QUALITY SPECIFICATION FOR CONCRETE BRIDGES VULNERABLE TO REINFORCEMENT CORROSION

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Abstract. Current policies of bridge management system at different road authorities in Croatia are presented in this paper. Although reinforcement corrosion is the major cause of concrete bridge deterioration, quality control plan that would provide efficient and effective bridge management system has not been implemented on satisfactory level to assure pro-active maintenance. Quality control plan for concrete bridges vulnerable to reinforcement corrosion, proposed in this research, includes visual inspection supplemented with the non-destructive testing and structural health monitoring as well as numerical models for service life predictions using recently developed 3D chemo-hygro-thermo mechanical model. The proposed quality control plans will be demonstrated on six concrete bridges of different load-bearing type, age, material and traffic demands exposed to continental and maritime environment.

Keywords: concrete bridge, structural health monitoring, corrosion, numerical model, service life prediction.

1. Introduction

According to the *Decision on the classification of public roads* (2017), the total length of the classified roads in Croatia is 26 822.85 km of which: motorways 1 419.5 km, national roads 7 129.62 km, county roads 9 486.69, local roads 8 787.04 km. The overwhelming majority of the bridges on the Croatian national roads are made of concrete: reinforced (RC) and prestressed (PC), while vast majority is girder type of bridges, followed by arch as the second most common load-bearing system (Tenžera *et al.* 2012). Similar distribution according to construction materials and load-bearing systems applies to other road bridges in Croatia.

The major cause of deterioration of RC and PC bridges and reduction of their service life is corrosion of steel in concrete. Bridge decks exposed to de-icing salts as well as elements of bridge in maritime environment in splash zone are particularly vulnerable (Kušter Marić et al., 2016).

Current policies of bridge management system in Croatia will be shortly presented in this paper, followed by new ideas for improvement of quality control plans for bridges vulnerable to reinforcement corrosion. In order to develop consistent maintenance policy that would provide efficient and effective management of RC and PC bridges, a new research project has started and includes (CODEbridges, 2017): (i) numerical model for service life prediction; (ii) structural health monitoring (SHM) on the existing bridges and (iii) laboratory testing.

2. Current policies of bridge management system in Croatia

In the framework of the current project (CODEbridges, 2017) researchers from the University of Zagreb collaborate with the University of Stuttgart and four road authorities (Table 1) responsible for management, construction and maintenance of approximately 3 300 bridges in total on different type of roads in Croatia: motorways, national, county and local roads as well as city bridges.

All four authorities have updated database of bridges, while bridge management systems (BMS) have been established only by two authorities responsible for roads of higher classes (motorways and national roads) in last two decades (Radić *et al.* 2007, Tenžera *et al.* 2012). However, regardless of the BMSs, decision on non-regular maintenance such as repair, strengthening and reconstruction are based on: (i) results of periodical visual inspections, mostly with more detailed programme such as annual or main inspection; (ii) natural (e.g. flood, landslide and earthquake) and mechanical (e.g. vehicle impact and boat collision) hazards, usually followed by non-periodical visual inspection. Once the decision on bridge intervention is made, special visual inspection and investigation works including destructive and non-destructive testing are conducted as part of a repair design project in order to define required scope of the project.

Although visual inspections are the most decisive method for making decision on bridge maintenance, time intervals between main inspections used to be longer than prescribed 6 years and carried out on an "as-needed" basis (Klanker *et al.* 2017). Authorities for roads of lower classes (county, local and un-classified roads) do not have uniform and standardized inspection protocol in order to assure objectivity of condition assessment. Furthermore, deficient comparison of condition assessment between current results and results of previous investigation works disables reliable

Table 1. Main data on bridge management used by road authorities included in the current research project CODEbridges

Road authority	Croatian Motorways Ltd.	Croatian Roads Ltd.	City of Zagreb	County roads of Krapina-Zagorje County
Total length of road network [km]	920.5 for each direction	7 129.62	2 589.0	661.23
Number of bridges	1 213 (l > 5 m)	≈ 1 800 (l > 2 m)	≈ 228 (l > 2 m)	70 (l > 5 m)
Road Classification	Motorways	National roads	Unclassified roads	County and local roads
Bridge Management System	Yes, since 2008	Yes, since 1996, updated in 2001	No	No
Updated bridge database	Yes	Yes	Yes	Yes
Type and frequency of visual inspection of bridges	Routine – regular road patrol; Seasonal – 2x/year; Main – 1x/6 years; Non-periodical – after hazards Special – as part of additional investigation works	Routine – regular road patrol; Annual – 1x/2 years, Main – 1x/6 years Non-periodical – after hazards Special – as part of additional investigation works	Routine – regular road patrol; Main – 1x/6 years; Non-periodical/ special – when needed	Routine – regular road patrol; Seasonal – 2x/year; Annual – 1x/2 years; Main – 1x/6 years Non-periodical/ special – when needed
Documents for unification and standardization of visual inspection	Guideline for bridge inspection, Handbook of damages on bridge elements, Guideline for bridge evaluation, Manual for repair and reconstruction of bridges, Standard inspection form, Graphic templates for recording defects and damages	Guidelines for bridge inspections, Handbook of damages on bridge elements, Guideline for bridge evaluation, Form for visual inspection and input in database, Graphic templates for recording defects and damages	-	Simple form for visual inspection
Duration of the program for investment in the maintenance	1 year	4 years	1 year	1 year
Basis for decision on repairs, reconstruction or demolition	Visual inspection and hazards	Visual inspection and hazards	Visual inspection and hazards	Visual inspection and hazards

estimation of current and future degradation rate of structure or its element, crucial for cost-effective management.

On the other side, the main cause of concrete bridge deterioration, reinforcement corrosion in concrete cannot be timely detected by visual inspection. During the initiation phase of reinforcement corrosion, there are no visible damages on concrete surface, while at the beginning of the propagation phase damage are hardly detected. Only damages in advanced stage of reinforcement corrosion, manifested in the form of cracking and spalling of concrete cover, can be detected during visual inspection.

3. Numerical models for prediction of service life of concrete bridges exposed to chlorides

Serious degradation of concrete bridges, caused by chloride induced corrosion, led to many complex and expensive repairs (Kušter Marić *et al.* 2016). In order to develop consistent maintenance policy that would provide efficient and effective bridge management, it is necessary to predict their remaining service life. To determine durability of new or already damaged structure, numerical models have been developed to realistically simulate corrosion processes in concrete and the consequences for the structure.

Generally, the models assume that the service life of the structure consists of two phases: initiation and propagation (Ranjith *et al.* 2016). The initiation phase is characterized by penetration of chlorides in concrete and ends with depassivation of steel rebar by reaching the threshold concentration of free chloride ions in concrete pore solution in contact with steel surface. The propagation phase includes electrochemical processes of dissolution of iron and formation of corrosion products (rust).

The mathematical models of processes before depassivation of reinforcement in un-cracked concrete have been developed in the last three decades and applied on existing structures exposed to chlorides (Stipanović Oslaković *et al.* 2010). On the other hand, there are a very limited number of coupled 3D chemo-hygro-thermo mechanical (CHTM) models that are capable of realistically simulate processes before and after depassivation of reinforcement bar in cracked concrete.

The recently developed 3D CHTM model used in this research for transient analysis of transport and corrosion processes in RC structures includes the following physical, electrochemical and mechanical processes (Ožbolt *et al.* 2010, 2011, 2012, 2016a, 2016b, 2017):

- transport of capillary water, heat, oxygen and chloride through the concrete cover;
- immobilization of chloride in the concrete;
- drying and wetting of concrete and related hysteretic property of concrete;
- transport of OH- ions through electrolyte in concrete pores;
- cathodic and anodic polarisation;
- mass sinks of oxygen on steel surface due to cathodic and anodic reaction;
- distribution of electrical potential and current density;
- transport of corrosion products in concrete and cracks;
- creep of concrete around the reinforcement bar, and
- concrete cracking due to mechanical and non-mechanical actions.

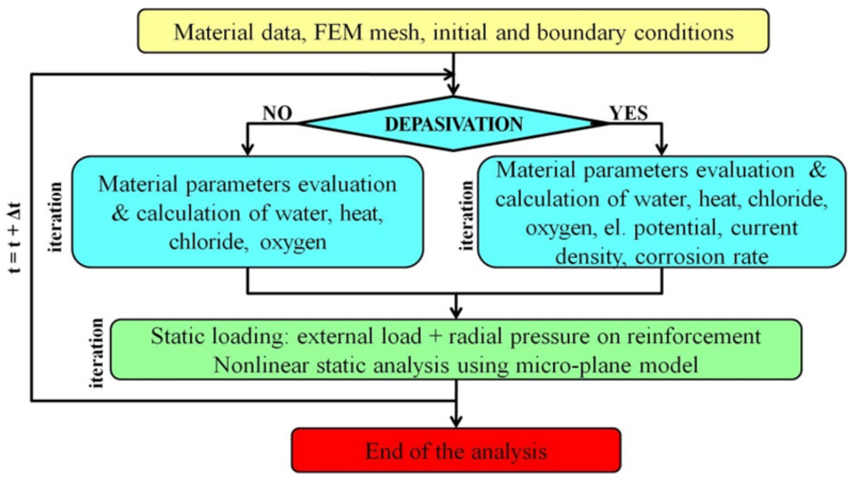

Fig. 1. Numerical algorithm of the 3D chemo-hygro-thermo mechanical model

The model was implemented into the 3D finite element code including the microplane model for concrete (Ožbolt et al., 2001). According to the available literature it is one of the most comprehensive models containing all of the following convenient features:

- The geometry of the structure and position of reinforcement bars can be optionally modelled in 3D spatial domain;
- The mechanical part of the model, based on the microplane model, is able to realistically simulate behaviour of a structure under different types of loading: static, dynamic, cyclic and impact loading
- Both phases, initiation and propagation are included;
- The model is able to simulate non-mechanical and mechanical processes and their interaction before and after depassivation of steel reinforcement;
- Influence of the concrete damages (e.g. cracks, voids, layering) on the transport and corrosion processes is taken into account by employing the concrete diffusivity as function of crack width based on the experimental results on concrete permeability;
- Transport processes are modelled to simulate both real effects of the maritime environment and laboratory conditions of accelerated corrosion by using time dependent boundary conditions.

One of the biggest advantages of the 3D CHTM model is taking into account many performance indicators (PIs) related to the material properties, environmental condition, concrete defects, structure geometry, mechanical loading and their multiple interaction. The 3D CHTM model proved its ability for realistically simulation of mechanical and corrosion processes on several case studies (Kušter Marić *et al.* 2016, 2017).

4. Case studies

Six concrete bridges exposed to chlorides are selected for visual inspection and NDT in the framework of this research (Table 2, Figure 2). The bridges are of different load-bearing type, age, material and traffic demands. Four of them are exposed to de-icing salts and continental climate, while two structures are located in maritime environment on the Adriatic Coast and attacked by sea salts and strong wind (Kušter Marić *et al.* 2016, Radić *et al.* 2008, Vlašić, Radić 2008).

Activities on the case studies are focused on achieving the following objectives:

- Determination of the structural elements of the bridges that are the most vulnerable to cracking and other damages in concrete due to mechanical and non-mechanical loading based on the performed ultrasonic testing on the bridges and numerical modelling;

Table 2. Case studies: basic data on bridges

Bridge	Maslenica Bridge	Šibenik Bridge	Žeinci Bridge	Adriatic Bridge	Bridge of Youth	Homeland Bridge
Type of bridge	Deck arch	Deck arch	Tied arch	Prestressed continuous girder	Composite girder	Externally prestressed box girder
Type of road	Motorway (4x3.50 m)	State road (7.5 m)	County road	Zagreb city road	Zagreb city road	Zagreb city road
Bridge authority	Croatian Motorways Ltd.	Croatian Roads Ltd.	County roads of Krapina-Zagorje County	City of Zagreb	City of Zagreb	City of Zagreb
Construction year	1993 -1997	1964-1966	1913	1981	1974	2006
Main span	200 m	246.40 m	24.50 m	63 m	66 m	120 m
Length	374.74 m	390.35 m	24.5 m	479 m	294 m	879 m
Width	20.40 m	10.76 m	6.0 m	36.8 m	36.5	34 m
Material of superstructure	Prestressed concrete	Prestressed concrete	Reinforced concrete	Prestressed concrete	Composite steel-concrete	Reinforced concrete
Material of substructure	Reinforced concrete	Reinforced concrete	Reinforced concrete	Reinforced concrete	Reinforced concrete	Reinforced concrete
Obstacle	Adriatic Sea	Krka river	Krapina River	Sava River	Sava River	Sava River
Environment	Maritime	Maritime	Continental	Continental	Continental	Continental
Year of last (main) visual inspections	2010	2005	2017	2017	2017	2017
Year of investigation works	2012	2009	-	-	1997*/2017* *approaching viaducts	-
Year of repair works	2017	2012	-	-	1997*	-

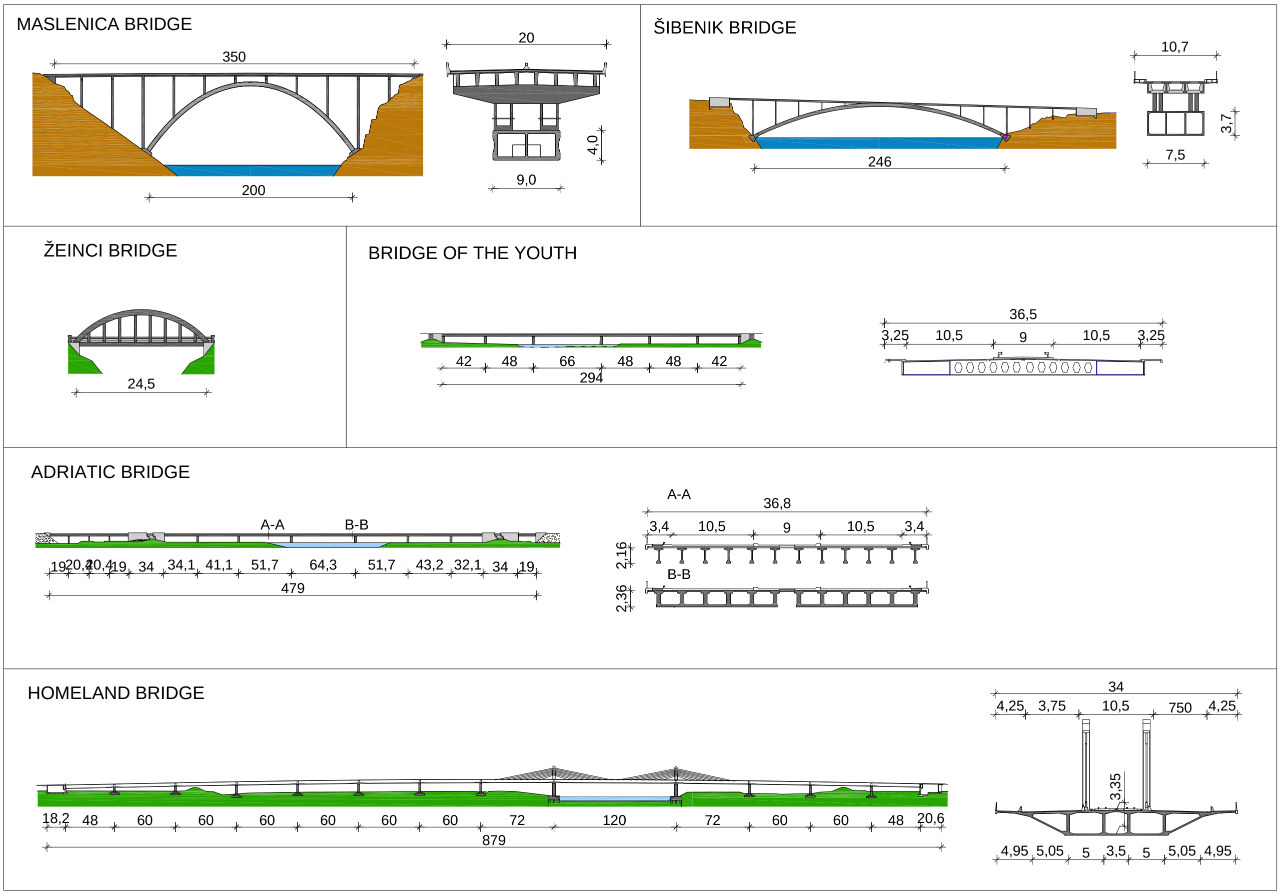

Fig. 2. Case studies: bridges layouts

- Determination of the structural elements of the bridges that are the most vulnerable to reinforcement corrosion based on the measured chloride profiles in concrete, the half-cell potential of steel rebar and electric resistivity of concrete on the existing bridges;
- Development of an empirical model of the impact of the concrete cracks on reinforcement corrosion based on the performed measurements of cracks in the concrete, electric resistivity of concrete and half-cell potential of steel rebar.

The case studies serve to verify and improve the 3D CHTM model, but also to evaluate feasibility, time, cost, adverse events and effect size (statistical variability) as a base for development of quality control plan for bridges vulnerable to reinforcement corrosion.

5. SHM programme for existing bridges

The assessment of bridge condition due to reinforcement corrosion is often based on the determination of the chloride content in concrete on the reinforcement level. Although taking concrete specimens for measuring chloride content in concrete is a reliable method for testing of reinforcement depassivation and propagation phase of corrosion, it is relatively expensive and, since it is destructive method, it is usually carried out once the damages are visible and decision on repair works was already made in order to determine the scope of intervention.

In order to switch maintenance policy from re-active to more efficient pro-active approach, new program of SHM is proposed based on the results of numerical modelling, investigation works on existing bridges and laboratory experiments. Ordinary visual inspection is method to detect only a progressive phase of corrosion, while comprehensive and continuous SHM including installation of large number of different type of sensors, due high cost, is feasible only for megastructures and the most important structures (Ahmad, 2003). Therefore effective quality control programme for concrete bridges program should include simple yet cost efficient NDT on PIs associated with structure load-bearing capacity as well as corrosion-related PIs.

The NDT (Table 3), that will be carried out on selected bridge case studies, is selected on the basis of the following favourable characteristics:

- Simple for use, fast to perform and cost-effective testing;
- Complemented by visual inspection, assure more reliable bridge assessment
- Measured PIs are included in the 3D CHTM model for service life prediction.

For sustainable QC plan it is necessary to correctly interpret the NDT results and on that basis to realistically predict remaining service life of bridges. Besides structural PIs, for a reliable simulation of RC or PC structure degradation, environmental and climate parameters (e.g. air temperature, relative humidity, wind direction, source and concentration of chloride contamination) are measured and included in the 3D CHTM model. Moreover, the measured values of chloride content in concrete, carried out in the framework of additional investigation works, will be used for the 3D CHTM model calibration and further application for a service life prediction of existing bridges.

Table 3. NDT included in SHM programme for the bridge case studies

NDT subject	NDT methods and techniques	PI	Impact on structure load –bearing capacity	Impact on reinforcement corrosion
Concrete quality and uniformity	Ultrasonic pulse velocity (UPV)	Compressive strength	●	
		Modulus of elasticity	●	
		Poisson's Ratio	●	
Cracks in concrete	Optical microscope	Crack width	●	●
	UPV	Crack depth	●	●
Concrete durability	Resistivity meter based on Wenner probe	Surface resistivity of concrete		●
Rebar assessment	Rebar locator	Rebar diameter	●	●
	Cover meter	Depth of concrete cover	●	●
	Voltmeter	Half-cell potential		●

6. Conclusions and further progress plan

1. Existing bridge management systems, where quality control plans are based on visual inspection, are not sufficient because some damages and defects can be detected in advanced stage only.
2. Since concrete is the most used material for road bridges and reinforcement corrosion is the main cause of concrete structure deterioration, quality control plans for concrete bridges should be improved to assure a more efficient pro-active approach to bridge maintenance.
3. Quality control plan for concrete bridges vulnerable to reinforcement corrosion, proposed in this research, includes visual inspection supplemented with the non-destructive testing and structural health monitoring as well as numerical models for service life predictions. Data obtained on the bridge will be used for calibration of the 3D chemo-hygro termo mechanical model in order to realistically predict the remaining service life of the structure.
4. The proposed quality control plans will be demonstrated on six reinforced or prestressed concrete bridges. Although results of measurements on the bridges and numerical models for simulation of the structure deterioration due to mechanical and corrosion processes cannot be directly generalized on the rest of the bridge network, it will present good case studies for assessment of roadway bridges vulnerable to the chloride induced corrosion, with valuable knowledge for bridge authorities, but also for the scientists and professionals dealing with the concrete bridge maintenance.
5. The 3D chemo-hygro termo mechanical model has proved its ability for realistically simulation of mechanical and corrosion processes on several case studies. However, quantifying the material, mechanical and corrosion related performance indicators and their interactions are still challenging tasks and main objective of the current research project. In order to improve 3D chemo-hygro termo mechanical model in terms of influence of concrete defects on reinforcement corrosion, an improved concrete diffusivity model will be developed as a function of crack width based on the laboratory testing on permeability of cracked concrete and investigation works on the bridges.

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