A NONLINEAR MECHANISTIC MODEL FOR DOWEL LOOSENESS IN PCC PAVEMENTS

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ABSTRACT

This paper describes a nonlinear mechanistic model that was developed to simulate the behavior of loose (or nonuniformly supported) dowel bars in rigid pavements. This model can be used in conjunction with other structural models to predict the responses of portland cement concrete (PCC) pavement to loads when various degrees of dowel bar looseness or loss of support exist.

Numerical examples are presented to demonstrate that longitudinal flexural stresses, which produce transverse cracking, are sensitive to the degree of dowel bar support. These examples indicate that each increase of 0.076 mm (0.003 in) looseness can produce a 10% increase in the maximum load-related stress at the pavement edge, a 14% increase of the maximum load-related stress at the middle of the slab, and a 14% decrease in load transfer efficiency. For PCC pavement thickness design procedures that are based on fatigue criteria, this additional longitudinal stress can be significant.

These results indicate that steps must be taken during construction to minimize initial dowel bar looseness, as has been suggested by many investigators. Research is needed to further quantify the effects of dowel bar looseness on concrete pavement behavior and performance with respect to the results of previous studies that were conducted assuming uniform dowel bar support.

INTRODUCTION

Many studies have demonstrated that the effectiveness of the transverse joint load transfer system significantly affects the ride quality and performance life of PCC pavements (1, 2, 3). Dowel bars are commonly used for transverse joint load transfer and generally provide reliable performance. With the introduction and use of finite element methods for rigid pavement analysis, the dowel bar mechanism has been simulated by many models, including the use of load transfer efficiency factors (4), modified beam elements (5, 6, 7), and refined element models (8). However, recent works (9, 10) have discussed the inadequacies of these models and have suggested that they are accurate only for dowels that are completely and uniformly supported within the concrete matrix (i.e., no looseness exists).

Experimental studies show that dowel bar looseness (produced by an imperfect fit or void between the dowel bar and the supporting concrete) greatly affects the load transfer efficiency, maximum deflection, critical stresses and the rate of pavement deterioration (2, 3, 11, 12, 13). Finite element analyses have shown that the maximum stresses in slabs modeled with and without dowel bars and subjected to the same traffic loads can vary by 100% or more (5, 6, 7). The responses of slabs with loose dowel bars should be somewhere between these two extreme cases.

Reference 14 summarizes the major findings of references 12, 13, 15 and 16 and establishes a model for considering dowel looseness by modifying the dowel bar diameter in the computer program RISC. An effective dowel bar diameter, $D' = k \times D$, is employed in numerical calculations, where k is a function of looseness and is always less than or equal to one.

The major assumptions of this model are:

1. Looseness is uniform for all dowel bars.

2. The loaded slab must deflect by an amount equal to the amount of looseness before the dowels become effective in load transfer (i.e., the loaded slab behaves as a single slab with a free edge until the deflection exceeds the amount of looseness, at which time the free edge is transformed into a joint with fully supported and effective dowel bars.

3. All dowel bars come into contact with the surrounding concrete at the joint face at the same time, regardless of their distance from the applied load(s).

4. A void (void depth equal to the amount of dowel

looseness) forms under the joint of the loaded slab due to the high stress concentration that exists under an effectively undoweled joint.

As explained by the author, these assumptions were made in order to analyze the effects of dowel looseness within a linearly elastic model.

The major disadvantages of this model include the following:

1. Dowel looseness is not actually uniform for all dowel bars. It is a function of dowel location, the distribution of the tire loads across the transverse joints, slab support conditions, etc.

2. The dowels do not necessarily come into contact with the supporting concrete at the same time. The contact order depends on the relative location of the loads and the looseness and location of each dowel bar. This indicates the need for a nonlinear load transfer analysis, rather than a linear analysis, as proposed in reference 14.

It is for these reasons that a nonlinear, elastic model is proposed in this paper to more accurately simulate the effects of dowel bar looseness.

This model can be used to predict doweled rigid pavement responses with consideration of the effects of dowel bar looseness. The looseness of each bar in the joint must be known (based on NDT measurements) or assumed. This information can then be used with the proposed model to calculate the order of dowel bar contact with the supporting concrete, determine the pavement responses, and estimate the critical stresses. Numerical examples are presented in this paper to demonstrate the validity of the model and to facilitate conceptual and quantitative understanding of the nonlinear load transfer mechanism. The accumulation and distribution of looseness over time (as caused by repeated traffic loads, climatic effects, and other factors) and the resulting variation in pavement response are not discussed in this paper.

DEVELOPMENT OF A NONLINEAR DOWEL BAR MODEL

Dowel Bar Stiffness Matrix

As discussed in reference 10, the following equation is often used as a general purpose dowel bar stiffness matrix:

$$K_{MJ1} = \begin{bmatrix} \frac{GA}{l}\xi & \frac{GA}{2}\xi & -\frac{GA}{l}\xi & \frac{GA}{2}\xi \\ \frac{GA}{2}\xi & \frac{GA}{4}l\xi+\frac{EI}{l}\eta & -\frac{GA}{2}\xi & \frac{GA}{4}l\xi-\frac{EI}{l}\eta \\ -\frac{GA}{l}\xi & -\frac{GA}{2}\xi & \frac{GA}{l}\xi & -\frac{GA}{2}\xi \\ \frac{GA}{2}\xi & \frac{GA}{4}l\xi-\frac{EI}{l}\eta & -\frac{GA}{2}\xi & \frac{GA}{4}l\xi+\frac{EI}{l}\eta \end{bmatrix} \quad (1)$$

where:

E	=	Elastic Modulus of the Dowel
I	=	Moment of Inertia of the Dowel Cross Section
G	=	Elastic Shear Modulus of the Dowel
l	=	Joint Opening or Width
A	=	Effective Cross-Sectional Area of Dowel in Shear

$$\xi = \frac{1}{1+\frac{2GA}{l*DCX}K_1} \quad (2)$$

$$\eta = \frac{1}{1+\frac{2EI}{l*DCXM}K_2} \quad (3)$$

where:

DCX	=	$2\beta^3EI$
DCXM	=	βEI
β	=	$(\Psi D/4EI)^{0.25}$
Ψ	=	Dowel - Concrete Interaction Coefficient
D	=	Dowel Bar Diameter
K_1,K_2	=	Constants that vary for different dowel systems. Reference 10 suggests $K_1 = 1$ and $K_2 = 1$ for solid dowel bars.

Since the joint load transfer effectiveness is generally dominated by shear resistance capability, equation 1 can be replaced by the following simpler matrix:

$$K_{MJ2} = \begin{bmatrix} \frac{GA}{l}\xi & -\frac{GA}{l}\xi \\ -\frac{GA}{l}\xi & \frac{GA}{l}\xi \end{bmatrix} \quad (4)$$

Numerical examples presented in reference 10 indicate that equations 1 and 4 provide very similar response predictions for results for pavements with solid dowel bar systems. Thus, equation 4 is employed in this paper to investigate the effect of dowel bar looseness. Regardless of the application of equations 1 or 4 or a different stiffness matrix, the concept of a nonlinear dowel looseness analysis is valid and can be applied to any suitable dowel bar stiffness matrix.

Load Transfer Mechanism for Load Transfer Systems with Loose Dowels

Figure 1 presents the load transfer mechanism for a loose or nonuniformly supported dowel bar. Figure 1(a) shows a cross-sectional view of a slab cut through an unloaded, uniformly loose dowel. Figure 1(b) shows the approach slab acting as a single slab (i.e., receiving no support from the leave slab) as the wheel load first approaches and the slab has not yet deflected enough to bring the dowel to bear on the concrete on either side of the joint. Figure 1(c) shows the dowel in full bearing and totally effective, since the relative deflection of the two slabs is equal to or exceeds the dowel looseness. As the dowel crosses the joint and departs the leave slab, a reverse loading condition develops.

Reference 3 presents the results of an excellent experimental study of dowel behavior with consideration of both initial looseness and the additional looseness that developed as a result of repeated load applications. Figure 2 (copied from reference 3) shows the observed relationship between magnitude of load and relative deflection after various numbers of load cycles and the effect of repetitive loading on the development of dowel looseness. Some of the study findings are summarized below:

1. During the application of the first 22.3 kN (5000 lb) of load, the relationship between load and relative deflection was nonlinear as the dowels were in a state of adjustment in which existing looseness was being taken up and a condition of full bearing was being established.

2. When the applied load was greater than 22.3 kN (5000 lb), the relationship between load and relative deflection was approximately linear, with the slope (but not the vertical position) of the line being independent of the number of accumulated load applications.

3. The amount of looseness present at any time may be estimated as the vertical coordinate of the point of intersection of the y-axis and the linear portion of the load-deflection curve measured at that time, as shown in figure 2(a).

The following assumptions may be added, based upon the results of this same research and the fact that all loads are assumed to be applied to the approach and leave slabs sequentially and evenly:

1. The void or gap between the dowel bar and concrete is uniformly distributed along the bar. This assumption implies that "The loaded slab has to deflect by the amount of looseness before dowel bars become effective in load transfer."

2. Before the application of any load (see Figure 1(a)), $\delta_{lu} + \delta_{rb} = \delta_{lb} + \delta_{ru} = L_0$, which is defined as looseness of the dowel bar (see figure 2(a)).

3. All dowel behavior is assumed to be linearly elastic; permanent dowel deformation is not considered. Thus, when the wheel load moves far away from the joint, the structural cross-section view of the slabs is as shown in figure 1(a).

4. The surfaces of the two slabs are in the same horizontal plane before each load is applied (i.e., permanent joint faulting or "step-off" is not considered and the interactive effects of dowel looseness and joint faulting on joint stiffness are not considered at this time).

The pavement slabs can still be modeled as elastic plates resting on either an extensionless Winkler base (5, 7), on multiple elastic layers (14), or on stress-dependent layers (6).

Based on the above assumptions, the behavior of a single loose dowel bar can be described graphically as in figure 3(a) and (b), where P is a load acting on a slab node and Δ represents the relative displacement between the loaded and unloaded slabs. K_0 is the stiffness contributed by the loaded slab, base and subgrade under the slab only, and $\Delta_0 = L_0$ is defined by the second assumption. Before the relative displacement between the loaded and unloaded slab nodes exceeds the dowel looseness L_0, the dowel is not considered effective in load transfer. When the relative slab deflection exceeds the dowel looseness (i.e., $\Delta_0 \geq L_0$), the dowel bar is assumed to be totally effective and joint stiffness K_1 is contributed by both slabs, their foundations, and the dowel load transfer system. The resulting force-deflection relation is a typical bi-linear model, as shown in figure 3(b).

Similarly, the functional behavior of a multiple dowel bar system can be described as shown in figures 3(c) and (d). Δ_0 indicates the first point of changing stiffness of the loose dowel system. Before the relative displacement exceeds Δ_0, no bar is effective in load transfer, and the loaded slab behaves as a single slab without an effective load transfer system. The joint stiffness of this slab is given as K_0. When the relative slab displacement is between Δ_0 and Δ_1, only one dowel is in contact with the supporting concrete and is effective in load transfer. The stiffness of the joint increases to K_1 in this range. A second bar becomes effective when the relative slab displacement equals or exceeds Δ_1 and the stiffness of the joint increases to K_2. More dowels become effective and the stiffness of the joint continues to increase as the relative slab displacement increases. The resulting force-deflection curve is shown in figure 3(d) and represents a multi-linear model which can be incorporated in a computerized structural analysis program to more easily estimate the response of the pavement system to incremental load applications.

VALIDATION OF THE MODEL

Looseness Distribution Assumptions

Figure 4(a) (copied from reference 3) indicates the effect of increasing the magnitude of the repeated load on the development of dowel looseness. Two significant findings that can be drawn from an analysis of figures 2(b) and figure 4(a) are:

1. About 40,000 load cycles (2% of the 2,000,000 total applied load cycles) produced about 50% of looseness observed after 2,000,000 load cycles. This indicates that most of the looseness is accumulated early in the loading program, assuming a constant load magnitude throughout. Later load applications appear to produce much smaller increases in dowel looseness.

2. When the magnitude of the repeated loads was increased during the later stages of the loading program, the rate of looseness was observed to increase rapidly, similarly to when the initial load cycles were applied, before again levelling off (figure 4(a)).

The above findings indicate that most increases in dowel looseness can be produced by the passage of a relatively few heavy trucks.

The lateral distribution of tire loads across a transverse joint can be illustrated as shown in figure 4(b). Although the distribution is not uniform, the proportion of loads carried primarily by each dowel could be more than 2%. If this is true, the experimental findings of reference 3 suggest that the lateral distribution of looseness across the transverse joint should not vary greatly. Therefore, the first step in investigating the effects of dowel looseness on pavement behavior is to employ a uniform looseness distribution in a numerical analysis (although the proposed multi-linear model is capable of dealing with any assumed looseness distribution).

Test Case Assumptions

The finite element mesh shown in figure 5(a) was used for a numerical analysis of the effects of dowel system looseness on pavement behavior. The selected pavement systems contains two slabs, each measuring 4.57 m long by 3.66 m wide (15 ft long by 12 ft wide) and is symmetrical in both the X and Y directions.

The two test load cases are:

Load case one: A concentrated 40.1-kN (9000-lb) load acting at point I in figure 5 (global X-coordinate = 4.57 m (180 in) on the approach slab, global Y-coordinate = 1.68 m (66 inch)).

Load case two: An 80.3-kN (18000-lb) single axle load with four tires configured as shown in figure 5(b) and placed on the approach slab at the transverse joint, as shown in figure 5(a).

Other principal input data include:

Concrete:

Slab Thickness	250 mm	(10 in)
Joint Width	6.4 mm	(0.25 in)
Elastic Modulus	34000 MPa	(5.0×10^6 psi)
Poissons Ratio	0.15	
Dowel Bar:		
Diameter	32 mm	(1.25 in)
Elastic Modulus	200000 MPa	(29×10^6 psi)
Poissons Ratio	0.3	
Looseness	As Indicated	
Subgrade Modulus	54 kPa/mm (200 psi/in)	
Dowel-Concrete Interaction	400 MPa/mm	(1,500,000 psi/in)

Numerical Examples

Displacement Shapes

Figures 6(a) through (e) show the slab displacement shapes under load case one for varying degrees of dowel looseness. These figures show the decrease in deflection or load transfer that accompanies increasing amounts of looseness. When all dowels are ineffective, the calculated approach slab displacements equal those of a single slab with a free edge.

Figures 7(a) through (c) present the computed displacement distributions along lines B-B, E-E and F-F (see figure 5(a)) for load case one. Figures 8(a) through (d) present the displacement distributions along lines B-B, A-A, E-E and F-F for load case two. These figures further illustrate the effects of increasing dowel looseness on pavement response to applied loads. For example, figure 8(b) indicates that a 0.15-mm (0.006-in) uniform dowel looseness increases the displacement at point E from 0.475 mm (0.0187 in) to 0.549 mm (0.0216 in), a 16% increase.

Stress Distributions

Figures 9(a) through (c) illustrate the computed stress distributions along lines B-B, E-E and F-F (see figure 5(a)) for load case one. Figures 10(a) through (d) present similar results along lines B-B, A-A, E-E and F-F for load case two (Fig. 5(a)). These figures show the effects of increasing dowel looseness on pavement stress response to applied loads. For example, figures 10(a) and (b) indicate that a uniform dowel looseness of only 0.15 mm (0.006 in) can produce an increase in the maximum longitudinal stress of more than 20%, while a uniform dowel looseness of 0.38 mm (0.015 in) can produce a 100% increase. For load case

two (single axle, dual wheel load), each 0.08 mm (0.003 in) increase in looseness produces approximately a 10% increase in the maximum stress along line A-A, and a 14% increase of the maximum stress along line B-B. When temperature gradient stress effects are considered, these load-related stress increases can easily become critical. For PCC pavement thickness design procedures based on fatigue criteria, the effects of additional stress due to the dowel bar looseness would be significant.

Where is the most critical point in the pavement? Which stress is more critical - the corner stress or the edge stress? Many investigators have concluded that the most critical edge stress lies along the longitudinal outside slab edge midway between the two transverse joints. However, this conclusion is generally based on the assumption of uniformly good load transfer at the transverse joints. Dowel looseness significantly increases the maximum corner stress while having little effect on the maximum edge stress.

Figures 9(b) and 10(c) demonstrate that the transverse stress distributions of line E-E are not sensitive to dowel looseness. Furthermore, the maximum transverse stress of 2.55 MPa (370 psi) presented in Figure 9(b) is not a realistic stress state because the assumed load case does not exist in practice and is included in this paper only for numerical comparison purposes. The results shown in figures 9(c) and 10(d) (stress distributions for line F-F) show sensitivity to dowel looseness, but the effect of increased looseness is to reduce the maximum transverse stress responses in the unloaded slab. Thus, these effects are insignificant in pavement thickness design.

Load Transfer Capability

Figures 11(a) and 12(a) present the variation of dowel bar shear forces due to the increase in assumed looseness for load cases one and two, respectively. For load case one, figure 11(a) indicates that the number of the effective dowels is reduced from 12 for looseness = 0 to 5 for looseness = 0.08 mm and 0.15 mm (0.003 in and 0.006 in) and to 3 for looseness = 0.23 mm (0.009 in). The corresponding results for load case two can be found from figure 12(a): 12 effective dowels for zero looseness, 9 for looseness = 0.15 mm (0.006 in), etc.

Figures 11(b) and 12(b) show the reduction in total load transmitted across the joint as looseness is increased (100% assumes no dowel looseness). For load case one, 0.08 mm (0.03 in) of looseness produces a 22% reduction in load transfer capacity. For load case two, each additional 0.08 mm (0.003 in) of looseness results in a load transfer capacity loss of approximately 14%.

Reference 14 states that 0.08 - 0.15 mm (0.003 - 0.006 in) of looseness is often found at in-service pavements and that the initial dowel bar looseness of new pavement could be greater than 0.08 mm (0.003 in) due to concrete shrinkage, excess dowel lubricants, etc. Thus, even small amounts of looseness can significantly reduce rigid pavement load transfer capability. This is just one more reason why the quality of dowel bar installation is critical to the concrete pavement performance quality and life. Furthermore, any coating material used for preventing dowel bar corrosion should be carefully evaluated to be certain that it will not produce an effect that is similar to dowel looseness.

CONCLUSIONS

Dowel looseness can produce significant changes in concrete pavement responses. It has been shown that the multi-linear model can be used to effectively quantify the effects of dowel looseness on concrete pavement behavior. Additional numerical analysis should be performed to expand upon the work begun here and to examine the effects of changing dowel looseness over time as a result of the accumulation of traffic loads and environmental conditions. Analyses of the resulting changes in looseness and pavement stress over time may be useful in future mechanistic pavement design procedures.

SUMMARY

Rigid pavement dowel load transfer systems are often constructed with or develop varying degrees of looseness or imperfect fit over time. The degree of looseness observed varies with construction practices, the accumulation of traffic loads, environmental conditions, etc. This paper proposes a nonlinear elastic model to simulate the mechanism of loose dowel bars in rigid pavement transverse joints. This model can be used in conjunction with existing finite element structural analysis programs to predict rigid pavement responses to applied and climatic loads for any given distribution of dowel system looseness.

Numerical analyses conducted using the proposed model indicate that each increase of 0.08 mm (0.003 in) of uniform dowel looseness can cause a 10% increase in the maximum edge stress, a 14% increase in the maximum interior stress, and a 14% loss of the load transfer capability. These results confirm that dowel looseness increases the potential for slab cracking, particularly when combined with certain temperature gradient stresses.

These findings suggest that future mechanistic pavement analyses and designs should seriously consider the inevitable development of dowel looseness in pavement thickness design. In addition, construction materials and procedures should be evaluated to ensure that they do not produce unacceptable amounts of initial dowel looseness.

Dowel looseness produces significant changes in pavement response. Additional analyses should be accomplished to further study these effects and refine and develop their applications in pavement analysis and design.

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1 in = 25.4 mm
1000 lb = 4.4 kN

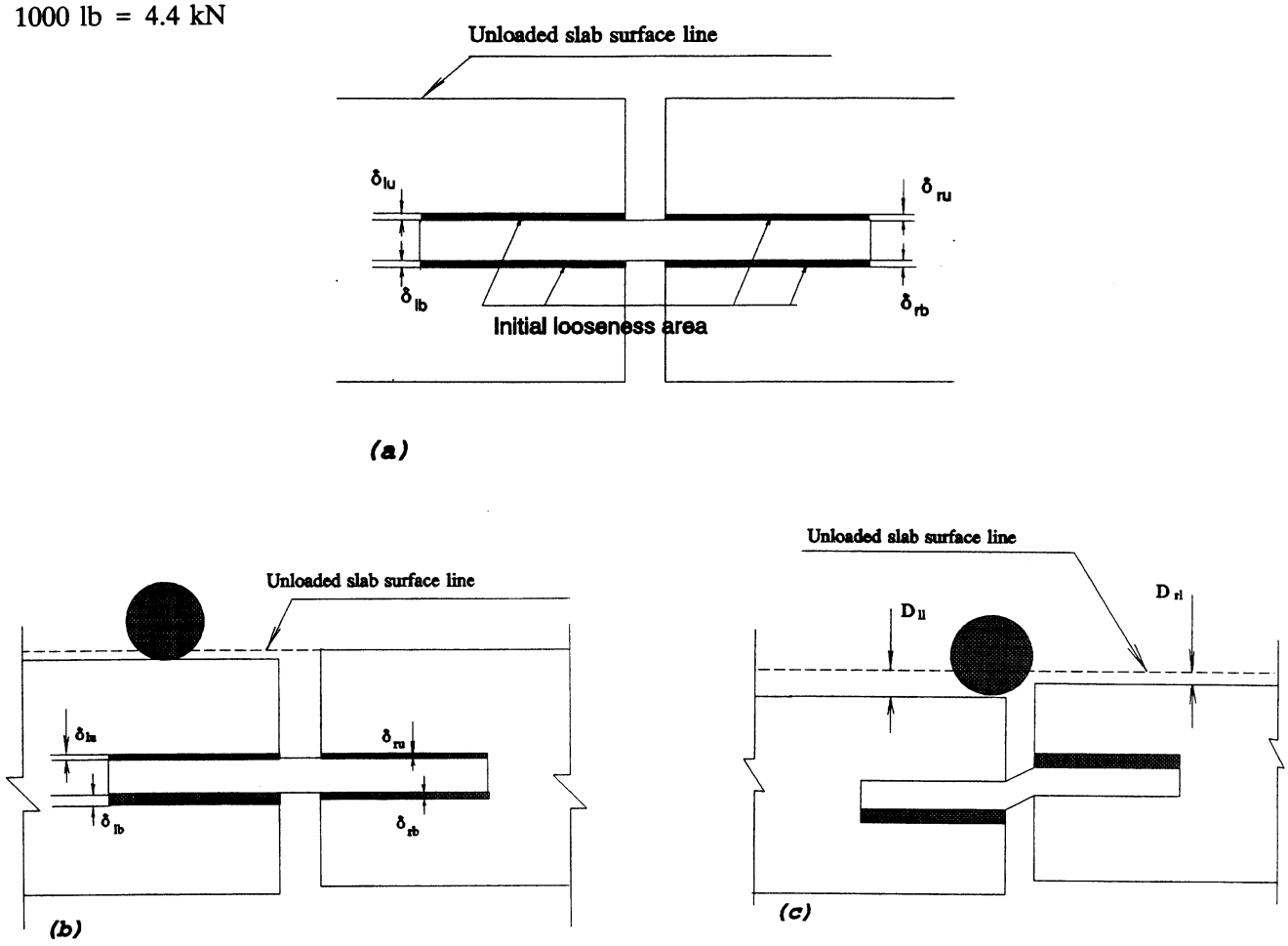


Figure 1. Dowel load transfer mechanism.

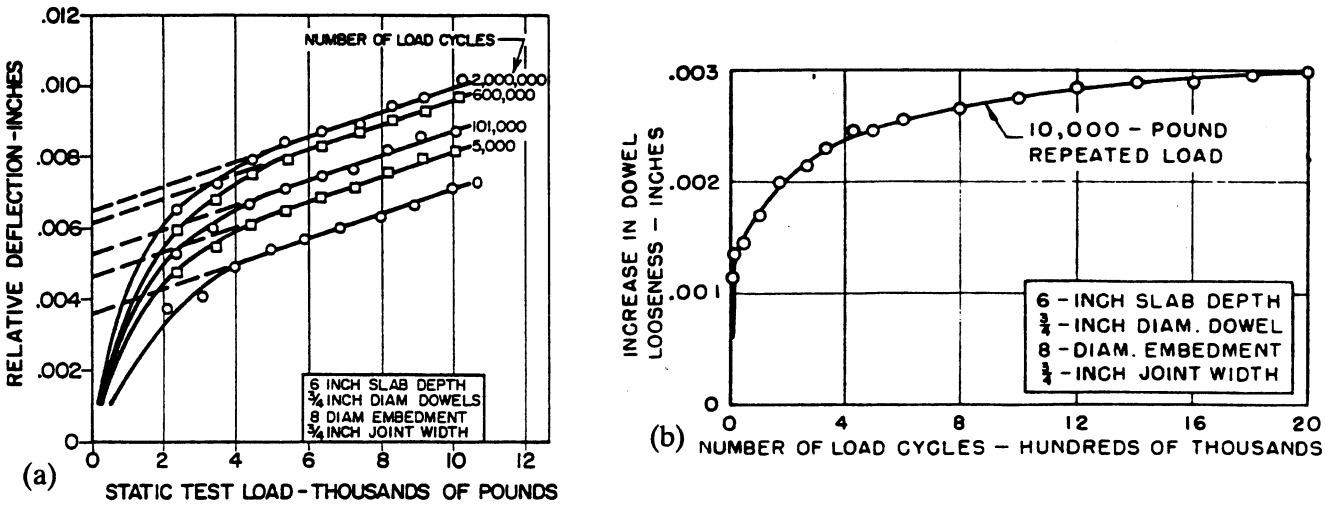
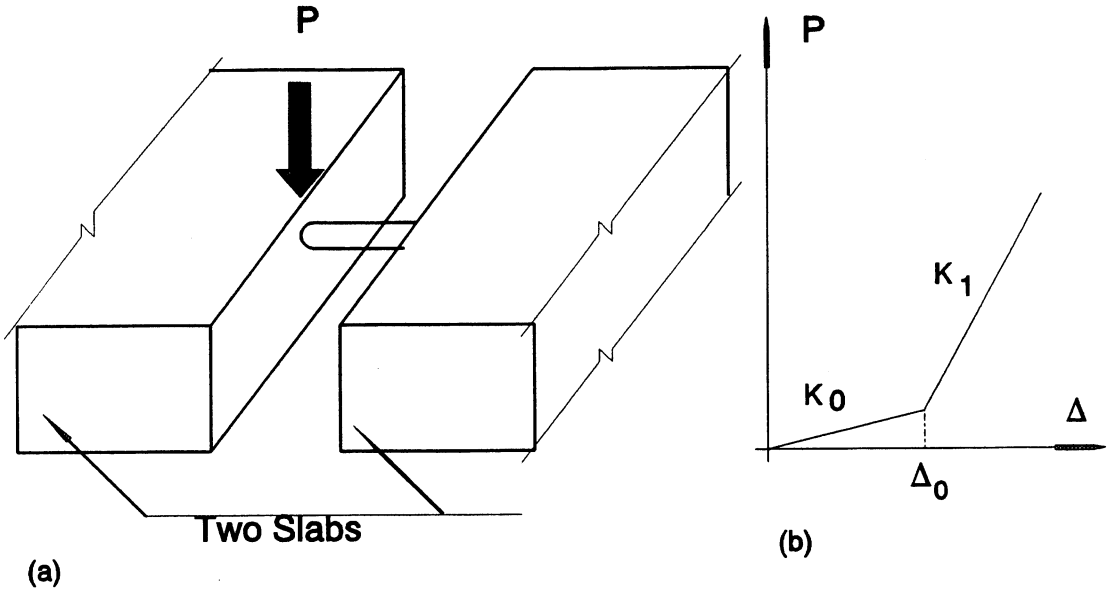
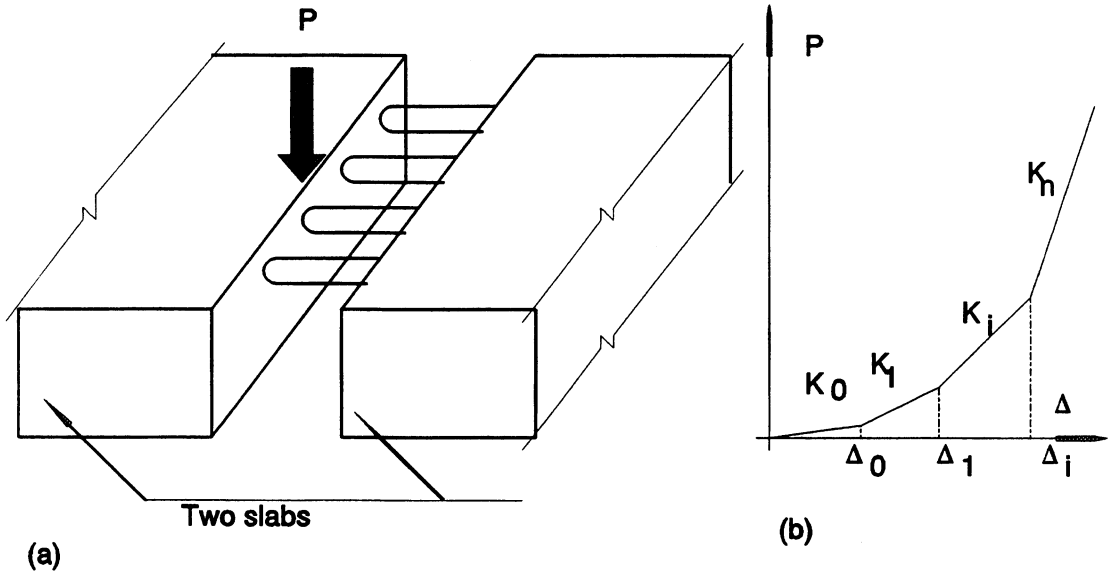


Figure 2. Experimental slab deflection and dowel looseness data (from Teller, 1959, figure 5).



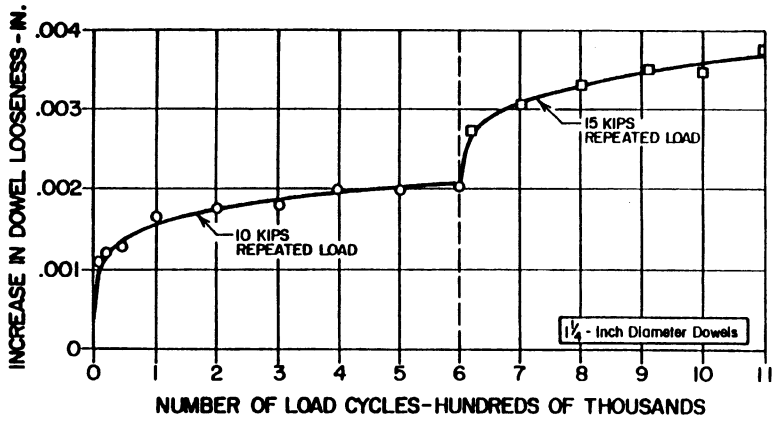
(a) Bilinear structural stiffness model for a single loose dowel.



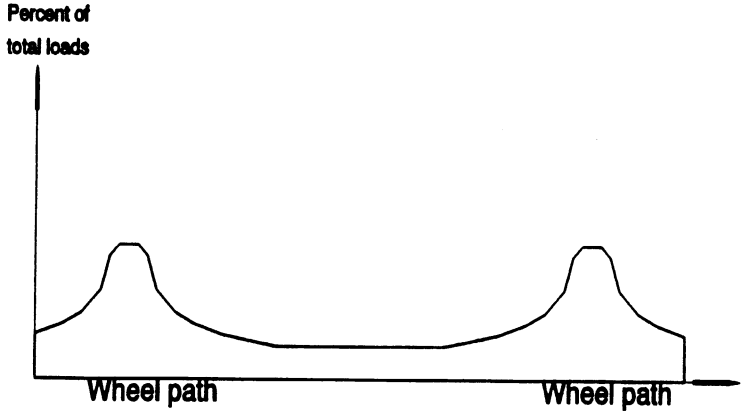
(b) Multilinear structural stiffness model for multiple loose dowels.

Figure 3. Nonlinear structural stiffness models for dowel looseness.

1 in = 25.4 mm
1 kip = 4.4 kN

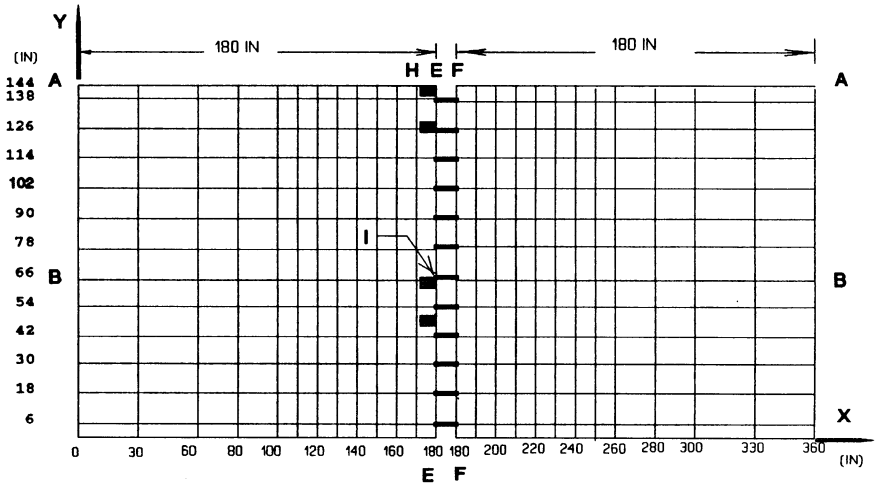


(a) Effect of increasing load magnitude on the development of dowel looseness (from Teller, 1959, figure 26).

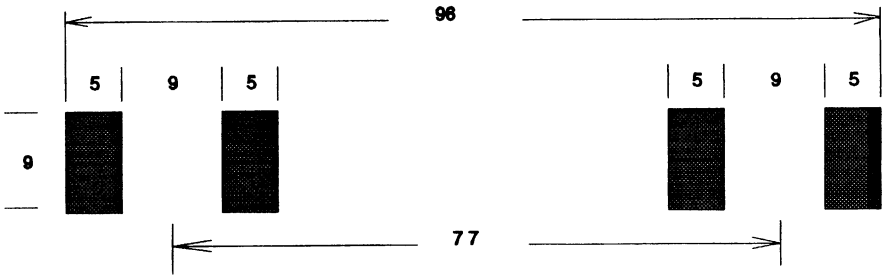


(b) Transverse distribution of tire loads across pavement.

Figure 4. Looseness distribution assumptions.

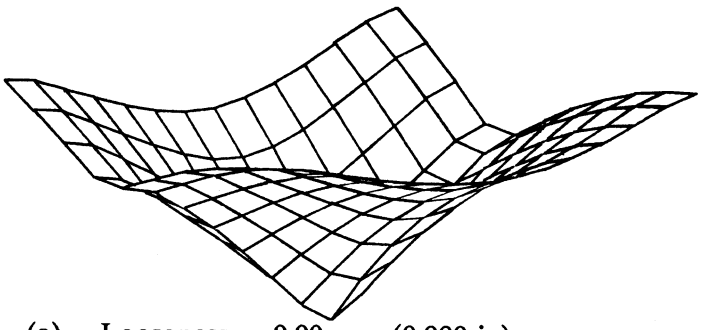


(a) Finite element analysis mesh.

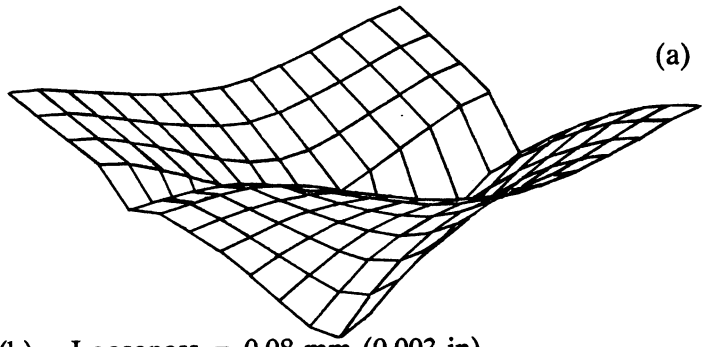


(b) Single axle configuration (80 kN (18,000 lb), 690 kPa (100 psi))

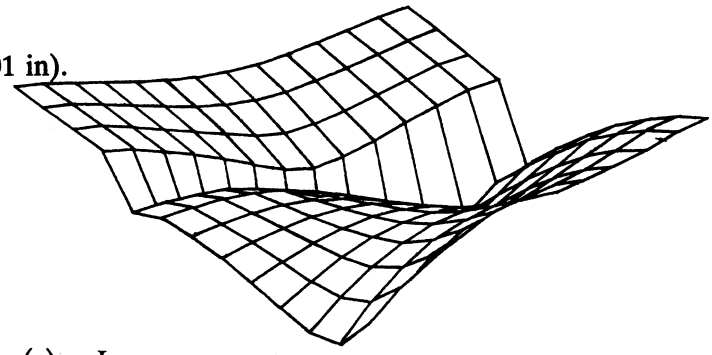
Figure 5. Finite element analysis assumptions.



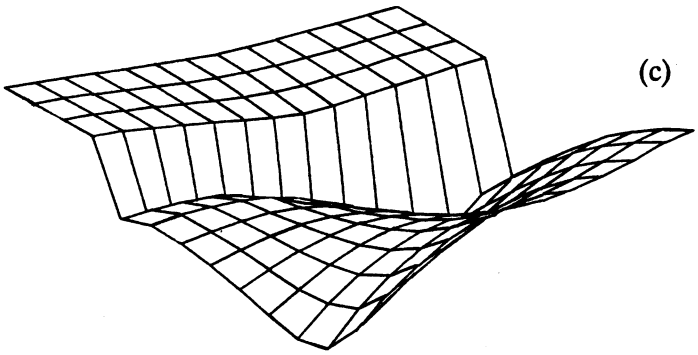
(a) Looseness = 0.00 mm (0.000 in),
maximum displacement = 0.22 mm (0.0086 in).



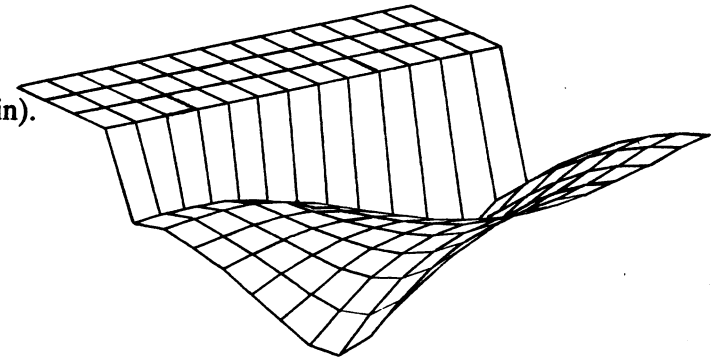
(b) Looseness = 0.08 mm (0.003 in),
maximum displacement = 0.257 mm (0.0101 in).



(c) Looseness = 0.15 mm (0.006 in),
maximum displacement = 0.292 mm (0.0115 in).



(d)Looseness = 0.22 mm (0.009 in),
maximum displacement = 0.328 mm (0.0129 in).



(e) Looseness = 0.38 mm (0.015 in),
maximum displacement = 0.391 mm (0.0154 in).

Figure 6. Slab displacement shapes (load case one).

1 in = 25.4 mm
1000 lb = 4.4 kN

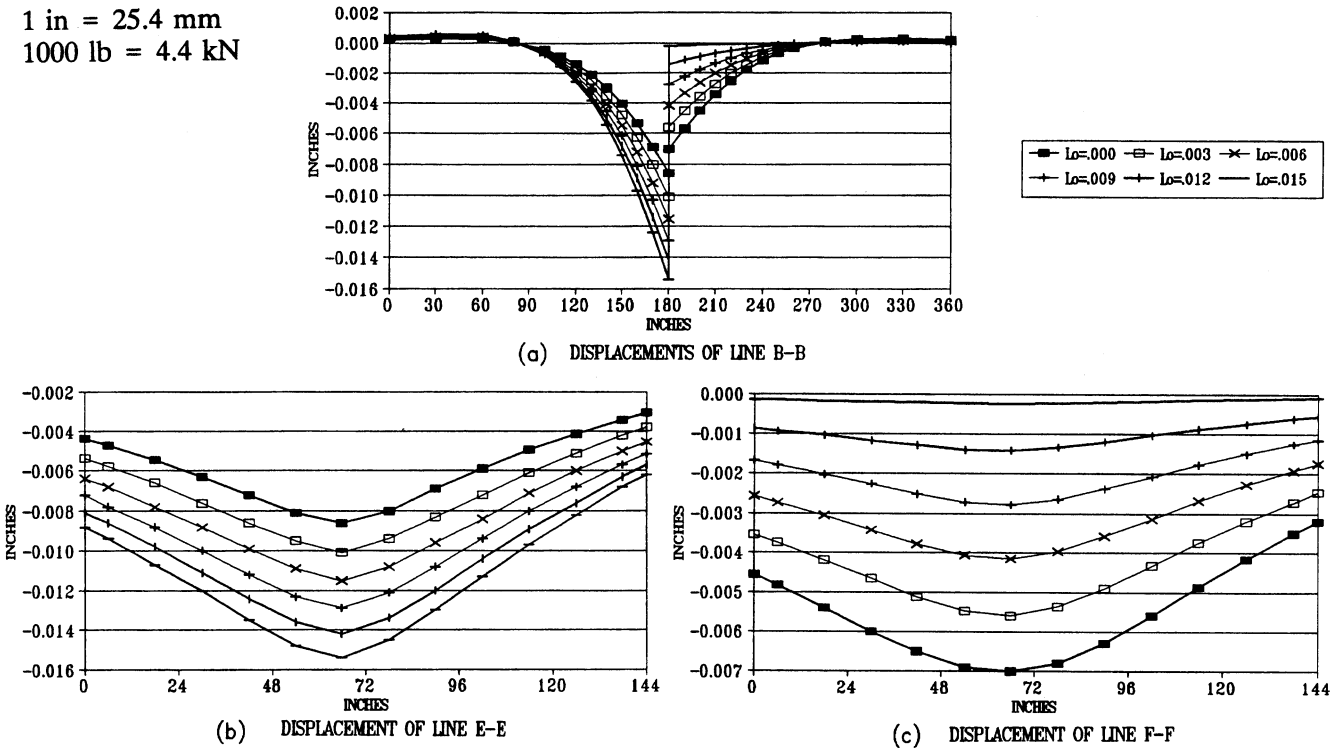


Figure 7. Displacement distributions (load case one).

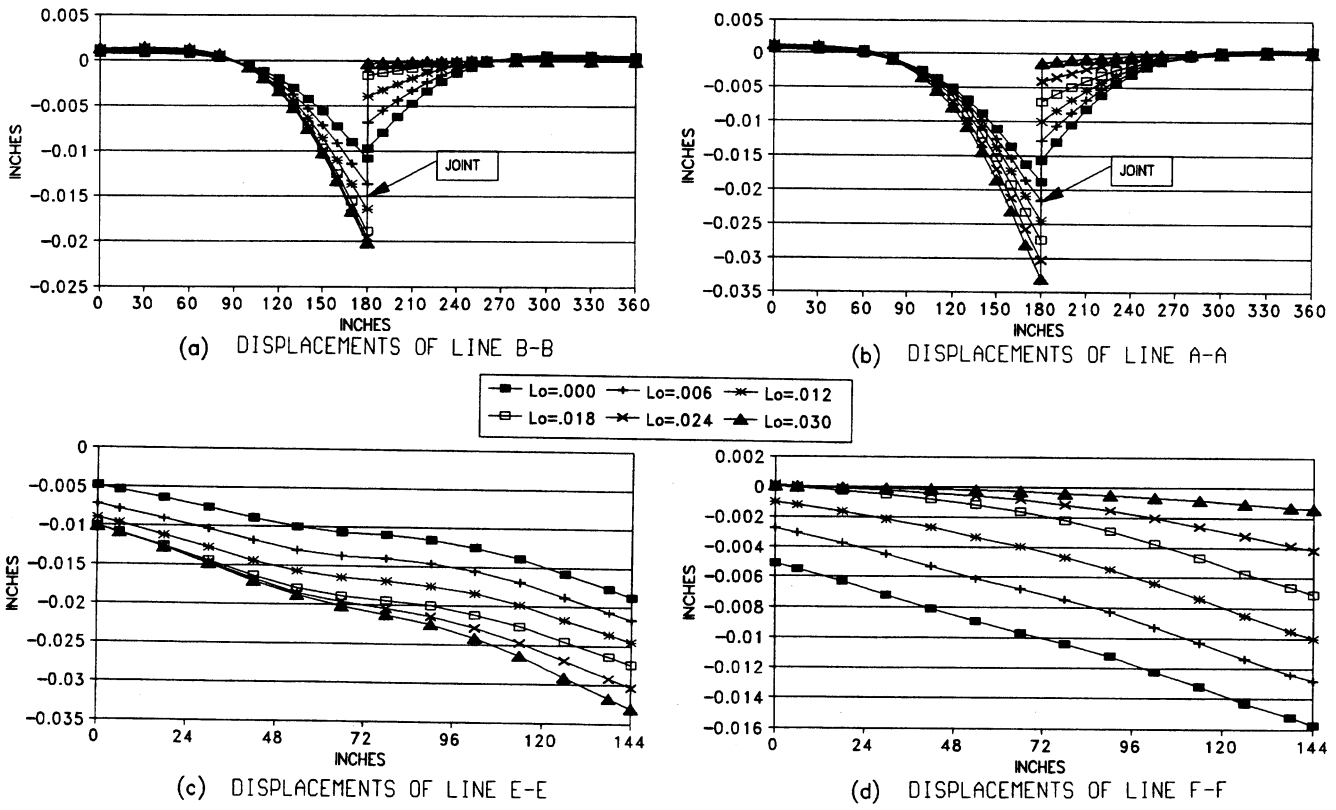


Figure 8. Displacement distributions (load case two).

1 in = 25.4 mm
1 psi = 6.9 Pa

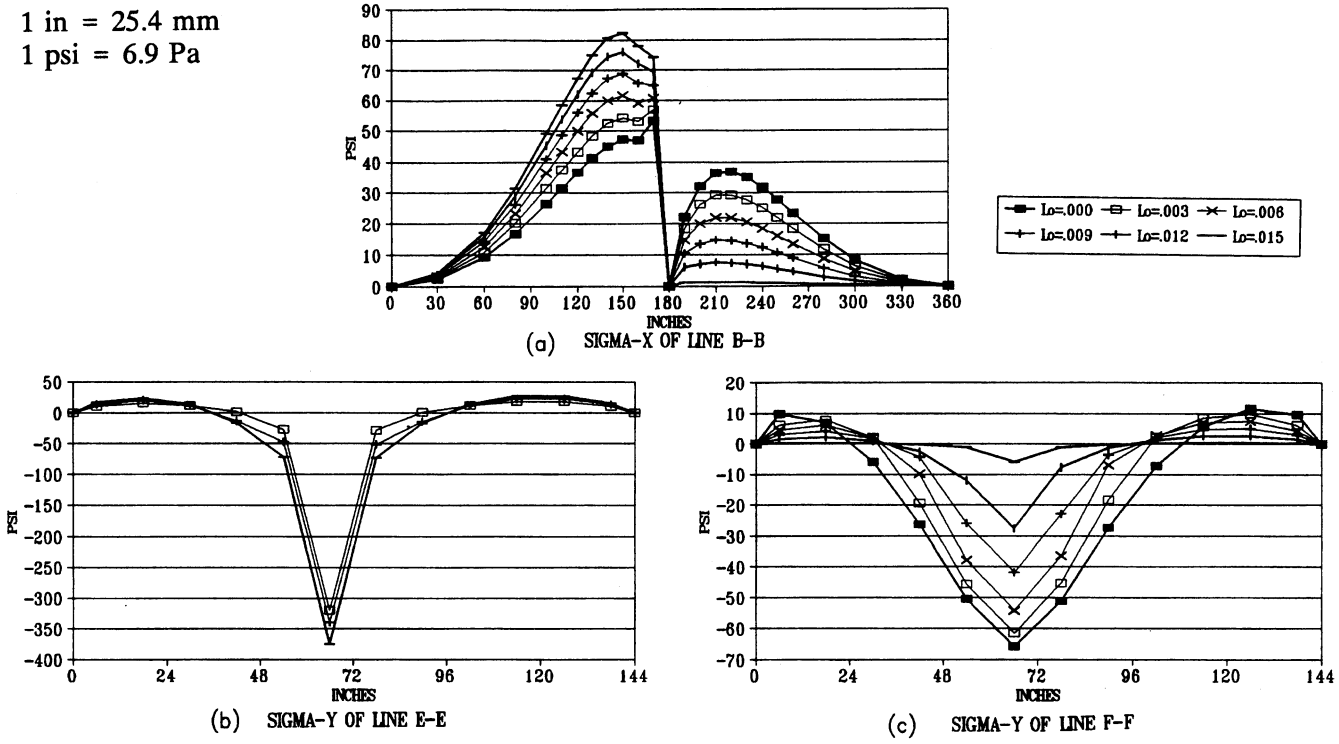


Figure 9. Stress distributions (load case one).

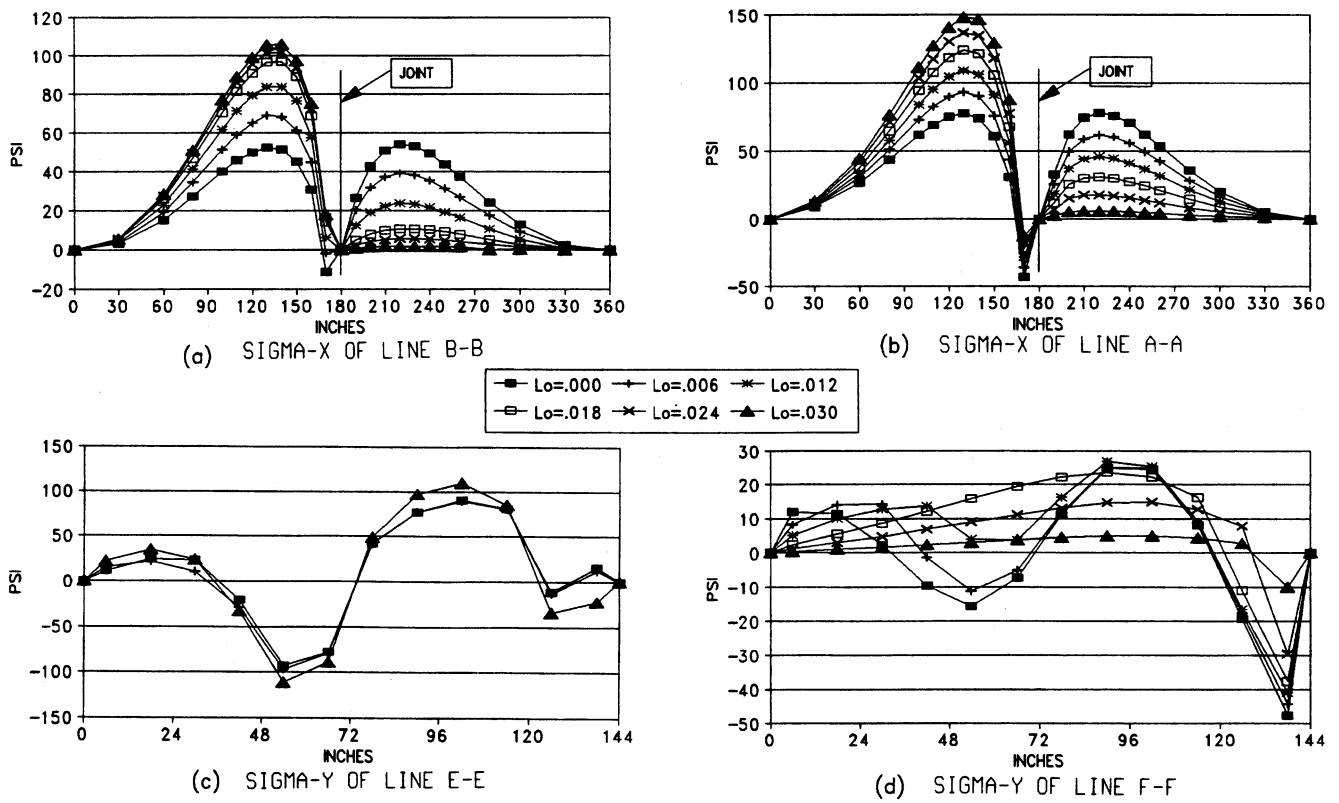
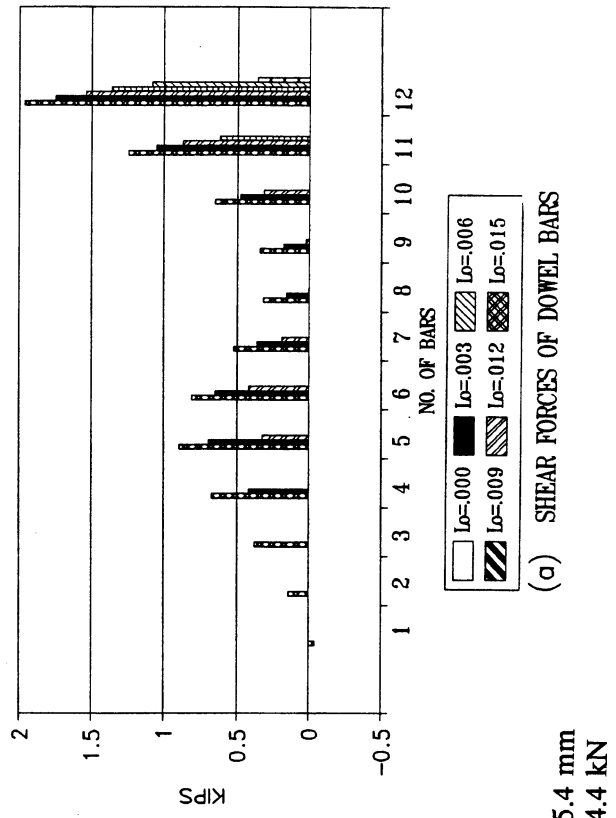
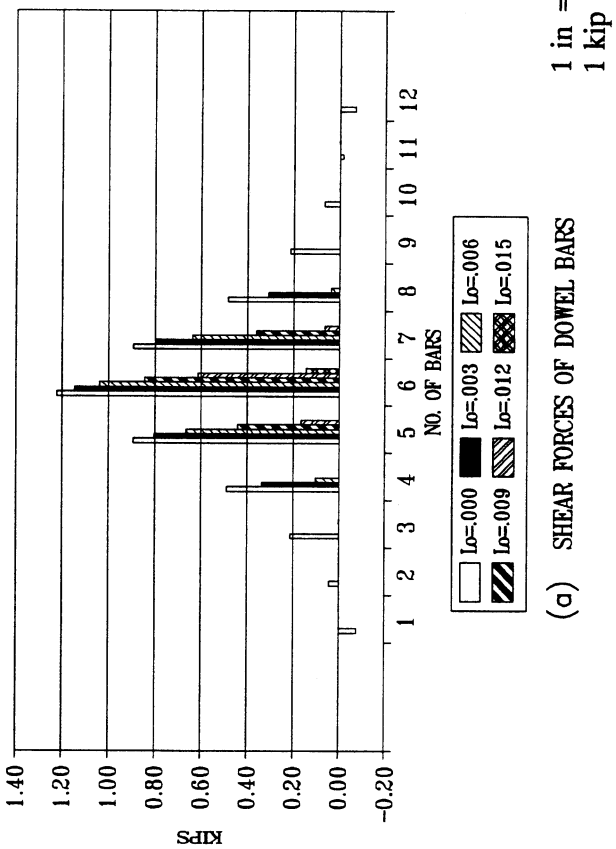


Figure 10. Stress distributions (load case two).





1 in = 25.4 mm
1 kip = 4.4 kN

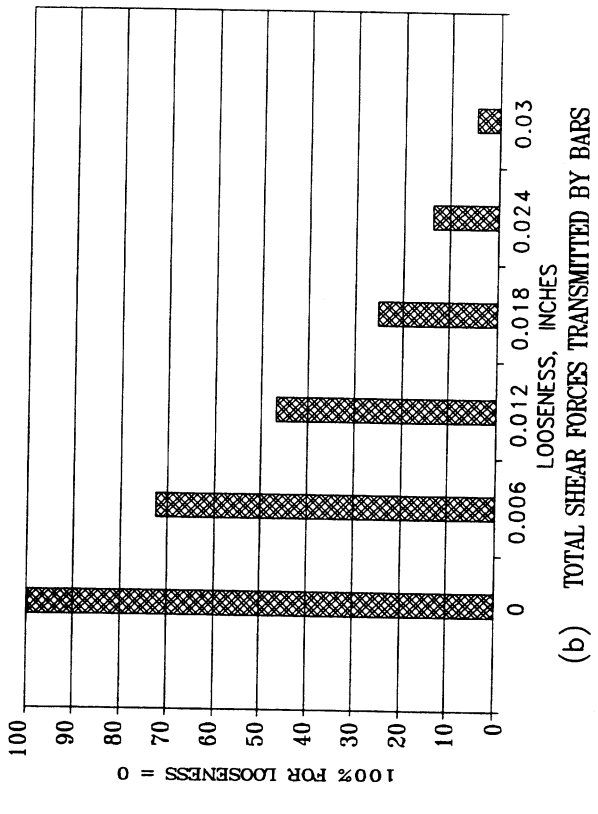


Figure 12. Load transfer properties (load case two).

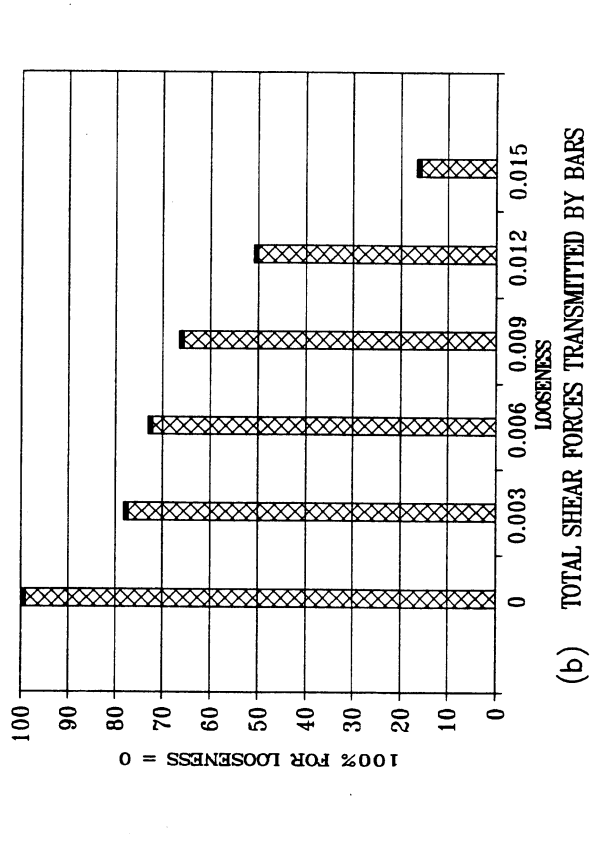


Figure 11. Load transfer properties (load case one).