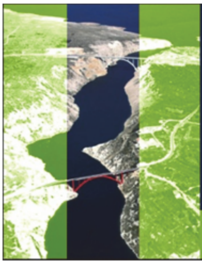

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MAINTENANCE STRATEGY AND METHOD OF CONCRETE ARCH BRIDGES IN LIFE CYCLE II: PERFORMANCE DEGRADATION ANALYSIS AND REPAIR REINFORCEMENT METHODS

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Abstract: *This paper emphatically analyzes some existing problems in planning, design, construction, operation, and maintenance of concrete arch bridges, including insufficient load bearing capacity caused by uneven settlement of bridge piers, horizontal displacement, change of temperature, overload, lower design load level in original bridge design, and poor durability and performance degradation of concrete structures caused by chloride permeability, steel bar corrosion, carbonization, cover spalling of concrete, aging cracking at the PE protective layer of suspenders, rain leakage, and corrosion of concrete arches etc. From the safety, applicability, durability, economy, environmental protection, and sustainability considerations in life cycle of bridges, the appropriate maintenance strategies and methods of arch bridges are explored for the different objectives and performance levels. It has certain theoretical significance and practical engineering value.*

1 INTRODUCTION

The durability problems of the designed and constructed concrete bridges and related research advances in China in past 30 years have been described in the sister paper [1]. It was pointed out that the performance of bridge structure life-cycle should include safety, suitability, durability, and environmental protection (sustainability and reparability). Performance requirements of bridges in three different performance levels have been presented. This paper will continue to discuss the analysis method for performance degradation of concrete arch bridges from the material, component and structural point of view, explore the time-varying factors influencing reinforced concrete structure resistance, and specify the environmental factors, which infuence bridge performance in RC material. Finally, the corresponding performance-based maintenance strategies and methods of arch bridges are proposed for the different objectives.

2 ANALYSIS METHODS FOR PERFORMANCE DEGRADATION OF CONCRETE ARCH BRIDGES

At present, we can analyze the performance degradation of concrete arch bridges from the material, component and structure point of view.

1) Regarding the material, the material degradation, mainly including concrete carbonation, chloride ion penetration and steel corrosion, is focused upon. There are a lot of researches on degradation models of concrete carbonation [2,3], chloride ion penetration [4,5], and steel corrosion [6,7]. But most of the researches only pay attention to establishing the mathematical models for considering every single material degradation and the relationship and difference among these models. The material degradation classification of concrete structure is shown in Figure 1 [8].

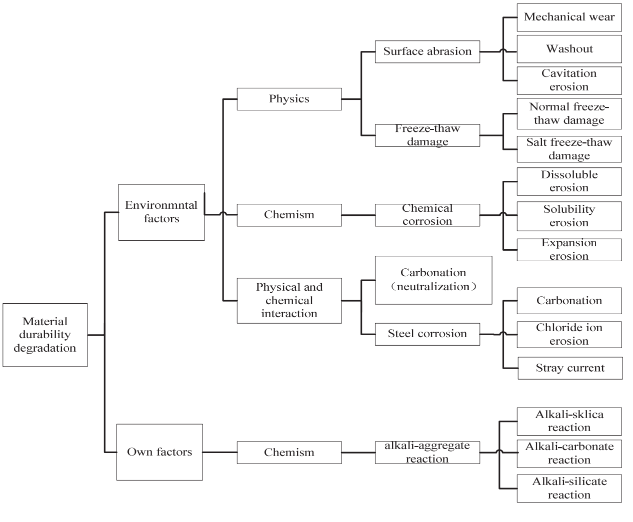

Figure 1: Material degradation classification of concrete structure

2) Regarding the structural components, we often analyzed and researched the resistance effect and design method of the structural components and payed less atttention to influence of the reinforcement corrosion under the environmental loads on the changes in the mechanical behaviours (including durability, resistance and residual load bearing capacity) of the RC members (beam, slab, column, nodes, etc.). With the increase of bridge collapses in recent years, the time-varying performance simulation test study of components have been gradually introduced. Because of the experimental limitation, the steel corrosion tests are generally accelerated by imposed electric current. In fact, the corrosion in accelerated test conditions is different from corrosion in natural environment. In most of the accelerated tests, no load is exerted on the components. Thus, the components in accelerated test can not perfectly simulate the practical working condition of the components during bridge operation, especially because the interaction of load and environment is not accounted for. Some researches had shown that the stress condition significantly influences durability and resistance degradation of components [9].

3) Regarding structure, the past researches mainly focused on obtaining the response of structural members under the loads and their combination by considering different actions and time-varying effects of prestressing, shrinkage and creep. The safety performances of various members of the structure were ensured by reasonable analysis design of components. At the same time, the suitability performance of structure was also ensured. This analysis method can not accurately predict the **safety performance** (or safety factor) of the whole structure in its life cycle, especially in regard to the time-varying load carrying capacity and the suitable performance of the structure in life cycle. Therefore, it is necessary to study the variation of the whole structural resistance and load and its effect on the structure safety and usability (including cracks) from the whole structure and life cycle point of view, understand the service condition and the safety degree of the structure and specify related suggestions for the maintenance of the structure performance.

Structural safety is about balance and change between structural resistance and exerted loads. The process of RC resistance degradation is very complex. On the one hand, it is influenced by many factors, including environmental factors, load factors, and material-self own factors [10]. On the other hand, the method for analyzing load carrying capacity of concrete structure involves some basic theory problems of material time-varying mechanisms, nonlinear constitutive equations and failure criteria. The related environmental simulations, calculation methods, calculation models, the economy and other issues remain for further research. Table 1 lists the factors, which influence concrete structure resistance [10].

Environment factors	Load factors	Other factors
corrosive liquid or gas, such as salt, acid, Chemicals & others	High stress effect or overload	Concrete strength degradation
Temperature variation	High-cycle or low-cycle load	Steel strength degradation
Interaction of wind, rain and high temperature	Interaction of load and environment	Alkali-aggregate reaction
Settlement and scour of piers and abutments	Shrinkage and creep	

Table 1: Time-varying factors of influencing concrete structure resistance

The ultimate load of concrete arch bridges for performance degradation can also be analyzed by using structural calculation method, establishing calculation model, and considering change of the environment and material.

3 MAINTENANCE INDEX OF PERFORMANCE-BASED CONCRETE ARCH BRIDGES

Under the action of natural environment, service environment and material internal factors, the structural performance of concrete arch bridges will degrade with time. Thus, the load bearing capacity will also decrease with time. The safety and serviceability of arch bridges will be affected. The structural residual service life will shorten. According to some existing performance degradation problems in the arch bridges, the purpose of structural maintenance is to guarantee that the structures and relevant performance index remain in normal state within the expected life by the corresponding maintenance measures based on the performance requirements of safety, serviceability, durability, and sustainability.

The maintenance indexes of concrete arch bridges was specified for four performance requirements of safety, serviceability, durability, and sustainability, based on Chinese code for maintenance of highway bridges and culverts (JTG H11-2004) [11] and Chinese specification for inspection and evaluation of load-bearing capacity of highway bridge (JTGT J21-2011) [12], which are shown in Figure 2.

4 MAINTENANCE STRATEGY AND METHODS

4.1 Maintenance strategy

Aiming at the problems on performance degradation in concrete arch bridges, it is necessary to further specify the relevant maintenance strategy and maintenance methods according to the above-mentioned performance requirements and maintenance indexes.

The connotations of the safety, serviceability, durability, and sustainability or reparability and the four performance requirements have been described in Ref [1]. The corresponding recommendations for adequate maintenance strategies are not difficult to give. Due to limited space this is not further discussed in detail.

As effective theoretical methods for maintenance and service life prediction of bridge structure life cycle performance, combining material or components degradation with structures are lacking, it is necessary to set up the nonlinear analytical theory of load carrying capacity and service life prediction method based on material degradation for concrete arch bridges by considering the interaction of all kinds of factors.

Normally, the load carrying capacity calculation of RC structures adopts simple calculation formula of half-theory and half-experience based on amount of experimental studies. The simple calculation method can satisfy engineering requirements for standard bridge design. In order to objectively and accurately predict and assess the load bearing capacity of some special concrete arch bridges influenced by complex environmental factors, various influencing factors need to be taken into careful account, including concrete creep, strength degradation, steel corrosion and cracks. Also the reasonable calculation theory and method is needed especially for the actual nonlinear state after bridges cracking.

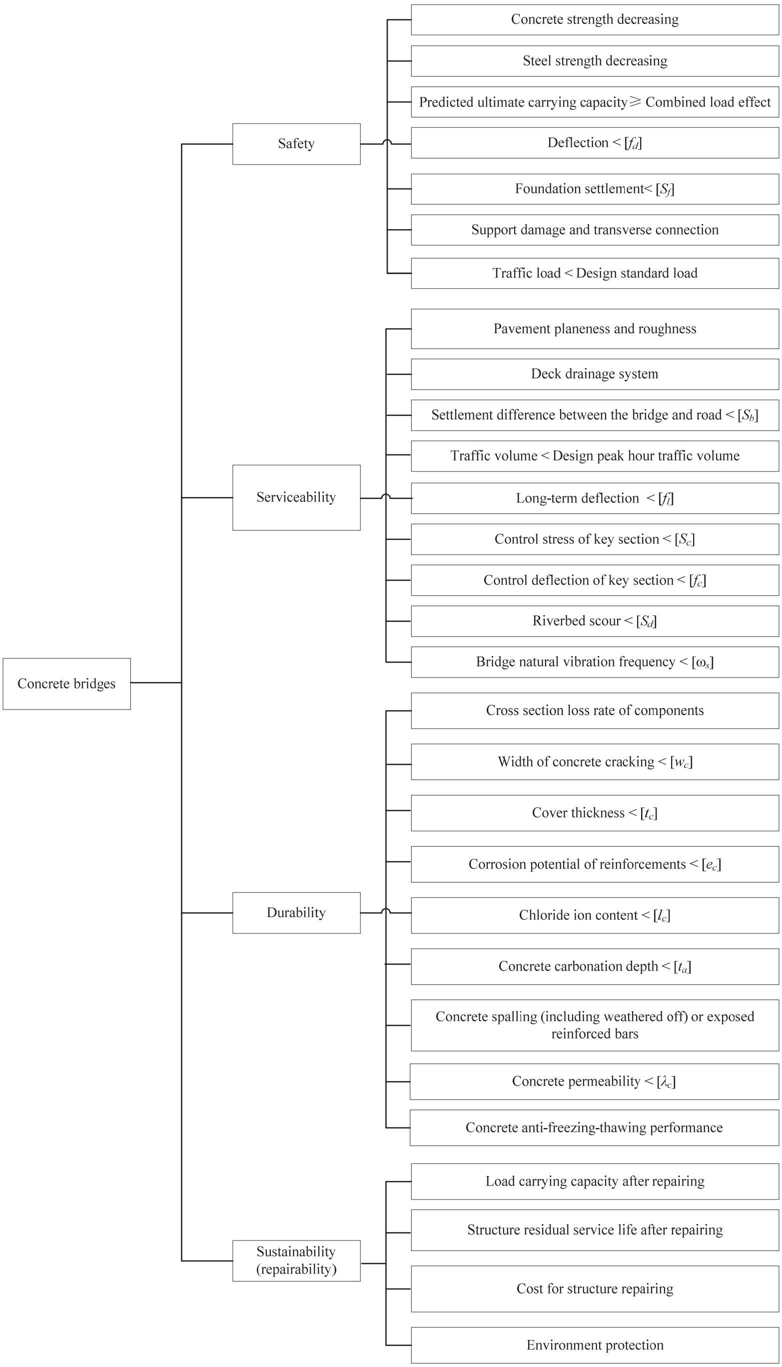

Figure 2: Maintenance index of arch bridges

At present, the plastic limit analysis theory and concrete nonlinear FEM are often used theories for assesing structural ultimate carrying capacity. The plastic limit analysis method is usually applied in engineering applications, but it only takes the structural plastic limit state into account. So the plastic hinge theory is not suitable for the complex arch bridges etc.

FEM has achieved significant progress after about 40 years development. In theoretical research, current studies mainly focus on establishing and improving mathematical models, especially concerning about the constitutive relations of time-varying concrete material, concrete cracking models and cracking criteria, and on introducing fracture mechanics into mathematical models, bond slip influence of concrete and steel and numerical calculation methods. In addition to theoretical exploration, the engineering application of all kinds of models is also emphasized [13].

4.2 Maintenance method

For the practical engineering problems of concrete bridges in different environment and locations, the relevant maintenance and repair reinforcement methods may be different.

1) Insufficient ultimate carrying capacity of RC arch bridges

For the insufficient ultimate carrying capacity of RC arch bridges, caused by piers' uneven settlement, horizontal displacement of abutments or temperature stress, there are two common ways to solve the problem: (1) The method of changing structural system , also called releasing energy method. For example, we may change the structure from fixed arch to hingeed arch by reconstructing the arch connection to its abutments. After this reconstruction the arch foots can slightly rotate to release cross section internal force of arch foot and decrease the negative moment there. The internal forces will of course be redistributed in the whole structure. The stress state of the original bridge will be improved. (2) The method for reinforcing pier, abutment and foundation. The method improves the local force distributionte of RC arch bridges and increases their load carrying capacity by various measures, such as the column strengthening by FRP, adding piles, enlarging area of pile foundation and restoring original location of arch abutments or shortening their horizontal distance by jacking. Secondly, for the insufficient ultimate carrying capacity caused by the smaller design loads or overloading, we may reinforce weak components and forbid these overload trucks to pass, such as: (1) Adding new material (spraying concrete on arch ring, cast-in-place additional concrete on raw arch rib, placing steel plates, steel strips, glass fiber and carbon fiber sheets on raw arch rib by epoxy adhesive etc.) to enlarge the cross section area of the arch ring. (2) Injecting the high grade cement mortar or epoxy cement mortar into the cracks to close them. (3) Installing external prestressing tendons or utilizing chemical glue to stick additional members to reinforce the components of arch bridges.

When the main deformation of arch bridges exceeds the allowable values in serviceability limit state, except for the above-mentioned measures, we may change the original simple arch system into the beam-arch system by making use of continuous beam features. Also we can reduce structural dead loads, including (1) Changing the spandrel filled arch bridge into arch bridge with empty spandrel. (2) Changing the heavier filler into lightweight filler. (3) Changing the thickness of spandrel filled arch to decrease the structure weight. For the some longitudinal cracks and poor transverse connection along arch bridges, we can reinforce the integrity of the whole structure and close the cracks by transverse prestressing.

2) Poor durability of concrete arch bridges

Poor durability often results in concrete cracking, steel corrosion, cracking at the PE protective layer of suspenders ahead of design life, serious chloride ion penetration and concrete carbonation in concrete arch bridges. The damage of concrete cover cracking, seepage, and spalling caused by concrete carbonation, cavitation erosion, freeze-thaw damage, chemical erosion may be repaired by surface repair method. The materials of surface repair method have cementitious repair material, organic polymer repair material, and polymer cement mortar etc. Steel corrosion should be paid high attention to, because it is the primary factor of causing damage to concrete structures [14]. There are four methods for preventing or delaying steel corrosion:(1) Adding steel bar rust inhibitors to concrete, such as sodium nitrite, potassium nitrite, barium nitrite, chromates dichromate, $SnCl_2$ (stannous chloride), and other migration corrosion inhibitors (MCI) [15-16]. (2) Painting protection layer on steel surface. Protection layer can avoid oxygen, water, and chloride ion contacting with steel directly [17].(3) Sacrificial anode protection method. Metallic media coating is painted on the steel surface to replace steel as the anode of electrochemical corrosion. At present, the hot-dip galvanizing steel wire is widely used. (4) Adopting fiber reinforced composites to replace steel bars, such as carbon fiber reinforced plastic (CFRP), glass fiber reinforced plastic (GFRP), and aramid fiber reinforced plastic (AFRP) [18].

Before the repair scheme of a bridge structure is determined, the economic, environmental protection and social benefits of proposed scheme should be considered comprehensively. In order to meet performance requirements of bridge structures in the life cycle, we emphasize the need to inspect and maintain these bridges periodically and to strictly restrict overload vehicles pass.

5 CONCLUSIONS

(1) The problems on performance degradation of concrete arch bridges can be analyzed and solved from the material, component and structure point of view. The time-varying factors of influencing reinforced concrete structure resistance are discussed. The relevant maintenance indexes are specified for four performance requirements of safety, serviceability, durability, and sustainability, based on related Chinese codes or specifications for inspection,evaluation and maintenance of highway bridges.

(2) It is necessary to set up the nonlinear analytical theory of load carrying capacity and service life prediction method in life cycle based on material degradation of concrete bridges and nonlinear analysis theory by considering the interaction of all kinds of factors.

(3) For some of concrete arch bridges which can not meet the needs of performance requirements in service in practical engineering, the relevant maintenance strategies and methods are proposed.

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