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IMPACT OF STRUCTURE TESTING AND MONITORING IN BRIDGE ASSESSMENT

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Abstract

The basis for decisions on the maintenance and management of bridges are reports on the main visual inspection, which are carried out regularly every six years. However, some damage in early phase and/or internal structural defects cannot be detected by a visual inspection but require additional testing and monitoring of the structural condition. This is particularly important if we want to intervene in the early stages of damage and prevent accelerated deterioration of the structure in the future. Only in this way we can achieve optimal maintenance of the bridge, with the aim of reducing maintenance costs and extending service life of the structure. In this paper, impact of non-destructive testing, laboratory testing on taken samples and structural health monitoring on bridge assessment will be discussed using a case study. As a case study Maslenica Motorway Bridge is chosen as a bridge of significant importance in multi-hazard environment. The applied new approach to bridge assessment focuses on five groups of key performance indicators, one of which is presented in detail: Safety, reliability and security. The results, based on visual inspection, non-destructive testing, destructive testing and laboratory testing, structural health monitoring and design, and numerical analysis, are presented and evaluated. The impact of each method in determining each performance indicator and the final KPI rate is identified.

Keywords: bridge, non-destructive testing, laboratory testing, assessment, visual inspection, durability, performance indicators

1 Introduction

The basis for decisions on the maintenance and management of bridges are reports on the main visual inspection, which according to Croatian legislation must be carried out every 6 years following a defined protocol [1]. However, some damage in early phase and/or internal structural defects cannot be detected by a visual inspection but require additional testing and monitoring of the structural condition. This is particularly important if we want to intervene in the early stages of damage and prevent accelerated deterioration of the structure in the future. Only in this way we can achieve optimal maintenance of the bridge, with the aim of reducing maintenance costs and extending service life of the structure. Moreover, a visual inspection cannot provide all the necessary information, e.g., an assessment of bearing capacity. Therefore, a new approach to bridge assessment is developed based on weighted average approach for qualitative bridge evaluation [2]. In this approach, a bridge is evaluated in groups of five key performance indicators: (1) safety, reliability, and security; (2) availability and maintainability; (3) costs; (4) environment; and (5) health and politics; based on comprehensive data analysis.

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This paper is focused only on one group of the key performance indicators: safety, reliability and security. The results, based on visual inspection, non-destructive testing, destructive and laboratory testing, structural health monitoring and design and numerical analysis are presented and evaluated. The impact of each individual method in determining the individual performance indicator as well the final KPI rate is determined.

2 Assessment of the key performance indicators of large bridge in aggressive environment

2.1 Case study: Maslenica Motorway Bridge

The Maslenica Motorway Bridge is reinforced concrete arch bridge built in 1997 on Croatian Adriatic coast (Figure 1). The Maslenica Bridge has a wide concrete superstructure and a narrow fixed reinforced concrete arch with a span of 200 m. The superstructure consists of eight single-span, post-tensioned precast girders connected by a concrete deck slab cast in-situ over 12 spans: 6+10x30+24 = 350 m. Superstructure width is 21,42 m and provides four lanes, a median and safety strips adjacent to the concrete safety barriers on both sides [2, 3]. Although special attention was paid to durability during design, the bridge required repair after 20 years of operation because of very agressive multi-hazard maritime environment [1-3]. Damage caused by chloride-induced corrosion has propagated significantly and the bridge is repaired in 2018. Surface protection of structural elements involves corrosion inhibiting impregnation, structural repair mortar and protective coating, while at the most ex-strength steel fibre reinforced concrete is applied and concrete cover depth is increased [3].

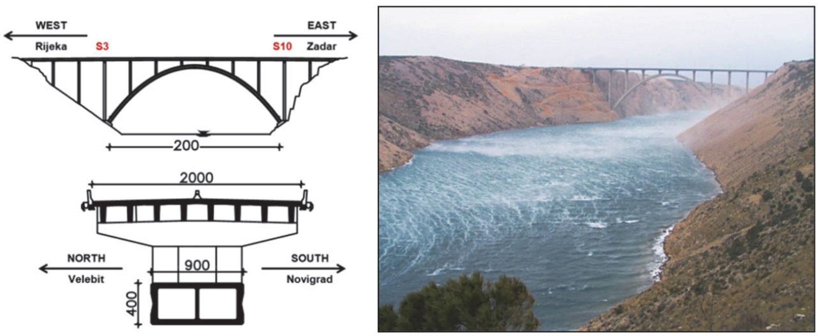

Figure 1 Maslenica Motorway Bridge: bridge layout (left) and Bora wind at the bridge location (right)

During the twenty years of operation, the following methods and measurements were carried out on the Maslenica Bridge: structural health monitoring of arch and superstructure, non-destructive testing of all elements, destructive testing and laboratory tests on samples taken from the structure; numerical analyses using the finite element method and meteorological monitoring of the environment. Prior to the repair of the structure, three major visual inspections were conducted: in 2006, 2010, and 2012 [2].
As a case study for new method of bridge assessment, the condition of the Maslenica Bridge is analysed before the repair works. The analysis includes an overview of the design project, structural health monitoring during construction and operation, numerous laboratory and in-situ testing, numerical analysis of structural capacity and remaining service life, and meteorological monitoring of the bridge site.

2.2 Novel approach to bridge assessment using performance indicators

A new approach to bridge assessment is developed which includes not only a deterioration index, but five groups of key performance indicators (KPI): (1) safety, reliability, and security; (2) availability and maintainability; (3) costs; (4) environment and (5) health and politics.

Table 1 Description of rating factor of the key performance indicators (r_{KPI}) [2]

r_{KPI}	**Description**
$0 \le r_{KPI} \le 1$	Good condition - no intervention needed.
$1 < r_{KPI} \le 2$	In generally good condition – maintenance is required.
$2 < r_{KPI} \le 3$	Marginal condition - minor rehabilitation is required.
$3 < r_{KPI} \le 4$	Poor condition - repair or rehabilitation is required.
$4 < r_{KPI} \le 5$	Critical condition - repair or rehabilitation is urgent.

At first performance indicators (PIs) are analysed in order to assess not only the durability of the bridge but also other important aspects – key performance indicators (KPIs). Furthermore, performance indicators are evaluated based on the degree of degradation described as rate (R = 1-5), but also considering the weight or significance of each PI to the corresponding KPI. The rate represents the degree of performance indicators (R = 1 means no damage, good condition, or observation favourable for the bridge, while R = 5 includes defects, conditions, or observation in the worst stage present serious danger to KPI, and intervention on the bridge is needed immediately or within 5 years at least). The weights represent the impact of PI on the respective KPI, where 0 means that there is no effect on the respective KPI during the remaining service life of the bridge, while 1 means that a particular PI has a very high influence on the respective KPI. The rating factor of the main five groups of key performance indicators (rKPI) can be calculated according to:

$$r_{KPI} = \frac{\sum_{i=1}^{n} R_i \cdot W_i}{\sum_{i=1}^{n} W_i} \tag{1}$$

where R_i is the rate of the PI_i and W_i is the weight of the PI_i for a certain group of the KPI. The description of the rating factor of the key performance indicators is shown in Table 1.

2.3 Assessment of PIs for Maslenica Bridge case study

A comprehensive list of PIs correlated with responding KPIs is the result of many years of research and large databases including results of visual inspections, provided NDT and laboratory testing, project documentation, bridge assessment, numerical modelling, etc. Some PIs are easier to determine (e.g. state of equipment based on the visual inspection and review of maintenance program), while another requires more study. However, in the framework of this study, all relevant PIs are included [2, 4-7].
In order to assess PIs and KPIs, it is necessary to define the main degradation mechanism, the most vulnerable zones, critical elements, and the dominant bridge load. Results of the investigation work clearly indicate that the chloride-induced corrosion of reinforcement is the main degradation mechanism, while the most deteriorated elements are piers above arch abutments, pier P3 and P10 (Figure 1) [2].

Weights or impacts 0-1 are assumed based on knowledge and experience with arch bridges in general, particularly those built on the Adriatic coast. Rates from 1-5 are based on the project design, results of SHM during construction and in service, load-testing prior to the bridge opening, results of previous visual inspections, laboratory and non-destructive testing, structural assessment, and numerical analysis on service life prediction [2].

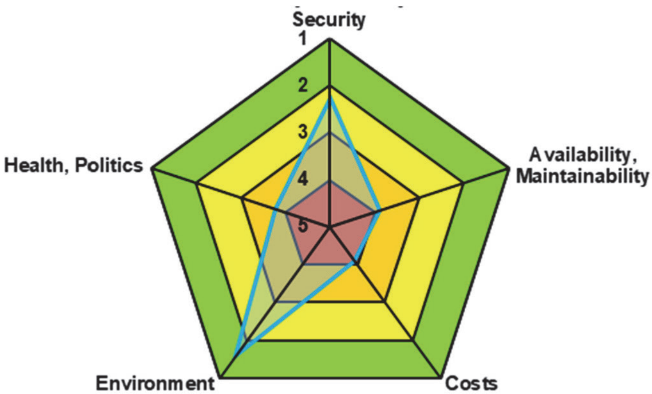

Figure 2 Spider diagram of all assessed key performance indicators (KPIs) for the Maslenica bridge prior repair [2]

The final results of all assessed KPIs are presented in the form of a coloured spider diagram (Figure 8). The spider diagram is represented by traffic light colours: green areas represent the most favourable rate, yellow and orange areas should warn the bridge operator, while red areas require immediate intervention [2].

2.4 Impact of testing and evaluation methods on assessment of KPI

The assessment of the KPIs relating to safety, reliability and security is presented in detail to analyse the impact of the various test and assessment methods on the assessment of the performance indicators. For this group of the KPI, the 66 PIs are divided into several groups: Concrete cover deficiencies, material parameters, structural performance, equipment, loads and environmental impact, in order to better systematise the work (Table 2) [2].
The results of construction monitoring are taken into account in the assessment of the following PIs: (i) arch displacement (ratification required); (ii) sag, deformation, denivelation, differential displacement; and (iii) cracks that occurred during or immediately after construction [2]. Defects in concrete cover: cracks, crumbling, delamination, detachment, segregation, concrete layers and insufficient thickness of concrete cover are mainly detected and assessed by visual inspection and non-destructive testing [2].
Chloride-induced corrosion of the reinforcement is analysed using all available methods: visual inspection, non-destructive testing, destructive testing and laboratory tests, numerical analysis to predict service life and structural condition monitoring. The results of the visual inspection, in-service corrosion monitoring, laboratory testing, non-destructive testing and service life prediction analysis allow the evaluation of the following PIs: pitting corrosion (chlorides); chloride content; corrosion rate (electrical potential, current density); degree of damage (expansion); deterioration index, remaining service life; application of the protective coating and aggressive maritime environment (Figure 3). The detailed investigation has shown that not only the elements in the splash zone, but all elements are susceptible to corrosion of the reinforcement due to the specific maritime environment, especially due to the influence of wind [2].

The results of the destructive and laboratory tests have shown that the strength and modulus of elasticity of the concrete are higher than the values specified in the design, while the permeability is higher than expected, which is unfavourable because it accelerates the penetration of chloride in concrete and active corrosion of reinforcement [2]. The analysis of the structure's bearing capacity is used to evaluate the KPI in terms of safety, reliability and security using the following PIs: bearing capacity, reliability index, safety index, frequency, stiffness, etc.
The rating factor for the key performance indicators related to safety, reliability and security is calculated as r_{SRS} = 2,25, which indicates a marginal condition requiring minor rehabilitation. This value results from the relatively good load-bearing capacity of the structure, the satisfactory mechanical parameters and conditions and the poor condition in terms of degradation of the structure and equipment due to the aggressive maritime environment [2] (Figure 3).

Table 2 Assessment of key performance indicators: safety, reliability and security based on different evaluation methods

KPI ASSESSMENT			**SOURCE OF ASSESSMENT***				
PI	**rating (1-5)**	**weighting**	**VI**	**NDT**	**DLT**	**SHM**	**DNA**
crack length	2	1	0,50	0,50			
crack orientation	3	1	0,50	0,50			
crack width	3	1	0,50	0,50			
crack spacing	2	1	0,50	0,50			
cracks generated during or immediatly after construction	4	0,8	0,50	0,50			
structural cracks	2	1	0,50	0,50			
corrosion induced cracks	4	1	0,50	0,50			
crumbling of concrete cover at safety barrier)	3	0,5	0,30	0,70			
delamination / detachment of concrete cover	4	1	0,30	0,70			
insufficient concrete cover	3	1	0,30	0,70			
layering (concrete)	3	0,8		1,00			
concrete segregation	3	0,8	0,30	0,70			
concrete strength deficiency: arch	1	0,7		0,50	0,50		
concrete strength deficiency: superstructure	1	0,8		0,50	0,50		
concrete strength deficiency: piers	1	1		0,50	0,50		
concrete strength deficiency: abutments	1	0,8		0,50	0,50		
concrete strength deficiency: foundations	2	0,7		0,50	0,50		
modulus of elasticity: arch	1	0,7		0,50	0,50		
modulus of elasticity: superstructure	1	0,8		0,50	0,50		

KPI ASSESSMENT			SOURCE OF ASSESSMENT*				
PI	rating (1-5)	weighting	VI	NDT	DLT	SHM	DNA
modulus of elasticity: piers	1	1		0,50	0,50		
modulus of elasticity: abutments	1	0,8		0,50	0,50		
modulus of elasticity: foundations	3	0,7		0,50	0,50		
arch displacement (reatification needed)	1	0,7	0,33	0,33	0,00	0,33	
sag / deformation / denivelation / differential displacement	1	1	0,33	0,33	0,00	0,33	
absent (missing) structural component	1	0,8	1,00				
presstresing cable failure: superstructure	1	0,8					1,00
carrying capacity factor	1	0,8					1,00
stiffness	1	0,5					1,00
damping	2	1		0,33		0,33	0,33
frequency	1	1		0,33		0,33	0,33
vibrations/oscillations	1	0,8		0,33		0,33	0,33
reliability index	1	0,5		0,33		0,33	0,33
safety index	1	0,3		0,33		0,33	0,33
element functionality level	1	1		0,33		0,33	0,33
importance of bridge element	4	0,8	0,50				0,50
asphalt pavement cracking	4	0,5	1,00				
deterioration of equipment component-stairs in arch	5	0.2	1,00				
approach slab settlement	1	0,2	1,00				
asphalt pavement wearing and tearing (rutting, ravelling)	4	0,3	1,00				
asphalt pavement wheel tracking and wrinkling and undulation	4	0,4	1,00				
blistering of protective coating	3	0,8	1,00				
cornicles and curbs defects	3	0,3	1,00				
corrosion related to equipment made of steel	4	0,9	1,00				
deterioration of protective coatings (e.g. corrosion protection, impregnate...)	4	0,8	1,00				
waterproofing deterioration/loss	2	0,5	1,00				
drainage	2	0,3	1,00				
bearings displacement/ deformations / defects	3	0,5	1,00				

KPI ASSESSMENT			SOURCE OF ASSESSMENT*				
PI	rating (1-5)	weighting	VI	NDT	DLT	SHM	DNA
insufficient height of railing (safety barrier)	1	0,3	1,00				
expansion joint (waterproof, damage)	4	0,7	1,00				
Assessment on trafic load	1	0,8					1,00
Assessment on wind load	1	0,8					1,00
Assessment on seismic load	1	0,8					1,00
seismic activity of the area	4	0,8				1,00	
Extreme traffic load	2	0,5				1,00	
Extreme wind	4	0,5				1,00	
inadequate clearance	1	0,3				1,00	
Erosion	1	0,1				1,00	
settlement	1	0,5				1,00	
wetting - drying	4	0,9				1,00	
carbonation depth	2	0,8			1,00		
pitting corrosion (chlorides)	3	1		1,00			
chloride content	5	0,9			1,00		
Corrosion rate (electrical potential, current density)	4	0,9		0,50	0,50		
Impact (e.g. of vehicles or ships)	1	0,3	0,50			0,50	
Rock fall	1	0,5	0,50			0,50	
Scour	1	0,5	0,50			0,50	
Total rating	**2,25**	**Percentage**	**35%**	**25%**	**10%**	**17%**	**13%**

* VI = visual inspection, NDT = non-destructive testing, DLT = destructive and laboratory testing, SHM = structural health monitoring, DNA = design project and numerical analyses

Figure 3 Corrosion of the reinforcement on structural elements of the Maslenica Bridge before and during repair

Table 3 Assessment of key performance indicators: safety, reliability and security based mainly on results of visual inspection

KPI ASSESSMENT			SOURCE OF ASSESSMENT*				
PI	rating (1-5)	weighting	VI	NDT	DLT	SHM	DNA
crack length	2	1	0,50	0,50			
crack orientation	3	1	0,50	0,50			
crack width	3	1	0,50	0,50			
crack spacing	2	1	0,50	0,50			
cracks generated during or immediatly after construction	4	0,8	0,50	0,50			
structural cracks	2	1	0,50	0,50			
corrosion induced cracks	4	1	0,50	0,50			
absent (missing) structural component	1	0,8	1,00				
importance of bridge element	4	0,8	0,50				0,50
asphalt pavement cracking	4	0,5	1,00				
deterioration of equipment component-stairs in arch	5	0.2	1,00				
approach slab settlement	1	0,2	1,00				
asphalt pavement wearing and tearing (rutting, ravelling)	4	0,3	1,00				
asphalt pavement wheel tracking and wrinkling and undulation	4	0,4	1,00				
blistering of protective coating	3	0,8	1,00				
cornicles and curbs defects	3	0,3	1,00				
corrosion related to equipment made of steel	4	0,9	1,00				
deterioration of protective coatings (e.g. corrosion protection, impregnate...)	4	0,8	1,00				
waterproofing deterioration/loss	2	0,5	1,00				
drainage	2	0,3	1,00				
bearings displacement/ deformations /defects	3	0,5	1,00				
insufficient height of railing (safety barrier)	1	0,3	1,00				
expansion joint (waterproof, damage)	4	0,7	1,00				
Impact (e.g. of vehicles or ships)	1	0,3	0,50			0,50	
Rock fall	1	0,5	0,50			0,50	
Scour	1	0,5	0,50			0,50	
Total rating	**2,83**	**Percentage:**	**80%**	**13%**	**0,00**	**5%**	**2%**

* VI = visual inspection, NDT = non-destructive testing, DLT = destructive and laboratory testing, SHM = structural health monitoring, DNA = design project and numerical analyses

If we consider only visual inspection as base for evaluation (at least in a share of 50% if combined with other methods), the number of analysed performance indicators will drop from 66 to 26, while for this case study rating factor for the key performance indicators related to safety, reliability and security would be r_{SRS} = 2,83 (Table 3). A bit higher rate is consequences of not including important performance indicators which cannot be assessed by visual inspection, e.g. assessment on traffic, wind and seismic load, chloride profile, corrosion rate etc. Using only a visual inspection, it is not possible to evaluate load-bearing capacity of the structure on the one hand, and on the other hand, the risk of corrosion is underestimated because the chloride content and corrosion rate cannot be accurately determined.

3 Conclusion

This paper presents a novel approach for the assessment of bridges, illustrated by a case study of Maslenica Bridge. This approach includes design, numerical analysis, structural health monitoring, laboratory and in-situ tests during construction and exploitation until repair. Based on all the data collected, a comprehensive assessment is made taking into account the five key performance indicators, which not only consider reliability and maintainability, but also economic, environmental, political and social aspects.
The assessment of the KPIs relating to safety, reliability and security is presented in detail in order to analyse the impact of the various testing and assessment methods on the evaluation of the 66 performance indicators. Based on the performance indicators analysed and assessed, the results of the visual inspection provide only one third of the information for a comprehensive analysis. A quarter of the data for PIs estimation relates to non-destructive testing. The next important method for assessing the condition of the bridge is continuous monitoring of the structure and the environment. Destructive and laboratory tests as well as data from the project and numerical analyses provide 10-15% of the information for the final assessment.
If safety, reliability and security of structure is analysed only based on visual inspection, the number of observed performance indicators is reduced by 60%. The overall rating will not necessarily be worse, but it will be less accurate, namely, a visual inspection cannot determine hidden capacity reserves as well as internal damage and earlier stages of degradation. Since bridge owners are always faced with limited resources and a high demand for maintenance and rehabilitation of the structures, it is crucial to obtain the most reliable assessment of the bridges in order to achieve the best possible prioritization of structural maintenance in the bridge management system.
The presented comprehensive assessment of the bridge is necessary to achieve optimal and proactive bridge management, which is especially important for large and important bridges in an aggressive environment.

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