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Ultimate flexural strength analysis of serving concrete main girders considering bridge deck pavement

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ABSTRACT:
Introduction:

Concrete girders are a type of widely used structures in small and medium span bridges. The ultimate flexural strength of concrete main girders serves as a critical foundation for assessing the structural performance of small and medium span simply supported girder bridges, and is essential for ensuring their safe operation. After the installation of prefabricated concrete girders, cement and asphalt concrete are sequentially poured on the top surface of the girders as bridge decks. The bridge deck pavement and concrete girder jointly bear the overall external loads. However, during the design and operation stages, the bridge deck pavement is typically regarded as secondary dead load when estimating bearing capacity, without considering its inherent reinforcement effect on the main girder. Thus, understanding the damage mechanism and destructive behaviour of concrete girders whilst considering the deck pavement effect is crucial for bridge safety assessment. The currently prevalent laboratory-based research method using scaled models can effectively elucidate the failure mechanisms of concrete girder members by controlling the experimental environment, the findings cannot be directly extrapolated to evaluate the service performance of actual bridge structures.

Description of the serving concrete main girders:

This study focused on retired concrete main girders from real-world service environments, conducting ultimate flexural strength tests. The full-scale retired prestressed concrete girder used in this study was taken from a highway bridge in Northeast China. The bridge span, deck width, and structural form are typical representatives of medium and small-sized highway concrete girder bridges in this region. The superstructure is a post-tensioned prestressed concrete hollow slab girder with a calculated span of 17.60 m. The total width of the deck is 13 m, and the width of the motor vehicle lane is 12 m. The deck pavement is made of 10 cm thick cement concrete and 8 cm thick asphalt concrete. When the bridge was demolished, the top layer of asphalt concrete was milled off first, and then a cutting machine was used for longitudinal cutting to remove the cement concrete deck pavement along with the main girder as a whole. The research object of this paper is one of the middle girders, with a girder height of 90 cm and a width of 124 cm. Both the main girder and the deck pavement are made of C40 concrete. The stirrups of the top slab use HPB300 steel bars with a diameter of 12 mm, while the remaining stirrups and longitudinal bars use HPB300 steel bars with a diameter of 8 mm. The specification of the prestressed steel strands is 1×7 $\varphi^s15.2$, with a standard strength of 1860 MPa and a low-relaxation high-strength steel strand, and the initial tensile stress is 1178 MPa.

To study the crack development and failure mode of full-scale prestressed hollow slab girders in combination with the bridge deck pavement layer, the material properties of the test girders were tested. The compressive strength test of concrete was carried out in accordance with the "Technical specification for inspecting of concrete compressive strength by rebound method" (JGJ/T 23 - 2011). Before the failure test, rebound tests were conducted on the web and bottom slab of the girder. A total of 18 test areas were selected on the web and bottom slab of the test girder at intervals of 1 m, with 16 test points in each area. The average carbonation depth was tested using alcohol phenolphthalein solution, which was 2.5 mm. The rebound values of the concrete in each test area of the web and bottom slab of the test girder were basically the same, with an average value of R_{mc} = 52.2. The concrete strength was converted using a unified strength curve, which was 56.1 MPa.

During the test, to restore the boundary conditions as accurately as possible, fixed and sliding supports were respectively set up at both ends of the test girder, with a center distance of 17.30 m. The loading points were arranged at 7 m and 11 m away from the girder ends, and four-point bending loading was carried out using reaction frames and jacks. The 4 m range at the mid-span of the test girder was the pure bending section. A pressure sensor with a range of 2000 kN was installed between the jack and the reaction frame to monitor the pressure value in real time. To prevent the stress concentration effect from crushing the bridge deck pavement concrete, a 0.5 m × 0.5 m pad was placed between the jack and the test girder. Strain gauges and displacement transducers (Linear Variable Differential Transducers, LVDTs) were used to monitor the response of the test girder under static loading. Measuring points were arranged vertically at intervals of 20 cm on both side webs, and were densified at the variable cross-section positions. LVDTs were installed below the webs at 1/4 span, mid-span and 3/4 span of the test girder to monitor the deflection. Considering that the supports would deform downward during loading, LVDTs were arranged below the sliding and fixed supports to calibrate the actual deformation of the test girder. LVDTs were arranged along the longitudinal direction of the girder at the end of the sliding support, and a high-speed camera was placed in front of the web in the pure bending section to record the crack propagation process. Loading and sensor arrangement for flexural test can be seen in Fig.1.

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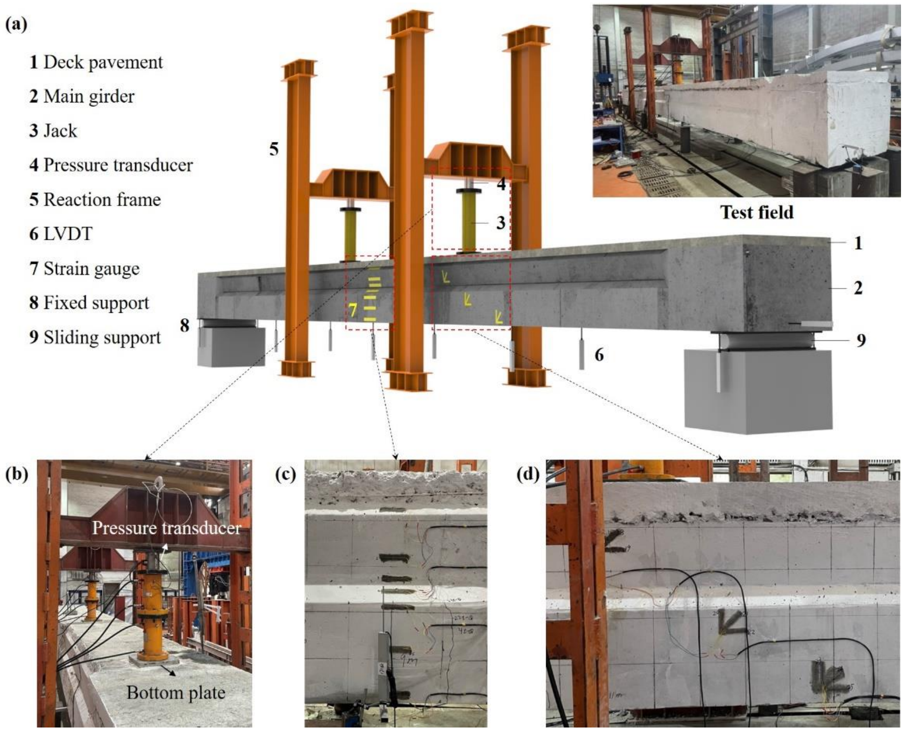

Fig.1. Loading and sensor arrangement for flexural test: (a) overall layout; (b) jack and pressure transducer; (c) strain gauge arrangement in mid-span; (d) strain gauge arrangement at shear position

Establishing of FEMs:

To further investigate the mechanical behavior of the failure process of retired prestressed concrete girders and the influence of bridge deck pavement, two three-dimensional FEMs were established based on ABAQUS, namely the model with bridge deck pavement (Model 1) and the model without bridge deck pavement (Model 2). Then, the global response (deflection) and local response (strain and cracking) at each load level were calculated. The dimensions of each component in Model 1 were the same as those in the test field. Reference points were established and connected to the action surfaces of the supports and loading points through "coupling", and the boundary conditions and loads were controlled through the reference points. The main girder, bridge deck pavement, loading block and supports were simulated using continuous linear three-dimensional stress elements (C3D8R) with a mesh size of 5 cm. The prestressed steel strands were simulated using linear three-dimensional truss elements (T3D2), and the "embedded" constraint method was used to bond the prestressed steel strands with the surrounding concrete elements. The prestress was applied to the steel strands through the thermal stress method. Python scripts were used to batch establish line elements between the top plate of the main girder and the bridge deck pavement and specify them as sliding plane elements. The FEMs can be seen in Fig. 2.

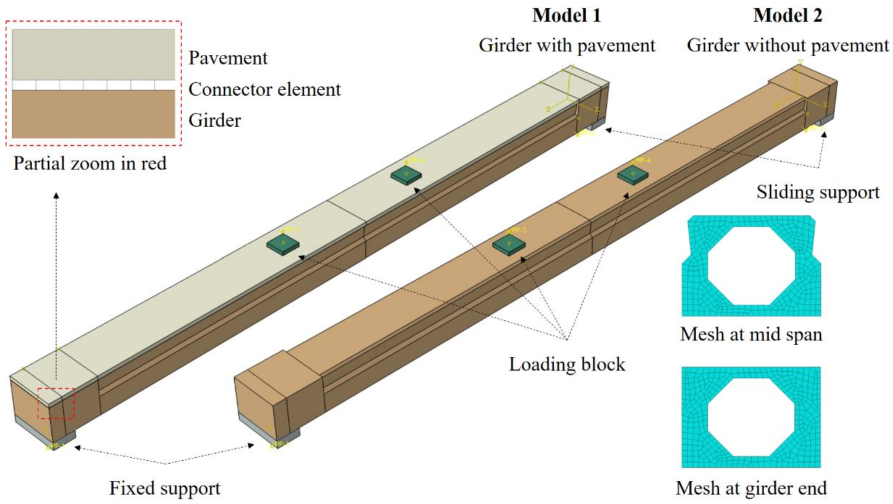

Fig.2. Establishing the FEMs

During the test, when a certain load was applied, a slip occurred between the bridge deck pavement layer and the main girder. This indicates that in the FEM, the connection between the bridge deck pavement and the main girder cannot be simulated by the

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"binding" consolidation method. In this paper, the detachment of the bridge deck pavement is simulated by the failure of the connecting element. This study refers to the shear strength proposed by Mohama, considers the adhesive effect of concrete and the shear friction effect between components, and modifies the expression. Based on the results of experimental tests and FEM calculations, the coefficient corresponding to the peak bond force was derived according to the load at which the bridge deck pavement and the main girder cracked. The coefficient of concrete friction force was derived based on the load when the bridge pavement completely slipped. The derived formula is as follows:

$$\tau = \left(0.2378\mathrm{e}^{0.237R_{\mathrm{pm}}}\right) f_{\mathrm{t}} + \left(0.5479R_{\mathrm{pm}}^{0.3978}\right)\sigma_{\mathrm{n}}$$

Through the observation of the test phenomena, the failure process of the test girder can be divided into three stages. The first stage is the elastic stage, during which the test girder is in an intact state as a whole, and the mid-span deflection increases linearly with the load. The second stage is the working stage with cracks. After reaching the cracking load, the cracks extend from the bottom plate to the web. As the load increases, the length and width of the cracks gradually increase, and they no longer extend when they approach the top plate. Cracks first appear between the bridge deck pavement and the main girder, and then they completely separate. The test girder enters the third stage of the failure process. At this time, the main girder mainly bears the load, and the strengthening effect of the bridge deck pavement on the main girder basically disappears. With the further increase of the load, the test girder completely breaks.

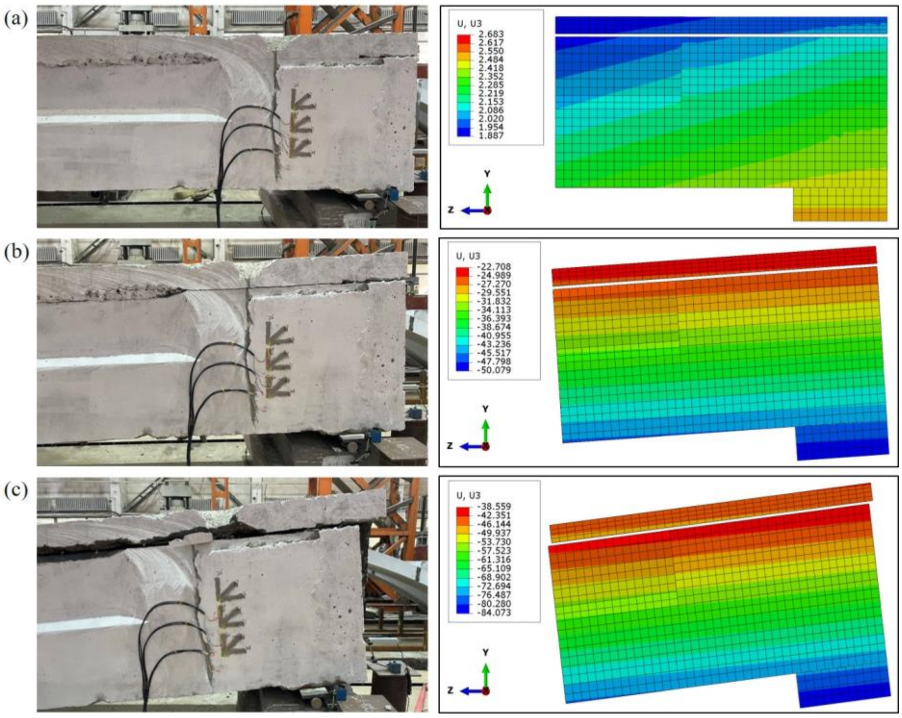

Fig.3. The three stages of main girder failure

Results and analysis:

The load-deflection curve at mid-span is the most direct indicator for evaluating the bearing capacity of the test girder, which can be seen in Fig.4. The state of the test girder can be divided into three stages: the first stage is the elastic state, where the load is within the range of 0 to 200 kN, and the load-displacement curve is basically linear. When the load reaches 200 kN, the deflection-span ratio of the test girder is 1/1193; the second stage is the working state with cracks, when the load is greater than 200 kN, as the cracks extend towards the top slab, the stiffness of the test girder significantly decreases, and the mid-span displacement begins to increase at a larger rate. When the load reaches 541.5 kN, the bridge deck pavement layer completely detaches from the main girder, at which point the deflection-span ratio is 1/95. The structural system undergoes a sudden change, and the load suddenly decreases; in the third stage, the test girder enters the plastic state, loses its bearing capacity, and the mid-span displacement increases significantly before complete fracture. Without considering the effect of the bridge deck pavement, the bearing capacity of model 2 is significantly lower than that of model 1. Due to the reduction in section height, the displacements corresponding to the cracking point and the inflection point of the curve are slightly larger than those in model 1. Similar to model 1, the inflection point of the curve lags behind the cracking point. The slope of the load-deflection curve can be used to characterize the stiffness of the test girder. In the elastic stage, due to the strengthening effect of the bridge deck pavement layer, the overall stiffness of the test girder increases by 27.7%, the cracking load increases by 16.4%, and the load at the state inflection point increases by 16.7%. After the bridge deck pavement layer is completely separated from the main girder, the strengthening effect of the pavement layer disappears, and the load is mainly borne by the main girder. The load at the complete fracture of the test

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girder is 496.7 kN, and the ultimate load before the bridge deck pavement detaches is 541.5 kN. Under the strengthening effect of the bridge deck pavement layer, the ultimate load of the test girder increases by 9.0%.

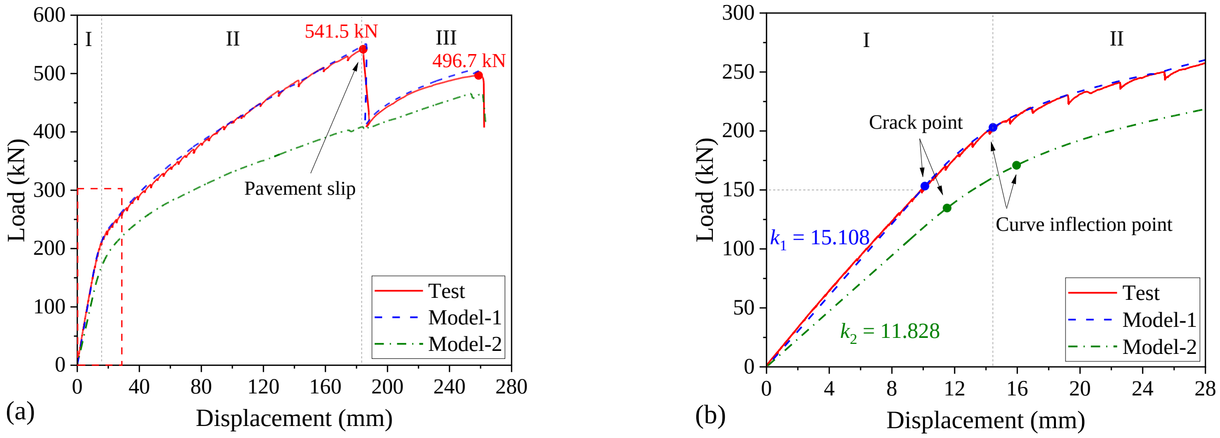

Fig.4. Load –displacement in mid span curves: (a) entire process; (b) local zoom in red box of (a)

The widths of key cracks under each loading step were recorded using a crack tester during the experimental process. Fig. 5 shows the maximum width of cracks under critical loads. According to the Specifications for design of highway reinforced concrete and prestressed concrete bridges and culverts (JTG 3362 – 2018), the maximum allowable crack width for PC components using steel strands in freeze–thaw areas under normal use is 0.10 mm. According to the test results, when the load was 170 kN (corresponding mid-span moment of 1190), the crack width reached the limit allowed by the specifications. The "condition rating" recommended by the International Atomic Energy Agency guidelines defines three types of damage levels based on the maximum crack width: grade I (minor damage: < 0.2 mm), grade II (moderate damage: 0.2–1.0 mm), and grade III (critical damage: > 1.0 mm). Based on the maximum crack width, the structure had minor damage when the load was 210 kN, when the load was approximately 210–320 kN, the structure was moderately damaged, and when the load exceeded 320 kN, the structure was critically damaged.

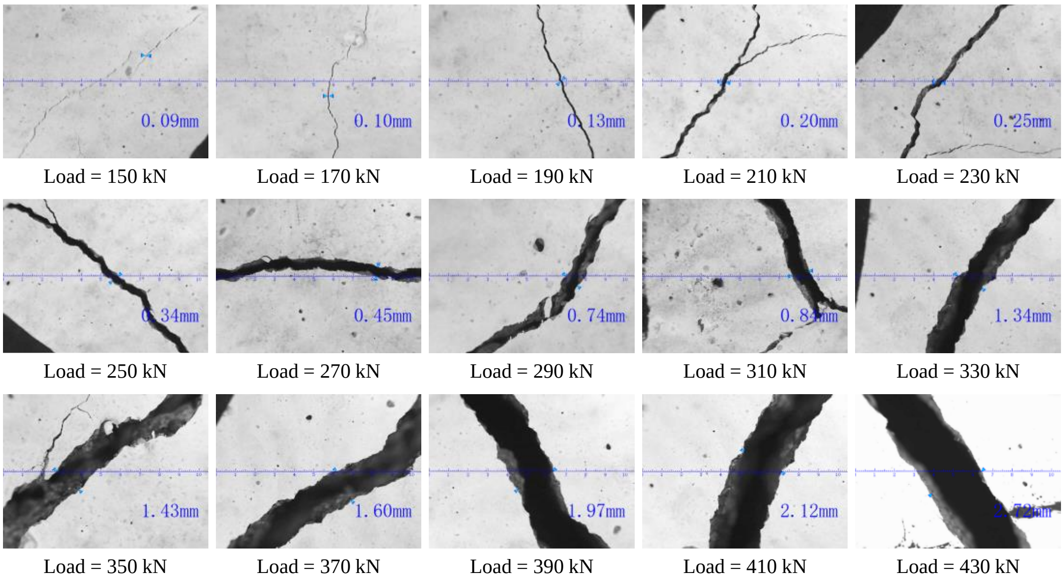

Fig.4. Maximum crack width in critical loads

In fact, for prestressed concrete girder bridges, whether in the design or inspection process, the strengthening effect of the bridge deck pavement on the main girder is not considered when calculating the bearing capacity of the main girder. Instead, it is applied to the main girder as a second-stage dead load. If its strengthening effect is taken into account, the design and inspection results are often overly conservative. The research on the strengthening effect of the bridge deck pavement on the main girder in this paper is not aimed at guiding the design optimization of prestressed concrete girder bridges. During the dynamic and static load inspection of prestressed concrete simply supported girder bridges in cold regions, the bridge deck pavement is also regarded as a second-stage dead load without considering its strengthening effect on the main girder. This will lead to an inability to grasp the true state of the main girder when inferring the bridge's bearing capacity from the inspection results, and thus an inaccurate assessment of its safety performance. If the structural state of the main girder does not meet the standards for normal use, the

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inspection results may still meet the requirements under the strengthening effect of the bridge deck pavement, which will pose potential risks during the operation of the bridge. If the strengthening effect of the bridge deck pavement is considered in the simulation calculation, the threshold for the safety assessment of prestressed concrete girder bridges can be corrected, thereby more accurately evaluating the safety margin of the bridge structure. At this time, it is very necessary to consider the reinforcing effect of the bridge deck pavement.

KEY WORDS: Bridge engineering, Full-scale concrete main girders, Bridge deck pavement, Ultimate flexural strength, Numerical simulation