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RESEARCH ON THE JOINTLESS RETROFIT OF MULTI-SPAN SIMPLY SUPPORTED HOLLOW SLAB BRIDGE

J.C. Dong[1,2], Z.R. Xiao[3], Y.Z. Zhuang[4], J.Q. Xue[4], B.C. Chen[4], C.W. Yang[1], B. Briseghella[4]

ABSTRACT

Although simply supported hollow slab bridge is widely used in China, there are many diseases which lead to the heavy tasks of retrofit. Taking a multi-span hollow slab bridge project as an example, the jointless retrofit scheme of the bridge is put forward on the basis of disease investigation, technical condition evaluation; the basic principles and the main types of the jointless bridge are firstly introduced as well as construction progress according to the retrofit scheme. The main measures of the jointless retrofit mainly include: continuous retrofit of two adjacent span simply supported girder at the pier, which improves the structure performance, cancels the expansion joints on the piers; the expansion joints at the abutment are cancelled by stretching deck slab; in addition to the reinforcement measures of pasting carbon fiber plate, steel bar, etc. Jointless retrofit by the change of structure system, not only improves the carrying capacity of the structure, reduces the cost of the sagging moment reinforcement, but also can effectively improve the performance of the bridge, avoid the expansion joint device maintenance problems, improve the ability of the sustainable development of the bridge.

[1] Student, Dept. of Civil Engineering, University of Fuzhou, Fuzhou, Fujian, P.R. China, 350116
[2] Deputy senior engineer, Shenzhen Municipal Design & Research Institute Co.,Ltd, Shenzhen, Guangdong, P.R. China.
[3] Director, Municipal design office, Fuzhou Planning Design & Research Institute, Fuzhou, Fujian, P.R. China
[4] Professor, Dept. of Civil Engineering, Fuzhou University, Fuzhou, Fujian, P.R.China 350116

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Research on the Jointless Retrofit of Multi-span Simply Supported Hollow Slab Bridge

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ABSTRACT

Although simply supported hollow slab bridge is widely used in CHINA, there are many diseases which lead to the heavy tasks of retrofit. Taking a multi-span hollow slab bridge project as an example, the jointless retrofit scheme of the bridge is put forward on the basis of disease investigation, technical condition evaluation; the basic principles and the main types of the jointless bridge are firstly introduced as well as construction progress according to the retrofit scheme. The main measures of the jointless retrofit mainly include: continuous retrofit of two adjacent span simply supported girder at the pier, which improves the structure performance, cancels the expansion joints on the piers; the expansion joints at the abutment are cancelled by stretching deck slab; in addition to the reinforcement measures of pasting carbon fiber plate, steel bar, etc. Jointless retrofit by the change of structure system, not only improves the carrying capacity of the structure, reduces the cost of the sagging moment reinforcement, but also can effectively improve the performance of the bridge, avoid the expansion joint device maintenance problems, improve the ability of the sustainable development of the bridge.

Introduction

Multi-span simply supported hollow slab beam bridge, with continuous deck, as a common bridge type for small and medium span bridges, has the similar mechanical characteristics to simply supported girder bridge in simplification of structure, convenience of construction and elimination of expansion devices over piers that leads to the cost saving in installation and repair of expansion devices as well as the amelioration of driving quality. Therefore, it has been applied in all parts of the world for quite a long time. With the increase of service period and the development of traffic volume, a large number of such bridges are challenged by the decreasing in load carrying capacity and the inadequacy of current design load. In order to improve the load-bearing capacity, safety and durability of these bridges, it is necessary to employ appropriate maintenance as well as necessary strengthening [1]. As a first step for that purpose, investigating the causes to common distresses was carried out, and then a scientific and reasonable solution was followed up. Taking an existing multi-span simply

[1] Student, Dept. of Civil Engineering, University of Fuzhou, Fuzhou, Fujian, P.R. China, 350116
[2] Deputy senior engineer, Shenzhen Municipal Design & Research Institute Co.,Ltd, Shenzhen, Guangdong, P.R. China.
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supported hollow slab beam bridge with continuous deck for example, the feasibility and design method of this kind of jointless and continuity transformation was analyzed.

Engineering background

Shili bridge, built in 1995 and located on No.503 county road, Shili village, Changtai County, Zhangzhou city, Fujian province, is 111.85 m long with 6-spans of simply-supported hollow slab beams and continuous deck (Fig.1). It consists of an old bridge and a new bridge, separated by a median between them (Fig. 2). Its total width is 26.85 m, of which 9.5 m is the left traffic lane of the old bridge. The original traffic design load is Truck-20 and Tractor trailer-100. The deck pavement is cementitious concrete. The superstructure is of precast C30 concrete hollow slab beam, and the substructure is of stone gravity-pier with spread foundation. As traffic volume and overloading vehicle continuously increase, longitudinal and transverse cracks, with the widest width of 1.2 mm, appear in the left part of the bridge. Therefore, it is urgent to take technical inspection and then carry out corresponding strengthening measures for the left bridge.

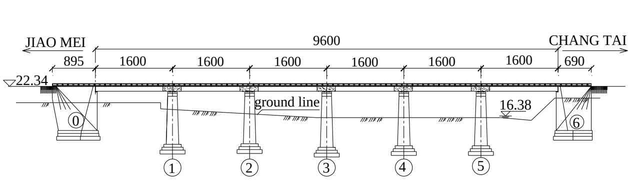


Figure. 1 Elevation layout (unit: cm)

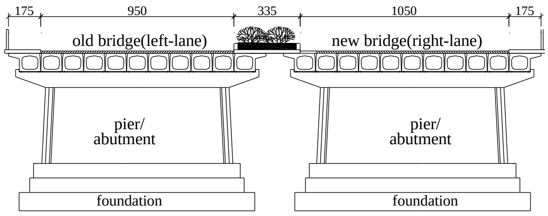


Figure. 2 Cross-section (unit: cm)

After many years of operation, longitudinal cracks, transverse cracks, serious damage to cross section, steel corrosion, concrete carbonation, and other distresses reduce the actual load bearing capacity of the bridge. The bridge appearance was inspected in details, the structural concrete strength in both superstructure and infrastructure were evaluated by using ultrasonic rebound synthetic method, and the dynamic properties were determined by dynamic loading test. The main distresses of the bridge are describes in the followings:

1）Longitudinal cracks appear on top of bridge deck and bottom of slab beam near hinged joint, with the maximum width of 1.2 mm (Figs.3-4). Meanwhile, transverse cracks appear on bridge deck over pier, with the maximum width of 1 mm (Fig.3). Besides, concrete spalling, corner-missing and bare steel also appear along hinged joints (Fig.5).

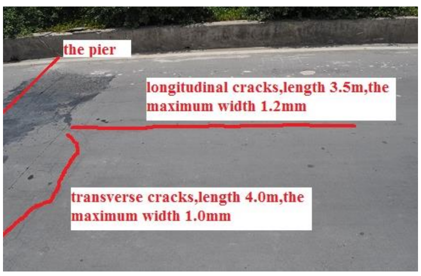


Figure.3. Cracks on the top of bridge deck

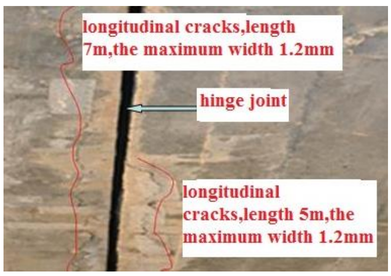


Figure. 4. Cracks on the bottom of beam

Figure.5. Concrete spalling

Figure. 6. Water seepage

2) Abutments and piers are in nearly good condition with no visible displacement, settlement and cracking, and the only noticeable distress is the serious water seepage (Fig.6).
3) Pavement concrete is crushed seriously (Fig.7). Besides, most EPS-bearing layers are damaged so that beam bottoms are in tight contact with the bent caps supporting them (Fig.8). Expansion joints don't go through the sidewalk slabs and the rails, which leads to the blockage of longitudinal thermal deformation. Consequently, in part of the sidewalk slabs have appeared transverse continuous seams. Meanwhile, most of the deck drain pipes have failed to function, which causes serious ponding on the bridge deck (Fig.9).

Figure.7 Pavement concrete crushing

Figure.8 Tight contact between slab bottom and bent cap

Figure.9. Rupture of bridge deck and side walk pavement

4) Dynamic test results show that the measured first order frequency is 5.37 Hz, and its ratio to theoretical frequency is 0.93, less than 1, which indicates that the bridge is in the unhealthy state.
According to the overall appearance inspection to the bridge and the technical condition evaluation in view of "Standards for Technical Condition Evaluation of Highway Bridges" (JTG/T H21-2011), the evaluated technical condition score is 59.2 points, which is classified as category IV [2]. It can be explained that the main components of the bridge have serious defects which seriously affect its performance function, reduce its load bearing capacity and jeopardize the safety of the bridge.

Ideas on structural transformation

In view of the present condition of the bridge and in order to guarantee the structure's durability, safety in operation, and meet the needs of the growing traffic, this paper puts forward a few repair and reinforcement schemes as followings:

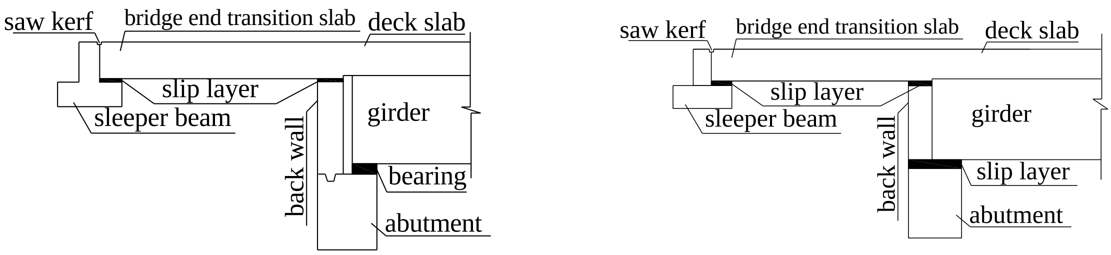
1) According to test results and calculation of finite element model, the load bearing capacity of the original structure can't guarantee the security of normal service. Therefore, it's necessary for the bridge to be carried out a reinforcement design. Two transformation methods, namely the superstructure reinforcement as well as system transformation, were adopted.

Measure I is to transform a simply-supported bridge structure into a continuous one. It can improve the load-carrying capacity and the service function of the structure, by improving the stiffness of the structure, reducing the mid-span moment of the structure, and simultaneously, eliminating the internal expansion joints between slabs, which makes driving more comfortable, maintenance more convenient, durability higher and earthquake more resistant. This kind of structural transformation overcomes the drawbacks inherent in traditional simply-supported bridges, such as poor deck continuity, large deformation and low durability after several years' operation [3].

Measure II is to simply stick carbon fiber sheet on the bottom of hollow slab, which is expected to improve the ultimate load bearing capacity and the safety reservation of the bridge.

2) Considering that materials and structure stiffness before and behind abutments differ greatly, the expansion joint devices at abutments, compared to those over piers, are more likely to be damaged. Additionally, vehicle bumping over the abutments due to the settlement of backfill has a great impact on the bridge. The paper tries to eliminate the expansion joints and corresponding expansion devices at abutments and carries out abutment jointless transformation. After that, the whole bridge's jointless transformation is achieved in addition to the above-mentioned system transformation. Jointless transformation doesn't only avoid or reduce the vehicle bumping, improves driving quality, reduce the expansion devices maintenance and replacement costs, but also eliminates the transport disruptions because of the maintenance, repair and replacement to the expansion joints. Meanwhile, jointless transformation eliminates the impact of noise and structural vibration on environment due to expansion joints, reduces the seam leakage, and improves the structural integrity, durability, seismic performance and service function.

Taking into consideration of the structures of girder, abutment and foundation, this paper adopts the transformation form of independent deck extension type (Fig.10a). Jointless bridge with deck extension refers to a bridge whose abutments and its superstructure are not united as a whole, and its approach slab, as a part of extended bridge deck, can slide over abutments and transfers the movement of deck slab to road. In this kind of jointless bridge, the movable bearings still exist on the top of abutments. According to the relationship between the girder and the back wall of abutment, it can be divided into independent deck extension type and dependent deck extension type (Figs.10a-10b). In independent deck extension type (Fig. 10a), the expansion joint (the gap) exist between girder and back wall, where the expansion and shrinkage deformation of the bridge can be accommodated there through its movable bearing and slip layer over back wall. Eventually, the deformation from the bridge is transferred to the connection road by the extension deck slab to eliminate the bridge expansion joint between girder and abutment. Whereas, in the dependent deck extension type (Fig.10b), the back wall is rigidly connected and longitudinally movable along with girder [4].



(a) Independent deck extension type (b) Dependent deck extension type

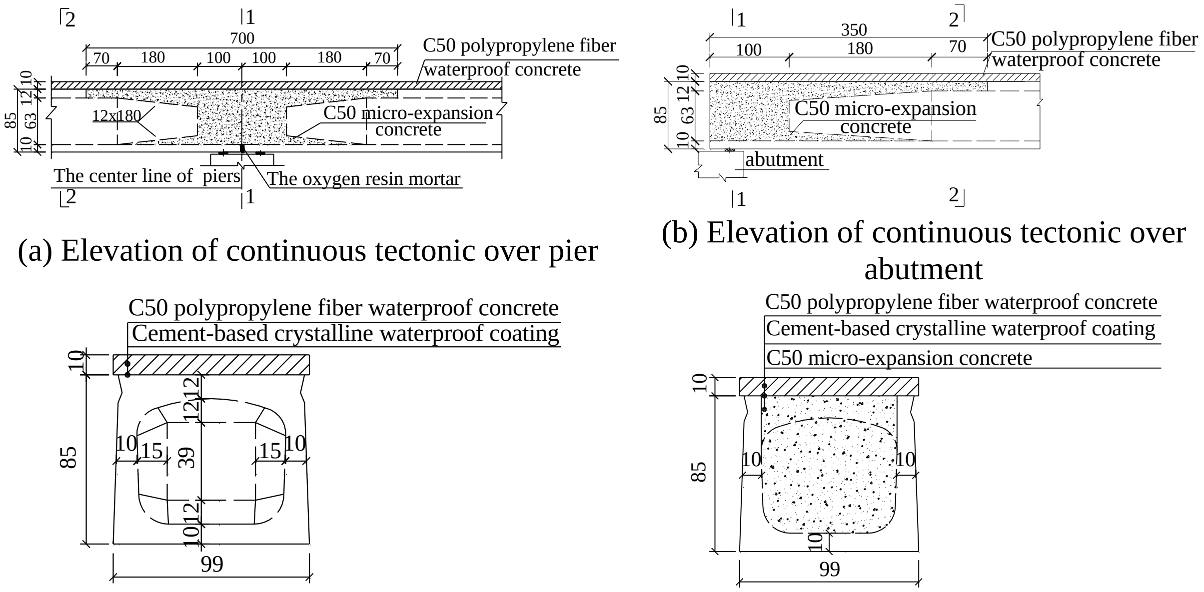
Figure.10 Jointless bridges with deck extension

3) Longitudinal cracks appear in the deck slab near the hinged joints, which states that the transverse stiffness of the structure declines and in the weakest cross section appears the great transverse stress resulting in longitudinal cracks. In order to increase the transverse stiffness and improve the transverse load distribution for bridges which show the phenomenon of losing transverse connection between slabs, the following renovation is designed to be implemented: remove the original deck pavement, refill the hinged joints, and finally add a new layer of cast-in-place RC pavement integrated with deck slab.
4) The whole bridge bearings are replaced. It’s important to ensure that all bearings over certain a pier or an abutment should be replaced simultaneously. Besides, cracks in girder and pier are closed by injecting grout, and pulping repair is carried out in the positions of concrete spalling and exposed reinforcing bars. Drainage system should be dredged and especially the accumulated soil should be removed from drain pipe. Meanwhile, the waterproof layer should be redesigned to avoid rainwater penetrated into beam and substructure.

Specific measures in the strengthening scheme

According to the above structural transformation ideas, and aiming to improve the structural load-bearing capacity and driving quality, as well as to reduce maintenance cost, some specific measures are provided as followings:
Measure I is to transform a simply-supported bridge structure into a continuous one.
A 6-span simply-supported hollow slab RC bridge is transformed to a continuous structure system by taking the following steps: remove the existing top flange concrete in beam ends (within the longitudinal scope of 7 m over pier and 3.5m over abutment); lay the longitudinal steel rebar to resist negative bending moment caused by the transformation of structural system (Figs. 11a-11b), and finally pour fresh concrete to connect the adjacent two spans as a whole. The hollow part of beam end (within a range of 1 m) is filled with concrete (Fig. 11c). In order to ensure the integrity of later pouring concrete and girders, the micro-expansive concrete is used.
All existing bearings are replaced with new ones. Theoretically, single bearing or double bearings affect slightly the force distribution in a continuous beam. Peak negative moment of continuous beam decreases due to double bearings, accordingly the unloading effect of mid-span moment decreases, but this adverse effect is very limited, especially for the common spans of 20-30 m bridges when they are strengthened by structural system transformation from a simply-supported bridge into a continuous one [5]. Therefore, this project adopts double bearings for the sake of construction convenience, and replaces the whole bridge bearings with ordinary rubber bearings. The ordinary laminated rubber bearings are set over piers, and the stainless steel PTFE laminated rubber bearings are set over abutments to accommodate the deformation.
The structural system transformation from simple supported to continuous can significantly improve the bending capacity of mid-span section, but can’t effectively improve the shear

bearing capacity of inclined section near supports. Therefore, the inclined section near support needs to be checked in shear bearing capacity. Based on the checking results, the cross-sectional dimension at support is widened, in which the web is thickened to 15 cm, the top and bottom flange to 12 cm (Fig. 11d). The linear gradient length is 1.8 m (Figs. 11a-11b).



(a) Elevation of continuous tectonic over pier

(b) Elevation of continuous tectonic over abutment

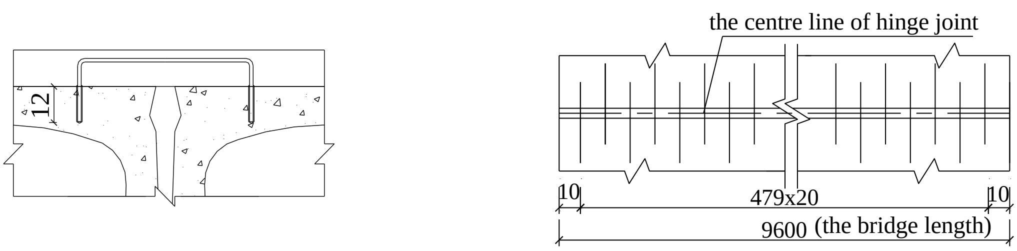
(c)1-1 section

(d)2-2 section

Figure.11. Simply-supported to continuous structure system (unit: cm)

Taking accounting of the needs for anti-cracking and waterproof of the cast in-place deck slab around over piers due to negative moment, C50 polypropylene fiber waterproof concrete with low shrinkage and good density are adopted (Fig.11c) to effectively control the concrete shrinkage crack. Moreover, steel mesh reinforcement with Φ10 mm bars is laid on the surface of the new concrete layer so as to control the shrinkage cracking of the concrete. Meanwhile, longitudinal steel rebar with Φ20 mm are also laid on the surface of the new concrete layer to meet the negative moment requirement at supports caused by the structural system conversion. The negative moment steel rebar is tied together with steel web, and Φ12 mm spacer bar is embedded into the top of the precast slab to guarantee the position of negative moment steel rebar. Finally cement-based crystalline waterproof coating is paved between girder and deck pavement to improve the ability of deck waterproof.

The new cast-in-place concrete deck pavement cooperates with the original structure as a structural layer. The reliable connection between them is the key for them to work together. To strengthen their reliable connection, in addition to roughing on the original concrete surface, shear connectors should also be installed. The shear connectors use R235 U-steel, 20 mm in diameter (Fig.12a), which are equally spaced along the hinged joints (Fig.12b).



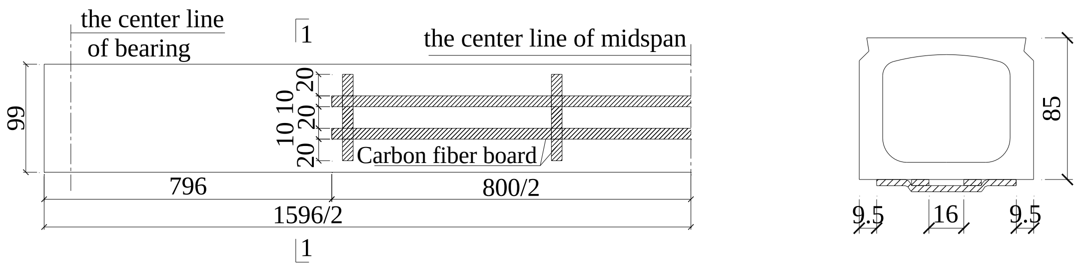
(a) Details of planting bars

(b) Layout plan of planting bars

Figure.12 Schematic diagram of connection between the cast-in-place deck pavement and the original structure (unit：cm)

Measure II is the reinforcement method by sticking carbon fiber sheet on the bottom of hollow slab.

In order to improve the ultimate load bearing capacity of main girder and bridge safety reservation, as well as considering the advantages of carbon fiber sheet such as its high strength, high elastic modulus, good corrosion resistance and high durability, no increase in structure self weight and volume, ease of construction etc., the reinforcement method by pasting carbon fiber sheet is adopted, in which two layers of carbon fiber sheet with a thickness of 1.4 mm are attached on the bottom of girder within the scope of 8 m at mid-span (Fig.13).



(a) The layout plan of half-girder reinforcement (b) Section 1-1

Figure.13 Schemes of girder reinforcement (unit: cm)

Measure III is the jointless renovation of abutment.

On the basis of remaining the original bridge as much as possible, the abutment modification is made to eliminate the expansion joint and device on both ends of the bridge. Remove the concrete at the beam end within the scope of 1 m, cut down the height of abutment backwall, and integrate the beam end and the approach slab by pouring new concrete, where the approach slab is able to slide over the modified backwall. Eliminate the bridge expansion joint and device between the beam end and the abutment in this way (Fig.14).

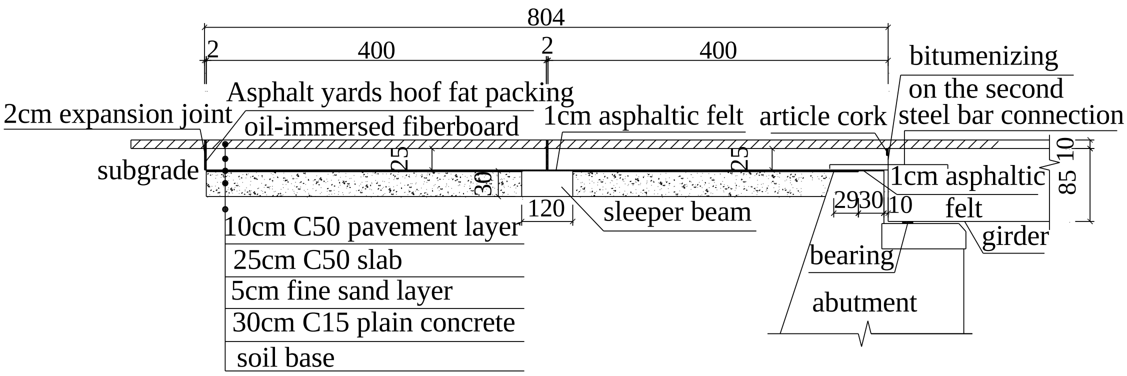


Figure.14. Elevation of jointless abutment (unit:cm)

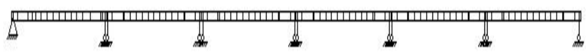
The modified superstructure still retains the original abutment and support. In order to accommodate the thermal movement of the bridge deck system, the sliding surface (a layer of 1 cm felt) is set on the top of backwall. Approach slab should be placed on the flat surface of backfill soil layer with low friction, so that a 5 cm thick layer of fine sand is evenly laid under the approach slab in order to reduce the frictional resistance between the approach slab and its base, and also to transfer girder expansion/contraction deformation more freely. A construction joint, aligned to the inner side of the backwall, is set between the beam end and the approach slab (a soft cork is filled into the top of the construction joint). The setting of this construction joint is to establish a hinge connection preventing from moment transmission, and controlling generation of cracks. The axial force between the main girder and the approach slab is transferred via steel bar connection.

Two pieces of 4 m long approach slabs are set behind each abutment. Two expansion joints are separately set between the two approach slabs and between the approach slab and the connection road to absorb various longitudinal displacement of the superstructure (including the approach slab system), and to relieve the longitudinal pressure caused by inflation restraint of rigid pavement. Sleeper beam is laid between and underneath the two approach slabs for stiffness transition to prevent/reduce the slabs from differential settlement.

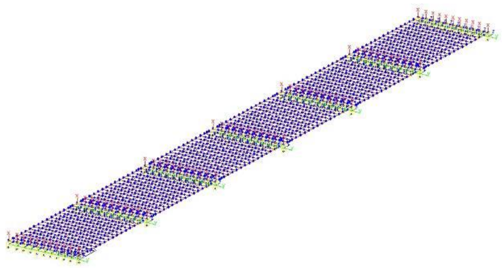
In order to ensure the bearing capacity of the approach slab bottom, a layer of 30 cm thick plain concrete is casted underneath the slab after the excavation of foundation to strengthen the slab subgrade.

Analytical calculation

The paper uses Doctor Bridge V3.2.0 software for modelling calculation and then Midas Civil 2010 software for checking (Fig.15). The original structure and the transformed continuous structure are established respectively.



(a) FEM model using Doctor Bridge V3.2



(b) FEM model using Midas Civil 2010

Figure. 15 Two full-bridge structure models

The calculation for this sort of structural transformation can be divided into two stages according to the mechanical characteristics: the simply-supported beam stage and the continuous beam stage. Primary dead load is calculated at the first stage in view of a simply supported beam, which refers to structural deadweight in a state of simply supported beam, including the original hollow slabs and the wet joints. Superimposed dead load is calculated at the second stage in view of a continuous system, which refers to structural deadweight in a state of continuous beam, including the cast-in-place slab concrete at the top of piers, the deck pavement and the green planting belt, etc. The system conversion from simply-supported to continuous has been completed at the second stage, and the negative moment at support will exist in the secondary dead load and live load in the service phase. Compared with the original simply supported beam, the moment at mid-span decreases and moment distribution becomes more uniform.

Checking of load-bearing capacity for the new transformed continuous bridge

The checking of load-bearing capacity includes two kinds of working conditions: bearing capacity limit state and serviceability limit state. Bearing capacity limit state checking includes flexural bearing capacity at mid-span and at support as well as shear bearing capacity at the inclined section near support. Serviceability limit state checking includes crack width at mid-span and at support as well as deflection at mid-span.

Based on the inspected distresses such as bridge cracks, concrete spalling, steel corrosion, etc, and the technical condition evaluation in view of "Standards for Technical Condition Evaluation of Highway Bridges" (JTG/T H21-2011) [6], the bridge is rated as category III that indicates that the bridge has a moderate defect, but still can maintain normal service. According to the damage condition ratings of bridge components and the "regulations of highway bridge bearing capacity evaluation" (JTG/TJ21-2011), reduction factor of bearing capacity is always adopted. This paper introduces comprehensive modification coefficient of existing bridge load-bearing capacity Z1, deterioration coefficient of loading-bearing capacity ξe, section reduction coefficient ξc and modified coefficient of live load ξq (Tab.5), and reflects the coefficients in the structural resistance expression. Finally, the checking calculation of bearing capacity refers to “Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridge and Culverts” (JTJ 023-85), considering the mechanical characteristics of simply-supported to continuous transformation by stages as well as the influence of structural damage [7].

Table.5. Reduction factors of load-bearing capacity for Shili Bridge

Z1	ξ_e	ξ_c	ξ_q
1.12	0.0704	0.980	1.06

Considering the above bearing capacity reduction factors and the analytical results are listed in Tab.6, showing that moment and shear force can satisfy the requirement of specification under the most unfavorable loading cases. The calculation crack width ranges from 1.2 mm to 0.104 mm at mid-span and 0.138 mm at support, which also meet the requirement of specification. Considering the growth coefficient of long-term deflection, the largest vertical deflection in mid-span is 13.3 mm, less than the standard limit of 26 mm, which meets the requirement of specification.

Table.6. The internal force checking of girder after strengthening

Section	M_u (kN·m)	M_j (kN·m)	M_u/M_j	V_u (kN)	V_j (kN)	V_u/V_j
Mid-span	1328	1206	1.1	-	-	-
Support	-1121	-860	1.3	914	446	2.1

Note: M_j-Calculating Moment of Section; M_u-Flexural Bearing Capacity of Section; V_j-Calculating Sheer Force of Section; V_u-Shearing Capacity of Section.

All the results show that the structural loading state and load-bearing capacity are both obviously improved after adopting the two strengthening measures: transformation from simply-supported structure to continuous one and pasting carbon fiber sheet at the bottom of hollow slab.

Conclusions

Based on Shili Bridge’s distress investigation and analysis, the paper puts forward a new kind of retrofitting scheme–system transformation from the simply-supported beam to a jointless structure. The reinforcing scheme is applied to the old bridge to make full use of the old bridge structure so that it can improve the load-carrying capacity and the service function of the structure. Meanwhile, it is necessary to monitor the construction process and service condition to guarantee the safety of structure. With the deepening of the study, the reinforcement scheme also needs to be constantly improved. The working performance and the force transmission mechanism of two nodes at the piers and abutments for the jointless retrofitting should be studied by experimental study and theoretical analysis, to demonstrate its feasibility and effectiveness. The design theory of this method is put forward to expand the bridge reinforcement technology development space.

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