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MAINTENANCE STRATEGY AND METHOD OF CONCRETE ARCH BRIDGES IN LIFE CYCLE I: PERFORMANCE LEVELS AND PERFORMANCE REQUIREMENTS

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Abstract: *Concrete arch bridges are one of the common types for highway bridges. They have advantages of graceful line shape and beautiful appearance, good behaviour and large spanning capacity. As far as the reinforced concrete arch bridges (or combined-system arch bridges) are concerned, this paper describes the durability problems of the designed and constructed concrete bridges and related research advances in China in past 30 years. It is pointed out that the performance of structure life-cycle should include safety, suitability, durability and environmental protection (sustainability and reparability). Performance requirements of bridges in three different performance levels are discussed by comprehensively considering these factors of safety, serviceability, durability, environmental protection, bridges location and importance. It lays the foundation for structural design, maintenance and strengthening, based on performance in life-cycle.*

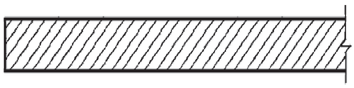
1 INTRODUCTION

The arch bridge is one of common bridge types for highway bridges. The arch ring is the main supporting member in the structures which are primarily subjected to the compressive force. The arch ring is constructed of masonry materials, such as brick or concrete. It may also be built of RC and as concrete-filled steel tube (CFST).

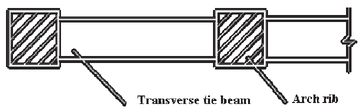
With the requirements of the bridge spanning capacity and the progress of construction technology, the arch bridge type has gradually diversified in recent years. According to structural combination types, there are simple system arch bridges (SSAB) and combined system arch bridges(CSAB). SSAB can further be divided into three-hinged arch bridges, two-hinged arch bridges and arch bridges without hinged joint. CSAB are the bridges which combine the two basic structures of the deck and arch together. They can carry together vertical loads and horizontal thrust. CSAB can also fully exploit the good characteristics of deck bending resistance and arch compression to achieve the purpose of saving material. They can generally be divided into two types of arch bridges with or without thrust. According to the position of the carriageway, they can be divided into the deck bridges, half-through bridges and through bridges. Most of the arch bridges are built of reinforced concrete. At the same time, according to the different span length, behaviour and the economy requirements of arch bridges, the different cross section types of main arch ring are selected. For arch bridges with short and medium span less than 30 m, the bending moments in these arch bridges are small, the arch ring is mainly subjected to axial compression, the plate arch bridges can be built by using concrete or reinforced concrete. With the further increase of span, the bending moment gradually increases, which leads to the tension in the main arch ring, which may result in cracks under action of eccentric load. The cross section is designed as a number of rib arches, which are strengthened by transverse connection. On the one hand, they can reduce structural weight. On the other hand, the higher depth of arch rib and steel reinforcement on tension side can form the effective resisting moment. For the structures with 80-300 m span, in order to further improve ability of structural bending moment resistance and increase torsional stiffness and bridge lateral connection, it is necessary that the main arch ring adopts box or multi-box section with RC or steel tube concrete frame. Figure 1 shows the main cross section types of arch bridges.

Traditional conceptual bridge design in China paid more attention to the strength or safety of the structures, while structural durability was less considered. Namely, traditional bridge design focused mainly on strength limit states and less on serviceability limit states after a number of year's service. Traditional bridge construction procedure in China was divided into several stages and every stage was considered separately. It only paid attention to construction stage and the task of construction was focused on the optimization of the construction cost during construction and the short-term structural performance. Traditional bridge design rarely considered planning, design, construction, operation, and maintenance as a whole system. It often led to underestimation of stress state in some structural parts and lacked specific design on anti-cracking, durability, and anti-collision measures, resulting in occurence of damages and accidents in some of bridges during the construction and operation.

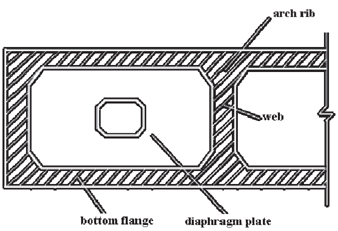
In early bridge design and construction (about 1980-2000) in China, we lacked the full understanding of the potential structural damages, due to concrete cracking, concrete spalling and steel corrosion of bridges, interaction of load and environment, and overloads etc. and their impact on load carrying capacity of bridges. In fact, the behaviour of all bridges will gradually deteriorate and the load carrying capacity and performance of bridges will reduce after many years service. When structural resistance is lower than the effect of actual loads, the bridge structure will collapse and endanger the traffic safety. Zhejiang, Jiangsu, Fujian and Guangdong province are the economic developed regions in China. These provinces are located in the coastal area of East Ocean and South Ocean in China and the climate is warm and humid. The traffic on the highway bridges was busy and many bridges were concrete bridges. Under the interaction of complex loads, sea water and chloride ions, the performance of concrete bridges was degraded and many diseases appeared for some bridges in this area. Figure 2 shows some cases of the concrete arch bridge collapses.



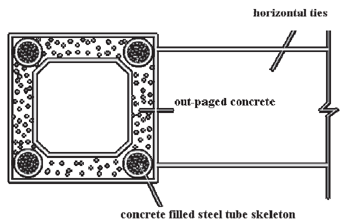
(a) RC slab arch bridge



(b) RC rib arch bridge



(c) RC box arch bridge



(d) box arch bridge with steel pipe skeleton

Figure 1: Main section types of arch bridges

Figure 2: Collapse cases of concrete arch bridge

Hence, it is very important and of practical value that the performance requirements of concrete bridges in different performance levels are studied by comprehensively considering these factors of safety, serviceability, durability, environmental protection, bridges location and their importance.

2 CONCRETE BRIDGE DURABILITY PROBLEMS AND RESEARCH ADVANCE IN CHINA

The above mentioned problems are mainly induced by the lack of adequate concrete durability, bridge overloading and fatigue. According to statistics, economic losses due to corrosion are about 2% to 4% of gross national product. The 7th corrosion loss investigation of structures in 2002 showed that the United States annual direct economic loss due to corrosion is $ 276 billion from 1999 to 2001, which accounts for about 3.1% of its GDP.
The gross domestic product (GDP) of China in 2008 was more than 30 trillion Yuan. Economic losses due to corrosion were more than 900 billion Yuan, if corrosion loss accounted for about 3.1% of GDP in 2008. If we did early research and took appropriateprotection measures against corrosion in concrete structures, 25 to 40% of the economic loss due to corrosion would be entirely avoided.
According to U.S. bridge statistics, the number of bridges was 620,000 by the end of 2011. From structural defects and functional aging data[1,2] statistics, it was found that the defective ratio of box girder bridges is higher than that of culverts of simple structural type and of cable-stayed bridges with less statistical data. From the material type point of view, the total number of prestressed concrete bridges with defect was the least of all bridges made of various materials.. However, in spite of this, total defective ratio of the box girder bridges was still 18.10 % and the defective ratio of prestressed concrete bridges was 13.43%.
According to relevant statistics, the number of bridges in China was 658,000 by the end of 2011, which is more than in the U.S. China is the country with the maximum number of bridges in the world. At the same time, there were more than 100000 bridges in service with different defects in China, of which the number of dangerous bridges was more than 13,000. Some bridges even collapsed. The number of collapsed bridges in China in 10 years from 2002-2011 is listed in Table 1 [3-5].

year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Bridge collapsed number	4	1	9	5	11	12	15	14	20	26

Table 1: Annual number of collapsed bridges in China from 2002 to 2011

From 1980s, China began a large-scale economic construction. Since the bridge structures built in the 1980s lacked the detailed durability design, some design level of load standard were low for many bridges, so they need to be repaired and their load carrying capacity improved.

As for the durability of the reinforced concrete structure, Niu etc. started theoretical and experimental research on durability problem of reinforced concrete corrosion, carbonation mechanism, assessment and life prediction of concrete structures from the 1990s in China. In 2003, Niu [6] summarized durability and life prediction of concrete structures and Jin [7] summed up the research results on durability in Zhejiang University.

The study on influence of concrete durability on bridge structure and residual service life prediction was paid attention to and began in recent 7-8 years in China. So far, the degradation regularity and mechanism of carbonation, steel corrosion, chloride ions penetration and alkali-aggregate reaction of RC under environmental effect have been studied and some research results have been applied in the structural durability design. But there were rare researches on ultimate bearing capacity of concrete bridges including arch bridges affected by material degradation and there is still a lot of work to do. It is more complicated for ultimate bearing capacity with the interaction of environmental influences and traffic loads. In recent years, the team lead by Prof. Xiang did a series of researches on durability and life prediction of concrete bridge structures in Zhejiang University. The author reviewed three basic residual service life prediction models and their applicability, which included the residual service life prediction model based on concrete durability, service life prediction model based on reliability and service life prediction model based on life cycle cost [8]. The RC bulge cracking of concrete bridges was analyzed by the coupled thermal-mechanical method and finite element method [9], according to the traditional Fick law and steel uneven corrosion expansion model under chloride ions' environment and thermal elastic mechanics theory.

The multi-factor model of chloride ions diffusing into concrete was revised by considering time-varying chloride ion diffusion coefficient and diffusion procedure influenced by concrete own defects [10].

Aiming at the background of concrete bridges in coastal area of Zhejiang, the differences of existing three concrete carbonation depth prediction models were discussed [11]. The carbonation residual service life prediction of the specific bridge component in this area was given by comparing the experimental data with the theoretical data. Based on this, the third model was revised by introducing water cement ratio influence coefficient into the model. The results showed that the revised model 3 was more suitable for practical issues in coastal areas.

The steel rust expansion radial displacement-time curves in case of steel uniform corrosion and steel non-uniform corrosion of RC Structures were derived by introducing the assumption of quality equality of steel corrosion product [12].

Based on comparison of current chloride ion diffusion models and steel corrosion models as well as test data of concrete bridges in the coastal area, the chloride ion diffusion models in concrete and steel corrosion model were revised by considering load and chloride ion binding capacity[13,14]. The updated model was compared with the model of considering only a single influence factor and the results showed the chloride ion diffusion model and proposed steel corrosion model was more reasonable.

Considering the actual box girder bridge construction steps, the cracking mechanism of box girder bottom flange during its construction was analyzed by the nonlinear analysis method and some protective measures were proposed [15]. The bottom flange cracking was caused by insufficient shear strength of concrete bottom flange cut short by embedded prestressed pipes in the concrete bottom flange. Based on this, the four kinds of concrete box girder bottom flange cracks were discussed and simple design method was put forward for controlling cracking.

In general, there are some durability problems in the life cycle of the RC structures, which seriously influence structure residual service life. The inspection and maintenance of bridges in the past 20 years in China mainly depended on the intuitive judgment of engineers and simple field testing, and lacked the material degradation assessment and estimate of the degradation impact on performance-based residual service life prediction of bridges. Engineers, alone, can not propose some effective maintenance strategies and methods based on life cycle. So, it is a great academic, economic and social value how to effectively analyze life cycle performance degradation law of concrete bridges including arch bridges, predict the their strength and residual service life and put forward corresponding performance-based maintenance strategies to improve bridge maintenance technology. From the life cycle point of view, this paper discusses and presents the performance level and requirements for concrete arch bridges.

3 PERFORMANCE LEVELS AND PERFORMANCE REQUIREMENTS OF STRUCTURE LIFE-CYCLE

Bridge life cycle refers to the whole process of planning, design, construction, operation, maintenance, and demolition or recovering of bridges. The objective of life cycle design is to achieve optimal design of overall performance (including function, cost, humanity and culture, and environment) in its life cycle. It has features of the globality, innovation, and multi-objective.

Globality: Engineers should pay more attention to all kinds of influence factors in the life cycle of bridges from the point of comprehensive, related and developing view and balance various performance requirements and seek for the maximal effect of bridge design.

Innovation: It is innovative procedure for bridge engineers from do nothing to do something and from concept to quantity.

Multi-objective: The engineers should meet the needs of the conceptual and landscape design, ecological environment, structural performance, management and maintenance, risk assessment, and life cycle cost analysis in different work stages for a bridge construction.

3.1 Bridge performance

The bridge performance should include safety, suitability, durability, and environmental protection (sustainability and reparability). Four performances correspond to load carrying capacity limit state, serviceability limit state, durability limit state, and reparability limit state, respectively. Load carrying capacity limit state judges whether the bridges are safe or not under loads. Serviceability limit state judges whether the bridge service function is satisfied or not under normal condition. Durability limit state judges the degradation condition of the material and structural members with time and their influence on the service function and ultimate strength of bridges. Reparability limit state judges whether the structural degradation and damaged condition under accidental load are reparable or not and the methods and measures of recovering the structural safety and serviceability. The bridge engineers should set different tolerances for different bridges [16].

Bridge safety is the key of structural construction, operation, and smooth traffic. It relates to structural strength, stiffness, and stability during construction and service.

Bridge suitability is to insure that there is enough bridge deck width to meet future traffic needs and there are no excessive deformations and cracks when bridge is subjected to design loads in the bridge life cycle. The suitability design of bridges needs to consider flood discharge, navigation and vehicle passing. When requested, the bridge should carry various pipelines, for example, water pipelines, electric power wire pipelines, gas pipelines and communication wire pipelines. To achieve the above mentioned function, the designer should first analyze function and needs of the bridge to be built and provide corresponding design solution.

The one of main problems of concrete bridges including arch bridges is cracking. The reasons for cracking involve shrinkage during construction, loads, temperature effects, construction quality, design analysis rationality and uneven settlement during operation. So, engineers need to study influence of the practical vehicle density, axle load distribution, structural uneven settlement, temperature, errors in construction and design analysis on the bridges. At the same time, the optimal maseures of construction technology and concrete mixture are proposed. The engineers should adopt more suitable construction steps and calculation models to consider relevant effects and accurately predict the possible excessive stress and deflections of bridges.

Bridge durability can be described from two aspects: (1) in the most general, structure durability is the ability of a structure to maintain its initial performance. (2) from the professional research and convenient quantification point of view, based on the equal construction and operation cost, structural durability is the ability to keep the expected design safety and suitability under action of external environments and other factors (design expected normal load).

The prominent issues of concrete bridges are thinner concrete cover, poor anti-penetration ability, steel bar corrosion, structural uneven settlement, and concrete carbonation. For the concrete bridges located in the splash zone in coastal area, the durability issue is more serious. Normally, the influence factors of concrete structural durability include own characteristics of concrete material(such as strength, mix ratio), bridge design, structural details, construction quality, environment, load, and protective measures.

Bridge sustainability (or economy and environmental protection) requires lower cost of structural construction and maintenance, smaller effect for environmental protection and sustainable development of society in meeting the needs of the designed bridge function and service life cycle.

Compared with the traditional bridge design, the performance design of life cycle bridges extends the design scope from construction to the whole life cycle. The life cycle performance design includes durability design, management and maintenance design, demolition, recycling design, risk assessment, insurance strategy, and life cycle cost analysis, some of which are not considered in the traditional design.

3.2 Bridge performance levels and requirements

Comprehensively considering these factors of safety, serviceability, durability, and environmental protection (repairability), bridges' location and importance degree, it is necessary to propose performance requirements corresponding to different performance levels aiming at four limit states of bridge structures. Three performance levels of existing bridges design in China are described in Table 2 based on the Refs.[16-18].

Performance level	Safety	Suitability	Durability	Environmental protection &Repair
	Load carrying capacity ultimate state (LCCUS)	Serviceability ultimate state (SUS)	Durability ultimate state(DUS)	Repairability ultimate state (RUS)
Performance level I	1) Bridge component or connection damage does not appear. 2) Bridge keeps overall stability. 3) Bridge does not transform into maneuvering system. 4) Progressive collapse of bridge does not appear. 5) The carrying capacity of foundation is maintained. 6) Fatigue damage of bridge does not appear.	1) Deformation of affecting bridge usage does not appear. 2) Partial destruction of affecting bridge normal use (including cracks) does not appear. 3) Other conditions of affecting bridge normal use do not appear.	1) The bridge normal service life is not limited by depassivation of reinforcement. 2) Main load carrying members of the bridge will achieve expected life without repairs during the service life.	No need to restore bridge function by repair.
Performance level II	1) Bridge has no apparent damage. 2) Bridge maintains original rigidity and strength. 3) Bridge works properly but the performance has been reduced.	1) Deformation of bridge can be controlled within limited scope. 2) Damage of bridge is local and allowable. 3) Bridge damage does not impede vehicles and pedestrians passing.	1) Bridge normal service life is limited, as the concrete cover is in cracking stage. 2) Adopt appropriate measures, the structure can meet designed expectation and it needs the large-scale repair after fixed year number.	Restore bridge function by simple repair.
Performance level III	1) Bridge has apparent damage. 2) Substantial reduction of bridge stiffness appears, but it can resist collapse. 3) Bridge requires a large-scale maintenance to meet the need of normal condition.	1) Larger deformation of affecting bridge use appears. 2) The bridge local damage exceeds the allowable values. 3) The bridge damage presents discomfort to the vehicle and pedestrian passing..	1) Bridge normal service life is limited, as the concrete cover is in cracking stage. 2) Adopt appropriate measures, the bridge can meet designed expectation and it needs the large-scale repair after fixed year number.	Restore structure function by large-scale repair.

Table 2: Performance levels and requirements of bridge structure

4 CONCLUSIONS

(1) The issues on safety and durability of concrete arch bridges are discussed and their development in China is summarized.
(2)The performance mainly include the safety, serviceability, durability, and sustainability of bridge structures in life-cycle. Aiming at structural locations and importance degrees of concrete arch bridges, the requirements in three performance levels are described for the four limit states of structural design and maintenance.
(3) It lays down the foundation for structural maintenance and strengthening, based on performance in life-cycle.

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