Application of LS-DYNA in Identifying Critical Stresses Around Dowel Bars

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Abstract

A detailed 3D Finite Element (3DFE) Model is developed to examine the triaxial state of contact stress that develops around the dowel bars due to both traffic and thermal loads. Dowel bars are modeled using 8-node solid brick elements. Sliding interfaces with friction that permit separation are modeled along the full cylindrical surface between each dowel and the surrounding concrete. The model results are validated through comparison with laboratory measured strains in dowel jointed concrete specimens. The model results reveal that under the standard axle load, tensile stresses of magnitude sufficient to initiate localized concrete failure may develop in the concrete surrounding the loaded dowel. Such stresses are responsible for initiating cracks in the concrete that lead to the rapid joint deterioration.

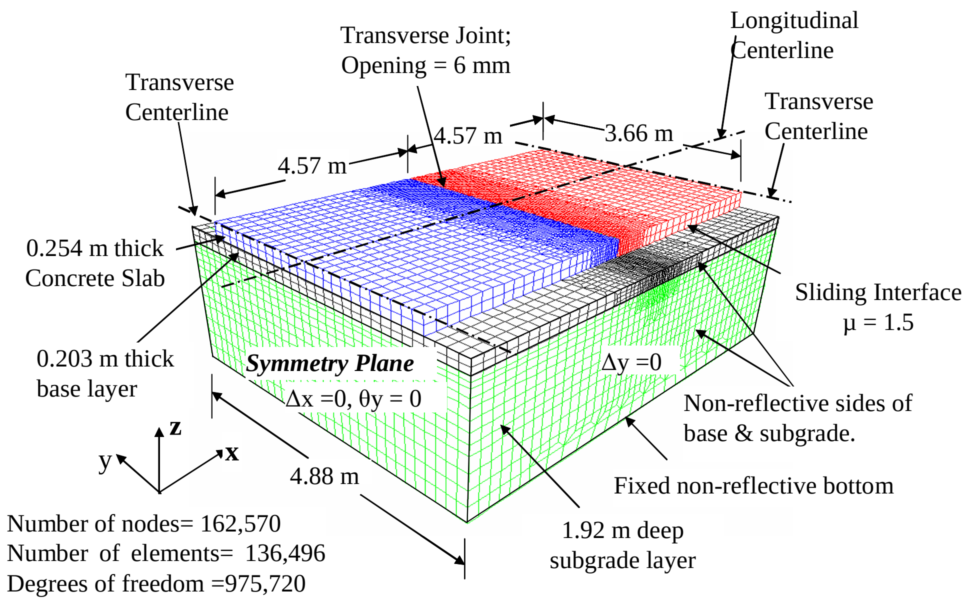
Introduction

Dowel bars are used across transverse joints in jointed concrete pavements to transfer the load across adjoining slabs. It was found that the use of dowel bars can minimize faulting and pumping *(Haung 1993)*. However, the slab discontinuity within the vicinity of the joint constitutes the region that can initiate pavement distress. Several signs of distress including spalling and premature cracking have been observed. Previous studies attempted to explain such failures in terms of the compressive stress that develops at the dowel-concrete interface (Friberg, 1938, Davids, 2001). Such an approach was based on modeling the dowel bar as a beam encased in an elastic media. Under the effect of a downward vertical load, the dowels deflect downwards creating compressive stresses at the bottom interface between the dowel and the concrete. Magnitude of such compressive stresses under the effect of wheel loads were found to be well below the concrete compressive strength and could not explain the initiation of fan cracks on the dowel sides observed in the laboratory doweled specimens (Friberg 1938, Shoukry et al., 2002).

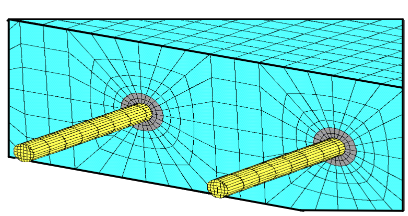
The work presented in this paper focuses on evaluating the magnitude and type of stresses induced in the concrete surrounding dowel bars. This is achieved through developing a detailed 3D finite element model of rigid pavement that makes use of solid brick element to simulate dowels. Each dowel is provided with sliding frictional interface that allows separation from surrounding concrete. The shear forces transferred by the dowel bars as well as the contact stresses at the dowel-concrete interfaces were computed and compared with those obtained by the classical methods currently used in rigid pavement analysis. The results show that despite the agreements of resulting compressive stress at the points of contact between the concrete and the dowel bar, only the approach presented in this study is capable of revealing the formation of high tensile stress in the concrete on both sides of the dowel bars. Such tensile stresses are responsible for crack initiation at the transverse joint and consequence deterioration of the slab.

Concrete Pavement Structural Model

A 3D finite element model was developed consisting of two dowel-jointed concrete slabs placed on a base layer and subgrade. A small gap of width 10 mm is introduced between the two slabs to allow the expansion and contraction of concrete simulating an expansion joint. In this case, the dowels are the only means of load transfer. All pavement layers were modeled using 8-node solid brick elements with 24 degrees of freedom per element. To eliminate improper effects of boundary conditions, the slabs were modeled at their full width of 3.66 ms and full length of 4.57 m. The base and subgrade widths were widened 0.61 m on each side of the slab. The depth of the subgrade layer was chosen to be 2.45 m according to measurements of depth to bedrock in West Virginia, which varies between 1.5 and 5 m. Dowel bars were modeled using extremely fine mesh, with an assumed initial clearance of 12 microns. This mesh was optimized to reveal the localized deformation and the development of contact stresses that take place between dowels and the surrounding concrete.



a. Finite Element Mesh.



b. Detailed Mesh of Dowels and Surrounding Concrete.

Figure 1 Finite Element Model of Concrete Pavement.

Sliding interfaces with frictional contact are assumed between the concrete and the subgrade (coefficient of friction μ=1.5) and between each dowel and the surrounding concrete (μ=0.05). Elastic material models were assumed for the base and subgrade, while an anisotropic brittle damage model developed by Govindjee et al. 1995 and incorporated in LS-DYNA was used for the concrete slabs. The material data were obtained for an existing rigid pavement on US Route 857 in Morgantown, WV through FWD testing. The material data used are listed in Table 1.

Table 1 Material Properties

Material	Material Model	Property	Value
Concrete	Anisotropic Brittle Damage	Density (Kg/m^3)	2400
		Compressive Strength (MPa)	19.10
		Tensile Strength (MPa)	2.89
		Modulus of Elasticity (MPa)	20,684
		Poisson's Ratio	0.18
		Fracture Toughness (kN/m)	0.14
		Shear Retention Factor	0.03
Dowel Bars	Linear Elastic	Density (kg/m^3)	7830
		Modulus of Elasticity (MPa)	2×10^5
		Poisson's Ratio	0.30
Base	Linear Elastic	Density (kg/m^3)	2100
		Modulus of Elasticity (MPa)	310
		Poisson's Ratio	0.30
Subgrade	Linear Elastic	Density (kg/m^3)	2040
		Modulus of Elasticity (MPa)	30.3
		Poisson's Ratio	0.40

Dowel Contact Stresses

Figure 2 (a) illustrates the deformation and the maximum principal stress that develop in a loaded dowel as the axle load is close to the joint edge. As a result of such deformation, localized stresses develop in the concrete surrounding each dowel. Figure 3 shows the fringes of the vertical stresses (Z-stress) around the dowel bar hole that is in the loaded slab under the wheel load (40 kN). The fringes of stresses indicate a formation of high compressive stress zone above the dowel bar hole accompanied by two high tensile stress zones on both sides. This is expected because as the load is applied, the slab tends to move downwards driving with it the dowel bars that are connected to the adjacent slab. Since the dowel bars are stiffer than the concrete, the concrete zone above the dowel bar will be compressed due to the application of load and the dowel bar hole will deform upwards as shown in Figure 2. As the surrounding concrete resists this deformation, high tensile stress zones are developed on both sides of dowel bars as shown in Figure 3 (a). Figure 3 (b) also illustrates a longitudinal section along the dowel bar hole. This section indicates that the zone of high stress is very close to the joint edge. Although this distribution of stresses is similar for all dowel bars, the maximum stress values significantly vary with the dowel bar position relative to the point of load application.

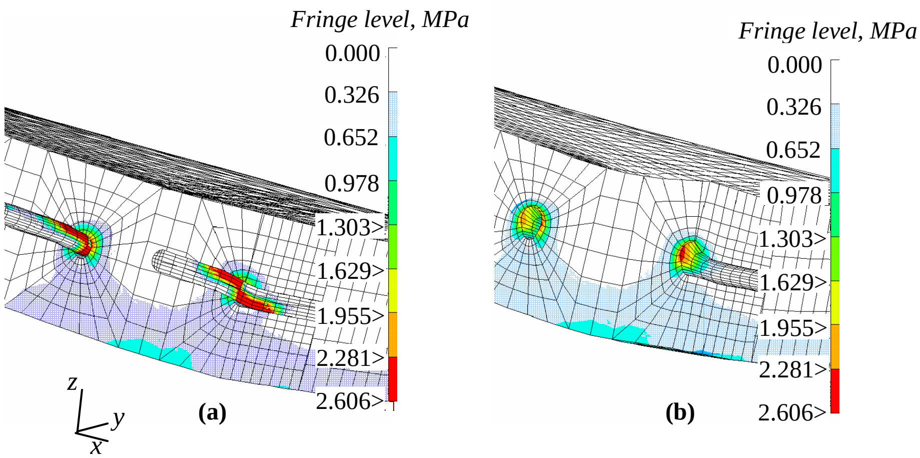


Figure 2 Fringes of Maximum Principal Stress.

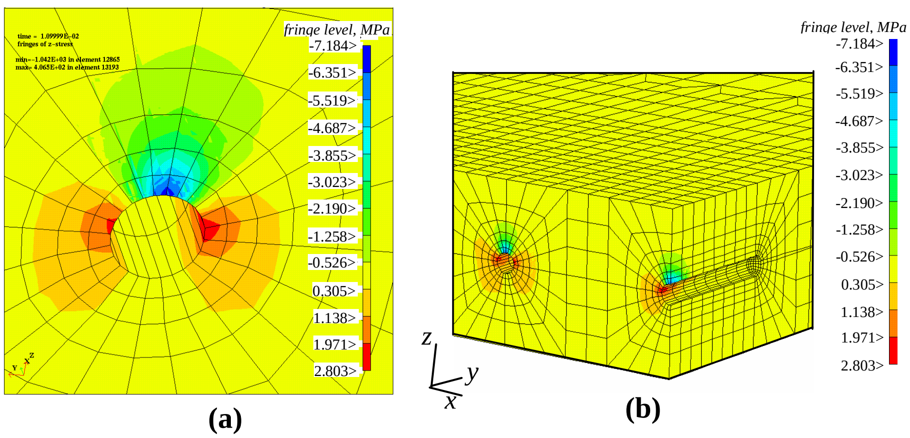


Figure 3 Fringes of Maximum Principal Stress.

Cracking of concrete is initiated as the maximum principal stress reaches the value of the concrete modulus of rupture. The distribution of the maximum principal stress around the edge of the dowel bar hole on both the loaded and the unloaded slabs is plotted in Figure 4. The plots were compared for slabs of two different grades of concrete. For the two grades of concrete, the stress intensity of the concrete surrounding the dowel bar reaches a maximum value that is equal to the modulus of rupture of that material. This indicates that if the there was not cutoff value on the maximum principal stress of the concrete; the maximum principal stress would reach a much higher value. Figure 4 also reveals that the maximum principal stresses occur at angular positions of 120 and 225 degrees approximately. However as indicated by Shoukry et al. (1998, 2002), these positions change with the increasing of dowel looseness. It can also be noticed that the angular position of the maximum principal stress on the unloaded side is symmetrical with those of the loaded one around the horizontal plane passing through the dowel bar center.

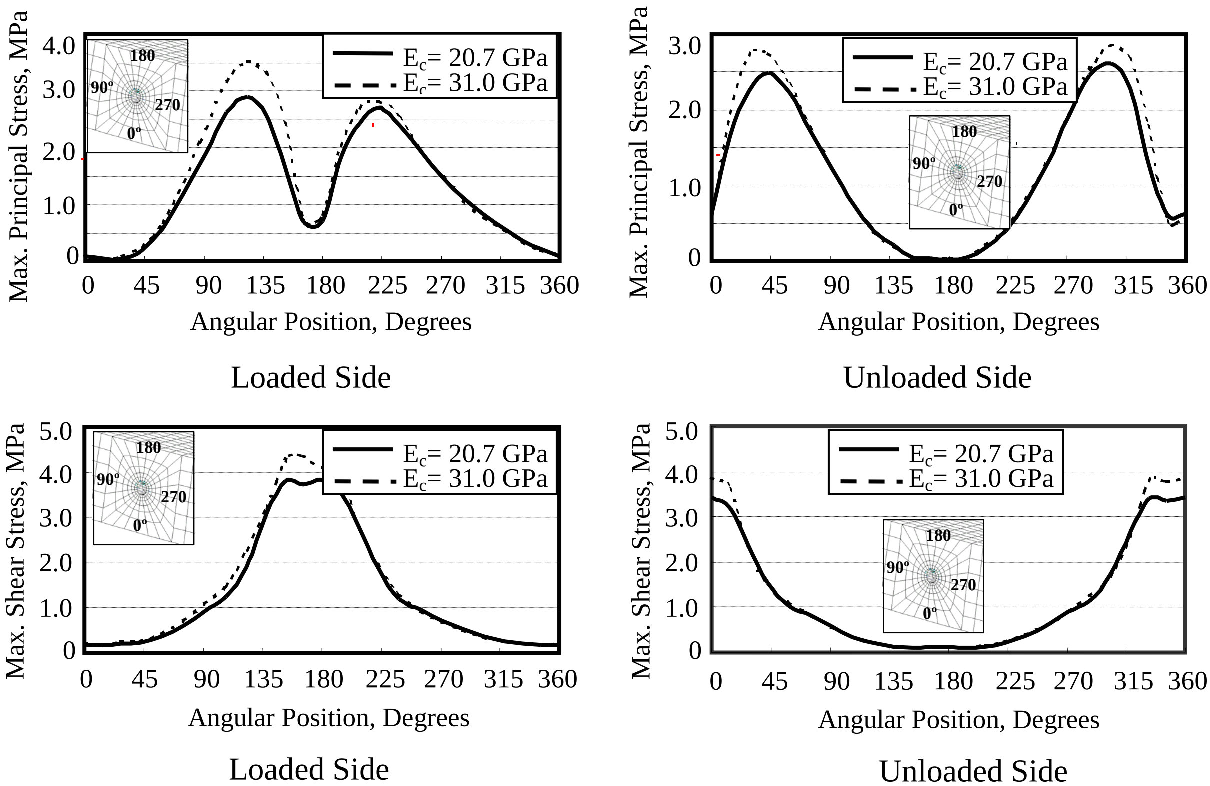
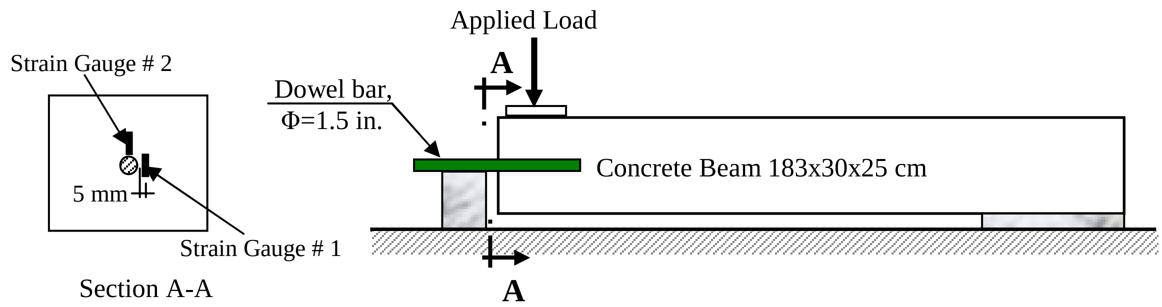


Figure 4 Distribution of Stresses Around the Dowel Bar Hole at Joint Edge.

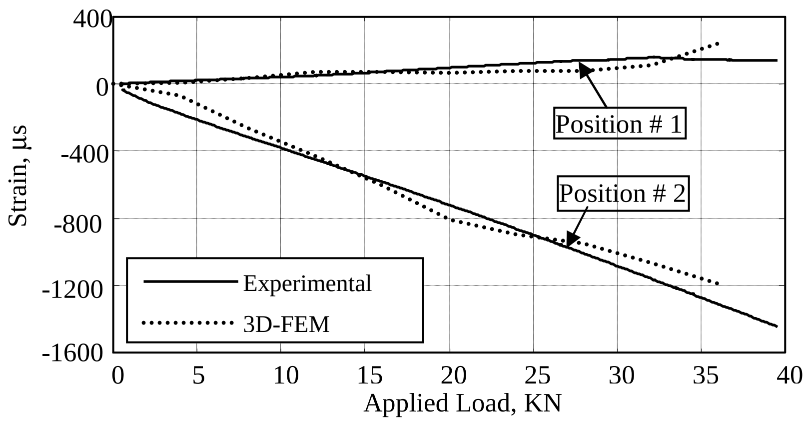
Figure 4 indicates that the tensile stress of concrete is accompanied by a relatively high shear stress, which facilitates the concrete failure in tension. The plots in Figure 4 reveal that the concrete slab starts cracking at the positions of maximum tensile stresses immediately after the load application. Obviously, these cracks will propagate with the increasing number of load cycles until the complete failure of the concrete at the joint. This explains the rapid deterioration of transverse joints in concrete pavements.

Model Validation

The concept of stress concentration around the dowel bars is verified by carrying out a set of laboratory experiments at West Virginia University. Portland cement concrete specimens, 30.5 cm wide x 25.4 cm thick x 183 cm long, were prepared. A dowel bar of 45 cm length was embedded in the concrete at one end of the specimen so that one half of the length is in the concrete and the other half extends freely as shown in Figure 5 (a). The crushing tests indicated that the average 28-days compressive strength of the used concrete was 39.3 MPa. The specimen was resting on the dowel bar from one end and on a steel pad on the other end as shown Figure 5 (a), so that the beam is subjected to pure shear. The load is applied by a hydraulic actuator on a rectangular contact patch 137 x 201 mm. The actuator was programmed to apply a ramp load from zero to 40 KN at a constant rate. Strains around dowel bars were monitored by mounting strain gages at positions shown in Figure 5. The measured strains were plotted against the applied load as shown in Figure 5 (a).



a. Experimental Setup.



b. Measured and Calculated Strains.

Figure 5 Model Verification.

3D Finite element model was developed to simulate the laboratory test. The used mesh is similar to that used in pavement model. The same brittle Damage model was used for the concrete after adjusting the model parameters according to the concrete compressive strength. The strains calculated from the model at the same locations of the strain gages were compared with the measured ones as shown in Figure 5 (b). The overall agreement is considered to be reasonably good. This validates both the formation of zones of high stresses around the dowel bars as well as the concrete material model used in the finite element modeling.

Conclusions

Despite the main objective of using the dowel bars at transverse joints that is enhancing load transfer efficiency, the finite element solution indicates that dowel bars may cause a significant deterioration of the joint which leads to signs of distress commonly observed on JPCC highways. Under current straight doweled joint design, the level of stresses induced in the contact zone between each dowel bar and the surrounding concrete is bound to initiate cracks when dowel bars are perfectly aligned. The results presented at this study led to the development of a new dowel bar design (Shoukry et al., 2002) that overcomes this contact stress problem and significantly reduces the stresses in concrete and pended for patent by Shoukry (1999). The performance of the new dowel design is currently tested in the field along Corridor H, West Virginia and the results will be published in a separate publication.

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