Characterization of Contact Stresses Between Dowels and Surrounding Concrete in Jointed Concrete Pavement

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Abstract— **In order to analyze the contact stresses between dowels and surrounding concrete in the dowel-jointed cement concrete pavement, the 3-D finite element model is used to simulate the stress concentration in concrete around the dowel bars under traffic loading. The stress and strain responses on the concrete surface have been calculated and they are also verified with self-design full-scale experiments. Results show that the strain data from the numerical simulation agrees well with the full-scale experiment. As a result, the research indicates that the 3-D finite element model is an efficient and accurate method to calculate the interaction characteristics between dowel bars and surrounding concrete. Besides, the high press stress concentration on the concrete up dowels and the tensile stress concentration on the concrete besides dowels will cause the initial crack development in the concrete material surrounding the dowels, which is the main reason leading to the dowel bar deterioration. In this paper, a more concrete and detailed numerical analysis method will be provided to analysis the stresses concentration at steel-concrete interface in the concrete structure.**

Index Term— **road engineering;concrete pavement;GFRP dowels;load transfer characteristics; ultimate bearing capacity; durability**

I. INTRODUCTION

As one of the main forms in road pavement, the cement concrete pavement has advantages of high stiffness, high strength and good durability[1].In order to alleviate the stress concentration caused by temperature and humidity variations, concrete pavement slabs are usually constructed with joints to control the fracture position in slabs [2].

For pavement with heavy traffic conditions, smooth round steel dowels will be placed across shrinkage joints to transfer wheel loads between adjacent slabs[3].Dowel bars mainly transfer the wheel load as shear force between pavement joints and the surrounding concrete and support the reverse force as the bearing material during load transfer process[4-5].Although the average expected service life of a dowel-jointed concrete pavement is about 30 years, the real service life is usually much lower than that. Besides, the shrinkage transverse joints usually deteriorate rapidly under heavy traffic cycling loading and environmental conditions[6].The serious stress concentration in the surrounding concrete caused by the small diameter and high strength dowel will lead to the crush and spall on the edge of concrete and becomes the main reason for the failure [7].Three Dimensional Finite Element (3-D FE) modeling is a useful and powerful tool that can be used to investigate the combined effect of concrete slab geometry, dowel bars at joints and wheel loads. In the past, many pavement computer response models based on the FE method were developed for the analysis of jointed pavement slabs, but important considerations were overlooked. These include the modeling of dowel bars or the modeling of their effect by using beam or spring elements. Other factors such as the sliding characteristics between the dowel bars and the surrounding concrete, as well as the friction at the interface between the concrete slab and the base course influence the response of rigid pavements to wheel loads were also neglected.

In this study nonlinear 3D-FE analysis that includes detailed consideration of slab constraints by dowel bars is used to analyze the problem of premature transverse cracking in jointed concrete pavements.This approach enhances the accuracy of FE solution with solid elements simulating the concrete slab and supporting layers. The model has the capability to handle different applied impact tire pressure affecting the pavement, it also handles the various design and loading conditions, including: (1)tire pressure, (2) dowel bar diameter,(3) dowel spacing,(4)slab Thicknesses,(5) concrete Grade,(6) subgrade type. The objective is to reveal the interaction laws between dowel bars and surrounding concrete at the doweled joints under realistic conditions of impact loads generated by traffic.

II. 3-D FE MODEL FOR PAVEMENT STRUCTURAL

A. *Construction of 3-D FE Model*

Nonlinear finite element analysis has been used in this paper to simulate the interaction between dowels and surrounding concrete. The finite element model is consisted of two concrete slab segments with a group of dowels connecting with each other. Two concrete slab segments are supported by

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base and subgrade. A 5 mm wide joint is settled between the two concrete slabs for free expansion and contraction and 15 dowels are settled in the middle of the slab thickness in the joints with the span of 30cm, as illustrated in Table 1.

TABLE I
Structural and Material Parameters for Pavement

Layer	Dimension /(m)	Elastic Modulus /(Mpa)	Poisson Ratio	Density /(Kg/m^3)
Slab	5×4.5×0.26	30000	0.15	2400
Base	11.1×5.5×0.2	800	0.3	2000
Subgrade	11.1×5.5×2	150	0.35	2100
Steel bar	Φ0.032	210000	0.3	7800
GFRP bar	Φ0.032	30000	0.28	2600

Solid element can capture severe deformation gradients in the concrete slab under multiple wheel loads, which is impossible with classical approaches using Kirchhoff plate elements. Further, solid elements used in supporting layers count on heterogeneous material properties of each layer. Hence, this approach can provide more accurate displacement field, which affects on the stress response of the concrete slab, than the classical approaches with Winkler foundation.The interaction between the dowel and the concrete slab is simulated from frictional contact. Further, pavement damage is simulated by using plastic constitutive models for the concrete in the vicinity of the dowel.A much finer mesh is necessary to simulate the dowel and concrete casing, while a coarser mesh is adequate to model the far–field behavior of the concrete slab and other parts of pavements. The software “ABAQUS” is used for this purpose [8], as shown in Figure 1.

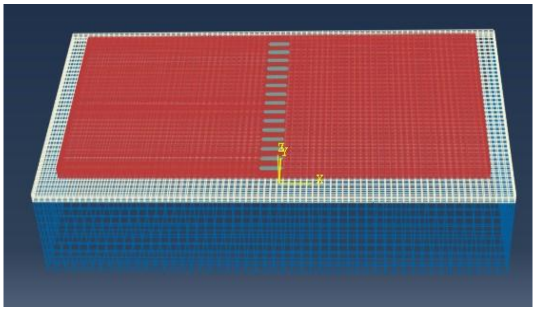


Fig. 1. 3-D FE Modeling of Dowel-Jointed Concrete Pavement

The concrete slab and the base layer are assumed to be frictional contact, and the slab-base friction value is 0.05[9]. The base layer and the subgrade are assumed to be bound connection. All dowels are settled as bound connection with the concrete slab on one side and frictional on the other side, the dowel-slab friction value is 0.1[10].

B. Validation of the 3D FE Model

The 3D FE model constructed in this study has been validated with the measured data from pavement expansion joints experiments conducted by the United States Naval Engineering Laboratory[11-12].The numerical displacement calculation in the model is compared with experimental results as in Table 2.

TABLE II
The Displacement at Different Positions of the Slab

Distance from central dowel（mm）	Displacement of loaded slab（mm）		Displacement of unloaded slab（mm）	
	Numerical result	Measured data	Numerical result	Measured data
0	2.1	2.26	2.03	1.85
300	2.06	2.21	2.01	1.83
600	1.97	2.08	1.96	1.78
900	1.88	1.95	1.88	1.73
1200	1.80	1.70	1.81	1.67

The result shows that the numerical methods can be accurate and effective to simulate doweled joint performance and conduct an effective mean for structural behavior of doweled joint in concrete pavement[13-14].

III. CONTACT STRESSES AROUND THE DOWEL BARS UNDER MAGNITUDES OF WHEEL LOAD

A. Loading condition

In order to simulate different load levels, three different magnitudes of tandem axle loads (10 t, 20 t,30 t) have been applied in the FE model. The relationship between ground pressure and tire pressure is calculated based on the following equation[15].

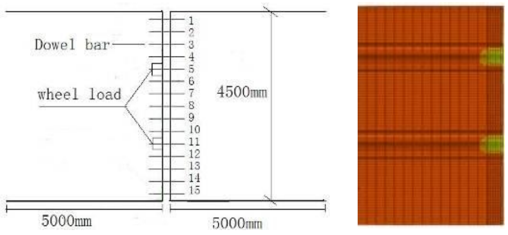
$$p = 0.0042 P_z + 0.29 p_i + 0.1448 \qquad [1]$$

where p is tire grounding pressure; p_z is tandem axle loading; p_i is tire pressure. Detailed in Table 3.

TABLE III
Loading data

Axle load	10 t,	20 t	30 t
Axle load/kN	100	200	300
Tire pressure/MPa	0.75	1.0	1.1
Grounding pressure/MPa	0.5723	0.85	1.1
Transverse Spacinga/cm	22	24	24
Longitudinal Spacingb/cm	19.8	24.5	28.4
Axle load/kN	100	200	300

For the analysis of the tandem axle load, two wheel loads are applied at the position as shown in Figure 2(a).Two refined mesh zones are located at the corresponding place of loads applied[16], as shown in Figure 2(b).



a b

Fig. 2. Wheel Load position and dowel number for pavement model

B. Contact stresses around the dowel bars

The dowel bars are embedded inside concrete at the transverse joint of the slabs. Whenever traffic load is applied, slabs will deform and incur moment in dowel bars, which leads to the contact stress between the dowel bars and concrete, as shown in Fig 3.

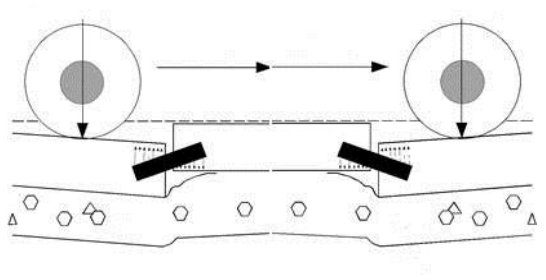


Fig. 3. Contact stresses formation

Figure 4 shows the distribution of the maximum principal stress at the concrete slab center in three loading conditions.

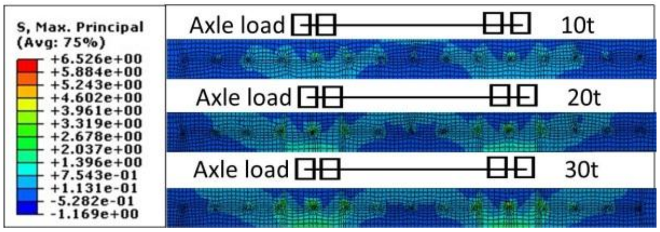
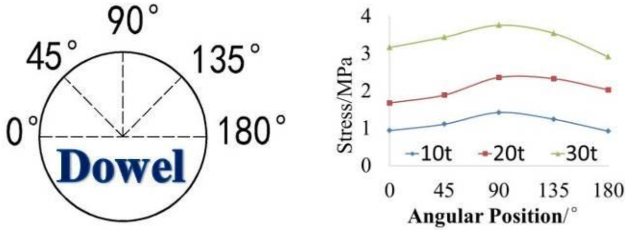
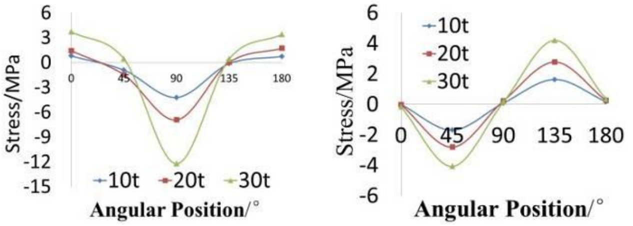


Fig.4 Maximum Principal Stress nephogram

From principal stress cloud pictures, the area of the stress concentration inside the concrete mainly distributes near the upper half-circle contact surface. Thus, it is possible that high contact stress exists in the interface between dowel bars and concrete. The figure shows the maximum principal stress, vertical stress (compressive and tensile) and shear stress distribution along the circle of dowel bars.



a Angular position b Principal Stress



c Vertical Stress d Shear stress

Fig. 5. Contact stress distribution around the dowel bar

The stress distribution around the dowel bar in plots reveals as follows：

i. The maximum value of the principal stress and compressive stress is on the top region of the dowel-concrete contact areas. The maximum tensile stress occurs at both sides around the dowel bar. The maximum shear tensile stress occurs approximately at 45° and 135° of the dowel-concrete interface.

ii. The amount of shear force transmitted by dowel bar system increased with the increase of applied tire pressure, that means more wheel load can be transferred to the adjacent concrete slab if wheel load pressure increases. The maximum value of the shear force transmitted by a dowel is 4.56 KN for the 10 t case, while 12.81 KN of the shear was carried by them for the 30 t case.

iii. The maximum value of the contact stress around dowel increases with the increase of applicated wheel load.The value of maximum tensile stress under 30t axle load is close to the tensile strength of concrete.

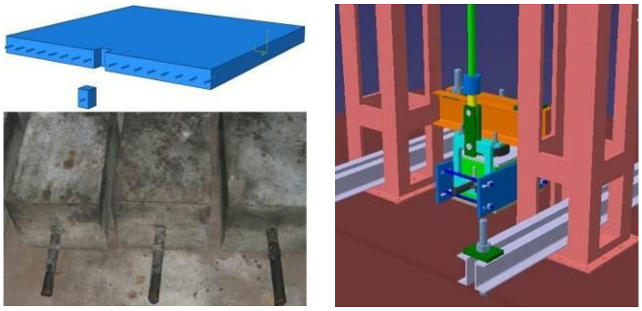
iv. The high wheel load increases the demand on a few inner dowels beneath the wheel load, which may produce the initialization and evolution of the cracks on the concrete at those areas , cause more damage to the joints and eventually lead to pavement failure.

IV. EXPERIMENTAL VERIFICATION

In this chapter, the strain response from numerical calculation has been validated from the experimental data.

A. *Test Specimens and Experiment*

Base on the principle of sub modeling method[17], the dowel specimen for transverse joint substructure is constructed with a dimensions of 300 mm x 400 mm x 260 mm concrete and a Φ32mm steel dowel bar (500 mm in length), which is half of the length, is embedded in concrete as shown in Fig.6(a).The dimensions of the specimen is the typical size standard based on the specifications of cement concrete pavement design for highway. The experimental work is conducted to investigate the performance of dowels. For all tests, the specimen is fixed under a rigid support beam to reduce the shake of the test machine during loading as shown in Figure 6(b) below.



a Substructure and specimen b self-design full-scale experiment

Fig. 6. The dowel bars specimen and loading equipment

B. *Loading device and boundary conditions*

The dowels are loaded in direct shear by a steel loading device to simulate the effect of the load transfer characteristics of dowel bar from shear action as shown in Figure 7(a,b). In theory, the deflection of the dowel bar within the concrete slab is unaffected to the amount of base support. Therefore, a rigid base (armor plate) can be used instead of a compacted granular material. Due to the structural solicitation of the specimen in the concrete pavement under service conditions, two rigid guard boards connected with the pressure pickup are used to simulate the top and both side boundary conditions of the concrete specimen as shown in Figure 7(c,d).

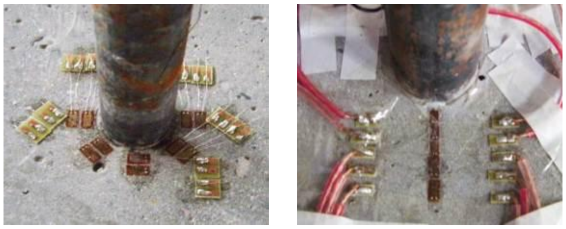
a The lading device b Direct shear loading

c The top boundary d The ambilatera boundary

Fig. 7. Loading device and boundary conditions

C. *Instrumentation*

The strain gauges are adhibited on the concrete near the joint face above the dowel to capture the strain response of the concrete as shown in Figure 8(a,b).



a Tangential direction b Normal direction

Fig. 8. Layout of strain gauges

D. *Strain Responses Comparison*

The dowel specimen are separately loaded up to 4.56 KN、8.73 KN and 12.81 KN. These forces represent the maximal shear force transmitted by a single dowel under each axle Load calculated form the 3-D FE model constructed in this study. Table 4 shows the comparison of the strain responses of the concrete near the joint .

Table 4 Comparison of the strain responses

Strain response	10 t		20 t		30 t	
	Model	Test	Model	Test	Model	Test
Normal/ (με)	457	570	983	1110	1321	1542
Tangentia/(με)	292	336	576	642	869	983

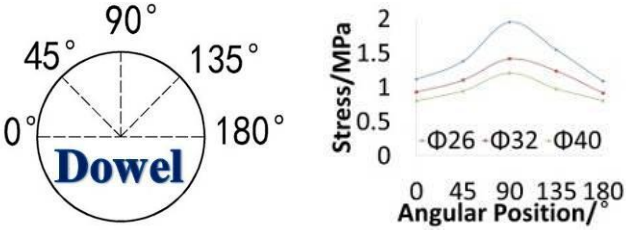
It indicates that the numerical stress distribution around the dowel bar agrees well with the full-scale test results. The research demonstrates that the 3-D finite element model is an efficient and accurate method to calculate the interaction characteristics between dowel bars and surrounding concrete.

V. MULTIVARIATE ANALYSIS

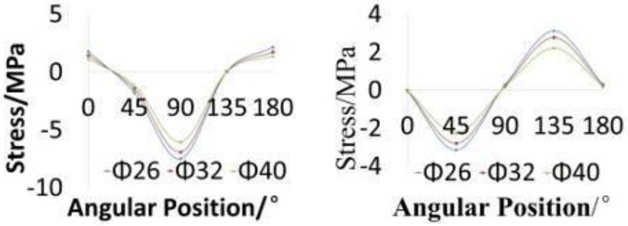
In order to analyze the influence of structural and material combination variation , the contact stress of the dowel-concrete interface is evaluated by dowel bar diameter, dowel spacing , slab thickness, concrete grade and subgrade type with the verified finite element model.

A. *Dowel bar diameter Variation*

Three FE models are constructed according to three dowel bar diameter 26, 32 and 40 mm from the verified modeling method. Figure 9 demonstrates the contact stress distribution along the dowel-concrete interface.



a Angular position b Principal Stress



c Vertical Stress d Shear stress

Fig. 9. Contact stress distribution under dowel bar diameter Variation

From the multiple diameter analysis, the contact stress at the dowel-concrete interface decreases with the increase of dowel bar diameter. The Φ40mm dowel bar makes 35% descent in tensile stress, 20% descent in compressive Stress and 29% descent in shear stress at dowel- concrete interface to Φ40mm dowel bar. It is concluded that the increase in bearing area between dowel and concrete is the main cause for the decrease of contact stress.

B. *Dowel Spacing Variation*

Three FE models are constructed according to three dowel spacing 20, 30 and 40cm. The results of numerical calculation show that the contact stress at the dowel-concrete interface increases with an increase in dowel spacing. The 40cm dowel spacing makes 34% descent in tensile stress, 28% descent in compressive stress and 37% descent in shear stress at dowel-concrete interface to 20cm dowel spacing.

C. *Slab Thicknesses Variation*

Four FE models are constructed according to four different concrete slab thicknesses20, 22, 26 and 40cm. The results of numerical calculation show that contact stress at the dowel-concrete interface decreases with an increase in slab thickness. The 40cm thicknesses of concrete slab make 18% descent in tensile stress, 12% descent in compressive stress and 17% descent in shear stress at dowel- concrete interface to 22cm thicknesses. It is concluded that the increase in stiffness of concrete slab is the main reason for the decrease of contact stress .

D. *Concrete Grade Variation*

Four FE models are constructed according to four different concrete grades C20, C30, C40 and C50. The results of numerical calculation show that the concrete grade variation has little impact on the contact stress distribution along the dowel-concrete interface. However, high-grade concrete can improve the crack resistance of concrete and enhance the durability of the doweled joint.

E. *Subgrade Type Variation*

Two different type of subgrade (Macadam Base and Cement Stabilized Base course, which are the two types of commonly used subgrade in pavement engineering) are applied in the FE model. The results show that the supporting capacity of macadam base is less than that of the cement stabilized base. Therefore a large slab deformation can lead to a high contact stress.

VI. CONCLUSION

This study focuses on examining the contact stresses between dowels and surrounding concrete in jointed concrete pavement due to wheel loads.The work of this study included the development of a detailed 3-D FE model whose main feature is the detailed modeling of dowel bars and their interfaces with the surrounding concrete at transverse joints.Based on the theoretical andexperimental results presented in this study, the following conclusions can be withdrawn:

i. The 3-D FE model used in this study provides an efficient and accurate method to calculate the contact stress distribution at dowel-concrete interface with respect to the variation of load level, dowel bar diameter,dowel spacing , slab thickness, concrete grade and subgrade type.

ii. The high contact stresses in the concrete surrounding the dowels can cause the development of the initial crack in the concrete material near dowel bars and it is also considered as the main reason for the dowel bar deterioration

iii. The axle load has a significant influence on induced contact stress at the dowel-concrete interface. The contact stress around dowel increases with the increase of applicated wheel load.The value of maximum tensile stress under 30t axle load is close to the tensile strength of concrete.

iv. Increasing the dowel bar diameter, slab thickness, and the subgrade supporting capacity are helpful in reducing the contact stresses between dowels and surrounding concrete in jointed concrete pavement. Besides, the usage of high-grade concrete can improve the crack resistance of concrete bearing material.

The work presented on this study is based on the assumption have a static effect on the concrete slab. Therefore, additional research work is needed to investigate its dynamic effect on the response of dowel jointed concrete pavements.

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