AN OVERVIEW OF PERFORMANCE INDICATORS FOR ARCH BRIDGES IN EUROPE

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SUMMARY

During implementation of asset management strategies, maintenance actions are required in order to keep assets at desired performance levels. In case of roadway bridges, specific performance indicators are established for their components and compared with performance goals in order to evaluate if quality control plans are accomplished. In Europe there is a large disparity regarding the way these indicators are quantified and how such goals are specified. Therefore, due to the considerable number of methodologies, arises COST Action "TU1406: Quality specifications for roadway bridges, standardization at a European level (BridgeSpec)" which aims to bring together, for the first time, both research and practicing community in order to accelerate the establishment of a European guideline in this subject. Thus, in this paper, special focus is placed at existing performance indicators for arch bridges in Europe. Both description and methodologies to achieve such indicators are highlighted.

Keywords: *Arch bridges, performance, indicators, standardization.*

1. INTRODUCTION

Roadway bridges are considered to be one of the most critical components of road infrastructures. Therefore, and due to their relevancy in the overall roadway infrastructure, quality control (QC) plans should be outlined and accomplished.

Bridge management systems are sustained by QC plans which in turn are supported in performance indicators. It is then of particular importance the analysis of such indicators in terms of user assessment frameworks (e.g. what kind of equipment and software is being used), and in terms of the quantification procedure itself. It is then necessary to proceed with the definition of:

a) Technical indicators – which characterize serviceability conditions and ultimate capacity;

b) Environmental based sustainable indicators – which characterize the environmental impact of a structure in the course of its total life cycle;

c) Other indicators – such as economic and social based, which capture additional aspects that may influence the decision process.

These indicators make it possible to define a set of objectives aimed to establish QC plans which ensure desired bridge quality service. However, those plans vary from country to country and, in some cases, within the same country. This leads to large variations in roadway bridges quality. Therefore, the COST Action aims to achieve the European economic and societal needs by standardizing the condition assessment and maintenance level of roadway bridges. Moreover, it will be important to address, in such plans, new indicators related to sustainable performance. This constitutes a scientific advance as, currently, QC plans do not consider them.

In order to establish a standardization procedure for the assessment of performance indicators, namely, those that should be considered in a QC plan, as well as to define performance goals, a network of experts is needed. Such network should incorporate people from different stakeholders (e.g. universities, institutes, operators, consultants and owners) and from various scientific disciplines (e.g. on-site testing, visual inspection, structural engineering, sustainability, etc.).

To summarize, there is a real problem which is the non-uniform way QC is actually developed for roadway bridges. This is surpassed by establishing a guideline comprising specific recommendations for assessing performance indicators, as well as for the definition of performance goals. The expected impacts from such recommendation are expressed in Tab. 1.

Table 1. *COST Action TU1406 impacts [4,5].*

Impact	Description
Environmental/Sustainability	Decrease of bridge life-cycle maintenance and repair costs; Increase of service life; Decrease of total energy consumption and carbon footprint; Increase of mechanical, durability and environmental performance.
Economic and societal	Improve user satisfaction; New job opportunities associated with new QC services; Improve economic efficiency; Increase competitiveness in structural engineering industry; Enhance risk management.
Well-being of general public	Decrease of maintenance, repair and reconstruction activities; Decrease of downtime situations; Decrease of disruptions; Increase of user comfort.
Research community	Better perception of the practice problems; Cooperation improvement between research and practice; Establishment of reliable comparisons between countries; Improvement on research developments and practical procedures; Reduction of the gap between countries.

In this present paper, following a brief description concerning the COST Action TU1406, the procedures developed in acquisition of performance indicators are described. Finally, specific performance indicators for arch bridges are discussed.

2. COST ACTION TU1406

2.1. Motivation

In the past few years, significant worldwide research has been done regarding condition assessment of roadway bridges, namely through the use of non-destructive tests, monitoring systems and visual inspection techniques. Obtained values, which provide information regarding the assessed bridge state condition, are then compared with previously established goals. As a result, there are currently several methodologies to evaluate bridge condition.

More recently, the concept of performance indicators was introduced, simplifying communication between consultants, operators and owners. However, large deviations continue to exist on how these indicators are obtained and, therefore, specific actions should be undertaken in order to standardize this procedure.

It is verified that QC plans should always address the assessed performance indicators and pre-specified goals. However, these latter values are even more difficult to obtain as they are highly subjective. As a result, a dispersion of QC plans is verified. Once roadway concession contracts are based on such plans, this may become an enormous problem for the future.

In the past a similar problem was addressed with roadway pavements. Although this was a worldwide problematic, in Europe it was solved through COST Action 354 (performance indicators for pavements). During this Action, a network of experts in the field of road pavements established specific recommendations for assessing performance indicators and indexes for road pavements taking into account the needs of road users and operators.

2.2. Objectives

The main ambition of this Action is to develop a guideline for the establishment of QC plans in roadway bridges, by integrating the most recent knowledge on performance assessment procedures with the adoption of specific goals [4,5]. This guideline will focus on bridge maintenance and life-cycle performance at two levels: (i) performance indicators, (ii) performance goals. The possibility to incorporate new indicators related to sustainable performance will also be considered. By developing new approaches to quantify and assess bridge performance, as well as quality specifications to assure expected performance levels, bridge management strategies will be significantly improved, enhancing asset management of ageing structures in Europe.

In order to reach this main general aim, the following more specific objectives/deliverables have been considered [4,5]: (i) to 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) to collect and contribute to up-to-date knowledge on performance indicators, including not only technical indicators but also environmental, economic and social ones; (iii) to establish a wide set of quality specifications through the definition of performance goals, aiming to assure an expected performance level; (iv) to 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) to create a data basis from COST countries with performance indicator values and respective goals, that can be useful for future purposes; (vi) to support the development of technical/scientific committees.

2.3. Scientific program

The scientific focus of the Action is centered in the creation of a recommendation for the establishment of QC plans for roadway bridges across Europe. In this context, this Action deals with recent developments on bridge safety, maintenance and management, according to a life-cycle outlook, aiming to define a standardized procedure for performance assessment as well as for the establishment of performance goals in order to accomplish a pre-specified service level. Moreover, it is intended to demonstrate the applicability of the developed guideline, and other recommendations, with case studies. The scientific work plan ensures the working progress in support of the established objectives. It is organized, based on the division of tasks (and subtasks) allocated for each WG, and according to a timetable. In the following, WG1 concerning performance indicators is highlighted.

3. PERFORMANCE INDICATORS

Within the scope of condition assessment and management systems, performance indicators are crucial since these, not only quantitatively describe a performance aspect, but also support QC plans. Therefore, it is highly important to analyze such indicators in terms of used assessment frameworks (e.g. what kind of equipment and software is being used), and in terms of the quantification procedure itself. In this particular work package, the objectives will be the definition of:

(a) Technical indicators: the goal is to explore bridge structures performance indicators, in the course of international research cooperation, which captures the mechanical and technical properties and its degradation behavior. Moreover, environmental condition, natural aging, and quality of material regarding to determined indicators will be investigated and evaluated in their meaningfulness. These considerations, however, also include service life design methods, aimed at estimating the period of time during which a structure or any component is able to achieve the performance requirements defined at the design stage with an adequate degree of reliability. Based on the input information quality (mainly concerning the available degradation models), it is possible to distinguish among deterministic methods, usually based on building science principles, expert judgment and past experience, which provide simple estimations of service life, and probabilistic methods;

(b) Sustainable indicators: in addition to technical performance indicators, which characterize the ultimate capacity as well as serviceability conditions, environmental based sustainability indicators will also be formulated. These variables characterize the environmental impact of a structure in the course of its total life cycle, expressed in terms of total energy consumption, carbon footprint (CO2 emissions), raw materials balance, etc. These indicators can be separated into direct and indirect, where the former are related to the construction/maintenance itself and the latter are caused e.g. as consequence of limited functionality;

(c) Other indicators: other sustainable indicators, economic and social based, may be used to evaluate bridge performance. These indicators, based on the technical performance of a structure, capture additional aspects that may influence the decision process and typically represent the discounted (accumulated) direct or indirect costs associated with construction and maintenance. Summed up over the full life-time, they represent part of or the full life-cycle costs. They can, in the context of multi-objective optimization, be understood as a weighting scheme to arrive to a single objective function to be minimized.

The objective is the publication of a report on these performance indicators. Such report will address a general description, how they are assessed (e.g. visual inspection, non-destructive tests and monitoring systems), with what frequency, what values are generally obtained and, finally, some general recommendations.

3.1. Procedure for acquiring Performance indicators

The determination of performance indicators for bridge structures from European countries and its harmonization on a European level is complex, extensive, and time consuming. These facts were confirmed in processing WG 1 "Performance indicators" of the COST TU1406 [1,4,5]. There are the following findings and important aspects associated with the Performance Indicator Survey Processes in the first year of COST TU1406 [2,3,6,7]:

a) A complete translation of codes or guidelines as used by owners and operators from the national language to international European format has been considered as unnecessary, since only some pages are devoted to the subject of interest (performance indicator, performance goal,…);

b) The nomination of a responsible to collect the relevant parts of existing guidelines and translate them to English turned out to be much more effective. The responsible person must have good knowledge and expertise on inspection/assessment of existing bridges in order to identify the relevant parts;

c) A request for replying the questions in the questionnaire, and for up-loading the relevant parts of the document, both the original and the translated versions was regarded as very significant. It supports to objectify the language translations, since (a) it was revealed that many times the same operation or concept has different English translations or wording, and (b) to avoid subjectivity in some way;

d) Because of the objective to propose enhancements to the existing practice of performance assessment by the different owners and showing recent advances and new performance indicators two types of documents are asked for: operator documents (actually in use by the different Agencies in the form of guidelines or recommendations) and research documents;

e) Due to the different languages used across Europe and the different formats of both type of documents (guideline or research oriented) it was decided to nominate in each country several persons with the following different tasks:

- One of the two nominated Management Committee members which are nominated by each participating country (according to COST Action rules) is responsible to contact owners and operators of highway bridges asking for available documents in practice;
- A Core Group of WG1 has been formatted for the preparation of tutorials for the screening of documents, processing screened documents, fill-in the data base and finally analyze the data base and to obtain the main results and conclusions;
- A nominated country responsible person is in charge of gathering, screening and processing national applied documents according to some guidelines and tutorials elaborated by the Core Group of the Working Group. He is also the

responsible, jointly with the nominated person from the MC to identify the research groups in each country and ask them to provide information about new proposal still in the researching phase for performance indicators.

As mentioned in [2], the COST TU1406 Geneva Workshop in September of 2015 served to the essential steps of the WG1 to WG3 in order to gather more information related to the performance indicators used in practice and under research. Each WG member were asked (a) in participating in the workshop, and (b) preparing a poster or oral presentations with the following order:

a) Extract from the available documents the most important (> 8) performance indicators;

b) Show the formulation and the procedure on how to obtain the PI;

c) Show the thresholds with respect to each PI, if available;

d) Show the goals with respect to each PI, if available;

e) Characterize, based on their experience, if their indicated or proposed PI are already applied by owners, operators, experts,…, in which project phases;

f) Characterize those groups that are important PI, but not applied now, or not applied now and needing further investigations in order to become fully implementable.

3.2. Performance Indicator Data Base

In parallel to the filling of the questionnaire and the development of the Performance Indicator database a glossary of terms was formed to support the survey process that should contain the data related to performance indicators/goals/thresholds etc.

Document	*Handbook of damages on bridge elements*			Add Chapter/Paragraph									
Chapter/ Paragraph/ Section	A. Oštećenja prilaza i čunjeva - A-1			Hide/Show Chapter									
				Ref	Ref	Ref		Ref	Ref	Ref	Ref	Ref	
A) Performance Level				B) Damage		C) Performance Indicator/Index				D) Performance Assessment			
level	system	component	material	type	characteristic	indicator	detection	evaluation	index	threshold	goal	criteria	
Element	All bridge types	Embankment		Damage_State	Erosion	Damage degree	Direct_Measurement			affected area	Damage Assessment		
Sub_System	All bridge types	Access roads		Damage_State	Asphalt pavement cracking	Damage degree	Direct_Measurement			crack width (	Damage Assessment		

Chapter/ Paragraph/ Section	B. Donji ustroj - B.1. Oštećenja temelja upornjaka i stupova - B1-1			Hide/Show Chapter									
				Ref	Ref	Ref		Ref	Ref	Ref	Ref	Ref	
A) Performance Level				B) Damage		C) Performance Indicator/Index				D) Performance Assessment			
level	system	component	material	type	characteristic	indicator	detection	evaluation	index	threshold	goal	criteria	
Element	All bridge types	Foundations		Damage_State	Scour/Erosions	Damage degree	Direct_Measurement			affected area	Damage Assessment		
Element	All bridge types	Foundations		Damage_State	Abrasion	Damage degree	Direct_Measurement			affected area	Damage Assessment		
Element	All bridge types	Foundations		Damage_State	Abrasion	Damage degree	Direct_Measurement			affected dep	Damage Assessment		
Element	All bridge types	Foundations		Damage_State	Settlements	Damage degree	Direct_Measurement			sag (cm)	Damage Assessment		
Element	All bridge types	Foundations		Damage_State	Degradation	Damage degree	Direct_Measurement			affected area	Damage Assessment		
Element	All bridge types	Foundations	Concrete	Damage_State	Spalling	Damage degree	Direct_Measurement			affected area	Damage Assessment		
Element	All bridge	Foundations	Concrete	Damage_State	Spalling	Damage degree	Direct_Measurement			affected dep	Damage		

Fig. 1. *Codes or guidelines database (Strauss et al. 2016 (a), (b)).*

The idea is to update the Glossary in the process of survey and screening the codes or guidelines as used by owners and operators, where every COST TU1406 country should add national specific information in their own language and translate it into English. The COST countries must choose beforehand the relevant documents from which the performance indicators and related information are going to be extracted. As shown in Fig. 1 the Database User interface for the survey is structured in MS Excel, where the data is structured in four groups [2,3,6,7]: Performance Level, Damage, Performance Indicator/Index and Performance Assessment. The users should fill up the data in these groups and update the Glossary information at the same time.

3.3. Categorization of the Performance Indicator Database

The data in the Performance Indicator Database of the first screening process of the 36 countries are partly heterogeneous and overlapping despite the detailed developed guidelines and glossary. It mainly results from free interpretation leeway and the different experience grade of nominated screening people in visual inspections, performance evaluation, performance assessment and decision making. Therefore the second COST TU1406 Budapest Workshop in January 2016 was used to discuss with the screening nominated people the screening process, missing elements, misinterpretations among others, and to define with them the following working program: (a) Completion of missing PI associated data sheets; (b) critical review of individual screening results based on the database inputs from other countries; (c) request for a critical feedback with respect to the content and the definitions in the developed PI database from MC members, from national bridge owners, bridge inspectors and inspectors commissioned by bridge owners. This feedback and review processes allow a fundamental PI-PG categorization and a synchronization of the database content at European level.

4. ARCH BRIDGES

4.1. Review of existing built environment

Transport infrastructure systems play an important role in the economic growth and development of society. Either roadways or railways involve a set of crucial assets for society. In particular, bridges provide important links allowing to cross waterways, valleys, highways and other infrastructure facilities. These structures can have multiple configurations and building materials, which depend on several factors, e.g. topology and geological characteristics, construction time, budget constraints and so on. Arch bridge is one of the oldest and most popular types of bridges. Since their basic principal is to transfer acting loads trough compression forces, numerous stone arch bridges where built by Romans throughout Europe. In modern times, building materials, such as cast iron, steel and concrete have been used to in the construction of arch bridges. Nevertheless, according to [8], masonry arch bridges are one of the most common bridge type in Europe, corresponding to 40% of all bridges. Besides, these bridges are older than 100 years and must be preserved due to their high heritage value. However, their behaviour is not so well understood compared to modern bridge types [8]. In this sense, special focus must be placed at the following issues:

a) investigation of existing structures regarding its materials dimensions and properties and the presence of defects/damages;

b) understanding system and element behaviour;

c) effectiveness of repair and strengthening techniques.

To tackle this, the assessment of masonry arch bridges must include quantitative and qualitative parameters, so that existing national guidelines concerning bridge management and maintenance detail additional performance indicators for this bridge type. According to the aforementioned review of these documentation, arch bridges composed by stone or brick materials are treated with special care during visual inspections. Notwithstanding, these recommendations are not given by all reviewed countries. Note that, traditional performance indicators must be followed in the case of arch bridges with concrete or steel as structural material. In the following, common defects and a summary of performance indicator respecting to masonry arch brides are highlighted.

4.2. Masonry arch bridges: review of common defects

Due to effects of ageing, weathering and traffic, numerous of masonry arch bridges have been deteriorating through their lifetime, affecting their performance either in terms of serviceability or service limit states. In this context, the main types of defects/damages are often perceptible by means of visual examination, since these involve significant deformations, visible cracking, leaking problems, materials degradation and so on.
Although in many cases only the type of defect can be easily identified, visual observation can provide important clues to determine the cause of damage. Combining past experience and engineering judgment, damage appearance (eg. crack pattern), location and extension can be helpful to diagnose the trigging event. However, this task can be time-consuming, since damage monitoring must be adjusted and comparable to structure's lifetime. Nevertheless, there are common defects that can be detected whose causes are often due to:

a) foundation anomalies – local erosion as result of scour, abutments/piers settlement, etc;

b) overloading – concentrated loads, reduction of load carrying capacity;

c) lack of waterproofing – absence of mortar joints, freeze thaw cycles, wind erosion.

Thus, in the following a summary of performance indicators for these bridges is presented.

4.3. Masonry arch bridges: summary of Performance Indicators

In the light of QC plans, condition assessment must be supported by performance indicators concerning different levels, namely, structural safety (ULS), serviceability (SLS), durability (D) and so on. As already mentioned, these indicators are directly linked with damage/defects. In this sense, a list of performance indicators regarding masonry arch bridges are shown in Table 2.

Table 2. *Performance Indicators for masonry arch bridges.*

Damage characteristic	Performance Indicator				
	Detection (1)	Evaluation (2)	Level		
			D	SLS	ULS
Joints deficiency	VI	DC	X	X	X
Joints leaking	VI	DC	X	X	X
Dewatering deficiency	VI	DC	X	X	X
Contamination	VI	I	X	X	X
Cracks	DM	DC	X	X	X
Spalling	VI	DC	X	X	X
Deformation	VI	DC	X	X	X
Displacement	DM	I	X	X	X
Loose of stones/bricks	VI	DC	X	X	X

Legend: (1) - DM: direct measurement, VI: visual inspection.
(2) - DC: damage catalogue, I: inspection

5. CONCLUSIONS

This work presents the objectives and methodologies oriented to define common quality specifications and control plans for highway bridges in Europe. This need comes from the existing free transportation and traffic between countries in the European Union. The methodology is based on a deep analysis of the existing bridge management policies existing in European countries and the main performance indicators used with the objective to define a common group of quality specifications and control plans that can be assumed by all these countries. This, with the aim to manage the existing roadway infrastructure from a European and not only a country-specific perspective. Although showing a European initiative, the methods proposed in this paper can be also applied to other parts of the world where homogeneity in quality control of the existing highway bridge stock is needed in order to facilitate the existence of a roadway network that allows the communication and freight transport from one region to another in a safe, reliable and cost-effective way.

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