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INSPECTION AND MAINTENANCE MEASURES FOR LONG-SPAN REINFORCED CONCRETE BOX ARCH BRIDGES IN MOUNTAIN HIGHWAY

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Abstract: *Xugou Bridge of Lianhuo expressway (G30), located in Yima city of Henan province, is a reinforced concrete box arch bridge with a main span of 220m. It was completed and opened to traffic in December 2001. The expressway is located in mountainous area. The traffic is heavy and the proportion of heavy vehicles is high. It is a key issue to establish routine inspection and maintenance system to monitor the operation status and the structural performance. This paper introduces the monitoring contents and methods of inspection of the main components of the bridge, damages and their causes, traffic flow, stresses and deformation, static and dynamic response of the main structure, etc. The information obtained from the monitoring system provides the base of management and maintenance measures of long-span reinforced concrete box arch bridges and ensures safe operation. The experience accumulated from this practice helps to improve the management and maintenance of similar bridges.*

1 INTRODUCTION

The reinforced concrete box arch bridge is especially suitable to cross the mountain valley because of its spanning capacity and adaptability to the terrain and geological condition in mountainous areas. The reinforced concrete box-arch bridge is widely used in the construction of highway long-span bridges in China. The lifetime and carrying capacity of the bridge are directly affected by unfavorable factors, such as environmental corrosion, structural damage, material aging, overloading of vehicles and *etc.*, with the increase of service time. It is crucial to search for detecting methods and maintenance measures for the safe operation of this kind of bridges.

2 PROJECT OVERVIEW

Xugou bridge, located in Lianhuo Expressway (G30) in Yima City of Henan Province, is a continuous uphill section with a total length of 493.14m. The span layout is 9×20m+220m+4×20m from east to west and the deck has a slope of 2% in the longitudinal direction, as shown in Figure 1. The approach is a prestressed concrete hollow core plank structure. The main bridge is a uniform cross section catenary reinforced concrete box hingeless arch with the arch axis coefficient of 1.543, the clear span is 220m, the net rise is 40m and the ratio of rise to span is 1/5.5. The main arch section is a three-grid box section which is 3.4m high and 9m wide. The 13-17.5m construction on the arch is prestressed concrete hollow core plank and double column frame with horizontal linkages between columns. The six horizontal linkages are arranged between the two pieces of the main box arch to enhance the lateral stability. The abutment is a gravity foundation seated on the intact sandstone. The design loads are QC-20 and G-120. The bridge design was based on the seismic intensity of seven degree while the real site seismic intensity is six degree. The bridge had been constructed in August 2001. The tubular scaffold, layered and segmented pouring, piecewise closure were used during the construction of the main arch.

Figure 1: Xugou Bridge

3 DETECTION DURING OPERATING PERIOD

Currently, the regular inspection, periodical inspection and special inspection are the main detection for the technical condition of bridges. The regular inspection is the basis for management and maintenance of the bridge. According to the bridge maintenance requirements [1], since opened to traffic, the technical condition of the Xugou Bridge has been tested five times in 2006, 2007, 2009, 2011 and 2012 so as to detect the bridge disease timely, formulate specific maintenance measures and ensure the safe operation of the bridge.

3.1 Test Contents

(1) Bridge Deck System

The longitudinal and transverse slope of the bridge deck pavement is appropriate or not. Any serious cracks, pits, vehicle bumping at end of bridge, water leakage for the waterproof layer; Any abnormal deformation, damage, falling off, water leakage for expansion joints; The bridge deck drainage is smooth or not; The drain pipe is intact and smooth or not; The bridge drainage function is in good condition or not; The conical slope is erosive and collapsed or not; The traffic signal, sign and mark on the bridge, the lighting installation are damaged or not; The communication system, power wires and equipments are in good condition or not.

(2) Construction on the Arch

Hinge joints of hollow core plank are closely knitted or not; The concrete flange and web are cracked and spalled or not; Any aging, cracking, shear deformation, void, deletion for rubber bearings; Any tilting and cracking for columns on the arch; Any cracking, spall, rebar exposure and corrosion for concrete bent-caps and horizontal linkages.

(3) Main Arch

Any cracking, rebar exposure and corrosion for the reinforced concrete box of the main arch.

(4) Arch Support

Any sliding, tilting and sinking for the arch support; Any frost damage, weathering, cracking, spall and rebar exposure for the concrete; The top surface of arch support is clean or not; Any unallowable scouring or tunneling at the bottom of the arch support; The foundation is corroded or not.

3.2 Test Methods

(1) Apparent Detection

In order to find out the damage and disease of the bridge examine all components and parts of the bridge thoroughly and systematically and record all the location, scope and extent of the defects. The detection of bridge deck system mainly depends on the apparent detection.

(2) Concrete Crack Detection

Detection of cracks is mainly carried out in the respect of the crack location, crack length, width, depth, direction and etc. The graph of cracks can be drawn with the information of the length and direction of the cracks which can be obtained by measuring the starting points, ending points and turning points of the cracks with a tape; The width of crack can be obtained by the crack width observation instrument while the depth can be obtained by ultrasonic detection method.

(3) Concrete Strength Test

The strength of concrete is an important index of concrete bridge structure. The rebound method or ultrasonic - rebound method is widely used to test concrete strength. When the test data is discrete, the drilling core sample method can be used to modify or finalize the concrete strength.

(4) Concrete Carbonation Test

Concrete is a weak alkaline material which can prevent the reinforcement from corrosion. However, concrete will slowly carbonize and then lose alkalinity under the influence of environment. The depth of the concrete carbonization and its degree of aging can be detected by using phenolphthalein reagent which turns to red in alkaline environment.

(5) Detection of Steel Corrosion

The degree of steel corrosion affects the structure internal forces directly. The probability of steel corrosion and its activity shall be detected with steel corrosion identification instrument by measuring the level of the potential corroded steel in the structural member.

(6) Shape and Deformation of Bridge Structure

Permanent observation points shall be set up on the bridge to observe the plane and elevation control network regularly, to measure the actual axis of arch, the settlement and inclination of piers, the layout and verticality of piers, foundation settlement and structure deformation.

3.3 Detection Results

Five times of comprehensive detection has been completed for Xugou Bridge since 2006. No damage was discovered on arch support. Other damage on the structure is in the following.

(1) Year 2006

Bridge Deck System: No disease.

Construction on the Arch: One place of minor water penetration at the hinge joint between the slabs existed on the left and right bridge respectively.

Main Arch: No disease. The average depth of carbonation of the main arch was 15.58mm as shown in Figure 2.

(2) Year 2007

Bridge Deck System: There were 3 pits in L22 lane on the left bridge with the area of 0.3m×0.5m、0.1m×0.2m、0.5m×1m respectively. The typical disease is shown in Figure 3. The drainage holes of deck drainage system were all blocked on the left bridge. There was 1 pits in R15 lane on the right bridge with the area of 0.2m×0.3m. The drainage holes of deck drainage system were all blocked on right bridge also.

Construction on the Arch: One place of water penetration at the hinge joint between the slabs existed on the left and right bridge respectively.

Main Arch: No disease. The average depth of carbonation of the main arch was 16.61mm.

(3) Year 2009

Bridge Deck System: There were 14 places of settlement and net cracking on the bridge deck pavement on the left bridge with the largest area of 5m×4m. There were 6 places of settlement and net cracking on the bridge deck pavement on the right bridge with the largest area of 6m×4m.

Construction on the Arch: There were 4 places of bearing shear deformation on the left bridge. The longitudinal crack with the length of 1.5m and width of 0.15mm was found on the the web of L10-12 beam. There were 7 places of bearing cavity and 39 places of bearing shear deformation on the right bridge. There were 8 places of water penetration at the hinge joint between the slabs on the left and right of bridge with the longest length of 16m as shown in Figure 4.

Main Arch: No disease. The average depth of carbonation of the main arch was 18.32mm.

(4) Year 2011

Bridge Deck System: There were 2 pits on the bridge deck pavement on the left bridge with the area of 1.2m×1.0m. There was no disease found on the right bridge.

Construction on the Arch: There were 11 places of bearing shear deformation on the left bridge. Three vertical cracks with the length of 0.4m and width of 0.2mm existed on L-22 bent-cap, see Figure 5. There were 26 places of bearing shear deformation on the right bridge. There was one place of concrete damage and rebar exposure on the cantilever beam.

Main Arch: No disease. The average depth of carbonation of the main arch was 19.78mm.

(5) Year 2012

Bridge Deck System: There were three pits on the bridge deck pavement on left bridge with the area of 1.2m×1.0m. There was 1 pit on the bridge deck pavement on the right bridge with the area of 0.4m×0.2m.

Construction on the Arch: There were 15 places of bearing shear deformation on the left bridge. Three vertical cracks with the length of 0.4m and width of 0.2mm existed on L-22 bent-cap. The vertical crack with the length of 0.5m and width of 0.15mm existed on the east side of L-13 bent-cap, see Figure 6. There were 28 places of bearing shear deformation and one place of water penetration with the length of 4.0m at the hinge joint between slabs. There was one place of concrete damage and rebar exposure on the cantilever end of the bent-cap.

Main Arch: No disease. The average depth of carbonation of the main arch was 20.82mm.

Figure 2: Concrete Carbonation Test (2006)

Figure 3: Bridge Deck System Disease (2007)

Figure 4: Water Penetration Between Slabs (2011)

Figure 5: Vertical Cracks on the Bent- cap (2009)

Figure 6: Vertical Crack on the Bent-cap(2012)

4 CAUSES OF THE DISEASES AND ASSESSMENT OF THE STATUS

4.1 Causes of the Diseases

Based on the test results analyze of the causes of diseases in order to provide scientific management and maintenance scheme for the bridge.

(1) In 2006 the first detection was performed 5 years after the bridge in operation. The bridge was in good condition with only minor damage.

(2) In 2007 the second detection was performed 6 years after the bridge in operation. The bridge was in good condition with minor damage such as pits on the bridge deck system and drainage system blocked. Deck system diseases mainly due to high traffic flow, high proportion of overloaded vehicles and bridge deck asphalt concrete aging etc. unfavorable factors cause partial damage.The left bridge due to the continuous downhill bring about adversely accelerating effect, therefore the diseases are more serious.

(3) In 2009 the third detection was performed 8 years after the bridge in operation. The damage of the bridge was not serious. In addition to the damage of the bridge deck system

micro cracks were observed on the individual beam and shear deformation was observed on parts of the rubber bearing. Several rubber bearing appeared cavity. The disease of the construction on the arch structure is mainly caused by the reduction of the overall strength and stiffness of bridge deck system and the damage of the longitudinal joint between the hollow core planks. The serious diseases are some hollow core planks working separately and rubber bearing cavity, which resulted in cracks on hollow core planks and beams due to the bearing of unfavorable loads.

(4) In 2011 the fourth detection was performed 10 years after the bridge in operation. The diseases, such as pits on the bridge deck system, micro cracks on beams, rubber bearing shear deformation and rubber bearing cavity, were found out. When compared with cracks observed in 2009 it indicated that special maintenance on the bridge deck system implemented in 2009 worked well. However, due to the large traffic flow the one way closed maintenance cannot be performed. And thus the reduction of the bridge deck integrity has not been improved.

(5) Because of the maintenance for the right bridge deck system in 2011 only slight damage was found during the detection performed in 2012. The cracks on beams were located mainly in the left bridge. And there was no disease found in the right bridge. No structural disease was found in arch support. But sediment pollution was observed on the top of the arch support.

(6) It was found that the depth of the concrete carbonization was increasing year by year by using phenolphthalein reagent to detect the depth of the concrete carbonization of the main arch. The average annual increment of the depth of the concrete carbonization was 0.83 mm for the bridge operation from 5 to 10 years. While the average annual increment of the depth of the concrete carbonization was increased to 1.04 mm for the bridge operation after 10 years, which indicated that environment of the bridge seriously affected on concrete aging.

4.2 Evaluation of Technical Condition

Because of the different structure between the main arch and approach of Xugou Bridge the main arch and approach shall be evaluated separately in order to objectively evaluate the actual technical condition of the bridge. According to Standards for Technical Condition Evaluation of Highway Bridges [2], the technology assessment of the main arch is in the following based on the test results obtained in 2012.

(1) The Right Bridge

Superstructure of the Main Arch: SPCI=91.25, Technical Condition: Grade 2;

Substructure: SBCI=100, Technical Condition: Grade 1;

Bridge Deck System: BDCI=100, Technical Condition: Grade 1;

The Whole Bridge: Dr=96.50, Technical Condition: Grade 1.

(2) The Left Bridge

Superstructure of the Main Arch: SPCI=91.25, Technical Condition: Grade 2;

Substructure: SBCI=100, Technical Condition: Grade 1;

Bridge deck system: BDCI=81.2, Technical Condition: Grade 2 ;

The whole bridge: Dr=92.74, Technical Condition Grade 2.

The worst technical condition of Xugou Bridge is grade 2 on the left. The operating is in good condition.

5 MAINTENANCE COUNTERMEASURES

Xugou Bridge as an important throat of east-west traffic artery G30 in China, is of special significance in the bridge construction history. In order to ensure the safety operation of the bridge it is necessary to strengthen the daily management and maintenance and special maintenance according to the results of the annual inspection. Because of the importance and complex traffic flow of the bridge, healthy monitoring system of the bridge shall be established in order to monitor the traffic flow and traffic condition of the bridge, measure the static response of stress and deformation, dynamic response of acceleration and vibration of main structure parts of the bridge, master the status of the bridge under loading timely [3]. Thus the environment, loads, stresses, deformation and vibration can be monitored timely and the dynamically assessment of the whole process of the state of internal force changing and structure damaging of the bridge can be realized. When the structure subjected to serious overloading, the system can provide warning timely to ensure the safety and durability of the bridge structure.

5.1 Daily Maintenance

In order to ensure the normal operation and improve the quality and level of services of the bridge maintenance personnel for maintenance and repair work on the bridge should be arranged. For all the problems found during the bridge inspection daily maintenance should include the following:

(1)Keep the surface of bridge structure clean and avoid the accumulation of water and dust; Clean the drain pipe regularly and keep the deck drainage smooth.

(2)Ensure the expansion joint device working normally and avoid structural member cracking due to its constrain condition changed.

(3)Clean the dirt on the main arch and the construction on the arch.

(4)Keep the arch support of the bridge in good condition and avoid the erosion and peeling of the arch foundation. Soils cannot be borrowed within 200m upstream and 200m downstream.

5.2 Special Maintenance

In order to eliminate the hidden danger the special maintenance and repair of the bridge should include the following based on the diseases of the bridge.

(1) The maintenance stair and platform should be added onto the main arch for convenience.

(2) For the diseases of rut, settlement and net cracking on the asphalt pavement the repair should be started after the pavement around the diseases has been chipped out.

(3) The deck waterproof of the bridge should be repaired when the leakage at the hinge joint is serious.

(4) The rubber bearing should be resetted when the rubber bearing cavity happened; The rubber bearing should be timely replaced for the damage of shear deformation, aging and cracking.

(5) The cracks found in the structural member during the inspection should be timely enclosed with epoxy resin or polyurethane under the dry or wet condition respectively.

(6) Even if there was no disease found for the main arch during detection, the concrete carbonation increased year by year. In order to ensure the operation safety in its design life the special maintenance measures, such as epoxy mortar resin coating to prevent the concrete from erosion, should be adopted to improve the durability of the bridge.

5.3 Health Monitoring scheme

(1) Working Environment Monitoring

The working environment monitoring includes the environmental temperature monitoring, vehicle loads, deck video monitoring and wind speed and direction monitoring at the site of the bridge.

The function of the temperature monitoring system of Xugou Bridge is mainly to detect temperature difference between inside and outside of the bridge in the working state, which provides the basic data for analysis of internal forces of the bridge structure due to the temperature difference between inside and outside, and also provides the basis for the temperature modification of the strain sensor. The distributed optical fiber temperature sensors were arranged on the bridge to observe the environment temperature and the temperature distribution on the bridge.

The vehicle loads monitoring system is used to provide the clear input for the performance of the bridge structure, to control the negative effects on the bridge structure caused by transfinite transportation, and to provide warnings for the overloading vehicles. The weighing system arranged on the bridge entrance with the combination of the deck video monitor can obtain and calculate the parameters of the vehicle weight, speed, passing time and passing lanes when the vehicles pass the bridge, and hence to monitor the operation condition of the bridge. The corresponding vehicle loading data should be input to the bridge health and safety monitoring system to understand the loading of bridge and analyze the structure under the loading.

Wind speed and direction monitor instrument set up at the bridge site is used to collect the data of wind speed and direction. Thus, the maximum annual wind speed can be catched and the strain observed can be compared with the design values.

(2) Overall Structural Performance Monitoring

The overall performance monitoring of the main structure of Xugou Bridge includes vibration monitoring and arch structure displacement monitoring of the bridge.

The dynamic characteristic coefficients of the bridge (frequency, mode and damping) and the level of vibration (vibration intensity and amplitude) are the safety sign of the whole bridge. The aging of concrete will cause the change of the structural vibration characteristics. Therefore, monitoring of the bridge dynamic characteristics and vibration level will be the health monitoring for the structure of the whole bridge. The vibration level can reflect the traffic safety and bridge pavement condition of the bridge. The status of the bridge can be obtained by vibration test in real time under the un-expecting condition (earthquake, typhoon, vehicle collision and etc.). In addition, the vibration characteristics of the vertical and horizontal wave can be obtained by collecting and analyzing the vibration characteristics (the three components sensor and the vertical-horizontal wave separation and analysis technology), which is very important to the safety status judgment of the bridge.

Arch axis is an important symbol of the safety status of the whole bridge under the dead loads. The main arch deflection is an important index of the evaluation of the service and safety of the bridge structure under live loads. It is also an important sign of the integral rigidity of the bridge. By monitoring the main arch deflection and operating loads, we can grasp the bridge health and safety as a whole.

(3) Stress Monitoring for Critical Sections

By the strain monitoring of the critical sections of the whole bridge we can grasp the stress changing in real time. The strain monitoring system plays an important role in the whole monitoring system of the bridge. By monitoring the stress of the critical sections, we can determine the trend of degradation of the bridge structure. And the maintenance personnel can make a reasonable maintenance plan for the bridge. The dynamic reaction of the structure is the most direct response on the vehicle load effects. By monitoring the dynamic response of the structure, we can better grasp the response of the bridge structure under dynamic loads (vehicles and earthquake) and obtain the structural safety situation by the dynamic magnification coefficient and load statistics.

6 CONCLUSION

By establishing of conventional detection and health monitoring system of Xugou Bridge we can realize the effective combination of the theoretical analysis and the actual situation. Regular disease detection can ensure the judgment of the damage status of each component of Xugou Bridge and determine the scope and manner of maintenance. Health monitoring system can overall grasp operation state of the bridge, master the internal force state and damage of the bridge structure at any time, provide warning and forecasting against the risk status of the bridge structure timely, and effectively monitor and assess the structure health and safe operation of the bridge during the operation period. The combination of the two can provide the basis of formulating maintenance measures for large span reinforced concrete box arch bridges, guarantee the operation safety and service life of the bridges, and accumulate experience for the similar bridge management and maintenance.

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