europe with flexibility to accommodate country-specific requirements
WHERE ARE WE NOW?

• Application process is still running
• Currently 40 applicants, only 16 with WG3 as the first choice
  – 11 are registered for Geneva Workshop
  – 6 Contributions
• The WG 3 will be established in Geneva
• The upcoming tasks:
  – Encourage the road authorities to submit both inspections and evaluation (decision support) documents
  – Analysis of submitted documents
• Tasks in 2016/2017
  – Enhancement of database
  – Establishment of causal relationship between values of Performance Indicators and Performance Goals (with WG2)
QUALITY

- Quality is often defined as fitness for purpose.
- In ISO 9000: Degree to which a set of inherent characteristics of a product or service fulfills requirements.
- Required performance (requirements) = actual performance (service)
- What public desires:
  - Maximum (no) weight posting
  - Maximum (unrestricted) clearance
  - Minimum (no) risk of failure due to traffic loading
  - Minimum (no) risk of failure due to natural hazard
  - Minimum (no) noise
  - Spotless visual appearance (no cracks, spalling, corrosion, etc.)
  - Minimum (no) costs for operation and MR&R
- These desires are contradictory and are resolved in a political process resulting in required performance.
REQUIRED PERFORMANCE

• Political process?
• The contradictory objective are supported by following stakeholders:
  – Users, which are represented by governments i.e. politicians
  – Owner, which is government itself or a agency controlled by the government i.e. politicians
  – General public, such as traffic associations, environmental groups, professional associations, mostly represented by politicians
• Based on the interests and public opinion the required performance can change, sometimes quite quickly:
  – Tunnel safety after Mont Blanc and Gotthard
  – Weight allowance
  – Clearance
PERFORMANCE GOALS I

• To cope with this (sometimes) volatile political process agencies, private owners and professional associations publish various guidelines, manuals, standards, best practices, etc.

• These documents explicitly or implicitly define the required performance (= performance goals) and the way how to evaluate and forecast actual performance on the long term.

• There are therefore the important part of the whole management process, which includes also estimation of financial needs.

• These documents are in essence quality control plans or parts of them.

• The quality control plans defines which data are required to evaluate the actual performance and the techniques to collect these data.

• European survey of various guidelines, manuals, standards, best practices, etc.
PERFORMANCE GOALS II

- Set of values of performance indicators that have to meet certain criteria, e.g.
  - Weight limit ≤ 440 kN
  - Failure probability (of some kind) ≤ 0.5\times 10^{-6}
  - Height ≤ 4.5 m
  - Maximum risk due to natural hazards ≤ CHF 100 Mio.
  - No spalling and cracks > 0.2 mm
  - No fatigue cracks

- Further performance goals such as
  - Minimizing societal losses
  - Maximizing availability
  - Marginal risk due to natural hazard ≥ CHF 10 Mio./saved life

belong to maintenance planning
DOCUMENTS

- Inspection documents
- Evaluation and assessment documents
- Background documents, e.g. BMS related documents
- Research documents
- Identified measurable performance indicators:
  - Visual appearance (tolerated observable damages)
  - Safety and Serviceability over time = Durability
    ~ Remaining service life
  - Availability
  - Environmental impact
  - LQI
  - Costs (agency, user and societal costs)
Performance indicators:
- Construction costs
- Serviceability -> OK or accepted margin for possible scenarios
- Safety -> OK or accepted margin for possible scenarios

Influence factors:
- Structure type incl. hydraulic design
- Geometry
- Structural materials
- Loads
- Environment
- Soil characteristics

Performance indicators:
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Influence factors:
- Damages
- Material condition
- Loads

Performance indicators:
- Inspection costs
- Serviceability -> OK or accepted margin for possible scenarios
- Safety -> OK or accepted margin for possible scenarios

Performance indicators:
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Influence factors:
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- Geometry
- Structural materials
- Loads
- Environment
- Soil characteristics

Commissioning
Inspection
Intervention 1
Intervention 2
Durability?
Time
today
RAVAGES OF TIME

- Slow, observable and therefore interceptable processes (corrosion, frost, alkali aggregate(?), climate, traffic)
- Slow unobservable and therefore non-interceptable processes (corrosion of posttensioning steel, alkali aggregate)
- Sudden events (flooding, earthquake, fire)
- These processes can lead significant change of performance indicators.
**BREAKDOWN OF TASKS**

- Focus on most common bridge types and systems
- No landmark bridges

<table>
<thead>
<tr>
<th>Interceptable processes</th>
<th>Damaging processes</th>
<th>Corrosion</th>
<th>Alkali Aggregate</th>
<th>Sulphate</th>
<th>Fatigue</th>
<th>Girder bridges</th>
<th>Arch bridges</th>
<th>Frame bridges</th>
<th>Etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interceptable processes (Observable processes)</td>
<td>Task 1</td>
<td>Task 2</td>
<td>Task 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Demand</td>
<td>Traffic volume</td>
<td>Traffic loading</td>
<td>Climate</td>
<td></td>
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<tr>
<td>Task 3</td>
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<tr>
<td>Sudden events</td>
<td>Earthquake</td>
<td>Gravitational hazards</td>
<td>Fire</td>
<td>Accidents</td>
<td></td>
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<tr>
<td>Non-interceptable processes</td>
<td>Task 4</td>
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<td></td>
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</tr>
<tr>
<td>Non-observable</td>
<td>Fatigue</td>
<td>Hidden damaging processes</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Non-observable Fatigue

Non-observable Hidden damaging processes
## ROAD MAP

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
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<tbody>
<tr>
<td>1</td>
<td>Survey of European QC Plans</td>
<td></td>
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<tr>
<td>2</td>
<td>Ground work for task groups</td>
<td></td>
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<tr>
<td>3</td>
<td>Task Groups Coordination</td>
<td></td>
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<tr>
<td>4</td>
<td><strong>Matrix tasks 1 - N</strong></td>
<td></td>
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<td></td>
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<tr>
<td>5</td>
<td>Definition of performance indicators</td>
<td></td>
<td></td>
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<tr>
<td>6</td>
<td>Monitoring equipment</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Inspection scheduling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Maintenance strategy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Draft for Guidelines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Guidelines for the establishment of QC Plans</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

*Note: The table indicates the progress of the tasks across different years.*
THANKS FOR YOUR ATTENTION!
BRIDGE QUALITY CONTROL SUPPORTED BY KNOWLEDGE-BASED EXPERT TOOLS

Jan Bień – Wrocław University of Technology, Poland
Mieszko Kużawa - Wrocław University of Technology, Poland
CONTENTS

I. Introduction
II. Hybrid knowledge representation
III. Load capacity of damaged plate girders
IV. Load capacity of damaged masonry arch spans
V. Load capacity of damaged RC slab spans
VI. Summary
I. INTRODUCTION

Bridge quality: degradation scheme

- Degradation stimulators
- Degradation mechanisms
- Degradation processes
- Defects
- Bridge condition
  - Technical condition
  - Serviceability
I. INTRODUCTION

Basic terms

Technical condition – measure of conformity between current and designed technical parameters of a structure (geometry, materials, etc.)

Serviceability – measure of conformity between current and required operational parameters of a bridge (load capacity, clearance, speed limit, etc.)

Bridge condition – general measure of structure technical condition and serviceability

Defect – result of degradation process diminishing structure condition

Bridge failure – structure out of service because low condition

Bridge disaster – structure collapse
## I. INTRODUCTION

### Main types of bridge defects

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contamination</td>
<td>Appearance of any type of dirtiness or not designed plant vegetation</td>
</tr>
<tr>
<td>Deformation</td>
<td>Geometry changes incompatible with the design, with changes of mutual distances of structure element points,</td>
</tr>
<tr>
<td>Deterioration</td>
<td>Deterioration of physical and/or chemical structural features in comparison with designed values</td>
</tr>
</tbody>
</table>
# I. INTRODUCTION

## Main types of bridge defects

<table>
<thead>
<tr>
<th><strong>Discontinuity</strong></th>
<th>not designed break in continuity of a structure material</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Displacement</strong></td>
<td>not designed displacement of a structure without changes of distances of structure element points (without deformation), also restriction in designed displacement capabilities</td>
</tr>
<tr>
<td><strong>Loss of material</strong></td>
<td>decrease of designed amount of structure material</td>
</tr>
</tbody>
</table>
I. INTRODUCTION

Railway bridges in Poland

Basic types of main girders

- Box girders 1.3%
- Rolled girders 4.3%
- Prefabricated beams 1.8%
- Monolithic beams 5.3%
- Plate girders 27.8%
- Monolithic slabs 21.4%
- Prefabricated slabs 3.3%
- Filler beams 8.0%
- Trusses 10.0%
- Masonry arches 16.9%

Age profile

Number of bridges

Age [years]

0-20 21-40 41-60 61-80 81-100 101-120 121-140 141-160 >161
II. HYBRID KNOWLEDGE REPRESENTATION

Railway Bridge Management System “SMOK”
II. HYBRID KNOWLEDGE REPRESENTATION

Expert tool creation based on the multi-level hybrid networks technology
II. HYBRID KNOWLEDGE REPRESENTATION

Graphical editor
III. LOAD CAPACITY OF DAMAGED PLATE GIRDERS

Structure geometry and defects
III. LOAD CAPACITY OF DAMAGED PLATE GIRDERS

Analysis procedure

- BRIDGE
- RESULTS OF STRUCTURE INSPECTION
- GEOMETRY
- MATERIAL
- LOADS
- BOUNDARY CONDITIONS
- DEFECTS
- LBA ANALYSIS
- MNA ANALYSIS
- IMPERFECTIONS
- GMNIA ANALYSIS
- DEFORMATIONS
- STRESSES
III. LOAD CAPACITY OF DAMAGED PLATE GIRDERS

Data base (results of numerical simulations)
III. LOAD CAPACITY OF DAMAGED PLATE GIRDER

**Artificial Neural Network (ANN)**

\[
\eta_w = \sum_{i=1}^{9} \alpha_i P_i
\]
III. LOAD CAPACITY OF DAMAGED PLATE GIRDERS

(Dr M. Kużawa)
IV. LOAD CAPACITY OF DAMAGED ARCH SPANS

Modelling of defects

- Modification of parameters of material
- Deleted model items
- Elements with reduced thickness
IV. LOAD CAPACITY OF DAMAGED ARCH SPANS

Analysis procedure

Data base (results of numerical simulations)
IV. LOAD CAPACITY OF DAMAGED ARCH SPANS

MyBriDE expert tool

(Dr T. Kamiński)
V. LOAD CAPACITY OF DAMAGED RC SLAB SPANS

Modelling of defects
V. LOAD CAPACITY OF DAMAGED RC SLAB SPANS

(Anaconda expert tool)

(Dr M. Maksymowicz)
V. LOAD CAPACITY OF DAMAGED RC SLAB SPANS

Load capacity envelopes
VI. SUMMARY

- Presented **expert tools** were elaborated for load capacity assessment of railway bridge structures with defects.
- Developed technology of knowledge representation based on **hybrid multi-level networks** can be also applied in **quality control of road bridges**.
- Obtained results confirm that the **expert tools** based on the hybrid knowledge representation can be an **effective instrument** in precise assessment of the bridge **technical condition** and **serviceability**.
- Promising results of pilot research projects in this area provide opportunities for **development and implementation**, in the near future, of a new generation of **intelligent tools** supporting decisions in **bridge quality control**, taking into account defects occurring during operation of bridge structures.
Case study: Bridge Management System at Rijkswaterstaat

Irina Stipanovic, Andreas Hartmann, Tania Viana da Rocha, University of Twente
Giel Klanker, Jaap Bakker, Rijkswaterstaat

UNIVERSITEIT TWENTE.
Case study - Rijkswaterstaat
Condition assessment

- The status indicator of a structure is represented through a qualitative scale that ranges from 0 (good condition) to 6 (very poor condition)
- deterioration level assessed by inspectors
- Reference document (RWS, 2014)
Risk and performance-based indicators

- Condition indicators → cause-effect analysis regarding desired functioning level →
  
  **RAMS SHEEP** criteria

- Method to correlate risks at an object level to required network performance and to prioritise maintenance tasks at network level
<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>PERFORMANCE CRITERIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.R</td>
<td>Satisfy reliability requirements for moving parts and equipment</td>
</tr>
<tr>
<td>1.2.R</td>
<td>Meet structural requirements in relation to damages</td>
</tr>
<tr>
<td>1.3.R</td>
<td>Meet structural requirements in relation to revised standards</td>
</tr>
<tr>
<td>1.4.R</td>
<td>Meet structural requirements in relation to different use</td>
</tr>
<tr>
<td>1.5.R</td>
<td>Meet structural requirements in relation to defects in design, execution or management</td>
</tr>
<tr>
<td>2.1.A</td>
<td>Meet object specific requirements with regard to the fulfilment of the object functions</td>
</tr>
<tr>
<td>2.2.A</td>
<td>Prevention of calamities</td>
</tr>
<tr>
<td>3.1.M</td>
<td>Meet requirements relating to the maintainability of elements</td>
</tr>
<tr>
<td>4.1.Sa</td>
<td>Meet object specific requirements with regard to the safe performance of the object functions</td>
</tr>
<tr>
<td>4.2.Sa</td>
<td>Prevent of calamities</td>
</tr>
</tbody>
</table>
### SHEEP criteria

<table>
<thead>
<tr>
<th>Security</th>
<th>5.1.Se</th>
<th>Meet the requirements with regard to the prevention of vandalism</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.2.Se</td>
<td>Meet the requirements relating to the protection of the object</td>
</tr>
<tr>
<td>Health</td>
<td>6.1.H</td>
<td>Meet health and safety decisions</td>
</tr>
<tr>
<td></td>
<td>7.1.E</td>
<td>Meet design requirements</td>
</tr>
<tr>
<td>Surrounding and environment</td>
<td>7.2.E</td>
<td>Meet environmental requirements</td>
</tr>
<tr>
<td></td>
<td>7.3.E</td>
<td>Comply with requirements relating to use/ comfort</td>
</tr>
<tr>
<td>Economics</td>
<td>8.1.Ec</td>
<td>Moisture management in order</td>
</tr>
<tr>
<td></td>
<td>8.2.Ec</td>
<td>Prevent widespread or irreparable damage</td>
</tr>
<tr>
<td>Politic</td>
<td>9.1.P</td>
<td>Meet requirements for image</td>
</tr>
</tbody>
</table>
Matrix of risk analysis

<table>
<thead>
<tr>
<th>CHANCE</th>
<th>NEGLECT</th>
<th>SERIOUS</th>
<th>VERY SERIOUS</th>
<th>CATASTROPHIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chance of falling is unacceptable (calamity)</td>
<td>3. Increased</td>
<td>4. High</td>
<td>5. Unacceptable</td>
<td>5. Unacceptable</td>
</tr>
<tr>
<td>Chance of falling is very high</td>
<td>3. Increased</td>
<td>3. Increased</td>
<td>4. High</td>
<td>5. Unacceptable</td>
</tr>
<tr>
<td>Chance of failing is high</td>
<td>2. Limited</td>
<td>3. Increased</td>
<td>3. Increased</td>
<td>4. High</td>
</tr>
<tr>
<td>Higher than immediately after delivery the accepted probability of failure is approached</td>
<td>1. Neglect</td>
<td>2. Limited</td>
<td>3. Increased</td>
<td>3. Increased</td>
</tr>
<tr>
<td>Higher than immediately after delivery but within the acceptable probability of failure</td>
<td>1. Neglect</td>
<td>1. Neglect</td>
<td>2. Limited</td>
<td>2. Limited</td>
</tr>
<tr>
<td>Not higher than immediately after delivery</td>
<td>1. Neglect</td>
<td>1. Neglect</td>
<td>1. Neglect</td>
<td>1. Neglect</td>
</tr>
</tbody>
</table>
Condition vs. Risk → Status Indicator

- DISK classifies the **object quality** based on:
  - (1) its **condition** (*i.e. the extent to which parts of the object meets the standards*), and
  - (2) **risks** (*i.e. the implications towards the performance requirements*).
Maintenance planning

- Determined based on the risk assessment
- For each risk a bandwidth is planned in which measure needs to be performed
- Measures are planned to manage one or more risks
- Measure needs to manage the risk and be effective from a life cycle perspective
The problem...

Supply

Collection

Data Input

Storage (in DISK)

Usage

INFORMATION USAGE

Usage Requirements

Bridge the gap and leverage opportunities

Demand

Collection Requirements

Bridge Management System at Rijkswaterstaat | Stipanovic et al.
Problems

• Ambiguous and subjective risk criteria

• Inconsistency of risk-based approaches between decision processes

• Lack of updating risk data between decision processes

• Relationship between the criteria should be coupled rather than decoupled assessment as is done at the moment
Structure of the model

- Part 0. System characterization
- Part 1. Risk profile on element level
- Part 2. Risk profile on structure level
Case study: Bridge Management System at Rijkswaterstaat | Stipanovic et al.
Part 1. Risk profile on element level
Part 2. Risk profile on structure level
Challenges

• Component → Object → Network level
• Are the relationships between inspection results and risk assessment methodology clear enough? (PIs vs. PGs)
• Are the risks or performance goals well understood?
• What is an impact on QC plans?
QUALITY CONTROL PLAN FOR BRIDGES WITH SHALLOW FOUNDATIONS EXPOSED TO LOCAL SCOUR IN SERBIAN ROAD NETWORK

Nikola Tanasić – Faculty of Civil Engineering, University of Belgrade, Serbia
OUTLINE

• INTRODUCTION
• CONSIDERATION OF FLOODING HAZARD IN SERBIAN ROAD NETWORK
• NOVEL METHODOLOGY
• NECESSARY PERFORMANCE INDICATORS
• QUALITY CONTROL PLANS – BACKGROUND & TIME SCHEDULE OF ACTIVITIES
• FURTHER STEPS
INTRODUCTION

• Local scour is No. 1 culprit for bridge failures due to natural hazards around the world / non-interceptable, sudden process
INTRODUCTION

- Extreme flooding in Europe / cyclone Tamara (May 2014)
- Over 1.6 million people directly affected
  ✓ Energetic sector and transportation infrastructure impaired

Precipitation 11-17 May
• In Serbia: 3500 roads damaged; 1800 at risk - landslides!
• Bridge failures
  ✓ Washing away of access roads
  ✓ Local scour
SERBIAN ROAD NETWORK

• 179 bridges affected by May floods
  ✓ Direct consequences - repair works of approx. 8.0 million €
  ✓ Indirect consequences (inadequate bridge performance) – ?

<table>
<thead>
<tr>
<th>Bridges in the database (state roads)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
</tr>
<tr>
<td>Arch</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>Frame</td>
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<tr>
<td>Beam</td>
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</tr>
</tbody>
</table>

• Main girder (beam):
  ✓ Slab, Double-tee

• Substructures
  ✓ Shallow foundations
  ✓ Caissons, Piles
SERBIAN BRIDGE DATABASE

- Inspection of items condition $\rightarrow$ Rating score

<table>
<thead>
<tr>
<th>ITEMS</th>
<th>Impact factor (6 values)</th>
<th>Condition rating (5 to 8 values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Serviceability</td>
<td></td>
<td></td>
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<tr>
<td>Expected</td>
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</tr>
<tr>
<td>deterioration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>prioritization</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Consideration of flooding hazard in the database
  - **NO systematic approach**
  - Entries and partial rating scores for foundations - **NOT convenient**
  - Average time of inspection is **12 years**!

- Comprehensive risk-based quantitative approach
  - Screening procedure - Identification of vulnerable bridges
  - Integration into future Bridge Management System
NOVEL METHODOLOGY

• Vulnerability as a criterion for initiating maintenance actions

\[
V_n^s = P_n^s \cdot (DC_n + IC_n)
\]

✓ \(P_n^s\) = conditional probability of a bridge failure in the mode \(n\)

✓ \(DC_n, IC_n\) = direct and indirect consequences of failure with reference to chosen failure mode \(n\)
PROBABILITY OF A BRIDGE FAILURE

- Example: two span RC girder with shallow foundations
  ✓ Failure scenario = Local scour at the middle

![Diagram of a bridge with local scour and resistance evaluation](image)
EVALUATION OF PERFORMANCE INDICATORS

SOIL RESISTANCE
- Cohesion
- Weight
- Internal friction angle

BRIDGE RESISTANCE
- Combined failure kinematic mechanisms
- Main girder geometry
- Ultimate bending moments in the main girder & piers
- Joint properties

LOCAL SCOUR EVALUATION
- Soil height at pier
- Median particle diameter
- Erodibility
- Extreme hydrographs
- Channel properties & geometry

COST ACTION TU1406
QCP FOR BRIDGES WITH SHALLOW FOUNDATIONS EXPOSED TO LOCAL SCOUR IN SERBIAN ROAD NETWORK | NIKOLA TANASIĆ
Elaborate the most relevant failure scenarios!

- Speeds-up evaluation of the probability of failure (MC simulations)
QUALITY CONTROL PLANS BACKGROUND

- **QCP-s** customized for bridge types and available data

<table>
<thead>
<tr>
<th>Data</th>
<th>Availability</th>
<th>Problem</th>
<th>Proposed action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme hydrographs</td>
<td>Republic Hydrometeorological Institute of Serbia</td>
<td>Only data for major rivers</td>
<td>Elaborate hydraulic studies</td>
</tr>
<tr>
<td>River bed geometry at bridge site</td>
<td>Database / Project Documentation</td>
<td>25 year old survey</td>
<td>Survey at site</td>
</tr>
<tr>
<td>Bridge geometry</td>
<td>Database / Project Documentation</td>
<td>See above + foundation data missing</td>
<td>Survey of substructure foundations</td>
</tr>
<tr>
<td>Soil geotechnical properties</td>
<td>Project documentation</td>
<td>Missing documentation</td>
<td>Survey at site</td>
</tr>
<tr>
<td>Rebar detailing &amp; Joints’ properties</td>
<td>Database / Manual for evaluation of maximum loading</td>
<td>Missing data in project documentation</td>
<td>Evaluate bending moment resistance</td>
</tr>
</tbody>
</table>
QUALITY CONTROL PLANS BACKGROUND

- **QCP-s** customized for bridge types and available data

<table>
<thead>
<tr>
<th>Data</th>
<th>Availability</th>
<th>Problem</th>
<th>Proposed action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct consequences</td>
<td>Serbian Highway Institute</td>
<td>No damage assessment manuals</td>
<td>Elaborate expenditures of common flood damage for different bridge types</td>
</tr>
<tr>
<td>Indirect consequences</td>
<td>Serbian Road Directory</td>
<td>Lack of traffic studies</td>
<td>Traffic simulations for a relevant part of the network</td>
</tr>
</tbody>
</table>

- Criteria for triggering maintenance actions
  - ✓ Vulnerability of a relevant part of the network (multiple bridge failure scenarios)
## QUALITY CONTROL PLANS – TIME SCHEDULE

<table>
<thead>
<tr>
<th>Data</th>
<th>Activity</th>
<th>Consideration</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme hydrographs</td>
<td>Update hydrologic data</td>
<td>Climate change</td>
<td>Once a year / After extreme flood</td>
</tr>
<tr>
<td>River bed geometry at bridge site</td>
<td>Regular inspection &amp; Special inspection</td>
<td>Properties vary in time</td>
<td>Periodically / After every flood</td>
</tr>
<tr>
<td>Foundation geometry</td>
<td>Special inspection</td>
<td>Unknown foundations</td>
<td>Once</td>
</tr>
<tr>
<td>Soil geotechnical properties</td>
<td>Special inspection</td>
<td>Infill of local scour cavities</td>
<td>After every flood</td>
</tr>
<tr>
<td>Superstructure, Substructure &amp; Joints</td>
<td>Regular inspection *</td>
<td>Deterioration of bridge elements</td>
<td>Periodically</td>
</tr>
<tr>
<td>Direct consequences</td>
<td>Update expenditures</td>
<td>/</td>
<td>Once a year</td>
</tr>
<tr>
<td>Indirect consequences</td>
<td>Update traffic data</td>
<td>Major detours &amp; roadworks</td>
<td>Once a year</td>
</tr>
</tbody>
</table>
FURTHER ACTIONS

• Threshold values of the indicators and acceptable vulnerability levels; Connection with \textbf{WG2}
• Application of vulnerability assessment approach for various non-interceptable processes
• Floods in Central Europe - 2013, South Eastern Europe - 2014 Are lessons learned?
THANKS FOR YOUR ATTENTION!

WWW.TU1406.EU
APPENDIX: POSTER CONTRIBUTIONS
### Table of Poster Contributions

<table>
<thead>
<tr>
<th>WG1 Performance indicators</th>
<th>WG2 Performance Goals</th>
<th>WG3 QC plans</th>
</tr>
</thead>
<tbody>
<tr>
<td>8. A monitoring-based indicator of local stiffness reduction</td>
<td>8. Defects and failures of Polish bridges – introduction to the study on structural robustness</td>
<td></td>
</tr>
<tr>
<td>9. Technical indicators for seismic assessment of bridges</td>
<td>9. SSI as a factor moderating seismic Demands in Bridge Piers</td>
<td></td>
</tr>
</tbody>
</table>
CROATIAN EXPERIENCES IN CATEGORISATION OF PERFORMANCE INDICATORS OF ROAD BRIDGES
Ana Mandić Ivanković, University of Zagreb, Faculty of Civil Engineering, CROATIA

COLLECTING EXPERIENCE from inspection, testing, assessment, monitoring

Although the interaction of different indicators that affect certain structural performance is inevitable, they need to be segregated in order to more easily identify methods for their quantification.

PERFORMANCE INDICATORS

- **STRUCTURAL**
  - GEOMETRY
  - DETAILS
  - MATERIAL PROPER.
  - INTEGRITY
  - DYNAMIC PROPER.
  - Ex. changes due to deterioration or changes due to repair

- **ENVIRONMENTAL**
  - EXPOSURE PARAM.
  - LOCAL TRAFFIC
  - TERRAIN CATEG.
  - SEISMIC ACTIVITY
  - WIND INFLUENCE
  - Ex: Strong wind, sea water splashing, tidals

- **ECONOMIC**
  - DIFF. INSPECTIONS METHODS
  - KNOWLEDGE LEVEL
  - RETROFIT MEASURES
  - OPTIMUM DURABILITY
  - Ex: Underestimation of maintenance role in the past, mainly due to lack of funding

Capturing all the indicators that affect certain structural performance

To define a correct structural model of the existing structure and to perform adequate structural analysis, it is crucial to capture all the indicators that affect certain structural performance at the desired knowledge level depending on bridge importance and consequences of its failure.

STRUCTURAL PERFORMANCES

- **SERVICE-ABILITY**
  - Ex: Localised models for revealing the corrosion influence at the Krk bridge piers

- **SEISMIC-PERFORMANCE**
  - Ex: Significant mode shapes in longitudinal direction and reference points for different pushover analyses

Comprehensive assessment of existing arch bridge

Assessment of an existing reinforced concrete arch bridge comprises of assessing different types of structural performances.

SMOOTH SERVICE AND EFFICIENT MANAGEMENT

- Ex: Beta distribution of the overall weight of vehicle model for the realistic traffic modelling

- Ex: Influence of wind direction on the results of nonlinear evaluation

- Ex: Data collection and minimum requirements

**Problem Statement**

Extraction of performance indicators based on ambient vibration response measurements.

**Problem characteristics**

Civil engineering structures are by default operating within continually changing environments.

**Benefits of fusing operational condition data into structural ID**

- Improved understanding of structural dynamics
- Improved design of new systems
- Improved Monitoring
- Condition Assessment
- Life - Cycle Management

**Stochastic Framework**

Consider a system $M$ which has $M$ uncertain input parameters represented by independent random variables $(\mathbf{\xi}_1, \ldots, \mathbf{\xi}_M)$ gathered in a random vector $\mathbf{\xi}$ of prescribed joint probability density function $p_\mathbf{\xi}(\mathbf{\xi})$. The system output denoted by $Y = \mathcal{M}(\mathbf{\xi})$ will also be random. Provided that $Y$ has finite variance, it can be expressed as follows:

$$Y = \mathcal{M}(\mathbf{\xi}) = \sum_{i=1}^{N} \theta_i \phi_i(\mathbf{\xi})$$

where $\phi_i(\mathbf{\xi})$ are Polynomial Basis (PC) functions orthonormal to $p_\mathbf{\xi}(\mathbf{\xi})$, $\theta_i$ the basis multi-indices vector, and $\mathbf{\xi} = \{\mathbf{\xi}_1, \ldots, \mathbf{\xi}_M\}$ deterministic coefficients of projection.

The PC basis functions $\phi_i(\mathbf{\xi})$ are orthonormal with respect to the joint probability density function of $\mathbf{\xi}$:

$$E[\phi_\alpha(\mathbf{\xi}) \phi_\beta(\mathbf{\xi})] = \delta_{\alpha\beta}$$

where $\delta_{\alpha\beta}$ is the Kronecker delta.

**Performance Indicator**

A single (independent) random input variable and a single feature variable are retained for constructing a performance indicator.

**Concluding Remarks**

- **Environmental condition data** which are nowadays available in modern SHM systems of large-scale civil engineering structures should be used in favor of identifying reliable models of structural response.
- Stochastic tools such as PCE & ICA may be used for providing a metamodel quantifying the effects of influencing agents (such as temperature, wind loads, traffic, etc) onto the measured response (output).
- The extracted performance indicators may be exploited for a monitoring based decision making framework toward pro-active infrastructure management.
- Further application case studies on a multiplicity of actual structural systems demonstrated the effectiveness and applicability of the proposed scheme and potential towards an automated framework.

**Acknowledgment**

Research Grant funded by Bundesamt fr Strassen - Astra (Federal Roads Office - FEDRO), Project # AGB 2012/015
ROBUSTNESS AS A PERFORMANCE INDICATOR FOR MASONRY ARCH BRIDGES

Vicente N. Moreira, João Fernandes, Daniel Oliveira, José C. Matos

Abstract

Masonry arch bridges (MAB) dates from past centuries, being preserved over the years due their historical importance. Sustainable Bridges stated that around 40% of all the bridges over Europe are MAB. However, some of these bridges are subjected to higher loads than those employed on project phase and presents deterioration due to their age. Hence, structural maintenance is required to assess their current safety condition. In order to do so, probabilistic methodologies combined with Ultimate Limit State (ULS) analysis may be applied to obtain the reliability index. Hence, with the obtained reliability index, through probabilistic analysis, it is possible to compute the robustness of the assessed structure. Structural robustness may be defined as the ability of a structure to support a certain amount of damage without global collapsing occurs. This work aims to present the quantification of the robustness index for a set of MAB in order to assess their structural condition.

Objectives

- Safety assessment of railway masonry arch bridges.
- Ultimate load-carrying capacity.
- Reliability-based analysis and robustness indexes.

Description

- Reliability-based assessment of railway masonry arch bridges: global verification.
- Simplified full-probabilistic methodology.
- Sensitivity analysis.
- Reliability-based robustness index, considering the intact and damaged structure.

Outcomes

- Reliable structural safety and robustness indexes.
- Simplified but powerful procedure to assess railway masonry arch bridges.
- Safe and accurate approach to obtain ultimate load-carrying capacity, as well as the structural ability of sustaining damage.
PERFORMANCE ASSESSMENT OF BRIDGES UNDER SCOUR EFFECTS

Bridge scour

Scour of foundations is one of the main causes of bridge failure worldwide. Scour risk is expected to increase due to climate change. In Europe, scour protective actions may be needed over the next decades in 20% of the bridge inventory [1].

Collapse of the Broadmeadow viaduct due to scour
(Photo credit: Fergus Wheatley)

Causes of bridge failure in the United States (1989-2000) (adapted from [2])

Scour assessment methodology

A new methodology is under development to assess scour in Mexican roadway bridges:

Phase I

Preliminary scour risk rating based on roadway bridge inventory data

Phase II

Efficient inspection and monitoring methods

Underwater ROV technology for scour detection

Phase III

Performance indicator consistent with Mexican rating methodology

Phase I: preliminary scour rating

A simple method is proposed to rate the potential scour risk based on limited data:

<table>
<thead>
<tr>
<th>Preliminary rating</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No specific scour inspection</td>
</tr>
<tr>
<td>1</td>
<td>Specific scour inspection at regular frequency</td>
</tr>
<tr>
<td>2</td>
<td>Specific scour inspection at increased frequency</td>
</tr>
<tr>
<td>3</td>
<td>Specific scour inspection at increased frequency and short-term monitoring</td>
</tr>
<tr>
<td>4</td>
<td>Priority inspection and long-term monitoring</td>
</tr>
<tr>
<td>5</td>
<td>Urgent inspection and long-term monitoring</td>
</tr>
</tbody>
</table>

References:

Contact info: Juan Murcia-Delso, T +34 609 408 897, juan.murcia@tecnicia.com

TU1406 WG Meeting, Geneva, September 21-22, 2015
Vehicle-Bridge-Soil Dynamic Interaction Model for Scour Damage Modelling

L. J. Prendergast$^{1,2,3}$ and K. Gavin$^{1,2}$

$^1$UCD Earth Institute, $^2$UCD School of Civil, Structural and Environmental Engineering

$^*$luke.prendergast@ucdconnect.ie

**Scour Erosion Process:**
- Removal of foundation soil by water action
- Loss in foundation stiffness
- Potential (sudden) bridge collapse

**Mathematical Modelling of Vehicle-Bridge-Soil Interaction:**
- Coupled VBI system

**Vehicle Equations**

$$[M_c] \begin{bmatrix} \ddot{x}_c(t) \\ \ddot{y}_c(t) \\ \ddot{z}_c(t) \end{bmatrix} + [C_c] \begin{bmatrix} \dot{x}_c(t) \\ \dot{y}_c(t) \\ \dot{z}_c(t) \end{bmatrix} + [K_c] \begin{bmatrix} x_c(t) \\ y_c(t) \\ z_c(t) \end{bmatrix} = \begin{bmatrix} F_x(t) \\ F_y(t) \\ F_z(t) \end{bmatrix}$$

**Bridge / Soil Equations**

**Integral Bridge Schematic:**

**Integral bridge in completed state**

**Sava Bridge, Zagreb, 2009**

**Malahide Viaduct, Dublin, 2009**

**Investing in your future**
Assessment of existing road bridges in Germany

Guideline for recalculation of existing road bridges (Nachrechnungsrichtlinie):

- Calculation scheme:
  - Preliminary investigations, Definitions - especially target load level -
  - Structural calculations and evaluation
  - Intermediate results and assessment
  - External examination of the calculations
  - Final assessment and definition of measures

- Computational examination of load-carrying capacity and serviceability in four stages:
  - **Stage 1:** Calculations exclusively according to technical DIN reports 101 to 104 or respective Eurocodes
  - **Stage 2:** Additional regulations of the guideline for calculations of stage 4
  - **Stage 3:** Consideration of experimental investigations and measurements
  - **Stage 4:** Application of scientific methods (e.g. nonlinear or probabilistic)

Case study: Prestressed concrete motorway bridge

- Inspection of the box girder
- Operational modal analysis
- Cracks caused by ASR
- Model validation

Analyses:
- **Stage 1:** Not all requirements satisfied
- **Stage 2:** Exceedance of limit values reduced
- **Stage 3 / Stage 4:** Analyses in progress

Institute of Structural Mechanics
Prof. Dr.-Ing. habil. Carsten Könke
Dr.-Ing. Volkmar Zabel

Bauhaus-Universität Weimar
Roughness of Roadbridge Decks
Jānis Barbars, Latvian State Roads

<table>
<thead>
<tr>
<th>Loading</th>
<th>Safety</th>
<th>Comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion joints and transition slabs - oblique or slanting vs. perpendicular design. Hypothesis - oblique joints lessen dynamic impact on both - vehicles and structures.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Technical indicators - what are the angles [compared to right angle] for expansion joint that effectively eliminate [lessen] the impact of heavy vehicle on dynamic loading.

Social factor: how to evaluate the drop in roughness of bridge approaches and expansion joints: traditional IRI (International Roughness Index) is not describing the one time events [single impacts] so well, as IRI is quarter car based model. There is a need to develop a full car/truck roughness/dynamic impact evaluation algorithm.

Safety effect: what are the parameters of the pavement roughness (joints, etc) that are dangerous at certain speeds and at certain curve radii on bridge ramps. Anecdotal evidence says that this is particularly important for the two wheel vehicles.
A MONITORING-BASED INDICATOR OF LOCAL STIFFNESS REDUCTION

M.P. Limongelli(1), M. Domeneschi(1), L. Martinelli(1), M. Dilena(2), A. Morassi(2)
(1) Politecnico di Milano, Milano, Italy
(2) University of Udine, Italy

ABSTRACT

The actual state of a structure can be reliably described by proper Performance Indicators (PI) estimated from monitoring information and compared to threshold PI values.

The latter should be properly defined in order to find the best possible trade-off between the probabilities of having costly false and dangerous missing alarms.

In this regards maintenance decisions can be greatly improved if monitoring based performance indicators, are chosen to describe the actual state of a structure.

Herein a monitoring-based indicator of local losses of stiffness is proposed.

The indicator can be calculated basing on (Operational or Modal) Deformed Shapes recovered from a network of sensors (e.g. accelerometers) installed on the structure.

Several examples of application are reported and show that the indicator can give reliable alerts about the structural condition (scarcely influenced by environmental sources such as temperature), provided high quality sensors, with a low noise/signal ratio are employed.

The possibility of estimating a% and b% depends on the type of monitoring: short (no one), periodical (a), continuous (both a and b).

The stiffness loss indicator

\[ E(z) = \sum_i |\text{ODS}_i(z) - \text{ODS}_i(z, f)|^2 \]

Should we stay or should we warn?

The actual state of a structure can be described by the stiffness loss indicator. The threshold value is set to distinguish between before and after damage conditions.

Accepted false alarm probability a% Accepted missing alarm probability b%

The possibility of estimating a% and b% depends on the type of monitoring: short (no one), periodical (a), continuous (both a and b).

The Dogna bridge. Valdogna, Italy

The Shimoutsi Seto suspension bridge

The I40 Bridge. Albuquerque, New Mexico, USA

The Bill Emerson Memorial cable stayed bridge

Temperature variations do not reduce the reliability of results

Periodical monitoring: seismic excitation

Damage to deck

Damage to cables 1 and 2

Damage to cables

Sensitivity to damage severity

Sensitive to sensors noise

CONCLUSIONS

• Reliable localization of damage if high quality sensors (low N/S ratio) available.
• Scarcely influence of temperature variation.
• Possibility to choose the accepted false alarm rate.

WORKS IN PROGRESS

• Extension to the use of measurements in terms of strains (fiber optics)
• Output only measurements (ODS and/or modal shapes)
• Detection of damage at supports (piles settlement, scour)
Technical indicators for seismic assessment of bridges

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Abstract
The main goal of this work is to propose technical indicators which could translate the seismic behaviour of bridges. The first step is to explore the performance indicators of bridge structures, which capture the mechanical and technical properties, and establish a correlation with the seismic risk exposure. The objective is to achieve simple quantities like the maximum pier high, pier cross section dimensions, concrete and steel strengths which could be considered as technical indicators. For the seismic safety assessment two methodologies can be adopted, one more simple based on the bridge displacements and another more complex based on a probabilistic analysis.

Simple methodology based on the bridge displacements
Comparison of maximum displacements required by a seismic action with the maximum displacement available in the structure

Probabilistic methodology through vulnerability functions
With the seismic action distribution (1) and the vulnerability function (3)

\[ f_a(y) = \alpha \exp(-\beta y) \]

probability distribution of maximum ductility demand (4)
collapse probability of the bridge (5)

References
DELGADO, PEDRO; MARQUES, M.; MONTEIRO, R.; DELGADO, RAIMUNDO e COSTA, ANÍBAL
Two ways of assessing the seismic vulnerability e seismic vulnerability of bridges, Proceedings of the First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th European Conference on Earthquake Engineering & 30th General Assembly of the European Seismological Commission), Geneva, Switzerland, 3-8 September, 2006

DELGADO, RAIMUNDO; COSTA, ANÍBAL; ARÉDE, ANTÓNIO; VILA POUCA, NELSON; MIRANDA GUEDES, JOÃO; ROMÃO, XAVIER; DELGADO, PEDRO e ROCHA, PATRÍCIO

DELGADO, PEDRO; ARÉDE, ANTÓNIO; VILA POUCA, NELSON; COSTA, ANÍBAL
Methodology for assessment of masonry arch bridges

Tomasz Kamiński, Wrocław University of Technology, Poland

Masonry arch bridges are still numerous and important components of the road infrastructure in the whole Europe. The aim of the proposed work is development of a complete methodology for assessment of that type of structures. The scope of problems covered by the assessment process includes:
1. methods applied to collection of structural technical parameters,
2. consistent evaluation of the bridge technical condition,
3. organization and carrying out of field tests with elaboration of their results,
4. creation and application of numerical models,
5. assessment of the actual load carrying capacity of the bridge.

Some theoretical bases as well as practical information related to these engineering issues are to be provided. The considered performance indicators are: the technical condition and the load carrying capacity.

As the first step, the technical condition compared to the expected design technical parameters should be evaluated. Strict assumption and measures should be applied at the structure rating to enable consistent and comparable evaluation of large bridge populations. Thus, one of the most important issues is a unified classification system of bridge defects.

Defect types of masonry bridges

<table>
<thead>
<tr>
<th>Defect type</th>
<th>Subtypes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contamination</td>
<td>- inorganic (aggressive, neutral), - organic (penetrating, superficial)</td>
</tr>
<tr>
<td>Deformation</td>
<td>- deflection, - bulging, - sliding</td>
</tr>
<tr>
<td>Deterioration</td>
<td>- physical (e.g. embrittlement, strength reduction), - chemical (e.g. calcium carbonate leaching, pH reduction)</td>
</tr>
<tr>
<td>Discontinuity</td>
<td>- cracking, - fracture, - delamination</td>
</tr>
<tr>
<td>Displacement</td>
<td>- rotation, - translation</td>
</tr>
<tr>
<td>Loss of material</td>
<td>- of masonry block, - of masonry joint, - of a piece of masonry, - of backfill</td>
</tr>
</tbody>
</table>

Rules of advanced numerical modelling and analysis should be defined. Bases for selection of optimum model classes and masonry modelling techniques strictly determined by the aim of calculations will be given as well as the most useful and practical approaches will be indicated.

Applied methodology of masonry bridge evaluation should be based on results of experimental testing limited to a minimum providing essential findings. Usefulness of various NDT or MDT techniques needs be evaluated. An important part of tests is measurement of structure response to applied loads. Useful information is provided by both the static and dynamic tests which all together should be applied in validation of numerical models.

A key part of the proposed methodology is mutual correlation and application of results generated by two groups of works, i.e. field tests and numerical analysis, related to calibration of models on the basis of test results on the one hand, and to definition and optimization of testing actions on the basis of numerical outcomes on the other.

Recommended modelling strategies: a) 2D, b) 3D

Clear definition of masonry arch bridge load carrying capacity calculated by means of a numerical model is required. Therefore applied loading scenario and criteria defining the state of reaching the load capacity by the bridge must be strictly determined.

Scheme for the process of masonry bridge assessment
1. BACKGROUND

- More than 35% of European railway bridges are over 100 years old.
- Large scale replacement is practically impossible due to heavily utilized networks and financial constraints.
- Techniques that can improve prediction capability with respect to remaining service lives, allowing a life extension even by a modest fraction, are actively being sought.
- Over the years, deterioration models of varying complexity and accuracy have been developed as summarised in Table 1.

2. DETERiorATION FRAMEWORK

Example of a Level 2 model (dose response function):

\[ C(t) = A t^B \left( \frac{TOW}{C_1} \right)^D \left( 1 + \frac{SO_2}{E} \right)^F \left( 1 + \frac{Cl}{G} \right)^H e^{J(T+T_0)} \]

where TOW is the time of wetness (h/year), SO_2 is the sulphur dioxide concentration (µg/m³), Cl is the chloride deposition rate (mg/m².d), C_1 = 3800 h/year, E = mean of measured values of SO_2, T is the air temperature (°C), and T_0 = 20 °C. A, B, D, F, G, H and J are empirical coefficients.

3. PERFORMANCE ASSESSMENT

- Level 2 models offer the opportunity to directly relate the environmental and atmospheric pollutant variables to the rate of corrosion (Figure 1).
- Probabilistic analyses, through the use of Monte Carlo simulation, on a typical metallic railway bridge have resulted in the reliability and risk profiles shown in Figures 2 and 3.
- Evolution of climatic parameters, atmospheric pollutants and bridge resistance variables were treated as random.
- Consequences of bridge failure were taken into account to estimate risk.
- Long-term reduction of SO_2 concentration in an area can reduce the failure risk of the exposed structure, but the time-dependent probability of failure and associated risk remain higher compared to a bridge exposed to less polluted environment throughout its service-life.

4. CONCLUSIONS

- Level 2 models could, in future, offer refined corrosion predictions, potentially also allowing changes in exposure conditions over time to be accommodated.
- Long-term performance profiles of bridge elements have also been developed, capturing the deterioration of both the coating as well as the material.
- Both condition and resistance based profiles can be developed through this modelling level.
Criteria for condition assessment of bridges

Sandra Skaric Palic¹, Jure Radic¹,²

¹ Institut IGH d.d., Zagreb, Croatia
² University of Zagreb, Faculty of civil engineering

There is approximately 1300 km of highway and semi highway roads in Croatia. Due to geographical structure of the State of Croatia there are a lot of infrastructural objects on these roads, a great part of it being bridges. A vital part of managing such a big fond of infrastructural objects is condition assessment process in which, for now, there is no standardization.

A very large part (approximately 1100 km) of highway and semi highway network of roads is managed through a BMS. This BMS contains all parts of the road (bridges, tunnels, pavement, drainage system etc.). Bridges are visually inspected in certain periods of time and graded accordingly with grades 0-5 (0 excellent, 1 very good, 2 good, 3 satisfactory, 4 bad, 5 very bad condition).

On bridges graded 4 or 5 detailed investigation works with in-situ and laboratory testing are performed. Based on results of these investigation works a condition assessment is established followed by design of repair and protection works. This sequence of actions in BMS is different only if a visual inspection reveals some unexpected or extraordinary condition or event, on inspected structure, in which case even a grade less than 4 can cause further actions.

Structure is divided into elements (elements into parts) for analysis of structure condition (picture in the left). Whole structure is evaluated as a function of evaluation of all elements. First functionality of elements is evaluated, then traffic safety and last safety of whole structure. Based upon this, together with extent of deteriorations/defects, grade for general condition of the whole structure is determined.

---

Republic of Croatia - classified public roads (July 2013)

Inspection of bridge equipment - includes inspection of expansion joints, pedestrian guard rail, traffic barrier, bearings - depends on the materials and type of equipment

Inspection of substructural elements consists of determining and documenting:
- Damage
- Degradation of material
- Movement (including settlement)
- Soil washing - for elements in or near water

Inspection of superstructural elements consists of determining and documenting:
- Damage
- Degradation of material
- Deformation
- Vibration

---

EVALUATION OF ELEMENTS FUNCTIONALITY

EVALUATION OF TRAFFIC SAFETY

EXTENT OF DETERIORATION / DEFECTS

EVALUATION OF STRUCTURAL SAFETY

GRADE FOR GENERAL CONDITION OF THE WHOLE STRUCTURE
1. INTRODUCTION

Structural system of stone arch bridges

Constituent materials
- Masonry: Good behaviour in compression
  - Limited tensile strength
- Infill: shear strength depending on the normal stress and conditions of friction and cohesion

Failure mechanisms
- Longitudinal direction
- Transversal direction

Methodology for assessment of existing bridges

Experimental Characterization
- General characterization of the bridge
- Geometry, damage and degradation
- Material characterization
- Laboratory and in situ tests
- Dynamic tests
- Model identification
- Load tests
- Response monitoring

Structural Evaluation
- Load-carrying capacity
- Structural response under incremental static loads

2. EXPERIMENTAL CHARACTERIZATION

Material laboratory testing
- Granite stone blocks
  - $E = 22.4 - 39.2$ GPa
  - $f = 3.7 - 5.4$ MPa
- Infill: granular and mixture of granular and cement
  - $E = 30.2$ MPa

Material in-situ testing
- Granite stone masonry
  - Infill cohesive material
- Dynamic in-situ testing
  - $E = 13.23$ GPa

3. NUMERICAL MODELLING

2D Detailed FE model, Cast3M
- Geometry: Masonry micro-modelling
  - Stone blocks, Solid elements
  - Stone-to-stone and stone-to-infill Joint/Contact elements
- Infill homogeneous material
  - Infill material Solid elements

2D Detailed DE model, UDEC®
- Geometry: Drucker-Prager material - Granular
  - Stone blocks: Rigid blocks
  - Stone-to-stone and stone-to-infill Contact elements
- Infill homogeneous material
  - Infill material Bar elements

2D Simplified Rigid blocks model, RING®
- Geometry: Linear elastic material - Stone blocks:
  - $E = 15.5$ GPa
  - $f = 21$ kN/m
- Coulomb friction material
  - Stone-to-stone dry joints:
    - $k_n = 6.24$ MPa/mm
    - $k_s = 0.53$ MPa/mm
    - $\alpha = 0$
    - $\tau = 0$
  - Stone-to-infill joints:
    - $k_n = 0.56$ MPa/mm
    - $k_s = 0.28$ MPa/mm
    - $\alpha = 0$
- $c = 0$

Material parameters
- Drucker-Prager material - Granular
  - $E = 15.5$ GPa
  - $f = 21$ kN/m
- Coulomb friction material
  - Stone-to-stone dry joints:
    - $k_n = 6.24$ MPa/mm
    - $k_s = 0.53$ MPa/mm
    - $\alpha = 0$
    - $\tau = 0$
  - Stone-to-infill joints:
    - $k_n = 0.56$ MPa/mm
    - $k_s = 0.28$ MPa/mm
    - $\alpha = 0$
- $c = 0$

4. RESULTS AND DISCUSSION

Structural response under incremental static loads

FE model, Cast3M®
- Dead Load + RSA vehicle
  - Model intensity level of P:
    - $P_0$ - $P_6$
  - $\alpha$:
    - $0$
  - $\tau$:
    - $0$
- $CEM$:
  - $0.03$
  - $0.06$
- $1.0$
- $0.01$
- $0.02$
- $0.03$
- $0.04$
- $0.05$
- $0.06$
- $0.07$
- $0.08$
- $0.09$
- $0.1$
- $0.12$
- $0.14$
- $0.16$
- $0.18$
- $0.2$
- $0.22$
- $0.24$
- $0.26$
- $0.28$
- $0.3$
- $0.32$
- $0.34$
- $0.36$
- $0.38$
- $0.4$
- $0.42$
- $0.44$
- $0.46$
- $0.48$
- $0.5$
- $0.52$
- $0.54$
- $0.56$
- $0.58$
- $0.6$
- $0.62$
- $0.64$
- $0.66$
- $0.68$
- $0.7$
- $0.72$
- $0.74$
- $0.76$
- $0.78$
- $0.8$
- $0.82$
- $0.84$
- $0.86$
- $0.88$
- $0.9$
- $0.92$
- $0.94$
- $0.96$
- $0.98$
- $1$
- $1.02$
- $1.04$
- $1.06$
- $1.08$
- $1.1$

Rigid Blocks model, RING®
- Dead Load + Maximum RSA vehicle force
  - Model intensity level of P:
    - $P_0$ - $P_6$
  - $\alpha$:
    - $0$
  - $\tau$:
    - $0$
- $CEM$:
  - $0.03$
  - $0.06$
  - $0.09$
  - $0.12$
  - $0.15$
  - $0.18$
  - $0.21$
  - $0.24$
  - $0.27$
  - $0.3$
  - $0.33$
  - $0.36$
  - $0.39$
  - $0.42$
  - $0.45$
  - $0.48$
  - $0.51$
  - $0.54$
  - $0.57$
  - $0.6$
  - $0.63$
  - $0.66$
  - $0.69$
  - $0.72$
  - $0.75$
  - $0.78$
  - $0.81$
  - $0.84$
  - $0.87$
  - $0.9$
  - $0.93$
  - $0.96$
  - $0.99$
  - $1$
- $S$:
  - $0.5$
  - $1.0$
  - $1.5$
  - $2.0$
  - $2.5$
  - $3.0$
  - $3.5$
  - $4.0$
  - $4.5$
  - $5.0$
  - $5.5$
  - $6.0$
  - $6.5$
  - $7.0$
  - $7.5$
  - $8.0$
  - $8.5$
  - $9.0$
  - $9.5$
  - $10.0$
- $R$:
  - $0.5$
  - $1.0$
  - $1.5$
  - $2.0$
  - $2.5$
  - $3.0$
  - $3.5$
  - $4.0$
  - $4.5$
  - $5.0$
  - $5.5$
  - $6.0$
  - $6.5$
  - $7.0$
  - $7.5$
  - $8.0$
  - $8.5$
  - $9.0$
  - $9.5$
  - $10.0$

Reasonable agreement between the response parameters obtained in the FE and DE detailed models. Failure modes show the hinges located at the same joints of the principal arch.

The rigid block analysis also show good agreement with the detailed modelling in terms of the hinge configuration of the failure mode and maximum applied force.

5. REFERENCES


1. Introduction
Macedonia is a country located in the wide region of South Europe that is classified with medium to high seismic hazard. Consequently, during all stages of design, construction and maintenance of the bridges, the estimation and monitoring of their dynamic characteristics attracts significant attention and consumes serious part of the time and efforts. From the available possibilities one of the most useful procedures is operational modal identification of the structural system by ambient vibration testing, short-time and/or continuous monitoring. Usual types of damage and implication to structural characteristics and response to earthquake excitation on a real bridge structure are presented below.

2. Methodology

3. Typical sources for variability in static and dynamic response of bridges

4. Case study: modal parameters—effects in seismic response

5. References
[1] NATO Project for Repairing and Strengthening of Bridges in Republic of Macedonia, 2005-2015; Civil Engineering Faculty-Skopje
Effect of deterioration-induced cracks on the modal properties of concrete beams

Tamás KOVÁCS, György FARKAS
Budapest University of Technology and Economics
Department of Structural Engineering

RESEARCH OBJECTIVES

Condition control systems for civil engineering structures are intended to identify damage of the following four levels (Lythe, 1978); Level 1: Detection, Level 2: Localization, Level 3: Quantification of the severity of the damage; Level 4: Prediction of the remaining service life.

Goals of the research: The global purpose is to fulfil Level 3b by crack-related damage assessment on concrete beams under experimental conditions in the following steps:

- Introduction of existing dynamic-based damage assessment methods.
- Modelling crack-related damage under experimental conditions on various types of concrete beams.
- Elaborating signal processing tools to process vibration data (measure the first two natural frequencies).
- Definition of damage indices to identify crack-related damage and to measure its extent.
- Establishment of relationships between the measured dynamic parameters and the related structural performance-characterizing properties.
- Practical application of the method (in one of its parts).

EXPERIMENTAL CRACK-RELATED DAMAGE ASSESSMENT

Interpretation and modeling of damage was modeled either by cracking for reinforced concrete beams or by the combination of cracking and tensile cuts for prestressed concrete beams. Damage was measured by the extent of reduction in the effective prestressed beams. Damage was measured by the extent of cracking for reinforced concrete beams. Interpretation and modeling of damage was performed using the non-model-based methods (e.g. a) harmonic identification of average frequency spectrums). The use of phase spectrums made the reproduction of mode shapes associated with the determined natural frequencies possible. Dynamic measuring equipment. After each loading step the two natural frequencies were measured. Two types of excitation were used. The first was a single mechanical impact made by a rubber covered mallet. The second was a nearly periodic excitation produced by a periodic exciter, by which only the closest cavity of natural frequencies were excited with about constant excitation force.

DEFINITION OF DAMAGE INDICES, DAMAGE ASSESSMENT

Damage indices: Damage indices are defined to express information on the structural condition in numerical form. Any damage in the structure changes the natural vibration parameters gained by the index and, consequently, indicated as change in the value of the damage index.

Non-model-based indices: The following non-model-based indices were either defined as static parameters measured under or after loading phases or deduced from those without any additional model:

- Growth of "total length of cracks" (\(L_{total}\)) - local index
- Growth of total (\(L_{total}\)) and residual (\(L_{residual}\)) deflection at midspan - global index
- Growth of crack width at midspan (\(w_{midspan}\)) - local index

Model-based indices: The model-based indices were based on the vibration parameters and deduced from them by the following calculations:

- Growth of "total of crack sections" (\(A_{total}\)) - global index
- Growth of calculated crack width at midspan (\(w_{calc}\)) - global index
- Growth of internal energy (\(Q_{int}\)) - global index

Assessment: The assessment of beams focused on relationships between the measured natural frequencies and the deterioration stages of the structure. The main goal was to set basic trends and to define the likely intervals of natural frequencies changes in typical deterioration stages.

PRACTICAL APPLICATION

The applicability of natural frequency measurements in practical damage identification and/or assessment was tested on a four-span reinforced concrete bridge (11.4 m main girder + 9.6 m piers). The goal was to verify that reliable determination of the first few natural frequencies of the structure was possible using the natural frequencies for load exclusion purposes. The 0\(^{th}\) signals were recorded simultaneously in the middle of the structure, the average frequency gaps were determined from sums and differences of 0\(^{th}\) signals belonging to the same location of selected measurement locations. Calculated signal were computed on the use of phase spectrums to reproduce the mode shapes associated with the determined natural frequencies possible.
MULTIDIMENSIONAL MATRIX FOR PRELIMINARY ESTIMATION OF BRIDGES’ CONDITIONS

Prof. G. Markovski
Civil Engineering Faculty, “Ss. Cyril and Methodius” University in Skopje, R. Macedonia

NATO PROJECT FOR REPAIRING AND STRENGTHENING OF BRIDGES IN R. MACEDONIA

- 62 CONCRETE BRIDGES
- BUILT 1960-80
- NO DESIGN DATA FOR MORE THAN 50%
- NO PROPER WATER PROOFING
- NO PROPER DRAINAGE SYSTEM
- CORROSION OF CONCRETE AND REINFORCEMENT
- INSUFFICIENT BEARING CAPACITY

DATA COLLECTION

PRELIMINARY PERFORMANCE ESTIMATION

<table>
<thead>
<tr>
<th>STANDARDS</th>
<th>TECHNOLOGY</th>
<th>KNOWLEDGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIVE LOAD</td>
<td>MATERIALS</td>
<td>DESIGN PHILOSOPHY</td>
</tr>
<tr>
<td>SEISMIC DESIGN</td>
<td>CONSTRUCTION METHODS</td>
<td>STRUCTURAL ANALYSIS</td>
</tr>
<tr>
<td>ULS</td>
<td>QUALITY CONTROL</td>
<td>SOFTWARE</td>
</tr>
<tr>
<td>DURABILITY</td>
<td>MAINTENANCE</td>
<td>EXPERTS</td>
</tr>
</tbody>
</table>

TU1406 COST ACTION

COST Action is supported by the EU Framework Programme

Map of MK road network with the location of bridges

LOT2

LOT1

LOT3

25 BRIDGES

20 BRIDGES

45,15 km

4 BRIDGES

25 BRIDGES

SRB

NO PROPER DRAINAGE SYSTEM

INSUFFICIENT BEARING CAPACITY

CORROSION OF CONCRETE AND REINFORCEMENT
Defects and failures of Polish bridges – introduction to the study on structural robustness

Tomasz Kamiński, Wrocław University of Technology, Poland

Polish road infrastructure contains over 30 thousand of bridges. Every year tens of them undergo accidents or sudden environmental influences causing more or less significant defects or failures of their structural elements. In such situations modifications of a damaged bridge structure takes place including changes of its geometry, boundary conditions or even material properties. Detailed analysis of consequences of these modifications for the load carrying capacity has a crucial meaning and should be considered for both the existing damaged structures as well as for designed new ones.

Various case studies of defects and failures of bridges taking place over the past several years were studied. The most common observed damage cases and their relationships to structural type and material of bridges is given in the table below. The possible causes of the considered damage cases are also collected and classified.

The types of structures especially prone to be damaged:
- beam and frame viaducts located over motorways (with low clearance)
- narrow through arch and truss bridges (without safety crush barriers)
- bridges in a mining damage area
- bridges in mountain area with high probability of floods

All findings are oriented towards development of a uniform procedure of the bridge robustness evaluation. Typical damage scenarios are going to be suggested for consideration in this kind of assessment. For selected damage cases the mechanisms of the bridge behaviour (taking into account its redundancy) will be carefully studied and real threats to the load carrying capacity will be analysed.

Types of permanent loads acting on the damaged structures and some of the live loads required to be still carried by the damaged bridges should be defined.

Classification of the observed damage cases

<table>
<thead>
<tr>
<th>Damage cases</th>
<th>Possible causes</th>
<th>Structural type</th>
<th>Material of damaged element</th>
<th>Continuous intensity variation</th>
<th>Redistribution of internal forces in the main girders</th>
<th>Representation in a numerical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of material in the main girder</td>
<td>impact, flaw, corrosion</td>
<td>beam, truss</td>
<td>RC, PC, steel</td>
<td>yes</td>
<td>transverse</td>
<td>modification of geom., characteristics, removal of model’s elements, modification of model’s geometry</td>
</tr>
<tr>
<td>Cracking in the main girder</td>
<td>fatigue, flow, error, impact, overloading</td>
<td>beam, truss</td>
<td>RC, PC, steel</td>
<td>yes</td>
<td>transverse</td>
<td></td>
</tr>
<tr>
<td>Deformation of the main girder’s cross-section</td>
<td>impact, fire</td>
<td>beam, truss</td>
<td>steel</td>
<td>yes</td>
<td>transverse</td>
<td></td>
</tr>
<tr>
<td>Deformation of a truss’ strut</td>
<td>impact</td>
<td>truss</td>
<td>steel</td>
<td>yes</td>
<td>transverse</td>
<td></td>
</tr>
<tr>
<td>Fracture of a hanger</td>
<td>impact, fire, flaw, fatigue, corrosion</td>
<td>truss, arch</td>
<td>steel, RC</td>
<td>no</td>
<td>longitudinal</td>
<td>removal of model’s elements</td>
</tr>
<tr>
<td>Breaking of a column</td>
<td>impact, error, corrosion, flaw</td>
<td>beam, frame</td>
<td>steel, RC</td>
<td>no</td>
<td>longitudinal</td>
<td></td>
</tr>
<tr>
<td>Displacement of a support/span</td>
<td>flood, flaw, error, mining, impact</td>
<td>all</td>
<td>steel, RC</td>
<td>yes</td>
<td>longitudinal</td>
<td>modification of boundary conditions</td>
</tr>
</tbody>
</table>

Potential ways of the internal force redistribution should be analysed. Some generalization in this matter is needed. Possible variation in the intensity of selected damage cases is one of the starting points for the analysis.
SSI as a factor moderating seismic Demands in Bridge Piers

A. KOTSOGLOU1 AND S. PANTAZOPOULOU1,2

1 Democritus University of Thrace, Dept. of Civil Engineering V Sofoias 12, 67100, Xanthi, Greece, akotsoglu@civil.duth.gr
2 Professor, Department of Civil & Environmental Engineering, University of Cyprus, pantaz@ucy.ac.cy on leave from DUTH, Greece

ABSTRACT: In the present work, the seismic performance of bridge piers is investigated with consideration of the foundation-soil interaction effects. Recent research studies [1] indicate that foundation interaction may alleviate deformation demands in the piers at the expense of some permanent residual deformation at the foundation. Although the above mentioned contribution of SSI effects may be considered to have beneficial effects on the seismic response of the entire system, catastrophic collapses may be observed as a result of the modification of the dynamic characteristics of the Soil-Foundation-Structure system (e.g. in case of near fault excitations) [2]. Therefore, it would be of great significance to investigate the impact of SSI effects on the seismic performance of bridge piers, considering both dynamic and kinematic contributing factors. The main objective is to quantify the contribution of SSI effects through analytical and detailed finite element computational studies. For this reason, detailed nonlinear response history (NRHA) and pushover analyses are conducted for the foundation-pier assembly using sophisticated plasticity constitutive models to represent structural and soil material behaviour. Provided analytical and computational results are then correlated in order to quantify the seismic performance of the entire system.

Considering that the pier-foundation system is the critical structural element that controls the stability of the entire bridge, the contribution of soil-structure interaction effects is examined and evaluated with reference to soil properties and structural system type. Based on the above, guidelines are proposed in order to account for controlled soil-structure interaction effects during design and assessment.

Typical US Overcrossings rest on bridge-embankments: Implemented F.E. models: (a) MRO- Meloland Road Overcrossing and (b) PSEO- Painter Strew Overcrossing. (c) Pier- Foundation Substructure: Contributions to work-equivalent stiffness for cases with compliant foundation

ASCE 7-10 Chapter 10

Performance Limits for a well-detailed Superstructure (corresponding to the increase of the ground motion intensity and associated damage level)

References


Cyclic horizontal loading - Application to Existing and Novel Structures and


A CONCEPTUAL FRAMEWORK FOR THE ASSESSMENT OF BRIDGE PERFORMANCE INDICATORS THROUGH THE INTEGRATION OF CONSTRUCTABILITY, SUSTAINABILITY AND RISK ANALYSIS

Dimosthenis Kifokeris & Yiannis Xenidis
Aristotle University of Thessaloniki, School of Civil Engineering, Thessaloniki, Greece

• **Constructability:** the optimum use of construction knowledge and experience in planning, design, procurement and field operations to achieve overall project objectives [1]
• **Sustainability:** the concept of promoting the development that meets the needs of the present without compromising the ability of future generations to achieve their own needs [2]
• **Risk analysis:** the collective mathematical methodology to assess risk which allows a systematic process of making decisions to accept a known or assumed risk and/or the implementation of actions to reduce the harmful consequences or probability of occurrence of the risk [3]

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REFERENCES

1. Infraestruturas de Portugal S.A.
   - State owned Portuguese general concessionaire for roadways and railways.
   - Formed in June 2015 from the merge of the former road general concessionaire and railway general concessionaire.

2. Relevant Numbers
   - 22,200,000,000 vehicles/yr.
   - 5300 Roadway bridges
   - 3000 Routine Inspections/yr.
   - 1000 Principal Inspections/yr.
   - 13,664Km Road Network
   - 325 Monitored Bridges

3. Schematic Representation of the BMS

4. Surveillance Levels

<table>
<thead>
<tr>
<th>Surveillance Level</th>
<th>Conditions</th>
<th>Routine Inspection Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Surveillance</td>
<td>ECO, EC1, EC2</td>
<td>Each 2 yrs. Principal Insp. each 6 yrs.</td>
</tr>
<tr>
<td>Re却 强化 Surveillance</td>
<td>EC3 or underwater components</td>
<td>Each 2 yrs. Principal Insp. each 4 yrs.</td>
</tr>
<tr>
<td>High Surveillance</td>
<td>EC4, EC5</td>
<td>Each 2 yrs. Principal Insp. each 4 yrs. Annual Damage Inspection</td>
</tr>
</tbody>
</table>

5. Overall Condition of the Assets

- EC0 (Optimal): E0 2,0%
- EC1: 10,4%
- EC2: 34,3%
- EC3: 10,4%
- EC4: 1,5%
- EC5 (Critical): 0,3%
ROAD NETWORK IN PORTUGAL

Bridge QC plans in Portugal have been built around GOA - BMS used as standard in Portugal. Besides its adoption by public bridge owners (roads and railways), the system is implemented by all private road owners, resulting in every kilometre of highway and national roads (including some municipalities) being managed by the same system.

GUIDING POLICIES

- Bridge conservation
- Investment optimization
- Planning repair work
- Service level maximization
- Guaranteeing functionality and security conditions
- Maintenance of aesthetical conformity

SOFTWARE

Input
- Inventory
- Routine Inspection
- Principal Inspection
- Surveys
- Underwater Inspection

Output
- Queries
- Visualization
- Reports

Only analysis:
- Number of bridges
- Administrative data
- Technical data
- Certification data

List of Maintenance events:
- Accident report
- Monitoring
- Tearing
- Technical/technical evaluation
- Work Quantity Type of Repair Cost Calculations

Tender specifications
- SH of Quantities

Preliminary Stage: Inventory

Visual Inspections

Routine
- Sufficient
  - Maintenance work in less than half of the bridge components

- Insufficient
  - Presence of priority maintenance work
  - Maintenance work on more than half of the bridge components

Periodicity
- Between 12 and 24 months

Principal
- CR = 0 (Excellent)
- CR = 1 (Good)
- CR = 2 (Fair)
- CR = 3 (Bad)
- CR = 4 (Very Bad)
- CR = 5 (Critical)

Rating Assessment

1. By individual component
   - Based on 
   - Defect nature
   - Extent/evolution of defect
   - Potential consequences of defect

2. Global Condition Rating
   - Based on 
   - Condition Rating of each component

Based on
- Previous CR of bridge
- Higher CR → lower time interval

Importance of bridge

Limits
- "Not always present"

Measures
- "Not always present"

Maintenance Work recommended in Routine Inspection
- Annual Maintenance Work (maintenance works with prioritizing attribute in GOA)

Repair Work recommended in Principal Inspection
- Deadlines for Repair Work
  - Typically CR=4 and CR=5 have short to immediate time frames for repair work
Using inspection data to probabilistically estimate the time-to-rehabilitation for deteriorating bridges

Filippos Alogdianakis, Dimos C. Charmpis and Ioannis Balafas
Department of Civil and Environmental Engineering, University of Cyprus, Nicosia, Cyprus

The need to handle aging bridge stocks

- Vast budgets spent annually for maintaining aging bridges all over the world
- Need for:
  1. reliable estimation of deterioration rate and lifetime of bridges
  2. handling of uncertainties involved in predicting the structural performance of bridges with time
  3. efficient and cost-effective planning

US National Bridge Inventory (NBI)

- The US Federal Highway Administration maintains the NBI database that contains various data for over 500,000 US bridges
- NBI is published annually using up-to-date inspection data
- Bridge condition ratings (0-9) recorded
  0: fair condition
  1: poor condition
  2: critical condition
  3: serious condition
  4: fair condition
  5: good condition
  6: very good condition
  7: excellent condition
  8: failed condition
  9: failed condition

New method for estimating bridge deterioration rate

- Probabilistic estimation of the future structural condition of a bridge utilizing only today’s inspection data of the whole stock
- Main assumption: All bridges in a data-stock are used, based on their ages, to represent the condition of a single bridge during its lifetime

Main steps of the method

1. Process bridge inspection data to calculate CCPs
2. Determine threshold age $t_{\text{cut}}$ (‘cutting age’) to define the part of data leading to reliable (‘trusted’) CCP-calculations
3. Data shifting: Complete missing CCP-points (beyond age $t_{\text{cut}}$) by copying calculated data from higher to lower CCP-curves
4. Data scaling: Horizontal spreading of shifted data by means of age scaling to adjust the inclinations of CCP-curves (lower deterioration rates expected for lower CCP-curves)
5. Fitting of Weibull distribution to original and shifted/scaled CCP-points

Statistical validation of the method

- For the case study processed, original data are available until the bridge age of 114 years
- The method is applied for various values $t_{\text{cut}} < 114$ years and the resulting predictions are compared with the ones from actual/original data
- Satisfactory consistency observed for various $t_{\text{cut}}$ values

Case study

Analysed sample: 33,810 concrete bridges exposed to deicing salts (north US) and high humidity (water passing underneath) - data from the US NBI database used

Macroscopic, probabilistic bridge performance indicator: time-to-rehabilitation linked to probability to reach certain bridge condition (e.g. ≤5)

- Indicator evaluated using macroscopic data acquired by inspecting the actual bridge stock only today
- Exploitation of fitted Weibull distribution - example:

<table>
<thead>
<tr>
<th>Probability to reach condition ≤5</th>
<th>30%</th>
<th>50%</th>
<th>70%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-to-rehabilitation (years)</td>
<td>60</td>
<td>81</td>
<td>103</td>
<td>138</td>
</tr>
</tbody>
</table>

- Essential information to optimally allocate budgets for maintenance/rehabilitation of bridge stocks
**Condition vs. capacity based maintenance**

- Variety calls for inspection based maintenance planning.
- Often corrosion is not uniformly distributed. Poor details => a special record and special maintenance.
- A detailed desk study should highlight details that are critical in relation to safety (ULS as well as FLS).
- Special attention to details that are hidden.
- In order to capture the real performance of a coated metallic bridge analysis of several scenarios may be required. These scenarios should try to correlate coating performance and critical details with respect to ULS and FLS capacity. The LCAT should be used for each scenario in order to show which maintenance scenario(s) that optimise future bridge performance and show the economic and environmental impact associated.

**Initial Conditions (1)**

- Establishment of the maintenance plan is based on the performance of one of three railway girders in the LCAT. It is assumed that economic and environmental impacts from maintenance of the entire bridge are extrapolated from that of one railway girder. Otherwise perform grouping.
- On next slide the initial condition of the railway girder is shown. A coating half-life (service life) equal to 6 years in C3 environment seems appropriate. Please notice a manually entered ratio of the steel area that is protected by coating ("Initial coating coverage").

**Intervention Triggers (1)**

- Intervention triggers are shown on next slide. The shear capacity governs ULS capacity, hence plating is driven by the remaining shear capacity. Recoating is performed either as touch-ups when e.g. 10% of the coating area is lost (as depicted on next slide) or as a full recoating when say 50% of the coating area is lost. Both of these recoating triggers ensure that plating as intervention will never become active. If recoating as intervention is disregarded investigation of the difference between condition and capacity based maintenance planning may be performed. No intervention is triggered by timing only in the present case study.

**Intervention Changes**

- Intervention changes are shown below. Recoating "as new" with a CSM-high durability system that has a service life of 20 year in C3 environment has been assumed if plating, recoating or replacement interventions are triggered. If plating is triggered a 3 mm plate will be added on webs only.

**Intervention Costs**

- Intervention costs are shown on next slide. The costs are for an entire bridge, triggered by railway girder interventions. It has been assumed that if plating is triggered all three railway girders will be plated. For illustrative purpose and along with the suggested values of ML5S-4 discount rate is taken as 4% (in this validation case study both for cash and CO2e) and monetary value of CO2e equal to 75 Euroton CO2e. Possible user costs associated with disturbance of underpass traffic (speed restriction and/or congestion) may be entered manually in the "speed restriction" cells.
- Replacement of element has not been priced (as it will not be triggered in the present study).

**Output**

![Graph showing output](image)
Multi-performance sensor network for efficient management of roadway bridges

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1 Dynamic Monitoring and Structural Identification of the “St. Francesco da Paola” bridge

- Dynamic output-only tests by a data real-time acquisition system
- Identification methods in frequency domain (FFT)
- Identification methods in time domain (stochastic subspace identification - SSI - by ARTEMIS software)

![Fig. 1](image1)

(a) “St. Francesco da Paola” bridge; (b) data real-time acquisition system (THOR, Wave); (c) setup of the accelerometers; (d) sample of time-history of accelerations and FFT (accelerometer A0 during the first five minutes of test 1); (e) identification in frequency domain; (f) SSI resulting from ARTEMIS analysis.

2 Reliability analysis under traffic-induced vibrations

- Dynamic monitoring of the manufacture
- Data elaboration, achievement of accelerograms
- Assimilation of human comfort under traffic induced vibrations to a serviceability limit state (EN1990)
- Construction of histograms

![Fig. 2](image2)

(a) Comparison among different acceleration thresholds available in literature; (b) time-history of accelerations with the Bachmann thresholds; (c) Histogram of accelerations with the Bachmann thresholds; (d) relation between acceleration values and the corresponding exceeding probability P, with reference to setup 1; (e) mean curve of exceeding probabilities with the Bachmann thresholds.

CONCLUSIONS: Vertical vibrations exceed all the three predefined limits (disturbing, clearly perceptible, just perceptible).

On the 14th of February there was a huge fire on Łazienkowski Bridge – one of the most important bridge in the center of Warsaw. Full steel structure with three wooden service decks. The fire started during the exchanging of these wooden elements under the first span. It started in the afternoon and was extinguished the next day in the morning. During that time three spans was under fire.

On the next day Department of Bridges from Warsaw University of Technology was designated to conduct the expertise consisted of three general parts: material investigation, geometrical verification and FEM model analysis to determine the behavior of bridge during thermal overloads.

- steel structure with four plate girders and orthotropic deck; deck made of steel S3M (S235), girders and lower cross-beams of steel 18G2A (S355)
- mostly welded (only assembly joints were riveted),
- covers two three-line roadways 10,50 m each, separated by 1,00 m security strip; additionally two cantilevers for pedestrian 2,88 m wide each
- three service decks covered with wooden boards situated between girders
- depth of girders constant along whole structure: 3800 mm for external and 3892 mm for internal girders; thickness of webs: 12, 14, 16 or 20 mm; lower chords: 700 mm wide and 24 or 30 mm thick (some parts with cover plates 20, 24 or 30 mm thick)
- orthotropic deck plate thickness: 12 mm in span, 18 mm on the supports and 10 mm in cantilevers, open-shape longitudinal ribs (180 mm x 12 mm) every 344 mm
- spacing of the top (deck) cross-beams: 1500 mm, spacing of the bottom cross-beams: 9000 mm (every second with double webs)
- The insulation was bituminous and pavement was asphalt with depth 5,0 + 4,0 cm
- between the internal girders installed cold water, two hot water and gas pipelines, also about 20 cables were located between two pairs of girders

**RECOMMENDATION FOR DISCUSSION**

- Surveying measurements results should be obligatory part of QC reports for the long structures (span longer than e.g. 50 m or total length of the bridge more than e.g. 300 m)
- Frequency of measurements should be: for new structures (to 5 years) every year, for old structures every five years
- Detailed surveying control should consist: formation line measurements and verticality measurements for every girder (formation line measurements include also information about displacement of supports)

**BENEFITS FOR DISCUSSION**

- Information about behavior caused by creep of concrete and composite structures (helpful to define the average concrete characteristic)
- Initial identification of forces correctness in cables for cable-stayed structures
- Information about torsional behavior of spans
- By identifications of asymmetry parts determine places for further control
- Collect data for quick assessment of structural condition in the case of some accidents