MECHANISTIC EVALUATION OF VERTICAL MISALIGNMENT OF DOWEL BARS AND THEIR EFFECTS ON JOINT PERFORMANCE

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ABSTRACT

This paper presents the results of finite element modeling of misaligned dowels. It shows that uniformly misaligned dowels perform similar to perfectly aligned dowels. On the other hand, non-uniformly misaligned dowels may cause joint lock-up and significant stresses in the surrounding concrete, which may lead to premature joint failure and reduce pavement life.

INTRODUCTION

Many transportation agencies use round steel dowel bars to ensure that adequate load transfer takes place across transverse joints in rigid pavements. Dowel bars are placed at pavement mid-depth, and care is taken to minimize the detrimental effects of misalignment. Desirably, dowel bars at contraction joints will be exactly parallel to both the surface and centerline of the hardened portland cement concrete (PCC) slab. If they deviate from the desired position, they are said to be *misaligned*. Misalignment may result from misplacement (initially placing the dowels in an incorrect position), displacement (movement during the paving operation), or both.

The dowel bars are typically placed in the joint by positioning them in wire basket assemblies, which in turn are pinned to the subbase or subgrade prior to paving. This secures the bars during paving when the concrete is placed. Recently, a new method of dowel placement has been used with automatic dowel bar inserter (DBI) equipment, inserting dowels directly into the plastic concrete.

Several major pavement performance studies (Yu et al. 1997, Khazanovich et al. 1998, Hoerner et al. 2000) demonstrated that properly placed dowels significantly reduce transverse joint faulting and corner cracking. However, dowel misalignment may cause unwarranted restraint at joints (locked joints) and result in transverse cracking, corner breaks, and spalling at the concrete face around the dowel. Moreover, once spalling occurs around a dowel, load transfer effectiveness may decrease and pavement roughness may increase. To prevent these detrimental effects, transportation agencies limit allowable dowel misalignment.

Currently, no clear consensus exists among State agencies regarding the level of practical limits on dowel placement tolerances. Normally, a maximum allowable alignment error of 0.25 in per 18 in length of dowel bar is specified. However, the Georgia Department of Transportation specifies an allowable tolerance of 3/8 in/ft in both the horizontal and vertical direction, and several other agencies specify an allowable tolerance of 1/4 in/ft in both the horizontal and vertical directions. These specifications were developed based on very limited data from field and laboratory performance studies.

Recently, the Michigan Department of Transportation, in cooperation with Michigan State University and ERES Consultants, initiated a study to develop justifiable tolerance levels that ensure that doweled joints do not cause high levels stresses due to misaligned dowels. This may lead to a possible construction cost savings without jeopardizing pavement performance. The first stage of this project involves the development of finite element models capable of accounting for dowel misalignment.

This paper presents several finite element models developed in this study using the commercial finite element package ABAQUS (Hibbitt et al. 1998). This includes finite element models of a pullout test, a single misaligned dowel, and a multi-slab system with misaligned dowels. Based on the results of the finite element analysis, the effect of dowel misalignment of joint performance is discussed.

MODELING OF FRICTION BETWEEN DOWELS AND PCC

Dowel–concrete slab interaction is a complex problem. Properly designed, manufactured, and installed dowels should provide desirable shear load transfer efficiency between the adjacent slabs and, at the same time, not resist the slab's horizontal movements during temperature contraction or expansion. Although dowel coating significantly reduces friction between the dowel and the surrounding concrete, results of pullout tests show that this friction is not completely eliminated and, therefore, has to be considered in the analysis.

The finite element method (FEM) was identified as the most appropriate analytical method for analysis of dowel–PCC interaction. A commercial general-purpose finite element package, ABAQUS, was selected as a tool for development of a finite element model. ABAQUS is a very powerful and reliable production-oriented, 3D nonlinear finite element code well-suited for the analysis of complex contact problems.

Selecting ABAQUS is further justified by the fact that the majority of 3D finite element rigid pavement models were developed using it. Zaghloul and White (1993) developed a nonlinear,

dynamic model of rigid pavements. Darter et al. (1995) used ABAQUS to investigate the effect of foundation support and base layers on pavement responses. Hammon (1997) used ABAQUS for a comprehensive analysis of joints in jointed plain concrete pavement (JPCP).

In this study, the following two approaches for modeling dowel–PCC interaction were explored:

- Using soft elements.
- Using special contact elements.

Each of these approaches is described below.

Modeling Contact Behavior Using Soft Elements

The simplest way to model dowel–PCC interaction in a finite element model is to place an interlayer of elastic or elastic-plastic elements rigidly connected to the dowel and the surrounding PCC elements (Tayabji 1988). Different degrees of bond between the dowel and the surrounding PCC can be modeled by varying the stiffness of this interlayer; a very stiff interlayer corresponds to full bond between the dowel and the PCC, whereas a very soft interlayer models a full slip interface condition. The advantage of this approach is the simplicity of its implementation. If only small elastic deformations are considered, this approach leads to reasonable results.

However, in this study, large inelastic displacements have to be modeled, so the use of a thin soft interlayer is not an appropriate approach. Large deformations cause significant distortion of the interlayer elements, which makes the entire solution unstable. Although an increase in the interlayer thickness improves the stability of the solution, it reduces the interlayer's ability to adequately describe contact behavior. Based on these observations, the soft interlayer approach was not used in this study.

Modeling of Contact Behavior Using Special Contact Elements

When surfaces are in contact they usually transmit shear stresses (as well as normal stresses). The ABAQUS finite element modeling software includes an option to model contact behavior by identifying and pairing potential contact surfaces. If this option is used, each contact condition is defined in terms of two contacting surfaces. One of the surfaces of the pair is the "slave" surface and the other is the "master" surface. The nodes of the master surface are constrained not to penetrate into the master surface. The *FRICTION suboption in ABAQUS provides a relationship between shear and normal components of contact stresses.

The friction model in ABAQUS is an extended version of the classical Coulomb friction model (Amoton's Law), which states that the contact surfaces do not slide over each other if the shear stress magnitude is less than μ, the coefficient of friction, times the pressure stress between them. This behavior is shown in figure 1.

In this study, the ABAQUS friction model was selected as the primary modeling tool for analysis of dowel–PCC interaction. The pullout test was identified as a benchmark test for establishing dowel–concrete interface parameters.

MODELING OF A PULLOUT TEST

Modeling of a pullout test was performed to establish defensible dowel–concrete interface parameters and to verify the robustness of the dowel–concrete interaction model.

In this study, axisymmetric models of the pullout tests were developed. The model treats a pullout test as a contact of two cylinders, as shown in figure 2. A larger (PCC) cylinder surrounds a smaller (steel) cylinder. The horizontal displacements of the PCC cylinder are restrained, whereas the right end of the steel cylinder is subjected to horizontal movement. The only discrepancy between this model and an actual pullout test structure is that the PCC block in a pullout test has a prismatic shape. However, this slight difference should not affect the magnitude of PCC resistance to dowel movements. On the other hand, an axisymmetric model is substantially more computationally efficient than the 3D alternatives.

Comparison of figures 1 and 2 immediately reveals a necessity to assign initial contact pressure on the PCC–dowel contact surface. Indeed, if this pressure is assumed equal to 0, the surrounding PCC should not show any resistance to the horizontal dowel movement. This contradicts the results of pullout tests, which show significant resistance of PCC to horizontal dowel displacement. Therefore, to model the pullout test using the friction model, it is necessary to introduce an initial contact pressure between the PCC and dowel in the finite element model.

Although the notion of initial contact pressure may appear artificial, it has several physical interpretations/justifications. Indeed, these stresses can be a result of PCC layer compaction after pavement placement or the result of dowel resistance to PCC shrinkage contraction. Another phenomenon that has a different physical mechanism but leads to an equivalent mathematical model is the effect of initial bonding. If the PCC and the dowel develop a certain physical bond, a certain shear stress will need to be applied to break this bond even if no normal pressure is acting. Figure 3 illustrates how this effect can be accounted for in the initial contact pressure model. By applying an additional contact normal pressure, the minimum shear stress required to move the dowel is set equal to the initial bond strength.

Three approaches for providing this contact pressure were explored in this study:

- Assignment of positive change of dowel temperature.
- Assignment of negative change of PCC temperature.
- Direct assignment of the external compressive forces at the dowel–PCC interface (figure 4).

The first two options are mathematically equivalent, but the first is more convenient in finite element realization. Therefore, the second option was eliminated from consideration. Although the first and last options produced very similar results, the first option was more numerically stable than the last. Therefore, initial contact pressure was provided in this study by assigning initial temperature expansion of dowels, and dowel temperature change was considered as one of the model parameters.

A factorial of ABAQUS runs with different model parameters was performed. The right edge of the dowel was subjected to horizontal displacement up to 0.1 in. The resulting dowel–PCC contact interface shear stresses were calculated and the resulting pullout forces were determined. Figure 5 presents the effect of the friction coefficient on the contact shear stresses. As expected, an increase in the friction coefficient leads to an increase in the contact shear stresses and resulting pullout forces. In this example, an increase in the friction coefficient from 0.3 to 0.5 resulted in an increase in the force required to displace the dowel 0.1 in from 2060 to 3200 lb.

The results were compared with typical results of pullout tests. Based on this analysis, the following baseline model parameters were selected:

Friction coefficient = 0.3.
Maximum slip tolerance level = 0.1.
Dowel temperature increase = 15.0^{o}F.

The contact interface shear stresses for these parameters are predicted to be between 50 and 65 psi. The resulting pullout force was determined to be equal to 2060 lb. These values agree with the results of typical pullout tests.

3D MODEL OF UNIFORMLY MISALIGNED DOWEL

The 3D ABAQUS model developed in this study consists of three parts, as shown in figures 6 and 7. One segment models a dowel connecting to other segments, which model two adjacent slabs. The height, length, and width of the PCC segments are equal to the PCC slab thickness, half the joint spacing, and half the dowel spacing, respectively.

The left longitudinal cross-section was restrained from transverse movements to simulate symmetrical boundary conditions. The left and right ends of the model were also restrained from horizontal displacement, and the bottom surface was supported by a Winkler foundation with k-value equal to 200psi/in. The dowel and PCC segments were connected using the special contact friction elements. An initial contact pressure between the PCC and dowel in the finite element model was introduced by assigning a positive change to the dowel temperature.

The effect of magnitude of vertical dowel misalignment was investigated in this study. Each analysis was performed in two loading steps. The first step involved an increase in dowel temperature to provide initial contact pressure between the dowel and surrounding PCC. The second step simulated temperature movements of the joint by decreasing PCC and dowel temperature by up to -200°F.

Figures 8 and 9 present stress distributions of equivalent Mises stresses and longitudinal stresses, respectively, in the dowels and the surrounding PCC when the joint opening is 0.2 in and dowel misalignment (i.e., the distance between the axis of an aligned dowel and the center of the dowel end section) is 1 in. The dowel diameter was 1.25 in, and the friction coefficient was assigned equal to 0.3, which corresponds to a pullout PCC shear stress of 60 psi for a perfectly aligned dowel. Figures 8 and 9 show that, although dowel misalignment leads to some non-uniformity of stress distribution around the dowel, this non-uniformity is not extremely pronounced.

Comparison of pullout forces for a case of a perfectly aligned dowel and a dowel with 1-in misalignment also showed an increase in pullout force only by about 10 percent.

3D MODEL OF NONUNIFORMLY MISALIGNED DOWEL

The 3D ABAQUS model described above assumed that all dowels in the joint are misaligned on the same magnitude and direction as the dowel considered, permitting the analysis of a dowel and the surrounding concrete independent from the behavior of other dowels, since the behavior of all dowels should be similar. If a point located at the mid-depth level between two dowels is forced to move downward due to the bending of a dowel located to the right, then the dowel located to the left of this point also forces it to move downward (see figure 10b). To account for the effect of non-uniform misalignment, the model was modified slightly. Two cases were considered:

- All dowels in the joint are misaligned on the same magnitude, but adjacent dowels are misaligned in the opposite direction (i.e., if the left end of a dowel is misaligned downward then the left ends of two adjacent dowels are misaligned upward).
- Only one dowel in the joint is misaligned and all other dowels are perfectly aligned.

Oppositely Misaligned Dowels

If two adjacent dowels are misaligned on the same magnitude but in the opposite direction, then if the pavement is subjected to uniform change in temperature loading the points located at the mid-depth level between these dowels should not experience vertical movements. Indeed, if both dowels are aligned (misalignment is equal to zero) these points will not experience vertical displacement. On the other hand, if non-zero misalignment of the right dowel forces a point located at the mid-depth level between two dowels to move upward, then the dowel located to the left of this point forces it to move downward. Therefore, the total vertical displacement of the points located between two dowels should be zero and restraining the nodes located at the mid-depth of the right longitudinal side of the model allows modeling of the effect of dowels misaligned in the opposite direction (see figure 10b).

Figures 11 and 12 present stress distributions of equivalent Mises stresses and longitudinal stresses, respectively, in the dowels and the surrounding PCC when the joint opening is 0.2 in and dowel misalignment is 1 in. The dowel diameter was 1.25 in, and the friction coefficient was assigned equal to 0.3, which corresponds to a pullout PCC shear stress of 60 psi for a perfectly aligned dowel. Figures 11 and 12 show that non-uniform dowel misalignment leads to a significant increase in PCC stresses in the area surrounding the dowels.

Single Misaligned Dowel

Uniformly misaligned dowels and oppositely misaligned dowels are two extreme cases. To model intermediate cases, the vertical restraints at the mid-depth points introduced in the previous model were replaced by vertical springs (see figure 10c). Lower spring stiffness represents higher uniformity in misalignment. Higher spring stiffness represents higher non-

uniformity in misalignment. In limited cases (very low and very high spring stiffness), the model approaches the cases of uniform misalignment and opposite misalignment.

If only one dowel is misaligned and the PCC is subjected to a uniform drop in temperature, then PCC slab movement will cause bending in the misaligned dowel which, in turn, will cause bending of the PCC slab. However, unlike bending of the uniformly misaligned dowels, this bending will be resisted not only by the strip of PCC located between two dowels but also by both PCC slabs adjacent to the joint.

To estimate the degree of resistance of the PCC slab to bending caused by the bending moment applied at the edge and the stiffness of spring capable to imitate that resistance, a factorial of finite element runs was performed using the computer program ISLAB2000. Details of that analysis are not included in this paper; the conclusion of that analysis is that a longitudinal spring stiffness of 40,000 psi/in represents the restraint provided by the PCC area not included in the 3D finite element model.

Analysis of a single misaligned dowel resulted in PCC stresses higher than in the case of uniformly misaligned dowels but lower than in the case of oppositely misaligned dowels, assuming that all other parameters are the same. Figure 13 present a comparison of pullout forces for the cases of aligned dowels, uniformly misaligned dowels, a single misaligned dowel, and oppositely misaligned dowels. Non-uniform dowel misalignment (single misaligned dowel and oppositely misaligned dowel) causes greater restraint to horizontal movements at the PCC joint than uniform misalignment. On the other hand, a single misaligned dowel causes less restraint than oppositely misaligned dowels.

ANALYSIS OF MULTI-SLAB SYSTEMS

To evaluate the effect of misalignment of one or more dowels in a multi-slab system on the entire system behavior, a 2D finite element model was developed. The model consisted of three PCC slabs connected with doweled joints. A center slab was modeled as a full-length slab, whereas only half of the right and left slabs were modeled directly because the centers of the right and left slabs were restrained from longitudinal movements (see figure 14). The PCC slabs were modeled using 2D plane stress elements. Dowels were modeled using spring elements. The stiffness of those springs was determined using the pullout force–joint opening relationships presented in previous sections.

The effect of dowel misalignment on the behavior of 15-ft long PCC slabs subjected to contraction caused by temperature drops of 200°F was investigated. In all cases, the modeled dowel diameter was 1.25 in and the coefficient of PCC–dowel interaction was 0.3. If a certain dowel was misaligned, the magnitude of misalignment was 1 in.

Three cases were considered:
Case 1. All dowels are perfectly aligned.
Case 2. All dowels are misaligned.
Case 3. All dowels in the left joint are perfectly aligned and all dowels in the right joint are misaligned.

The analysis for Case 1 showed that the stress distribution is quite uniform, with slight stress concentration near dowels. The magnitude of longitudinal stresses at the middle of the center slab was 48 psi. An average joint opening was found to be 0.176 in.

In Case 2, the magnitude of stresses both near and far from dowels increased compared to the stresses from Case 1. The magnitude of longitudinal stresses at the middle of the center slab was 178 psi. However, the average joint opening does not differ significantly and is 0.166 in.

On the other hand, in Case 3, the magnitude of stresses both near and far from dowels is higher than the corresponding stresses from Case 1 but lower than the corresponding stresses from Case 2. The magnitude of longitudinal stresses at the middle of the center slab was 53 psi. At the same time, the opening of a joint with misaligned dowels was 0.038 in, whereas the opening for the joint with aligned dowels was 0.312 in.

This analysis suggests that if several consecutive joints are locked up, a significant uniform drop in temperature may cause significant longitudinal stresses and lead to premature cracking if acting together with heavy axle loading and slab curling. On the other hand, if only one joint has misaligned dowels and all neighboring joints do not, then the adjacent joints may open widely and prevent the joint with misaligned dowels from forming properly. This may lead to an increase in effective joint spacing and, in turn, to random cracking near the joint.

CONCLUSIONS

A finite element analysis was conducted to evaluate the effect of vertical dowel misalignment on joint performance. Several finite element models were developed using a commercial finite element package—ABAQUS. A comprehensive PCC–dowel interaction model was developed and calibrated/validated using the results of a pullout test.

The analysis of misaligned dowels showed that uniform vertical misalignment did not cause significant resistance to joint horizontal movements. At the same time, non-uniform misalignment may cause joint lock-up and premature pavement failure. Future studies should include comprehensive laboratory and field testing, as well as finite element modeling of a fragment of a joint with at least three dowels.

ACKNOWLEDGMENTS

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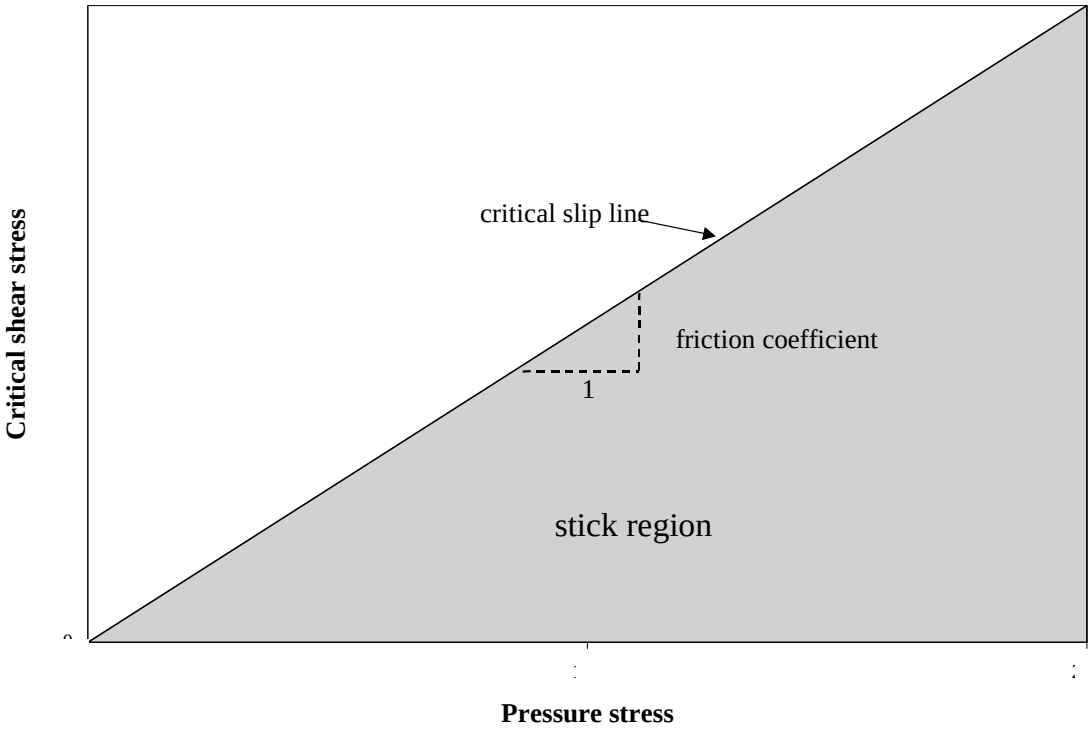


Figure 1. Coulomb friction model.

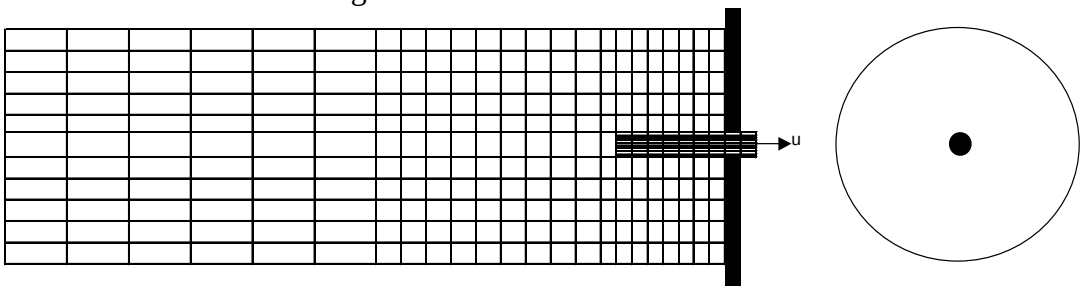


Figure 2. Axisymmetric model of pullout test.

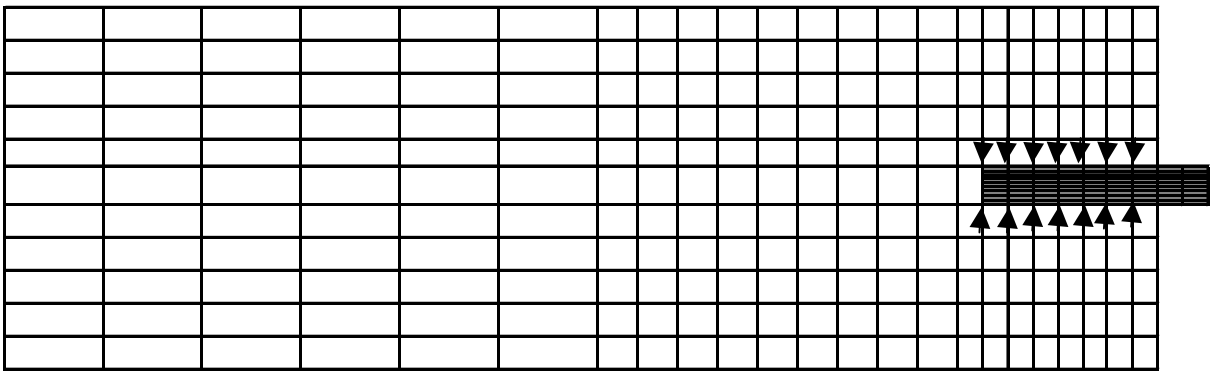


Figure 3. Direct assignment of the initial normal contact pressure.

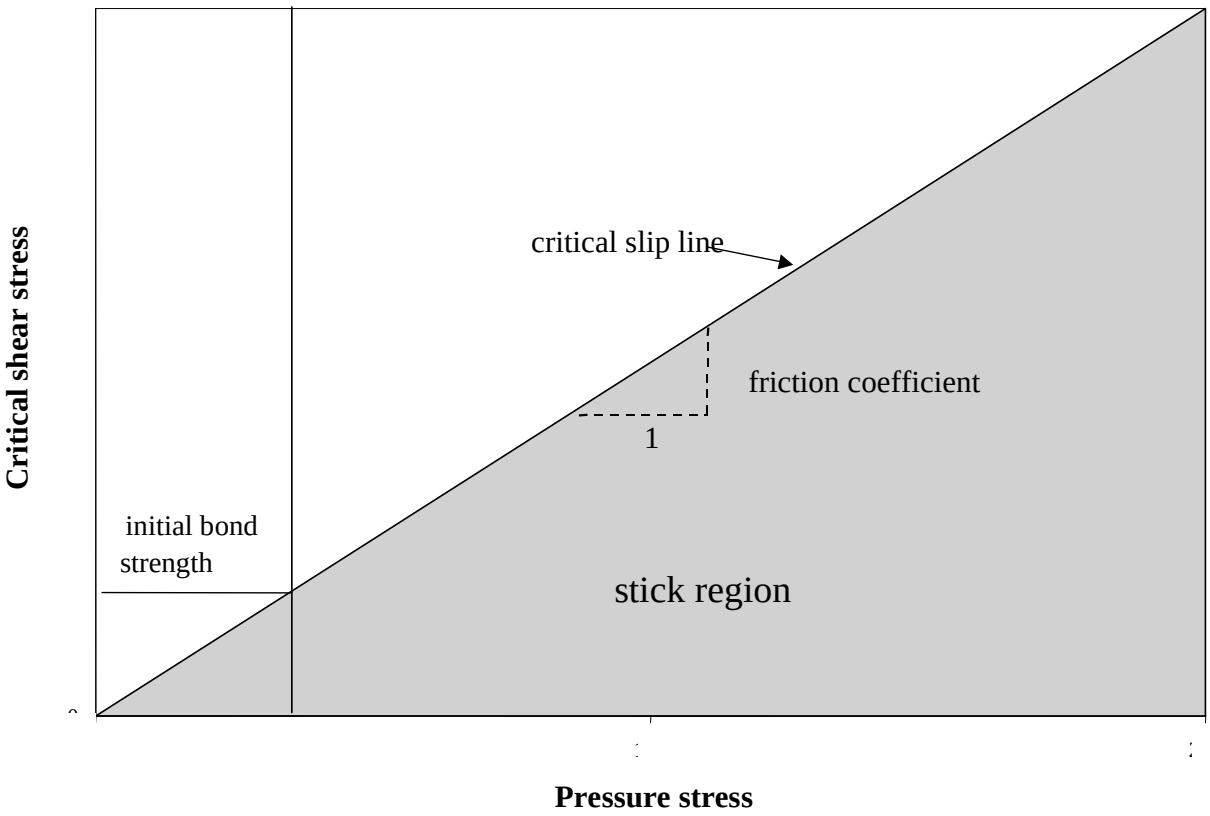


Figure 4. Accounting for initial bond strength.

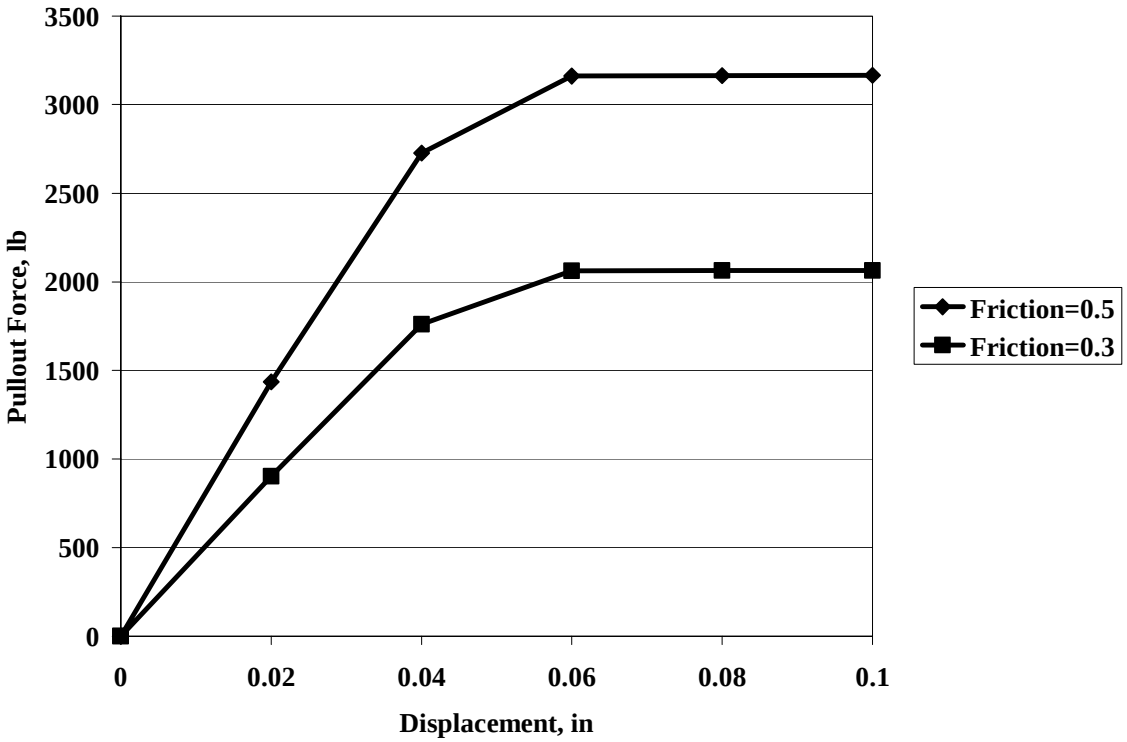


Figure 5. Effect of friction coefficient on pullout force magnitude.

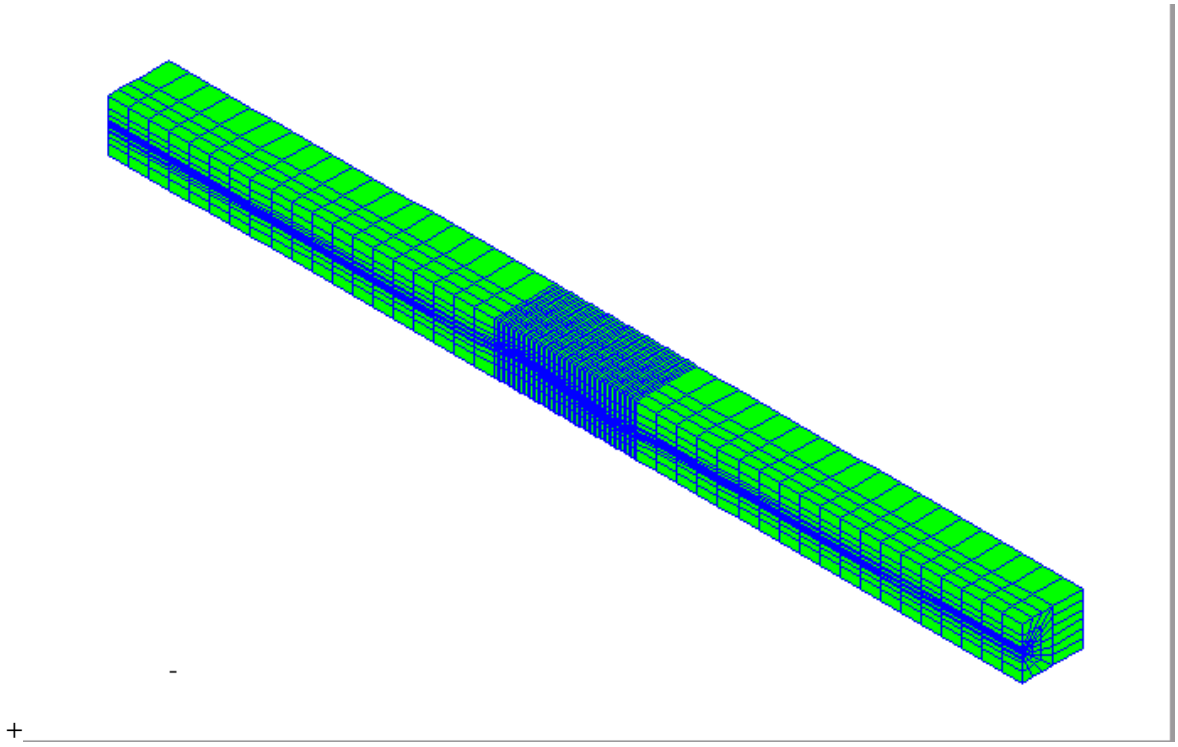


Figure 6. 3D model of vertically misaligned dowel.

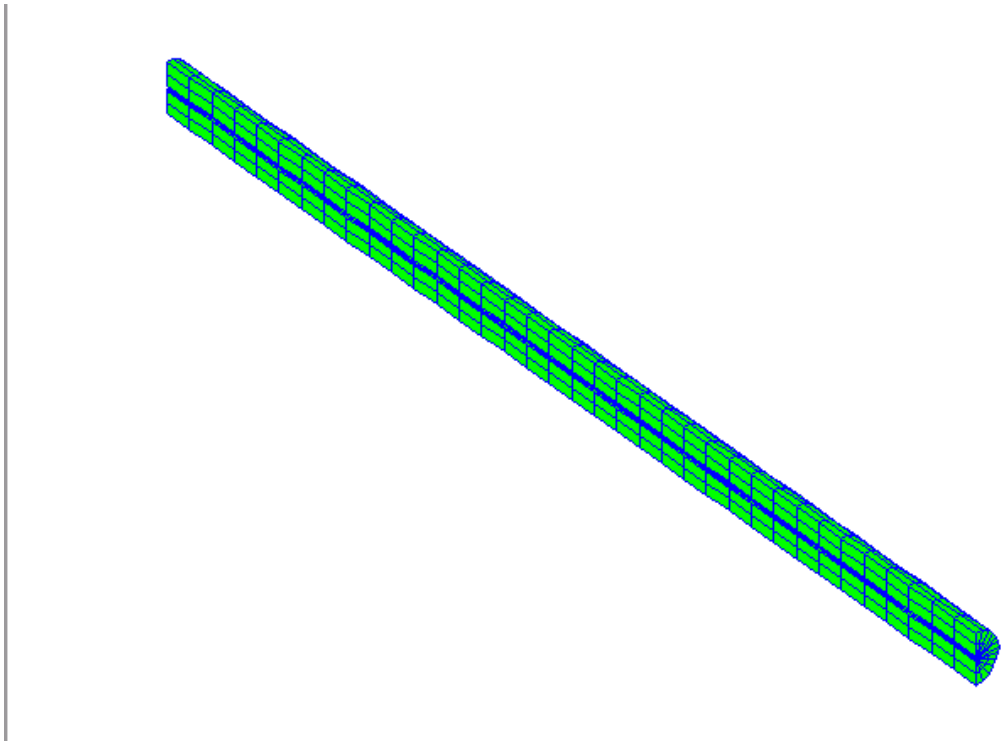


Figure 7. 3D model of a dowel.

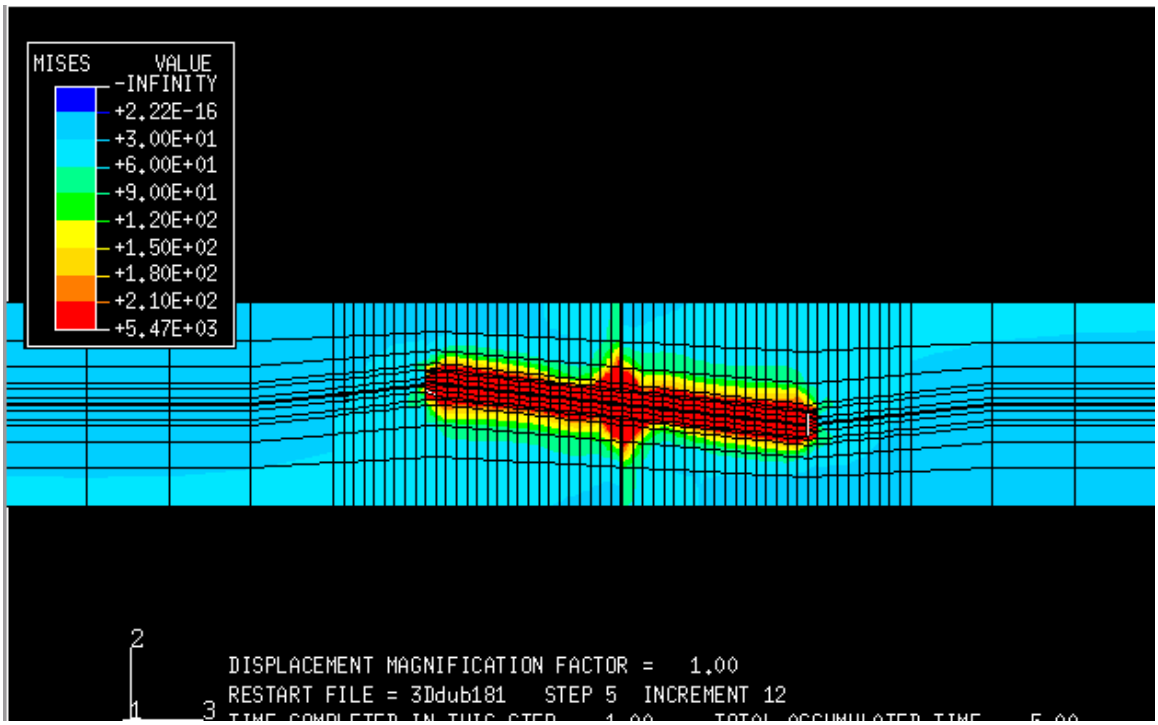


Figure 8. Distribution of Mises equivalent shear stresses for a uniformly misaligned dowel; misalignment is 1 in.

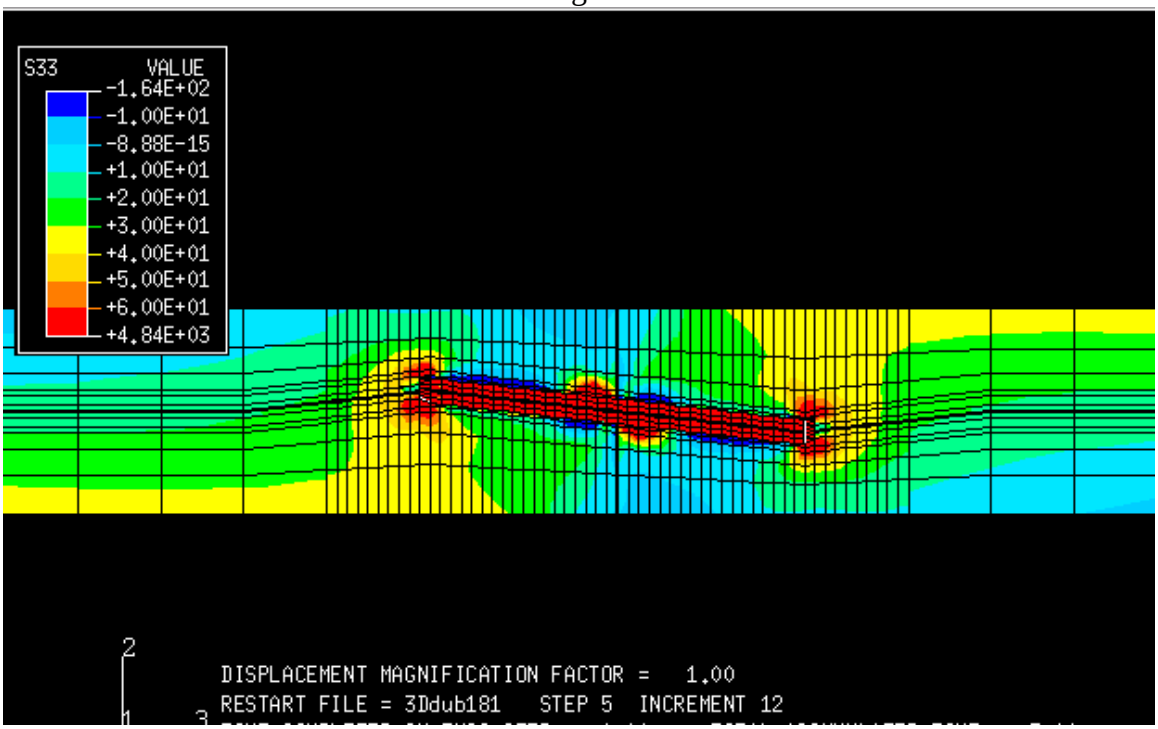
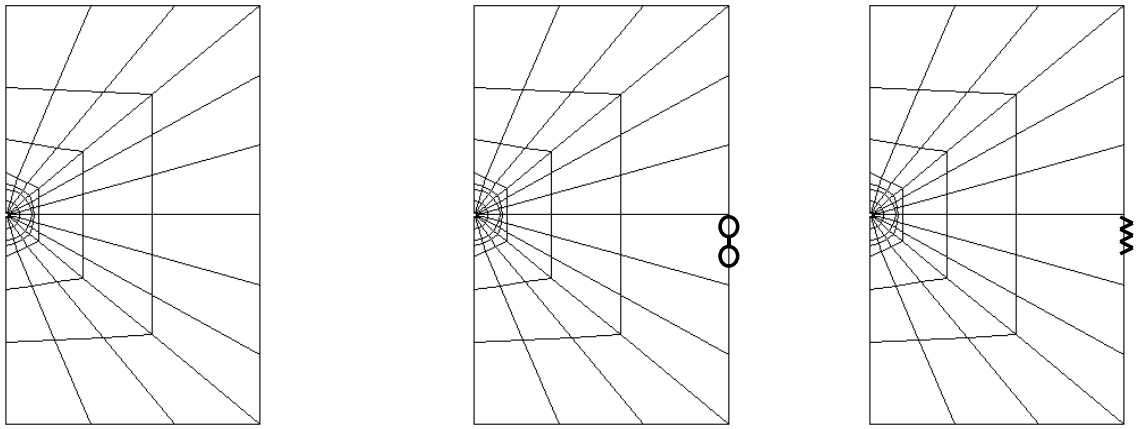


Figure 9. Distribution of longitudinal stresses for a misaligned dowel; misalignment is 1 in.



a. Uniformly misaligned dowel

b. Oppositely misaligned dowel

c. Single misaligned dowel

Figure 10. Finite element model modification.

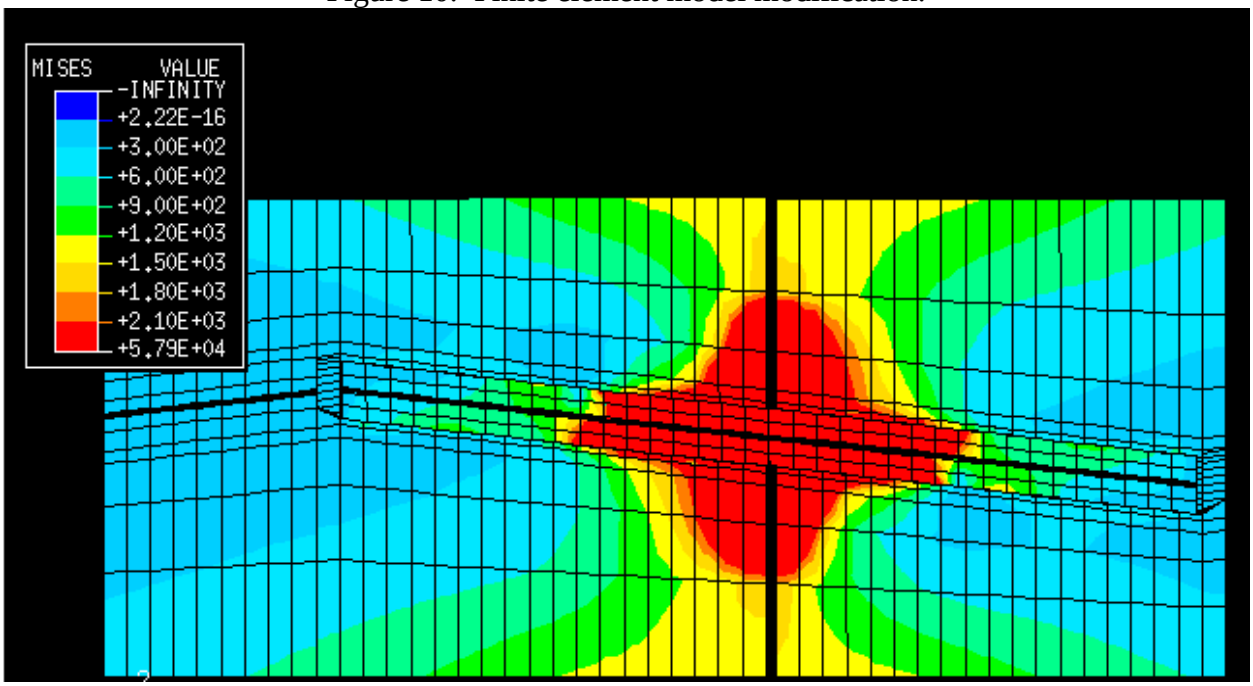


Figure 11. Distribution of Mises equivalent shear stresses for a uniformly misaligned dowel; misalignment is 1 in.

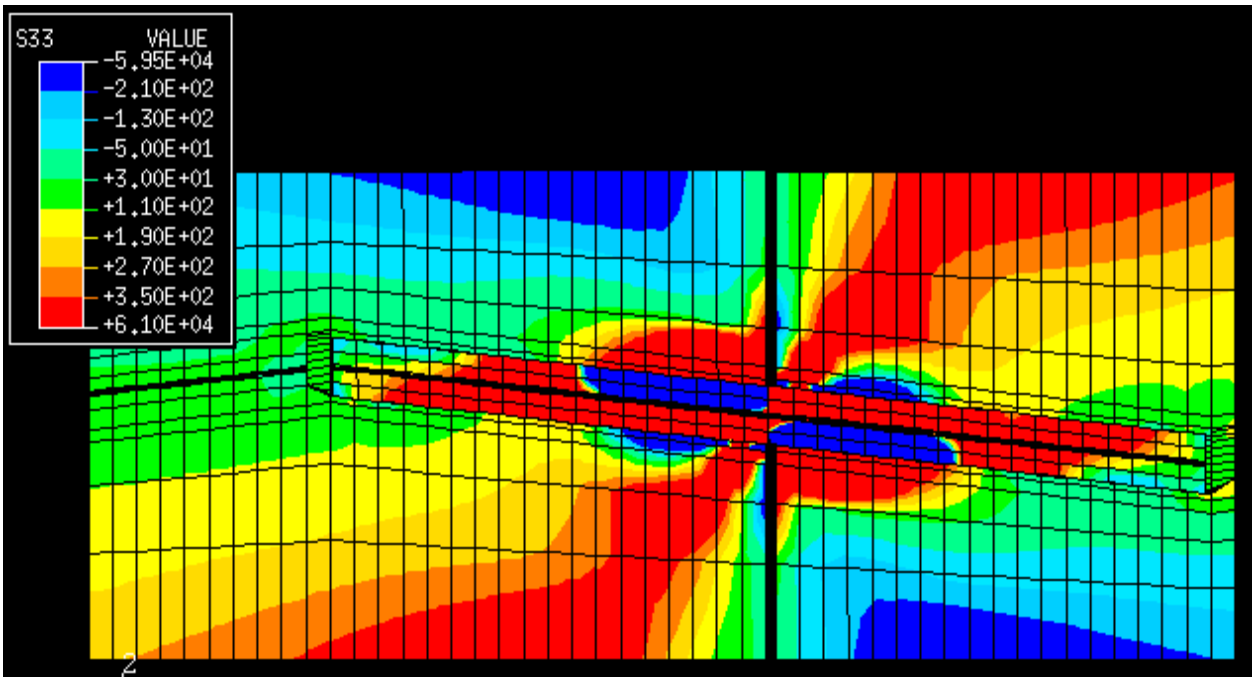


Figure 12. Distribution of longitudinal stresses for a uniformly misaligned dowel; misalignment is 1 in.

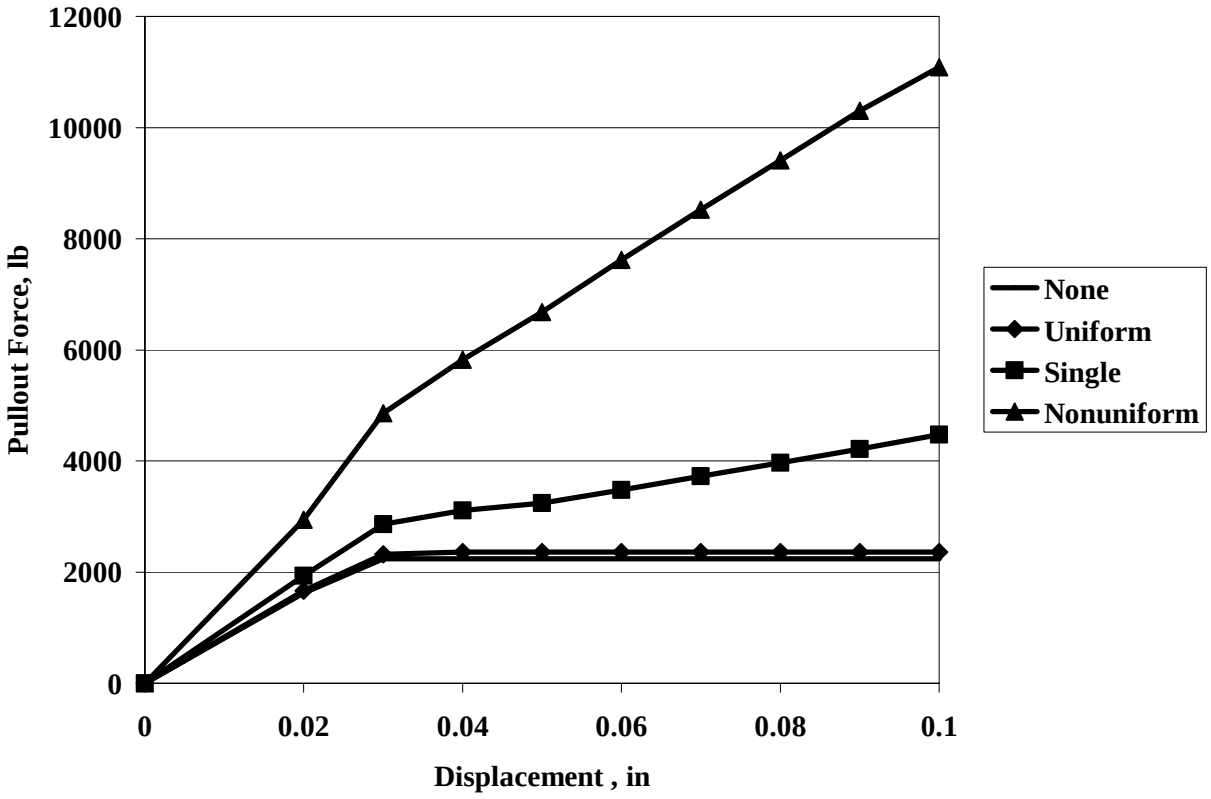


Figure 13. Effect of misalignment uniformity on pullout force magnitude.

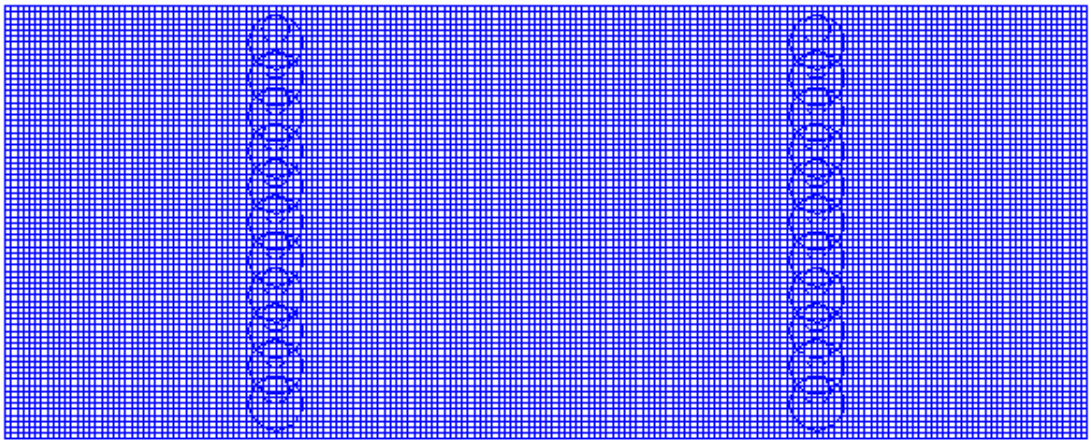


Figure 14. 2D model of a multi-slab system.