QUALITY SPECIFICATIONS FOR ROADWAY BRIDGES, STANDARDIZATION AT A EUROPEAN LEVEL

eBook for the 8th Workshop Meeting
Barcelona, 27th September 2018

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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 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 trans-national 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 conferences topics. This is accomplished through the organization of conferences and workshops as the one organized at UPC-Barcelona-Tech in Barcelona.

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

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 project topics. This eighth Workshop, organized by UPC-BarcelonaTech in the North Campus of the University addresses the following topics:

- Methods and experiences of bridge Life-cycle Assessment;
- Establishment of Quality control plans;
- Quality control measurements, techniques and methods;
- Applications to Case Studies;
- Guidelines for implementation of Quality Control Plans;
- Quality control and standardization;
- Bridge management systems.

This e-book contains the contributions presented by the participants and shows the last works carried out within the Action.

Joan R. Casas
Vice Chair COST Action TU1406
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• **Welcome and opening session**
  by José Matos, Chair of COST Action TU1406, Joan R. Casas, Vice-Chair of COST Action TU1406 and Local Organizer.

• **A study on data driven strategy of management and maintenance of large-scale bridges**
  by Prof. Airong Chen, Tongji University, Shangai, China [Keynote Lecturer]

• **Economy and societal performance indicators for bridge maintenance prioritization**
  by Sandra Škarić Palić, Infra Plan konzalting, Croatia

• **On the development of key performance indicators for a rapid seismic assessment of roadway bridges**
  by Andrej Anžlin, Slovenian National Building and Civil Engineering Institute, Slovenia

• **Tecnalia´s vision on bridge life cycle management through innovation: A practical example through GENIA tool for inspection and assessment**
  by Jesus Isoird, TECNALIA, Derio, Spain [Keynote Lecturer]

• **Life-cycle assessment of a masonry arch bridge**
  by Naida Ademovic, University of Sarajevo, Bosnia and Herzegovina
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• **Automatically identify damage of a bridge deck using low-cost UAV-based images**
  by Linh Truong-Hong, University College Dublin, Ireland

• **Human errors and corresponding risks for reinforced concrete bridges**
  by Neryvaldo Galvão, University of Minho, Portugal

• **Quality control infrastructure managements systems and their implementation in medium-size highway networks**
  by Flora Faleschini, University of Padova, Padova, Italy [Keynote Lecturer]

• **Quality control of roadway bridges – reliability assessment**
  by Nikola Tanasić, University of Belgrade, Serbia

• **East bridge over the Channel of the Prague Port in Warsaw – Poland**
  by Paulina Bielecka, Warsaw University of Technology, Poland

• **Implementation of quality control plan into two case studies**
  by Marija Docevska, University Cyril and Methodius-Skopje, Republic of Macedonia
WORKGROUPS & SUBGROUPS WORKSHOP

Technical University of Catalonia

Barcelona, 27th September 2018

José C. Matos – Chairman
BACKGROUND

- Decay Process
- Efficient Management
- Public Demands
- Public Expectations
- Limited Resources

COST ACTION TU1406
BACKGROUND

Visual Inspection

NDT Testing

Monitoring System

Performance Indicator

Performance Goal

Quality Control Plan
There is a **REAL NEED** to standardize the quality assessment of roadway bridges at an European Level.
REASONS FOR THE ACTION

CSO Approval: 13-11-2014
Start of the Action: 16-04-2015
End of Action: 15-04-2019 (extension to end 2019)
Total Number of COST countries accepting MoU: 37
Total Number of COST countries intending to accept MoU: 0
The overall intention of the Action is to **develop a guideline for the establishment of Quality Control (QC) plans in roadway bridges** reachable by pursuing the following 5 objectives:

(i) Systematize knowledge on QC plans for bridges, which will help to achieve a state-of-art report that includes performance indicators and respective goals;

(ii) Collect and contribute to up-to-date knowledge on performance indicators, including technical, environmental, economic and social indicators;

(iii) Establish a wide set of quality specifications through the definition of performance goals, aiming to assure an expected performance level;

(iv) Develop detailed examples for practicing engineers on the assessment of performance indicators as well as in the establishment of performance goals, to be integrated in the developed guideline;

(v) Create a database from COST countries with performance indicator values and respective goals, that can be useful for future purposes.
ORGANIZATION

Management Committee
Including:
- MC Chair
- MC Vice-Chair
- WG’s Leaders and Vice-Leaders
- General Secretariat
- STSM Leader and Vice-Leader
- M&E Leader and Vice-Leader
- Innovation Leader and Vice-Leader
- R&D Leader and Vice-Leader

Core Group
- MC Chair
- MC Vice-Chair
- WG’s Leaders
- General Secretariat
- STSM Leader
- M&E Leader *
- Innovation Leader *
- R&D Leader *

Advisory Board
- Industry/Owners/Operators
- External Advisors (MC Observers)

MC Observers
- Australia
- Chile
- Japan
- South Africa
- United States of America

An MC Observer per Continent

* under an “ad-hoc” basis
SCIENTIFIC PROGRAM

WG5. Drafting of guidelines/recommendations
- Existing documentation (format and content)
- Document preparation
- Easy to use document

WG4. Implementation in a case study
- Benchmarking
- Validation
- Discussion

WG1. Performance indicators
- Technical indicators
- Environmental indicators
- Others

WG2. Performance goals
- Technical goals
- Environmental goals
- Others

WG3. Establishment of a QC plan
- Bayesian nets
- Procedure to develop a QC plan for a single bridge
## SCIENTIFIC PROGRAM

<table>
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<th>Activity/Months</th>
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<th>6</th>
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<td>M2</td>
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<td>M3</td>
<td></td>
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<td>M4</td>
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**M1:** WG1 – Performance indicators  
Elaborate a report of performance indicators

**M2:** WG2 – Performance goals  
Elaborate a report of performance goals

**M3:** WG3 – Establishment of a QC plan  
Prepare recommendations for the establishment of Quality Control plan

**M4:** WG4 – Implementation in a Case Study  
Prepare database from benchmarking

**M5:** WG5 – Drafting of guideline/recommendations  
Prepare guideline/recommendations for the establishment of QC plan
MEMBERS

- All participants: 264
- MC Member: 67
- MC Substitute: 35
- MC Observers: 5
- WG Members: 249
- ESR: 94
- Countries: 56
WG1. Milestone

**WG1**

**Technical Report**

Performance Indicators for Roadway Bridges of Cost Action TU 1406

- **General**
  - Performance Indicators terms after surveying

- **Operators**
  - Operators list of documents and database per country

- **Research**
  - Research list of documents and database per country

- **Glossary**
  - Glossary and specific term sheet per country

available on website: [www.tu1406.eu](http://www.tu1406.eu)
WG1. PERFORMANCE INDICATOR DEFINITION

**Measurable** and **quantifiable** parameter related to bridge performance that can be directly compared with a **target measure** of a **performance goal** (absolute measure of performance) or can be used for **ranking** purposes among a bridge population (relative measure of performance) in the framework of a **Quality Control Plan** or life-cycle management (decisions, i.e., actions involving economic resources).

Value derived from a combination of different measurable parameters (combined performance indicator).
WG1. From PI to KPI

1. **Survey phase**  
   Screening of national documents

2. **Clustering and homogenization of PI (from more than 700 to 385 PI)**  
   - WG 1 – Categorization of the PI in clusters  
   - NR – Verifying the PI inputs by comparing it with the homogenized and categorized terms

3. **From PI to KPI (from 385 to 108 PI)**  
   In order to move on with the reduction of the list of Performance Indicators, an Expert Group was asked to specify a reduced list of 108 PIs according to the following points:

   - **Level** (Component Level, System Level or Network Level)  
   - Is the PI **measureable**? (Technical, Socio Economical or Sustainable)  
   - PI **belongs to the Key Performance Indicator(s)**? (Reliability, Availability, Maintainability, Safety, Security, Environment, Costs, Health, Politics, Rating/Inspection)  
   - **Assessment** (Threshold, Goal, Rating)
WG2. Milestone

**WG2**

**Technical Report**

Performance Goals for Roadway Bridges

OF COST ACTION TU 1406

Performance Goals

- Reliability
- Performance Assessment

- Economy, Societal and Environmental Assessment

Glossary

- Multi-Objective Optimization Models

available on website: [www.tu1406.eu](http://www.tu1406.eu)
WG2. Interaction of PI with PG

COMPONENT LEVEL
- Damage degree & extension
  \[ PI \]
- Damage assessment
  \[ G(T) \]
- Element functionality
  \[ PI \]

SYSTEM LEVEL
- Importance of bridge element
  \[ WP \]
- Bridge condition assessment
  \[ G(T) \]

NETWORK LEVEL
- Bridge importance in the network
  \[ WP \]
- Priority repair ranking
  \[ G(T) \]
- Quality control plan
  \[ G(T) \]

\[ PI \] – Performance Indicators
\[ G(T) \] – Goals (Tasks)
\[ WP \] – Weighting Parameters
WG2. Performance Goals

**SYSTEM / BRIDGE LEVEL STRUCTURAL PERFORMANCE**

- Bridge inspection (visual, destructive testing, non-destructive testing) → Pls
- Monitoring data (SHM) → Pls
- On-site measurements (load testing) → Pls

**SYSTEM RELIABILITY ASSESSMENT**

- Assessment at the ULS
- Assessment at the SLS
- Seismic assessment
- Scour assessment

**EVALUATION OF STRUCTURAL PERFORMANCE → THRESHOLDS → CURRENT, FUTURE PERFORMANCE**

**MAINTENANCE OPTIONS**

- Do nothing
- Minor repair
- Major repair

**ECONOMIC ASPECTS**

- Construction costs
- Maintenance costs
- End of life cost

**AVAILABILITY ASPECTS**

- Traffic delays (caused by maintenance)

**ENVIRONMENTAL IMPACTS**

- Air, soil and water pollution

**SAFETY ASPECTS**

- Traffic safety during maintenance activities

**COMPARATIVE EVALUATION (WLCCA)**

**RELIABILITY KPI VALUE**

- Reliability index
- Bridge Condition Index

**SOCIETAL AND ENVIRONMENTAL KPI VALUE**

- User delay cost
- Environmental impacts

**ECONOMY KPI VALUE**

- Owners costs

**SAFETY KPIS VALUE**

- Traffic safety

**AVAILABILITY KPI VALUE**

- Availability of road (%)
- Downtime
- Importance on the network

**NETWORK LEVEL PERFORMANCE ASSESSMENT**

**MATRIX WITH KPIs FOR THE INVENTORY OF BRIDGES**

- Reliability
- Availability
- Economy
- Environment
- Safety

**MULTI-OBJECTIVE OPTIMIZATION FOR MAINTENANCE PLANNING (RANKING OF BRIDGES)**
WG3. Milestone

Quality of Road Bridges
Damage Processes

PI’s & Obs. Performance Assessment

Quality Control (QC) Framework

Application of the QC Framework

Human Resources and Equipment

Glossary

available on website: www.tu1406.eu
WG3. General Approach

Basis of design:
- Material properties
- Design Loads
- Environment
- Soil properties
- etc.

Design requirements and costs:
- Long-term costs -> Construction costs
- Serviceability -> Fulfilled
- Safety -> Fulfilled

Bridge data:
- Bridge type
- Geometry
- Construction type
- Construction method
- Construction year
- etc.

Assessment:
- Long-term costs -> Add inspection costs
- Serviceability -> Fulfilled
- Safety -> Fulfilled

Forecast at Top:
- Long-term costs -> Add in-depth investigation and intervention costs
- Serviceability -> Fulfilled
- Safety -> Fulfilled

Forecast at Tul:
- Long-term costs -> Add in-depth investigation and intervention costs
- Serviceability -> Not fulfilled
- Safety -> Fulfilled

Long-term costs ≠ Min

Commissioning

Inspection

Intervention 1

Intervention 2

today

Top

Tul

Time
WG3. Key Performance Indicators
### WG3. Damage Processes

<table>
<thead>
<tr>
<th>No</th>
<th>Proposed Damage Processes</th>
<th>Material</th>
<th>Impact</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Concrete</td>
<td>Steel</td>
</tr>
<tr>
<td>1</td>
<td>abrasion</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>aggradation (alluviation)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>erosion</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>pitting corrosion</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>5</td>
<td>changing geotechnical conditions</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>6</td>
<td>aging of material</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>7</td>
<td>alkali aggregate reaction</td>
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</tr>
<tr>
<td>8</td>
<td>chemical action</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>9</td>
<td>corrosion related to prestressing steel</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>10</td>
<td>corrosion related to reinforcement steel</td>
<td>✓</td>
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<tr>
<td>11</td>
<td>corrosion related to structural steel</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>12</td>
<td>fatigue</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>13</td>
<td>sulphate reaction</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>14</td>
<td>corrosion related to equipment made of steel</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>15</td>
<td>corrosion related to fixings, connectors</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>16</td>
<td>overloading of an element</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>17</td>
<td>biological growth</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>18</td>
<td>freeze-thaw</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>19</td>
<td>high temperature</td>
<td>✓</td>
<td>✓</td>
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</table>
### WG3. Common Drivers for PIs

| Damage Process | Abrasion | Aggradation (alluviation) | Erosion | Changing geotechnical properties | Aging of material | Alkali aggregate reaction (alkali-silica reaction) | Sulphate reaction | Chemical attack | Fatigue | Pitting corrosion | Corrosion related to prestressing steel | Corrosion related to structural steel | Corrosion related to reinforcement steel | Corrosion related to equipment made of steel | Corrosion related to fixings, connectors | Overloading of an element | Biological growth | Freeze-thaw | High temperature |
|----------------|----------|--------------------------|---------|---------------------------------|-------------------|---------------------------------|------------------|----------------|---------|------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|-------------------|----------------|----------------|
| Cracks         | ●        | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |
| Crossing       | ●        | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |
| Rippling       | ●        | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |
| Degeneration   | ●        | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |
| Scaling        | ●        | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |
| Debonding      | ●        | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |
| Deformation    | ●        | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |
| Wire break     | ●        | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |
| Prestressing cable failure | ● | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |
| Reinforcement bar failure | ● | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |
| Fracture       | ●        | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |
| Loss of section | ●     | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |
| Deteriorated mortar joint | ● | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |
| Frequency      | ●        | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |
| Vibration/oscillations | ● | ●                        |         | ●                               | ●                 |                                       | ●                | ●               | ●       | ●                | ●                               | ●                               | ●                               | ●                               | ●                               | ●                 | ●               | ●               |

**Observations / Performance Indicator:**

- ●: Low damage
- •: Medium damage
- ●: High damage
- ★: Extreme damage
WG3. Quality Control Framework

Inventory
- Structure
- Component
- Construction type

Performance indicator
KPI

Failure mode

Vulnerable zone
Damage Process
Observation
Design and construction
WG3. Protocol for Performance Evaluation

- Structure
  - Component
  - Construction type
- Performance indicator
- Vulnerable zone
- Observation
- Design and construction
- KPI
- Damage Process
- Inventory
- Failure mode
- Time

### Main Girder
- Reinforced concrete: 1970

### Deck
- Reinforced concrete: 1970

### Curb
- Granite: 1970

#### Bending Failure Mode
- HSS

#### Shear Failure Mode
- HSS

### Reliability (Structure safety)
- Corrosion
- 3 years

### Safety (Life and limb)
- Overloading
- 2 years
- Corrosion
- 4 years
- Damaged
- 4 years

### Corrosion
- Crack
- Spalling
- Efflorescence

### Overloading
- Falling chunks
- Spalling
- Corrosion

### Damage Process
- None
WG3. Inspection Protocol

Acceptance
Scope of regular inspection

Event e.g. rockfall, flooding, etc.

Inspection incl. in-depth investigations

Doubts?

yes

Include additional investigation and/or analytical methods

Improvement

no

yes

Rehabilitation Maintenance

Interval to the next inspection

yes

no

Performance goals fulfilled?

Further investigations?

no

no

Demolition

yes

Bridge needed?

Static (snapshot) QC

Dynamic QC
## NEXT EVENTS

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<th>LOS</th>
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<td>1-4 Oct. 2018</td>
<td>Yiannis Xenidis Panagiotis Panetsos</td>
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<th>Date</th>
<th>LOS</th>
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<tr>
<td>WG &amp; MC meeting + Workshop</td>
<td>Guimarães, Portugal (PT)</td>
<td>25-26 Mar. 2018 (2D)</td>
<td>José Matos ???</td>
</tr>
<tr>
<td>FINAL CONFERENCE</td>
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Call for Papers deadline: **##th aaaaaaaa 2018**
You are invited

Towards a Resilient Built Environment
Risk and Asset Management

27-29 March 2019
Guimarães, Portugal

Hope to see you soon
CLOSING

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E: jmatos@civil.uminho.pt

www.tu1406.eu
EUROPEAN ASSOCIATION ON QUALITY CONTROL OF BRIDGES AND STRUCTURES

José C. Matos
Chairman of the Executive Committee

Supported by:
Established

• Portugal, June 7, 2017
• Founding members
  – José C. Matos, University of Minho, Guimarães, Portugal
  – Joan R. Casas, BarcelonaTech, Barcelona, Spain
  – Alfred Strauss, BOKU, Vienna, Austria
• Supported by COST Association
• Formed following the work carried out in the framework of COST Action TU1406 – Quality specifications for roadway bridges, standardization at a European level (BridgeSpec)
• International non-profit association under Portuguese law
Aim

Promote, at a European level, the understanding and advancement of practice on quality control of bridges and structures
Objectives

• Improvement of quality of bridges and structures in Europe;
• To promote worldwide cooperation and understanding through the exchange of knowledge and experience in quality control;
• To encourage awareness and responsibility of structural engineers towards the needs of society;
• To encourage actions necessary for progress of quality control in bridges and structures;
• To improve and foster cooperation and understanding between organisations with similar objectives.
Initiatives

• Organise meetings, seminars, conferences and related activities independently or in collaboration with other organisations;
• Collaborate with other organizations and institutions having objectives consistent with those of the Association;
• Identify research and development needs;
• Initiate and support research activities;
• Publish reports, communications, periodicals, books, amongst others.
Activities

• Conferences on odd years (1st Conference will be held in 2019, and will coincide with the Final Conference of COST TU1406) [open to proposal for 2021];
• Training Schools (open to proposals for 2020);
• E-Newsletter and E-Books of the Conferences;
• Publish reports, communications, periodicals, books, amongst others;
• Facebook, LinkedIn, YouTube channels.
Organization

- General Assembly;
- Executive Committee;
- Advisory Committee;
- Audit Committee;
- National Groups (to be constituted in an independent way).

Elections for three year periods (limited to two consecutive terms)
Organization

• Executive Committee
  – President
    • José Matos
  – Vice-President
    • Joan Casas
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  – President
    • Jan Bień
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    • Sérgio Fernandes
  – Rapporteur
    • Yiannis Xenidis
Membership

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- Institutional members which shall appoint three representatives who may attend meetings and participate in the Association's scientific meetings programme with the same privileges as individual members;
- Young members, with 25 years or less;
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A STUDY ON DATA DRIVEN STRATEGY OF MANAGEMENT AND MAINTENANCE FOR LARGE-SCALE BRIDGES

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Bridge Design Methods and Processes
DATA DRIVEN STRATEGY OF MANAGEMENT AND MAINTENANCE OF LARGE-SCALE BRIDGES

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Abstract. The maintenace and management of large-scale bridges are difficult tasks. Traditional strategy is mainly determined based on the experiences of engineers and over-subjective. To increase the objectivity of the strategy, the data driven method can be used. This paper mainly introduces some recent engineering practices to use the data driven method to determine the proper strategy of the maintenance and management of large-scale bridges in China. Based on these practices, the following conclusions and perspectives can be made, (1) The raw data needs proper analyses to extract the information which is helpful to decision making. Otherwise, the data is useless; (2) The data standardization is of great importance to improve the data sharing and efficiency of data storage, transfer and processing; (3) The computer vision and deep learning are efficient tools to deal with images and extract the characteristics inside the images; (4) The data fusion theory should be widely used to obtain a more comprehensive evaluation of data from different sources.

Keywords: data driven, maintenance, management, large-scale bridge, computer vision.

1. Introduction

During the past twenty years, a lot of cable-stayed and suspension bridges have been built in China. Owning to the complicated environmental conditions, the safety, service and durability performances of these large-scale bridges will gradually deteriorate during the service life. To maintain and further improve the performances, proper strategy of the maintenance and management is needed. For a long time, the strategy is determined mainly based on the experiences of engineers and the preference of bridge managers against cost, risk, etc. This kind of bridge maintenance and management is, therefore, over-subjective. To increase the objectivity and efficiency of maintenance and management, the strategy and decision making should be based on the data which can represent the real conditions of the bridge. Usually, the data can be obtained from the health monitoring system (Ko and Ni 2005, Kim et al. 2007, Catbas et al. 2008). Being pre-installed in large-scale bridges, the health monitoring system can produce gigabytes of data every day. Useful information, which can provide valuable suggestions to the maintenance strategy, may be found by proper analyses of the data. This data driven strategy is helpful to determine the perfect timing and plan for the bridge maintenance, and thus increase the efficiency.

This paper contains some recent engineering practices to use the data driven method to determine the proper strategy of the maintenance and management of large-scale bridges in China. The focus of this paper is mainly to introduce the processing method to extract useful information from raw data, and the importance of further necessary analyses in the decision making. Besides the health monitoring system, the data from other sources, e.g., images, is also analyzed. It is expected that through this paper, the engineers, technicians and managers of bridges can further realize the great value of the data and buried information, and apply the data driven based strategy in the maintenance and management of large-scale bridges.

2. Framework study

2.1 Philosophy

To determine the proper strategy of the maintenance and management of bridges, the bridge condition should be assessed, which is one of the most important tasks during the service life. Only with the accurate condition assessment can the proper decisions on the strategy of the maintenance and management be made. To improve the objectivity of the bridge condition assessment, the data driven method can be proposed. The brief framework of the data driven assessment method is schematically shown in Fig. 1. The entire framework is divided into four levels, i.e., data acquisition and processing, evaluation method, component conditions and strategy. In the framework, the strategy is the ultimate output, which is controlled by the conditions of different components such as the girder, tower and cable. The component conditions as the second level are assessed by corresponding methods depending on the data. Thus, the assessment method is the third level in this framework. To conduct the assessment, different types of data as the last level need to be collected and analyzed.

With the framework in Fig. 1, for each bridge component, a pie chart with different levels can be finally obtained, as shown in Fig. 2. In the chart, three types of bridge component parameters are distinguished by three colors, the
innermost fan-type annotates the performance type, and outer rings denote: parameter, data source, evaluation method and corresponding counter-measures. The outermost arrow indicates that some parameters may affect different conditions at the same time. For example, the crack width can decrease the service performance of the concrete component by an uneasy feeling of the structural safety, and affect the durability performance at the same time, as the crack facilitates the penetration of harmful agents such as chloride ions and carbon dioxide. The pie chart in Fig. 2 can provide a preliminary suggestion to the decision making on the maintenance strategy.

![Framework of data driven method for strategy](image1)

**Fig. 1.** Framework of data driven method for strategy.

**Fig. 2.** Parameter hierarchy of suspension bridge pylon.

### 2.2 Data

Compared with the data commonly used in structural design, the term “data” in data driven method for the decision making has two special characteristics. The first one is “big”, which means that the data has a huge size which requires a large database, as well as a special approach to storage and process. For example, the health monitoring system of the Sutong bridge, a cable-stayed bridge with a main span of 1088 m, generates about 10 GB data per day, which is about 3.65 TB per year. The other characteristic of the data is “multi-source”, which means that the data used nowadays is not limited to the classical time-domain signals usually obtained from sensors in the health monitoring system. Images, records of sound and even unstructured texts can be also used. Owing to the diversity of the data source, another concept of “data fusion” or “information fusion” may be introduced into the civil engineering. The data fusion means that the decisions are not made based on only one data source, e.g., data from a typical sensor, but with the help of different data sources, e.g., data from a array of sensors. The application of the data fusion can enable a more comprehensive and convincing assessment of the bridge condition.

One of the big problem of the data in the field of bridge engineering is that the formats of the data in different health monitoring systems are incompatible. Therefore, the corresponding storage, transfer and processing systems are also different, which hinders the data sharing. One possible solution of this problem is the data standardization, which in our opinion follows the flowchart in Fig. 3. Firstly, a pre-analysis is conducted to judge which kind of and how much data is needed. The pre-analysis can also provide suggestions to the settlement of sensors in the health monitoring system. The sensors should be installed at key positions of the bridge components which are identified from a structural analysis.

After the pre-analysis, the required data is acquired from in-situ monitoring or inspection. The collected data is then transferred to the control center, where the raw data is preprocessed, e.g., cleansing, repairing and compression. This step is the core of the data standardization and of great importance to the further data processing. The preprocessed data is further uploaded and stored in the cloud. The techniques of cloud computing and cloud storage can be adopted to increase the efficiency of data transfer, storage and processing. With the cloud computing, the heavy task of data mining can be divided and distributed to various kinds of terminal devices such as the computing server, workstation and personal computer. With the cloud storage, the qualified end-users can access the data everywhere in the world for further structural analysis, performance evaluation, decision making, etc.

### 2.3 Assessment

The data standardized throughout the flowchart Fig. 3 establishes the base for the assessment of individual components and overall bridge conditions. Depending on the data, the condition assessment can be conducted by the direct or indirect methods. The direct assessment means that the component condition can be assessed simply based on the data collected from the health monitoring system or periodic inspections. For example, based on the longitudinal and transversal deflections at the top of the pylon which can be obtained from GPS monitoring, the safety performance of the pylon can be assessed according to the permitted deflections in standards and specifications.

In the indirect method, collected data need to be further analyzed to generate any valuable information. The indirect method can be further divided into numerical analysis and machine learning. The former is often used when the relationship between input parameters and output results is clear. If the relationship is not clear, the technique of “machine learning” can be used to find the implicit relationship between the input and output. The term “implicit” here means that, with machine learning, we know that typical inputs lead to corresponding outputs, but we do not know how. In other
words, we do not know the exact mechanism hidden behind the data. In most cases, however, this implicit relationship is already enough for the decision making on the strategy of the maintenance and management.

![Fig. 3. Data standardization analysis process.](image)

**2.4 Condition**

The conditions of different bridge components can be categorized into three types: safety condition, service condition and durability condition. These conditions may have different proportions for different components. For example, the condition of the deck pavement is dominated by its service conditions as it is closely related to the driving comfort. But for the suspender cable, the safety is absolutely the first concern of its condition assessment. As a common approach, the bridge condition is usually assessed based on the condition of each component. Thus, to facilitate the condition assessment, the bridge components need to be classified. In the current engineering practice, the components of large-scale bridges are usually classified into structural components and auxiliary facilities based on their importance levels. This classification, however, is over-simplified and does not fully consider the above different proportions of conditions for different components. Thus, a proper and refined classification of bridge components is needed in the framework of the data driven method for the strategy of the maintenance and management of large-scale bridges.

In the following parts of this paper, several recent engineering practices by us to use the data driven method to determine the proper strategy of the maintenance and management of large-scale bridges in China are presented.

**3. Prediction of vortex-induced vibration**

**3.1 Background**

The Xihoumen bridge is a suspension bridge in the East China Sea. It has a main span of 1650m which is the second largest span all over the world. The girder of the bridge is a separated steel box girder with a height of 3.51m and a width of 36m. The pylon of the bridge is 211m high. As a sea crossing bridge, the wind environment is very complicated. To ensure the safety of the bridge in extreme weather conditions, e.g., typhoon in the summer, monsoon in the winter, a high level of safety performance against the wind disaster is required in the structural design of the bridge. However, corresponding maintenance is still necessary during the operation stage.

**3.2 Data acquisition**

To provide reliable data to assess the safety of the bridge under wind effect, two propeller anemometers and six three-directional ultrasonic anemometers were installed to collect the wind field data of the bridge site. As is shown in Fig. 5, propeller anemometers and three-directional ultrasonic anemometers were installed on the top of the pylon and the deck, respectively. Two propeller anemometers (AN1, AN2) were installed in the north and south pylon of the bridge. The three-directional ultrasonic anemometers (UA1-UA6) were installed on the upper and lower sides of the stiffened
girder at the 1/4, 1/2 and 3/4 of the main span, respectively. Based on the records, a lot of vortex-induced vibration occurred between 2013 and 2015. With the help of the sensors shown in Fig. 5, key data, e.g., wind speed, direction, duration, etc., has been recorded. The further analyses is based on this raw data.

![Fig. 5. Layout of wind speed sensors in Xihoumen bridge.](image)

3.3 Data processing

3.3.1 Wind speed and direction

Based on a preliminary analysis, the wind speed and direction can be obtained. The results show that, (1) the vortex-induced vibration mainly occurs when the wind speed is between 8.5 m/s and 10.5 m/s; (2) the wind direction during the vortex-induced vibration is between 125 and 150 degrees or 305 and 330 degrees. Through the above analysis, the wind speed and direction have obvious characteristics in the case of vortex-induced vibration. Therefore, the wind speed and wind direction must be taken as parameters to conduct the occurrence probability analysis of the vortex-induced vibration.

3.3.2 Occurrence probability analysis

Since the wind speed and direction are both fundamental parameters related to the vortex-induced vibration, the occurrence probability can be calculated based on the wind speed and direction individually. According to the records of the vortex-induced vibration events of the long-span suspension bridge, the vortex-induced vibration mainly occurs in July and August. Therefore, totally 32 vortex-induced vibration events between July and August 2015 are selected. The results show that the occurrence probability of vortex-induced vibration is 15.7% and 12.3% based on the wind speed and direction, respectively. However, a more reasonable approach is to calculate the occurrence probability based on combined wind speed and direction. According to the data collected by the three-directional ultrasonic anemometer (UA1), totally 208 conditions are available for both the wind speed and wind direction, and 141 of 208 conditions is the vortex-induced vibration. Thus, it can be calculated that the occurrence probability of vortex-induced vibration of the bridge is 67.7%. Similarly, based on the data recorded by the sensors UA2 and UA3, the occurrence probability of vortex-induced vibration is 59.4% and 64.3%, respectively. Obviously, the occurrence probability differs when we use the data from different sensors. The data fusion theory (Linas and Hall 1998, Khaleghi 2013) can be then used to determine the proper occurrence probability. Here, the Dempster-Shafer evidence combination theory is used (Zadeh 1986, Yager 1987, Sentz and Ferson, 2002). The final result of occurrence probability, based on the data fusion theory, is 84.6%, which is much higher than that based on a single sensor.

3.4 Strategy of management

Based on the a series of analyses, the raw data from the sensors is processed to obtain the useful information, i.e., occurrence probability of vortex-induced vibration. The result is important to the decision making of the management. If the event that the wind speed is between 8.5 m/s and 10.5 m/s is defined as E1, while the event that the wind direction is between 125 and 150 degrees or 305 and 330 degrees is defined as E2, then if both E1 and E2 occur, there is a high probability of the vortex-induced vibration. In this case, counter-measures, e.g., traffic control, should be taken to avoid accidents. However, if only E1 or E2 occurs, the probability of the vortex-induced vibration is small, and no special actions are needed with an acceptable level of the risk.

4. Fatigue issue of steel box girder

4.1 Background

With consideration of the aerodynamic characteristics for wind resistance and the load carrying capacity per unit weight, the steel box girder is one of the most common structural types in design and construction of large-span bridges, e.g. the Millau Viaduct, the Great Belt Bridge, the Jiangyin Yangtze River Bridge, etc. To prevent or slow down the performance degradation induce by fatigue problems in the long-term, the maintenance and management works in the service life is the key. The data driven approaches will be highly valuable for the maintenance and management of steel box girder by identifying the traffic load. As the direct cause of the fatigue damage on the steel box girder, the traffic load is the most important live load during the life cycle of the bridge. A common method to obtain the traffic load is to apply weigh-in-motion (WIM) system, while the transverse in-lane positions of the traffic load on the critical section is still to be solved. In that case, a data driven approach is proposed to provide the real-time traffic load distribution.
4.2 Data processing based on computer vision

Besides the data from sensors in the health monitoring system, as previously introduced in this paper, images can be another source of data. In this case study, our task is to analyze the traffic flow on the Jiangyin Bridge, which is a suspension bridge with a main span of 1385 m. To acquire the images of vehicles on the bridge, cameras can be usually installed on the top of the pylon. In this case study, the raw data is the video stream from the cameras. The video stream can be further cut into several images. Then, the computer vision integrated with the deep learning (Deng and Yu 2014, Schmidhuber 2015, Lecun et al. 2015) is applied to find different types of vehicles, e.g., car, van, truck. To conduct the deep learning, a convolutional neural network (CNN) is formed. After the necessary training, the CNN can detect the vehicles on the other images on its own, as shown in Fig. 6 and Fig. 7.

![Vehicle detection by computer vision and deep learning.](image1)
![Result of traffic tracking.](image2)

The spatial spectrum traffic load can be obtained based on the identified traffic information by the CNN and the vehicle weight from the toll stations. The statistical transverse distribution of axles is given by different types of vehicles. As a result, the spatial spectrum of those weigh more than 10 tons is presented in Fig. 8(a), while the spatial spectrum of the cumulative load is in Fig. 8(b). Accordingly, the most vulnerable region is along the lane line. Particularly, attentions should be paid to the separating line between the slow land and the middle lane due to the superposition of the axle of heavy vehicles on these two lanes. Therefore, a maintenance strategy of conducting more inspections in this region can be expected.

![Vehicles with weight larger than 10 tons](image3)
![All vehicles](image4)

**Fig. 8.** Spatial spectrum of axle weight.

### 4.3 Fatigue analysis

Furthermore, the above result can be applied on the finite element models to generate a long-term history of the stresses at the key points, which enables to obtain the realistic fatigue cycles. By integrating the realistic fatigue cycles, inspection results, and the numerical models, an accurate fatigue assessment method with respect to the fatigue process can be established. Accordingly, the maintenance and management strategy can be modified in a flexible way to reach the target life.

### 5. Analysis of saddle sliding-resistance of suspension bridge

#### 5.1 Background

The main cable is the heart of the suspension bridge and of great importance. To ensure the safety performance of the bridge, it is not allowed that the cable saddle to slide, meaning that the saddle sliding-resistance performance should be evaluated during the maintenance. Currently, the following equation is often used in China to calculate the safety factor of the saddle sliding-resistance,

\[
K = \frac{\mu a_s}{\ln \left( \frac{r_{as}}{r_{cld}} \right)} \geq 2
\]  

(2)
where $\mu$ is the friction coefficient which is specified in design standards, $F_{a1}$ and $F_{a2}$ are cable forces on the left and right side of the cable, which can be either directly measured or calculated. The wrapping angle $\alpha_s$, however, is difficult to measured. Thus, in this case study, the computer vision is used to obtain $\alpha_s$.

5.2 Image acquisition and processing

The image acquisition in this case study is simple. Only two images are taken to partially cover the left and right sides of the saddle, respectively. Then, a panorama is obtained by image stitching (Lowe 2004, Brown and Lowe 2007), as shown in Fig. 9. Then, the methods of the Canny edge detection (Canny 1986) and Hough line transform (Hough 1962) are used to detect all edges in the panorama image. Irrelevant edges are removed from the output of the detection manually. Only the edges along the orientations of the cables are left. Based on these edges, it is easy to calculate the wrapping angle, which is $47.7^\circ$ in this case to be specific. When the wrapping angle is determined, the safety factor can be calculated by Eq. (2). Thus, the saddle sliding-resistance performance of the suspension bridge can be evaluated by checking whether the safety factor is larger than 2.0, which is specified in standards.

![Fig. 9. Calibration of wrapping angle based on computer vision.](image)

6. Conclusions

This paper mainly introduces some recent engineering practices to use the data driven method to determine the proper strategy of the maintenance and management of large-scale bridges in China. Based on these practices, the following conclusions and perspectives can be made, (1) A framework with four levels from data to strategy is proposed to develop the data driven method to determine the proper strategy of the maintenance and management of large-scale bridges; (2) The data standardization is of great importance to improve the data sharing; (3) Currently, the health monitoring system is still the main source of data. The other sources such as images, however, are also available; (4) The computer vision and deep learning are efficient tools to deal with images and extract the characteristics inside the images; (5) The data fusion theory should be widely used to obtain a more comprehensive evaluation of data from different sources.

References


A STUDY ON DATA DRIVEN STRATEGY OF MANAGEMENT AND MAINTENANCE FOR LARGE-SCALE BRIDGES

Airong CHEN – Tongji University, China
During the past 20 years, a lot of large-scale cable-stayed and suspension bridges have been built in China.
Framework
GENERAL PHILOSOPHY

• A framework with four levels
  – data acquisition and processing
  – assessment method
  – component and bridge performance
  – strategy decision

• Data is **base**

• Assessment method is **kernel**

• Performance is **main concern**
  – safety
  – service
  – durability

• Strategy is **ultimate purpose**
DATA

• Characteristics
  – “BIG”: huge amount of data
    • storage
    • processing
  – “MULTI”: multi sources
    • sensor, image, word, sound,…
    • data fusion theory
• Standardization is the key
  – pre-analysis to arrange data collection
  – raw data collection from in-situ test
  – preprocessing to filter useless data
  – remote data storage and deep processing
  – qualified end users to access data
ASSESSMENT

- “DIRECT”: simple condition index
  - Index is decided by a single type of data
- “INDIRECT”: complex condition index
  - Index is decided by multi-types of data
  - Numerical analysis
    - Numerical model is available
    - The relationship of “raw data ~ condition index” is clear
  - Machine learning
    - No model is available
    - The relationship of “raw data ~ condition index” is unknown
CONDITION

- Safety
- Service
- Durability
Pattern Analysis
Raw data is usually full of “chaos”
Pattern analysis is needed to “mine” data
Damper condition assessment

• Damper is an ancillary facility, but plays an important role in maintaining health condition of large-scale bridges

• However, various kinds of diseases exist during service life of bridges

• Damper has its own design service life, which is determined based on the laboratory test.

• In complex environment, however, the real service life of dampers may be far from the expect owing to the predictable and unpredictable diseases.

• So, how to evaluate the current condition and predict the remaining service life of dampers in large-scale bridges?
Damper condition assessment

• Raw data can be collected from sensors.
• How to mine useful pattern from raw data?
  – First, a proper assessment index is chosen: system damping ratio
  – Second, a mathematic model (method) is needed.
• Our purpose of the pattern analysis
  – deterioration of assessment index
  – judgement of current condition and decision making
    • periodic inspection?
    • repair?
    • replacement?
Damper condition assessment

Sutong Bridge
Main span: 1088m
Deck: box-girder, steel
Pylon: 300m height, concrete
Open: 2008

8 dampers were mounted between the pylon and the deck for the bridge

67DP-17621-01 dampers of Taylor company
Applied at Sutong Bridge
Damper condition assessment

- **Workflow**
  - raw data: from sensors
  - pre-processing: remove noise
  - data processing: wavelet transform filtering
  - pattern analysis: parameter identification
    - frequency
    - damping ratio
  - final result
    - current condition
    - future tendency

1. On-site acquisition of longitudinal vibration data
2. Data processing to remove noise
3. Power spectrum extraction in lower frequency range by wavelet transform filtering
4. Parameter identification of frequency and damping ratio
5. Damping ratio tendency over years
Damper condition assessment

- Raw data acquisition
  - two measuring points at each damper end connecting to deck.
  - sampling frequency: 128 Hz
  - sampling time: 60 minutes
Damper condition assessment

• What does the raw data look like?

The mathematical model needs the basic frequency

\[ S_Y(\omega) = \left| H(\omega) \right|^2 S_X(\omega) = \frac{S_0}{m^2 \left[ (\omega_0^2 - \omega^2) + 4\xi^2 \omega_0^2 \omega^2 \right]} \]

basic circular frequency

simplified system
Wavelet transform is used to remove high frequency from raw data.

The first-order longitudinal frequency of the deck is identified to be around 0.06Hz.

Thus, the system damping ratio can be calculated.

raw data in frequency domain

signal after seven layer of wavelet transform
Damper condition assessment

- Using raw data collected during different time periodic, different system damping ratios can be obtained.
  - 2014-04-17
  - 2015-04-27
  - 2016-11-09
- System damping ratio gradually decreases with time, which reflects the slow degradation of the damper condition.
- To better predict the deterioration of damper condition, it is necessary to repeat the experiment for more data and further analysis.
- It is possible to predict the remaining service life of dampers and help the decision making on repair or replacement
Data fusion
Multi data sources exist
Which one should be used?
VORTEX-INDUCED VIBRATION

• The Xihoumen bridge, a suspension bridge in East China Sea, is one of the largest sea-crossing bridge between Zhoushan mainland and islands link project.

• The span of the bridge is 578 m + 1650 m + 485 m which is the second largest span suspension bridges.
Owing to the severe sea environment, vortex-induced vibration is a common event on this bridge.

Through the records of the bridge manager, the bridge has occurred 97 times vortex-induced vibration from 2013 to 2015, including 26 times in 2013, 35 times in 2014, 36 times in 2015.

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</table>
VORTEX-INDUCED VIBRATION

- To monitor the vortex-induced vibration, sensors are installed on the bridge.
  - propeller anemometers (AN1, AN2)
  - three-directional ultrasonic anemometers (UA1 ~ UA2)
- These sensors transfer back huge amount of data everyday.
- What can we get from the data?
VORTEX-INDUCED VIBRATION

- Two indices are chosen,
  - wind speed
  - wind direction

- Critical range
  - vortex-induced vibration occurs when
    - wind speed: 8.5 m/s ~ 13.5 m/s
    - wind direction: 125° ~ 150° or 305° ~ 330°

- What is the occurrence probability?

Wind speed (m/s)

8.5 m/s

13.5 m/s

Calculation condition number

Vortex-induced vibration
Normal condition
Bridge axis

Wind speed in the plane $U$

wind direction angle $\Phi$

North Tower

AN1

UA1/UA2

UA3/UA4

UA5/UA6

South Tower

UA1

UA2

UA3

UA4

UA5

UA6
VORTEX-INDUCED VIBRATION

• Divide the time domain into several “10-minute” segments

10 min. 10 min. 10 min.

average wind speed (10 min.)

• The event “wind speed or direction is in critical range” happens $M$ times.
• The vortex-induced vibration happens $N$ times.
• The occurrence probability is

$$P = \frac{M}{N}$$
VORTEX-INDUCED VIBRATION

- Occurrence probability
  - only based on wind speed (speed is in critical range)
    - sensor U1: 15.7%
    - sensor U2: 14.6%
    - sensor U3: 14.3%
  - only based on wind direction (direction is in critical range)
    - sensor U1: 12.3%
    - sensor U2: 11.8%
    - sensor U3: 12.1%
  - based on both wind speed and direction (both speed and direction are in critical ranges)
    - sensor U1: 67.7%
    - sensor U2: 59.4%
    - sensor U3: 64.3%

different sensors have different results!
The result from which sensor should we believe?
  – Each sensor only provides a limited amount of information
  – The data from all sensors should be considered meanwhile

Data fusion theory can be introduced.
  – “1 + 1 > 2”: multiple data sources are more consistent than a single data source
  – The Dempster-Shafer Evidence (DSE) theory, a kind of data fusion theory, is used here

Final result of occurrence probability is 84.6%, much larger than the result of a single sensor.

The result means, when it is found that the wind speed and direction are both in the critical ranges, there is 84.6% probability that the vortex-induced vibration happens.
Computer vision
Images can also provide information

How to “dig” data from images?
SADDLE SLIDING-RESISTANCE

• Engineering background
  – Taizhou Bridge crossing Yangtz River
    • three-tower suspension bridge
    • span: 390 m + 2 X 1080 m + 390 m
    • steel box girder

• The capability of the saddle on middle tower against sliding is of great importance to ensure the bridge safety.

• How to evaluate the saddle sliding-resistance?
SADDLE SLIDING-RESISTANCE

- Sliding-resistance of saddle could be evaluated through safety factor,

\[ K = \frac{\mu \alpha_s}{\ln \left( \frac{F_{ct}}{F_{cl}} \right)} \geq 2 \]

- But, the wrapping angle cannot be directly measured.
- Only images are available. The data of the wrapping angle is hidden inside the images.
- Thus, a computer vision based technique is applied to dig the data.
SADDLE SLIDING-RESISTANCE

- First, a panorama is obtained by image stitching.
SADDLE SLIDING-RESISTANCE

- Second, line detection and Hough transform are implemented to find the edge.

- Thirdly, the wrapping angle is got through easy calculation, to be specific, which is 47.693° in this case.

- Finally, the safety factor of saddle sliding-resistance is calculated and the result shows that the safety margin is enough.

\[
K = \frac{\mu \alpha_s}{\ln \left( \frac{F_{ct}}{F_{cl}} \right)} \geq 2
\]

satisfied
Machine learning
Deal with “Big Data” more “intelligent”
TRAFFIC LOAD

- The traffic load information is of great importance for a loading test.
- At present, Weigh In Motion (WIM) systems are usually used to provide traffic load information.
- But, …
  - WIM systems may be unavailable in some bridges
  - WIM system could only provide information of a certain section
  - WIM system could not reflect vehicle driving characteristics on bridge

Is there any other method to acquire the traffic information on bridges?

WIM system on bridge
TRAFFIC LOAD

- Our solution: **Computer Vision + Deep Learning**
- Only computer vision is not enough.
  - Classic computer vision technique has limitations
    - parameters of algorithm need *manual* update according to the image quality
    - detection result and quality needs *manual* confirmation
    - thus, not intelligent enough!
- Deep learning can simulate the way we human beings think
  - training
  - learning
  - searching

Different images should have different threshold for binarization. Otherwise, the cracks cannot be properly detected. Also, whether the detection result is correct or not should be judged manually.
TRAFFIC LOAD

• What can Computer Vision + Deep Learning do?
  – Classification: it is a cat.
  – Localization: the cat is there.
  – Detection: there are a cat, a dog and a duck in this image.
  – Segmentation: the outlines of the cat, dog and duck can be cut from the image
TRAFFIC LOAD

• Traffic tracking is essentially a problem of **object detection**.
• How to track the traffic?
  – We feed the computer several images containing different types of vehicles.
  – We manually tell the computer where the vehicle is and what type it is.
  – After training, the computer can automatically learn the essential characteristics of a vehicle with a typical type (car, van, bus, etc.).
  – Then, the computer can find the vehicles in the other images.
  – The process is just the same as we teach a child to identify different objects in the environment.
• **Our ultimate objectives: real-time vehicle loading distribution (time vs space)**
  – Real-time testing, real-time evaluation, accident reporting, traffic jam alarming…. 
TRAFFIC LOAD

• To acquire images, cameras are installed at the top of pylons.
• From the video stream, totally 4,375 images \((295 \times 1920 \text{ px})\) are selected and labeled to form the Jiangyin vehicle detection dataset.
• The vehicles are classified into four types, i.e., car, bus, truck and van.
TRAFFIC LOAD

• Before learning, the computer needs training
  – We should teach the computer which is a car, which is a truck, etc.
  – To conduct the training, different vehicles in the images are manually labelled.

It is a car

It is a truck

daytime

night
After training, object detection framework shows its capability in accuracy and stability both in the daytime and night.

**TRAFFIC LOAD**

- **Daytime**
  - Truck
  - Car
  - Van
  - Bus

- **Night**
  - Truck
  - Car
  - Van
  - Bus
TRAFFIC LOAD

- Tracking based on detection results is implemented to obtain vehicle trails.
- Kalman filter and designed tracking strategies are proposed to modify detection results.
- Modified vehicle type, trails and velocity are obtained after tracking.
TRAFFIC LOAD

- Vehicle information can be obtained based on tracking results.
- Vehicle flow, hourly distribution, traverse distribution, speed distribution, tyres distribution surface...
- All the needed information related to the vehicle load can be obtained.

![Traverse distribution of different types of vehicles](image)
STEEL COATING DISEASE

- Apparent diseases can be initiated and propagated under severe environment
- Periodic inspection is important to identify these diseases.
- For the girder, inspection vehicle is usually installed.
- But, …

Thus, it is unsafety to send workers by the inspection vehicle for manual inspection.
STEEL COATING DISEASE

• For the pylon, the drone inspection is often used.
• But, …
• The drone is not stable, and greatly affected by the wind environment and signal interruption.
• The battery of the drone is currently quite limited.
STEEL COATING DISEASE

- **Computer Vision + Deep Learning**: a more efficient approach to detect bridge apparent diseases?

### Diagram:

- **Image acquisition**
  - Reasonable hardware
  - Image capture
  - Image stitching

- **Disease identification**
  - Disease semantic segmentation
  - Network architecture
  - Network training
  - Network inference
STEEL COATING DISEASE

- **Case study:** visual inspection of steel box-girder in Jiangyin Bridge
STEEL COATING DISEASE

- **Hardware:**
  - Industrial camera: 2058 pixel $\times$ 1536 pixel, up to 120 fps with full resolution.
  - Camera support: 400 mm length slide.
  - Only cameras are installed in the inspection vehicle.
STEEL COATING DISEASE

- Image acquisition by inspection vehicle
  - Sampling rate: 0.5 fps
  - Vehicle speed: 0.35 km/h
STEEL COATING DISEASE

- Set a reasonable sampling rate and vehicle speed, to keep the overlap area between two image more than 25% for the image stitching.
- The panorama by image stitching enables us to not only find the disease, but also know where the disease is.

blue line: partially overlapped region for image stitching
read line: the same crack
result of stitching
STEEL COATING DISEASE

- The sequence of images are stitched together to form a global view
  - Measured view: 97 cm × 69 cm / image, with full resolution, namely 0.47mm /pixel.
  - Image number: 17,755 with 2 cameras.
  - Image stitching: 100 images / group, 138 groups obtained in total.
STEEL COATING DISEASE

• Result of image stitching
STEEL COATING DISEASE

- Design of deep neural network: DeepLab with Atrous Spatial Pyramid Pooling (ASPP)
**STEEL COATING DISEASE**

- Disease identification
  - After deep neural network is trained, it can automatically detect the similar diseases
  - Disease area and occupied percentage can be counted

Disease area: 0.576 m², occupy 7.24%
STEEL COATING DISEASE

Low Probability of Disease

High Probability of Disease
STEEL COATING DISEASE

- **Condition evaluation**
  - Statistical analysis of different levels of diseases
  - As a whole, the condition of the steel box-girder painting is good.
  - The box girder in the north is worse than the one in the south, since there are more industry.
  - The evaluation and the evolution results of diseases during periodic inspection can be used in maintenance of steel coating.

7 levels are applied for evaluation.
Conclusion and Prospect
Conclusion and Prospect

- Data is the elementary (One can't make bricks without straw)
  - Which kind of Data? How to get? In more efficient way?
  - New generation of structural monitoring system?
  - How to connect with structural performance?
  - More performance indicators for long span bridges?
  - Standardisation?
  - .......

A STUDY ON DATA DRIVEN STRATEGY OF MANAGEMENT AND MAINTENANCE FOR LARGE-SCALE BRIDGES  |  AIRONG CHEN
THANK YOU FOR YOUR ATTENTION!

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ECONOMY AND SOCIETAL PERFORMANCE INDICATORS FOR BRIDGE MAINTENANCE PRIORITIZATION

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Irina Stipanović - University of Twente, The Netherlands
ECONOMY AND SOCIETAL PERFORMANCE INDICATORS FOR BRIDGE MAINTENANCE PRIORATIZATION

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Abstract: Strategic decisions regarding preservation activities encompassing both reactive and preventive maintenance as well as capital investments should be based on solid facts and reliable data, especially in the context of considerable impacts on economy, society and environment. The circumstances for infrastructure networks have changed during the last decades due to the increasing performance requirements, less public acceptance of risk, higher legal requirements and a limited budget. Sustainability in most business practices, as well as decision making process in bridge management is still often assessed only from economical point of view while environmental and especially societal dimension is underrated or even completely excluded from the analysis. Several issues add up to this complex problem among which are lack of indicators, metrics to assess environmental and societal pillars, and existence of trade-offs between the pillars and the stakeholder groups. This is even more valid and present in bridge management decision making process because of uncertainties regarding a number of different life cycle stages, a number of parties included and long service period of structures involved. In this paper a model for the development of maintenance plan for bridges which integrates multiple performance objectives has been proposed. Key performance indicators (KPIs) for reliability, economy, availability and societal impacts have been proposed, in order to support performance based decision making which needs to satisfy multiple performance goals. The proposed matrix with KPIs has been applied on the case study in Croatia, where different regions and number of bridges have been analysed.

Keywords: economy performance indicators, societal performance indicators, bridges, maintenance planning

1. Introduction

The road network facilitates the movement of people and goods, allowing for social interaction and economic growth. The road infrastructure needs to satisfy number of performance objectives related to operation, safety, economy, environment and other. Optimization of maintenance activities regarding technical and economic requirements is essential for road owners to fulfil societal expectations. Due to the long life time of the road infrastructure, especially bridge structures (often longer than 50 years), assessment of technical and economic performance is necessary in order to optimize budget expenditure. It is estimated that the ratio of expenses per route km of bridges is 10 times the average expense per route km of roads. The length of bridges compared to the whole length of road networks is only approximately 2% but at the same time they present 30% value of the whole network (PIARC,1999). During the last decade a new network management philosophy, Asset Management has emerged, which puts the customer - the traffic user - into the centre, and, at the same time, methods to allocate the socio-economic optimal amount of money to each specific asset (roads, bridges, tunnels, lighting, signs, guard rails, etc.). The circumstances for infrastructure networks have changed during the last decades due to the increasing performance requirements, less public acceptance of risk, higher legal requirements and a limited budget. (Wijnia & Herder, 2009)

Within asset management, physical assets are to be considered in relation with all other activities of the organization to deliver the required performance. For physical assets such as bridges, this means bridge management is to be part of the management of the network, and the bridge performance has to fulfil the network performance goals (Velde et al. 2010). Therefore the asset management has transformed into a performance management process that supports performance-based decision-making at both the network and object levels.

There is a large disparity in Europe regarding the way performance indicators are quantified and how performance goals are specified. Therefore, COST TU 1406 Action aims to develop an overview or a database of existing performance indicators. (COST TU 1406 WG2, 2017, Strauss et al. 2016). In this paper the model for development of maintenance plan for bridges which integrates multiple performance objectives has been proposed. Key performance indicators (KPIs)
for reliability, economy, availability and societal impacts have been proposed, in order to support performance based decision making which needs to satisfy multiple performance goals.

2. KPIs for Multiple performance objectives

Bridge performance goals should serve as the basis for bridge remediation priority ranking, based on the chosen maintenance strategy and assessment of the bridge condition and analysis of possible remediation alternatives. Some of the aspects of performance goals can be also seen as the client constraints, e.g. changes in governance strategies or minimal work implication.

Road agencies around the world have defined their own strategic goals. For example, UK Government has defined Strategic Road Network Specifications, in which following requirements on the network level have been defined (Department for Transportation, 2013):

- A strategic road network which supports and facilitates economic growth;
- A strategic road network which is maintained to a safe and serviceable condition;
- An efficiently and effectively operated strategic road network;
- A strategic road network which minimizes its negative impacts on users, local communities and the environment;
- A strategic road network which balances the needs of individuals and businesses that use and rely on it.

In the paper Stipanovic Oslakovic et al. (2016) the overview of strategic, tactical and operational level performance goals with the suggested performance indicators has been presented. Some of these indicators have been chosen for the development of MAUT model (Allah Bukhsh et al. 2018).

In the Table 1 the summary of suggested KPIs for different performance aspects are presented.

<table>
<thead>
<tr>
<th>Performance aspect</th>
<th>Performance goals (examples)</th>
<th>Key Performance indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>RELIABILITY</td>
<td>To provide safe and reliable road network, responsive and sustainable network;</td>
<td>Technical indicators:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Condition Index (BCI)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- reliability index</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- risk levels</td>
</tr>
<tr>
<td>AVAILABILITY</td>
<td>To minimize its negative impacts on the road users,</td>
<td>Availability of the road (% of time)</td>
</tr>
<tr>
<td></td>
<td>- To balance the needs of individuals and businesses that use and rely on it.</td>
<td>- Traffic delays caused by road works</td>
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<tr>
<td></td>
<td></td>
<td>- Availability of the road during rush hour</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- User Delay Costs (UDC)</td>
</tr>
<tr>
<td>ECONOMY</td>
<td>To provide an efficiently and effectively operated strategic road network;</td>
<td>Life cycle costs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maintenance Costs (MC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- operational costs</td>
</tr>
<tr>
<td>ENVIRONMENT</td>
<td>To minimize its negative impacts on the environment;</td>
<td>Environmental indicators:</td>
</tr>
<tr>
<td></td>
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<td>- air pollution</td>
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<tr>
<td></td>
<td></td>
<td>- noise</td>
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<tr>
<td></td>
<td></td>
<td>- soil and water pollution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Environmental Costs*</td>
</tr>
<tr>
<td>SOCIETY AS A WHOLE</td>
<td>To support and facilitate economic growth;</td>
<td>Traffic intensity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- (Un)Employment rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Personal income</td>
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<tr>
<td></td>
<td></td>
<td>- Property values</td>
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<td></td>
<td>- GDP</td>
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</tbody>
</table>

* see paper Allah Bukhsh et al. 2018

3. Case study Croatia

Transport infrastructure in the Republic of Croatia consists of app. 30.000 km of roads and motorways, 3000 km of railways, 6 seaports, 800 km of inland waterways and 9 airports. Construction of highways in Croatia began in 1970s with approximately 240 km (two routes, Zagreb-Karlovac and Zagreb- Slavonski Brod) of full profile highways in use when Croatia declared independence in 1991. In the year 2000, the process of accelerated highway construction began resulting in a network of almost 1300 km of highways across the country (http://www.huka.hr/mreza-autocesta). Large part of this network is connecting continental parts of Croatia with the touristic areas along the Adriatica coast.

The significance of road infrastructure network has been additionally articulated by the fact that transport connection is a pre-codition of regional and tourist developmet of a country, as well as of a better geo-strategic positioning in the European integration processes. When speaking of international traffic flows in Croatia, the importance of the tourist traffic should be especially evaluated, therefore we have proposed a new indicator related to the average summer daily traffic.
3.1 Description of the case study

A new economy performance indicator was introduced in the case study to incorporate the impact of tourism on the traffic quantity and transport infrastructure management for the purpose of wider strategic planning. Two different aspects are discussed through the case study in this paragraph. First is the ratio between average annual daily traffic and average summer daily traffic introduced as a performance indicator highlighting importance of a bridge in the context of tourism as an economical driver. In Croatia in tourist areas construction works are not to be performed from July to September due to tourist season. Second aspect of the case study is analysis of difference between user delay cost in March and July (if the works were to be performed in tourist season) to monetize the benefit of this regulation.

Three counties in Croatia are analysed as shown in Figure 1, two being in a popular tourist area (Zadar County) and one in eastern part of Croatia that is not exposed to high level tourism. 28 bridges, listed in Table 2, on highway sections in these counties are analysed with the following four performance indicators used to decide which bridges should be prioritized for maintenance planning: condition rating, maintenance costs, economy tourism performance indicator and user delay cost. Results of these analysis are presented in the next paragraph.

Table 2. List of bridges analysed in the case study

<table>
<thead>
<tr>
<th>Bridge number</th>
<th>Highway section</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Condition rating</th>
<th>Average annual daily traffic (AADT) 2017</th>
<th>Average summer daily traffic (ASDT) 2017</th>
<th>Ratio ASDT/AADT - Economy KPI (tourism)</th>
<th>AADT in March 2017</th>
<th>AADT in July 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A1 Maslenica south</td>
<td>374.74</td>
<td>23.40</td>
<td>4</td>
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<td></td>
<td></td>
<td></td>
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<td>2</td>
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<td>44.96</td>
<td>9.10</td>
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<td>3</td>
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<td>76.34</td>
<td>8.40</td>
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<td>4</td>
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<td>45.90</td>
<td>12.45</td>
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<td>5</td>
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<td>45.90</td>
<td>12.45</td>
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<td>46.02</td>
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<td>A1 Posedarje south</td>
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<td>18</td>
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<td>83.60</td>
<td>11.20</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>A3 Babina Greda east</td>
<td>21.00</td>
<td>14.20</td>
<td>1</td>
<td></td>
<td></td>
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</tbody>
</table>
### 3.2 Results

The multiple performance criteria can be combined into a so-called utility function, in which all the criteria are brought into a single scale. In order to transform the various out into a single (mostly monetary) scale it is necessary to establish weight factor for the individual type of criteria. Some of the weight factors are available in some countries (for example weight factor for traffic delays, noise, injuries etc.), depending on the selection of criteria, some weight factor may still need to be developed.

In the development of the weight factors the starting point can be taken in the qualitative approach mentioned above, from which the apparent relative weight can be deducted. Once the possible outcomes have been brought to a single scale, the best decision can be found as a formal optimised decision process, in which option with the maximum “utility” shall be selected as the recommended decision.

Multi attribute utility theory (MAUT) provides a systematic approach to reduce the qualitative values of various attributes (i.e. performance indicators) into utility functions (Ishizaka & Nemery, 2013). The resulting scores are then aggregated based on the relative importance of attributes. The final score assign a ranking to each alternative based on either minimization or maximization function. This method assigns the relative importance of performance indicators (e.g. condition, cost, economy etc.), while comparing number of bridges.

A decision maker choose among the set of possible outcomes while exposed with uncertainty and risk (Keeney and Raiffa, 1993). The uncertainty is usually originated because of unavailable and dynamic nature of data, and involvement of number of stakeholders. For instance, in the bridge planning the exact estimation on number of users affected due to maintenance activity is difficult to define. MAUT integrates a body of mathematical utility models and a range of decision assessment methods in order to assist in decision ranking problem (Thevenot et. al., 2006). The single attribute utility function is calculated for each performance indicator, which reflects the risk attitude of the decision maker.

The mathematical formulation of MAUT is represented as follows:

$$U(x) = k_1 U(x_1) + k_2 U(x_2) + \ldots \ldots + k_n U(x_n)$$

Where

- $U(x)$ is overall utility value of each alternative
- $k_i$ is a scaling constant that provides the relative importance of each performance indicator
- $U_i(x_i)$ is a utility value of each performance indicator $i$ for the alternative $x$

$$U_i(x_i) = A - B e^{(RT/x)}$$

Where

- $A$ and $B$ are scaling constants
- $RT$ is risk tolerance

The details of MAUT application on maintenance planning decision-making problem can be found at Allah Bukhsh et al. (2018).

The single utility scores of each performance indicator is computed. A decision maker is provided with a lottery questions representing the minimum and maximum value of a certain performance indicator. The median values between the maximum and minimum is called Expected Value (EV), where the selection of values greater or smaller than EV define the Certainty Equivalent (CE). The CE also represents the risk attitude of a decision-maker. In such case, a $CE > EV$ represents risk taking attitude, $CE = EV$ shows risk neutral, whereas $CE < EV$ represents risk avoiding attitude. Throughout this case study, we have considered risk-avoiding attitude as a decision maker wants to improve the economy and focuses on direct user costs.
Table 3 provides the minimum, maximum, EV and discerned CE, and relative importance weights of each considered performance indicators. For the economy indicator the maximum and minimum values are reversed. This is because the economy indicator is the only aspect, which we aim to maximise where the rest of the indicators are here for minimization.

Table 3. Details to discern Single utility function of performance indicators

<table>
<thead>
<tr>
<th>Key Performance indicators</th>
<th>Maximum value</th>
<th>Minimum value</th>
<th>EV</th>
<th>CE</th>
<th>U(CE)</th>
<th>Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio ASDT/AADT (EPI)</td>
<td>1.54</td>
<td>2.56</td>
<td>2.05</td>
<td>1.70</td>
<td>0.27</td>
<td>70</td>
</tr>
<tr>
<td>Condition score (BCI)</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>2.50</td>
<td>0.22</td>
<td>80</td>
</tr>
<tr>
<td>Maintenance cost (MC)</td>
<td>1167639</td>
<td>2500</td>
<td>585069</td>
<td>300000</td>
<td>0.22</td>
<td>60</td>
</tr>
<tr>
<td>User delay cost (UDC)</td>
<td>470252</td>
<td>3954</td>
<td>237103</td>
<td>130000</td>
<td>0.33</td>
<td>40</td>
</tr>
</tbody>
</table>

EV = Expected Value, CE = Certainty Equivalent, U(CE) = Utility of CE, relative importance weights

By utilizing the specific KPIs (see Table 3), the single utility and aggregated utility scores with respect to their relative weights is computed. The utility scores and final ranking is provided in Table 4.

Table 4. Ranking of bridges based on utility (minimization) function

<table>
<thead>
<tr>
<th>Bridge No.</th>
<th>BCI</th>
<th>MC</th>
<th>UDC</th>
<th>EPI</th>
<th>BCI_u</th>
<th>MC_u</th>
<th>UDC_u</th>
<th>EPI_u</th>
<th>MAUT</th>
<th>MAUT_rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>3</td>
<td>22.952,67</td>
<td>92.604,05</td>
<td>2.55</td>
<td>0.36</td>
<td>0.10</td>
<td>0.53</td>
<td>0.01</td>
<td>0.26</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>112.024,37</td>
<td>260.621,87</td>
<td>2.56</td>
<td>0.00</td>
<td>0.42</td>
<td>0.90</td>
<td>0.00</td>
<td>0.28</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>74.235,63</td>
<td>470.252,51</td>
<td>2.56</td>
<td>0.00</td>
<td>0.30</td>
<td>1.00</td>
<td>0.00</td>
<td>0.29</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>16.427,20</td>
<td>142.626,04</td>
<td>2.56</td>
<td>0.36</td>
<td>0.07</td>
<td>0.70</td>
<td>0.00</td>
<td>0.29</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>69.063,66</td>
<td>112.860,60</td>
<td>2.56</td>
<td>0.36</td>
<td>0.28</td>
<td>0.61</td>
<td>0.00</td>
<td>0.31</td>
<td>5</td>
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<tr>
<td>8</td>
<td>3</td>
<td>69.526,60</td>
<td>112.860,60</td>
<td>2.56</td>
<td>0.36</td>
<td>0.29</td>
<td>0.61</td>
<td>0.00</td>
<td>0.31</td>
<td>6</td>
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<tr>
<td>3</td>
<td>4</td>
<td>123.090,28</td>
<td>386.278,85</td>
<td>2.56</td>
<td>0.00</td>
<td>0.45</td>
<td>0.98</td>
<td>0.00</td>
<td>0.31</td>
<td>7</td>
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<tr>
<td>11</td>
<td>4</td>
<td>193.586,62</td>
<td>278.650,19</td>
<td>2.55</td>
<td>0.00</td>
<td>0.62</td>
<td>0.92</td>
<td>0.01</td>
<td>0.32</td>
<td>8</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>193.586,62</td>
<td>278.650,19</td>
<td>2.55</td>
<td>0.00</td>
<td>0.62</td>
<td>0.92</td>
<td>0.01</td>
<td>0.32</td>
<td>9</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>1.167.639,52</td>
<td>138.664,20</td>
<td>2.56</td>
<td>0.00</td>
<td>1.00</td>
<td>0.69</td>
<td>0.00</td>
<td>0.33</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>2.500,00</td>
<td>7.446,34</td>
<td>2.56</td>
<td>1.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
<td>0.33</td>
<td>11</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>2.500,00</td>
<td>7.066,17</td>
<td>2.55</td>
<td>1.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.01</td>
<td>0.33</td>
<td>12</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>2.500,00</td>
<td>7.854,81</td>
<td>2.55</td>
<td>1.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.01</td>
<td>0.33</td>
<td>13</td>
</tr>
<tr>
<td>13</td>
<td>2</td>
<td>2.500,00</td>
<td>10.473,08</td>
<td>2.55</td>
<td>1.00</td>
<td>0.00</td>
<td>0.05</td>
<td>0.01</td>
<td>0.33</td>
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<tr>
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<td>3</td>
<td>21.908,00</td>
<td>54.407,35</td>
<td>1.54</td>
<td>0.36</td>
<td>0.09</td>
<td>0.35</td>
<td>1.00</td>
<td>0.49</td>
<td>15</td>
</tr>
<tr>
<td>27</td>
<td>3</td>
<td>31.195,20</td>
<td>55.365,22</td>
<td>1.54</td>
<td>0.36</td>
<td>0.13</td>
<td>0.36</td>
<td>1.00</td>
<td>0.50</td>
<td>16</td>
</tr>
<tr>
<td>28</td>
<td>4</td>
<td>169.812,48</td>
<td>138.413,06</td>
<td>1.54</td>
<td>0.00</td>
<td>0.57</td>
<td>0.69</td>
<td>1.00</td>
<td>0.54</td>
<td>17</td>
</tr>
<tr>
<td>22</td>
<td>4</td>
<td>148.476,39</td>
<td>198.531,86</td>
<td>1.54</td>
<td>0.00</td>
<td>0.52</td>
<td>0.82</td>
<td>1.00</td>
<td>0.56</td>
<td>18</td>
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<tr>
<td>25</td>
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<td>2.500,00</td>
<td>3.954,66</td>
<td>1.54</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
<td>0.60</td>
<td>19</td>
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<tr>
<td>26</td>
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<td>2.500,00</td>
<td>3.954,66</td>
<td>1.54</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
<td>0.60</td>
<td>20</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>2.500,00</td>
<td>5.013,94</td>
<td>1.54</td>
<td>1.00</td>
<td>0.00</td>
<td>0.01</td>
<td>1.00</td>
<td>0.60</td>
<td>21</td>
</tr>
</tbody>
</table>

3.3 Other parameters

There are different societal and economy aspects that are influenced by traffic infrastructure development as well as management. The problem is that performance indicators connected with this aspects are mainly qualitative and it is often difficult to quantify them and incorporate in the analysis with other well known PIs such as eg condition index. One of PIs proposed in this paragraph is economy index unemployment rate. Philosophical aspect of connection between development of traffic infrastructure and influence on society through economic growth and development of new jobs is a well known fact. In this paragraph we are establishing connection between construction of highway to Zadar County
which finished in 2003 and decrease of unemployment rate to show the actual numbers proving interaction between the two. Table 5 is presenting the data about average annual and summer daily traffic on highway section Zadar 1 and unemployment rate in Zadar County through the years. The correlation between the increase of traffic intensity, especially in the summer period, and decrease of unemployment rates is clearly visible and can be referred to the tourism.

Table 5. Traffic quantity data and unemployment rate through the years in Zadar County

<table>
<thead>
<tr>
<th>Highway section</th>
<th>Year</th>
<th>Average annual daily traffic (AADT)</th>
<th>Average summer daily traffic (ASDT)</th>
<th>Unemployment rate in Zadar county (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zadar 1</td>
<td>1998</td>
<td>-</td>
<td>-</td>
<td>29.8</td>
</tr>
<tr>
<td></td>
<td>2003</td>
<td>5019</td>
<td>9872</td>
<td>28.8</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>6803</td>
<td>18537</td>
<td>22.4</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>9775</td>
<td>25897</td>
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</tr>
<tr>
<td></td>
<td>2016</td>
<td>11757</td>
<td>31153</td>
<td>16.0</td>
</tr>
</tbody>
</table>

4. Conclusion

Traffic itself and transport infrastructure including bridges influence society and economy in many different ways. Most of these interconnections are well known but mainly on a qualitative basis and without quantitative performance indicators which would enable detailed measurements of certain impacts. Strategic decisions regarding transport networks and bridges should be directed towards societal and economical development based on solid facts, reliable data and quantifiable measures. In this paper establishment of connections between tourism as an important economic branch, traffic intensity, unemployment rate and infrastructure management is presented through a case study in Croatia. Novel performance indicators regarding society and economy presented in this paper suggest an approach towards sustainable strategic decision making and should be further developed in a multidisciplinary manner. For this kind of analysis professionals from different areas of expertise such as economists, sociologists and demographers should be included in the research to achieve reliable and concrete results.

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ECONOMY AND SOCIETAL PERFORMANCE INDICATORS FOR BRIDGE MAINTENANCE PRIORITIZATION

Sandra Škarić Palić - Infra Plan konzalting, Croatia
Zaharah Allah Bukhsh - University of Twente, The Netherlands
Irina Stipanović - University of Twente, The Netherlands

27th – 28th September 2018
Barcelona, Spain
INTRODUCTION

- Required service life of bridges – 70 to 100 years (or more)
- Expense per route km of bridges is 10 times the average expense per route km of roads
- Requirements for infrastructure networks:
  - less public acceptance of risk
  - higher legal requirements and
  - limited budget
- New network management philosophy - the traffic user in the centre

Technical requirements

MAINTENANCE ACTIVITIES

Economic requirements

DECISION MAKING

Societal expectations
Movement of goods and people → social interactions → economic growth
KPIs FOR MULTIPLE PERFORMANCE OBJECTIVES

- Key performance indicators (KPIs) for reliability, economy, availability and societal impacts - multiple performance goals
- Road agencies define their own strategic goals. For example:
  - Supporting economic growth
  - Road network which is maintained to a safe and serviceable condition
  - Efficiently and effectively operated strategic road network
  - Minimize negative impacts on users, local communities and the environment
  - Balance the needs of individuals and businesses that use and rely on the road network
<table>
<thead>
<tr>
<th>Performance aspect</th>
<th>Performance goals (examples)</th>
<th>Key Performance indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RELIABILITY</strong></td>
<td>- To provide safe and reliable road network, responsive and sustainable network;</td>
<td>Technical indicators:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Condition Index (BCI)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- reliability index</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- risk levels</td>
</tr>
<tr>
<td><strong>AVAILABILITY</strong></td>
<td>- To minimize its negative impacts on the road users,</td>
<td>- Availability of the road (% of time)</td>
</tr>
<tr>
<td></td>
<td>- To balance the needs of individuals and businesses that use and rely on it.</td>
<td>- Traffic delays caused by road works</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Availability of the road during rush hour</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- User Delay Costs (UDC)</td>
</tr>
<tr>
<td><strong>ECONOMY</strong></td>
<td>- To provide an efficiently and effectively operated strategic road network;</td>
<td>- Life cycle costs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Maintenance Costs (MC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- operational costs</td>
</tr>
<tr>
<td><strong>ENVIRONMENT</strong></td>
<td>- To minimize its negative impacts on the environment;</td>
<td>Environmental indicators:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- air pollution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- noise</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- soil and water pollution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Environmental Costs*</td>
</tr>
<tr>
<td><strong>SOCIETY AS A WHOLE</strong></td>
<td>- To support and facilitate economic growth;</td>
<td>- Traffic intensity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- (Un)Employment rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Personal income</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Property values</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- GDP</td>
</tr>
</tbody>
</table>

Overview of performance goals and suggested KPIs (Allah Bukhsh et al. 2018)
CASE STUDY CROATIA

- Transport infrastructure in the Republic of Croatia: 30,000 km of roads and motorways, 3000 km of railways, 6 seaports, 800 km of inland waterways and 9 airports
- 1970s – first highways in Croatia constructed
- Until 1991 – 240 km
- 2000 - process of accelerated highway construction began - resulting in more than 1300 km of highways
CASE STUDY CROATIA

• Transport connection:
  – pre-condition of regional and tourist development of a country
  – better geo-strategic positioning in the European integration processes

• International traffic flows in Croatia – importance of tourist traffic - certain sections of highway have up to 6.5 times more traffic during summer months

• e.g. data for toll station Zadar 1 for year 2016 are: 19,802 vehicles in January and 132,443 vehicles in August
CASE STUDY CROATIA

• A new economy performance indicator - impact of tourism on the traffic quantity
• Importance for wider strategic planning in transport infrastructure management
• Analysis of two different aspects:
  – Ratio between average annual daily traffic and average summer daily traffic - PI highlighting importance of a bridge in the context of tourism as an economical driver
  – Difference between user delay cost in March and July - monetizing the benefit of performing maintenance in off tourist season months
CASE STUDY CROATIA

- Three counties:
  - two in a popular tourist area (Zadar County)
  - one in eastern part of Croatia
- 28 bridges
- Four performance indicators for prioritization in bridge maintenance planning:
  - condition rating
  - maintenance costs
  - user delay cost
  - economy tourism performance indicator
## CASE STUDY CROATIA

<table>
<thead>
<tr>
<th>Bridge number</th>
<th>Highway section</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>BCI</th>
<th>Average annual daily traffic (AADT) 2017</th>
<th>Average summer daily traffic (ASDT) 2017</th>
<th>Ratio ASDT/AADT - Economy KPI (tourism)</th>
<th>AADT in March 2017</th>
<th>AADT in July 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>374,74</td>
<td>23,40</td>
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<td>17217</td>
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<td>4</td>
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## CASE STUDY CROATIA

<table>
<thead>
<tr>
<th>Bridge number</th>
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<th>Length (m)</th>
<th>Width (m)</th>
<th>BCI</th>
<th>Average annual daily traffic (AADT) 2017</th>
<th>Average summer daily traffic (ASDT) 2017</th>
<th>Ratio ASDT/AADT - Economy KPI (tourism)</th>
<th>AADT in March 2017</th>
<th>AADT in July 2017</th>
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## CASE STUDY CROATIA

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MAUT – Multi Attribute Utility Theory

- Systematic approach to reduce the qualitative values of various attributes (i.e. performance indicators) into utility functions
- The multiple performance criteria - bring all criteria into a single scale - utility values
- Establish relative importance of performance indicators (e.g. condition, cost, economy etc.) - weight factors
- Formal optimised decision process - Option with the maximum or minimum “utility” shall be selected
- The resulting scores are then aggregated based on the relative importance of attributes
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Other parameters

- Different societal and economy aspects are influenced by traffic infrastructure development
- Economy PI - unemployment rate
- Correlation between construction of highway finished in 2003 which connected Zadar County with the rest of Croatia and Europe and decrease of unemployment rate

Graph showing:
- Average annual daily traffic (AADT)
- Average summer daily traffic (ASDT)
- Unemployment rate in Zadar county (%)
CONCLUSION

• Traffic and transport infrastructure influence society and economy
• Interconnections are well known but mainly on a qualitative basis
• Strategic decisions - solid facts, reliable data and quantifiable measures.

• Case study in Croatia - novel performance indicators regarding society and economy → sustainable strategic decision making → further development in a multidisciplinary manner
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ON THE DEVELOPMENT OF KEY PERFORMANCE INDICATORS FOR A RAPID SEISMIC ASSESSMENT OF ROADWAY BRIDGES

Andrej Anžlin – Slovenian National Building and Civil Engineering Institute, Slovenia
Juan Murcia-Delso – The University of Texas at Austin, United States of America
ON THE DEVELOPMENT OF KEY PERFORMANCE INDICATORS FOR A RAPID SEISMIC ASSESSMENT OF ROADWAY BRIDGES

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Abstract. Nowadays, the condition assessment of roadway bridges is mainly performed using visual inspection techniques and more rarely through the use of non-destructive tests or structural health monitoring methods. In order to identify, how feasible can be the integration of the seismic hazard in the condition assessment process of a roadway bridge, the first steps on the development of key performance indicators for a rapid seismic assessment of such structures are made. The general definition of the seismic performance indicator is presented. The most important seismic pathologies are discussed and afterwards, two group’s of indicators are identified, i.e. simple and complex seismic performance indicators. Finally, the concept of implementing the simple seismic performance indicator in the visual inspection of roadway bridges is presented.

Keywords: seismic performance indicators, rapid seismic assessment, seismic deficiencies

1. Introduction

In order to identify seismic performance indicators for bridges, one has to consider both the seismic hazard (demand) and the structural characteristics (capacity). As a starting point, the uncertainties in estimation of seismic hazard will be always present, even with increased knowledge. In the last decades, the seismic hazard maps, which are used to calculate the design seismic demands for structural design, have continually changed with the increase of ground motion data and the improvement of analytical methods of hazard evaluation (see example in case of Italy presented in Fig. 1). Ergo, even though a bridge may be located in a zone considered of low hazard and may not warrant a seismic assessment it is possible that the hazard category may change in the future so the importance of the seismic deficiencies could drastically increase.

![1999 Map vs 2006 Map](image)

Figure 1: Comparison of successive Italian hazard maps, which forecast some earthquake locations well and others poorly. The 1999 map was updated after missed 2002 Molise earthquake and the 2006 map will be updated after it missed the 2012 Emilia earthquake (Stein et al. 2013).
ON THE DEVELOPMENT OF KEY PERFORMANCE INDICATORS FOR A RAPID SEISMIC ASSESSMENT OF ROADWAY BRIDGES

Fig. 2: Fully corroded cross tie in hollow box bridge column with improperly or sub standardly positioned transverse reinforcement placed on the inside of the longitudinal bars

Another source of uncertainty is the seismic capacity of a structure. Recently, interesting study analysing the influence of uncertainty of material characteristics and in manufacture have shown that the biggest influence on the ductility of columns can be attributed to the detailing of the stirrups, since different type of perimeter hook angles were constructed by the contractors. The influence was observed in the post-capping non-linear response of the column, after reaching the maximum strength capacity of the specimen (Kramar et al. 2016). In this sense, after the bridge inspector identifies a perimeter hoops or cross-ties completely corroded to a level, where no confinement of the concrete core can be provided (Fig. 2), the negative impact of the degradation process has to be taken into account also from the seismic perspective. Therefore, due to all of described uncertainties in both demand and capacity, there is a strong need to adequately identify such indicators, which will provide the reduction of these uncertainties on the condition assessment of roadway bridges throughout its entire lifetime.

2. Seismic pathologies

Several existing bridges were built prior the modern seismic codes were implemented in the design of such structures. In the past the capacity was generally thought of in terms of strength capacity, whereas nowadays the focus is on deformation and energy dissipation capacity. Several seismic pathologies or inappropriate seismic detailing principles can therefore be found in these structures (see an example of improperly positioned transverse reinforcement in Fig. 2). This can in case of a seismic event lead to potentially undesired nonductile structural response. Deficiencies can also result from wrong assumptions during the analytical methods used in design. For example, seismic deflections are underestimated when the gross section characteristics were used in the design, rather than cracked sections. Due to low seismic design forces, the incorrect sign of moment due to gravity-load domination could also be calculated. In such case, the amount of lateral and longitudinal reinforcement would have been drastically underestimated.

Modern bridges are designed to dissipate energy due to the earthquake loading in a controlled way in specified locations called plastic hinge regions. The level of damage control and structural integrity is highly governed by the appropriate detailing of the reinforcement, especially the lateral reinforcement. The task of this reinforcement is to prevent brittle shear failures, and to delay flexural failures caused by crushing of the confined concrete core and failure due to the buckling of longitudinal reinforcement (see example in Fig. 3). In some cases, even after the implementation of adequate provisions, in many bridge structures the lateral reinforcement of columns has been typically designed for the prevention of shear failure only, while the other two failures were often insufficiently addressed. These two failures can be even more pronounced in the case of columns with barbell cross-section (Anžlin et al. 2015).

In bridge piers with branched cross-sections sometimes the design of lateral reinforcement can be challenging due to the larger dimensions, and due to the constraints of the pier shape. The task of providing equal amounts of lateral reinforcement in both transverse directions can therefore be burdensome. It was shown that the assessment of the effective lateral confinement stress in sections with different amounts of lateral reinforcement is rather uncertain (Anžlin 2017). Most probably in EC8/2 (CEN 2005b) the minimum amount of confining reinforcement is therefore not identical for circular and rectangular bridge piers. Additionally, according to parts 1 and 2 of Eurocode 8 (CEN 2005a, CEN 2005b) the amount of designed lateral reinforcement for rectangular columns in bridges is double what is required in buildings, which shows how important indicator is the lateral reinforcement in bridge columns.
Fig. 3: Failure of an I-shaped column due to the global and local buckling of longitudinal bars

Columns are the most critical seismic-resistant components of bridge structures since they ensure the dissipation of energy through the formation of plastic mechanisms. However, there are also other bridge elements that can be damaged, and can potentially trigger bridge collapse, if they are not designed to sustain the forces resulting by the overstrength of the hinging columns or have insufficient displacement capacity to ensure deformation compatibility. These may include abutments, foundations, column-superstructure and column-foundation joint regions, bearings, expansion joints, and, if present, shear keys and cable restrainers.

Table 1. The evolution of the analysis (adopted from Fajfar 2017) and some detailing provisions in seismic codes

<table>
<thead>
<tr>
<th>Year</th>
<th>Country</th>
<th>Description</th>
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<td>1909</td>
<td>Italy</td>
<td>The first seismic regulations for buildings worldwide, with provisions for equivalent static analysis.</td>
</tr>
<tr>
<td>1924</td>
<td>Japan</td>
<td>The first seismic code in Japan. The seismic coefficient was equal to 10%</td>
</tr>
<tr>
<td>1933</td>
<td>USA</td>
<td>First mandatory seismic codes in the United States (the Field and Riley acts in California). The seismic coefficient varied from 2 to 10%</td>
</tr>
<tr>
<td>1957</td>
<td>USSR</td>
<td>Implementation of the modal response spectrum method, which later became the main analysis procedure in Europe</td>
</tr>
<tr>
<td>1977</td>
<td>Italy/Slovenia</td>
<td>A very simple pushover procedure for masonry buildings was implemented in a regional code in Friuli, Italy</td>
</tr>
<tr>
<td>1978</td>
<td>New Zealand</td>
<td>The empirical slenderness ratio ( s/d_{sl}=6 ) was firstly introduced in NZS 3101 to prevent local buckling of longitudinal reinforcement</td>
</tr>
<tr>
<td>1981</td>
<td>Yugoslavia</td>
<td>Adoption of linear and nonlinear response history analysis for very important buildings and prototypes of prefabricated buildings in the seismic code</td>
</tr>
<tr>
<td>1986</td>
<td>USA</td>
<td>The pushover-based Capacity Spectrum Method was implemented in the “Tri-services” guidelines</td>
</tr>
<tr>
<td>2006</td>
<td>New Zealand</td>
<td>In seismic provision SANZ 2006 the 90° hooks are not permissible for the use in seismic detailing in plastic hinge regions</td>
</tr>
<tr>
<td>2008</td>
<td>Slovenia</td>
<td>The first country where Eurocode 8 became compulsory</td>
</tr>
<tr>
<td>2010</td>
<td>USA</td>
<td>Explicit probabilistic analysis permitted in ASCE 7-10</td>
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</table>

In summary, there are a number of issues that need to be considered when assessing the seismic performance of a bridge. They can be listed as:

- Level of seismic hazard (e.g. probability that the peak ground acceleration (PGA) occurs in 475 years)
- Adequacy of seismic design and detailing for hinging columns (amount of transverse reinforcement, restrictions about the local and global anti-buckling requirements, centre-to-centre distances between hoops and engaged bars, detailing of hooks).
- Adequacy of seismic design of other bridge elements for force or displacement capacity (element resistance for column overstrength, seat width, gap in expansion joint).
- Seismic guideline (specification, standard or code) adopted during the design period of the bridge. To illustrate the strong changes in seismic practice within the last decades a list of important provisions in seismic codes for buildings, which are relevant also for bridges and some milestone from detailing point of view are listed in Table 1.
The list above represents issues related to earthquake shaking which should be addressed in the quality control of the roadway bridges located in the seismically active areas. Additional issues could be included if seismic hazards other than shaking, e.g. soil liquefaction and fault rupture, are considered.

3. Evolution of the seismic assessment of bridges in the USA

Important advances in the seismic design, assessment and retrofit of bridges have been made in the last decades based on the lessons learned after a number of strong earthquakes in California. The 1971 San Fernando earthquake caused major damage and collapses in bridge infrastructure in Southern California. As a result, significant changes were introduced in the seismic design practice to ensure the ductility of structures. A retrofit program was also put in place. This program initially focused on reducing vulnerabilities related to joint separation and superstructure unseating by providing cable restrainers. The 1987 Whittier Narrows and 1989 Loma Prieta earthquakes revealed again the vulnerability of existing bridge columns to brittle shear failures, which increased funding for the retrofit program to install steel jackets in vulnerable columns. Modern bridges and retrofitted structures performed generally well during the 1994 Northridge earthquake, but bridges with complex configurations, such as large skews, presented significant damage.

To evaluate the bridges at risk and prioritize retrofit actions, The California Department of Transportation (Caltrans) has developed and refined over time a screening algorithm that provides a score that takes into account the structural vulnerability, the seismic hazard, and the bridge importance. The latest developments on this method have be included new types of hazards, such as bridges on liquefiable soils and bridges located over active faults, as well as new bridge vulnerabilities, such as bridges with early retrofits that have not been fully effective and bridges with short seats and stiff restrainers (Ostrom 2016).

Fragility curves, which define the probability of exceeding a specific damage state for a given earthquake intensity, have also been developed to assess the probable seismic performance of bridges (e.g., Ramanathan 2012). These are useful tools for pre-event planning and post-earthquake emergency response. However, they are specific for a given bridge structure or prototype configuration as well as the seismic region for which they were developed. To develop fragility curves, different demand parameters associated to a bridge component and/or damage mode are defined (column deformation, abutment seat displacement, shear key displacement, etc.). Fragility functions are commonly developed by running multiple nonlinear time-history dynamic analyses of increasing intensity and then performing a statistical analysis of the exceedance of damage thresholds for each of the demand parameters. The demand parameters and thresholds values can be regarded as performance objectives and goals.

Simple indicators have also been proposed for post-earthquake damage evaluation based on visual inspection. For example, Veletzos et al. (2008) developed a visual catalog that documents damage from laboratory experiments and from historic earthquake. This catalog defines five levels of damage for different bridge components (e.g., columns, foundations, abutments) and bridge sub-assemblies. Each level of damage has associated a performance level (from fully operational to collapse) and description of intervention needs (from no repair to replacement). Quantitative indicators based on simple field measurements have also been used by Caltrans to characterize the bridge response after an earthquake, such as markers at expansion joints to track bridge movements or tension indicators on cable restrainers to indicate yielding of the cables.

4. Seismic performance indicators

The seismic performance indicator (SPI) is a parameter, which is obtained from (a) visual inspection, (b) non-destructive or destructive measurements, (c) analytical methods or (d) project documentation and can be further used to estimate seismic performance of a bridge before an event occurs or to evaluate the actual performance after the event. The impact of a SPI is related to the seismic performance of a structure in relation to its strategic goals and objectives. For example, the permissible/threshold value of the residual displacement of bridge piers after an earthquake is in the case of the high-speed railway line somewhat more rigorous than in the case of the structure located in the remotely accessed areas due to the need to operate the system even after the seismic event. Such indicator can be measured in the case after the seismic event has occurred or in the design or assessment process by means of non-linear time-history dynamic analysis, from which the anticipated drift value is calculated. The level of attained residual displacement is highly correlated with the seismic detailing (standard vs. substandard detailing) or the presence of seismic pathologies. These are again manifested after the seismic event, which will expose some (not all, because the response depends on the characteristics of the ground motion) shortcomings of the structure.

Different types of seismic performance indicators with different levels of complexity can be developed for pre-event quality control of bridges. They can be related to design and detailing practices, nonlinear response predictions, and also the level of seismic hazard. However, the author suggests, that only two groups, simple and complex SPI’s, should be defined. The former SPI is simply obtained from visual inspection or as-build drawings, in some cases even non-
destructive or destructive techniques may be needed to complement such data. The latter, more complex SPI is based for example on a moment-curvature analysis and plastic hinge model: curvature or displacement ductility capacity of columns. Nonlinear time-history analyses may be needed to characterize the response of complex bridge structures and predict the force and displacement response of the different elements of a bridge. Comprehensive discussion about the complex SPI’s is not primary focus of this paper, since these indicators cannot be evaluated by the bridge inspector.

However, the evaluation and identification of simple SPI’s can be easily implemented into the process a bridge inspection, by periodically collecting simple SPI’s using standardized “seismic data sheets”, which would encapsulate all seismic issues presented in this paper (level of lateral reinforcement, detailing, period of seismic design, level of seismic hazard, etc.). In this way the complex SPI’s will be more accurately and efficiently defined by a structural or seismic engineer. To some extent, this is already done by bridge inspectors, but clearly not from the seismic perspective presented in this paper. For example, when the detailing in bridge columns does not meet current seismic standard, the near collapse rotation of bridge columns is according to Eurocode 8/3 (CEN, 2005c) reduced for nearly 20%. When the bar slenderness ratio, which is defined as the ratio between the stirrups distance and diameter of longitudinal reinforcement, is below the threshold value of 6 or 8, the local buckling of bars is prevented when severe or moderate curvature ductility demands for DCH or DCM ductility class are designed, respectively. Furthermore, no limits of RC needs to be placed on the allowable strain ranges, if the limit value 6 is considered, since a stress greater than yield can be sustained over the entire compression range.

5. Conclusions

The condition assessment of roadway bridges from the perspective of the seismic performance is analysed in this paper. The seismic pathologies relevant for roadway RC bridges are therefore presented. Afterwards, general definition of the seismic performance indicator is introduced. It was concluded, that these indicators must be put in two groups, simple and complex seismic performance indicators (1st conclusion). They are defined in a way that the evaluation of former one can be performed by a bridge inspector, while the latter are post festum analysed by the structural engineer (2st conclusion). By performing the inspection of bridges taking into account presented indicators, the uncertainties in both seismic demand and capacity can be decreased and consequently the probability of damage caused to the infrastructure in case of a seismic event (3rd conclusion). A detailed overview of complex SPI’s should be given in future studies. A single seismic index for a rapid seismic assessment of roadway bridges, like that used in the screening program of Caltrans, but more generic, could be afterwards developed by weighting indicators related to the bridge configuration, design and detailing, and the seismic hazard.

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ASCE 7-10


NZS 3101

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ON THE DEVELOPMENT OF KEY PERFORMANCE INDICATORS FOR A RAPID SEISMIC ASSESSMENT OF ROADWAY BRIDGES

ON THE DEVELOPMENT OF KEY PERFORMANCE INDICATORS FOR A RAPID SEISMIC ASSESSMENT OF ROADWAY BRIDGES

Andrej Anžlin – Slovenian National Building and Civil Engineering Institute, Slovenia
Juan Murcia-Delso – The University of Texas at Austin, United States of America
Development of KPI for a seismic assessment of roadway bridges | Anžlin and Murcia-Delso
Poor seismic design / seismic pathologies
Development of KPI for a seismic assessment of roadway bridges | Anžlin and Murcia-Delso
False design
False seismic design

- Seismic deflections were underestimated (gross vs. cracked section)
- Low seismic design forces → incorrect sign of moments due to gravity-load domination (design of reinforcement)
- **Inappropriate detailing** in potential hinge locations
  - Shear vs. Flexural or non-ductile vs. ductile failure
  - Problem EVEN today (Code errors, misinterpretations)
  - Some parameters are influenced by the processes of degradation (concrete cover spalling, bar corrosion)
False seismic design

Standard columns with seismic deficiencies

STD/135 (3φ8/8 cm)  
STD/90 (3φ8/8 cm)
False seismic design

Standard columns with seismic deficiencies

### STD/135

<table>
<thead>
<tr>
<th>Phase #</th>
<th>Rotation amplitude [%]</th>
</tr>
</thead>
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<tr>
<td>10</td>
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<tr>
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<td>5.2</td>
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<td>12</td>
<td>6.4</td>
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<td>13</td>
<td>7.6</td>
</tr>
<tr>
<td>14</td>
<td>8.8</td>
</tr>
</tbody>
</table>

### STD/90

Faza 09
False seismic design

Standard columns with seismic deficiencies

\[ \theta_{NC} = 7.5\% \]

\[ \theta_{NC} = 6.9\% \]
Seismic Performance Indicators

- A parameter obtained before/after a seismic event, which can be used to estimate the seismic performance of a bridge before/after the seismic event
- A parameter obtained from
  - Visual inspection (degradation process)
    - Bar slenderness ratio change
    - Spalling of the concrete cover
  - Non-destructive/destructive measurements
  - Project documentation
    - Birth certificate, history of interventions
    - Which seismic design principles were assumed?
  - Analytical methods
    - Sectional full moment-curvature analysis
    - Near collapse rotation of the column
    - Effective buckling ratio of lateral reinf.
    - Non-linear dynamic analysis

the relevance of a SPI
Seismic Performance Indicators

- A parameter obtained before/after a seismic event, which can be used to estimate the seismic performance of a bridge before/after the seismic event
- A parameter obtained from
  
  • Visual inspection (degradation process)
    - Bar slenderness ratio change
    - Spalling of the concrete cover
  • Non-destructive/destructive measurements
  • Project documentation
    - Birth certificate, history of interventions
    – Which seismic design principles were assumed?
  
  • Analytical methods
    - Sectional full moment-curvature analysis
    - Near collapse rotation of the column
    - Effective buckling ratio of lateral reinf.
    - Non-linear dynamic analysis

Simple SPI
  (bridge inspector)

Complex SPI
  (structural engineer)
Seismic Performance Indicators

• When should they be addressed?
  – No EQ/seismic risk → no SPI’s?
  – Aleatoric uncertainties in estimation of seismic hazard
• The evolution of hazard maps

Stein et al. (2013)  SHARE Consortium
Seismic Performance Indicators

- What about uncertainties in the estimation of the seismic capacity?
- How "accurate" must be the estimation?

Degradation processes

Uncertainty in manufacture and material characteristics
Main conclusions

• The definition of a seismic performance indicator was presented
  – Simple SPI (bridge inspector)
  – Complex SPI (structural engineer)

• The introduction of SPI in a quality control of bridges can reduce the uncertainties in the estimation of the seismic capacity of such structures

• Future studies:
  – A detailed overview of SPI’s should be given
  – Single seismic index for a rapid seismic assessment of roadway bridges (e.g. Caltrans), but more generic, can be afterwards developed
THANK YOU FOR YOUR ATTENTION!
WWW.TU1406.EU
Bridge life cycle management through innovation: A practical example with GENIA tool for inspection and assessment

Jesus Isoird - Tecnalia, Spain. Director of Infrastructures business area
Iñaki Piñero – Tecnalia, Senior Researcher
ABSTRACT. Roads, and infrastructures of a country have a direct influence on its economic and social development, which is why their proper maintenance is fundamental. Regular inspections are essential to detect incidents or pathologies in time. The inspections, as part of maintenance processes, are really useful, since they allow us to know the functional and resistant status of the different elements that are integrated within a road, confirming if this state is adequate to offer the service in a safe way and there are no risks that could endanger the users. Such is the case of bridges, one of the most common structures in all road infrastructures. In the specific case of road bridge inspections, in Spain, they are carried out every five years (on the roads that depend on the Ministry of Public Works). This period is shortened if unforeseen situations occur that could damage the structure (floods, earthquakes, vehicle impact, etc.). The first inspection is performed before putting the bridge into operation, allowing other subsequent revisions to observe the evolution of damage or deterioration.

These inspections involve technical teams that have sufficient knowledge to perform these tasks, in addition to being supervised by a structural engineer. These professionals must have sufficient knowledge to know the structural behavior of the bridges, degradation and deterioration of the structures and also have information to prepare the inspection properly.

The Sustainable Construction Division of TECNALIA, through its Infrastructures Business Area, has developed an innovation in the procedures of main inspections bridge as well as the digitalization and management of the structures, as many of them begin to show significant signs of deterioration sooner than expected. In order to prolong the life of deteriorated structures, maintenance measures can be applied that delay the spread of damage, or reduce the degree of damage [9]. Frangopol and Soliman (2016) [10] described the actions necessary for efficient maintenance...
planning to maximize the structure’s benefits during the life cycle under budgetary constraints. García-Segura et al. (2017) [11] optimized the maintenance of prestressed bridges from the point of view of economic, social and environmental sustainability based on optimized designs with multiple objectives (economic, durability and safety).

The maintenance of bridge elements of wide spans located in coastal areas damaged by corrosion accounts for most of the cost of the life cycle of these structures [12]. Kendall et al. [13] proposed a model that integrated life cycle analysis and associated costs from a sustainability perspective. Lee et al., [14] evaluated the reliability of a bridge when corrosion and heavy truck traffic affected the structure. They proposed a realistic methodology of costs throughout its life cycle, including initial costs, maintenance costs, those expected in rehabilitation, losses due to accidents, user costs of the road and indirect socio-economic losses. Penadés-Plà et al. [15] [16] studied the life cycle of bridges with a single girder section and through girder bridges. Navarro et al. [17] analyzed in a recent work the cost of the life cycle of maintenance strategies in prestressed bridges exposed to the attack of hydrochloric.

Neves and Frangopol (2005) [18] indicated how the evaluation of the safety of a structure is a basic indicator to measure its performance, given the fact that there are times that the state of the structure is not a precise indicator to assess the safety and functionality of a bridge. Liu and Frangopol (2005) [19] studied the best planning of the maintenance of a bridge during its life cycle through a multi-objective optimization of the useful life, the level of security and the cost of maintenance.

As can be seen, the objectives of structural performance and economy have been added to social and environmental aspects of the maintenance actions of the structures [20] [21] [11].

3. Operation, conservation and improvement

The preventive measures of operation, conservation and improvement can be considered to begin in the Planning and Project phase. A good design of a structure thinking not only as the factors that affect its construction but later its conservation. Involving the study and definition of a series of constructive, resistant and accessibility details that improve the useful life of the structure, delaying the age of intervention and facilitate the own tasks of conservation and maintenance. The next phase is the construction of the structure itself. It is particularly important during the construction of the structures to take care of and respect all those details established in the Project, from the cover to reinforcements to the quality of the waterproofing system. This is the only way to guarantee a good durability of the work executed, guaranteeing the absence of defects or weak points of the structure.

Finally, once the work is executed and put into service, the conservation and maintenance phase of the infrastructure begins. In this phase it is particularly important to carry out regular maintenance and monitoring of the structures in order to ensure the conservation of the construction work, as well as to anticipate damages or pathologies of great extent due to a poor performance of the work or, simply, by the passage of the weather [22].

Among the most common damages and pathologies that tend to present the different elements that make up the bridges are three: foundations, especially in those piers and abutments located inside the river beds or similar; bearings, regardless of their type and size; and the drainage and waterproofing systems, including the expansion joints.

Many of these damages and pathologies are not detected only in old bridges but many of them are found in modern bridges (less than 10-15 years old). Structures that the size is usually an important factor in the solution and repair of damages, without consider their own severity. All this from a functional point of view -which are normally located in high intensity traffic routes- and structurally -because of the greater dimensions and technologies currently used [22].

4. The importance of management systems

Each bridge management system, firstly place, must establish its needs and scope according to the size of the network, allowing its scalability if necessary. The most common variables that are usually collected by bridge management systems are usually: the materials with which the bridge is built, date of construction and subsequent updates or extensions, typology, shape and dimensions, particularities, etc.

Once a database with the structures that make up the network to be managed is established, a systematic review and inspection of the structures should be established. Inspections can be considered as a set of operations of a technical nature aimed at obtaining the necessary data for the evaluation of the state of the structure. Generally, the inspections must consist of a previous programming, being advisable that they are carried out in a systematic way, according to a catalog of damages. So that the later evaluations can serve to solve the possible problems with the sufficient advance and to be able to verify the evolution of possible problems in an appropriate way.

Although each Administration has different levels of inspection, it is quite common to accept three levels of inspection: basic or routine, main and special inspections.

- **Basic or routine inspection:** They are carried out by the personnel in charge of the regular conservation of the road (not necessarily specialized in the structural field, but properly instructed by basic notions in this regard) in which the structure is located, being of a visual nature, trying to detect urgent problems of importance in an early manner. This level of inspection makes it possible to detect early deteriorations and
thus prevent them from becoming serious, as well as to locate damages that need urgent repair. The periodicity of this type of inspections is usually established in the environment of 1 year.

- **Main inspection**: This is a detailed visual inspection of the state of all elements of the structure to be inspected. It is recommended a first main inspection, called “Zero Inspection” that is performed before the bridge is put into service and that serves as a reference to determine the evolution of the deterioration. They are made by specialized technical personnel. It is usual to use “damage libraries” for avoiding the subjectivity of the inspection, in order to unify the criteria of the different inspectors and to know with sufficient accuracy the level of deterioration of the structure. In this case, the periodicity of the inspections varies greatly between the different Administrations, from the minimum of 5 years of the General Directorate of Roads of the Ministry of Public Works [1], to the maximum 15 years established in ITPF-05 [23]. Likewise, this type of inspections is usually recommended after exceptional events such as the impact of a vehicle, earthquakes or floods.

- **Special inspection**: Special inspections are not systematic, but are the result of significant deterioration detected in a Main Inspection or by any special situation. Usually they are the previous step to works of rehabilitation, repair or reinforcement of the structure. They require a multidisciplinary technical team, qualified and highly specialized in structural, geotechnical and material deterioration analysis. Here it is no longer a matter of performing a visual inspection, but rather complete quantitative data is required for the evaluation of the bridge. Trials and destructive or semi-destructive tests are common, through the realization of trial pits, specimen extraction and other tests related to durability. With the results obtained, a characterization and damage assessment report or a repair project is written.

Once defined what is a management system and established the usual levels of inspection that are usually available, it is necessary to follow up and to control the structures. Every management system must be easily manageable and offer objective data on the status of the bridges. From the conservation status of the structures, depending on their severity, investment cost, the importance of the road, the possibility of alternative itineraries, etc., it should help to establish investment priorities. Likewise, a complete management system must have the capacity to perform the control and follow-up of the repairs undertaken, which will serve to evaluate the effectiveness of the adapted measures, as well as to calibrate and correct future actions.

5. **The role of innovation in bridge inspection**

The knowledge economy is transforming the global economic landscape. The speed and intensity with which economic activities absorb new technologies and the ease with which information is obtained and shared is drawing a new economic reality. This situation highlights the enormous importance of innovation and human capital as a source of competitiveness and growth of a country. In response to this challenge, TECNALIA is creating and incorporating new methodologies and technologies in the field of infrastructures and their management, among which include:

- **Use of Drones in inspection and maintenance tasks.**

The field of inspection and maintenance of infrastructures, especially in height, is about to change radically due to the irruption of drones. Traditionally to perform inspection and maintenance tasks, in infrastructures, there was only the possibility of choosing between lifting platforms or special inspection vehicles, ladders, scaffolding structures or directly performing work at height. Regardless of the method used to carry out the task, the associated times, costs and hazards remain a challenge and present a great opportunity for improvement. Most of them also require the closure of lanes with the economic losses that implies. Therefore, the use of drones presents a great opportunity that is expected to revolutionize inspection and maintenance work in the coming years.

Although drones have already been used in recent years for certain inspection tasks, they have mainly focused on taking visual and infrared images that need to be analyzed by a qualified operator to determine the state of the infrastructure and actions of associated maintenance. However, this type of drone operation does not solve the entire inspection problem since the visual inspection only covers one of the phases of the necessary procedure. For this reason the use of drones for the inspection of infrastructures has not yet become popular, since if they are only able to solve a phase of a complete process, and it is necessary to make use of traditional methods (cranes, scaffolding, work at height)
for the other phases (detail and contact inspection), then the added value of general visual inspection through the use of drones is drastically reduced.

- **Structural Health Monitoring, SHM.**

  Structural Health Monitoring (SHM) is the process of assessing the health status of a structure based on data from the instrumentation. It supposes four phases or subprocesses:
  
  ✓ Instrumentation: is the set of sensors and data acquisition systems that collect the physical structural parameters object of control and analysis.
  ✓ Monitoring: it is the service, transmission, web publication and distribution in real time.
  ✓ Analysis: is the set of techniques that allow converting data into knowledge and understanding structural behavior. Implementation of systems for assessing the state of the structure for the detection of damage and its location.
  ✓ Management: helps decision making on the performance and maintenance.

  The purpose of SHM is the detection of damage before it evolves until reaching a limit value thus achieving the following impacts:
  
  ✓ Prolongation of the useful life and economic savings in its life cycle by detecting damage before reaching the critical state.
  ✓ Reduction of the time spent outside the structure, minimizing the socio-economic impact.
  ✓ Technification / objectification of inspection work.
  ✓ Focus of inspections on areas susceptible to damage. Improvement of work efficiency.

  The detection of damage through SHM systems can also allow to determine the current condition of the structure. The SHM combines a variety of technologies to measure, record and analyze data (temperature, humidity, stress, deformations, displacements, accelerations ...) in real time, allowing to know the behavior and detect the state of the structure early and thus decrease maintenance costs and repairs. The absence of monitoring in some cases can lead to serious problems that are not evident until the situation is critical or irreversible, having to adopt costly solutions.

- **Digital Twin based on BIM technology.**

  Digital Twin is one of the concepts that is changing the dynamics of the infrastructure maintenance sector. These are virtual replicas of objects or processes that simulate the behavior of their real counterparts. The purpose is to analyze its effectiveness or behavior in certain cases to improve its effectiveness.

  Digital Twins will transform the processes of construction and the maintenance of infrastructures. They will offer new ways to reduce costs, monitor assets, optimize maintenance, reduce downtime and allow the creation of new connected products. This concept is already part of the strategy of companies dedicated to innovation and product design of Industry 4.0.

  Innovation in this area must develop knowledge and technology that allows to digitalize and treat automatically the information obtained in the inspection tasks. In this way it is possible to geo-reference all the images acquired for later use in maintenance tasks, being possible to detect and locate anomalies, such as effects of corrosion on surfaces or deformations in bridges compared with a digital twin based on BIM technology.

  Through the development tasks of strategic planning methodologies of the drone inspection processes (previously mentioned) and the implementation of digital twins based on BIM technology for the advanced capture of information, Reliability and Maintenance Indicators can be visualized in platforms that enhance performance and meet the objectives of bridge management in two directions:
  
  ✓ Inward, facilitating the processes of data management, process improvement and information exploitation.
  ✓ Outward, improving design and user experience (client).

6. **TECNALIA Bridge Management System**

Having a useful management tool can help in different aspects:

✓ Technically: It helps to identify the characteristics and constructive typologies and to know the actual updated status of the assets.
✓ Services for the most needy asset: You can control at all times the assets of an infrastructure, bridges, tunnels, etc. and thus be able to offer a better service to those which need more emergency actions. You can optimize life cycle cost ann the service to users. It will help, in short, to better understand the needs of action.
Elements and materials: It allows to know the most deteriorated elements and the materials and products that must be available to conserve, repair, rehabilitate or replace them.

Historical: The programmed inspections will give rise to a history of the asset that will allow the rapid detection of the evolution of existing pathologies or the appearance of new damages, as well as the repairs or actions carried out in them.

The bridge management system developed by Tecnalia is an effective system that implements a methodology for the assignment of the bridge condition index derived from the main inspections.

The MIVES methodology (created by TECNALIA together with the University of the Basque Country, the Polytechnic University of Catalonia and the University of La Coruña) has been developed and implemented in the tool for obtaining the bridge evaluation index and helps in decision-making. MIVES is a multicriteria decision-making methodology that evaluates each of the alternatives that can solve a defined generic problem, through a value index [24] [25] [26] [27]. This methodology is included in the multi-attribute utility theory, since to obtain the value index of each alternative, a weighted sum is made of the valuations of the different criteria considered, admitting that there is certainty. That is, the preferences of the decision maker, with respect to the proposed indicators, are known [6] [28].

For the definition of the elements of a bridge, a gradation criterion has been adopted in levels, according to the detail with which it is intended to decompose the whole of the bridge in its different elements, thus defining 4 levels. Thus, for example, LEVEL 1 is constituted by a single element, the Bridge. While in LEVEL 2 it is broken down into 5 components: Foundation, Substructure, Superstructure, Connection elements and Equipment. Levels 3 and 4 deepen this decomposition into elements and sub-elements [29].

Throughout this process it is essential that the inspectors are experienced technicians with training in the field of structures, the durability of materials and the equipment of bridges.

The tool comes up with libraries of damages depending on the materials. It allows to distinguish between damage associated with poor performance and associated with poor durability. Different types of damage to elements and equipment have also been taken into account.

This methodology allows implement an objective and transparent procedure for obtaining of the condition index of the bridge, once the main inspection has been carried out, and based on the allocation of weights to the different indicators and the assignment of value functions to the different alternatives [29].

The bridge management system of Tecnalia solves the following objectives:

- It has operational, congruent and easily accessible information about the characteristics, status and possible deterioration of each of the bridges that it manages.
- Evaluates the safety and the state of conservation of the bridges in an agile manner and with a clearly objective method, independent of the technician who carries out the inspection.
- Optimizes and prioritizes the use of limited budgets to undertake the actions that are required depending on the state of the bridges (in process).

The aforementioned objectives are achieved through the execution of a series of activities, which are listed below:

1. Inventory of all bridges and general data of them.
2. Systematization of Inspection tasks.
3. Evaluation of the condition index of the bridge.
4. Strategic prioritization for intervention.
5. Estimation of the cost of repair work (in process).

The bridge management tool of Tecnalia is designed to integrate advanced modules among which stand out, for example, instrumentation and monitoring, BIM methodologies or the implementation of drone inspection.

Acknowledgements

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Bridge life cycle management through innovation: A practical example with GENIA tool for inspection and assessment

Jesus Isoird - Tecnalia, Spain. Director of Infrastructures business area
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27th – 28th September 2018
Barcelona, Spain
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6. Conclusions
1. Introduction

• Appropriate bridge life cycle management (inspection, assessment and maintenance / upgrading) is fundamental to ensure safety, infrastructure availability and for optimizing the life cycle cost.
• Every bridge management system requires inspection and assessment (at different scope levels) of any possible damage and its evolution.
• In Spain, three levels of inspection (General directorate of roads): Basic; Main and Special.
• INSPECTION is understood as all technical actions carried out in an organised way that provide all necessary data to assess in a particular time moment the state of conservation of a bridge (functional and resistant status), being the basis to define maintenance operations.
• This process must be managed and supervised by experts.
2. The perspective of the life cycle in bridges

- Safety, availability and cost (sustainability) are key criteria for lifetime of bridges that must be considered since design phase and extended to construction, operation and dismantling.
- Budget constraints are reducing conservation investments in infrastructure and extending structures expected lifetime.
- Further research is needed to understand better material and structure degradation models, combined with additional studies on life cycle cost optimization and maintenance investments.
- Harmonized structural safety evaluation codes based on deep structural / material knowledge are necessary (in discussion within eurocodes).
- SHM and embedded sensors present a relevant opportunity to contribute to real time management of critical structures.
3. The role of innovation in bridge inspection and assessment

- VR / AR Virtual bridge inspection
- Genia – Bridge management
- Condition Based Maintenance
- Robotic inspection
- Structural Health Monitoring
- Damage detection
- Structure and material models
- Data Analytics
- Upgrading
- MEASURE
- DECIDE
- PREDICT

Bridge life cycle management through innovation: A practical example with GENIA tool for inspection and assessment | Jesus Isoird ET AL
3. The role of innovation in bridge inspection and assessment

Use of Drones and robotics for inspection and maintenance tasks.

- Improving the visual inspection methods. (Digital information, automatised inspections)
- Reducing costs and improving safety of inspectors.

Pilot inspection for the Dutch province ‘Gelderland’

CableScan® IPC, USA

Current visual inspection
3. The role of innovation in bridge inspection and assessment

**Structural Health Monitoring, SHM.**

- Reduction of monitoring costs increases the interest for the use of sensing technologies.
- Research is needed to improve structural models.
- Hybrid models with data analytics can make a step forward in the use of data.
- SHM can be design for critical structures or focused on specific elements to be controlled.
- The detection of damage through SHM systems can also allow to determine the current condition of the structure.
3. The role of innovation in bridge inspection and assessment

Digital Twin based on BIM technology.

- Virtual replicas of objects or processes that simulate the behavior of their real counterparts. The purpose is to analyze its effectiveness or behavior in certain cases to improve its effectiveness.
- Digital Twins will transform the processes of construction and the maintenance of infrastructures.
- They will offer new ways to reduce costs, monitor assets, optimize maintenance, reduce downtime and allow the creation of new connected products. This concept is already part of the strategy of companies dedicated to innovation and product design of Industry 4.0.
3. The role of innovation in bridge inspection and assessment

Relevant EU coordinated research projects in development.


- **Fasstbridge** (infravation) on fast and effective solutions for Steel bridges live extension [https://fasstbridge.eu/](https://fasstbridge.eu/)

- **FORESEE** (H2020) on resilient infrastructure with specific focus on real time data management and structural diagnosis.
4. The importance of bridge management systems

Every management system must be easily manageable and offer objective data on the status of the bridges along their life. They should include:

1. Inventory of all structures and general data of Project
2. Inspections based on systematic tasks
3. Evaluation of structure condition index
4. Estimated cost of repair work
5. Strategic prioritization for intervention

A complete management system must have the capacity to perform the control and follow-up of the repairs undertaken, which will serve to evaluate the effectiveness of the adapted measures, as well as to calibrate and correct future actions.
5. Genia: Tecnalia’s bridge management system

Value-based method and tool for assessment condition.

This tool reduces the subjectivity derived from the inspector during inspection work.

It aids decision making.
5. Genia: Tecnalia’s bridge management system

- GENIA integrates all Project data valid for serveral operation needs from inventory, inspection, assessment and reporting, and investment decision support module.

- It is developed with the concept of Software as a Service (SaaS) through a web tool giving access to the users from the desktop or on the field during inspection works.
5. Genia: Tecnalia’s bridge management system

- Introducing Bridges:
  - Databases
  - Catalogues
  - Inventory
  - Historic information

- Detailed information and elements:
  - Structuring information and component naming (by levels)
  - Typology and definition of elements
  - Extension to similar elements with different naming.
5. Genia: Tecnalia’s bridge management system

- **Activate and asigne bridges:**
  - Activate inspection
  - Asigne inspection: dates and inspectors

- **Inspection:**
  - Identify damages
  - Attache images and relevant information
5. Genia: Tecnalia’s bridge management system

- Bridge Assessment:
  
  ✓ General condition assessment and by levels.
  ✓ Automatic PDF Output Report Format

![Bridge Assessment Diagram]

**Objective and Consistent Assessment**
5. Genia: Tecnalia’s bridge management system

DAMAGE LIBRARY of more than 270 damages classified by materials and bridge component.
5. Genia: Tecnalia’s bridge management system

Genia: Tecnalia’s bridge management system

Genia aims at becoming a reference for inspection and assessment of bridges, integrating other modules related to SHM and links with digital twins/BIM.

**GENIA ADDED VALUE**

- **Design, scalability and usability:**
  - **To the client:** user friendly, accurate and accessible, improving user experience
  - **To the inspector:** improving data management and processes, data exploitation

- **Inspection and assessment:**
  - Objectiveness and transparency in the structural assessment
  - Capable of using digital information (drones, SHM, ...)
  - Different users profiles and restricted information access
  - Availability of information (desktop and online)
  - Interaction among users and modules
  - Synthetised historical data
6. Conclusions

- Bridge inspection and assessment based on strong knowledge and expertise.
- New knowledge and technologies will impact infrastructure management.
- New management tools like GENIA should contribute to:
  - Improve the processes for inspection and assessment (quality and safety)
  - Possess operational, consistent and easily accessible information on the characteristics and status of deterioration of all structures.
  - Assess the safety and condition of structures with an objective method.
  - Provide decision support for maintenance actions and optimizing the use of limited budget.
  - The integration of data from the digital inspection technologies, SHM, and new digital environments.
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LIFE-CYCLE ASSESSMENT OF A MASONRY ARCH BRIDGE

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Abstract. Design of the new bridges takes care of the economic, technical, and safety issues. Still the issue of their environmental performance and influence is not tackled in the right way. It is the global methodology of Life Cycle Assessment which takes into account not only economical but also environmental and lately some attempts are done to take into account socio-cultural impacts. The paper elaborated the environmental impact of the bridge reconstruction and indicates the impact data for stonework maintenance. Bridges are designed for life of 120 years, while masonry arch bridges have proven to be sustainable long-lasting structures requiring low maintenance. Special attention has to be given to bridges of cultural heritage.

Keywords: life cycle assessment, environmental impact, masonry arch bridges, deterioration, maintenance, strengthening

1. Introduction

Bridges are an integral part of the transportation vain in one country and a vital part of the modern society. Apart from that, masonry arch bridges are a cultural bench mark of a certain historical period and special procedures have to be respected during its rehabilitation and strengthening procedures. Numerous examples in literature are available regarding Life Cycle Assessment of concrete, pre-stressed and steel bridges (Gervasio, deSilva 2008), (Rantala 2010), (Dequidt 2012), (Mousavi 2013), (Mousavi, deSilva 2013), (Mara et al. 2013), (Du, Karoumi 2013), (Du, Karoumi 2013a), (Hammervold 2013), (Ademovic 2018). However, there is very limited data regarding masonry arch bridges. On the basis of the European research project “SeRoN – Security of Road Transport Networks”, which was concentrated on the investigation on bridges and tunnels on major highways of the Trans European Road Network (TEN-T roads), on the length of 26.400 km, a number of various bow bridge/arch bridge in respect to their type and material exist: reinforced concrete bow having reinforced or prestressed concrete deck and composite deck; steel bow of composite deck and steel deck, and brick bow made of masonry/stone (Kaundinya, Heimbecher 2011). In Europe 25% of all road bridges are masonry (Bieñ, 2007), whereas for the railway bridges 60% are made of masonry, 23% concrete, 22% metallic (Sustainable bridge project, 2004).

In the process of life assessment of bridges several elements have to be considered; the ones of age which is directly connected to maintenance and different procedures of rehabilitation, repair or strengthening, and the others relating the increase in the weight of trucks and the transport facilities going over the bridge. It is amazing that taking all these considerations into account, masonry bridges aged over 200 years are still standing and taking over the passing traffic. It was concluded (Transportation Research Board of the National Academy of Sciences 2013) that this can be connected with bridges which have been feasible to maintain, adaptable to changes in traffic demands and originally overdesigned.

One has to pose a question, why are masonry bridges not constructed anymore? They have proved to have a much longer life than concrete or steel bridges (life expectancy less than 120 years) on one hand, and on the other require low maintenance needs in comparison with bridges made of concrete or steel.

In order to complete the Life Cycle Assessment, it is vital to start taking into account environmental impact and sustainability into account.

2. Sustainability

How do we define if something is sustainable or not? There are various definitions regarding this issue, one given by the World Commission on Environment and Developments, says: “Sustainable development is development that meets the needs of the present, without compromising the ability of future generations to meet their own needs”.

1
There are three primary objectives of sustainable development. One of economic growth, environmental protection and social inclusion. Each of these elements is equally important and in order to achieve sustainable development no hierarchy among them should exist. This indicates that all of these objectives are cross linked and sustainable development is in the center of this interaction as denoted in Fig. 1.

Fig. 1. Sustainable development (https://www.quora.com/What-are-the-advantages-of-sustainable-development)

3. Brick Arch Bridge in Bosnia and Herzegovina-Mehmed Paša Sokolović Bridge

Bridge Mehmed-paša Sokolović over the Drina river in Višegrad was built at the end of the 16th century (1571-1577). The construction of the bridge was entrusted to the famous builder of the Ottoman Empire Mimar Koça Sinan ibn Abd al-Mannan. This bridge represents one of the pearls of monumental architecture throughout the Ottoman Empire (Ademović, Kurtović 2017). The 179.5 m length bridge consists of 11 stone arches ranging from 11 m to 15 m and an access ramp at a right angle to 4 ports on the left bank of the Drina River (Fig. 2).

Fig. 2. Bridge Mehmed-paša Sokolović over the Drina river in Višegrad (http://www.avlija.me/kulturna-bastina/mehmed-pase-sokolovica)

During its long history the bridge experienced various damages due to floods (1664, 1875, 1896, 1911, 1939 and 1940), war actions (1914-1915 and 1939-1940) and underwent several rehabilitation and reconstruction scenarios. During one of its reconstruction a temporary steel arch structure was constructed over the bridge in 1915 and stayed there until 1939 (Fig. 3). Additionally, due to the natural and manmade disasters, the bridge was exposed to heavy traffic for which it has not been designed. However, it was only in 1977, given the traffic load, which was then 10,000 kg per 24 hours, concluded that the bridge was endangered (Ademović, Kurtović 2017). As a result, a design for rehabilitation of the bridge was conducted including strengthening of the foundations, rehabilitation of piers and replacement of the deck structure.

Further, the construction of two power plants, one downstream of the bridge in 1968, and the other upstream of the bridge in 1989, had a significant impact on the bridge. It was already in 1977 that damages were observed on the bridge not only due to bad maintenance and heavy traffic but also due to the operation of the power plant. The bridge is now located between two accumulation basins which significantly changes the atmospheric actions on the bridge elements. One of the elements to be considered is the micro climate that is very specific to this region. The maximum relative humidity of the air in Višegrad ranges from 77% in August to 88% during the winter months (Ademović, Kurtović 2017).

Long lasting bridges are the ones that have had a good form, material, construction, abutments, and maintenance and no
military damage (Marland and Weinberg 1998). Regardless of all this, the construction of the bridge has remained remarkably firm and steady (Hadzimuharemović 2007).

**Fig. 3.** Bridge Mehmed-paša Sokolović after destruction of the spans during I World War and with the steel arch structure (http://www.avlija.me/kulturna-bastina/mehmed-pase-sokolovica)

It can be concluded that traffic and environmental effects, were the two main causes for deterioration of bridges, which was the case here as well, leading to critical conditions followed by required repair/strengthening and replacement of some elements of the bridge (Tomor 2013). In that respect a new road bridge 2 km downstream of the Bridge Mehmed-paša Sokolović was built in the 1980’s (Gojković 1989).

In March 2003, the Commission for the Preservation of National Monuments of Bosnia and Herzegovina made the decision to declare the historic monument Mehmed-paša Sokolović Bridge in Višegrad as a national monument of Bosnia and Herzegovina (Odluka 2003) and on the 31st session the bridge was placed on the list of UNESCO monuments. The restauration of the bridge took place from 2013 and was finalized in 2015. Foreseen works were the remediation of bridge foundation damaged by erosion in the river bed; laying stone blocks in the river basin 30 meters upstream and downstream of the bridge to prevent further erosion of the foundation; self-cleaning vegetation; removal of cement mortar from joints connecting the stone blocks, and repointing with appropriate lime mortar; remediation of access ramps on the left bank of the Drina river; removal of a carriage way structure and laying of stone slabs; and removal of lighting on the bridge and installation. Additionally, it was decided, after many years, to close the bridge for traffic and its use now is for pedestrians only.

4. **Life Cycle Assessment**

Life Cycle Assessment (LCA) determines the environmental impacts of products, processes or services, through production, usage, and disposal. It is a method being independent of the construction or material (Ademović 2018). Life cycle of a bridge is a rather unique feature, which depends on numerous influencing factors, even for bridges that have a similar or common service. In this respect each structure has to be elaborated separately and no general conclusions can be made ad hoc.

Frequency of the maintenance activities were taken from the proposal given by (Steele et. al 2003) and presented in Table 1.

<table>
<thead>
<tr>
<th>Maintenance activity</th>
<th>Activity frequency: years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation removal</td>
<td>5</td>
</tr>
<tr>
<td>Coping stone replacement/realignment</td>
<td>10</td>
</tr>
<tr>
<td>Brickwork maintenance: repoint/renew</td>
<td>15</td>
</tr>
<tr>
<td>Parapet repairs/replacement</td>
<td>15</td>
</tr>
<tr>
<td>Invert clearance</td>
<td>20</td>
</tr>
<tr>
<td>Cutwaters replaced</td>
<td>40</td>
</tr>
<tr>
<td>First refurbishment scheme</td>
<td>120</td>
</tr>
<tr>
<td>Second refurbishment scheme</td>
<td>200</td>
</tr>
</tbody>
</table>

Due to the lack of maintenance the bridge was at risk from self-sown vegetation (Fig 4.).
Fig. 4. Vegetation growth - the bridge is at risk from self-sown vegetation

Historically it is known that some kind of works on the bridge were done in several occasions (around 1664, then in 1875, 1911 and 1939 and 1940, and from 1949 to 1952). The major rehabilitation works on the foundations (see Fig. 5) were done in 1980 and 1981 (Gojković 1989).

Fig. 5. Repair details of the foundations 1980-81 (Gojković 1989)

The first preventive measure was done in the 1980’s as the bridge was closed to freight traffic, but it was only in 2003 that the bridge was closed to all motor vehicles.

Although several rehabilitations processed have taken place on the bridge, only the last rehabilitation procedures that took place in 2013 is considered in the paper.

The boundaries of the LCA are shown in Fig. 6. Three life cycles were analyzed, those being bridge construction, service life and structure strengthening respecting ICOMOS regulations and Venice Charter as the bridge is on the UNESCO World Heritage list. Profiles in the database and the set-up defined in Fig. 6 were used for development of different estimates. All the available documentation, reports and site visit were utilized to conduct this activity as accurate as possible in respect to the available documentation and knowledge. Bridge construction estimates were developed for different types of stone, mortar, fill material and new stones placed on the carriageway of the structure. Mortar was made of cement, lime and sand and water. Adequate energy demands were taken into account regarding cement mixing, compaction of fill material and transportation demands for delivery of the materials to the site.

Fig. 6. System of the study - background and foreground
Repointing of the stonework and replacement of the stonework represent material replacement activities. The entire surface of the bridge was investigated and depending on the state of the surface different levels of maintenance were defined (good, average and poor), which would take place at a standard 15-year frequency. Taking into account the amount of the stone and mortar replacement as well as repointing, material quantities were calculated. Replacement of the fill in material was taken as the disposal material and transport of this material to the disposal site was taken into account at a distance of 20 km.

5. Impact assessment

The starting point for determination of the environmental impact various impact categories were utilized. Within the impact categories, substances are grouped into classes in respect to their contribution to environmental impact. The quantity of each emission is weighted by damage factors in order to present the contribution of a certain emission to the impact category (Stelle et al. 2003). Three damage categories were considered: Human Health (HH), Ecosystem Quality (EQ) and Resources (R). Within in HH three impact categories were taken into account HH – Carcinogen: cancers due to toxic chemicals in air, drinking water and food; HH - Respiratory organic: respiratory diseases due to toxic chemicals in air, drinking water and food and HH - Respiratory inorganic: respiratory diseases due to toxic chemicals in air, drinking water and food. Two Ecosystem Qualities: EQ - Eco-toxicity: the potentially affected fraction of species in relation to the concentration of toxic substances and EQ - Acidification and eutrophication: a measure of reduction in plant and animal diversity. Resources were taken into account as Fossil fuels; qualitative structure of resources and continued decreasing concentration.

5.1. Results and discussion

Results obtained form the environmental analysis of the selected bridge structure are presented in Fig. 7. It is straightforward that the demand for the stone replacement represents the biggest issue of all the investigated categories. This is quite understandable due to a large amount of material and reopening of the quarry and explanation of the stone, as well as all required processes required for stone preparation. The next larges impact is one of the mortar production used in the repointing process of the large area of the bridge.

![Fig. 7. Environmental impact of the bridge reconstruction](image)

![Fig. 8 Impact data for stonework maintenance](image)

Repointing in respect to renewal of stonework has a much smaller impact. As it can be seen from the Fig. 8 stone removal represents always an amount greater than 73%. On the other hand, repointing is less than 22%, having minimal impact on the environments and represents a valuable investment. The increase from poor to good maintenance is 15%, which is much smaller in respect to the removal of the bridge structure, which is in this situation not acceptable as it is a UNESCO monument. It is well known that good maintenance prevents and prolongs the structure deterioration and as a consequence extends the life of the structure. In that respect stonework maintenance can be seen as an environmental saving.

6. Conclusion

Environmental impact of a stone bridge was investigated utilizing a proposed methodology. Several key impact categories were selected in order to analyze environmental impact with the utilization of the life cycle assessment.

This was an attempt to use the methodology provided by Steele (Stelle et al. 2003). It is evident that larger works encompassing of renewal of the stone works represents the biggest contribution to the environmental impact during the
life time of a bridge. Maintenance on the other hand has been identified to have a rather small impact on the environment and prolongs the life of the bridge.

In the process of application of the life cycle assessment it is necessary to expand our views and besides environmental impacts take into account socio-cultural aspect, even though they are difficult to assess. Sometimes these aspects can lead to different scenarios in respect to the ones obtained from economic and environmental assessment (Ademović 2018). This is not taken into account in this paper but should be something to be considered and evaluated.

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LIFE-CYCLE ASSESSMENT OF A MASONRY ARCH BRIDGE

Naida Ademović - University of Sarajevo, Faculty of Civil Engineering, Bosnia and Herzegovina
LIFE-CYCLE ASSESSMENT OF A MASONRY ARCH BRIDGE

• Introduction
• Life Cycle Assessment
• Mehmed-Paša Sokolović Bridge
• Conclusion
INTRODUCTION

• Life Cycle Assessment of concrete, pre-stressed and steel bridges—numerous examples
• Masonry arch bridges as cultural benchmark lasting over 200 years
  – Maintain, adaptable to changes in traffic demands and originally overdesigned.

Europe-Road bridges

Europe-Railway bridges

- 75%
- 25%
- masonry
- other

- 57%
- 22%
- 21%
- masonry
- concrete
- metallic
INTRODUCTION

- Bridge Assessment:
  - **Age**-maintenance and rehabilitation, repair, strengthening
  - **Increase of weight**-trucks and transport facilities
- Masonry bridges – over 200 years
- Why are masonry bridges not constructed anymore?
  - Longer life;
  - Low maintenance
LIFE CYCLE ASSESSMENT

• Sustainability (World Commission on Environment and Developments):

“Sustainable development is development that meets the needs of the present, without compromising the ability of future generations to meet their own needs”

• Economic growth
• Environmental protection
• Social Inclusion
MEHMED PAŠA SOKOLOVIĆ BRIDGE

- Bridge Mehmed-paša Sokolović over the Drina river in Višegrad was built at the end of the 16th century (1571-1577).
- L=179.5 m
- 11 stone arches ranging from 11 m to 15 m
- and an access ramp at a right angle to 4 ports on the left bank of the Drina River
DAMAGES TO THE BRIDGE

- damages due to floods (1664, 1875, 1896, 1911, 1939 and 1940)
- war actions (1914-1915 and 1939-1940)
- underwent several rehabilitation and reconstruction scenarios
DAMAGES TO THE BRIDGE

• construction of two power plants: 1968 downstream and in 1989 upstream
• In 1977: bad maintenance + the traffic load + operation of the power plants - the bridge was endangered.

As a result, a design for rehabilitation of the bridge was conducted including strengthening of the foundations, rehabilitation of piers and replacement of the deck structure. Regardless of all this, the construction of the bridge has remained remarkably firm and steady.
BRIDGE DETERIORATION

• Traffic impact
• Environmental effects
• New road bridge was built 2 km downstream of the Bridge Mehmed-paša Sokolović was built in the 1980’s

• UNESCO monument- since 2003
• Restauration works 2013-2015
BRIDGE DETERIORATION

• Restauration works:
  – remediation of bridge foundation damaged by erosion in the river bed;
  – laying stone blocks in the river basin 30 meters upstream and downstream of the bridge to prevent further erosion of the foundation;
  – self-cleaning vegetation;
  – removal of cement mortar from joints connecting the stone blocks, and repointing with appropriate lime mortar;
  – remediation of access ramps on the left bank of the Drina river;
  – removal of a carriage way structure and laying of stone slabs;
  – and removal of lighting on the bridge and installation.

• Closure of the bridge for traffic **pedestrians use only.**
LIFE CYCLE ASSESSMENT

- Frequency of the maintenance activities
- 3 life cycles: construction, service life, strengthening

Primary resources

Stone Sand Lime Cement Gravel Fill

Design Bridge construction Bridge service life Bridge strengthening End of life

Mix mortar Fill material

Stone replacement

Maint. 30 years

45 years 60 years 75 years 90 years 105 years

Repainting and renewal activities

Removal of fill material Placement of new fill Placement of new stone blocks

Landfill

Emissions

Wastes

Background system

Frequency of the maintenance activities

3 life cycles: construction, service life, strengthening
IMPACT ASSESSMENT

Impact category

Human Health (HH)
- HH – Carcinogen
- HH – Respiratory organic
- HH – Respiratory inorganic

Ecosystem Quality (EQ)
- EQ - Eco-toxicity
- EQ - Acidification and eutrophication

Resources (R)
- Fossil fuels
RESULTS AND DISCUSSION

- demand for the **stone replacement** represents the biggest issue of all the investigated categories:
  - large amount of material
  - reopening of the quarry
  - and explanation of the stone,
  - all required processes required for stone preparation
- **mortar production** used in the repointing process of the large area of the bridge
RESULTS AND DISCUSSION

• stone removal represents always an amount greater than 73%. Repointing is less than 22%, having minimal impact on the environments and represents a valuable investment.

• Good maintenance prevents and prolongs the structure deterioration and as a consequence extends the life of the structure. Stonework maintenance can be seen as an environmental saving.

![Graph showing relative impact percentages for various impact categories including Average stone renewal rate, Average stone repointing rate, and Disposal of waste.](attachment://image.png)
CONCLUSION

- Methodology provided by Steele was used.
- Renewal of the stone works represents the biggest contribution to the environmental impact.
- Maintenance has been identified to have a rather small impact on the environment and prolongs the life of the bridge.

- Further step take into account socio-cultural aspect. Sometimes these aspects can lead to different scenarios in respect to the ones obtained from economic and environmental assessment.
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AUTOMATIC BRIDGE DECK DAMAGE EXTRACTION USING LOW-COST UAV-BASED IMAGES

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AUTOMATICALLY IDENTIFY DAMAGE OF A BRIDGE DECK USING LOW-COST UAV-BASED IMAGES

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Abstract: Bridge structures are subjected to deterioration due to excessive usage, overloading, aging, and environmental impacts. Use of visual inspection by live, on-site inspectors predominates the requisite inspection of these structures, despite the known disadvantages of subjective results, high costs, and traffic disruptions due to lane closures needed for close-range inspection access. Over the last two decades, significant advancements have occurred in the field of remote sensing for bridge inspection. Prominent amongst these are a point cloud based inspection using unmanned aerial vehicle (UAV)-based image. The approach offers quickly acquiring surface details and can overcome many of the shortcomings of live, visual inspection. This paper proposed a robust and efficient method to automatically extract a point cloud of a bridge deck through a cell-based region growing segmentation. Next, locations and areas of the patch deterioration can be automatically determined by comparing elevations of the point clouds to the surface of the undamaged bridge deck. Finally, a deep learning method, a one-class autoencoder, was proposed to classify the point cloud of the bridge deck into cracking area and undamaged one.

Keywords: bridge inspection, bridge deck, UAV, point cloud, segmentation, patch deterioration, cracking, deep learning, autoencoder

1. Introduction

The most recent American Society of Civil Engineers’ (ASCE) Report Card on infrastructure reported more than 50% of 614,387 nation’s bridge are over 40-year-old with about 9.1% of them subjected to structural deficiencies (ASCE 2017). Similar quantities were also found in 6 European nations, a majority of the bridges were built in the period 1945-1965, undergone significant reduced because of excessive usage, overloading, material aging, and environmental impacts. As such, accurate assessment of a bridge’s condition is needed for maintaining a safe, functional, and reliable structure. Additionally, inspection is needed to updating asset inventories and bridge management. In practice, visual inspection with on-site inspectors associated with special equipment is the predominant method. This approach, albeit the most common one, has many downsides: subjective and highly dependent upon an inspectors’ experience, slow and expensive inspectors, and traffic closures (Metti and Hamel 2007; Phares et al. 2004).

In contrast, with development of robotics and computer vision, low-cost unmanned aerial vehicles (UAVs) have been introduced and widely used in topographic surveying. The method can capture high resolution images of surfaces from an air, and then high dense, accurate three-dimensional (3D) data points of the components can be generated. Following, features and 3D models of objects can be extracted from those point cloud. That leads to using UAV for bridge inspection to be emerging an alternative method, which can partially replace to or to provide complement information for current methods. That is because the method does not require traffic closure, on-site experienced inspectors.

Researchers have preliminarily deployed UAV-based images for bridge inspection, but their works only focused on specific tasks. For example, Kim et al. (Kim et al. 2015) detected cracks in bridge superstructures. Ellenberg et al. (Ellenberg et al. 2016) analysed an error budget of an UAV with an integrated 10-megapixel camera measuring in situ displacements of a steel girder in a laboratory. Result showed deviations of up to 31.5%. Recent efforts on reconstructing 3D point clouds from overapping images have been developed for bridge assessment, but reported accuracies are relatively low. Neitzel and Klonowski (Neitzel and Klonowski 2011) showed point cloud-based images having an absolute deviation of up to 20 cm. Moreover, Escobar-Wolf et al. (Escobar-Wolf et al. 2017) have used infrared and digital single-lens reflex (DSLR) Nikon D800 cameras mounted on UAV to image the bridge deck for identifying delamination. The study has been tested on Merriman and Stark Road overpass bridges, located on highway I-96 in Detroit, Michigan, and reported that infrared and DSLR images can give acceptable results of delamination. Recently,
Lovelace (Lovelace 2015) investigated ability of using UAV technology to apply to bridge safety inspections based on UAV field results. The project has used to capture surface of the bridge components of 4 bridges located through Minnesota. Based on analysing of effective as well as UAV-based results compared to visual inspection, the author has concluded (1) UAV are a suitable tool for inspection of the bridges, and (2) defects can be identified from images. However, UAV cannot replace on-site inspectors in case to use tactile functions (cleaning or measuring) to detect damage. This paper proposed a robust and efficient method to automatically extract a point cloud of a bridge deck, which was generated from a bundle image captured by a low-cost UAV. The point cloud was then decomposed into 2D adjoin cells, and a cell-based region growing was proposed to group adjacent cells having deviations of features satisfying predefined conditions. Moreover, backward and forward algorithms were proposed to minimize over- and/or under-segmentation, Next, locations and areas of the patch deterioration can be determined by comparing elevations of the point clouds of the bridge deck to the undamaged surface of the bridge deck. Finally, a deep learning method, an autoencoder-based one class, was proposed to extract cracking location of the bridge deck.

2. A proposed method

The proposed workflow consists of 3 main parts: (I) Data acquisition and preprocessing, (II) Bridge deck extraction and (III) Bridge deck damage detection (Fig. 1). This paper mainly focuses on parts II and III, while in the part I, a point cloud was generated from images captured from UAV by using a commercial software and noise data points was semi-automatic removal by using an open-source software. To facilitate for identifying damage of a pavement surface of the bridge, in Part II, a robust, efficient segmentation was proposed to automatically extract the point cloud of the bridge pavement surface. Additionally, an aim of Part III is to report a condition of a bridge deck including patch deterioration and cracking.

![Fig. 1. Proposed workflow](image)

3. Test-bed bridge

To test the proposed workflow, the Blessington bridge connected Kilbride Rd. to Lake Dr Rd., cross over Liffey Lake in County Wicklow, Ireland was selected as a case study. The bridge is a reinforced concrete, about 130 m long, 8m wide with 2 traffic lanes plus 1 pedestrian lane (Fig. 2). A low-cost UAV, DJI Phantom 4 quadrotor with a 4K camera was used to capture the bridge. The 4K camera has field of view of 94 degrees, a focus length of 35 mm. This can take an image with 4000 x 3000 pixels, which can translate to the ground sampling distance of 10 mm/pixel from a height of 15 m.

![Fig. 2. Blessington bridge and flight paths for data capture](image)

![Fig. 3. A point cloud of the bridge from a image acquired from UAV](image)

Data capture was designed to ensure images fully covered the bridge deck, which consisted 7 parallel flight paths including 2 paths for each side and 3 paths above the desk. The flight attitude was about 8 m to 15 m above the bridge deck. Total of 212 images have been captured within an hour. A 3D data point describing a bridge structure was generated from images by employing Agisoft PhotoScan (AgiSoft 2017). In this process, the images were imported to the software to eliminate distorted or blurred images or inadequate overlap (Siebert and Teizer 2014). Next, the software was automatic detected common features and to align them together. Finally, a dense point cloud was automatically generated from the matching images. A total of 16.8 million points with x, y, z coordinates associated with red-green-blue (RGB) colors was generated (Fig. 3a). The process was taken about 1 hour on a Dell XPS with i7 CPU with a speed clock 2.8 GHz, 4 cores and 16 Gb RAM, on Window 10 operation system.
In fact, when generating a point cloud from a bundle of images, the point cloud contains irrelevant points that do not represent the bridge components or scene, which are majorly caused by reflection of water’s waves and self-shadow. The irrelevant points particularly occurred underneath the bridge. As such, a pre-processing data is needed to eliminate these points, which was done by the noise removal algorithm implemented in an open source, CloudCompare V2.9 (Filter 2018). A resulted noise removal was illustrated in Fig. 3b, in which the data set of 12 542 215 points was remained for further processing. More details of the noise removal can refer to Chen et al. (Chen, et al. 2018).

4. Bridge deck extraction

A goal of this step is to extract a point cloud of a bridge deck. This can be achieved through a novelty method called a cell-based region growing proposed in this study. The process starts to decompose 3D point cloud into 2D horizontal plane, and a 2D bounding box containing entire input data was created, which is defined as a pair of the corners \([x_{\text{min}}, y_{\text{min}}]\) and \([x_{\text{max}}, y_{\text{max}}]\) derived from 3D point cloud. Next, the quadtree (Samet 1984) was employed to recursively subdivided the bounding box into 4 smaller adjoining 2D cells until terminate criteria are reached. In this study, the maximum cell size of 0.5 m was set as the terminated condition. Cells were classified as “empty” if the cell does not contain any data points, otherwise, it was “full”.

However, the full cell may contain the point clouds of multiple components of the bridge located in a vertical direction, for example, Fig. 4 showed the cell contains the data points of the safety rail, bridge deck and pier. As such, the new algorithm was proposed to eliminate the point cloud which is not potentially of the bridge deck. The algorithm is based on the observation that the point cloud of the bridge deck is often in form of the highest peak of a probability density shape generated from elevation of the point cloud. For example, the circle filled blue are the point cloud of the bridge deck. Results are secure the cell contains a point cloud of only one surface or parts of bridge’s component.

Next, the cell-based region growing was proposed to segment the point cloud on the same surface. Local features of each cell were priority computed, which are a normal vector and the residual. In this study, the point cloud within the cell was assumed to describe a plane. The centroid \((p_0)\) of the surface \((S)\) can expressed in Eq 1, while a principal component analysis (PCA) was employed to determine the surface normal \(n = (n_x, n_y, n_z)\), which is the eigen-vector corresponding to the smallest eigen-value determined from the covariance matrix given in Eq 2. The surface of the cell can be expressed in form \(S(p_0, n)\). Finally, the distances, \(d(p, S)\), from all points in the cell to the surface \(S\) were computed and the residual (res) is defined as the root mean square of these distances.

\[
p_0 = \frac{1}{N}\sum_{i=1}^{N} p_i
\]

\[
C = \sum_{i=1}^{N} (p_i - p_0)(p_i - p_0)^T
\]

where \(p = (x, y, z) \in \mathbb{R}^3\) is \(x\), \(y\), \(z\) - coordinates of the data points.

The cell-based region growing is a process to incrementally group adjoin cells having deviation of features satisfying conditions. The process starts with the cell having the smallest residual, which call a searching cell. The adjoin cells can be considered as the same region with the searching cell, if deviation of the normal vectors and of the elevations between the searching cell and the adjacent cells are less than the angle and elevation thresholds, which is empirically selected as 2.5 degrees and 50 mm, respectively. Two conditions were here introduced to ensure continuity of the region. The new cells of the region satisfying two conditions above, were considered as the searching cells, if the residual values of these cells are less than the residual threshold of 10 mm to be adopted herein. The process is continuously to search new cells of the region until there is no searching cell available. Additionally, the segmentation is complete when all cells were checked. The process implemented herein is similar to works of Vo et al. (Vo et al. 2015).

Since the cell on a region boundary may contain the point cloud of multiple surfaces of components, for example, the cell may contain the point cloud of a traffic lane and a pedestrian path. Thus, results at this stage can be over- and/or under-segmentation. Backward and forward algorithms were introduced to overcome this problem. The backward
algorithm is to remove the points of other segments out of the current segment, while the forward algorithm is to group the points of the current segment have not included. From the cell $C_i$ on the boundary of the region $R_i$, its neighbour cells, $C_j$ was extracted. The $C_i$ were classified as 3 groups: (1) interior cell(s), $C_{in}$ of $R_i$, (2) boundary cell(s), $C_b$ of $R_i$, and (3), out-region cell(s) $C_{ou}$ of $R_i$. Next, the fitting surface $S_i$ was created the point clouds within $C_i$ by using PCA. In the backward algorithm, the points $(p_i)$ in $C_i$ were removed out of $C_i$ if the distance, $d(p_i, S_i)$, is larger than the distance threshold of 10 mm. Similarly, in the forward algorithm, the points $(q_i)$ in $C_{ou}$ was considered to merge to $R_i$ if the distance, $d(q_i, S_i)$, is smaller than the distance threshold of 10 mm. Figure 5a-d was illustrated processes of the backward and forward algorithms, while Fig. 5e showed the bridge deck automatically extracted from the proposed method. Finally, performance pf the proposed method was evaluated by comparing the point cloud of the bridge pavement extracted to a reference data that manually extraction. That showed the proposed method can automatically extract these points high accurately, with $F_1$-score of 0.95. Moreover, an executing time is about 171.4 seconds when the algorithm was implemented in Matlab script and run on HP 2570p with a processor i7-3520M CPU @ 2.9 GHz and 16GB RAM.

5. Bridge deck condition

5.1 Patch deterioration

A goal of this step is to identify damage of the bridge deck from a point cloud. Damage including patch deterioration and cracking are mostly interested in this study although other types of damages can be available. The patch deterioration caused parts of the surface to be peered and additional material can be filled during road pavement maintenance. In this case, geometry of the patch is often different from undamaged areas. Therefore, it is assumed small portions of the patch deterioration in the bridge deck, which implied the fitting surface through a point cloud can represent the undamaged surface. The fitting surface of the bridge deck expressed in Eq 3 can be obtained by employing a 3D curve fitting algorithm built in Matlab software (MathWorks 2016). The fitting results showed R-square of 0.998 with RMS of 12.7 mm, which implied the fitting surface can be accepted to represent the bridge deck in undamaged condition. Additionally, elevation differences ($e_i$) from the point cloud to the fitting surface was then computed according to Eq 4.

\[ S(x, y) = 47.32 - 0.03x + 0.04xy - 0.002xy - 0.003x^2 - 0.0007y^2 \]  

\[ e_i = z_i - S(x_i, y_i) \]  

where $x$ and $y$ are $x$- and $y$- coordinates of the point cloud, while $x_i$, $y_i$, and $z_i$ are coordinates of a point $p_i$ in the data set.

Figure 6. Identifying patch deterioration of a bridge deck
Results showed $e_i$ varying in a range from -114.1 mm to 100.2 mm with the mean ($\mu$) of 0.0 mm and the standard deviation ($\sigma$) of 12.7 mm (Fig. 6a), and the area of each range $e_i$ was showed in Fig. 6b. It can be seen the patch deterioration with $e_i$ in the range from $\mu \pm 1\sigma$ to $\mu \pm 2\sigma$ is around 247.8 m² with 28.8% of the bridge deck (Fig. 6b). Moreover, area of the damage patch having $e_i$ from 25.4mm to 38.1mm ($[\mu + 2\sigma, \mu \pm 3\sigma]$) is 46.8 m², about 5.4%. Interestingly, the damage patch having $e_i$ larger than 38.1mm are mostly on a boundary of the pavement surface, which can be the point cloud of other segments (e.g. ones of the pedestrian lane) due to over-segmentation.

5.2 Cracking extraction

In addition, in undamaged areas, the sampling step of a point cloud, a distance between two adjacent data points, is often equal, except for mixing data. The sampling step is to be large at locations where cracking is available because the surface is discontinuity in these locations. In theory, Laefer et al. (Laefer et al. 2014) stated that the crack can be detected if the crack width is larger than two times of the sampling step. However, in practice, noise and mixed data points cannot be inevitable, which cause the small crack width can be difficulty to automatically determine from a point cloud (Truong-Hong et al. 2016). Interestingly, the point clouds of the cracks present as dark regions while ones of other areas are brighter (Valença et al. 2017). That implied colours of the point cloud in the crack differs from those of others.

A machine learning technique, Autoencoders-based one class were employed to extract the crack regions on the bridge pavement surface. An autoencoder is a neural network consisting of two parts: encoder and decoder. The encoder plays as a feature extractor that explicitly represents input data $X$ into a feature space. Let $f_{\theta}$ denote the encoder, and $X = \{x_1, x_2, ..., x_n\}$ be a dataset. The encoder $f_{\theta}$ maps the input $x_i$ into a latent vector $z_i = f_{\theta}(x_i)$, where $z_i$ is the code or latent representation of $x_i$. The decoder $g_{\theta}$ map $z_i$ back into the input space, which forms a reconstruction $\hat{x}_i = g_{\theta}(z_i)$. The encoder and decoder are commonly represented as single-layer neural networks in the form of non-linear functions of affine mappings as follows:

$$f_{\theta} = \psi_s(W_{\theta}x + b_1)$$
$$g_{\theta} = \psi_t(W_{\theta}x + b_2)$$

where $W_{\theta}$ and $b_1, b_2$ are the weight matrices and biases of the encoder and decoder, $\psi_s$ and $\psi_t$ are the activation functions of the encoder and decoder, such as a sigmoid or tanh function.

Autoencoders learn to minimize the reconstruction error (RE) between the input and its reconstruction values at the output layer regard to the parameters $\theta = \{W_{\theta}, b_1, b_2\}$. The reconstruction loss function can be the mean squared error (MSE) or the cross-entropy loss. By compressing input data into a lower dimensional space, the classical autoencoder avoids simply learning the identity, and removes redundant information (Japkowicz, et al. 1995). As such, AEs are often applied for constructing one-class classifiers (Cao et al. 2016; Cao et al. 2018). Thus, the REs can be used as classification score, which means that a query point having classification score below a pre-determined threshold is classified in the in-class, otherwise it is categorized into the out-class.

In this experiment, to develop a model to predict crack areas, point clouds of the crack regions were manually extracted (Fig. 7a). A total of 12 164 points was used as a training data set. The AE was designed with two hidden layers, and three neurons in each. With an effort to to reduce the number of hyper-parameters of the AE, Adadelta algorithm (Zeiler 2012) together with early-stopping techniques (Prechelt 1998) were employed.

After a learning algorithm, two data sets extracted from an entire data set of the pavement surface of the bridge deck were used to predict cracks’ locations. Results of the prediction were shown in Fig. 7b and c. A visualisation evaluation showed that most of the cracks in Data set 2 and 3 were extracted (Fig. 7b and c). However, the method was given over-prediction, where the point clouds along boundaries of the bridge deck were also recognized as the crack because these points cloud having RGB colors similarly to ones in the crack locations. This issue can be eliminated by comparing shapes of the predicted cracking to a real one. Moreover, additional attribution of the point cloud may be included in a training model to improve an accuracy of the classifier.

6. Conclusions

1. The cell-based region growing was proposed to automatically extract a point cloud of the bridge deck. The evaluation showed the proposed method can extract the bridge deck with F1-score of 0.95 and processed 12 542 215 data points in 174.1 seconds
2. Patch deterioration of the bridge deck was automatically identified by comparing elevations of the point cloud to the undamaged bridge deck surface. Both location and area of the patch can be reported and can be used for decision making and bridge management. However, an evaluation of the proposed method should be evaluated to an independence method.
3. Implementation of a deep learning, Autoencoder-based one class was extracted most of cracks in the bridge deck, in which only RGB colors of the point cloud were used during training a model. Over-extraction was still available for regions along boundaries of the bridge deck. This can be solved by analysing shapes of the
extracted cracks. Furthermore, additional attributes of the point cloud can be used to improve an accuracy of the proposed method.

Acknowledgements

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AUTOMATIC BRIDGE DECK DAMAGE EXTRACTION USING LOW-COST UAV-BASED IMAGES

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Debra F. Laefer - New York University, United States of America
OUTLINE

• Motivation

• A proposed method for determining surface deterioration and extracting cracks

• Test-bed bridge: Bridge configuration, data acquisition, point cloud generation

• Bridge deck extraction: cell-based region growing segmentation method, and backward and forward propagation for refining segmentation outcome

• Bridge deck condition: Patch deterioration and crack extraction

• Conclusions
MOTIVATION

• In the US, with nearly 25% of the 600,000 highway bridges considered to be in a deficient, and the majority of the bridges have average life span about 70 years

• In 6 European nations (Slovenia, Poland, Hungary, Czech Public, Norway and Austria), most bridges were built in the period 1945-1965 and have undergone significant deterioration

• In practice, visual inspection is the predominant method for bridge assessment, which requires physical inspectors and special machines/devices.
MOTIVATION

• This approach, albeit the most common one, has many downsides:
  ✓ Subjective results: depending on inspector experience
  ✓ Requirement of experienced and trained inspectors
  ✓ Slow and expensive procedure: in US, $300-400 million/year with a standard general inspection.
  ✓ High safety risks for inspectors: several fatal of inspectors was reported per year
  ✓ Traffic closures
  ✓ Difficulty in comparing or tracking damage propagation for different inspection cycles: the photo, tables, hand-sketches and remarks are common used during an inspection.

Unmanned aerial vehicle (UAV)-based images is cost-effective and flexible to capture 3D information of structures’ surface, which can be an alternative approach to partially replace current visual inspection. *This paper is to investigate ability of UAV-based images in determined surface deterioration and cracks of the bridge deck.*
A PROPOSED METHOD

BRIDGE STRUCTURE

(I) Data acquisition & preprocessing
- UAV image capture
- Point cloud generation

(II) Bridge deck extraction
- Cell-based region growing segmentation

(III) Bridge deck damage detection
- Patch deterioration
- Cracking extraction
TEST-BED BRIDGE

- Blessington bridge connecting Kilbride Rd. to Lake Dr Rd., crossing Liffey Lake
- Reinforced concrete: 130 m long and 8m wide
  2 traffic lanes and 1 pedestrian lane

DJI Phantom 4

- Image: 4000x3000
- FoV: 94 degrees
- A focal length: 35 mm
- Resolution: 10mm/pixel
TEST-BED BRIDGE

- No. flight paths: 7 (2 along each side, 3 above the desk)
- Flight attitude: 8 m - 15 m
- No. images: 212
- No. point cloud: 16.8 mil. points

3D point cloud of the bridge generated from UAV images

3D point cloud after removing noise data
BRIDGE DECK EXTRACTION

Depth = 0

Depth = 1

Depth = 2

Quadtree representation

Bridge deck

Safety rail and bridge deck

Curb, bridge deck and pier

Cells containing point clouds of different bridge components
BRIDGE DECK EXTRACTION

Principal Component Analysis (PCA):

\[ p_0 = \frac{1}{N} \sum_{i=1}^{N} p_i^r \]

\[ C = \sum_{i=1}^{N} (p_i^r - p_0)(p_i^r - p_0)^T \]

\[ n = (n_x, n_y, n_z) \]

\[ d(p_i, S) = \frac{n_x x_i + n_y y_i + n_z z_i}{\sqrt{n_x^2 + n_y^2 + n_z^2}} \]

\[ \text{residual} = \sqrt{\frac{\sum_{1}^{N} d^2(p_i, S)}{N}} \]

Cell-based region growing segmentation
BRIDGE DECK CONDITION: Patch deterioration

A point cloud of Ri and adjacent segments

Classification of neighbour cells

Result of the backward algorithm

Result of the forward algorithm

Segmentation results

F1-score = 0.95
BRIDGE DECK CONDITION: Patch deterioration

The fitting surface of the bridge deck ($R^2 = 0.998$; RMS = 12.7 mm)

$$S(x, y) = 47.32 - 0.03x + 0.04y - 0.002xy - 0.003x^2 - 0.0007y^2$$

Elevation differences ($e_f$) from the point cloud to the fitting surface

$$e_i = z_i - S(x_i, y_i)$$

Distribution of patch deterioration

<table>
<thead>
<tr>
<th>Area of patches:</th>
<th>$A$</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_{fi} : [\mu - 1\sigma, \mu + 1\sigma]$</td>
<td>$562.7 \ m^2$</td>
<td>(65.4%)</td>
</tr>
<tr>
<td>$e_{fi} : [\mu - 2\sigma, \mu - 1\sigma] &amp; [\mu + 1\sigma, \mu + 2\sigma]$</td>
<td>$247.4 \ m^2$</td>
<td>(28.8%)</td>
</tr>
<tr>
<td>$e_{fi} : [\mu - 3\sigma, \mu - 2\sigma] &amp; [\mu + 2\sigma, \mu + 3\sigma]$</td>
<td>$46.8 \ m^2$</td>
<td>(5.4%)</td>
</tr>
<tr>
<td>$e_{fi} : &lt;\mu - 3\sigma \ &amp; &gt;\mu + 3\sigma$</td>
<td>$3.9 \ m^2$</td>
<td>(0.4%)</td>
</tr>
</tbody>
</table>

Area of patches:

- $A = 562.7 \ m^2$ (65.4%)
- $A = 247.4 \ m^2$ (28.8%)
- $A = 46.8 \ m^2$ (5.4%)
- $A = 3.9 \ m^2$ (0.4%)
BRIDGE DECK CONDITION: Crack extraction

Autoencoders-based one class
BRIDGE DECK CONDITION: Crack extraction

Data set 2 and resulted cracking

Data set 3 and resulted cracking
CONCLUSIONS

- A cell-based region growing was proposed to automatically extract a point cloud of the bridge deck robustly and efficiently, which was given F1-score of 0.95 and processed more than 12 million data points in 174.1 seconds.

- Patch deterioration of the bridge deck was automatically identified by comparing elevations of the point cloud to the undamaged bridge deck surface.

- An evaluation of the proposed method should be evaluated against an independent method.

- Implementation of deep learning in the form of an Autoencoder-based one class was successful in extracting most of cracks in the bridge deck, in which only RGB colors of the point cloud were used in the training model.

- Over-extraction occurred along bridge deck boundaries, but can be solved by analyzing shapes of the extracted cracks. Furthermore, additional attributes of the point cloud can be used in learning the model to improve an accuracy.
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HUMAN ERRORS AND CORRESPONDING RISKS IN REINFORCED CONCRETE BRIDGES

Neryvaldo Galvão – 1st PhD student at University of Minho, Portugal
José Matos – Professor at University of Minho, Portugal
Daniel Oliveira – Professor at University of Minho, Portugal
João Fernandes – 2nd PhD student at University of Minho, Portugal

27th – 28th September 2018
Barcelona, Spain
HUMAN ERRORS AND CORRESPONDING RISKS FOR REINFORCED CONCRETE BRIDGES

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Abstract. Concerning the bridges failures that have been arising over the years, experts have pointed out as the principal cause of bridges failures, the human errors that usually take place in the design, construction and operation stages. The main goal of this paper is the identification of the design and construction errors that represent a higher risk for reinforced concrete bridges. Therefore, a human error survey was developed together with design and construction experts on this subject, to collect and assess these errors by using risk-based indicators (probability of occurrence and consequences). The survey results, given by design and construction experts, are analysed by using a decision-making tool, named Analytic Hierarchy Process (AHP), which will allow the identification of the errors with higher consequences and a higher probability of occurrence. The outcome of the performed qualitative risk-based evaluation of the errors is also presented in this paper.

Keywords: Design Errors, Construction Errors, Reinforced Concrete Bridges, Risk Analysis, Analytic Hierarchy Process (AHP), Bridge Failure.

1. Introduction

The collapse of bridges is very often connected to tremendous consequences for society and the local economy once it is part of an imperative network system for the growth of an economy and the fulfilment of human happiness (Scheer, 2010) (Imhof, 2004) (Cavaco, 2013). To improve the reliability of bridges is first required, the documentation of the main source of the issues (uncertainties) that are leading to their failure (Campos e Matos, 2013). Relying on a bridge failure database developed by (Syrkov, 2017) which contain several common bridge failure cases with their leading causes of failure, since 1966 to 2017, we can state that design and construction error has a vital role to play in this matter, representing 31% of the failures. Although, the operation errors are responsible for most of the collapses, with a percentage of 51% (Fig. 1).

![Fig. 1. Leading causes of failure for reinforced concrete bridges (Syrkov, 2017)]
The design and construction errors is a vast subject, and when it comes to being explicitly defined the engineers can find themselves very confused about their boundaries and how can they be identified in the multifaceted conception process of a bridge. Therefore the human errors are defined as design, construction and operation errors that are not beyond the engineering knowledge and occurred because of bad work conditions, miss guidance, and lack of oversight. Similar definition can be find in (Tylek et al., 2018) and (Brehm et al., 2018). These errors can represent different risks when compared with each other. Thus, it is essential the identification of those that might represent a higher risk.

2. Human Error Risk-Based Analysis

The risk analysis is defined as the systematic use of available information to identify hazards and to estimate the risk to individuals, property, and the environment (Rausand, 1997). It is a field of risk management, and it is established in three steps: (i) the hazard identification; (ii) the frequency analysis; and (iii) the consequence analysis. The identification of the hazards, in this case, is the identification of possible design and construction errors that may affect a reinforced concrete bridge (Decò & Frangopol, 2011). To identify these errors, a brainstorm meeting with some experts in the subjects was carried out to identify design and construction errors specifically. The frequency analysis and the consequence analysis was performed through a survey that allows a qualitative analysis of the errors.

The risk analysis is usually followed by a risk evaluation, where the risk of a hazard is compared with the acceptance criteria, which sometimes are hard to define and can vary for different industries. These acceptance criteria also direct the proper action for a specific hazard, to get a risk as low as reasonably practicable (ALARP). The ALARP concept is directly related to the established acceptance criteria, and it groups the hazards into three categories, the critical region, the ALARP region and the acceptable region. The critical region is known for including hazards with a tremendous risk that should not ever be accepted, so it must be reduced at all cost. The ALARP region is defined as the region where the hazards must be studied, to find out if the cost of its reduction is economically justifiable or unjustifiable until a certain point, when compared to the obtained risk reduction. The acceptable region covers the hazards that represent a low consequence and frequency, so its reduction is not a priority, even though, it must not be neglected because the association of many of these hazards can lead to catastrophic accidents. In this work, the critical, ALARP and acceptable region, is defined respectively by the “red colour”, ”Yellow, orange and dark green colour” and “light green colour” (Table 2.3 and Table 2.4).

2.1. Survey Structure

To perform a qualitative, frequency, consequence and risk analysis, all the errors identified, were grouped according to Fig. 2 The qualitative study comprises five levels, and it is supported by the errors listed in Table 1 and Table 2. A survey with 20 design errors and 29 construction errors was put together, allowing the assessment of each error according to its frequency and consequence by experts in bridge design and construction. The survey is also prepared to put together errors that experts might think that are important to consider in future analysis.

![Survey Structure](Fig. 2. Survey Structure)
2.2. Analytic Hierarchy Process

A decision-making tool named AHP, which is based on linear algebra, was used to rank the results from the survey. The AHP is based on numerous pair-wise comparison between different objects, which is normally represented by a comparison matrix. From the comparison matrix, a ranking vector can be determined through the matrix eigenvector allowing the identification of the objects or, in this case, the errors with higher or lower frequency and consequence. To implement the AHP, a MATLAB algorithm was developed according to (Goepel, 2013), to overcome the high volume of information collected from the survey and to manage all the necessary matrix operation required by the AHP, which can be very exhaustive.

In cases such as surveys, where several participants can be involved, from the AHP a consensus index can be computed. The index ranges from 0%, when there is no consensus between the different decision makers, to 100%, when there is a full consensus among the decision makers. The quantification of this indicator is of utmost significance once it can support the claim of convergence in the identification of the errors with a higher or a lower frequency and consequence.

Table 1 Identification and ranking of Design Errors

<table>
<thead>
<tr>
<th>Errors Cluster</th>
<th>ID</th>
<th>List of Errors</th>
<th>PO</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Analysis and Design</td>
<td>1</td>
<td>Error due to a non-conservative arrangement between design and load regulations from different countries, leading to a less reliable structure</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Errors in regulations interpretation</td>
<td>9</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Error in live loads quantification due lack of data (wind, snow, seismic)</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Error in dead load quantification</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Error in the definition of the most significant load combinations</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Error defining the gravity centre for highly compressed elements, as arches, or defining load eccentricity in these elements</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Error defining a cross section shear centre (torsion effects)</td>
<td>7</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Error quantifying the deck displacement effects due to creep, shrinkage and temperature variation in columns, associated with 2nd order effects</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Error defining the buckling length of an element</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Error defining/describing the location of pre-stressing tendons</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Error in the decompression limit state calculation</td>
<td>14</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Error defining the pre-stressing hiperstatic effects</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>Error defining the soil-structure interaction (support conditions and differential settlements)</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Error due to lack of consideration of different structural systems that a bridge or an element will be subjected, through the construction process</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Error modelling the connections between structural elements as the deck, beam and column</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Detailing</td>
<td>16</td>
<td>Error due to lack of consistency in the design assumptions and the detailing rules</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>Error in reinforcement cross-section area</td>
<td>17</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>Error in reinforcement spacing (shear, transverse and longitudinal reinforcement)</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>Error in concrete and reinforcement classes indication</td>
<td>19</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Error defining the quota of implantation</td>
<td>6</td>
<td>13</td>
</tr>
</tbody>
</table>
The Table 1 and Table 2, list all the errors collected to create the survey and its respectively ranking position for frequency and consequence, obtained from the AHP. Another valuable aspect of the AHP is the fact that it allows the use of different weighting factors to enhance the influence of the input of different decision makers in the outcome. For instance, the informations given by a civil engineer with more professional experience should have more influence on the outcome, than the contribution of a civil engineer with less experience. Therefore, four weighting factors were used, according to the years of experience of each engineer, 1.0 (1-10 years), 1.5(10-20 years), 1.75 (20-30 years) and 2.0 (30-40 years).

Table 2. Identification and ranking of Construction Errors

<table>
<thead>
<tr>
<th>Errors Cluster</th>
<th>ID</th>
<th>List of Errors</th>
<th>FR</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Quality Control Errors</td>
<td>1</td>
<td>Errors leading to alkali-aggregate reaction</td>
<td>19</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Error in the quantification of cement hydration heat</td>
<td>18</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Error in the evaluation of aggregates humidity</td>
<td>13</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Error due to poor concrete workmanship leading to a concrete with characteristics and properties different from the requested</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>Reinforcement Errors</td>
<td>5</td>
<td>Errors leading to reinforcement corrosion</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Error using a wrong reinforcement class especially when different reinforcement classes are also used in construction</td>
<td>29</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Error related to reinforcement cross-section area</td>
<td>26</td>
<td>14</td>
</tr>
<tr>
<td>Execution Errors</td>
<td>8</td>
<td>Error due to wrong positioning of supports</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Error due to expansion joints deficiency and wrong positioning</td>
<td>3</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Error due to wrong interpretation of the design project</td>
<td>21</td>
<td>8</td>
</tr>
<tr>
<td>Generic Errors</td>
<td>11</td>
<td>Error in topographic implantation</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Error due to wrong concrete vibration</td>
<td>20</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>Error in the reinforcement cover</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Error in the longitudinal shape due to shrinkage and creep effects that were not correctly computed in the design project</td>
<td>9</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Error due to consideration of support conditions different from those defined in the design project</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>Error due to the establishment of wrong final support conditions</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>Error due to wrong evaluation of the foundation soil properties</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>Error due to geometric imperfections (inclination and cross section imperfection)</td>
<td>11</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>Error due to poor evaluation of the foundation soil properties of the scaffolds, and variation of these properties before different rainfall conditions</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Error due to poor preparation of the scaffold foundation using gravel material and/or poor positioning of the timber elements that support the scaffold</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>Error due to deficiency in the continuous scaffold bracing, leading to global instability</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>Error due to a deficient maintenance plan leading to poor scaffold material quality</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>Error in the scaffold clamping elements (connectors and couplers)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>Error in movable scaffolds due to non-controlled hyperstaticity reduction to perform his movement</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>Error in the assessment of the formwork and scaffold deformability properties</td>
<td>7</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>Error due to wrong positioning of formwork ties</td>
<td>17</td>
<td>21</td>
</tr>
<tr>
<td>Scaffolding Execution Errors</td>
<td>27</td>
<td>Error due to insufficient prestressing tension</td>
<td>28</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>Error due to over loss of prestressing tension</td>
<td>24</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>Error due to insufficient concrete curing, necessary, to bond the concrete with the prestressed steel by static friction (pre-tensioned concrete)</td>
<td>27</td>
<td>9</td>
</tr>
<tr>
<td>Prestressing Errors</td>
<td>27</td>
<td>Error due to insufficient prestressing tension</td>
<td>28</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>Error due to over loss of prestressing tension</td>
<td>24</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>Error due to insufficient concrete curing, necessary, to bond the concrete with the prestressed steel by static friction (pre-tensioned concrete)</td>
<td>27</td>
<td>9</td>
</tr>
</tbody>
</table>
2.3. Risk Analysis

After ranking the errors, it is important to determine those that represent a better relationship between the frequency and consequence, leading to the errors that represent higher risk. The AHP can be very tricky because during its numerical procedures there is a loss of information regarding the error magnitude, once after ranking the errors through the eigenvector of the comparison matrix, it is not known which are the qualitative level of the errors. On the other hand, a qualitative risk-based analysis that relies on a weighted geometric mean evaluation of the survey to determine the risk of an error can be inefficient since most of the errors will fall into the same qualitative level (see Table 3 and Table 4). Merging the AHP results and the qualitative risk analysis based on a weighted geometric mean evaluation, a better understanding of the errors risk and its magnitude shall be obtained. With the qualitative risk matrix, the qualitative risk level of each error is presented and for the errors with the same qualitative risk, relying on the AHP ranking, it is identified which one of them represents a higher risk. Let’s take the design errors with ID 7 and ID 8 in Table 3, for example. Both of them represent a high risk, but checking the AHP ranking it is observed that the error 8 has a better rank position for frequency (1 vs 8) and consequence (16 vs 18), therefore a higher risk.

Table 3. Risk Matrix for Design Errors

<table>
<thead>
<tr>
<th>DESIGN ERRORS RISK \ Frequency</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very Low</td>
</tr>
<tr>
<td>Very High</td>
<td>5</td>
</tr>
<tr>
<td>High</td>
<td>4</td>
</tr>
<tr>
<td>Average</td>
<td>3</td>
</tr>
<tr>
<td>Low</td>
<td>2</td>
</tr>
<tr>
<td>Very Low</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4. Risk Matrix for Construction Errors

<table>
<thead>
<tr>
<th>CONSTRUCTION ERRORS RISK \ Frequency</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very Low</td>
</tr>
<tr>
<td>Very High</td>
<td>5</td>
</tr>
<tr>
<td>High</td>
<td>4</td>
</tr>
<tr>
<td>Average</td>
<td>3</td>
</tr>
<tr>
<td>Low</td>
<td>2</td>
</tr>
<tr>
<td>Very Low</td>
<td>1</td>
</tr>
</tbody>
</table>

The used qualitative risk matrix (Table 3 and Table 4) was provided by a Portuguese construction company that has been working with risk management for a while. From the bibliography review, it was found different risk matrix, but this one was selected because of its direct relation to civil engineering risk management.

3. Discussion and Conclusions

1. The result of the AHP and the qualitative risk-based analysis, lead to conclude that in construction, some of the errors with higher risk are directly related to scaffolding and geotechnical issues (see Table 5). An interesting fact is that during the meetings, these were the ones that usually first came out as the errors with higher risk. Every risk analysis is reliant on a context, so it is important to know that the error list created was towards a girder bridge with 3 spans of 18, 27.8 and 18 meters with a column height of 13 meters. It is important to note that this typology reflects one of the most used typologies in road bridges in Portugal. The same approach on a suspended, arc or cable-stayed bridges, or even in girder bridges of other proportions, might lead to changes in the ranked errors, once the consequence and frequency magnitude can increase or decrease for different circumstances. The survey dissemination was performed through the COST Action TU1406 networking and the Portuguese engineers with a ranged professional experience from 5 to 40 years old.

2. The consensus index obtained from the AHP is about 87.16% for the design error and 73.40% for construction errors, which means that among the engineers the common awareness about design errors risks is higher than the construction errors risk, although the difference is not significant.
3. From the qualitative analysis, for the very low-risk category, no error was identified. It is believed that this is because of the prerequisite used in the identification of the errors. The errors list used in the survey already stand for those that may represent a higher risk.

4. At this point is important to say that this work was developed aiming the identification of damages on a structure caused by human errors with direct impact on the reliability of the structure. A hierarchy of the listed errors gives us also a clue of where should be put the efforts to increase the safety of structures, effectively. A better understanding of the human errors risk will allow a better-quality control plan to increase the safety of roadway bridges.

Table 5. Top five design and construction errors with higher risk

<table>
<thead>
<tr>
<th>Design Errors</th>
<th>Construction Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error due to lack of consideration of different structural systems that a bridge or an element will be subjected, through the construction process (ID = 14)</td>
<td>Error due to poor evaluation of the foundation soil properties of the scaffolds, and variation of these properties before different rainfall conditions (ID = 19)</td>
</tr>
<tr>
<td>Error modelling the connections between structural elements like deck, beam and column; (ID = 15)</td>
<td>Error due to deficiency in the continuous scaffold’s bracing leading to global instability (ID = 21)</td>
</tr>
<tr>
<td>Error due to lack of consistency in the design assumptions and the detailing rules (ID = 16)</td>
<td>Error due to wrong evaluation of the foundation soil properties (ID = 17)</td>
</tr>
<tr>
<td>Error defining the soil-structure interaction (support conditions and differential settlements) (ID = 13)</td>
<td>Error in the scaffold clamping elements (connectors and couplers) (ID = 23)</td>
</tr>
<tr>
<td>Error in reinforcement spacing (shear, transverse and longitudinal reinforcement) (ID = 18)</td>
<td>Error in movable scaffolds due to non-controlled hyperstaticity reduction needed to perform his movement (ID = 24)</td>
</tr>
</tbody>
</table>

4. Bibliography


HUMAN ERRORS AND CORRESPONDING RISKS IN REINFORCED CONCRETE BRIDGES

Neryvaldo Galvão – 1st PhD student at University of Minho, Portugal
José Matos – Professor at University of Minho, Portugal
Daniel Oliveira – Professor at University of Minho, Portugal
João Fernandes – 2nd PhD student at University of Minho, Portugal

27th – 28th September 2018
Barcelona, Spain
Design errors lead to the failure of the tower:
- Pre-stress insufficiency
- A low density of reinforcement
- Detailing error of the reinforcement
CONTEXTUALIZATION – BRIDGE COLLAPSE DATA BASE

Concrete Bridges Failure

- Design & expertise error of new objects
- Design & expertise error of repairs, demolitions
- Design, expertise, construction & supervise errors
- Construction & supervision error during repairs, demolitions
- Construction & supervision error during new building
- Managerial & organizational error during operation
- Inspection, testing error during operation
- Maintenance error
- Unpredictable case
- Infrastructure User's Error

Human Error 82%

Hazard Events and Misuse 18%
HUMAN ERROR

• The design and construction errors is a wide subject and when it comes to being defined specifically we can find ourselves very confused about its boundaries and how can we identify them in the complex conception process of a bridge;

• In order to clarify its domain several brainstorm meeting with experts were scheduled, leading to the identification of numerous human errors;

• Therefore the human errors are defined as design, construction and operation errors that are not beyond the engineering knowledge and occurred because of bad work conditions, miss guidance, and lack of oversight;
HUMAN ERROR SURVEY STRUCTURE

<table>
<thead>
<tr>
<th>Errors Cluster ID</th>
<th>List of Errors</th>
<th>Occurrence Probability</th>
<th>Consequences / Impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Very Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

1st Stage - Design Errors
2nd Stage - Construction Errors
3rd Stage - New Errors Identification

- With 20 Design Errors
- With 29 Construction Errors
- 14 New Design Errors
- 18 New Construction Errors

Professional Experience | Years
Construction | Design

Concrete
Reinforcement
Generic
Scaffolding Errors
Pre-stressing Errors
HUMAN ERROR RANKING

- The analytical hierarchy process (AHP) is a decision-making tool, based on linear algebra that through numerous pair-wise comparison between different objects allows the establishment of a comparison matrix;

- The Eigenvector of the comparison matrix allows the ranking of the compared objects;

- Using a Matlab script the AHP was implemented allowing to rank the Human errors;
### HUMAN ERROR RISK MATRIX

**Design Risk Matrix**

<table>
<thead>
<tr>
<th></th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very Low</td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td></td>
</tr>
<tr>
<td>Very High</td>
<td>5</td>
</tr>
<tr>
<td>High</td>
<td>4</td>
</tr>
<tr>
<td>Average</td>
<td>3</td>
</tr>
<tr>
<td>Low</td>
<td>2</td>
</tr>
<tr>
<td>Very Low</td>
<td>1</td>
</tr>
</tbody>
</table>

**Construction Risk Matrix**

<table>
<thead>
<tr>
<th></th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very Low</td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td></td>
</tr>
<tr>
<td>Very High</td>
<td>5</td>
</tr>
<tr>
<td>High</td>
<td>4</td>
</tr>
<tr>
<td>Average</td>
<td>3</td>
</tr>
<tr>
<td>Low</td>
<td>2</td>
</tr>
<tr>
<td>Very Low</td>
<td>1</td>
</tr>
<tr>
<td>Design Errors</td>
<td>Construction Errors</td>
</tr>
<tr>
<td>------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Error due to lack of consideration of different structural systems that a bridge or an element will be subjected, through the construction process;</td>
<td>Error due to poor evaluation of the foundation soil properties of the scaffolds, and variation of these properties before different rainfall conditions;</td>
</tr>
<tr>
<td>(Risk Level - V)</td>
<td>(Risk Level - V)</td>
</tr>
<tr>
<td>Error modelling the connections between structural elements like deck, beam and column;</td>
<td>Error due to deficiency in the continuous scaffold's bracing leading to global instability;</td>
</tr>
<tr>
<td>(Risk Level - IV)</td>
<td>(Risk Level - V)</td>
</tr>
<tr>
<td>Error due to lack of consistency in the design assumptions and the detailing rules;</td>
<td>Error due to wrong evaluation of the foundation soil properties;</td>
</tr>
<tr>
<td>(Risk Level - IV)</td>
<td>(Risk Level - IV)</td>
</tr>
<tr>
<td>Error defining the soil-structure interaction (support conditions and differential settlements);</td>
<td>Error in the scaffold clamping elements (connectors and couplers);</td>
</tr>
<tr>
<td>(Risk Level - IV)</td>
<td>(Risk Level - IV)</td>
</tr>
<tr>
<td>Error in reinforcement spacing (shear, transverse and longitudinal reinforcement);</td>
<td>Error in movable scaffolds due to non-controlled hyperstaticity reduction needed to perform his movement;</td>
</tr>
<tr>
<td>(Risk Level - IV)</td>
<td>(Risk Level - IV)</td>
</tr>
</tbody>
</table>
DISCUSSION AND CONCLUSION

• In construction, the errors with higher risk are directly related to scaffolding and geotechnical issues;

• The consensus index obtained from the AHP is about 87.16% for the design error and 73.40% for construction errors;

• For the very low-risk category, no error was identified which means that the errors list used in the survey, already stand for those that represent higher risks;

• Most of the errors listed fall into the ALARP region, which means that the relation between the risk and its reduction costs should be assessed;
THANK YOU FOR YOUR ATTENTION!
WWW.TU1406.EU
QUALITY CONTROL, INFRASTRUCTURE MANAGEMENT SYSTEMS AND THEIR IMPLEMENTATION IN MEDIUM-SIZE HIGHWAY NETWORKS

Flora Faleschini - University of Padova, Italy
Mariano Angelo Zanini - University of Padova, Italy
Carlo Pellegrino - University of Padova, Italy
Quality control, infrastructure management systems and their implementation in medium-size highway networks

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¹,²,³University of Padova, Dept. of Civil, Environmental and Architectural Engineering, Via Marzolo 9, 35131 Padova, Italy

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Abstract. Bridge maintenance is a key issue in deteriorating infrastructure systems. The present work aims to illustrate the real perception of such topic in the Italian context, and describing bridge maintenance practices currently in use among roadway infrastructure owners in Italy. Furthermore, an in-depth description of the activities related to the development of Bridge Management Systems for reliable Quality Control at the University of Padova - Department of Civil, Environmental and Architecture Engineering (UNIPD) is outlined. In the final part of the work, some results coming from the application of the tools developed at UNIPD and applied on an existing infrastructure asset belonging to a medium-size highway network located in the North-Eastern part of Italy are presented.

Keywords: bridge management; deterioration; performance indicators; quality control; visual inspections.

1 Introduction

Bridges are usually subject to deterioration depending on several factors e.g. environmental condition, natural aging, quality of the material, and planned maintenance. These structures are the most highly exposed to deterioration induced by harsh climatic conditions, aging, and increased volumes and weights of traffic axle loads. Greater demand to improve the management protocols for bridges is becoming increasingly evident. Many road managing authorities have made significant efforts to develop bridge management systems (BMSs) (Zonta et al. 2007, Pellegrino et al. 2011). A BMS is a systematic method through which a public authority can manage all the activities related to maintenance of its bridge assets, to optimize their life-cycle management and avoid any kind of damage or out-of-service situation, which could involve severe indirect losses to infrastructure users. Several BMSs have been developed over the years: examples can be found in Thoft-Christensen (1995), Markow (1995) and Kitada et al. (2000). During the last decade, several research projects focusing on management at network level of existing bridges have been financed by the European Commission and corresponding guidelines have been produced (BR.I.M.E. (2001), COST345 (2004), SA.MA.R.I.S. (2005) and Sustainable Bridges (2006)). In currently available BMSs, decision-making mainly depends on combined quantitative/qualitative information coming from in-situ investigations and visual inspections. Natural aging cannot be considered the unique source of damage, since in many situations other different kinds of natural or anthropic hazards - like earthquakes, floods, tsunamis, vehicle collisions - might severely affect the stability of existing bridges. In addition, the combined effect of deterioration with such hazards can lead to premature failures (Zanini et al. 2013). Past experience has shown how, during their lifetime, bridges undergo structural problems due to environmental conditions and natural disasters: concrete cover damage exposes bars to the atmosphere, steel may become corroded by freezing/thawing cycles, and aging of structural materials are some of the causes leading to degradation of the mechanical properties of reinforced concrete (Biondini et al. 2014), thus amplifying the effects of earthquakes and increasing the risk of seismic damage (Franchin et al. 2006; Morbin et al. 2015). It is therefore relevant to perform surveillance and to promptly carry out retrofit measures aimed at strengthening structurally deficient bridges in order to avoid failures and related socio-economic impacts. In the present work, issues related to the development of rational maintenance programs are addressed looking at the Italian context and current practices, and illustrating the regulatory framework, the state-of-art of the implementation of BMSs, describing research on this field carried out at UNIPD and finally presenting, as virtuous example, the long-term bridge surveillance program of Concessioni Autostradali Venete S.p.A., a medium-size highway concessionaire company of northeastern Italy.
2 The Italian context: legislative prescriptions and state-of-art on BMSs

In Italy there is a substantial lack of clear regulatory prescriptions on the maintenance activities to be carried out by infrastructure owners in order to guarantee an adequate structural safety level for existing bridges. The first indication can be found in the Ministerial Circular 6736/61A1 (1967), in which it is evidenced the issue of a proper maintenance to be carried out in order to preserve structures over time. After more than two decades, the Ministerial Circular 34233 (1991) provided rough suggestions on frequency and types of inspections, highlighting how managing authorities should plan a periodic assessment of the static conditions with a frequency - arbitrarily defined by the owner - also in relation to the specific importance of a bridge with respect to the network to which it belongs. An interesting manual devoted to the maintenance of railway bridges (Istruzione 44C, 1994) was approved in 1994, reporting a wide series of defects that can be detected on steel, reinforced concrete and masonry bridges during a visual survey. Istruzione 44C (1994) gives in addition precise indications on how to rate them and to use ratings for the subsequent calculation of a health indicator at structure level, useful for priority ranking purposes. In recent years, new National Building Codes were approved in 2008 (NTC2008, actually replaced by NTC2018), where issues related to maintenance actions are slightly mentioned in the chapter related to existing structures, suggesting to take into account the quality and the state of maintenance of the materials and components of an existing structure, but without providing clear prescriptions on frequency and types of inspections. However, an interesting document was enacted by the Autonomous Province of Bozen (2011), inspired by German (DIN1076) and Austrian (RVS 2011) regulations, which defines 4 types of inspections, providing clear indications on frequency, activities to be carried out, how and to perform them and which type of technician has to be involved, and contents of the reports.

In Italy, most of bridges were built in between 1960-1980, when the infrastructure roadway and highway networks were characterized by an exponential growth, and the design philosophy was more focused in developing novel construction practices and design approaches than to take into account issues related to long-term behavior of structures, including in the design insights related to aging, sustainability and life cycle costs (LCC) analyses, as nowadays in many parts of the world.

In addition, the actual administrative configuration is fragmentary: highways are mainly managed by different private concessionaire companies, that should be subject to periodic audits by the Italian Ministry of Infrastructure, whereas, as regards roadways, are mainly managed by public administrations at regional, provincial, and municipal level.

The combination of such factors, i.e. the absence of a clear regulatory framework for maintenance activities, aging bridges with an average service life of 40-60 years and designed with poor detailing with respect to maintenance issues, and administrative fragmentation in the management of infrastructure systems, constitute an issue of national relevance that can no more be postponed and need urgent measures to be implemented over the entire territory. The awareness of this huge issue has been exponentially increased over the recent years, also due to a series of relevant bridge failures (Figure 1).

Fig. 1. Examples of recent bridge failures in Italy (2014 – 2017).
In addition to aging phenomena, many bridges were designed without stringent prescriptions with respect to seismic actions and therefore can undergo to brittle failures when infrastructure networks are hit by earthquakes, affecting public safety and interrupting vital lifelines.

Actually, each concessionaire company handles maintenance activities without a common standardization, and BMSs are mainly based on visual inspection data and subsequent processing with the aim to define a priority ranking. However, ratings are assigned using qualitative performance indicators without a specific relationship with quantitative measures (e.g. reliability), and in addition, BMSs lack the use of prediction models based on probabilistic-models to forecast future deterioration scenarios.

3 Procedures for the deterioration and seismic vulnerability assessment of bridges developed at UNIPD

Two specific procedures for the deterioration state evaluation and the seismic vulnerability assessment of bridge structures have been developed at UNIPD with the aim to enclose them in a BMS environment. The procedure for bridge qualitative deterioration assessment proposed by Zanini et al. (2017), based on a refinement of the original one proposed by Pellegrino et al. (2011) was adopted here, with improvements taking into account the costs of maintenance operations. A brief description of the method, improved with the part related to costs, is given below. The inspection system used is the visual survey method, according to the standards adopted by countries (BR.I.M.E. 2001, NTCs2008). Visual inspections can be carried out on main structural and non-structural elements of bridges, to assess their condition without the need for special equipment or restrictions on traffic flow. The method defines the Total Sufficiency Rating (TSR) parameter, a global qualitative indicator of the "state of health" of each bridge. Figure 2 shows a general overview of the TSR assessment framework.

Calculation of TSR involves a specific algorithm, based on the definition of the Condition Value (CV) of each element composing the bridge under analysis. The CV is a qualitative variable, representing a condition related to a precise group of defects of the element for which it is estimated. A CV value ranging from 1 to 5 can be defined.
for every element of a bridge; if no evaluation can be expressed, CV is assumed to be zero. In this specific procedure, CV is defined through a multi-criteria decision analysis (MCDA) based on the assessment of the set of defects detected on each element. In this way, the inspector verifies the potential presence and extent of a list of defects, specifically defined for each structural element and construction material, leading to a univocal value of CV for each bridge element, computed through the MCDA. Once a CV for each visible element has been defined, specific Condition Factor (CF), Location Factor (LF) and Weight (W) are examined, to assign a different significance to each bridge element, in relation to its importance in defining the TSR. All such parameters are summarized in the TSR index, which takes into account deterioration on each element and at the same time its relative importance on a bridge.

Regarding seismic vulnerability assessment, the procedure adopted is described in Pellegrino et al. (2014) but is integrated here with a section concerning seismic retrofit intervention protocols and related costs. The particular vulnerabilities of the structural elements constituting masonry/stone arch bridges - arches, spandrel walls, piers, abutments and foundations - were studied in depth. For each masonry or RC/PRC bridge, the minimum safety factor value $F_{C_{i,\text{min}}}$ (of those calculated) was assumed to represent the main seismic vulnerability indicator for each structure, since it is related to the governing failure mode in the case of a seismic event.

Such procedures were used for the calibration of cost models, based on results derived by the assessment of maintenance state and seismic vulnerability for common road bridge types. Figure 3 shows a general overview of the key points of the cost model analysis calibrated from a stock of bridges in the district of Vicenza, North-East Italy. Cost values used for the calibration of the models partly derived from estimations retrieved in seismic retrofit projects by structural engineers (about 35% of cases) and the real costs of operations by contractors (45%), if available. As these data were not available for all the bridges in the stock analyzed here, estimations were made by the authors (20%) according to official prices given by the managing authorities (the usual approach of practicing engineers). Seismic retrofit costs were estimated for each bridge, characterized by a $F_{C_{i,\text{min}}}$ value lower than 1, as the sum of the seismic retrofit costs of each component specifically calculated for each bridge.
decreasing linear relationship with $F_{C_{\text{min}}}$ was identified and compared with guidelines provided by the Italian OPCM 3362/04 (2004) model. Lastly, significant correlations were detected between $TSR$ and $UTC$s. The proposed formulations allow public authorities and private managing companies to estimate economic indicators, to be able to evaluate the resources required to manage both maintenance of bridges and their seismic retrofit.

4 Application to a medium-size highway network in northeastern Italy

Some of the above procedures are currently applied and are being updated on a real bridge stock in the framework of an agreement between the Department of Civil, Environmental and Architectural Engineering of the University of Padova and the highway authority Concessioni Autostradali Venete S.p.A., which manages about 150km of highways between the cities of Padova, Venice and Treviso. Figure 4 illustrates a portrait of the managed bridges.

5 Conclusions

The present paper briefly outlined the perception of issues related to quality control of road and highway infrastructure in the Italian context. Furthermore, an in-depth description of the activities related to the development of BMS at the University of Padova - Department of Civil, Environmental and Architecture Engineering was illustrated. Although the need to adequately manage an aging roadway network such as that in the Italian context is of upmost importance, and the perception of this urgency is growing fast after recent tragic failures occurred in the last years, a gap of national guidelines and regulation is still evident. Some virtuous examples of managing authorities that are developing long-term bridge surveillance programs however exist. Here, as indicative example, some results coming from the application of the tools developed at UNIPD and applied on an existing infrastructure asset belonging to a medium-size highway network located in the North-Eastern part of Italy are presented.
Acknowledgements
The authors would thank Concessioni Autostradali Venete S.p.A. who founded the development of part of the procedures described above.

References
Autonomous Province of Bozen (2011) Disposizioni tecniche sul collaudo e sul controllo statico e periodico dei ponti stradali (in Italian).
QUALITY CONTROL, INFRASTRUCTURE MANAGEMENT SYSTEMS AND THEIR IMPLEMENTATION IN MEDIUM-SIZE HIGHWAY NETWORKS

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Mariano Angelo Zanini - University of Padova, Italy
Carlo Pellegrino - University of Padova, Italy

27th – 28th September 2018
Barcelona, Spain
INTRODUCTION

• Bridge maintenance is a key issue in deteriorating infrastructure systems.
• The present work aims to illustrate the real perception of such topic in the Italian context, and describing bridge maintenance practices currently in use between roadway infrastructure owners in Italy.
• Furthermore, an in-depth description of the activities related to the development of Bridge Management Systems for reliable Quality Control at the University of Padova - Department of Civil, Environmental and Architecture Engineering is outlined.
• In the final part of the work, some results coming from the application of the tools developed at UNIPD and applied on an existing infrastructure asset belonging to a medium-size highway network located in the North-Eastern part of Italy are presented.
Which are the main aims of an infrastructure owner?
- To ensure adequate safety levels for road users
- And at the same time, To minimize infrastructure management costs
INTRODUCTION

... and with reference to bridges?
- To ensure adequate structural reliability levels, both in case of latent (i.e. ageing) and sudden (i.e. natural hazards) events.
- To optimize budget allocation for maintenance actions and rationally plan them on the basis of results coming from a BMSs
- To minimize the impact of such interventions on infrastructure functionality
INTRODUCTION

... however, many Italian bridges are structurally deficient due to advanced deterioration phenomena...
INTRODUCTION

... however, many Italian bridges are structurally deficient due to advanced deterioration phenomena...
INTRODUCTION

… however, many Italian bridges are structurally deficient due to advanced deterioration phenomena…

…that over time may result in bridge failures!

Bridge failures can be related to lack of maintenance, design without taking care of suitable detailing, occurrence of natural hazards like floods, earthquakes, landslides…

Looking at the Italian history of bridge failures in the last 10 years…
RECENT BRIDGE FAILURES IN ITALY

Tramonti di Sopra (UD) – 15/12/2004
RECENT BRIDGE FAILURES IN ITALY

Fossa (AQ) – 06/04/2009

EARTHQUAKE
RECENT BRIDGE FAILURES IN ITALY

San Rocco (PC) – 30/04/2009

FLOOD
RECENT BRIDGE FAILURES IN ITALY

Bridge over Cesano river (AN) – 01/03/2011
RECENT BRIDGE FAILURES IN ITALY

Finale Emilia (MO) – 20/05/2012

EARTHQUAKE
RECENT BRIDGE FAILURES IN ITALY

Ribera (AG) – 02/02/2013

https://youtu.be/2dikgtA6m0
RECENT BRIDGE FAILURES IN ITALY

Carasco (GE) – 22/10/2013
RECENT BRIDGE FAILURES IN ITALY

Oloè (NU) – 18/11/2013

FLOOD
RECENT BRIDGE FAILURES IN ITALY

Norgheri (NU) – 18/11/2013
RECENT BRIDGE FAILURES IN ITALY

Rubbianello (AP) – 02/12/2013

FLOOD
RECENT BRIDGE FAILURES IN ITALY

SS Palermo-Agrigento – 07/07/2014

AGEING
RECENT BRIDGE FAILURES IN ITALY

SS Palermo-Agrigento – 23/12/2014
RECENT BRIDGE FAILURES IN ITALY

Mormanno (RC) – 02/03/2015

WRONG MAINTENANCE
RECENT BRIDGE FAILURES IN ITALY

Scillato (CT) – 10/04/2015
RECENT BRIDGE FAILURES IN ITALY

Casalduni (BN) – 15/10/2015

FLOOD
RECENT BRIDGE FAILURES IN ITALY

Bruzzano Zeffirio (RC) – 02/11/2015

FLOOD
RECENT BRIDGE FAILURES IN ITALY

Amatrice (RI) – 24/08/2016
RECENT BRIDGE FAILURES IN ITALY

Annone Brianza (LC) – 28/10/2016
RECENT BRIDGE FAILURES IN ITALY

Camerano (AN) – 09/03/2017

WRONG MAINTENANCE
RECENT BRIDGE FAILURES IN ITALY

Fossano (CN) – 19/04/2017
RECENT BRIDGE FAILURES IN ITALY

Genova – 14/08/2018

AGEING
RECENT BRIDGE FAILURES IN ITALY

Genova – 14/08/2018
RECENT BRIDGE FAILURES IN ITALY

Genova – 14/08/2018
RECENT BRIDGE FAILURES IN ITALY

Genova – 14/08/2018

[Diagram showing details of a bridge failure]
RECENT BRIDGE FAILURES IN ITALY

Genova – 14/08/2018
In Italy there is a substantial lack of clear regulatory prescriptions on the maintenance activities to be carried out by infrastructure owners in order to guarantee and adequate structural safety level for existing bridges.

- The first indication can be found in the Ministerial Circular 6736/61A1 (1967) in which it is evidenced the issue of a proper maintenance to be carried out in order to preserve structures over time.
- After more than two decades, the Ministerial Circular 34233 (1991) provided rough suggestions on frequency and types of inspections, highlighting how managing authorities should plan a periodic assessment of the static conditions with a frequency arbitrarily defined by the owner also in relation to the specific importance of a bridge with respect to the network to which it belongs.
THE REGULATORY FRAMEWORK IN ITALY

• An interesting manual devoted to the maintenance of railway bridges (Istruzione 44C, 1994) was approved in 1994, reporting a wide series of defects that can be detected on steel, reinforced concrete and masonry bridges during a visual survey.

• Istruzione 44C (1994) gives in addition precise indications on how to rate them and to use ratings for the subsequent calculation of a health indicator at structure level useful for priority ranking purposes.
In recent years, new National Building Codes were approved in 2008 (NTC2008, actually to be replaced by NTC2018), where issues related to maintenance actions are slightly mentioned in the chapter related to existing structures, suggesting to take into account the quality and the state of maintenance of the materials and components of an existing structure, but without providing clear prescriptions on frequency and types of inspections.

However, an interesting document was enacted by the Autonomous Province of Bozen (2011), inspired by German (DIN1076) and Austrian (RVS 2011) regulations, which defines 4 types of inspections, providing clear indications on frequency, activities to be carried out, how and to perform them and which type of technician has to be involved, and contents of the reports.
THE REGULATORY FRAMEWORK IN ITALY

- A summary of the indications provided by the codes.

- 4 main types of inspections are classified, indicating frequencies, who has to do it, how to do it, what to look for, and how to report survey outcomes.
The 4 types of inspections mentioned are:

- **Fast survey**: daily, without reporting, only to check if all is ok.

- **Surveillance inspection**: every 3 months, with a simple reporting.

- **Simple inspection**: every 2/3 years, visual survey with condition assessment rating and reporting with photos and notes.

- **Complex inspection**: every 6 years, visual survey with condition assessment rating and reporting with photos and notes, in-situ survey for characterizing materials. Frequency of such types of inspections can be set by the infrastructure owner also on the basis of structural assessment carried out by structural engineers.

- **Special inspection**: visual survey after the occurrence of a natural/antropic hazardous event (e.g. flood, earthquake, landslide, tornado, explosion, collision, fire)
THE REGULATORY FRAMEWORK IN ITALY

However, failures and progression of ageing and deterioration is allowed mainly due:

• Lack of reliable information about many bridges and viaducts;

• Lack of a rational surveillance and maintenance planning;

• Lack of financial funds to periodically perform visual surveys and subsequent tests for improving the level of knowledge of existing bridges;

• Underestimation of risks related to bridge failures or reduced functionality levels;

• Lack of a culture of prevention, often emergencies are the triggers.
In addition, the actual administrative configuration is fragmentary: highways are mainly managed by different private concessionaire companies, that should be subject to periodic audits by the Italian Ministry of Infrastructure.
ADMISTRATIVE CONFIGURATION IN ITALY

Highways
Motorways
As regards roadways, are mainly managed by public administrations at regional, provincial, and municipal level.

Autostrade in gestione diretta: 939,354 Km
Raccordi autostradali: 355,101 Km
Strade Statali: 20,676,266 Km
Strade in corso di classifica o declassifica (NSA): 485,713 Km
Svincoli e Complanari: 4,831,771 Km
INFRASTRUCTURE MANAGEMENT IN ITALY: AN ISSUE OF RELEVANT CONCERN

- The combination of such factors, i.e. absence of a clear regulatory framework for maintenance activities, ageing bridges with an average service life of 40-60 years and designed with poor detailing with respect to maintenance issues, and administrative fragmentation in the management of infrastructure systems, constitute an issue of national relevance that can no more postponed and need urgent measures to be implemented over the entire territory.

- In addition to ageing phenomena, many bridges were designed without stringent prescriptions with respect to seismic actions and therefore can undergo to brittle failures when infrastructure networks are hit by earthquakes, affecting public safety and interrupting vital lifelines.
Actually, each concessionaire company handles maintenance activities without a common standardization, and BMSs are mainly based on visual inspection data and subsequent processing with the aim to define a priority ranking.

However, ratings are assigned using qualitative performance indicators without a specific relationship with quantitative measures (e.g. reliability).

BMSs lack the use of prediction models based on probabilistic models to forecast future deterioration scenarios.

No preliminary cost estimations are automatically carried out in order to support decision making.

Lack of any systematic consideration of other impacts like environmental, social, etc.
BMS DEVELOPMENT @ UNIPD

- When dealing with the management of medium-to-large size bridge portfolios, visual inspections – if properly performed - can be a cost-effective solution.
- How to rank bridges for maintenance planning purposes?

At component level

1. Defect detection
2. Multi-Criteria Decision Analysis
3. Condition Value

Performance Indicator

Performance Goal
BMS DEVELOPMENT @ UNIPD

- The first step is defect detection based on visual inspection survey.
- Defects are classified according to a specific defect database.
- Both structural and non-structural elements are evaluated.
- Technicians are trained with a theoretical and practical course aimed to reduce the subjectivity in their evaluation.

At component level
At component level

Performance Indicator

<table>
<thead>
<tr>
<th>Description of defects</th>
<th>Severity</th>
<th>Condition Value (CV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1, C2, C3, C4, C5, C6, C9</td>
<td>no present</td>
<td>0</td>
</tr>
<tr>
<td>C1, C2, C3, C4, C5, C6, C9</td>
<td>25% - 50%</td>
<td>1</td>
</tr>
<tr>
<td>C1, C2, C3, C4, C5, C6, C9</td>
<td>&gt; 50%</td>
<td>2</td>
</tr>
<tr>
<td>C1, C2, C3, C4, C5, C6, C9</td>
<td>severe defects</td>
<td>3</td>
</tr>
<tr>
<td>C1, C2, C3, C4, C5, C6, C9</td>
<td>non-functional element</td>
<td>5</td>
</tr>
</tbody>
</table>

For each structural/non-structural bridge element observed defects are converted into a specific Condition Value (CV) through the application of Multi-Criteria Decision Analysis.
**BMS DEVELOPMENT @ UNIPD**

- **CVs** are condensed in a global qualitative indicator *TSR* as:

**At system level**

**Performance Indicator**

Element Weights $W_i$

**Performance Goal**

\[
TSR = \frac{\left[TSR_{REALE} \sum_{i=1}^{n} W_i + TSR_{NV} (\sum_{i=1}^{n} W_i - \sum_{i=1}^{t} W_i)\right]}{\sum_{i=1}^{n} W_i}
\]

\[
TSR_{REALE} = \frac{\text{PF}\left(\sum_{i=1}^{n} CF_i W_i\right)}{\sum_{i=1}^{n} W_i}
\]

\[
TSR_{NV} = \frac{\text{PF}\left(\sum_{i=1}^{n-t} CF_i W_i\right)}{\sum_{i=1}^{n-t} W_i}
\]

BMS DEVELOPMENT @ UNIPD

At network level, performance goals are represented by intervention urgency ($TSR$) and restoration costs.
BMS DEVELOPMENT @ UNIPD

- Visual inspection data are useful also for deterioration forecasts.
BMS DEVELOPMENT @ UNIPD

- Information on time intervals between consequent inspections and related CVs are stored in datasets.
- For each element it is possible to define deterioration curves updated when new data are available.
BMS DEVELOPMENT @ UNIPD

- $TSR$ scenario forecasts for planning maintenance.
BMS DEVELOPMENT @ UNIPD

- A cost model was calibrated on the basis of TSR and simplified seismic vulnerability assessment of a stock of bridges in North-Eastern Italy.
- Restoration protocols have been defined for each CV and bridge element based on available data.

\[
\text{State } \#1, \#2 \\
UTC = UMCs_{HE} + USRC
\]

\[
\text{State } \#3, \#4 \\
UTC = UMCs_{HE} + UMCs_{VE}
\]


BMS DEVELOPMENT @ UNIPD

BMS DEVELOPMENT @ UNIPD

UNIPD & CAV

Agreement with UNIPD and Concessioni Autostradali Venete S.p.A. for the development of an integrated Bridge Management System.
Concessioni Autostradali Venete S.p.A. manages one of the oldest highways built in Italy (first opening in October 15, 1933).
UNIPD & CAV

- Web application for CAV BMS for 130 bridges.
UNIPD & CAV

- Web application for CAV BMS: inventory
UNIPD & CAV

- Web application for CAV BMS: inventory
UNIPD & CAV

- Web application for CAV BMS: inspection schemes
UNIPD & CAV

- Web application for CAV BMS: inspection schemes

Pier and abutment IDs

Bearing and joint IDs
UNIPD & CAV

- Web application for CAV BMS: visual inspections
UNIPD & CAV

- Web application for CAV BMS: asset priority ranking
UNIPD & CAV

Next steps:

• Implementation of deterioration model to forecast ageing;

• Seismic and flood structural assessment;

• Structural Health Monitoring for most important bridges;

• Evaluation of environmental impacts.
Thank you for your attention!

Contact:
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THANK YOU FOR YOUR ATTENTION!

WWW.TU1406.EU
Quality control of roadway bridges  
– Reliability assessment –

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Jose Matos – University of Minho, Portugal
QUALITY CONTROL OF ROADWAY BRIDGES – RELIABILITY ASSESSMENT

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Abstract. The elaboration of adequate quality control plans is one of the crucial tasks in bridge management today. This is the topic of the ongoing COST TU1406 action, where it is proposed to control quality focus by means of key performance indicators. To this date, the qualitative methodology for the assessment of the indicators is suggested, with a framework that can be upgraded to a full quantitative approach in future. The methodology is envisioned to enhance current management practices, which predominantly rely on visual inspections, and use only the essential data from bridge inventory and inspections for decision-making. The pivotal key performance indicator is suggested to be reliability, the assessment of which is performed for likely bridge failure modes. Here, it is required to include the impact of physical features (e.g. damages, symptoms) observed in inspections, especially those which may considerably affect the reliability. The two approaches suggested within COST Working Group 3 report to assess the reliability and the possibilities for their application in practice are presented in this paper.

Keywords: Quality control, Key Performance indicators, Reliability, Bayesian net, Vulnerable zones, Failure modes.

1. Introduction

The majority of current bridge quality control procedures are solely based on the results of visual inspections. The results are used to evaluate a qualitative performance indicator, i.e. a condition rating/state, which is used to roughly define necessary maintenance interventions and their urgency. However, in the face of the increasing traffic volume and loading, decreasing budget as well as the climate change, existing bridges are in need of more comprehensive approaches to assess their performance over the entire service life and provide timely and affordable, i.e. optimal maintenance. Here, there is a need to reduce subjectivity and perhaps overly conservative rules in the current practice. Recognizing the value of inspections and condition rating, the methodology is introduced to use this information to estimate key performance indicators (KPI) with the focus on the reliability related to structural safety and serviceability.

Within the COST Action 1406, the Working Group 1 (WG1) performed a survey for performance indicators (PI) which are applied in European countries (Strauss & Manić Ivanković, 2016). Further, in the Working Group 2 (WG2) report (Stipanovic, et al., 2017), the performance goals and key performance indicators (KPIs) based on the Dutch RAMSSHEEP approach (Rijkswaterstaat, 2012) were defined. Finally, the Working group 3 (WG3) proposed a framework (Hajdin, et al., 2018) aimed at establishment of standardized quality control plans for European bridge management practice. The suggested qualitative methodology is based on the application of KPIs: Reliability, Availability, Safety, Economy and Environment, with a possibility for an upgrade to a full quantitative approach. The widely recognized indicator is Reliability as it accounts for structural safety and serviceability. In order to evaluate it, all relevant information from inventory and inspections must be considered and coupled with engineering judgement. The latter is based on the knowledge on possible bridge failure modes and their vulnerable zones i.e. parts/segments of a bridge where damages have the most significant impact on the bridge performance.

The paper discusses the two approaches suggested by WG3 to evaluate the KPI of Reliability and further include the results of inspections to update its value. To tailor the approaches to their own needs with respect to the bridges in national networks and currently available inventory and inspection data is left to the owners/operators.

2. Approach in the COST TU1406 Working Group 3

The ontology of the Working Group 3 (WG3) framework has been presented in Figure 1 in a form of an Entity Relationship Diagram (ERD). Here, the “crow foot” symbolizes one-to-many relationship whereas the “crow foot with a circle” stands for one-to-zero or one-to-many relationships. Firstly, the definitions of the main entities are given, which is followed by the explanation of the ERD.
The entity “Structure” includes bridge types (e.g. a girder, a frame and an arch bridge) and the entity “Element” all element types (e.g. beams, decks, piers). In the entity group “Inventory”, there can be other entities apart from “Construction type” such as “Geometry” and “Construction method”. The entity “Design and construction” include several other entities related to original design such as construction year, design loads, soil characteristics, etc.

The entity “Observation” relates to a perception of human senses or data measured by instrument that is regarded as relevant within the context of the inquiry (e.g. damages and geometry changes). Observations can be qualitative i.e. only the absence or presence of a property is noted, or quantitative, if a numerical value is coupled to the observed phenomenon by counting or measuring. The “Performance indicator“ (PI) is related to measuring the fitness for purpose of a bridge or its element. Thus, the difference between observations and PIs is that the first are “just the fact” and the latter is already an interpretation of its impact on a bridge performance.

![Diagram of WG3 framework ontology](image)

Generally, there is no clear distinction between PIs and KPIs. In the WG3, the KPI of Reliability is defined as the probability that a bridge will be fit for purpose during its service life, complementary to the probability of structural failure (safety), operational failure (serviceability) or any other failure mode.

The “Failure modes” represent quasi-permanent or transient situations that violate code specifications or owner’s/ operator’s provisions. This includes but is not limited to overall bridge collapse. Some of these situations, e.g. Ultimate Limit State (ULS) and Serviceability Limit State (SLS), are specified in bridge design. Due to slow (deterioration) and sudden (e.g. natural hazard) processes, damages may occur that result in additional failure modes. Finally, owners/operators may define situations (e.g. spalling, corrosion traces, etc.) that are regarded as failure modes since they might comprise public perception of safety and owner’s/operator’s reputation.

The “Vulnerable zones” are those segments and/or elements of a bridge structure in which damages have the largest impact on safety and serviceability. One vulnerable zone may be related to several failure modes. The damages outside vulnerable zones can also trigger failures, but for them to occur the extent of damages need to be significantly larger than in the vulnerable zones. If this seems likely, one needs to define an additional failure mode that can be triggered by the observed damages.

The diagram in Figure 1. can be interpreted as follows: there is an observation (e.g. a crack) with a certain property (e.g. a crack width), on an element of a certain type (e.g. a beam), with the location in a vulnerable zone that is related to a specific failure mode of a structure. With an influence of other data (e.g. the construction year), this observation will have an impact on a KPI expressed by a performance value. The damage process is derived based on observations and on original design and construction data. It governs the development of the observed damages in the future and allows a forecast of the KPIs. The decision is up to owner/operator how to combine different failure modes in the evaluation of a KPI. For instance, a certain crack width can be chosen to be a failure criterion as it affects serviceability, but this failure mode cannot be rationally combined with those failure modes related to structural safety (i.e. collapse), as an adequate consequence analysis is necessary (i.e. a risk-based approach). Alternatively, an owner/operator can introduce own performance thresholds and assessment procedures (e.g. a weighted sum) to distinguish failure mode type importance in structuring of a quality control plan, which is again, implicitly risk-based approach.

3. The simplified evaluation of the „virgin“ reliability

The partial safety factors in modern codes are calibrated to satisfy the reliability requirements (safety and serviceability). According to (CEN EN 1990, 2002), non-landmark bridges are in RC2 class which have the target annual reliability index for structural safety of 4.7 (occurrence probability of 1.3 \(10^{-6}\)) and for serviceability 2.9 (occurrence probability of 1.9 \(10^{-3}\)). The bridge is considered as safe and serviceable if specified reliability indexes are not below these target values. The assessment of the reliability of existing bridges can be tedious task as there is a need to model all actions and material properties as stochastic variables. But, based on experience and available data, a simplified assessment can be performed.

The “virgin” reliability is obtained as the reliability of an undamaged bridge for the resistance based on the original codes and the live load actions from the current codes. The original design load situation thus is used to assess the characteristic value of resistance against the chosen failure mode. The mathematical distributions for the self-weight as well as for other loading actions can be derived based on percentile assumption of their characteristic values following the recommendations from literature, e.g. (JCSS, 2013). The traffic load is normally modelled by extreme distributions (e.g. Gumbel max), which is supported by measurements and simulation performed within research project all over the
world, e.g. (Freundt & Bönning, 2011) and (Caprani, 2013). Even for the most complex systems, the load effect can be determined on the simplified structural system i.e. simply supported beam and the reliability index can be easily computed. This approach is widely used for load rating.

The value of reliability obtained in this manner can be regarded as a rough estimate but sufficient for decision making. These results can be improved if reliability analyses would be performed on the relevant sample of bridges of same type. Herein, the known errors in some bygone codes e.g. regarding shear capacity, should be duly considered. Also, the known conceptual weaknesses and detailing issues for certain bridge systems (e.g. Gerber hinge) should be accounted as well.

4. The qualitative approach to assessment of KPI Reliability - the reliability curves

For structures of a similar system, structural type and cross section type, reliability curves can be elaborated (e.g. Figure 3) with respect to a similar/same dominant failure mode. These curves show the influence of a resistance reduction in the section which governs the failure mode, on the reliability index and probability of failure.

![Reliability index and probability of failure](image)

**Fig. 2. An example of KPI Reliability assessment using reliability curves, from (Hajdin, et al., 2018)**

Following the principle explained in the previous section, virgin reliability index is evaluated for an investigated bridge and this is a starting point on the reliability curve (Fig. 2). An update in terms of the resistance reduction, based on an inspection and experience, can be used to assess the KPI of Reliability. Here, a qualitative Reliability rating can be related to the quantitative results (see Table 1).

<table>
<thead>
<tr>
<th>Reliability index</th>
<th>Quantitative scale (β)</th>
<th>Urgency of intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&gt; 4.00</td>
<td>Regular inspection</td>
</tr>
<tr>
<td>2</td>
<td>3.25-4.00</td>
<td>Reassessment should be performed to update the period between inspections</td>
</tr>
<tr>
<td>3</td>
<td>2.50-3.25</td>
<td>Reassessment should be performed to plan an optimal time of an intervention</td>
</tr>
<tr>
<td>4</td>
<td>2.00-2.50</td>
<td>Reassessment and possible intervention shall be performed shortly after an inspection</td>
</tr>
<tr>
<td>5</td>
<td>&lt; 2.00</td>
<td>Immediate action/intervention is required</td>
</tr>
</tbody>
</table>

Table 1. Qualitative reliability scale (structural safety) and related reliability indices, from (Hajdin, et al., 2018)

The method to elaborate the curves and discussion on their properties are presented here in brief. Probabilistic modelling of a bridge resistance (Re), self-weight (SW), and live load (LL), is based on recommendations from literature e.g. (JCSS, 2013), (Caprani, 2013). The resistance and self-weight are modeled as log-normal distributions, while for the live load a Gumbel max extreme distribution is used. The distributions are defined with coefficients of variation (covRe, covSW and covLL) and the percentiles of their characteristic values (percRe, percSW and percLL). The significant input in modelling the ratio of live load and self-weight, denoted as the parameter r, and the safety factors used in the design. Here, as an example, the ULS failures were elaborated where the global safety factor of 1.725 is used.

In Figure 3a, for $r=0.25$ and three values of $covRe=(0.05; 0.10; 0.15)$, the reliability curves and related probabilities of failure are evaluated for different values of the resistance reduction of a section which governs a failure mode. Here, the adopted values in modelling were covSW=0.1 with percSW=0.5, while covLL=0.3 with percLL=0.999. It should be noted that additional capacity for some failure modes and vulnerable zones may extend the diagram to the right, i.e. probabilities of failure can be even lower than shown in the diagram. It can be observed that the higher values of covRe yield lower reliability indices in general, but the related reliability curves have a “less” decline.

In Figure 3b, the value of the parameter r vs. reliability index is presented for three values of $covRe=(0.05; 0.10; 0.15)$. For this example, a factor for resistance reduction is set to 0.8 (i.e. estimated damage at an investigated section yields 20% of resistance loss). For $0.2 < r < 0.4$ (see the dashed rectangle in Figure 3), which are roughly the limits corresponding to girder bridges, it is seen that the value of covRe affect the reliability index to span over two or even three categories.
5. The quantitative assessment of Reliability – application of Bayesian nets

The methodology for introducing Bayesian nets in a bridge reliability assessment was discussed in (Isailovic, Hajdin, & Matos, 2018). In a simplified form, the net is shown in Fig. 4. The nodes “Current loads” and “Resistance” represent random variables of traffic load and self-weight on one side and a resistance of the virgin i.e. undamaged bridge on the other. The “Failure” node represents evaluation of the probability of failure via the limit state function. The results of an inspection are used to assess the resistance reduction (“Inspection findings” node), which implies an increase probability of failure i.e. a decrease of reliability due to the observed damages.

In general, when assessing structural safety, the reliability of bridge is evaluated taking into account several potential bending and shear failure modes. The Bayesian net for a system consisted of n failure modes has n couples of “Current loads” and “Resistance” nodes corresponding to each node “Failure mode”. In terms of reliability, bridge structure can be represented as a series system of different failure modes, which can be mutually statistically dependent i.e. correlated. Since the correlation is often difficult to estimate, a failure probability of the system P_f is assessed by evaluation the lower and upper bound limits of the of failure probability (Melchers, 1999).

\[
\max_{i=1}^n \{P(FM_i)\} \leq P_f \leq 1 - \prod_{i=1}^n (1 - P(FM_i)) \quad (1)
\]

where \( P( FM_i ) \) – probability of a structure failure in a failure mode \( i \).

The lower bound corresponds to the case where failure modes are fully correlated, while the upper bound relates to the case where there are completely uncorrelated failure modes. An actual failure probability is somewhere between these bounds.

5.1 Case study

The subject bridge is a RC plate, three-spanned overpass from 1983 with the total length of 29.4 m (Fig.

Fig. 4. Conceptual Bayesian net for a bridge reliability assessment
The bridge design load is in accordance with Portugese national documents REBA (Regulamento de Estruturas de Betão Armado – 1967) and RSEP (Regulamento de Solicitações em Edifícios e Pontes – 1961). The bridge vulnerable zones are denoted in Fig. 5a. They correspond to the locations of extreme bending moments for the design load (Fig. 5b).

The two failure modes, FM1 and FM2 are considered in the reliability analysis (Fig. 6).

The three random variables: “Resistance” (undamaged bridge), “Traffic load” (current traffic load according to Eurocode) and “Self-weight” are modelled using probabilistic distributions and parameters provided in Table 2. The limit state functions are written for each mechanism, including the plastic bending moments at hinges and the total load as the sum of Self-weight and Traffic load. In Table 3, the resulting virgin reliability is obtained using first order reliability method (FORM) and Eq. (1).

Table 2. Recommended distribution parameters, according to (JCSS, 2013)

<table>
<thead>
<tr>
<th>Random variable</th>
<th>Distribution type</th>
<th>Characteristic quantile</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance</td>
<td>Lognormal</td>
<td>0.05</td>
<td>0.15</td>
</tr>
<tr>
<td>Self-weight</td>
<td>Lognormal</td>
<td>0.50</td>
<td>0.10</td>
</tr>
<tr>
<td>Traffic load</td>
<td>Gumbel</td>
<td>0.999</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 3. Virgin reliability of the bridge

<table>
<thead>
<tr>
<th>Probability bound</th>
<th>$P_F$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>9.81E-8</td>
<td>5.20</td>
</tr>
<tr>
<td>Lower</td>
<td>8.74E-8</td>
<td>5.22</td>
</tr>
</tbody>
</table>

For the investigated bridge, a Bayesian net is created (Fig. 7). Here, the bridge resistance can be affected by none, one or two potential damages i.e. cracks. The vulnerable zones are assumed at the locations of potential plastic hinges for the two discussed mechanisms. The adopted width of these zones is 2.0m. In the proposed net, only the damage in a vulnerable zone will reduce the related plastic moment, otherwise it remains unchanged. The reductions due to a crack in the vulnerable zone is defined via “Crack Severity” field. Here, the adopted likelihoods are: 5% reduction – chance 60%, 10% reduction – chance 20%, 15% reduction – 10% chance and 20% reduction – chance 10%.
The evaluation of the probability of failure using the proposed net for several cases is presented in Table 4. For the a priori state, i.e. state before an inspection, the three cases are evaluated: the virgin state and the two states when a damage or two damages are present on the bridge, without information on location and severity. The location of a crack was adopted to have a uniform distribution (based on the lengths of vulnerable zones), while severity was accounted as a percentage of the plastic moment reduction.

For an a posteriori state, a few inspection scenarios are analyzed, where one or two cracks were found at vulnerable zones in an inspection.

Table 4. Case study results

<table>
<thead>
<tr>
<th>State</th>
<th>Case</th>
<th>Dominant FM</th>
<th>$P_E$ lower</th>
<th>$P_E$ upper</th>
<th>Reliability index</th>
</tr>
</thead>
<tbody>
<tr>
<td>a priori</td>
<td>Virgin (non-damaged state)</td>
<td>FM2</td>
<td>1.47E-08</td>
<td>1.82E-08</td>
<td>5.51 &lt; $\beta$ &lt; 5.54</td>
</tr>
<tr>
<td></td>
<td>One crack, arbitrary location &amp; severity</td>
<td>FM2</td>
<td>1.84E-08</td>
<td>2.58E-08</td>
<td>5.45 &lt; $\beta$ &lt; 5.51</td>
</tr>
<tr>
<td></td>
<td>Two cracks, arbitrary location &amp; severity</td>
<td>FM2</td>
<td>2.30E-08</td>
<td>3.85E-08</td>
<td>5.37 &lt; $\beta$ &lt; 5.47</td>
</tr>
<tr>
<td></td>
<td>One crack, 15% severity, VZ1</td>
<td>FM1</td>
<td>2.17E-08</td>
<td>3.64E-08</td>
<td>5.39 &lt; $\beta$ &lt; 5.48</td>
</tr>
<tr>
<td></td>
<td>One crack, 15% severity, VZ2</td>
<td>FM1</td>
<td>4.39E-08</td>
<td>8.12E-08</td>
<td>5.24 &lt; $\beta$ &lt; 5.35</td>
</tr>
<tr>
<td></td>
<td>One crack, 15% severity, VZ3</td>
<td>FM2</td>
<td>7.99E-08</td>
<td>8.34E-08</td>
<td>5.23 &lt; $\beta$ &lt; 5.24</td>
</tr>
<tr>
<td></td>
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<td>FM2</td>
<td>2.74E-07</td>
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</tr>
<tr>
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<td>7.99E-08</td>
<td>1.02E-07</td>
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</tr>
</tbody>
</table>

It is seen that one damage can have a significant impact on the probability of failure which can change even 8-fold, but the related reliability index does not change significantly. Only when two damages are present in the vulnerable zones, there is a considerable effect i.e. the reliability index reduces by 10% in respect to the virgin state. This is the consequence of bridge being a hyper-static system. As a further research for the investigated bridge, it would be of interest to evaluate failure modes for shear as well as serviceability failure modes, which could possibly give more severe reductions of reliability index than those presented herein.

6. Conclusion

The paper gives examples of the two approaches to assess the key performance indicator of Reliability according to the COST TU1406 WG 3 framework for establishing of quality control plans for roadway bridges. The both approaches are based on possible bridge failure modes and related vulnerable zones. The idea is to use the crucial data from inventory and inspections in the evaluation of bridges for the two states, a priori i.e. a non-damaged state (virgin) and a posteriori i.e. state of damage location/severity update following an inspection.
The qualitative approach comprises application of reliability curves, which elaboration and properties are discussed. For structures of similar type and failure modes, the resistance of a section governing the failure mode, self-weight and live load actions are modelled using adequate probabilistic distributions defined with characteristic values and percentiles, using existing codes, experience and available literature. By reducing the resistance of the section, the reliability curves are obtained. Upon estimation of the virgin reliability for an investigated bridge, an update of its reliability index can be done based on the related curve and outcome of an inspection i.e. the observed resistance reduction assessed by an inspector.

The approach with Bayesian nets was presented in the example of a multiple span bridge. The two bending failure modes were accounted, which are mutually exclusive for live load action, but correlated for resistance and self-weight. The upper and lower bound of probability of failure were estimated for several cases – for arbitrary locations of damages with specific severity. The obtained results show the importance of accounting for the bridge failure modes in hyper-static systems and provide crucial information on the impact of damages in vulnerable zones on a bridge reliability.

References
Isailovic, D., Hajdin, R., & Matos, J. (2018). Bridge quality control using Bayesian net. IABSE.
Quality control of roadway bridges – Reliability assessment –

Nikola Tanasić, Dušan Isailović & Rade Hajdin - University of Belgrade, Serbia
Jose Matos – University of Minho, Portugal
OUTLINE

• Introduction

• Work Group 3 Approach

• „Virgin“ Reliability – simplified assessment

• Assessment of KPI Reliability
  – Qualitative approach / Reliability curves
  – Quantitative approach / Bayesian nets
Introduction

• **Quality control** in bridge management today = visual inspections & condition rating

• Increasing traffic volume & loadings, higher exposure to natural hazards (effects of climate change)
  – The performance of bridges in the future is questioned
  – Optimal maintenance strategies are necessary

• **COST TU1406 WG1, WG2, WG3 Reports**
  - **KPI-s:** Reliability, Availability, Safety, Economy, Environment
  - **Bridge performance = KPI** evaluation – tailored according to needs of operators/owners
  - Qualitative and quantitative approach possible
WG3 Approach

- **Entity Relationship Diagram**
  - **Observation** = “just a fact” (e.g. a damage)
  - **Performance indicator** = measuring the fitness for purpose of a bridge
  
  An interpretation of observation’s impact on a KPI!

- **Vulnerable zone** = specific location on an element where the observations have the largest impact on a KPI
  It can be related to several failure modes!

- **Other data** (e.g. construction year) and **damage process** can be accounted in evaluation. They have an impact on a performance value!
“Virgin” reliability

- **Simplified evaluation:**
  - Non-landmark bridges, simplified structural systems
  - Undamaged bridge, resistance based on a design code
    (RC2 annual $\beta = 4.7 & 2.9$ / structural safety & serviceability)
    - Self-weight
    - Design load
  - Relevant sample of bridges of same type
    - Errors in bygone codes, conceptual weaknesses/detailing issues to be duly considered

Characteristic values & quantile assumptions
KPI Reliability - Qualitative approach

- Reliability curves
  - Similar bridges with similar dominant failure modes
  - Influence of a resistance reduction on a reliability index
- Inspection, experience and various methods of evaluation

Graph showing reliability index vs. probability of failure with different resistance reduction levels. Virgin reliability index estimated as 3.8.
KPI Reliability - Qualitative approach

- Qualitative reliability scale

<table>
<thead>
<tr>
<th>KPI Reliability scale</th>
<th>Quantitative scale (β)</th>
<th>Urgency of intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&gt; 4.00</td>
<td>Regular inspection</td>
</tr>
<tr>
<td>2</td>
<td>3.25-4.00</td>
<td>Reassessment should be performed to update the period between inspections</td>
</tr>
<tr>
<td>3</td>
<td>2.50-3.25</td>
<td>Reassessment should be performed to plan an optimal time of an intervention</td>
</tr>
<tr>
<td>4</td>
<td>2.00-2.50</td>
<td>Reassessment and possible intervention shall be performed shortly after an inspection</td>
</tr>
<tr>
<td>5</td>
<td>&lt; 2.00</td>
<td>Immediate action/intervention is required</td>
</tr>
</tbody>
</table>
KPI Reliability - Qualitative approach

- **Resistance (Re), Self-weight (SW) and Live load (LL):**
  - \( \text{Re} \) = log-normal distribution (e.g. \( \text{cov} = 0.15; \text{quant}=0.05 \))
  - \( \text{SW} \) = normal or log-normal distributions (\( \text{cov} = 0.50; \text{quant}=0.10 \))
  - \( \text{LL} \) = Gumbel distribution (e.g. \( \text{cov} = 0.30; \text{quant}=0.999 \))
  - Ratio of live and dead load, here denoted as \( r = \frac{\text{LL}}{\text{SW}} \)
KPI Reliability - Quantitative approach

• Bayesian nets
  – Simplified

  ![Bayesian Network Diagram]

  – Bending and shear failure modes, lower and upper bound limits of probabilities of failure

  \[
  \max_{i=1}^{n} \left\{ P(FM_i) \right\} \leq P_F \leq 1 - \prod_{i=1}^{n} (1 - P(FM_i))
  \]
KPI Reliability - Quantitative approach

- Case study / Overpass in Portugal
  - RC, three-span bridge

**Vulnerable zones**

- VZ1
- VZ2
- VZ3
- VZ1

**Envelope (traffic load + self-weight)**

- Probability bound
  - upper: \(9.81 \times 10^{-8}\) \(\beta = 5.20\)
  - lower: \(8.74 \times 10^{-8}\) \(\beta = 5.22\)
KPI Reliability - Quantitative approach

- Bayesian net – evaluation, a priori and a posteriori
- Resistance reduction with Cracks = \( f \) (Location, Severity)
KPI Reliability - Quantitative approach

- Bayesian net – results & discussion

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</tr>
</tbody>
</table>
Conclusion

- **Two approaches suggested to assess Reliability in COST TU1406**
  - Failure modes and vulnerable zones are accounted for
  - *A priori* (“virgin”) and *a posteriori* (“damage update”) states

<table>
<thead>
<tr>
<th>Approach</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qualitative Reliability curves</td>
<td>• Convenient &amp; clear for similar bridges and dominant failure modes</td>
<td>• Several curves per bridge type for different failure modes</td>
</tr>
<tr>
<td>Quantitative Bayesian nets</td>
<td>• Simultaneous effect of several damages on resistance</td>
<td>• Somewhat complex</td>
</tr>
<tr>
<td></td>
<td>• Analysis of various failure modes</td>
<td>• Knowledge on observations’ impacts on the resistance</td>
</tr>
<tr>
<td></td>
<td>• Different bridge types</td>
<td></td>
</tr>
</tbody>
</table>
THANK YOU FOR YOUR ATTENTION!
WWW.TU1406.EU
East bridge over the Channel of the Prague Port in Warsaw - Poland

Paulina Bieleckia - Warsaw University of Technology, Poland
Kacper Wasilewski - Warsaw University of Technology, Poland
Patryk Mazur - Warsaw University of Technology, Poland
Wojciech Karwowski - Warsaw University of Technology, Poland

Warsaw University of Technology
27th – 28th September 2018
Barcelona, Spain
CASE STUDY OF THE EAST BRIDGE OVER THE CHANNEL OF THE PRAGUE PORT IN WARSAW

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Abstract

The paper presents a structural diagnostic case study of the East Bridge over the Channel of the Prague Port in Warsaw in the framework established by working groups of TU1406 COST Action. The report is based on the exploitation documents of the bridge, such as: former technical reviews, technical book and technical card of the object, which are documents required for each bridge object in Poland) and an authors’ evaluation of technical condition of the bridge. The analysis is followed by analysis and comparison of two maintaining strategies – reference and preventive. The paper presents implementation of procedure of quality control planning established by WG 3 of TU1406 COST.

Keywords
combined steel-concrete road bridge, technical report of the bridge, technical condition of the bridge, failure modes of the bridge, maintenance of the bridge, costs of maintenance of the bridge

1. Introduction

The aim of this paper is a structural diagnostic case study of the East Bridge over the Channel of the Prague Port in Warsaw. Based on the previous reviews [Zobel 2008, Protocol of Periodic Inspection of the East Bridge over the Channel of the Prague Port in Warsaw], bridge’s documentation [Technical Card of the East Bridge over the Channel of the Prague Port in Warsaw, Technical Book of the East Bridge over the Channel of the Prague Port in Warsaw] and an evaluation of technical condition of the bridge, made by authors, the pathologies and damages of the bridge were listed. The Polish law requires the annual general reviews of the bridge structures and detailed review performed every 5 years [Directive 1994.89.414. Construction Law of 7 July 1994, Directive 2000.63.735. of the Minister of Transport and Maritime Economy of 30 May 2000 on Technical Conditions of Road Engineering Facilities and Their Location]. The instruction for preparing reports from the reviews are given by the General Directorate for National Roads and Motorways (GDDKiA) [Janas et al. 2011] and discussed in several works [Madaj, Wołowicki 2013, Mistewicz 1992, Jaromiński 1991, Jaromiński et al. 2011].

For each of structural elements the estimates failure time was determined as well as costs of its repair or replacement. As the conclusion authors perform comparison of two approaches – referenced and preventive. In the referenced approach the structural elements are replaced only after failure, and the preventive approach is based on regular repairs of worn elements. Analysed performance factors were: cost, safety, availability and reliability. The framework of the quality control is stated in working groups reports of TU1406 COST Action [Hajdin et al. 2018, Stipanovic et al. 2017, Strauss et al. 2016].

2. General data of the bridge

2.1. Basic information

The investigated bridge is a 104,60 meters three-spans combined steel-concrete bridge structure built in 2001. The bridge carries road no. 801 (Wybrzeże Szczecińskie Street) across the Channel of the Prague Port in Warsaw.

2.2. Description of the bridge structure

The bridge is based on the bored pile foundations of 1200 mm diameter. The substructure of the bridge is formed by two abutments and two wall piers made from reinforced concrete. The angle between deck axis and support axis is 60 degrees. The superstructure is 104,60 meters long composed of 3 spans: 30,55 + 42,00 + 30,55, designed as combined steel-concrete structure. Main load bearing members are 4 plate girders placed in 2,52 m spacing. Two girders on the east side of the bridge are placed 126 mm higher than the western pair. Webs of the girders are 1200 mm high in the span section and it rise to 2400 mm in the sections above supports. The steel girders are connected with reinforced concrete slab, which is 22 cm high (increased above girders’ top flanges). The slab’s cantilevers
are 1.47 m long (from the external girders axis) on both sides of the bridge. Total width of slab is 10.5 m. The slab under the road and pavement is formed with inclination of 2.5% in direction of western carb and 4% of counter inclination under the service sidewalk. The intersection of the both inclination is located under the road in a distance of 20 cm from the wester carb.

The deck slab is paved with modified asphalt concrete road surface layer. The pedestrian sidewalk is made of reinforced concrete, covered by bituminous surface and surrounded by stone carbs. Road barriers located on two sides of bridge and also pedestrian safety rail are made of steel. Pot bearings are pinned on each pier and movable bearings are on the north side abutment. Expansion joints are located on 1 and 4 pier. The drainage is provided by several bridge gullies which collect water and then drained it out by horizontal tubes to the back of abutments.

The photo and technical drawings of the bridge are presented below (Fig. 1 – Fig. 2).

![Fig. 1 East side view of the bridge and cross-section of the bridge](image)

![Fig. 2 Elevation of the bridge](image)

### 2.3. Load capacity

The load capacity of the bridge was calculated according to Polish standards [PN-85/S-10030]. The bridge was designed to bear “class A” loads, which are equally distributed load of 4.0 kN/m$^2$ and “K vehicle” load of 800 kN divided to 4 axles of 200 kN.

### 2.4. Condition rating

According to technical review made in August 2017 [Report of Detailed Technical Review of the East Bridge over the Channel of the Prague Port in Warsaw], the rating of the bridge is 3.0. It means that condition of the bridge is disturbing and in case of not repairing damages, the period of safe exploitation will be shortened.

### 3. Technical Condition

#### 3.1. Collection of defects

The main defects discovered during bridge review are:

- corrosion of structural elements such as steel girders and steel transoms,
- reinforcement corrosion, spalling and cracks on reinforcement structure,
- efflorescence on reinforcement elements,
- contamination and vegetation on substructures,
- contamination and corrosion of accessories,
- cracks, deformation and leak of pavement,
– lack of soil on abutment slope,
– trees reducing the clearance.

4. Vulnerability assessment

4.1. Vulnerable zones

The vulnerable zones are presented in the pictures below.


4.2. Potential failure mode of the bridge

According to current state of the bridge following failure modes are considered:

Failure modes related with reliability of the structure:

– Beam failure – loss of stability under live loads due to the significant reduction of cross-section caused by increased corrosion of steel beams.
– Piers and abutment failure – stability loss due to cracking and overloading.
– Deck failure – loss of stability under live loads due to the significant reduction of cross-section caused by increased corrosion of reinforced concrete slab.
– Bearing failure – loss of functioning of the bearings due to corrosion and accumulation of debris.
– Expansion joints failure – loss of functioning of the expansion joints due to accumulation of debris.
– Drainage failure – loss of functioning of the drainage system due to clogging of drainage pipes.
– Waterproofing failure – loss of functioning of the waterproofing system due to perforations and discontinuities caused by incidental impact, execution defects or material aging.

Failure modes related with safety of the structure:

– Disturbance to pedestrians or drivers – due to sudden changes in pavement, such as cracks or deformations etc.
– Falling of the deck – due to damaged barriers, as a result of, for example, corrosion of connectors, impacts etc.
– Falling concrete chunks – threat to the people under the bridge caused by falling chunks of concrete as a result of corrosion.

5. Key performance indicators

Key performance indicators (KPI) are provided in accordance with best practice knowledge of the team and the experience with bridge inspection in Poland. The indicators are evaluated and failure modes of the bridge are estimated. Two life time cycle approaches are shown to evaluate the life time costs, reliability, availability and safety of considered truss bridge in following 100 years.

First, referenced approach, considers a lack of any repairs of the bridge except of very basic ones on the pavement. The bridge defects are developed until component or system failure and a comprehensive intervention is performed for the relevant component or system only while others are continuing to deteriorate.

Second, preventative approach, consider first major rehabilitation of the bridge and a later periodical set of timely interventions during the life time cycle to prevent further defect development and overall damage to the structure.
### 5.1. Current state evaluation

According to current condition of the described bridge structure following KPIs are considered:

#### Table 1. Current state evaluation

<table>
<thead>
<tr>
<th>Structure type</th>
<th>Group</th>
<th>Component</th>
<th>Material</th>
<th>Design &amp; Construction</th>
<th>Failure mode</th>
<th>Location/Position</th>
<th>Damage/Obervation</th>
<th>Damage process</th>
<th>KPI</th>
<th>Performance indicator component level</th>
<th>Performance value</th>
<th>Estimated failure time [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel beams</td>
<td></td>
<td>Beam bending failure mode</td>
<td>Steel</td>
<td>2001</td>
<td>Bottom flanges (HMS region)</td>
<td>Corroded flanges</td>
<td>Corrosion</td>
<td>3</td>
<td>Reliability</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Beam shear failure mode</td>
<td>Steel</td>
<td>2001</td>
<td>Top flanges (HMS region)</td>
<td>Corroded flanges (connection with deck)</td>
<td>Corrosion</td>
<td>3</td>
<td>Reliability</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transoms</td>
<td></td>
<td>Beam shear failure mode</td>
<td>Steel</td>
<td>2001</td>
<td>Beams’ webs</td>
<td>Corroded webs</td>
<td>Corrosion</td>
<td>2</td>
<td>Reliability</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piers</td>
<td></td>
<td>Pier failure</td>
<td>Reinforced concrete</td>
<td>2001</td>
<td>Abutment 1 (north) and abutment 2 (south)</td>
<td>Reinforcement corrosion</td>
<td>Corrosion</td>
<td>2</td>
<td>Reliability</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pier failure</td>
<td>Reinforced concrete</td>
<td>2001</td>
<td>Abutment 1 (north)</td>
<td>Contamination and vegetation</td>
<td>Debris and biological growth</td>
<td>(Symptom)</td>
<td>(2)</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abutment</td>
<td></td>
<td>Expansion joints</td>
<td>Steel</td>
<td>2001</td>
<td>EJ 1 (north) and EJ 2 (south)</td>
<td>Contamination of expansion joint</td>
<td>Debris</td>
<td>Reliability</td>
<td>4</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pedestrian deck slab</td>
<td></td>
<td>Expansion joints</td>
<td>Reinforced concrete</td>
<td>2001</td>
<td>Deck bending failure</td>
<td>Bottom</td>
<td>Reinforcement corrosion</td>
<td>Corrosion</td>
<td>Reliability</td>
<td>3</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Pedestrian deck slab</td>
<td></td>
<td>Deck bending failure</td>
<td>Reinforced concrete</td>
<td>2001</td>
<td>Bottom</td>
<td>Spalling</td>
<td>Corrosion</td>
<td>Reliability</td>
<td>3</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abutment slope</td>
<td></td>
<td>Pedestrian deck slab</td>
<td>Reinforced concrete</td>
<td>2001</td>
<td>Bottom</td>
<td>Spalling</td>
<td>Corrosion</td>
<td>Safety</td>
<td>3</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bearings</td>
<td></td>
<td>Abutment slope</td>
<td>Soil</td>
<td>2001</td>
<td>Abutment 2 (south)</td>
<td>Lack of soil</td>
<td>Soil failure</td>
<td>Safety</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>80</td>
</tr>
<tr>
<td>Safety barrier</td>
<td></td>
<td>Pedestrian pavement</td>
<td>Bitumen</td>
<td>2001</td>
<td>Disturbance to pedestrians</td>
<td>Expansion joints and safety barriers surroundings</td>
<td>Cracks and deformation</td>
<td>Corrosion and locking of expansion joints</td>
<td>Safety</td>
<td>2</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>Road pavement</td>
<td></td>
<td>Pedestrian pavement (approach)</td>
<td>Concrete paving blocks</td>
<td>2001</td>
<td>Disturbance to pedestrians</td>
<td>Approach</td>
<td>Deformation</td>
<td>Soil failure</td>
<td>Safety</td>
<td>3</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>Cores of expansion joints</td>
<td></td>
<td>Cores of expansion joints</td>
<td>Steel</td>
<td>2001</td>
<td>Disturbance to pedestrians</td>
<td>Expansion joints</td>
<td>Deformation</td>
<td>Corrosion</td>
<td>Safety</td>
<td>4</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Drainage installation</td>
<td></td>
<td>Drainage installation</td>
<td>PCV</td>
<td>2001</td>
<td>Failure of drainage</td>
<td>Connectors</td>
<td>Corrosion</td>
<td>Reliability</td>
<td>2</td>
<td>2</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Waterproofing</td>
<td></td>
<td>Pedestrian traffic clearance</td>
<td>Asphalt felt</td>
<td>2001</td>
<td>Failure of waterproofing</td>
<td>Deck bottom</td>
<td>Leaks</td>
<td>Discontinuity-perforations</td>
<td>Reliability</td>
<td>4</td>
<td>4</td>
<td>15</td>
</tr>
</tbody>
</table>

### 5.2. Referenced approach

In the referenced approach to the maintenance of the bridge it is assumed that there is lack of any repairs of the bridge structure and accessories except removing the trees disturbance to pedestrians clearance. This approach leads to the defects escalation which ends with the bridge failure. The time history of KPI for referenced approach are given in Fig. 4. The existing structure defects development and estimated failure times are assumed below.

In 10 years:
- expansion joints failure – due to corrosion and contamination,
- safety barriers failure – due to corrosion of connectors or accidental impact.

In 15 years:
– bearing failure – due to corrosion and accumulation of debris,
– pedestrian and road pavement failure – due to cracks and deformation,
– drainage failure – due to clogging of drainage pipes,
– waterproofing failure – due to perforations and discontinuities.

In 30 years:
– pedestrian deck slab – due to reinforcement corrosion, spalling and efflorescence.

In 40 years:
– expansion joints failure – due to corrosion and contamination,
– safety barriers failure – due to corrosion of connectors or accidental impact,
– steel beam failure – due to increasing corrosion,
– transoms failure – due to increasing corrosion.

In 50 years:
– bearing failure – due to corrosion and accumulation of debris.

In 70 years:
– expansion joints failure – due to corrosion and contamination,
– safety barriers failure – due to corrosion of connectors or accidental impact,
– drainage failure – due to clogging of drainage pipes,
– waterproofing failure – due to perforations and discontinuities.

In 80 years:
– abutment failure – due to reinforcement corrosion, contamination and vegetation,
– piers and abutment failure – due to reinforcement corrosion and cracks.

In 85 years:
– bearing failure – due to corrosion and accumulation of debris.

---

![Graphs showing time history for KPI for referenced approach.](image)

**Fig. 4** Time history for KPI for referenced approach.
5.3. Preventive approach

In the preventive approach to the maintenance of the bridge it is assumed that the object will be completely rehabilitated in following two years. Most of the damages that could be observed on the object are related to the natural deterioration after 20 years of exploitation, exaggerated by lack of regular maintenance. Therefore, the cost and range of immediate actions will be similar to the actions that will be performed every 40 year from now (according to preventive approach). The time history of KPI for preventive approach are given in Fig. 5.

The planned interventions are as follows:

− Every 10 years intervention, includes: cleaning and repainting steel and concrete structures. The costs includes the temporary traffic arrangements.
− Every 40 years interventions, includes 10 years interventions plus: change of bearings, change of infill of expansion joints, change and repairs of waterproofing and pavements, repairs of drainage system, repairs of handrails and barriers. The costs includes the temporary traffic arrangements. During this intervention the bridge will be completely out of service (traffic will be redirected to the Western Bridge).

![Fig. 5 Time history for KPI for preventive approach.](image)

5.4. Comparison of the approaches

A comparison of the two considered approaches is shown in “spider” diagram below which represents the state of each of KPI in 100 years.

Comparing two approaches, the preventive approach is more appropriate for this bridge. The costs in both approaches are at the similar level but other indicators are more favourable. The availability, reliability and safety are kept in higher levels all over the period.
6. Conclusions

1. The paper presents all stages of implementation of procedure of quality control planning established by Working Group 3 of TU1406 COST, which derives from the framework set up by the work of Working Group 1 and 2.
2. From the comparison of two maintenance approaches, presented as a comparison of Key Performance Indicators levels in 100 years, it could be concluded that the preventive approach is more appropriate for the analysed bridge. The costs in both approaches are at the similar level but other indicators are more favourable. The availability, reliability and safety are kept in higher levels all over the period.
3. The comparison of Key Performance Indicators in one specific year could be misleading for people in charge of maintenance of the bridge. Much more valuable and clear for people not familiar with analysed quality control planning would be presentation of the comparison as a graph that represents cumulative values of Key Performance Indicators levels up to required date. It is particularly important in case of cost required for the maintenance of a bridge.

7. References

15. Technical Card of the East Bridge over the Channel of the Prague Port in Warsaw. Municipal Road Authority in Warsaw.
East bridge over the Channel of the Prague Port in Warsaw - Poland

Paulina Bielecka - Warsaw University of Technology, Poland
Kacper Wasilewski - Warsaw University of Technology, Poland
Patryk Mazur - Warsaw University of Technology, Poland
Wojciech Karwowski - Warsaw University of Technology, Poland

Warsaw University of Technology

27th – 28th September 2018
Barcelona, Spain
**GENERAL DATA – METRIC OF THE BRIDGE**

<table>
<thead>
<tr>
<th>No.</th>
<th>Characteristic</th>
<th>Metric</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Type of construction</td>
<td>Structure</td>
<td>Steel gantry crane</td>
</tr>
<tr>
<td>2.</td>
<td>Type of construction of pier supports</td>
<td>Concrete</td>
<td>Concrete column</td>
</tr>
<tr>
<td>3.</td>
<td>Method of foundation</td>
<td>Pile</td>
<td>Pile foundation</td>
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<tr>
<td>4.</td>
<td>Water level at high water</td>
<td>10.2 m</td>
<td>Water level</td>
</tr>
<tr>
<td>5.</td>
<td>Bridge span</td>
<td>30 m</td>
<td>Span length</td>
</tr>
<tr>
<td>6.</td>
<td>Bridge deck width</td>
<td>3.5 m</td>
<td>Deck width</td>
</tr>
</tbody>
</table>

![Bridge Diagram](image-url)
GENERAL DATA – METRIC OF THE BRIDGE

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Konstrukcja mostu</td>
<td>Most Świętokrzyski</td>
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<tr>
<td>2</td>
<td>Konstrukcja przyczółków</td>
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<tr>
<td>3</td>
<td>Szerokość mostu</td>
<td>4220</td>
</tr>
<tr>
<td>4</td>
<td>Artyleryjny modyfikowany</td>
<td>3050</td>
</tr>
</tbody>
</table>

KARTA OBIEKTU MOSTOWEGO

CHARAKTERYSTYKA OBIEKTU

1. Rodzaj konstrukcji mostu: most
2. Rodzaj konstrukcji przyczółków: pełnowymiarowy, beton z drewnem
3. Sposób ponoszenia podpór: podpór
4. Rodzaj nawierzchni: nawierzchnia asfaltowa
5. Rodzaj nawierzchni: nawierzchnia betonowa
6. Klasa obciążenia: A
7. Podstawa określania klasy obciążenia (numer normy): PN-89/S-100110
8. Nośność utrzymana: 500 kN
9. Numer klasyfikacyjny obciążenia wojskowego wg standardów NATO: 
10. Miejsce przechowywania dokumentacji: Tr. Świętokrzyska sp. z o.o.
11. Rok budowy / rok modernizacji: 2001
12. Asortyment zlokalizowanych rezerw: 

CHARAKTERYSTYKA PRZESZKODY

<table>
<thead>
<tr>
<th>Stan rzeki przy średniej wodzie</th>
<th>Szerokość mostu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Głębszość wody</td>
<td>Prędkość wody</td>
</tr>
</tbody>
</table>

PRZEKRÓJ PÓRZĘCZNY

SENTOJACIA

SLIDE 299
GENERAL DATA - LOCALIZATION

- Road no. 801 (Wybrzeże Szczecińskie Street)
- Across the Channel of the Prague Port in Warsaw
- Built in 2001
GENERAL DATA

East side view of the bridge.

View along the road over the bridge from the south side.
GENERAL DATA - STRUCTURE

Cross section of the bridge.

Elevation of the bridge.
GENERAL DATA - ACCESSORIES

- Road and pedestrian pavement
- Road barriers and pedestrian safety rails
- Pot bearings
- Expansion joints
- Drainage system

*Accessories of the bridge - pot bearing and road barrier.*
GENERAL DATA – LOAD CAPACITY

- Polish standard PN-85/S-10030:
  - real value: 500 kN
  - „Class A”
  - $q = 4 \text{ kN/m}^2$
  - $K = 800 \text{ kN (4 x 200 kN)}$

The load’s scheme according to Polish standards.
GENERAL DATA – CONDITION RATING

- August 2017:
  - Mean value: 3.31
  - Rate: 3.0

0 – emergency
1 – preemergency
2 – insufficient
3 – distressing
4 – acceptable
5 – sufficient

Condition rating protocol.

<table>
<thead>
<tr>
<th>Lp.</th>
<th>Element</th>
<th>Kod rodzaju uszkodzenia</th>
<th>Ocena stanu</th>
<th>Potrzeba wykonania</th>
<th>Tryb wykonania</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Naspyny i skarpy</td>
<td>PT</td>
<td>3</td>
<td>NIE</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Dojazdy w obrębie skrzydeł</td>
<td>DA, RA, NA</td>
<td>5</td>
<td>NIE</td>
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<tr>
<td>3</td>
<td>Nawierzchnia jezdni</td>
<td>DB, WB, RM, OM, DM, PB</td>
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<td>NIE</td>
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</tr>
<tr>
<td>4</td>
<td>Nawierzchnia chodników, krawężniki</td>
<td>KS</td>
<td>4</td>
<td>NIE</td>
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<tr>
<td>5</td>
<td>Balustrady, barier ochronne, osłony</td>
<td>KS</td>
<td>5</td>
<td>NIE</td>
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<tr>
<td>6</td>
<td>Belki podporczowe, gzymsy</td>
<td>CM</td>
<td>2</td>
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<tr>
<td>7</td>
<td>Urządzenia odwadniające</td>
<td>CA</td>
<td>2</td>
<td>NIE</td>
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<tr>
<td>8</td>
<td>Izołacja pomostu</td>
<td>RB, OB, CB, UB, KZ</td>
<td>3</td>
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<td>9</td>
<td>Konstrukcja pomostu</td>
<td>AS, KS</td>
<td>3</td>
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<tr>
<td>10</td>
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<td>NS, AS, KS</td>
<td>3</td>
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<td>11</td>
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<td>AS, BS</td>
<td>2</td>
<td>NIE</td>
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<tr>
<td>12</td>
<td>Urządzenia dylatacyjne</td>
<td>NB, OB, CB, WB</td>
<td>3</td>
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<tr>
<td>13</td>
<td>Przyczółki</td>
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<td>3</td>
<td>NIE</td>
<td></td>
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<tr>
<td>15</td>
<td>Koryto rzeki, przestrzeń podmostowa</td>
<td>NT, UT, PT</td>
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<td>Przęsyby</td>
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<td>17</td>
<td>Konstrukcje oporowe, skrzydła</td>
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<td>Urządzenia ochrony środowiska</td>
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<td>Zakotwienia ciągian</td>
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<td>Cięgna</td>
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<tr>
<td>21</td>
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<td>NS, KS, OS</td>
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</tbody>
</table>

Stan pogody: sucho
Temperatura: 21 °C
Ocena średnią obiektu: 3,31
OCENA CAŁEGO OBIEKTU: 3,00

WG4 and WG5 WORKSHOP
27th – 28th September 2018
Barcelona, Spain

SLIDE 305
TECHNICAL CONDITION – MAIN DEFECTS

- Corrosion of structural steel elements
TECHNICAL CONDITION – MAIN DEFECTS

- Corrosion of structural steel elements
TECHNICAL CONDITION – MAIN DEFECTS

- Reinforcement corrosion, spalling and cracks on reinforced concrete structure
TECHNICAL CONDITION – MAIN DEFECTS

- Efflorescence on reinforced concrete elements
TECHNICAL CONDITION – MAIN DEFECTS

- Contamination and vegetation on substructures
TECHNICAL CONDITION – MAIN DEFECTS

- Contamination and corrosion of accessories
TECHNICAL CONDITION – MAIN DEFECTS

• Contamination and corrosion of accessories
TECHNICAL CONDITION – MAIN DEFECTS

- Contamination and corrosion of accessories
TECHNICAL CONDITION – MAIN DEFECTS

- Cracks, deformation and leak of pavement
TECHNICAL CONDITION – MAIN DEFECTS

- Cracks, deformation and leak of pavement
TECHNICAL CONDITION – MAIN DEFECTS

- Lack of soil on abutment slope
TECHNICAL CONDITION – MAIN DEFECTS

- Trees reducing the clearance
VULNERABLE ZONES

- Sagging (label HMS region)
- Hogging (label HMH region)
- High shear regions
- Bearing area
POTENTIAL FAILURE MODES

- Failure modes related with reliability of the structure:
  - beam failure,
  - piers and abutment failure,
  - deck failure,
  - bearing failure,
  - expansion joints failure,
  - drainage failure,
  - waterproofing failure.

- Failure modes related with safety of the structure:
  - disturbance to pedestrians or drivers,
  - falling of the deck,
  - falling concrete chunks.
## CURRENT STATE EVALUATION

<table>
<thead>
<tr>
<th>Structure type</th>
<th>Group</th>
<th>Component</th>
<th>Material</th>
<th>Design &amp; Construction</th>
<th>Failure mode</th>
<th>Location/Position</th>
<th>Damage /Observation</th>
<th>Damage process</th>
<th>KPI</th>
<th>Performance Indicator component level</th>
<th>Performance value</th>
<th>Estimated failure time [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC3 Structural elements</td>
<td></td>
<td>Steel beams</td>
<td>Steel</td>
<td>2001</td>
<td>Beam bending failure mode</td>
<td>Bottom flanges (HMS region)</td>
<td>Corroded flanges</td>
<td>Corrosion</td>
<td>Reliability</td>
<td>3</td>
<td></td>
<td>40</td>
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<tr>
<td></td>
<td></td>
<td>Steel beams</td>
<td>Steel</td>
<td>2001</td>
<td>Beam bending failure mode</td>
<td>Top flanges (HMH region)</td>
<td>Corroded flanges</td>
<td>Corrosion</td>
<td>Impact</td>
<td>2</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transoms</td>
<td>Steel</td>
<td>2001</td>
<td>Beam shear failure mode</td>
<td>Beams’ webs</td>
<td>Corroded webs</td>
<td>Corrosion</td>
<td></td>
<td>3</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transoms</td>
<td>Steel</td>
<td>2001</td>
<td>Beam shear failure mode</td>
<td>Bearing area</td>
<td>Corroded webs</td>
<td>Corrosion</td>
<td>Reliability</td>
<td>2</td>
<td></td>
<td>40</td>
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<tr>
<td></td>
<td></td>
<td>Piers</td>
<td>Reinforced concrete</td>
<td>2001</td>
<td>Pier failure</td>
<td>Pier 2</td>
<td>Horizontal crack</td>
<td>Corrosion</td>
<td>Reliability</td>
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<tr>
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<td>Piers</td>
<td>Reinforced concrete</td>
<td>2001</td>
<td>Pier failure</td>
<td>Pier 2</td>
<td>Reinforcement corrosion</td>
<td>Corrosion</td>
<td>Reliability</td>
<td>2</td>
<td></td>
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<td>Reinforced concrete</td>
<td>2001</td>
<td>Pier failure</td>
<td>Pier 2</td>
<td>Efflorescence</td>
<td>Water penetrability (Symptom) (2)</td>
<td></td>
<td>4</td>
<td></td>
<td>80</td>
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<tr>
<td></td>
<td></td>
<td>Abutment</td>
<td>Reinforced concrete</td>
<td>2001</td>
<td>Abutment failure</td>
<td>Abutment 1 (north) and abutment 2 (south)</td>
<td>Reinforcement corrosion</td>
<td>Corrosion</td>
<td>Reliability</td>
<td>2</td>
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<td>Reinforced concrete</td>
<td>2001</td>
<td>Abutment failure</td>
<td>Abutment 1 (north)</td>
<td>Contamination and vegetation</td>
<td>Debris and biological growth (Symptom) (2)</td>
<td></td>
<td>4</td>
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<td></td>
<td>Expansion joints</td>
<td>Steel</td>
<td>2001</td>
<td>Locking of expansion joint</td>
<td>EJ 1 (north) and EJ 2 (south)</td>
<td>Contamination of expansion joint</td>
<td>Debris</td>
<td>Reliability</td>
<td>4</td>
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<td>Reinforced concrete</td>
<td>2001</td>
<td>Deck bending failure</td>
<td>Bottom</td>
<td>Reinforcement corrosion</td>
<td>Corrosion</td>
<td>Reliability</td>
<td>3</td>
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<td>Reinforced concrete</td>
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<td>Bottom</td>
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<td>Reliability</td>
<td>3</td>
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<td>2001</td>
<td>Deck bending failure</td>
<td>Bottom</td>
<td>Efflorescence</td>
<td>Water penetrability (Symptom) (3)</td>
<td></td>
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<td></td>
<td>30</td>
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<td></td>
<td>Abutment slope</td>
<td>Soil</td>
<td>2001</td>
<td>Disturbance to pedestrians</td>
<td>Abutment 2 (south)</td>
<td>Lack of soil</td>
<td>Soil failure</td>
<td>Safety</td>
<td>3</td>
<td></td>
<td>80</td>
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</tbody>
</table>

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**Note:** Table showing the current state evaluation of the East bridge over the Channel of the Prague Port in Warsaw – Poland, focusing on structural elements such as beams, transoms, piers, abutments, expansion joints, and pedestrian deck. The table details the failure modes, location/position, damage observation, and reliability indicators, along with estimated failure times.
## CURRENT STATE EVALUATION

<table>
<thead>
<tr>
<th>Structure type</th>
<th>Group</th>
<th>Component</th>
<th>Material</th>
<th>Design &amp; Construction</th>
<th>Failure mode</th>
<th>Location/Position</th>
<th>Damage/Observation</th>
<th>Damage process</th>
<th>KPI</th>
<th>Performance Indicator component value</th>
<th>Performance value</th>
<th>Estimated failure time [years]</th>
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<tr>
<td></td>
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<td>Elastomer and steel cast</td>
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<td>Bearing failure</td>
<td>Bearings</td>
<td>Corrosion of casts</td>
<td>Corrosion</td>
<td>Reliability</td>
<td>2</td>
<td>2</td>
<td>15</td>
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<tr>
<td></td>
<td></td>
<td>Safety barrier</td>
<td>Steel</td>
<td>2001</td>
<td>Falling of the deck</td>
<td>Safety barrier</td>
<td>Corrosion (connection with deck)</td>
<td>Corrosion</td>
<td>Safety</td>
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<td>2</td>
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<tr>
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<td></td>
<td>Road pavement</td>
<td>Asphalt</td>
<td>2001</td>
<td>Disturbance to driver</td>
<td>Expansion joints</td>
<td>Deformation of pavements, cracks</td>
<td>Locking of expansion joints</td>
<td>Safety</td>
<td>2</td>
<td>2</td>
<td>15</td>
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<td>Pedestrian pavement</td>
<td>Bitumen</td>
<td>2001</td>
<td>Disturbance to pedestrians</td>
<td>Expansion joints and safety barriers surroundings</td>
<td>Cracks and deformation</td>
<td>Corrosion and locking of expansion joints</td>
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<td>Approach</td>
<td>Deformation</td>
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<td>Safety</td>
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<td>15</td>
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<td>Expansion joints</td>
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<td>Corrosion</td>
<td>Safety</td>
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<td>4</td>
<td>10</td>
</tr>
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<td>PCV</td>
<td>2001</td>
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<td>Connectors</td>
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<td>Asphalt felt</td>
<td>2001</td>
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<td>Deck bottom</td>
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<td>Discontinuity, perforations</td>
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<td></td>
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<td>-</td>
<td>2001</td>
<td>Disturbance to pedestrians</td>
<td>Pedestrian sidewalk</td>
<td>Trees reducing the clearance</td>
<td>Biological growth</td>
<td>Safety</td>
<td>4</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>
MAINTENANCE APPROACHES

- Referenced approach

In 40 years:
- expansion joints failure,
- safety barriers failure,
- steel beam failure,
- transoms failure.
MAINTENANCE APPROACHES

- Preventive approach

Every 10 years:
- cleaning and repainting steel and concrete structures.

Every 40 years:
- change of bearings,
- change of infill of expansion joints,
- change and repairs of waterproofing and pavements,
- repairs of drainage system,
- repairs of handrails and barriers.
MAINTENANCE APPROACHES

- Comparison

Preventive vs. Reference

Cost

Reliability

Availability

Safety

Preventive 100

Reference 100

East bridge over the Channel of the Prague Port in Warsaw – Poland | Paulina Bielecka
CONCLUSIONS

• The paper presents all stages of implementation of procedure of quality control planning established by Working Group 3 of TU1406 COST.

• From the comparison of two maintenance approaches it could be concluded that the preventive approach is more appropriate for the analysed bridge.

• The main issue of the implemented approach is final presentation of obtained results. It has to be comprehensible by people in chargé of the object.
THANK YOU FOR YOUR ATTENTION!

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IMPLEMENTATION OF QUALITY CONTROL PLAN INTO TWO CASE STUDIES

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IMPLEMENTATION OF QUALITY CONTROL PLAN INTO TWO CASE STUDIES

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Abstract. Most of the quality control plans are element-oriented, facing with the lack of holistic approach in
assessment of concrete bridges. Without considering the structural system and without linking the damage type, damage
position and damage process with the type of structural system, it is hardly possible to derive key performance
indicators (reliability, safety, etc.). Here, quality control methodology established within WG3 of COST Action 1406
was implemented into two case studies, concrete bridge located in Portugal and in Macedonia, both arch with similar
topology. The applied quality control plan considers ‘virgin’ reliability, focuses on failure modes and related vulnerable
zones. To consider all these aspects, results from visual inspections were used and numerical models of the bridges
were built. In both case studies, different life time cycle approaches were applied to qualitatively evaluate different key
performance indicators over time. Finally, the results are compared in order to find the most effective scenario.

Keywords: quality control plan, arch concrete bridges, vulnerable zone, virgin reliability, key performance
indicator, visual inspection

1. Introduction

Quality control (QC) of bridges is differently implemented from country to country. However, most of them have the
same basic approach consisting of inspection and rating of each bridge element separately. This element-oriented
procedure is facing with a lack of holistic approach to the bridge assessment (Isailovic et al. 2018). Without considering
the structural system and linking the damage type, damage position and damage process with the type of structural system,
it is hardly possible to derive key performance indicators. Additionally, the inspector should bear in mind all possible
failure modes.

Applied QC plan considers the vulnerability of the structural system to the defects locations. It takes into consideration
the ‘virgin’ reliability, focuses on failure modes and related vulnerable zones. A general approach for QC plans was
already developed in the scope of WG3 for all types of structures and is now analyzed within the scope of arch bridges.
In this paper, evolution in time of performance indicators of two existing arch bridges, in terms of reliability, safety, costs
and availability, was performed qualitatively under no maintenance, corrective and preventative maintenance.

2. Case studies

In this section, a protocol for a quality control plan is used to demonstrate the methodology established in WG3 of COST
Action TU1406. The research presented in this paper is performed during a short-term scientific mission at University of
Minho, Guimaraes, Portugal in March 2018.

The quality control plan was performed in few steps:
- collecting the general data of the bridge (original drawings, construction year, inspection/intervention year, location,
  obstacle type, climate, exposure, etc.)
- comparison of current traffic load to traffic load model used for the previous calculation
- estimation of an initial ‘virgin’ reliability index $\beta_0$
- assessment of damage extend, intensity and identification of damage processes
- qualitative assessment of resistance reduction based on observed damages (rough assessment of resistance reduction on
  structural level (reliability))
- definition of various maintenance scenarios, evaluation of KPIs for all of them and comparison.
IMPLEMENTATION OF QUALITY CONTROL PLAN INTO TWO CASE STUDIES

Fig. 1. Degradation models for reliability index under no maintenance (left), corrective (middle) and preventative (right) scenario

Four different maintenance scenarios were considered: “running to failure” or “do-nothing and rebuild” scenario, corrective scenario, preventive scenario and hybrid scenario (corrective plus preventive) through application of linear degradation models for reliability index proposed by Frangopol (Frangopol et al. 2001) (Fig.1).

2.1 Case study 1 – Arch concrete bridge located in Portugal

The first case study is arch concrete bridge located in Guarda district, Portugal. The subject bridge is one span open spandrel deck arch with total length of 24 m and rise of 4.65 m. General view of the bridge along with the longitudinal section and bridge location are shown on Fig.2. The subject bridge carries the regional road 324(ER) over the river Cro and consists of: two traffic lanes 2.53 m and 2.51 m, two safety strips 0.45 m and 0.51 m and two sidewalks of 1.0 m width.

Fig. 2. Side view of the bridge (left), longitudinal section (middle) and location (right)

In order to define possible failure modes and to link the vulnerable zones with the observed defects, it is necessary to define the bridge structural elements: deck slab (1), arch slab (2), arch abutment/springing (3), spandrel wall piers (4) and wall piers at the springing (5) (WG3 Report 2018).

Fig. 3. Subject bridge with appropriate labels of vulnerable zones and defects

Considering load bearing elements of the bridge, there are some regions which are highly vulnerable depending on a structural system. For such a structural system, the following vulnerable zones are defined: high moment regions (A, B, C, D), high compression regions (E, F), high deflection regions (D) and high compressive stress regions (E). They are acknowledged on Fig.3 where photos from visual inspection are also incorporated.

The protocol for performance bridge evolution enhanced by the anticipated failure modes is applied and presented in Table 1. Only findings related to vulnerable zones, regarding structural reliability and safety are listed in the table.
Table 1. The protocol

2.1.1 Semi-quantitative assessment of bridge reliability

For each scenario, qualitative evolution of the following KPIs was made: R-reliability, C-costs, A-availability and S-safety. The reference information needed to evaluate KPIs in time, is the evaluation performed on damage-free state of the bridge, so-called “virgin” state (WG3 Report 2018). Therefore, an initial reliability index $\beta_0$ was roughly calculated using Monte Carlo simulation and First Order Reliability Method (FORM) as the shortest distance from the origin in the n-dimensional space of reduced variables to the curve described by $g(R,S) = R - S = 0$.

Ultimate bending moment from the unfavourable load combination taken from the original design project is presented on the Fig.4 below. The axial force was low and therefore neglected.

The bending moments at the supports are very low comparing with the bending moment at the midspan, showing that the system is simple supported. Therefore, the overall reliability of the bridge was obtained as the reliability of the midspan section of the arch (Nowak, Collins 2000). The limit state function for the bending failure mode is the following:

$$R = M_{bd} = F_{std} \cdot d - F_{cd} \cdot k_a \cdot x = A_e \cdot f_{yd} \cdot d - f_{cd} \cdot \alpha_e \cdot x \cdot b \cdot k_a \cdot x$$

$$S = M_{sd} = 170kNm$$

$$g(R,S) = R - S = A_e \cdot f_{yd} \cdot d - f_{cd} \cdot \alpha_e \cdot x \cdot b \cdot k_a \cdot x - M_{sd}$$

Herein, the depth and width of the cross-section were considered as deterministic parameters, while $M_{std}, A_e, f_{yd}$ and $f_{cd}$ were considered as random variables, which parameters are taken from the literature (Nowak, Collins 2000). With both methods a value of 5.05 was obtained. On the basis of the report from the last visual inspection of the bridge, approximately 5% resistance reduction was assessed, since the last inspection was taken 5 years after repairing of the bridge and the bridge is in overall good condition. Therefore, the initial reliability index for the further analysis was reduced from 5.05 to the value of 4.90 using the abacus presented in W3G report.
2.1.2 Evolution of KPIs for different maintenance scenarios

For each considered scenario, qualitative evolution of the following KPIs was made: R-reliability, C-costs, A-availability and S-safety. All KPIs are expressed on the scale of 1 to 5 (1-best, 5-worst) in order to generate 4-leg spider diagram.

‘Running to failure’ scenario

In this scenario, the bridge defects are developed until bridge failure and finally the bridge is replaced with a new structure. The effect of the essential maintenance action, like replacement of several deteriorated bridge components or replacement of the whole structure (like in this case), means that probability of failure (and therefore reliability index) should be set to its initial value (i.e., at t=0) (Neves, year).

Corrective scenario

First corrective (essential) maintenance action in this scenario was taken while the bridge is still in overall good condition (Reliability level 3). Identical corrective actions (for example: sub- and superstructure repairs, expansion joint and bearing replacement, drainage improvement etc.) were assumed to be taken periodically over 13 years with a lower improvement in reliability ($\gamma = \frac{\beta_0-\beta_{	ext{latest}}}{n} = \frac{4.90-2}{6} = 0.48$).

Preventive scenario

The effects of preventative maintenance actions (for example: deck sealing and applying over-layers, cleaning and lubricating bearings and expansion joints, cleaning bridge drainage system etc.) were modeled through a delay of a degradation process for a period of time $t_p$ immediately after application of the action, without any improvement in reliability index.

A hybrid scenario was also considered where preventative actions are performed between each two corrective actions. Comparison of the scenarios will be presented in Section 3.

2.2 Case study 2 – Arch concrete bridge located in Macedonia

The second case study is fixed-end slab-type arch concrete bridge located in Macedonia, Section Katlanovo-Veles. Its central part (arch-type slab) has a span of $L=54$ m, and its approaching structures consist of three spans at the side of Skopje and five spans at the side of Veles, each with 6 m span (total length 17x6m=102m) (Fig.7). The project documentation of the bridge was not at disposal. Thus, taking into account the time period when the bridge has been
constructed (year 1963), it could be concluded that the bridge has been designed in accordance with the “old” Technical regulations PTP-5 for loading of road bridges (issued 1948/1949). The bridge carries the National road M-1 (E-75) and its overall width is B=2x3.80 m + 2x0.60 m + 2x0.20 m = 9.20 m.

At the time of bridge inspection, considerable number of defects were observed (Fig.8): improper construction (A), inappropriate water drainage (B), very heavy damages due to corrosion of concrete and steel reinforcement of deck slab and longitudinal girders (B), expressed process of carbonization on entire deck slab surface (B), insufficient or spalled concrete cover (A and B), cracks at the connection with the column (C), improper expansion joint (F), visible reinforcement due to missing parts of concrete on the railing parapets (E) and inappropriate concreting and segregation (A and D). Photos of the defects from visual inspection linked with the vulnerable zones of this bridge are shown on Fig.8.

After inspection, the present condition of the bridge was estimated with index 4, meaning that heavy repairs are necessary. The protocol of performance bridge evolution is presented in Table 2.

2.2.1 Semi-quantitative assessment of bridge reliability

In order to obtain the initial reliability index of the arc-deck slab, numerical model of the bridge was built in Radimpex Software TOWER 6.0. The bridge was analysed according to current codes in Macedonia and according to “old” Technical regulations PTP-5 for live loads of road bridges (PTP-5, 1949). Since the arch slab is fixed-end slab, the overall reliability index was obtained considering the arch as a parallel system, meaning that for the overall system to fail, failure at mid-span and supports section is required (Nowak, Collins 2000).

The limit state function \( g(R,S) = R - S = 0 \) for the unfavourable failure mode (in this case bending failure) is the following:

\[
R = M_{Rd} = F_{cd} \cdot z + F_{s,2d} \cdot (d - a_2) - N_{sd} \cdot \left(\frac{d}{2} - a_1\right) \\
S = M_{sd} (support) = 1405kNm \; ; \; S = M_{sd} (midspan) = 405kNm
\]
### Table 2. The protocol

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Vulnerable area</th>
<th>Element</th>
<th>Damage observation</th>
<th>Damage process</th>
<th>KPI</th>
<th>Performance value (1-5)</th>
<th>Overall rating</th>
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<tr>
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<td></td>
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<tr>
<td>A1</td>
<td>Arch-slab</td>
<td>Segregation</td>
<td>Poor construction</td>
<td>Symp.</td>
<td></td>
<td></td>
<td>R=4 S=3</td>
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<tr>
<td>A2</td>
<td>Arch-slab</td>
<td>Spalled concrete</td>
<td>Corrosion</td>
<td>R</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>Deck slab</td>
<td>Brown spots</td>
<td>Corrosion</td>
<td>R</td>
<td>4</td>
<td></td>
<td></td>
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<td>Deck slab</td>
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<td>R</td>
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<tr>
<td>C</td>
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<td>Exp.Joint</td>
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<td>Compression failure mode</td>
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<tr>
<td>D</td>
<td>Arch slab</td>
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<td>Poor construction</td>
<td>Symp.</td>
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<tr>
<td>/</td>
<td>Piers</td>
<td>Segregation</td>
<td>Poor construction</td>
<td>Symp.</td>
<td>/</td>
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<tr>
<td>F</td>
<td></td>
<td>Parapet</td>
<td>Spalled concrete</td>
<td>Poor construction</td>
<td>S</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>F</td>
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<td>Rust</td>
<td>Corrosion</td>
<td>S</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

The bridge overall reliability index using Monte Carlo and FORM, as well as, the approach with the parallel systems, was obtained 2.15 (since the bridge is originally designed according to old, less conservative codes for loads). According to the relation between qualitative and quantitative reliability scale proposed in WG3 Report, this bridge belongs to reliability level 4 ($\beta = 2 - 2.50$) where old bridges with major resistance reduction belong (WG3 report, 2018).

#### 2.2.2 Evolution of KPIs for different maintenance scenarios

Two life time cycle approaches are shown to evaluate all key performance indicators considered for the bridge in the following 100 years.

In the first scenario (Reference – “Do nothing” scenario) (Fig.10 left) the bridge will be repaired and strengthened in the next years, since the reliability and availability for heavy vehicles are already limited. When the reliability reaches level 5, the bridge will be reconstructed and thus inserts the reliability to level 1. In between, lack of any major repairs of superstructure was considered, except basic pavement repairs each 20 year. With this scenario, defects were developed up to the bridge failure. The cost of the reconstruction was assumed to be 1 Milion EUR (on the basis of the original project for the bridge reconstruction), big repairs 500 000 EUR and small (pavement) repairs 100 000 EUR.

![Fig. 9. Ultimate bending moment from the unfavourable load combination](image)

![Fig. 10. Evolution of KPIs for the reference (left) and preventative (right) scenario](image)
Second scenario (Fig.10 right) consists of set of bridge major rehabilitations each 40 year and minor rehabilitations (new top asphalt, new railing, etc.) every 20 years. In this scenario, denoted as preventative scenario, actions are taken while the bridge is still in overall good condition (Reliability level below 5). Since the price of the bridge repair is different to set the reliability to its initial value from different reliability levels (Neves, year), lower prices for major bridge rehabilitations are considered in this scenario in comparison with the previous one.

3. Comparison

Four-leg spider (Fig.11) was constructed for both case studies in order to compare all considered maintenance scenarios.

![Fig. 11. Four-leg spider diagram for the considered maintenance scenarios for the first (left) and the second (right) case study](image)

For the first case study, hybrid scenario is the most effective one with the largest spider area, while for the second case study the preventative scenario is more effective than the reference („do-nothing“ scenario) one.

4. Conclusion

The quality control plan established for all types of structures within the scope of WG3 of COST Action TU1406 was implemented here into two case studies, arch concrete bridge located in Portugal and in Macedonia. With the applied quality control plan, ‘virgin’ reliability, anticipated failure modes and related vulnerable areas were taken into account, bringing some advantages in terms of other element-oriented quality control methodologies. With such a holistic approach, preventative maintenance and possible rehabilitation can be planned and optimized. Established methodology is applicable also in the quantitative manner, which is the aim of the further research.

References


Privremeni Tehnicki Propisi za Optovaruvanje kaj Patnite Mostovi PTP-5 1948/49 godina.
IMPLEMENTATION OF QUALITY CONTROL PLAN INTO TWO CASE STUDIES

Marija Docevska – University Cyril and Methodius-Skopje, R. of Macedonia
Leart Taravari - University Cyril and Methodius-Skopje, R. of Macedonia
Jose Campos e Matos – University of Minho Guimaraes, Portugal
Goran Markovski - University Cyril and Methodius-Skopje, R. of Macedonia
OUTLINE

QUALITY CONTROL PLAN

STEP 1
General data of bridge

STEP 2
Define: structural system, failure mode, vulnerable areas and defects

STEP 3
Calculate: Virgin reliability through FEM models

STEP 4
Application of maintenance scenarios

STEP 5
Qualitative evolution of KPIs and comparison

IMPLEMENTATION OF QUALITY CONTROL PLAN INTO TWO CASE STUDIES | MARIJA DOCEVSKA

SLIDE 329
General data of bridge

STEP 1

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- Location
- Current traffic load vs. traffic load model from design
- Visual inspections
- Results from NDT tests
- Exposure, Climate
...

STEP 3
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QUALITY CONTROL PLAN
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General data of bridge

IMP...
IMPLEMENTATION OF QUALITY CONTROL PLAN INTO TWO CASE STUDIES | MARIJA DOCEVSKA

OUTLINE

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QUALITY CONTROL PLAN

- Location
- Current traffic load vs. traffic load model from design
- Visual inspections
- Results from NDT tests
- Exposure, Climate

β₀ = \frac{\mu_g}{\sigma_g} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}
OUTLINE

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QUALITY CONTROL PLAN

- Location
- Current traffic load vs. traffic load model from design
- Visual inspections
- Results from NDT tests
- Exposure, Climate
...

\[ \beta_0 = \frac{\mu_g}{\sigma_g} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \]
General data of bridge

Step 1

Step 2

Define: structural system, failure mode, vulnerable areas and defects

Step 3

Calculate: Virgin reliability through FEM models

Step 4

Application of maintenance scenarios

Step 5

Qualitative evolution of R,S,C,A and comparison

Outline

Implementation of Quality Control Plan into two case studies

MARIJA DOCEVSKA

SLIDE 334

TU1406 COST ACTION

27th – 28th September 2018
Barcelona, Spain
QUALITY CONTROL PLAN

TWO CASE STUDIES

ARCH CONCRETE BRIDGES

/1/>

GENERAL DATA

PORTUGAL

- Construction year: **1940**
- Category of road: **Regional road 324**

MACEDONIA

- Construction year: **1963**
- Category of road: **National road M-1 (E-75)**
- Designed acc. to a previous Code of practice
QUALITY CONTROL PLAN

STEP /2/

TWO CASE STUDIES

STRUCTURAL SYSTEM

Open spandrel deck arch (simple supported)

Open spandrel deck arch with approaching structure (fixed end)

VULNERABLE AREAS

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HMR</td>
<td>HCR</td>
<td>HDR</td>
</tr>
<tr>
<td>1,2-ULS; 2,3-SLS</td>
<td>▲ ▼</td>
<td>▽ ▽</td>
<td>△ △</td>
</tr>
</tbody>
</table>

HMR - High Moment Region
HCR - High Compression Region
HDR - High Deflection Region
QUALITY CONTROL PLAN

<table>
<thead>
<tr>
<th>STEP</th>
<th>TWO CASE STUDIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>/2b/</td>
<td>DEFFECTS IN VULNERABLE AREAS - Portuguese bridge</td>
</tr>
</tbody>
</table>

Diagram showing defects in vulnerable areas of a bridge.
## QUALITY CONTROL PLAN

### TWO CASE STUDIES

#### THE PROTOCOL – Portuguese bridge

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Vulnerable area</th>
<th>Element</th>
<th>Damage observations</th>
<th>Damage process</th>
<th>KPI</th>
<th>Performance value (1-5)</th>
<th>Overall rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending failure</td>
<td>A</td>
<td>Deck</td>
<td>Efflorescence</td>
<td>Leaching</td>
<td>Symp.</td>
<td>/</td>
<td>R=4 S=2</td>
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<tr>
<td></td>
<td></td>
<td>Deck</td>
<td>Wet spots</td>
<td>Water permeability</td>
<td>R</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Arch</td>
<td>Surface cracks</td>
<td>Corrosion</td>
<td>R</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Arch</td>
<td>Spalling</td>
<td>Corrosion</td>
<td>R</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Arch</td>
<td>White spots</td>
<td>Carbonization</td>
<td>R</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Compression failure</td>
<td>C</td>
<td>Deck</td>
<td>Efflorescence</td>
<td>Leaching</td>
<td>Symp.</td>
<td>/</td>
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<tr>
<td></td>
<td></td>
<td>Deck</td>
<td>White spots</td>
<td>Carbonization</td>
<td>R</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>Arch</td>
<td>Longitudinal crack</td>
<td>Structural damage</td>
<td>R</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Arch</td>
<td>Surface cracks</td>
<td>Corrosion</td>
<td>R</td>
<td>3</td>
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<td>E</td>
<td>Arch</td>
<td>No damage</td>
<td>/</td>
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<td>/</td>
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<tr>
<td></td>
<td>F</td>
<td>Walls</td>
<td>Surface cracks</td>
<td>Corrosion</td>
<td>R</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Walls</td>
<td>Brown spots</td>
<td>Corrosion</td>
<td>R</td>
<td>3</td>
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<tr>
<td></td>
<td></td>
<td>Railing</td>
<td>Spalling</td>
<td>Corrosion</td>
<td>S</td>
<td>2</td>
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<tr>
<td></td>
<td></td>
<td>Railing</td>
<td>Cracks</td>
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QUALITY CONTROL PLAN

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<th>STEP</th>
<th>TWO CASE STUDIES</th>
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<tr>
<td>/2b/</td>
<td>DEFFECTS IN VULNERABLE AREAS - Macedonian bridge</td>
</tr>
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DEFFECTS IN VULNERABLE AREAS - Macedonian bridge
## QUALITY CONTROL PLAN

### TWO CASE STUDIES

#### THE PROTOCOL - Macedonian bridge

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Vulnerable area</th>
<th>Element</th>
<th>Damage observation</th>
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<th>KPI</th>
<th>Performance value (1-5)</th>
<th>Overall rating</th>
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<td>Bending failure mode</td>
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<tr>
<td>A1</td>
<td>Arch-slab</td>
<td>Segregation</td>
<td>Poor construction</td>
<td>Symp.</td>
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<td>R=4 S=3</td>
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<tr>
<td>A2</td>
<td>Arch-slab</td>
<td>Spalled concrete</td>
<td>Corrosion</td>
<td>R</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>Deck slab</td>
<td>Brown spots</td>
<td>Corrosion</td>
<td>R</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>Girder</td>
<td>Spalled concrete</td>
<td>Corrosion</td>
<td>R</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Column</td>
<td>Cracks</td>
<td>Structural</td>
<td>R</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Exp.Joint</td>
<td>Longitudinal crack</td>
<td>Structural</td>
<td>R</td>
<td>3</td>
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<td>Compression failure mode</td>
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<td>Symp.</td>
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<td>Spalled concrete</td>
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<td>S</td>
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<td>Rust</td>
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</table>
QUALITY CONTROL PLAN

TWO CASE STUDIES

INITIAL RELIABILITY INDEX

\[ M_{Sd}(\gamma_G, \gamma_Q) \leq M_{Rd}(\gamma_C, \gamma_S) \]

\[ N_{Sd}(\gamma_G, \gamma_Q) \leq N_{Rd}(\gamma_C, \gamma_S) \]

\[ n = \frac{M_{Sd}}{M_{Rd}} \text{ (or) } \frac{N_{Sd}}{N_{Rd}} \]

<table>
<thead>
<tr>
<th>section</th>
<th>M_{Sd}</th>
<th>M_{Rd}</th>
<th>n</th>
<th>N_{Sd}</th>
<th>N_{Rd}</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-span</td>
<td>124.1</td>
<td>594.7</td>
<td>0.21</td>
<td>1383.9</td>
<td>20000</td>
<td>0.07</td>
</tr>
<tr>
<td>Support</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>section</th>
<th>M_{Sd}</th>
<th>M_{Rd}</th>
<th>n</th>
<th>N_{Sd}</th>
<th>N_{Rd}</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-span</td>
<td>450</td>
<td>756</td>
<td>0.60</td>
<td>1789</td>
<td>25352</td>
<td>0.07</td>
</tr>
<tr>
<td>Support</td>
<td>1405</td>
<td>1470</td>
<td>0.96</td>
<td>2259</td>
<td>41751</td>
<td>0.05</td>
</tr>
</tbody>
</table>
QUALITY CONTROL PLAN

STEP

TWO CASE STUDIES

/3/

INITIAL RELIABILITY INDEX

Limit state function: \( g(R, S) = R - S = 0 \)

\[ S = M_{sd} = 124.06 \text{kNm} \]

\[ \beta_0^{\text{mid.}} = 5.25 \]

\( \beta_0^{\text{bridge}} = \beta_0^{\text{mid-span}} = -\Phi^{-1}(P_f) \)

\( \beta_0^{\text{bridge}} = 5.25 \)

\[ R = M_{Rd} = F_{cd} \times z + F_{sd2} \times (d - a_2) - N_{sd} \times \left( \frac{h}{2} - a_1 \right) \]

\[ S(\text{mid}) = M_{sd} = 450 \text{kNm} \]

\[ S(\text{supp.}) = M_{sd} = 1405 \text{kNm} \]

\( \beta_0^{\text{supp.}} = 0.66 \)

\( \beta_0^{\text{bridge}} = -\Phi^{-1}(P_f) \)

\[ \beta_0^{\text{bridge}} = 2.87 \]
QUALITY CONTROL PLAN

STEP /3a/

TWO CASE STUDIES

RESISTANCE REDUCTION

\[ \beta_0 = 5.25 \]
\[ \beta_0' = 4.90 \]

\[ \beta_0 = 5.25 \]
\[ \beta_0' = 4.90 \]

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QUALITY CONTROL PLAN

NO MAINTENANCE
‘Do-nothing and rebuild’

CORRECTIVE

PREVENTIVE

\[ \alpha_1 \] — degradation rate

\[ t_i \] — time of initiation of damage

\[ \gamma \] — reliability improvement

\[ \theta \] — decrease in degradation rate

\[ t_{PD} \] — delay of degradation process

\[ t_{PD} \] — duration of maintenance effect

\[ t_p \] — time of reapplication of the actions
QUALITY CONTROL PLAN

STEP

TWO CASE STUDIES

MAINTENANCE SCENARIOS

NO MAINTENANCE
‘Do-nothing and rebuild’

CORRECTIVE

PREVENTIVE

\[
\beta(t) = \begin{cases} 
  \beta_o, & 0 \leq t \leq t_i \\
  \beta_o - (t - t_i)\alpha, & t \geq t_i 
\end{cases}
\]

\[
\beta(t) = \begin{cases} 
  \beta_o, & 0 \leq t \leq t_i \\
  \beta_o - (t - t_i)\alpha, & t \geq t_i \\
  \beta_1 - (t - t_{P1})\alpha, & t_{P1} < t \leq t_i \\
  \beta_1 - [t - (t_{P1} + t_{P2})]\alpha, & t_{P1} + t_{P2} < t \leq t_{P1} + t_{P2} \\
  \beta_n - [t - (t_{P1} + (n - 1)t_{P1} + t_{PD})]\theta, & t_{P1} + (n - 1)t_{P1} + t_{PD} < t \leq t_{P1} + (n - 1)t_{P1} + t_{PD} \\
  \beta_n' - [t - (t_{P1} + (n - 1)t_{P1} + t_{PD})]\alpha, & t_{P1} + (n - 1)t_{P1} + t_{PD} < t \leq t_{P1} + (n \cdot t_{P1} + t_{PD}) 
\end{cases}
\]
QUALITY CONTROL PLAN

TWO CASE STUDIES

MAINTENANCE SCENARIOS

CORRECTIVE

- Crack sealing
  - Action: [0.5 1.5 3]
  - $\delta$ [years$^{-1}$]: [0.7 0.8 0.9]
  - $\gamma$ [/]: [2 1 1]

- Depth conc. repair
  - Action: -
  - $\delta$ [years$^{-1}$]: -
  - $\gamma$ [/]: [1 0 0]

- Waterproofing
  - Action: [2 3 3]
  - $\delta$ [years$^{-1}$]: [0.75 0.8 1.0]
  - $\gamma$ [/]: -

- Bearing replacement
  - Action: -
  - $\delta$ [years$^{-1}$]: -
  - $\gamma$ [/]: [2 2 2]

PREVENTIVE

- Deck washing
  - Action: [1 1.5 2]
  - $\delta$ [years$^{-1}$]: -
  - $\gamma$ [/]: -

- Minor spall repairs
  - Action: [1.5 2 3]
  - $\delta$ [years$^{-1}$]: -
  - $\gamma$ [/]: -

- Concrete spot painting
  - Action: [4 6 8]
  - $\delta$ [years$^{-1}$]: [0.3 0.4 0.5]
  - $\gamma$ [/]: -

- Bearing cleaning
  - Action: [0.5 1 2]
  - $\delta$ [years$^{-1}$]: -
  - $\gamma$ [/]: -
## QUALITY CONTROL PLAN

<table>
<thead>
<tr>
<th>No.</th>
<th>Picture</th>
<th>Defect description</th>
<th>Corrective action</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1.jpg" alt="Picture" /></td>
<td>Three to four isolated moderate spalls and delamination of the pavement, moderate riding quality.</td>
<td>Repairing the asphalt wearing surface (1), applying thin overlay and anti-slip pavement (2).</td>
<td>(1) 50EUR/m² (2) 40EUR/m²</td>
</tr>
<tr>
<td>2</td>
<td><img src="image2.jpg" alt="Picture" /></td>
<td>A lot of cracking due to corrosion of reinforcement</td>
<td>Replacement of the concrete railing</td>
<td>50EUR/m’</td>
</tr>
<tr>
<td>3</td>
<td><img src="image3.jpg" alt="Picture" /></td>
<td>Over 50% of the walls have cracks, brown spots and leakage</td>
<td>Repair the walls</td>
<td>250EUR/m³</td>
</tr>
<tr>
<td>4</td>
<td><img src="image4.jpg" alt="Picture" /></td>
<td>Localized areas of white and wet spots, surface cracks</td>
<td>(1) Replacement of the concrete deck slab; (2) Improvement of drainage system (3) waterproofing placement</td>
<td>(1) 200EUR/m² (2) 100EUR (3) 50EUR/m² + 10EUR/m’</td>
</tr>
<tr>
<td>5</td>
<td><img src="image5.jpg" alt="Picture" /></td>
<td>Failure of the sealer material. Water and debris can freely enter the opening and damage the bridge elements below.</td>
<td>Repair / Replacement of the expansion joints including surrounding concrete (‘viajoint’)</td>
<td>200EUR/m’</td>
</tr>
</tbody>
</table>
## QUALITY CONTROL PLAN

<table>
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<tr>
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<th>Defect description</th>
<th>Prevent. action</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Reduced diameter of the sinks</td>
<td>Cleaning the sinks and scuppers</td>
<td>/</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Vegetation and deterioration</td>
<td>Cleaning and Repairing the sidewalks (execution of new RC sidewalk)</td>
<td>50EUR/m2</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Over 50% of the walls have cracks, brown spots and leakage</td>
<td>Cleaning and surface repair of concrete (&lt;30mm) in localized areas, removing degraded concrete, cleaning and protecting the reinforcement</td>
<td>30EUR/m2</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Localized areas of white and wet spots, surface cracks</td>
<td>Cleaning and concrete deck sealing (1); filling or sealing of cracks with width &gt;0.30mm (2)</td>
<td>(1)100EUR/m' (2) 50EUR/m'</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Three to four isolated moderate spalls and delamination of the pavement, moderate riding quality.</td>
<td>Clean the bridge, sealing the cracks in the asphalt, apply overlayers</td>
<td>20EUR/m2</td>
</tr>
</tbody>
</table>
QUALITY CONTROL PLAN

TWO CASE STUDIES

MAINTENANCE SCENARIOS

Do-nothing and rebuild

\[ \alpha = 0.07 \text{ years}^{-1} \]
\[ \gamma = 3.25 \]
\[ \text{tpi} = 40 \text{ years} \]
\[ \text{tpD} = 6 \text{ years} \]

Corrective maintenance

\[ \alpha = 0.07 \text{ years}^{-1} \]
\[ \gamma = 0.45 \]
\[ \delta = 0.02 \text{ years}^{-1} \]
\[ \text{tpi} = 23 \text{ years} \]
\[ \text{tpD} = 6 \text{ years} \]
\[ \text{tp} = 13 \text{ years} \]

Preventive maintenance

\[ \alpha = 0.07 \text{ years}^{-1} \]
\[ \gamma = 0.00 \]
\[ \theta = 0.00 \text{ years}^{-1} \]
\[ \text{tpi} = 23 \text{ years} \]
\[ \text{tpD} = 3 \text{ years} \]
\[ \text{tp} = 6 \text{ years} \]
Qualitative evolution of KPIs – Portuguese bridge
QUALITY CONTROL PLAN

TWO CASE STUDIES

Qualitative evolution of KPIs – Macedonian bridge

STEP /5/

QUALITY CONTROL PLAN

TWO CASE STUDIES

Qualitative evolution of KPIs – Macedonian bridge

Implementation of Quality Control Plan into Two Case Studies

MARIJA DOCEVSKA
QUALITY CONTROL PLAN

TWO CASE STUDIES

COMPARISON – spider diagram

<table>
<thead>
<tr>
<th>Maintenance scenario</th>
<th>Spider Area [ / ]</th>
<th>In terms of Replacement 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replacement 1</td>
<td>14.23</td>
<td>/</td>
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<tr>
<td>Corrective</td>
<td>16.02</td>
<td>12.58%</td>
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<tr>
<td>Preventative</td>
<td>12.47</td>
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</table>
QUALITY CONTROL PLAN

CONCLUSION

• With the applied quality control plan, ‘virgin’ reliability, anticipated failure modes and related vulnerable areas were taken into account, bringing some advantages in terms of other element-oriented quality control methodologies. With such a holistic approach, preventative maintenance and possible rehabilitation can be planned and optimized.

• Established methodology is applicable also in the quantitative manner, which is the aim of the further research.
THANK YOU FOR YOUR ATTENTION!

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