Performance of existing concrete arch bridges

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Abstract

Numerous issues, including structural, environmental and economic indicators, that are to be considered in order to achieve efficient and effective performance of existing concrete arch bridge will be systematized and elaborated in this paper through the examples of several Croatian Adriatic arch bridges.

Keywords: existing arch bridges; performance indicators; structural; environmental; economic.

1 Introduction

Numerous existing Croatian arch bridges designed according to former design codes are in daily use and deficiencies and degradation during years of service have additionally reduced their designed reliability levels. 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. In this paper, numerous issues that need to be considered in order to achieve efficient and effective performance of existing concrete arch bridge will be systematized and elaborated. The performance indicators may be grouped as structural, environmental and economic. They will be elaborated through the examples of several Croatian Adriatic arch bridges (Figure 1). Šibenik bridge spanning 246 m and Pag Bridge with a span of 193 m, constructed in 1960s by suspended cantilever method, are very similar in appearance and design. Pag bridge was reconstructed in 1999 with a completely new superstructure in steel. 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. To achieve exceptionally large spans it was necessary to reduce the dead load as much as possible.

2 Structural indicators

Structural indicators may be listed as geometry, details, material properties and dynamic criteria. Adequate data on geometrical and material properties and structural details need to be collected using documents overview, visual inspection and different inspection methods. To define a correct structural model of the existing structure, and to perform an appropriate structural analysis, additionally, the existing and desired levels of knowledge about the existing structure must be specified based on the bridge importance. Required knowledge levels may be obtained through an appropriate collection of data including location (critical cross sections) and extension of in-situ inspection methods.

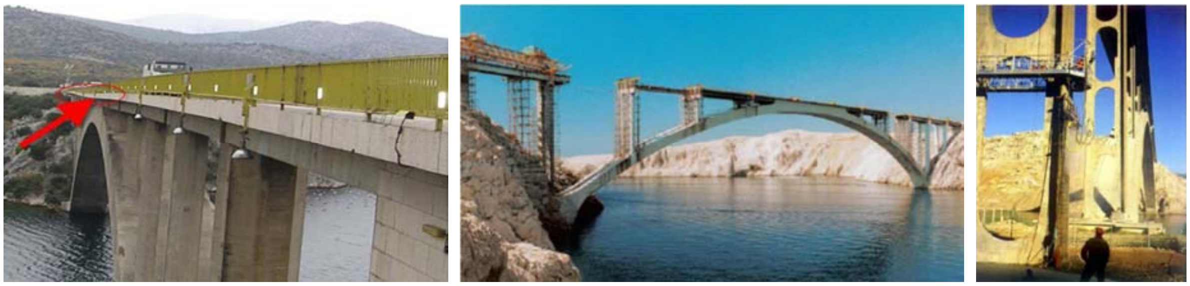


Figure 1. Deflected vertical alignment of the Šibenik bridge (left); Installation of a new superstructure of the Pag bridge by launching truss (middle); repair of columns of the Krk bridge (right)

2.1 Geometry and details

For arch bridges important geometrical properties and structural details are presented in Table 1. Those data should include changes developed due to deterioration processes and structural degradation but also changes made with repair through the years of bridge service. For example, 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 1 left). Namely, deformations of arch due to the creep and shrinkage were much larger than anticipated in the design. Adequately, to perform an appropriate structural analysis of existing structure, data on arch (axis and top edge), roadway (grade line of both edges), grade line of both curbs and grade line of both cornices were collected by geometrical surveying. Additionally, visual inspection, material testing and measurements of concrete cover thickness were performed.

What needs to be addressed carefully when considering concrete arch bridges is that influence of any repair works on the arch behaviour has to be carefully checked and monitor. Often, the rehabilitation design has to reduce the permanent loads to allow for the increase in traffic loads (as it was the case for Pag bridge). Since the arch axis is designed as a thrust line for certain permanent load, distribution of the changed loading can be unfavourable and adversely affect the arch integrity. This issue is of utmost importance in load-carrying capacity assessment and reliability analysis as well as devising a repair strategy for a concrete arch bridge [1].

The new superstructure of Pag bridge is lighter than the original one (Figure 1 middle). 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 [2] corresponding to Eurocode concrete class of C-50 is accounted for.

2.2 Material properties

Cross sections of the bridge are to be defined with their actual as built reinforcement and using materials according to characteristics defined in Eurocode for concrete structures EN 1992-1-1. Material properties that need to be established are shown in table 1. Partial factors for materials are modified based on measured data and assessment of concrete strength in finished structure according to Annex A of EN 1992-1-1. Instead of γ_s = 1,15 for designing of the new structure the partial factor for steel $\gamma_{s,red2}$ = 1,05 may be used for existing one and instead of γ_c = 1,5 the partial factor for concrete $\gamma_{c,red4}$ = 1,3. Any change developed due to deterioration processes (chloride ingress, corrosion process, alkalinity properties) but also increase of compressive strength of concrete since the bridge construction (based on testing cores) and changes made with repair through the years of bridge service are to be included in the assessment of an existing bridge.

To determine mechanical properties of the constituent materials to be used in the seismic analysis of an existing arch bridge, appropriate confidence factors CF in accordance with required knowledge level are to be applied (see 2.3).

For retrieving seismic demands on structural elements for the interaction of axial force and bending moment $f(N_E, M_E)$, bridge is modelled with mean values of material properties. For retrieving seismic shear demand V_E, bridge is modelled with mean values of material properties $f_{i,m}$ multiplied with the confidence factor CF. From actual as-built reinforcement, design resistances for the interaction of axial force and bending moment $f(N_{Rd}, M_{Rd})$ are based on mean values of material properties $f_{i,m}$ and shear resistance V_{Rd} is based on mean values of material properties divided by CF and by partial factor γ ($\gamma_{c,acc}$=1,2 for concrete and $\gamma_{s,acc}$=1,0 for reinforcement).

Stresses of constitutive materials for unconfined concrete $\sigma_{c,E}$ (arch, bridge deck, columns outside plastic hinge regions), confined concrete in plastic hinge regions $\sigma_{c,E}^{pl.hinge}$ and reinforcement $\sigma_{y,E}$, should be lower than mean material strength f_{cm}, $f_{cm,c}$, f_{ym}, respectively, divided by the confidence factor CF and a partial factor $\gamma_{c,acc}$ and $\gamma_{s,acc}$.

2.3 Knowledge levels

Based on the analogy with EN 1998-3 for assessment of buildings for earthquake resistance, guidelines provided for bridges [3] and research on Croatian arch bridges [4,5,6] recommendations for data collection on arch bridges are developed. Required knowledge levels, adequate data collection methods including in-situ inspections (location and extension) for arch bridges and confidence factors CF to determine properties of existing materials to be used in the seismic analysis are presented in Table 1 with a critical cross sections of an arch bridge shown at the Figure 2.

For the bridges of the average importance that are not critical for communications, knowledge level KL2 is to be required. For bridges of critical importance for maintaining communications, especially in the immediate post-earthquake period and for major bridges where longer design life is required the knowledge level KL3 would be more appropriate.

2.4 Dynamic criteria

Based on research on performance of existing reinforced concrete arch bridge under seismic action, the criteria for the seismic assessment are improved and developed and properly incorporated in a new procedure dedicated to seismic assessment of reinforced concrete arch bridges [4].

It was established that, for arches, acceptable performance may be proved at the first level based on linear multimodal spectral analysis employing effective stiffness of columns. Namely, the response of arches under seismic event is generally linear due to their robustness. For spandrel columns (particularly short ones near the arch crown), it will be necessary to go through the second level of assessment based on non-linear pushover analysis because their response under seismic action is inelastic [6]. Multimodal analysis of numerous existing arch bridges showed that capturing all modes, whose effective masses add up to 90% of the total mass according to EN 1998-2, is too conservative and might need considering up to a very high number (hundreds) of modes of which most are negligible [7] as their participation factor is very low (less than 1%).

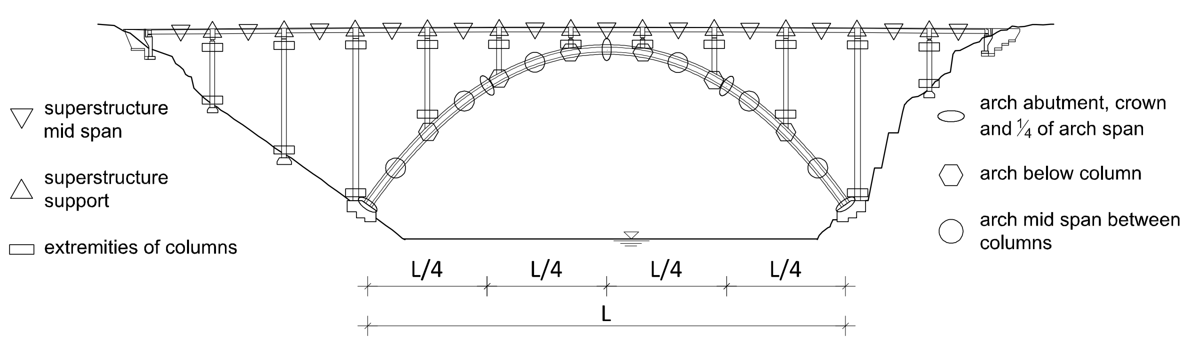


Figure 2. Critical cross sections of an arch bridge example

Namely, it is extremely difficult to activate parts of the arches near their abutments (5-10% of an arch length) that have significant weight, especially in horizontal directions. Therefore, authors [4] suggested that, for the accuracy of a linear multimodal spectral analysis for arch bridges, less rigid rule, requiring participation of effective mass in the amount of 80% of a total mass, should be adopted.

Second level of assessment is based either on non-linear single-mode pushover analysis N2 [7] or a Modal Pushover Analysis MPA [8] if necessary. If assessed arch bridge has a dominant mode shape in longitudinal or transversal direction with effective mass of more than 75% of a total mass [9], single mode pushover N2 based on this mode shape may be applied which will neglect the higher mode shapes. Otherwise, MPA needs to be carried out using all modes whose participation factor is more than 1% and which will altogether capture at least more than 80% of a total mass.

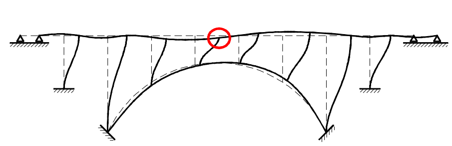
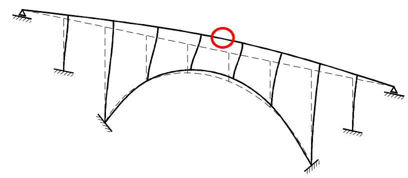
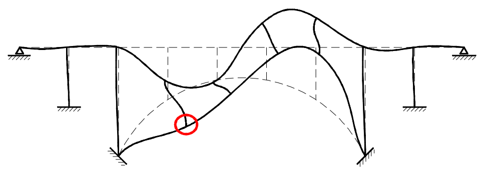
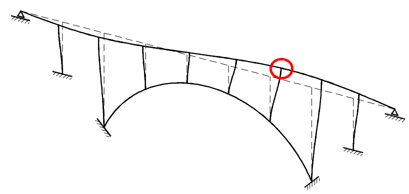
The reference points for each analysis method are presented in Table 2. Dynamic specificity of arch bridges is the flexibility of an arch as support for spandrel columns and great amount of the bridge mass located generally in the middle of the bridge, what comes from the position and the mass of arch. During inelastic response of arch bridge due to the initial seismic stroke, the greatest deformation demands are posed on the shortest columns which results in their excessive cracking and finally after damage causing earthquake the need for their repair or retrofit. Upon the cracking of shortest columns and appurtenant stiffness reduction, deformation requirements are moved following from the crown to the coastal columns which results with their degradation as well.

Table 1. Structural indicators for performance assessment of arch bridges

	Data collection and minimum requirements of in-situ inspection and testing			
	Geometry	**Details**	**Materials**	
Knowledge level	Arch and pier axis, superstructure grade line, cross section dimensions.	Amount and detailing of longitudinal reinforcement, 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	Concrete strength, Steel yield strength, ultimate strength and ultimate strain, modulus of elasticity	**Confidence factor**
KL2	Sample geometry measures on selected element's locations to be compared with available outline construction drawings from the original bridge documentation.	Checking correspondence between the actual details of the 20% of the most critical structural cross sections with available incomplete detailed construction drawings. If bridge documentation does not exist, a 40 % of the most critical structural cross sections are to be inspected.	Complementing the information on material properties derived from the original design or test reports or standards at the time of construction with the in-situ tests in the 20% of the most critical structural cross sections. If bridge documentation or test reports do not exist a 40 % of the most critical structural cross sections are to be tested in situ for material properties.	**1,2**
KL3	If bridge documentation does not exist a full survey to reconstruct the bridge geometry and dimensions is to be performed.	Checking correspondence between the actual details of the 20% of the most critical structural cross sections with complete detailed construction drawings. If bridge documentation does not exist, a 60 % of the most critical structural cross sections are to be inspected.	Complementing the information on material properties derived from previous test reports with the in-situ tests in the 20% of the most critical structural cross sections. If bridge documentation or test reports do not exist, a 60 % of the most critical structural cross sections are to be tested in-situ for material properties.	**1,0**

That excessive cracking should be taken into the account appropriately with effective stiffness of column cross sections as described in the detail in the paper [4]. In this way, the response of the bridge and the degradation of its elements through time are described.

Table 2. Dynamic criteria for performance assessment of arch bridges

Participation of effective modal mass		**Reference points for the construction of the capacity curves**	
Linear analysis	80%	Longitudinal direction	Transversal direction
Single mode pushover N2	75%		
Modal Pushover Analysis	80%	 + the point at the middle of the highest abutment pier (local oscillation of the highest pier)	

2.5 Numerical models

The global numerical models of all bridges for assessment due to lateral loads (wind load and seismic action) are to be made of beam type final elements of the superstructure, piers and arch following geometrical properties and details as described in 2.1 and 2.3. Cross sections of the bridge need to be defined with their actual as built reinforcement and using materials according to rules given under 2.2. In general arch bridges (as most of the Croatian bridges) are founded on sound rock ground so support points of numerical models may be defined as fixed.

For seismic assessment particular subdivision of elements needs to be applied. The extremities of the column constitute the locations for potential plastic hinges, which may be assumed to extend for one twentieth to one tenth of the member length, depending on the boundary conditions [10]. For this reason each pier has been subdivided into six elements, of length equal to 5%, 10%, 30%, 40%, 10% and 5% of its length [11] (Fig. 3 left). For the cracked extremities of the column $E_cI_{eff,in,i}$ is assigned and for inner part of column $E_cI_{gross,i}$ is assigned. For sake of accuracy, the mesh of each span near the connections to columns, where the change of stiffness and properties of the mesh are important may be refine [11].

This subdivision of elements in the model should be re-arranged following changes developed through the years of bridge service, for example if some additional cross sections are evaluated as damaged in the visual inspection or certain cross sections are changed with repair activities. As an example, the model of the Krk bridge needed to be subdivided into elements following changes made with repair (Figure 5, [12]) on exact length of each pier.

The original superstructures of all those Adriatic bridges of old generation were designed as a series of simply supported grillages so in the numerical model superstructure beams were modelled with hinged ends (Fig. 3 middle). According to the renewal design of Pag bridge boundary conditions at pier tops were significantly changed by the realization of the new steel superstructure. The old spandrel structure restrain all piers in longitudinal direction as cross-girders above supports also assumed the role of head beams of bridge piers. In the new superstructure, the longitudinal restrain is realized at the positions of fixed bearings which were planned at the final four support positions toward Pag and final three support positions toward the mainland, while other piers with movable bearings remain longitudinally unrestrained. According to the changes made with a repair, changes in the numerical model of the Pag bridge were adopted (Fig. 3 right). Separate models of a superstructure grillage are to be used for assessment due to traffic load, and some particular localised models need to be developed for revealing the corrosion influence [13].

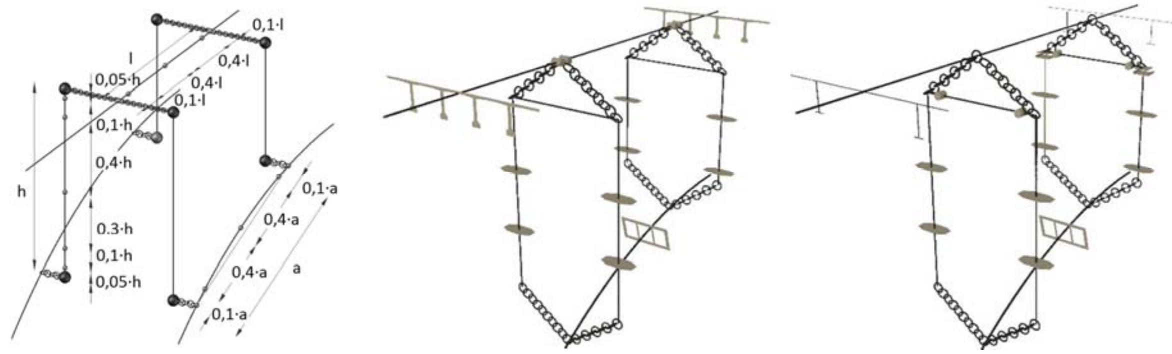


Figure 3. Discretization of an arch bridge numerical model for seismic assessment (left), model which follows the original superstructure of old Adriatic bridges (middle) and model according to the repair of Pag superstructure and piers (right)

3 Environmental indicators

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. Namely, over the years many deficiencies and advanced stage of deterioration processes were identified on older Adriatic Bridges (see Figure 4). Chloride attack due to maritime exposure, followed by cracking, delamination, splitting and peeling off of concrete is identified as major deterioration mechanism [1].

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. Major reconstruction started in 1991 with the repair of the arch and was finally finished in 1999 when the original concrete superstructure was dismantled and replaced by a completely new structure in steel (Fig. 1 middle). Columns were repaired by encasing in steel and concrete.

Repair works on the Krk Bridge started several years after its completion focusing on superstructure supports. In the 1990's the works were broadened to include the repair of columns of the smaller arch (Fig. 1 right). Different repair techniques had to be devised for spandrel and approach columns (Figure 5). Starting from the year 2004, the smaller arch has been repaired by removal of 2 to 3 cm of the contaminated concrete, its subsequent replacement with shotcrete and adding protective coating. The repair of the larger arch presents major challenge to engineers. The arch is actually supported on submerged inclined struts. After many years of research and testing of various corrosion protection systems, cathodic protection method was selected for this part of the structure.

Figure 4. Deterioration of Adriatic bridges

All of these repair works are not only expensive, but technically demanding tasks and very difficult to perform which is in correlation with the following chapter as economic parameters will depend on the proper maintenance programme offered and adequate activities performed.

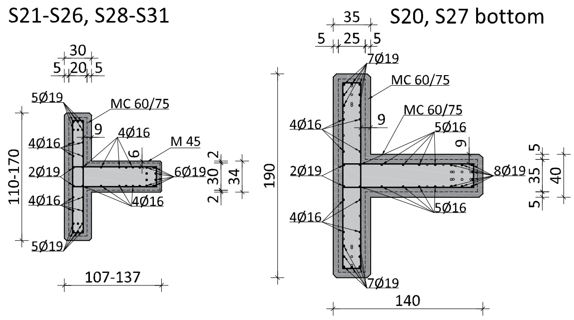


Figure 5. Cross sections of repaired columns of the Krk bridge

Additionally, considerable number of existing Croatian bridges is located in the regions of high seismicity and some of them built decades ago were designed with no regard to seismic actions at all. Bridges along the coast are exposed to the effects of sea salt and high winds and those of the old generation were designed according to former design codes with much lower wind pressures, traffic load and very small concrete covers comparing to contemporary requirements.

In the assessment of bridge superstructures for traffic load, the Model 1 of the European traffic reduced by adjustment factors [14] based on realistic traffic analysis is to be used. At the first assessment level, for the realistic simulation of the heaviest Croatian road traffic, data of the year average daily traffic at the location with the largest number of heavy vehicles were used. At the second level of assessment (when the first one failed) the traffic load may be even more localised by using data of traffic flow at the exact bridge location.

To assess the bridge exposed to significant wind load, local characteristics such are wind velocity, terrain roughness and dominant wind direction need to be established. According to the basic wind velocity map given in a new Croatian National Annex for Sibenik and Pag bridges wind velocity without traffic loading is 35 m/s and for Krk bridge 40 m/s. For the bridges with traffic, a wind velocity of 23 m/s is used. Additionally, it is possible to reduce the wind load based on its dominant direction against longitudinal bridge axis.

To define appropriate seismic action at the bridge location, peak ground acceleration and soil type are the basic data. For existing bridges, which remaining life (t_L) is less than 50 years, it is appropriate to take into the account the reduced value of peak ground acceleration $a_{g,red}$ that has a probability of exceedance p = 0,1 in a shorter reference return period $T_{R,red}$ compared to the reference return period of the seismic action for the no-collapse requirement T_{NCR}. The equation $a_{g,red}/a_{g,R} = \left(T_{R,red}/T_{NCR}\right)^k; T_{R,red} = 1/(1-(1-p)^{1/t_L})$ offers an acceptable approximation for reduction of peak ground acceleration where the value of the exponent k depends on the seismicity of the region and normally ranges from 0,30 to 0,40.

Interaction of those environmental indicators and structural ones are mandatory. For example recorded representative real traffic data need to be multiplied by a dynamic amplification factor which depends on the roughness and the quality of the pavement. Considering seismic action, to define design response spectrum the behaviour 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. One more example is the dependency of a wind load on a bridge type, slenderness of elements, parapets types and the angle between the dominant wind direction and the bridge axis.

4 Economic parameters

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. This also requires establishing optimum durability (remaining life-time) of the structure.

Inspections of major bridges are more exhausting and require well-experienced personnel to identify the damage and determine its cause and consequences. But 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. So it is of a great importance to establish the most significant locations of the arch bridge to be inspected and tested (Fig. 2). Additionally the most critical structural cross sections are the ones evaluated as damaged in the visual inspection.

It should be said that one of the causes for rapid structural degradation of the first generation of Croatian Adriatic arches was also underestimation of maintenance role in the past, mainly due to lack of funding for regular maintenance activities. Most of the work was carried out only when structural safety was evidently compromised. The importance of preventive maintenance work was completely underestimated. Performance in service and monitoring of large Adriatic bridges taught us that major structures need to be treated with special care when planning repairs and maintenance strategy. Otherwise unlimited funds will be needed to ensure the structural safety and serviceability.

5 Conclusions

To eliminate the errors of the past and ensure efficient and effective performance of existing concrete arch bridges all relevant issues elaborated in this paper need to be properly addressed and incorporated in the appropriate maintenance strategy. Only comprehensive knowledge on all indicators; structural, environmental and economic ones, will ensure the smooth service and efficient management of large arch bridges.

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