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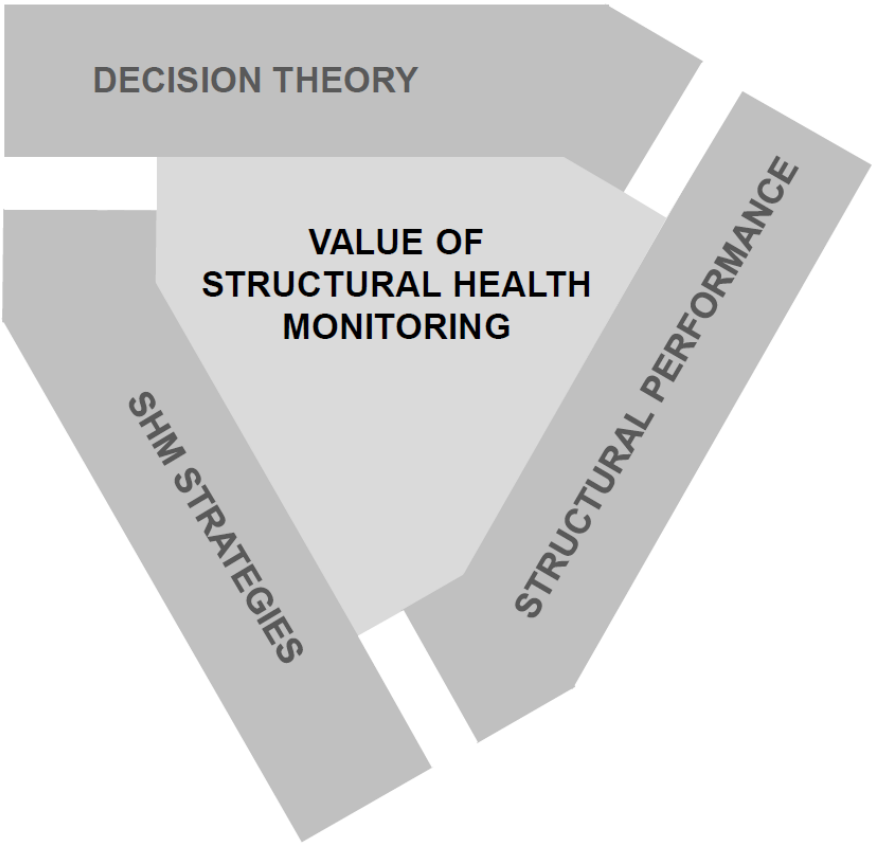
COST Action TU1402: Quantifying the Value of Structural Health Monitoring



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Finding a link between measured indicators and structural performance of concrete arch bridges

Ana Mandić Ivanković, Faculty of Civil Engineering, University of Zagreb
Jure Radić, Faculty of Civil Engineering, University of Zagreb
Mladen Srbić, Faculty of Civil Engineering, University of Zagreb

Objectives, abstract and conclusions

Objective of this paper is to establish the relationship between the research on existing arch bridges in Croatia and objectives of the Working Group 2– SHM technologies and structural performance of the COST action TU 1402. Research on development of assessment procedures for existing arch bridges is developing through last few years in Croatia as a part of an extensive project to develop their appropriate maintenance strategy. We believe that this experience is a good basis to create a valuable link between a certain indicator measurement and corresponding structural performances of interest for arch bridges.

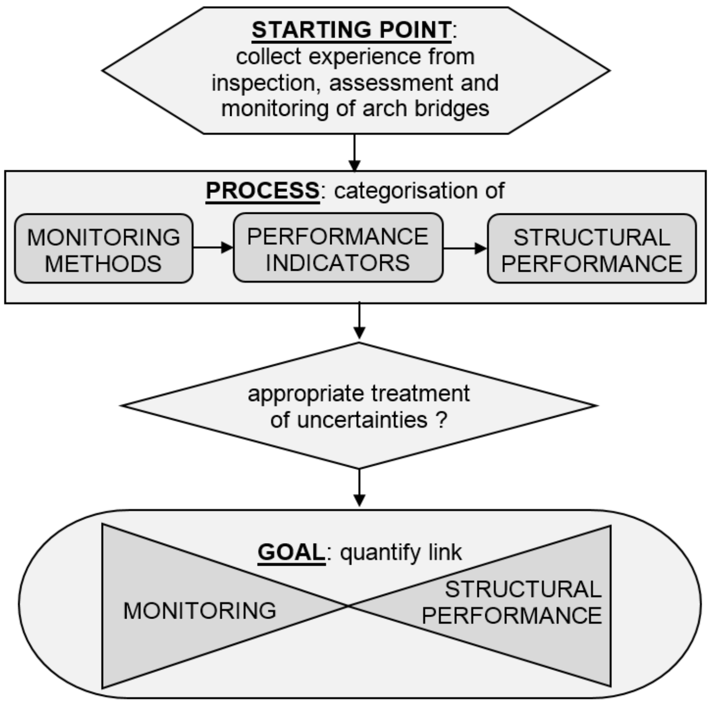


Figure 1: Flowchart of a proposed research activity

One of the causes for rapid structural degradation of the first generation of Croatian Adriatic arches was underestimation of maintenance role in the past, mainly due to lack of funding for regular maintenance activities. More recently constructed arch bridges of second generation are designed taking into account the experience from in-service performance of older arch bridges and are equipped with a range of sensors for long-term monitoring, but again due to lack of founding those are not exploited appropriately. To eliminate the errors of the past and ensure efficient and effective performance of existing but also the future concrete arch bridges, the appropriate monitoring and maintenance strategy should be further developed.

In this paper, the idea of the activity flow with particular steps of the process to establish this relationship between Croatian research and WG2 objectives is elaborated (Figure 1).
Upon collecting experience on Croatian arch bridges, the categorization of monitoring methods, performance indicators and structural performances are to be deliver. Uncertainties in measuring data, collecting data and combining appropriate performance indicators that affect certain structural performance should be appropriately treated within the theoretical framework of this COST Action.
An overview of inspections, repair, monitoring and assessment of large Adriatic arch bridges, as a starting point of the activity, will be presented in more detail in this paper.

1 Introduction

Numerous issues need to be considered in order to achieve efficient and effective performance of existing concrete arch bridge. To define a correct structural model of the existing structure and to perform adequate structural analysis in order to properly assess the existing bridge it is necessary to identify desired knowledge level of the existing structure based on the bridge importance. For the bridges of the average importance that are not critical for communications, lower knowledge level may be required together with a higher value of confidence factor to determine properties of existing materials. For bridges of critical importance for maintaining communications, especially in the immediate post-accidental period and for major bridges where longer design life is required the higher knowledge level would be necessary with a lower value of confidence factor.
In order to get a valuable link between a certain indicator measurement (performance indicator) and corresponding property of structure (structural performance) of interest at the desired knowledge level, it is of a great importance to establish adequate data collection using approporiate methods (SHM methods) for arch bridges.
Therefore the first step of a research is to identify monitoring methods in regard to the quantity that is indicated, the second step is to categorise performance indicators important for efficient and effective performance of arch bridges and the third step is to define all types of structural performances important for arch bridges (Figure 2).
The final goal of the research, in accordance with the WG2 intention, is to find adequate relations between each step with approporiate treatment of uncertainties. Between the first and the second step, where we need to establish which monitoring method (technique) is to be used for measure certain quantity in order to define adequate performance indicator, uncertainties in measured data and in collecting data may appear. Beetwen the second and the third step of a research process, while capturing all the indicators that affect certain structural performance, uncertainties in combining approporiate indicators should be appropriately treated.

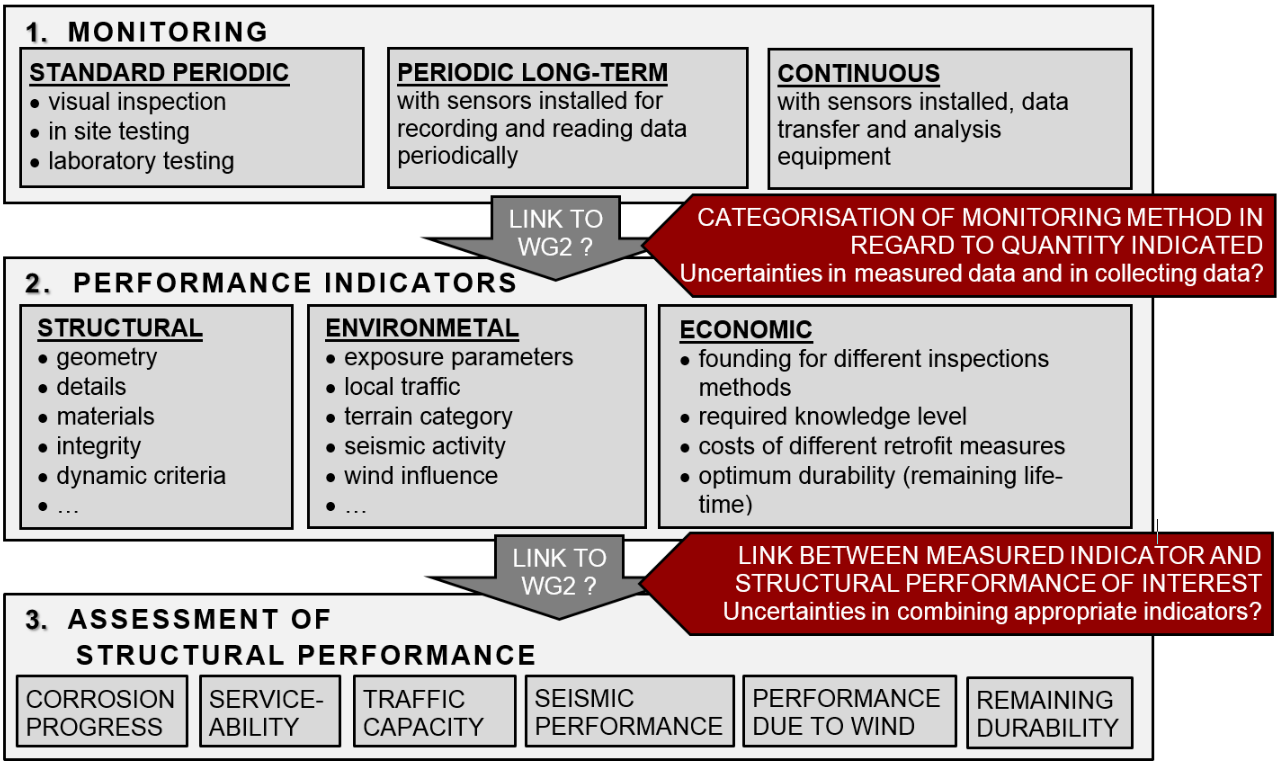


Figure 2: Research steps for quantifying the value of SHM of arch bridges

The experience with Adriatic arch bridges would be a solid base to prepare comprehensive guidelines for data collection on arch bridges to reach required knowledge level and to properly assess their performance abilities. Hopefully this paper, together with the paper submitted for the IABSE Conference 2015 (Mandić Ivanković et al. 2015), will present the start of this work plan to be further developed under the auspices of COST Actions TU 1402 and TU 1406.

2 Monitoring

According to COST 345 report (2008), monitoring can be defined as any periodic or continuous operation where the behaviour of a structure or structural components is quantified in some way so that its serviceability and stability can be evaluated. Reliability of a condition assessment of a structure will depend on the quality of the inspection. Two types of inspection can be considered:

- standard periodic inspections which will provide data on the structural condition in a particular time, but immediately after the inspection damage can be inflicted and deterioration processes can commence or accelerate which will require remedial works when the time between successive inspections is too long,
- continuous or long term monitoring with sensors installed at the structure, complete with data transfer and analysis equipment, to provide the data required to continuously and remotely track the condition of structure

In such sense SHM as a wider term, comprise standard inspection techniques performed periodically but following regular maintenance plan and continuous or periodic but long-term measurements of time variant measures.

Examples of standard inspection and investigation methods that are used in particular time at the Adriatic arch bridges are:

- geometrical surveying, visual inspection, loading tests,
- non-destructive methods such are: hammer sounding, rebound hammer, half-cell potentials, ultrasonic method, crack width measurements, …
- destructive test such are: pull of test, taking cores for laboratory testing for physical and mechanical properties, for permeability properties, for alkalinity properties and chloride content, for bond strength, ...

Additionally at the Skradin and Cetina bridge monitoring systems allows:

- periodic long-lasting displacement measurements with respect to the stabilized permanent datum marks
- periodic measurements with the help of anode-ladder sensors installed during construction to evaluate the corrosion progress.

Examples of measures that may be measured continuously are:

- strain, temperature and humidity on the structure of Skradin and Cetina bridge
- strain, acceleration, temperature, humidity, wind speed and direction and corrosion progress at Maslenica bridge and
- strain and temperature at two piers of the smaller Krk bridge.

3 Performance indicators

The performance indicators of arch bridges may be grouped as structural, environmental and economic. Structural indicators may be listed as:

- geometry (arch and pier axes, superstructure grade line, cross-section dimensions, …);
- details (built in reinforcement including amount and detailing of longitudinal and shear reinforcement and amount and detailing of confining reinforcement in critical regions, depth of concrete cover, connection between members (arch-pier, pier-superstructure, arch superstructure, continuous superstructure or the simply supported set of beams), support conditions, surface conditions,…;
- material properties (concrete strength, steel yield strength, modulus of elasticity, ..).

Additionally, dynamic criteria such are the required participation of effective modal masses, adequate stiffness distribution of spandrel columns and determination of reference point for forming capacity curves, need to be properly incorporated in seismic assessment (Franetović et al. 2014).
Environmental indicators include exposure parameters (of which most dangerous are sea-water splashing, tides, de-icing agents), local traffic, seismic activity, terrain category, wind influence.
Over the years, many deficiencies and advanced stage of deterioration processes were identified on older Adriatic Bridges. Chloride attack due to maritime exposure, followed by cracking, delamination, splitting and peeling off of concrete is identified as major deterioration mechanism (Radić et al. 2006).
Economic parameters will comprise, on one hand, founding for different inspections methods for establishing desired knowledge level of existing structure and, on the other hand, costs of different retrofit measures that may be offered based on the bridge assessment results.

4 Structural performances

Assessment of an existing reinforced concrete arch bridge comprises assessing bridge serviceability, its capacity for traffic, seismic performance and performance due to wind load (Mandić et al. 2010). Revealing corrosion progress is important to identify the effect of deterioration on the structural performance of each type. Based on those performance aspects, the prediction of service life (remaining lifetime) of the bridge in agreement with optimum durability request should be established.
Interaction of all types of indicators in assessing a performance of an existing arch bridge is inevitable. Some examples are as follows.

- Cross section dimensions might be changed due to deterioration processes from combined exposure to the sea and wind or on the other hand because of applied repair activities. This may result in reducing or improving a certain structural performance ability.
  Numerical model for realistically simulate the corrosion of reinforcement is currently under development. The structural health monitoring system installed on the Adriatic arch bridges could provide valuable data for verification and improvement of the model, but also for the more precise determination of relevant parameters (Radić et al. 2012)
- Recorded representative real traffic data need to be multiplied by a dynamic amplification factor that depends on the roughness and the quality of the pavement. At the first assessment level, for the realistic traffic simulation, data of the year average daily traffic at the location with the largest number of heavy vehicles in whole country may be enough. Only at the second level of assessment (when the first one failed) the traffic load may be even more localized by using data of traffic flow at the exact bridge location as elaborated in Mandić et al. 2010.
- To define design response spectrum representing seismic action, the behavior factor based on ductility capacities of the structure needs to be adopted and on the other hand, the distribution of load for different pushover methods will depend on significant mode shapes of the structure. Ductility capacities of the structure will depend on detailing of confining reinforcement in critical regions (Franetović et al. 2014) and mode shapes of the structure might be changed due to changes of stiffness or structural joints for example.
- Wind load on a bridge will depend on slenderness of elements (which might be changed due to deterioration or with repair as shown at the Krk bridge example in Mandić Ivanković et al. 2014), parapets types (due to adding windshields to provide better serviceability) and the angle between the dominant wind direction and the bridge axis.

Economic parameters are hidden in required knowledge level for a particular bridge in accordance with its importance and consequences of its failure. Higher knowledge level will require more extensive inspection works and comprehensive bridge monitoring. In general, Inspections of major bridges are more exhausting and require well-experienced personnel to identify the damage and determine its cause and consequences. However, we need to be aware that the extent of inspections and test would greatly depend on the available costs provided by the investor so very often the engineer will need to assess the bridge condition based on a limited data collection. Therefore, it is of a great importance to establish the most significant locations of the arch bridge to be inspected, tested and monitored (Mandić Ivanković et al. 2015). Additionally the most critical structural cross sections are the ones evaluated as damaged in the visual inspection.

5 Collecting experience from Adriatic arch bridges

The Šibenik bridge spanning 246 m, built in 1966 was the first in the world to be constructed entirely by the free cantilevering method. The Pag bridge completed in 1968 with a span of 193 m is very similar in appearance and design. Three-cell box arches gradually increase depth from the springing towards the crown. They were constructed by suspended cantilever method with temporary stay cables and tie-backs anchored into the abutments of the superstructure at Šibenik bridge and directly into the rock at Pag bridge. Krk bridges, constructed in 1980 by an innovative procedure forming a trussed arch cantilevers, consists of two large reinforced concrete arches, of 390 m and 244 m span. Both arches are of three-cell box cross-section. To achieve exceptionally large spans it was necessary to reduce the dead load as much as possible. The structural members of minimum statically admissible dimensions were utilised, with very small concrete covers. The original superstructures of all those Adriatic bridges of first generation were designed as a series of simply supported grillages consisting of precast prestressed concrete girders joined by cast-in-place cross beams at supports and in the thirds of span.
More recently constructed Maslenica and Skradin bridges, serving two-lane carriageways, and Cetina bridge for a state road, are designed taking into account the experience from the in-service performance of older arch bridges and are equipped with a range of sensors for long-term control of stresses, strains and corrosion progress. The intention was to closely monitor both structural performance and durability related performance in order to facilitate the future maintenance activities by triggering timely adjustments and interventions (Radić et al. 2012).

5.1 Inspections and repairs of the first generation of Adriatic arches

The **Šibenik Bridge** is somewhat less exposed to aggressive maritime environment than other long span concrete arch bridges (Radić et al. 2003). The grade line of the Šibenik bridge was designed in one way slope with the convex camber of 5 cm. Already after 10 years of service, the grade line above the arch crown was 30 to 35 cm below the designed level (Figure 3 left). Namely deformations of arch due to the creep and shrinkage were much larger than anticipated in the design. The bridge was thoroughly inspected in 2005 (HIMK 2005). This was just third major inspection performed on this bridge over its 40 years history.
Following data were collected by geometrical surveying:

- arch (grade line of axis and top edge) at the distance of 5 m,
- roadway (grade line at the middle and at both edges of roadway next to curb, grade line of upper edges of both curbs and both cornices) in the cross-sections at abutments, piers, mid span and arch crown).

Visual inspection (Radić et al. 2008) comprised inspection of:

- traffic surface and adjecent bridge equipment: asphalt wearing course, sidewalks, railings, drainage system, expansion joints and bearings. They were checked for deterioration, cracking, water tightness and proper functioning (locking of expansion joints and bearings).
- massive structural concrete members were inspected for cracks, wetting, deficiencies in concrete cover, corrosion, honeycombs, splitting, scaling, spalling and delamination using special vehicle for inspection of hardly reachable parts of bridge.

Additionally,

- limited material testing comprising measurements of chloride ingress by rapid chloride test
- and measurements of concrete cover thickness

were performed at 20 locations of the bridge.

The most affected areas are at superstructure supports, designed as half-joints, where cracks opened in roadway slab above, allowing ingress of water as no waterproofing was installed.

Figure 3: Deflected vertical alignment of the Šibenik bridge built in 1966 (left) and deterioration of the superstructure (middle) and columns (right)

This is the main cause of deterioration of main griders and cross beams above pears (Figure 3 middle) showing poor condition of concrete (concrete cover spalling) and corroded steel reinforcement. Concrete sealing of cable ends are greatly damaged, and at few places even corroded cables are sticking out (Medak et al., 2006). Additionally, traces of wetting, cracks, corroded reinforcement and delaminations (Figure 3 right) were detected at most structural elements, but were not deemed to be critical for immediate repair. Measurements of concrete cover thickness fall into range of 4 to 80 mm, with the mean value of 37 mm. The chloride ions content testing showed that critical values were exceeded only at the location of arch springings.

Repair works on the **Pag Bridge** started already after a decade of its service, but did not prove efficient in terms of stopping the corrosion process. The detailed concrete arch inspection in the year 1998. showed severe cracking near the arch springings and peeleng off of the concrete cover at approximately 10 % of exposed surfaces due to the reinforcement corrosion. Arch deflections under test load were 25% larger than under the same loads in the first test performed prior to bridge opening. These disturbing results called for complete repair of the arch, comprising removal of the damaged concrete cover by a hydrodemolition device, grouting of all visible cracks, placing shotcrete minimum 4.0 cm thick strengthened by anchored reinforcement mesh and protected by special long-lasting elastic coating (Bleiziffer et al. 2011). These works were carried out in 1991. Both the superstructure and piers deteriorated even more inducing serious functional difficulties.
Major reconstruction commenced in 1999 when the original concrete superstructure was dismantled and replaced (Figure 4 left) by a completely new structure in steel (Šavor et al. 2008). The structural solution comprising steel provided reduction in the weight of the structure allowing for the increase in traffic design loads. It is important to notice that the dead load was already increased by 9.3% in 1991 with the measures applied for the repair of the arch. The bridge reconstruction solution comprising steel enabled that, after the new superstructure and column strengthening was executed, the dead load was 9.7% smaller than in the original bridge design. The new superstructure is lighter than the original one, but since the arch axis is designed as a thrust line for a certain permanent load, the distribution of lighter permanent load can be unfavourable and adversely affect the arch behaviour. The calculations revealed that the arch is capable of withstanding new loading within the designated threshold level only if the arch reinforcement contributes in the compressive zone and if the actual measured compressive concrete strength corresponding to Eurocode concrete class of C-50 is accounted for. The original design was based on the concrete grade C-35. Prior to the bridge re-opening to service the proof testing was carried out. The static and dynamic testing of the renovated bridge proved the

accuracy of the assumptions incorporated in the reconstruction design calculations, as the numerical and experimental results agree well. Columns were repaired by encasing in steel and concrete.

The latest inspection was carried out in 2009 (Bleiziffer et al. 2011) focusing on steel structure, but limited testing and visual inspection of the accessible parts of the arch were carried out as well. Inspection works included:

- visual inspection which revealed cracks, evidence of water penetration through cracks, seepage in from of calcification, corrosion stains, delamination, spalling of shotcrete and places with exposed corroded reinforcement ,
- hammer sounding which indicated delamination and cracks,
- rebound hammer to access concrete quality in-situ,
- half cell potential measurements at locations were visual inspection indicated active corrosion process revealed either medium or high risk of corrosion or parts where corrosion already propagates.
- laboratory testing of 19 concrete core samples
  - for physical and mechanical properties (concrete strength and modulus of elasticity),
  - for permeability properties (capillary absorption and gas permeability) indicating concrete quality,
  - for alkalinity properties and chloride content which at the reinforcement level is either below or above the critical value
  - for mortar/concrete adhesion
  - for shotcrete and coating thickness

These revealed substantial defects in the reinforced concrete arch protection system (Figure 4 right) and that further assessment works are necessary.

Figure 4: Pag bridge originally built in 1968 was repaired in 1999: new steel superstructure was installed by launching truss (left); delamination at the edge of the arch abutment as an example of defects in rc arch protection system (right, Bleiziffer et al. 2011)

Krk bridges are located in very aggressive marine environment including very high salinity (approximately 3,5%), very strong winds carying sea spray and winter drops of temperature below freezing point. They were designed with a too thin designed concrete cover of only 2.5 cm and althougt it had been planned to apply protective coating to the entire structure, only some parts were protected: some with epoxy coating and some with brittle polymer cement mortar (Ille et al. 2011). The former, as it is known, was not physically compatible with concrete and the latter as porous brittle coat even increased surface chloride concentration and penetration in concrete.

Maintenance works of the reinforced concrete structure of Krk Bridge started immediately after opening for traffic. (Beslać et al. 2010). The first general monitoring and restricted testing were performed in the years 1985 and 1986. Testing was restricted because the main part of the structure was not accessible. The conclusion was that the whole reinforced concrete structure must be protected. Towards the end of 1980's more than 20 protective systems were tested on-site in order to find the best solution for the protection of the entire reinforced concrete structure. Only two or three of them were partly satisfactory. Some of them that have being forced for the application made the reinforcement protection even worse. The reinforcement corrosion was accelerated, what is understandable because 1 to 2 cm of very good concrete cover was removed and replaced with more porous mortar. At the time, there were no chloride impermeable coats. Some parts of the bridge near the sea level were protected with best of those systems but they did not solve the problem. They helped only by the absorption of chlorides in the added mortar and prolongation of their penetration in the concrete. Examination of the underwater foundation elements of the larger arch revealed that their surface was covered by sea flora and fauna and concrete cover was damaged by the sea shell dwellings.

The repair works on the Krk Bridge started several years after its completion focusing on superstructure supports. Stiff framed connections between columns and longitudinal girders with cross girders were greatly deformed and cracked, probably because of concrete shrinkage and temperature change (Beslać et al. 2008). The bearings were completely reconstructed on 20 of 31 columns. Affixed connections through cross girders were destroyed, elastomeric bearings were built in and new pretensioned cross girders executed. This was done on the big arch bridge before more than 20 years ago.

In the 1990's, when very complex multipurpose moveable scaffolding was constructed specifically for the Krk Bridge, the works were broadened to include the repair of columns (Figure 5). Different repair techniques had to be devised for spandrel and approach columns. In general on short columns and on high columns above 15 m above sea level, 2 cm of concrete cover was demolished and reconstructed with 2 cm of high quality repair mortar M45 and polymeric coating and in some parts with 5 cm of high strength micro-reinforced concrete MC60/75 and impregnation. It was considered that weakened cross section of short columns (about 15%) is compensated by the increase of compressive strength of concrete, from concrete grade C40/50 after bridge construction up to C60/75 which was estimated lately on a number of cores from the structures. On lower parts of high columns, up to 20 m above sea level, from which 3 cm or even more of concrete cover was demolished, reconstruction was made with 5 cm of high strength self-compacted concrete MC60/75 reinforced with 50 kg steel fibres per m3 of concrete volume (Beslać et al. 2008, IGH 2001). The concrete was designed to be of the same compressive strength and static modulus of elasticity as the concrete in columns (C60/75, E 40 to 45 GPa). Starting from the year 2004 the arch has been repaired by removal of 2 to 3 cm of the contaminated concrete, its subsequent replacement with shotcrete and adding protective coating. Nearly all columns and lower parts of the arches have been protected. The efficiency of the system has been tested after 7 years of use by comparing chloride ingress in the protective system with the threshold value for the Krk Bridge and assessed as satisfactory (Ille et al. 2011).

For the investigation and testing of composite cross sections of repaired columns under load, optical sensors were built in columns S20 (abutment pier towards St. Marko) and S26 (highest spandrel column towards Krk island), of the small arch (Mavar et al. 2007) with different repair technologies (Figure 5 right). Optical sensors are 2 m long and have the possibility of measuring the deformation of 1 micron on length of 1 m (2 microns on length of 2 m). Before the bearings reconstruction on column S26 and its unloading some mechanical properties of its 25 years old concrete under the load of 1.750 kN were measured by optical sensors (Beslać et al. 2008). Those are surface of column cross section, relative deformation, compressive stress in concrete, static modulus of elasticity and temperature coefficient.

Cathodic protection was envisaged for the submerged elements that support the larger arch of the Krk Bridge (Ille et al. 2011). During 2010 an investigation into the efficiency of 9 protective systems applied at 13 trial surfaces was carried out. This included laboratory and on-site testing. Six protective systems were assessed as inadequate, due to one or combination of the following deficiencies: cracking and delamination observed on site, low adhesion, low thickness, low resistance to freeze/thaw in chloride aggressive environment, low crack bridging ability, discoloration in UV resistance test. The remaining three protective systems were assessed as provisionally adequate, as improvements are required to increase the adhesion to fully meet design specifications.

The works on the Krk Bridge initiated a further research into durability design of reinforced concrete structures in aggressive maritime environment, namely in developing further specifications for application of surface protection systems on damaged structures as well as integrating surface protection systems with concrete cover in the design of new structures in aggressive maritime environment.

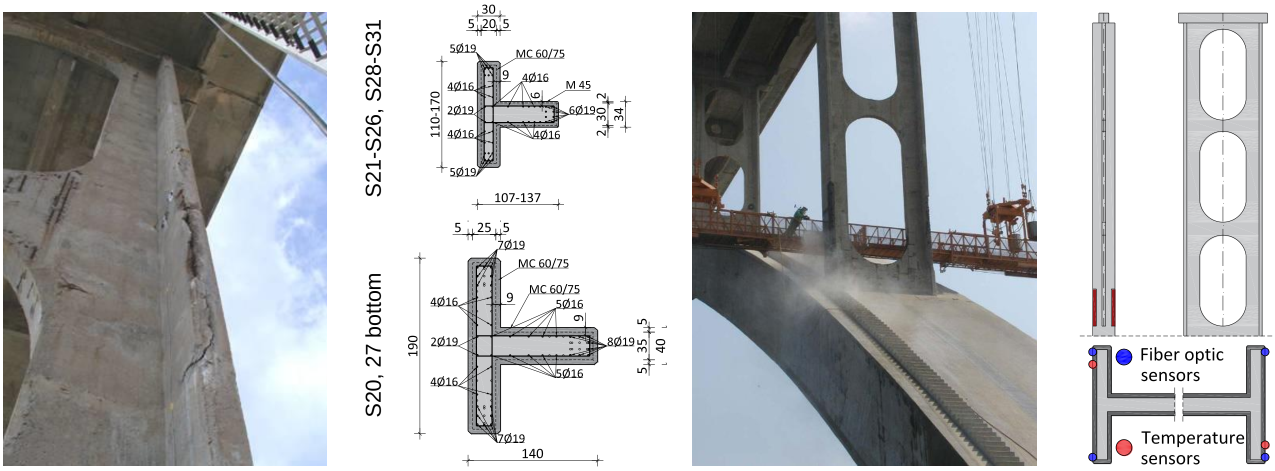


Figure 5: Deterioration (left) and repair (middle) of Krk bridge columns with the position of optical sensors embedded into columns during repair work (right, Mavar et al. 2007)

5.2 Monitoring of the second generation of Adriatic arches

The construction of the **Maslenica** highway **bridge** - a concrete arch of 200 meters span and rise of 65 metres (Čandrlić et al. 1999), started during war and was completed in 1997. It symbolizes the continuation of the tradition of building large concrete arches in Croatia. The cross section of the fixed arch is a double-cell box of constant depth. The bridge superstructure comprises eight simply-span precast prestressed girders made continuous over intermediate supports and interconnected by deck-plate cast in place, with cross-girders provided only at supports. The bridge design was strongly influenced by the severity of the marine environment and the seismicity of the site. Structural details and cross section were simplified to minimise execution problems. In order to avoid reinforcement congestion and increase durability all structural dimensions were increased, compared to previously built concrete arch bridges in the Adriatic coast area. The low permeability concrete has been designed which increased the bridge durability in marine exposures. The minimum concrete cover for all the bridge structural elements was set at 5.0 cm and for the arch foundations nearest to the sea at 10.0 cm. The number of structural joints has been reduced to a minimum, with most of the piers fixed to the superstructure and the expansion joints placed at the abutments only.

The monitoring system of Maslenica bridge (Šimunić et al. 1999), applied for the first time in Croatia, was used to record relative strains and accelerations (which serves to calculate stresses, velocities and displacements) at various construction stages and under load-testing prior to opening the bridge to the service. Monitoring of prestressed girders was used to investigate deflections, strains and stresses due to self weight and prestressing, natural frequencies of the girder after prestressing and strains and stresses in reinforcement due to creep and shrinkage. Strains and stresses of the arch during construction and dynamic properties before the construction of the superstructure were investigated as well (GF 2005). It appears that there was a considerable shrinkage of concrete in girders after their pouring because of a relatively small moisture level at summer time when the measurements were undertaken. This caused compression in the reinforcement. The stiffness of girders was determined by means of the

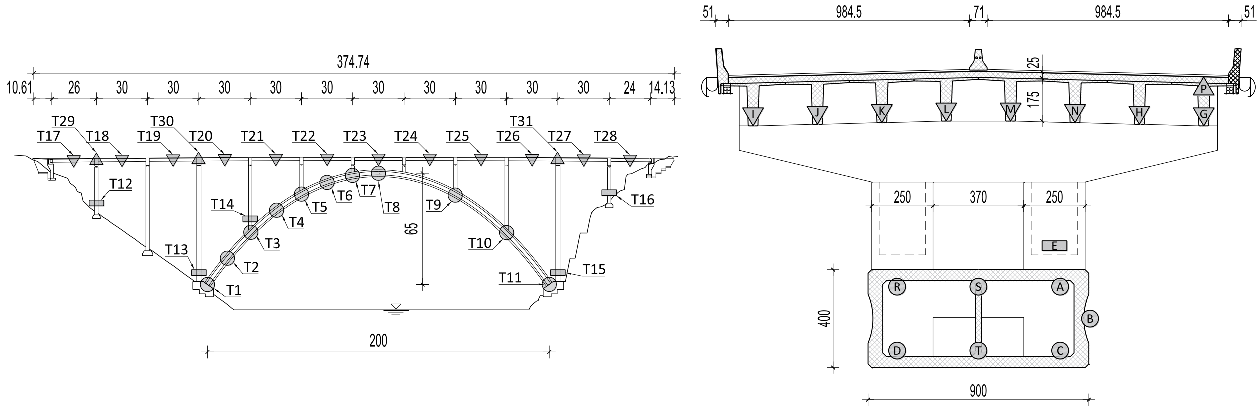
modulus of elasticity, by measuring their natural frequencies, and by means of concrete compression strength. By measuring stresses and displacements during construction and by comparing it with the values obtained by means of software which includes the material and geometrical non-linearity, a solid qualitative correspondence between theoretical and experimental research results has been established (Šimunić et al. 1999). Additionally, monitoring the environmental parameters such as air temperature, humidity, wind speed and direction was anticipated. Also the corrosion monitoring system was introduced which measures the strength of the corrosion current, electrochemical potential of the anode and the temperature and electrolytic resistance of concrete. Corrosion sensor contains electrodes made of reinforcing steel embedded at different distances from the concrete surface and at least one electrode made of stainless material that acts as a cathode. Using the conductor outside the concrete, the current between the electrodes and the electrical resistance of concrete, as an indicator of moisture content, are measured. As long as the electrodes are in carbonate and chloride free concrete, they are passively protected by the concrete alkalinity, so there is no flow of current between the electrodes. If the critical chloride concentration is exceeded, or alkaline protection disappeared due to the carbonation, reinforcement becomes exposed to the process of corrosion, as opposed to stainless material, and with the presence of oxygen and moisture the electrical circuit is formed.
The system consists of 92 strain-gauges as shown at Figure 7 top (18 on concrete and 74 on the reinforcement), 40 temperature sensors and 21 corrosion sensors (anode-ladder) mounted at carefully chosen spots on the arch and girders of the superstructure (Figure 8 top). They are connected by electrical wiring to a central unit, where recorded data is collected and processed by multi-channell measurement computer. These documented the initial condition of the structure needed as a reference for future measurements. Unfortunately, the monitoring project was stopped soon afterwards.
Thirteen years after the bridge was opened to traffic (Bleiziffer et al. 2011), in 2010, investigation works were carried out on Maslenica Bridge. They comprised:

- visual inspection of all structural members which was carried from mobile underbridge inspection unit and an arch inspection unit (Figure 6 middle), recording defect and registering cracks, together with identifying locations for taking specimens,
- chloride content measurements at 10 concrete samples taken at 2 positions of the arch abutments, 60 samples taken at 12 positions at the arch rib, 20 samples taken at the 4 positions of the column S3, 20 samples taken at the 4 positions of the column S10 and 10 samples taken at 2 positions of the superstructure (Figure 6 right).

Those investigation works revealed that the bridge is generally in good condition and in most structural members corrosion process is stil in the initiation stage. But there are some localized damage observed at the columns S3 and S10 (Figure 6 left) with the areas of exposed corroded reinforcement, and evidently concrete cover is at those locations less than 5 cm specified in the bridge design. This requires immediate repair and protection. Chloride measurements show that chloride penetration in concrete cover is uneven, and depends on location, with the higher content and deeper penetration in concrete members facing north. As there are locations where chloride content is reaching the threshold limit, it is suggested to apply a protective system to the entire bridge structure, in order to mitigate the future repair costs.

Figure 6: Maslenica bridge (Bleiziffer et al.2011): reinforcement corrosion on column S10 (Left); under bridge inspection unit (middle); taking dust samples for determination of chloride content and depth of chloride penetration into the concrete (right)

MASLENICA



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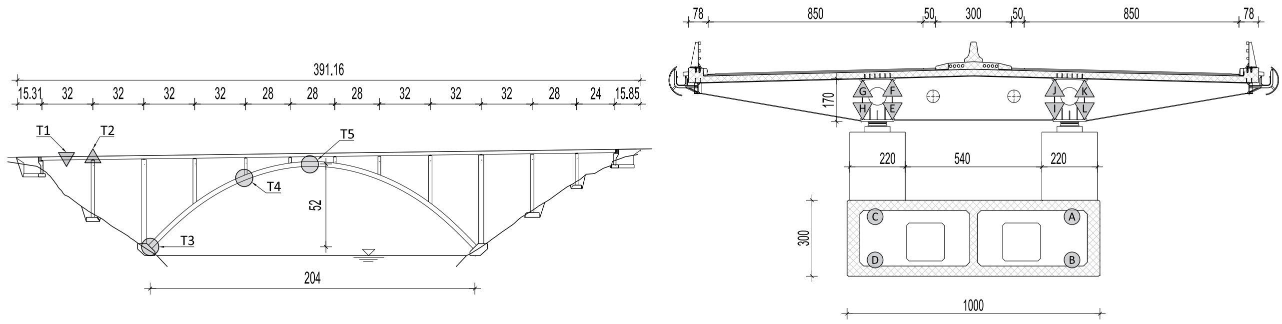
SKRADIN



T1	T2	T3	T4	T5
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CETINA

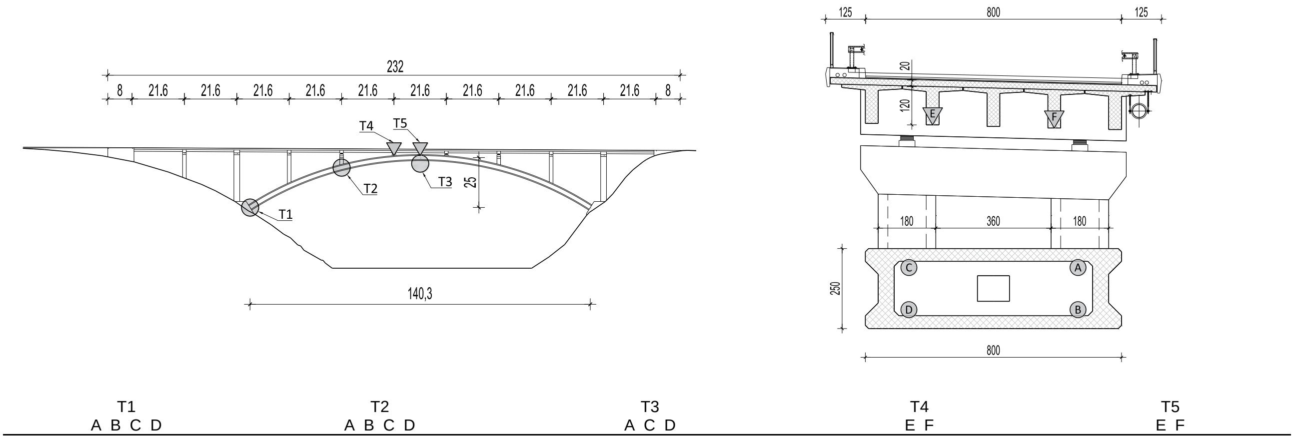

Figure 7: Location of strain gauges installed on Maslenica, Skradin and Cetina bridges

A concrete arch **Skradin Bridge** was constructed across the Krka River canyon (Radić et al. 2010) in the year 2005. Bridge spans 204 m with a rise of 52 m. It holds a unique position in the family of existing Croatian reinforced arch bridges because the bridge superstructure has been designed as a composite structure comprising steel girders and reinforces concrete deck plate, which resulted in substantial reduction of permanent actions. The arch itself is of considerably smaller dimensions than for the alternative solution with a prestressed concrete superstructure. The reduction of the total weight of the structure facilitated earthquake design as the bridge is located in the region of high seismicity. The arch was constructed by free cantilevering on traveling formwork carriages in 5.25 m long segments. The steel superstructure was erected by longitudinal launching in three phases. The concrete deck is formed by full depth precast slabs interconnected by on-site concreting of longitudinal and transverse joints above shear connectors. Steel corrosion protection has been adopted according to the latest standards for the most severe maritime environment.

Skradin bridge monitoring comprises structural and durability performance monitoring, with a smaller number of gauges than installed on the Maslenica bridge. The monitoring system (Rak et al. 2006) includes continuous monitoring of strain (Figure 7 middle), temperature and humidity on the structure, periodic displacement measurements, and periodic measurements to evaluate the corrosion progress (Figure 8 middle). The superstructure is instrumented with 16 strain gauges, 12 temperature sensors, and 1 humidity sensor. The arch is instrumented with 6 corrosion sensors (anode-ladder), 12 strain gauges, 9 temperature sensors, and 1 humidity sensor. Sensors were installed and some measurements were carried out even during the bridge construction phases.

The actual strain monitoring started during proof load testing in June 2005, before the start of bridge exploitation, and an initial report with measured values at all measurements locations is prepared. After that, the sensors are attached to loggers and strain, temperature and humidity data can be transferred via modem connection to the electronic computer, where they are read, stored and processed (Rak et al. 2010). Displacement control is performed twice a year at 13 spots in 4 lanes (each edge of each carriageway). Measuring points are located at abutments and over each pier. The displacement measurement is carried out with geodetic method with the use of precise geometric levelling (Rak et al. 2006). Reinforcing steel corrosion state measurements is carried out with the help of an instrument that measure following parameters: electric current, voltage, resistance of concrete and the temperature of the built-in sensors. Initial corrosion measurements were performed in May 2004. The expected frequency of the corrosion sensors readings is 2 to 4 times a year (Radić et al. 2008).

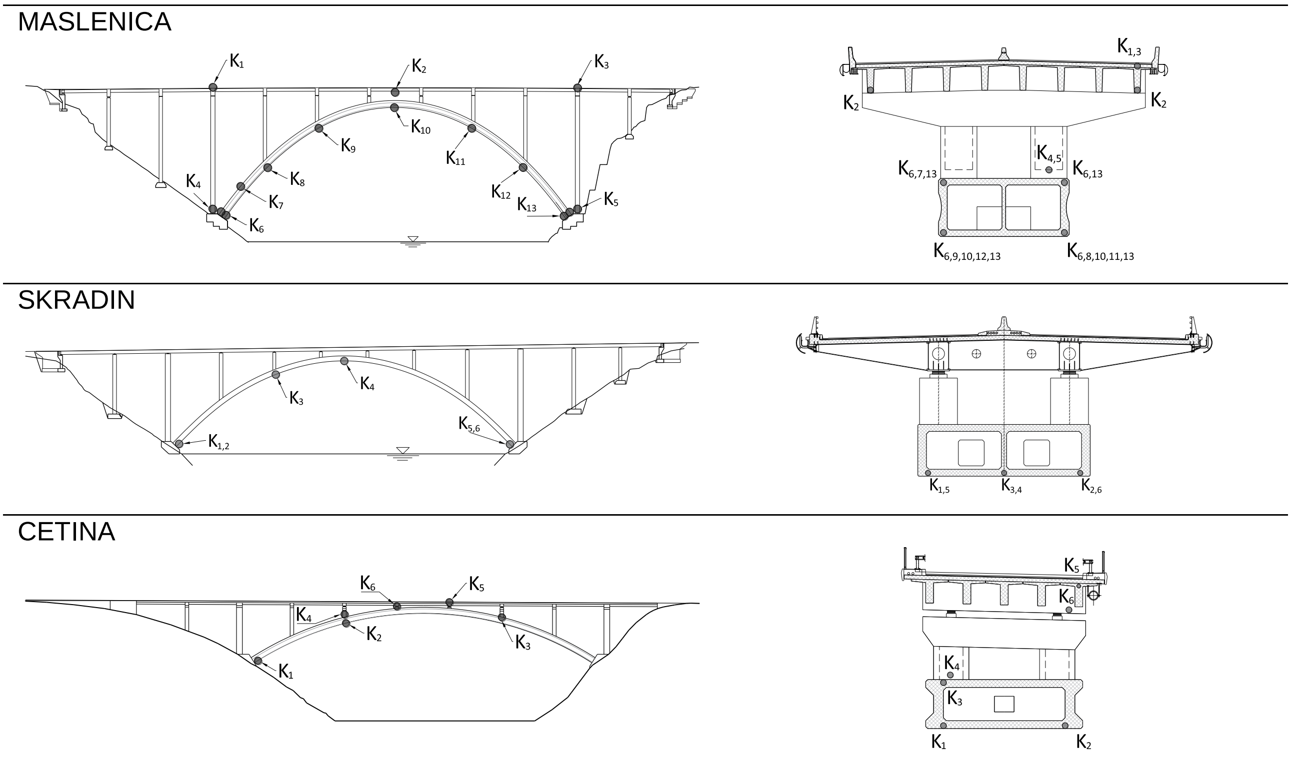

Figure 8: Location of corrosion sensors installed on Maslenica, Skradin and Cetina bridges

Concrete arch **Cetina bridge** spanning 140 m with a rise of 21.50 m was constructed across the Cetina River canyon that is an environmentally protected area. The arch is fixed of single-cell cross-section and the continuous bridge superstructure comprise five precast prestressed concrete girders, cast-in-site deck plate and cross-girders at supports only. The whole cross section of the arch was constructed by free cantilevering, on travelling formwork carriages, in segments 5.0 m long, symmetrically from arch springings. Every phase of the building process was monitored on site, thus providing necessary input for the adjustment of the structural analysis covering the bridge construction. The deviations of bridge geometry from the designed one were reduced to the minimum, amounting to about 2.0 cm for the arch axis (Žderić et al. 2008).
Cetina bridge monitoring system is similar to system installed on Skradin bridge but with less sensors (Rak et al. 2010). The monitoring system includes continuous monitoring of strain, temperature and humidity on the structure, periodic displacement measurements, and periodic measurements to evaluate the corrosion progress. The superstructure is instrumented with 4 strain gauges and 2 temperature sensors. The arch is instrumented with 6 corrosion sensors (anode-ladder), 11 strain gauges, 4 temperature sensors, and 1 combined humidity + temperature sensor. The expected frequency of the corrosion sensors reading is 2 to 4 times a year.
Unfortunately, once after the investor (Croatian Motorways Ltd. and Croatian Roads Ltd.) took over the facilities, they have not shown the interest in the maintenance of monitoring system. Both at the Skradin and Cetina bridges, monitoring system is installed based on the design request, but after releasing the system and collecting first results (in a year or a two years period) no one showed interest to finance costs of monitoring results and maintenance of the system. Nevertheless, a small investment could revive the monitoring project.

Contact information

Ana Mandić Ivanković
Associate professor, Faculty of Civil Engineering, Kačićeva 26, 10000 Zagreb
+385 1 46 39 424
mandicka@grad.hr

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