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Numerical Simulation Analysis of a Strengthening Method for Shear Capacity of a Voided Slab Bridge Using Finite Element Software ABAQUS

Chuanli Shen, Linlin Zhang, He Liu, Baoqun Wang

School of Transportation and Civil Engineering, Shandong Jiaotong University, Jinan, 250357, Shandong, China

Abstract: *To solve the problem of low shear capacity of existing voided slab bridges, the research proposed a strengthening method for improving shear capacity of existing voided slab bridge. Taking a voided slab girder of 10 m long as the research object, the finite element software ABAQUS was used to carry out numerical simulation on the voided slab and analyze influences of the thickness of the bridge deck overlay on improvement of shear capacity of the voided slab bridge. Analysis results show that the strengthening method of paving a bridge deck overlay can improve shear capacity of the voided slab and the shear capacity rises with the increment in the overlay thickness.*

Keywords: *voided slab bridge; shear capacity; finite element simulation; paving a bridge deck overlay*

1. Introduction

Expressways were first constructed in 1980s in China and those constructed in the early stage have many shortcomings in aspects including the design philosophy, technical standard, construction quality, and traffic capacity. During long-term service, various defects are likely to occur in voided slab bridges with the increasingly larger traffic volume and the growing number of heavy vehicles, which may render such bridges to have insufficient bearing capacity and pose a huge threat to safe passage of vehicles [1-3].

In recent years, scholars across the world have conducted a series of studies to investigate strengthening methods of voided slab bridges using bridge deck overlays. Wang [4] used the finite element software ABAQUS to establish models of voided slab bridges of different spans, so as to study influences of different thicknesses of the bridge deck overlay on the deflection and stress of the voided slab bridge. The results showed that the deflection and stress of the voided slab bridge decrease with the increasing thickness of the bridge deck overlay and the overlay thickness exerts basically consistent influences on the deflection and stress of the voided slab bridges of different spans. However, the overlay thickness differs when the deflection and stress of the voided slab bridges of different spans reach their minimums. Taking an assembly voided slab bridge as the research object, Li [5] adopted the universal finite element software ABAQUS to build a finite element model. On this basis, Li analyzed influences of the thickness of the bridge deck overlay on failure modes of hinge joints, such as cracking load and fracture distribution of a voided slab bridge, as well as on cracking load, midspan deflection, and stress of voided slabs. Yuan and Huang [6] carried out finite element simulation on voided slabs with a span of 13 m to simulate the shear capacities of the voided slabs before and after setting the bridge deck overlay. Analysis pointed out that a 15-cm-thick bridge deck overlay can increase the cracking load by 28.4% and improve the ultimate shear capacity by 30.7%. In summary, scholars across the world have conducted numerous studies on the strengthening method of voided slabs by adding bridge deck overlays and the method also has been widely used.

The research took a voided slab girder in the length of 10 m before and after being strengthened with a bridge deck overlay as the research object. ABAQUS was used to analyze influences of paving bridge deck overlays of different thicknesses on the failure modes, concrete strain, and shear capacity of voided slab bridges. The effect of the strengthening method in improving the shear capacity of the voided slab girder was also verified.

2. Engineering background

The Linyi-Honghuabu section (passing by Lanshan, Luozhuang, Cangshan, and Tancheng in Linyi city) with a total length of 9.657 km on Beijing-Shanghai expressway borders with Linyi section of the expressway in the north and with Jiangsu province in the south and has been open to traffic since November 2000. The bridge width is B=2(50+1250+50+100/2)=2800 cm for large and medium bridges and B=2(75+1175+100+100/2)=2800 cm for small bridges. The precast slabs are arranged along the transverse direction of the bridge, with the width of B=124.5+1+11×99+10×1+1+124.5=1350 cm. Concrete (grade C40) was used to fabricate the voided slab girder, pave bridge deck overlay, and strengthen hinge joints; while C25 concrete was used to build the crash barrier. The bridge deck overlay was composed of cement of 10 cm thick and bituminous concrete of 8 cm thick. The cross section of the voided slab bridge is shown in Fig. 1.

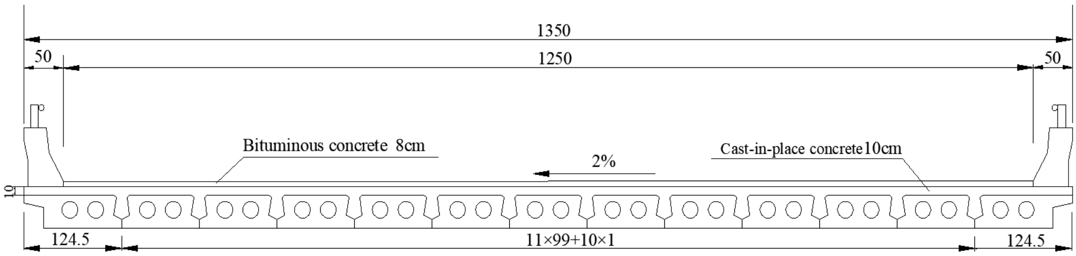

Figure 1: Cross section of the voided slab bridge (unit: m)

3. Establishment of the finite element model

Through finite element simulation of the voided slab girder, the research verified the improvement effect of the strengthening method of using a thick bridge deck overlay on shear capacity of the voided slab. The load-displacement relation, load-strain relation, and damage to the voided slab before and after strengthening were analyzed. A single voided slab of 10 m long was selected for simulation, which had a slab length of 9.96 m, height of 0.4 m, top width of 0.79 m, and bottom width of 0.99 m. The thickness of the bridge deck overlay was separately set as 0, 10, 15, and 20 cm, which were labeled as L-1, L-2, L-3, and L-4, respectively.

3.1. Material Parameters of the Finite Element Model

Table 1: Concrete parameters of the finite element model

Element	Strength grade of concrete	Elastic modulus/MPa	Poisson's ratio	Mass density /(kg·m^{-3})
Voided slab girder	C40	32500	0.2	2500
Hinge joints	C40	32500	0.2	2500

Table 2: Plastic damage parameters of concrete

Expansion angle /(°)	Ratio of compressive strength	Viscous parameters	Eccentricity ratio	Yielding parameter
35	1.16	1e-05	0.1	0.667

Table 3: Main material parameters of regular reinforcements and prestressed steel strands

Type of reinforcements	Poisson's ratio	Elastic modulus E/(MPa)	Density (Kg/m^3)	Coefficient of linear expansion
HPB235	0.3	2.1×10^5	7900	/
HRB335	0.3	2.0×10^5	7800	/
φ^j12.7 steel strand	0.3	1.95×10^5	7800	1.2E-005

The reinforcements mainly included regular reinforcements HPB235 and HRB335 and prestressed Φ112.7 steel strands in the voided slab. The main parameters of the concrete and reinforcements are listed in Tables 1 ~ 3.

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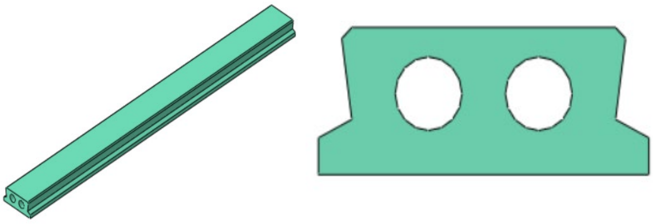
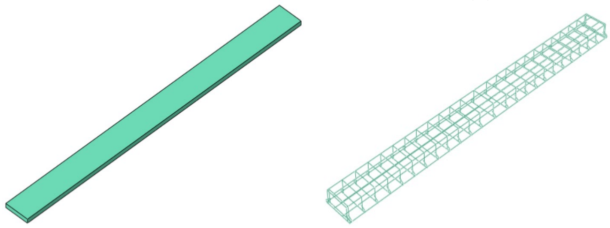
3.2. Establishment of the geometric model

1) Establishment of components.

Models of solid structures including the voided slab, bridge deck overlay, regular reinforcements, and prestressed steel strands were mainly constructed for simulation. Concrete of the voided slab, bridge deck overlay, and reinforcement framework composed of reinforcements in the voided slab were simulated according to dimensions in the design drawing, as shown in Figs. 2(a), (b), (c), and (d).



(a) Cross section of the voided slab *(b) Normal section*



(c) Bridge deck overlay *(d) Reinforcement framework*

Figure 2: Main components of the model

2) Interaction and loading mode

①*Interaction*

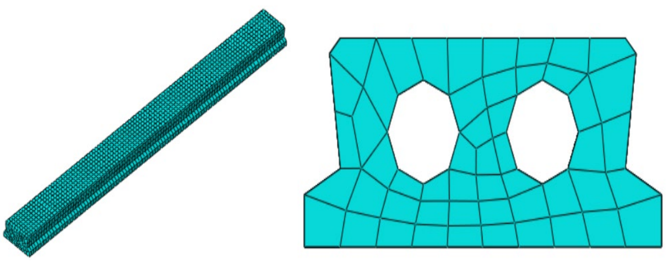
Longitudinal reinforcements and stirrups in the voided slab are integrated as the reinforcement framework. The prestressed steel strand simulated using the falling temperature method is embedded in the concrete via interaction. The reinforcing mesh in the bridge deck overlay is also embedded in the overlay. The contact area between the bridge deck overlay and the voided slab is regarded to be free of relative slip and the two are bound via the "tie" command of interaction.

②Establishment of load and boundary conditions

To facilitate convergence of the nonlinear structures in the simulation, the displacement-controlled loading was applied to the model. As for boundary conditions, the bottom of the support of the voided slab was set as simply supported, that is, rotation at one end in the Z direction was unconstrained while movement at the other end in the horizontal direction was constrained. The unilateral loading was adopted.

③Mesh generation

The research mainly took the voided slab as the research object, for which the mesh was refined. Solid element C3D8R was selected for concrete; reinforcements, as beam or truss elements, were simulated using T3D2 element. The size of these elements was controlled to be 0.05 in the simulation, while the size of other structures was 0.1. Mesh generation of each component of the voided slab girder is illustrated in Fig. 3.



(a) Concrete in the voided slab

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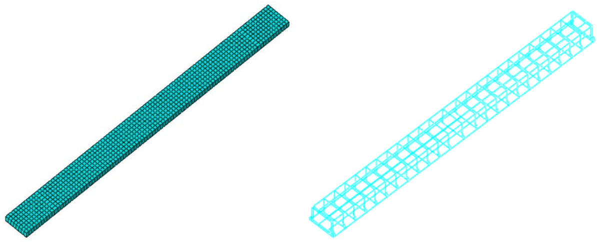


(b) Bridge deck overlay *(c) Reinforcement framework*

Figure 3: Mesh generation of each component

By using the above modeling method, the model for improving shear capacity of the voided slab by paving bridge deck overlays of different thicknesses is illustrated in Fig. 4.

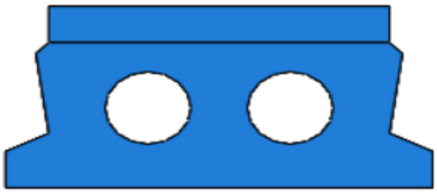
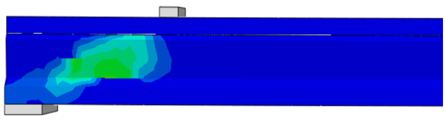
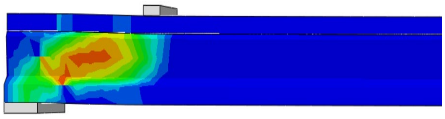


Figure 4: Model of paving a bridge deck overlay

4. Failure modes of the voided slab girder

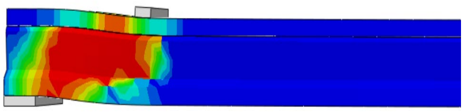


(a) Occurrence of oblique fractures in the voided slab

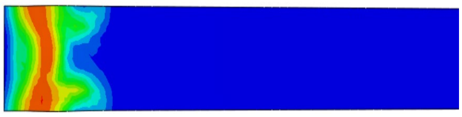


(b) Development of the oblique fractures in the voided slab

(c) Propagation of the oblique fractures in the voided slab to the bridge deck overlay



(d) Failure of the voided slab



(e) Tensile failure at the bottom of the voided slab

Figure 5: Failure modes of the voided slab obtained in the finite element simulation

The failure modes of the voided slab under different thicknesses of the bridge deck overlay were simulated using ABAQUS. Here, cloud pictures for failure modes of the L-2 experimental girder were discussed (Fig. 5), and other experimental girders show similar failure modes.

Figure 5 shows the whole failure process of the experimental girder L-2. Fig. 5(a) displays the cloud picture when the oblique fracture just appears. With the increase in load, tensile damage occurs to the web plates at the supporting point and loading point as well as concrete at bottom of the girder.

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When the load continues to rise, oblique fractures appear in the web plates and constantly propagate upwards, and these fractures constantly expand, so do their number and range. The propagation of the oblique fractures is illustrated in Fig. 5(b). With the further increase in load, the oblique fractures propagate to the bridge deck overlay (cloud picture in Fig. 5(c)). Finally, the oblique fractures run through the bridge deck overlay, resulting in formation of a coalesced failure plane in the whole cross section of the voided slab. In addition, concrete at the bottom of the voided slab girder is found to be crushed and the failure of the voided slab is shown in cloud pictures in Figs. 5(d) and (e).

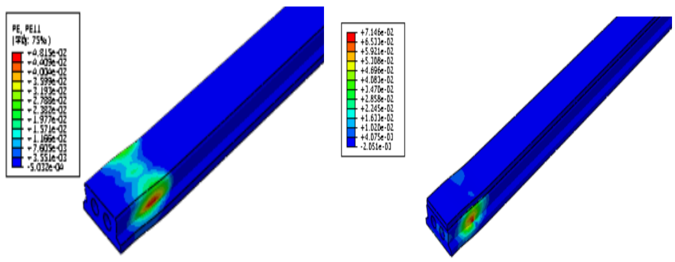
The above results indicate that the failure mode of concrete voided slabs in the experiments is same as that obtained in finite element simulation. The experiment and simulation both show a failure mode in which the main oblique fractures appearing between the supporting point and the loading point run through the whole cross section of the voided slab to damage the structure.

5. Influences of bridge deck overlays on shear capacity of the voided slab and analysis

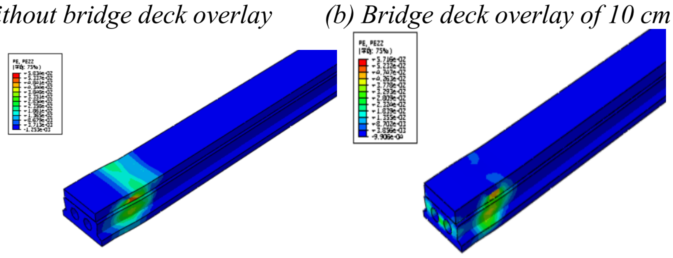
Based on the finite element calculation results, influences of bridge deck overlays of different thicknesses on the concrete strain and load-displacement curve of voided slab girders were analyzed and the effect of the strengthening method based on the bridge deck overlay was verified.

5.1. Concrete strain

The cloud pictures for concrete strain of web plates at final failure of the voided slab girder were selected, as displayed in Fig. 6.



(a) Without bridge deck overlay *(b) Bridge deck overlay of 10 cm thick*



(c) Bridge deck overlay of 15 cm thick (d) Bridge deck overlay of 20 cm thick

Figure 6: Cloud pictures for strain of the voided slab

When no bridge deck overlay is paved, there is a large strain affected area in the cloud picture of the voided slab girder. As the overlay thickness increases, the strain affected area in the cloud picture of the voided slab girder gradually shrinks and the strain level also reduces. When the thickness of the bridge deck overlay is 20 cm, the strain affected area and the strain level are both lowest in the cloud picture, indicating that the bridge deck overlay also has participated in load bearing of the structure. The results indicate that the strain of concrete decreases at failure of the voided slab and the shear capacity of the slab is improved, with the constant increment in the thickness of the bridge deck overlay.

5.2. Load-displacement curve

1) Temporary fixation devices

Through ABAQUS simulation, the load-displacement curves at the loading points of four voided slab girders were obtained, as illustrated in Fig. 7. Comparison of load-displacement curves of various experimental girders showed that the curves linearly ascend in the initial loading stage; as the load is increased constantly, fractures and local damage appear in the girders and the load-displacement curves are no longer linear. The girders are damaged when the load reaches the ultimate shear capacity.

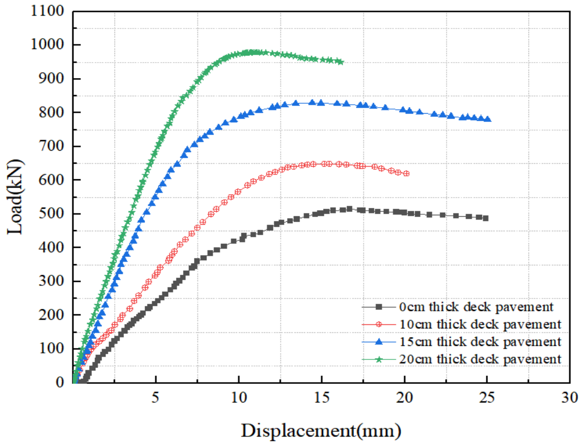


Figure 7: Load-displacement curves in the finite element simulation

The load-displacement curves obtained in the finite element simulation of shear capacity of the voided slab show that the ultimate shear capacity of the voided slab increases to different extents as the thickness of bridge deck overlays grows. In addition, as the thickness of the bridge deck overlays increases from 0 to 20 cm, the vertical displacement of the voided slab also reduces correspondingly.

6. Conclusions

1) According to the load-displacement curves obtained in the finite element simulation, the failure modes of the voided slab can be divided into the elastic stage, concrete cracking stage, and failure stage of the voided slab.

2) The strengthening method of paving a bridge deck overlay enables the overlay to participate in loading bearing together with the main girder. This improves the ultimate shear capacity and reduces the concrete strain at failure of the voided slab girder.

3) The shear capacity of the voided slab enlarges with the increasing thickness of the bridge deck overlay.

Acknowledgments

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