

Guidelines for Dowel Alignment in Concrete Pavements

APPENDIX C LABORATORY TESTING

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**Kyle Hoegh, Research Assistant
Lev Khazanovich, Ph.D., Associate Professor
University of Minnesota**

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Appendix C. Laboratory Testing

The results of the laboratory testing are used to develop models that can be used to estimate the stresses associated with any given type and combination of dowel misalignment observed in the field and provide information that can be used to determine acceptable levels of dowel misalignment. This appendix presents the activities and analysis of the laboratory testing, including detailed discussions of:

- Previous studies
- Laboratory objectives
- Testing equipment
- Testing procedure
- Experimental design
- Results analysis

C.1 Previous Studies

C.1.1 Standard Pullout Test

As shown in Figure C.1, the standard pullout test measures a pullout force vs. dowel displacement curve. The results of this test were used to calibrate a finite element model (Khazanovich et al., 2001). This is a well-controlled test capable of providing valuable information related to dowel-PCC friction. Nevertheless, the test procedure required improvement to better characterize the interaction between a misaligned dowel and surrounding concrete:

- The direction of dowel displacement should not necessarily be along the dowel length to enable modeling of the effect of rotations.
- The steel plate should be removed to eliminate bearing stresses.
- Rotation of the beam during testing should be avoided by using a proper anchoring system.

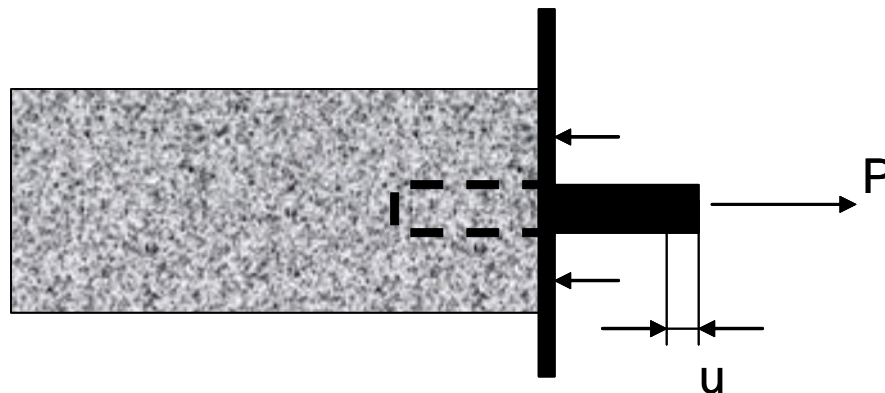


Figure C.1. Schematic of a dowel pull-out test.

Necessary modifications to the setup were made in the modified pullout test to address these limitations and create an expanded data set.

C.1.2 Shear Pull Testing

Laboratory efforts in the past have been limited to pullout tests that focus on dowel resistance to joint opening with pullout force measurements and evaluation of distresses in concrete. The shear pull test was added to the laboratory work for this study to address the effect of misalignment on shear performance in a controlled laboratory environment.

The following tests were conducted in the laboratory portion of this study:

- Modified dowel pullout test
- Vertical dowel shear pull test
- Repeated shear pull fatigue test

All three of these tests were either a modification of a previous test (modified pullout test), or a newly designed test (vertical shear pull test, repeated shear pull test). These tests were performed to update the current knowledge and data that relate dowel alignment to pavement performance and to determine the relationships between dowel alignment and stresses that can develop under various restraint conditions.

C.2 Objectives

The laboratory testing was needed to determine the effects of dowel misalignment on dowel behavior in pavement slabs. These tests result in performance parameters such as maximum required pullout force, dowel shear stiffness, and ultimate dowel shear capacity. The objectives for each type of test are presented below.

C.2.1 Modified Individual Dowel Pullout Test

The force required to pull the dowels out of the concrete for different misalignments and other factors provides insight into the conditions under which a joint may lock. Joint lockup refers to conditions that prevent concrete slab from free expansion and contraction. The pullout force also gives information about possible additional restraint to joint opening and closing due to dowel rotation that may cause micro-damage and minor spalling around dowels. Although invisible at the surface, these distresses may reduce the dowel load transfer efficiency.

Through the modified individual pullout testing, the relationship between the aligned or misaligned dowel displacements with respect to the concrete versus pullout force was obtained. The results were used to evaluate the effect of different misalignments on the maximum pullout forces. The model was also used to calibrate the finite element models that

were essential in developing guidelines that highway agencies can use to account for the effects of dowel misalignment on pavement performance.

C.2.2 Shear Pull Test

Although the modified pullout test provided valuable information about longitudinal restraint, it was not able to characterize the effect of the reduction of LTE due to dowel misalignment. To address this limitation, the dowels that were subjected to the pullout test were then tested for shear load resistance. This resulted in a relationship between the shear pull force and dowel displacement due to deformation of the concrete. From this relationship, the dowel shear stiffness and dowel ultimate shear capacity were obtained in each test to assist in assessing the ability of dowels at various misalignment levels in transferring a load.

The effects of the micro-damage caused by rotational misalignments, loss in concrete cover due to vertical translation, and reduced embedment lengths due to longitudinal translational misalignment could then be assessed with these shear performance measures. The results of this test also were used to validate the finite element model developed in this study.

C.2.3 Repeated Shear Fatigue Test

The effect of misalignment on repeated shear loading was analyzed. By testing the dowels in repeated load cycles, the effect of a one-time load to failure on strength and stiffness from the shear-pull test could be related to the effect of a repeated load fatigue test.

C.3 Test Equipment

To perform these tests, the following equipment and procedures were developed:

- A special beam mould, jigs, and installation procedures for dowel alignment
- A beam preparation procedure
- An actuator/dowel fixture
- A beam clamping mechanism
- Modifications to an existing test stand apparatus

Test Specimen Design: Figure C.2 shows the test specimen dimensions for the individual dowel testing. The selected beam thickness was based on the minimum typical PCC slab thickness of doweled pavements; the width was chosen as the most efficient width for casting and testing the dowels using the available testing apparatus; and the height was selected to ensure that the beam represents a “long” PCC slab (i.e., the specimen has sufficient length in the direction of dowel embedment that boundary conditions do not significantly influence test results). This selection was made on the basis of a finite element simulation of the modified pullout test. Based on observations from the simulation, it was concluded that

increasing the beam height beyond 18 in. would not provide any advantages, but would increase the specimen weight, making them more difficult to handle.

The 1.25-in. and 1.5-in. dowel diameters were chosen because they are common for concrete pavements in the United States. The distance between the dowels was selected to ensure that the specimen clamping mechanism could be placed on the beam at a sufficient distance from each dowel being tested. It also provided sufficient distance between the dowels so that damage of the beam after pulling out any one dowel should not affect the test behavior of neighboring dowels.

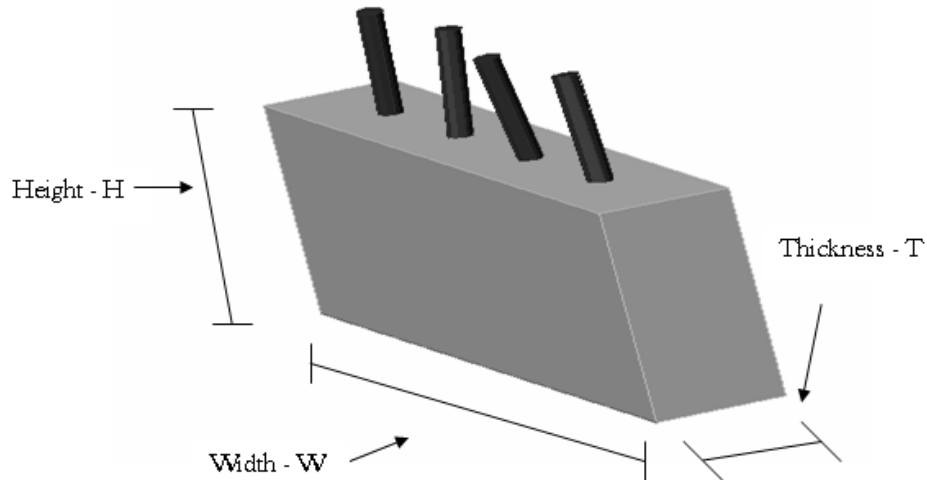


Figure C.2. Test specimen dimensions.

Metal Form: A reusable metal mould was designed for casting and transporting the beam test specimens. This mould, shown in Figure C.3, consists of four angles (3"x 3"x 5/16"), two metal plates (18"x 48"x 1/4"), two channel sections (18"x 8"), and two metal rods (20"x 5/8"). The angles will be welded to the metal plates, and then attached to the channel sections using eight hex cap bolts (2"x 5/8") in the corners.

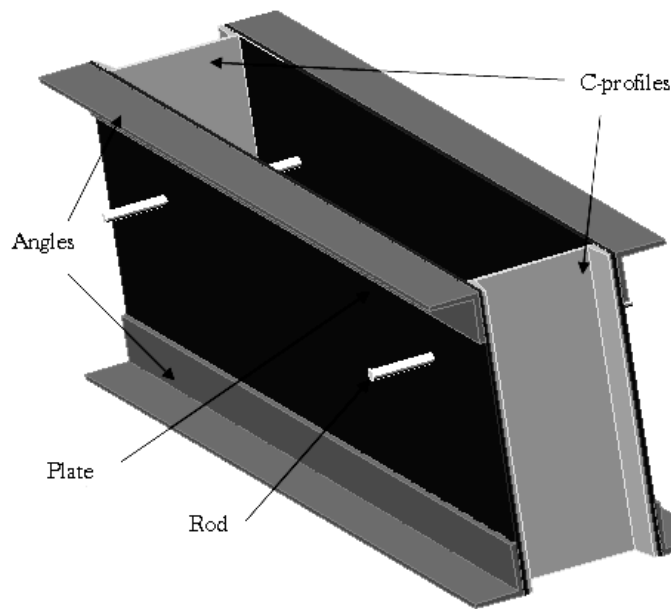


Figure C.3. Metal beam mould for the individual dowel testing.

Dowel Installation Jigs: Since the misalignment levels were relatively small, precision was required when installing the dowels at the correct misalignment. To address this concern, a dowel jig was developed for setting dowels at the correct misalignment (see Figure C.4). Each jig features two holes that are offset to provide the desired misalignment. The top end of each dowel is tapped with a thread to allow a dowel extension to be screwed into place. The extended dowel is inserted through the jig holes and set at the proper embedment length. After the concrete has been placed and has cured sufficiently, the dowel extension and jig are removed, leaving an embedded dowel ready for pullout testing.

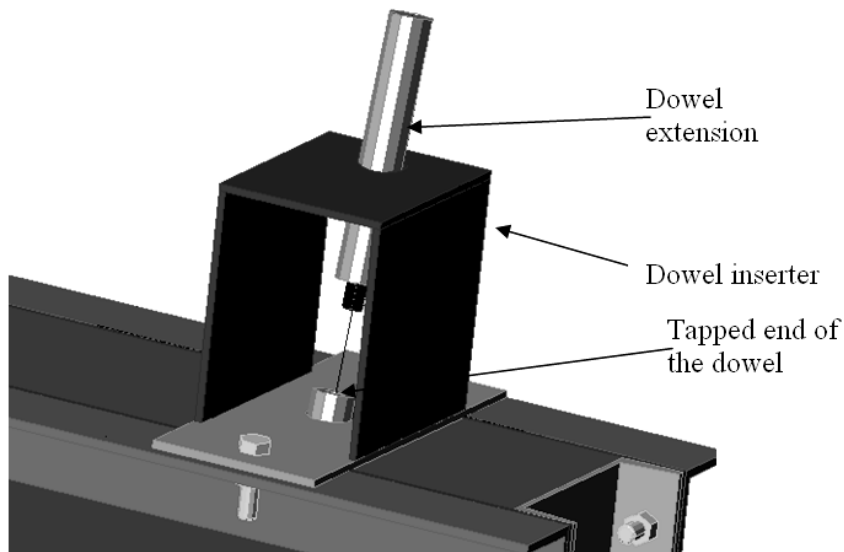


Figure C.4. Use of a dowel extension and alignment jig to ensure the specified misalignment level.

Actuator/Dowel Fixture: To minimize the effect of machine stiffness on the pullout results, a way to ensure that the connection between the actuator and dowel could not slip was designed. Traditional actuator grips cannot guarantee that there will be no slippage. For this study, a load-rated, swivel-action eyebolt, such as the one shown in Figure C.5 was screwed into the thread-tapped end of the dowel to allow the actuator to pull the dowel with no slipping. The eyebolt could then be connected to the actuator with a modified lifting grip so that the pull can be performed without any slipping that would otherwise affect the measurements.

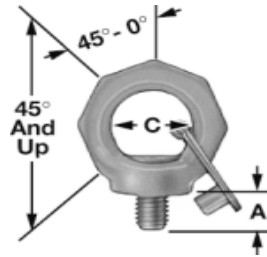


Figure C.5. Swivel-action eyebolt. (www.mcmaster.com)

Beam Clamping Mechanism: As described by Tayabji (1986), it is important to ensure that the beam does not rotate to accommodate the misalignment while the dowel is being pulled. Figure C.6 shows the actuator and clamping mechanism used in this study with more detail. An LVDT was clamped to each dowel and used to measure the displacement of the dowel with respect to the concrete. This displacement was used in analysis.



Figure C.6. Actuator and clamping mechanism.

Test Stand Apparatus: Several test frames in the University structural laboratory were considered, but the MinneALF structure was selected as the most appropriate test stand. Only slight modifications of the MinneALF apparatus were required to accommodate the modified pull-out test. These modifications included adjustment of the actuator positions and installation of the beam clamping mechanism.

C.4 Testing Procedure

The following procedure was used to prepare the doweled concrete specimens for testing:

1. Control of the level of misalignment for each dowel was established by preparing dowel alignment jigs with offset dowel insertion holes, as described and shown previously.
2. The test dowels (with dowel extensions attached) were positioned in the alignment jigs.
3. A release agent was used to coat the insides of the specimen mould and dowels to minimize the bond between the concrete and metal.
4. The concrete was placed and consolidated in the mould in 6-in. lifts; each lift was vibrated, and the surface was hand-floated level with the top of the form.
5. After 24-30 hours, the dowel extensions, alignment jigs, and formwork were removed, and the concrete specimen was placed in a bath and water cured for 6 days.

After 7 days of curing, the specimens were ready for individual dowel testing. The following procedure was used to test the dowels in pullout testing:

1. Eyebolt swivels were screwed into the tested dowel.
2. The concrete beam specimen was transported to the test stand by attaching a crane to the four metal rod handles.
3. To eliminate any confining effect around the dowel during the test, the beam clamps were no more than 3 in. wide and placed at least 6 in. away from the dowel being tested. This test setup minimized potential for any vertical or horizontal movement of the concrete beam.
4. After each dowel had been subjected to the pullout test, the beam clamps were loosened to allow the concrete beam to be repositioned for testing of the next dowel in the beam.
5. A visual inspection of the tested dowel and surrounding concrete was completed and the beam was re-clamped in preparation to test the next dowel.
6. After the last dowel was tested and examined, the steel handles on the side were removed so that the beam could be laid on its side for shear pull testing.

The shear pull test procedure involved the following operations:

1. The specimens used for the modified pullout test were rotated 90 degrees so that the dowels were parallel to the test stand surface.

2. An extension eyebolt was added to the actuator in order to grip the dowels at this lower level.
3. The specimen assembly was properly located and clamped to the test stand.
4. The vertical shear test was performed until failure.
5. After each test, the clamps were loosened and the beam slid to the next position for testing the next dowel. A visual inspection of the tested dowel and surrounding concrete was completed to document all observed distresses (e.g., spalling, dowel looseness and cracking).
6. After the last dowel was subjected to the vertical shear test, the beam was removed so that the next beam could be placed on the stand for testing.

The laboratory setup was the same for the repeated load testing as for the previous shear test. The only change was that the dowels were not tested in displacement controlled mode until failure, but rather, in repeated 3 kip loads for more than 10,000 load cycles.

C.5 Experimental Design

Misalignments in the form of vertical and longitudinal translations as well as vertical and horizontal rotations (vertical tilt and horizontal skew) were evaluated in the laboratory testing. It should be noted that rotational misalignments are expressed per 9-in. embedment length of the dowel since all tests were conducted simulating one side of the pavement joint with a maximum embedment length of 9 in.

The following misalignment combinations were tested:

- Properly embedded and aligned dowels (i.e., dowels located at mid-depth, oriented perpendicular to the joint face, and embedded 9 in. into the concrete; see Figure C.7)

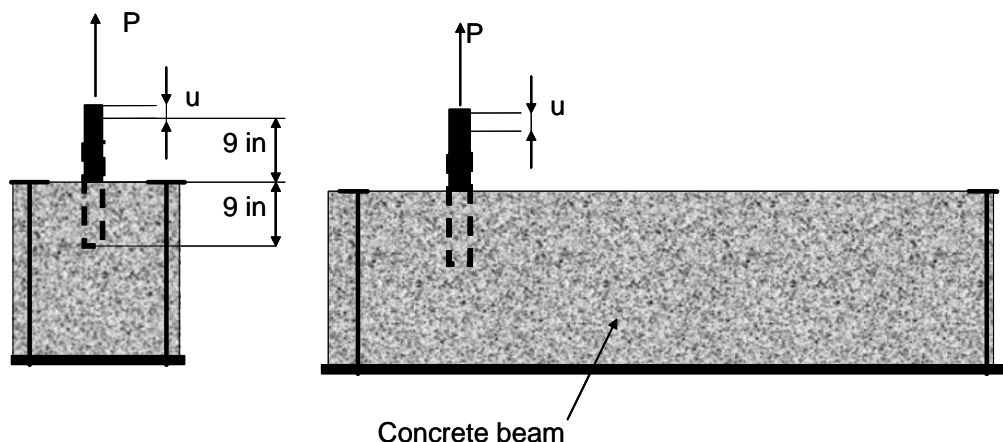


Figure C.7. Modified pullout test of a properly aligned dowel.

- Vertically tilted dowels (i.e., dowels rotated towards the surface of the pavement, expressed in inches of rotation 0.5 in., 1 in., and 2 in. along a 9-in. dowel; see Figure C.8)

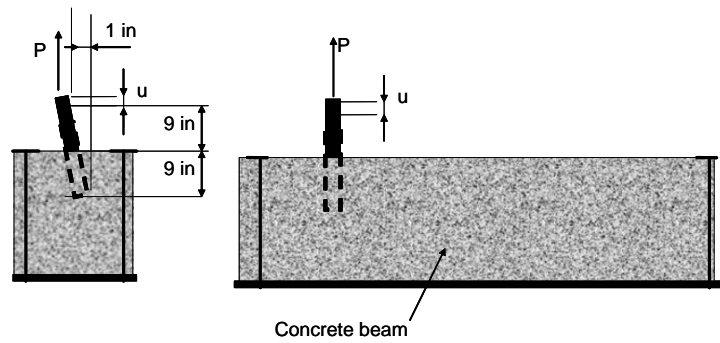


Figure C.8. Modified pullout test of a vertically misaligned dowel.

- Horizontally skewed dowels (i.e., dowels rotated in the transverse direction, expressed in inches of rotation 0.5 in., 1 in., and 2 in. along a 9-in. dowel; see Figure C.9)

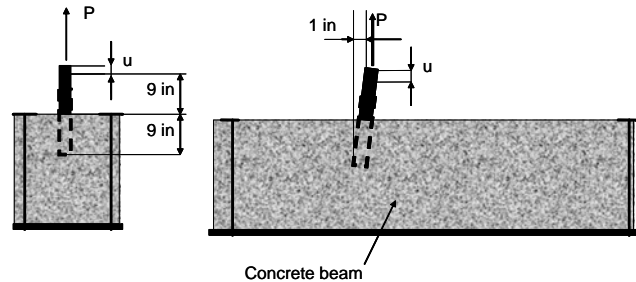


Figure C.9. Modified pullout test of a horizontally misaligned dowel.

- Longitudinal translation resulting lower dowel embedment length (i.e., dowels translated in the longitudinal direction by 2 in., 3 in., 4 in., and 6 in. so that one end of the dowel has less than half of the dowel embedded; see Figure C.10)

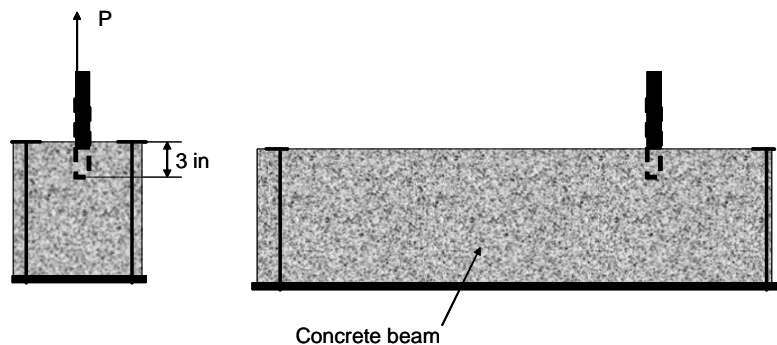


Figure C.10. Modified pullout test of a longitudinally misplaced dowel.

- Vertical translation resulting in lower concrete cover (i.e., dowels translated vertically so that there is less concrete between the dowel and surface or base; see Figure C.11)

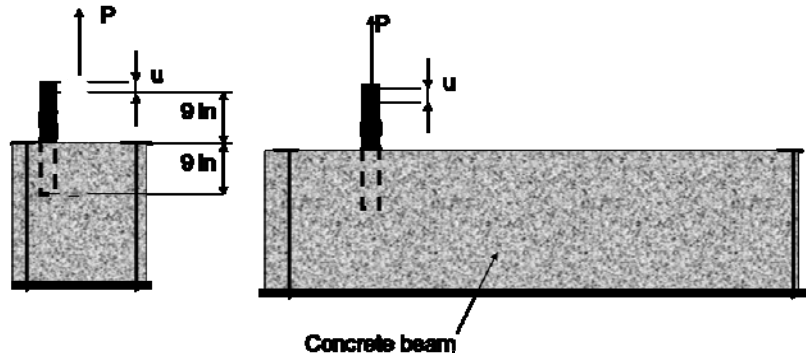


Figure C.11. Modified pullout test of a vertically translated dowel.

The tests described above were implemented in a series of specimens containing four dowels with various types and levels of misalignment for pullout testing. After the pullout testing, two dowels in each beam were tested in shear or repeated shear. Table C.1 presents the prescribed dowel alignments for each dowel tested in this study. Each beam contained one ungreated dowel to verify consistency of testing from beam to beam. Each dowel has a unique ID specifying beam number, and dowel position in the beam. For example, dowel B3D2 is the second dowel tested (D2) in beam 3 (B3). Table C.1 below uses the abbreviations A for aligned, HS for horizontally skewed, and VT for vertically tilted.

Table C.1. Laboratory testing factorial.

Dowel ID	Alignment Type	Rotational Misalignment (in/9 in embedment)	Embedment Length (in)	Vertical Translation (in)	Grease Type	Dowel Diameter	Loading P-pull S-shear R-rep
B1D1	A	0	9	0	MnDOT	1.5	P/S
B1D2	A	0	6	0	None		P
B1D3	HS	1	9	0	MnDOT		P
B1D4	HS	1	9	0	MnDOT		P/S
B2D1	VT	1	9	0	MnDOT	1.5	P/S
B2D2	VT	1	9	0	MnDOT		P
B2D3	A	0	6	0	None		P
B2D4	A	0	6	0	MnDOT		P/S
B3D1	A	0	4	2	MnDOT	1.5	P/S
B3D2	A	0	4	0	MnDOT		P
B3D3	A	0	6	0	None		P
B3D4	A	0	3	2	MnDOT		P/S
B4D1	A	0	9	2	MnDOT	1.5	P/S
B4D2	VT	1	3	0	MnDOT		P
B4D3	A	0	6	0	None		P

Dowel ID	Alignment Type	Rotational Misalignment (in/9 in embedment)	Embedment Length (in)	Vertical Translation (in)	Grease Type	Dowel Diameter	Loading P-pull S-shear R-rep
B4D4	A	0	3	0	MnDOT		P/S
B5D1	VT	1	3	0	MnDOT	1.5	P/S
B5D2	A	0	6	0	None		P
B5D3	VT	1	9	2	MnDOT		P
B5D4	VT	2	9	0	MnDOT		P/S
B6D1	A	0	9	0	MnDOT	1.5	P/S
B6D2	HS	1	6	0	MnDOT		P
B6D3	A	0	6	0	None		P/S
B6D4	VT	1	6	0	MnDOT		P
B7D1	HS	2	9	0	MnDOT	1.5	P/S
B7D2	A	0	6	0	None		P
B7D3	VT	2	9	0	MnDOT		P
B7D4	VT	1	6	0	MnDOT		P/S
B8D1	VT	1	9	0	MnDOT	1.5	P/S
B8D2	HS	2	9	0	MnDOT		P
B8D3	A	0	6	0	None		P
B8D4	A	0	6	0	MnDOT		P/S
B9D1	A	0	9	2	MnDOT	1.5	P/S
B9D2	HS	1	6	0	MnDOT		P
B9D3	A	0	6	0	None		P
B9D4	A	0	3	0	MnDOT		P/S
B10D1	VT	1	6	0	MnDOT	1.5	P/S
B10D2	VT	2	6	0	MnDOT		P
B10D3	A	0	6	0	None		P
B10D4	A	0	3	2	MnDOT		P/S
B11D1	VT	0.5	9	0	MnDOT	1.5	P/S
B11D2	A	0	6	0	None		P
B11D3	VT	0.5	3	0	MnDOT		P
B11D4	A	0	2	0	MnDOT		P/S
B12D1	A	0	9	0	MnDOT	1.5	P/R
B12D2	A	0	6	0	None		P
B12D3	A	0	3	0	MnDOT		P

Dowel ID	Alignment Type	Rotational Misalignment (in/9 in embedment)	Embedment Length (in)	Vertical Translation (in)	Grease Type	Dowel Diameter	Loading P-pull S-shear R-rep
B12D4	VT	1	9	0	MnDOT		P/R
B13D1	A	0	9	2	MnDOT	1.5	P/R
B13D2	VT	2	9	0	MnDOT		P
B13D3	A	0	6	0	None		P
B13D4	A	0	3	2	MnDOT		P/R
B14D1	A	0	9	0	MnDOT	1.25	P/S
B14D2	HS	1	9	0	MnDOT		P
B14D3	A	0	6	0	None		P
B14D4	VT	1	9	0	MnDOT		P/S
B15D1	A	0	3	0	MnDOT	1.25	P/S
B15D2	VT	1	6	0	MnDOT		P
B15D3	HS	1	6	0	MnDOT		P
B15D4	A	0	9	2	MnDOT		P/S
SBD1	A	0	3	0	MnDOT	1.5	P/S
SBD2	A	0	6	0	MnDOT		P
SBD3	A	0	6	0	None		P
SBD4	A	0	9	2	MnDOT		P/S

Shear testing of the first two beams highlighted difficulties in testing all four dowels within one beam due to appearance of horizontal cracks (see Figure C.12). To obtain the ultimate shear of the dowel, only the outside dowels could be tested due to interference with the adjacent dowels from the crack formulation. A decision was made that in each beam only the outside dowels were tested in shear as shown in Figure C.13.



Figure C.12. Damage of the concrete around dowels. This macro-crack can affect the shear capacity of the adjacent dowel.

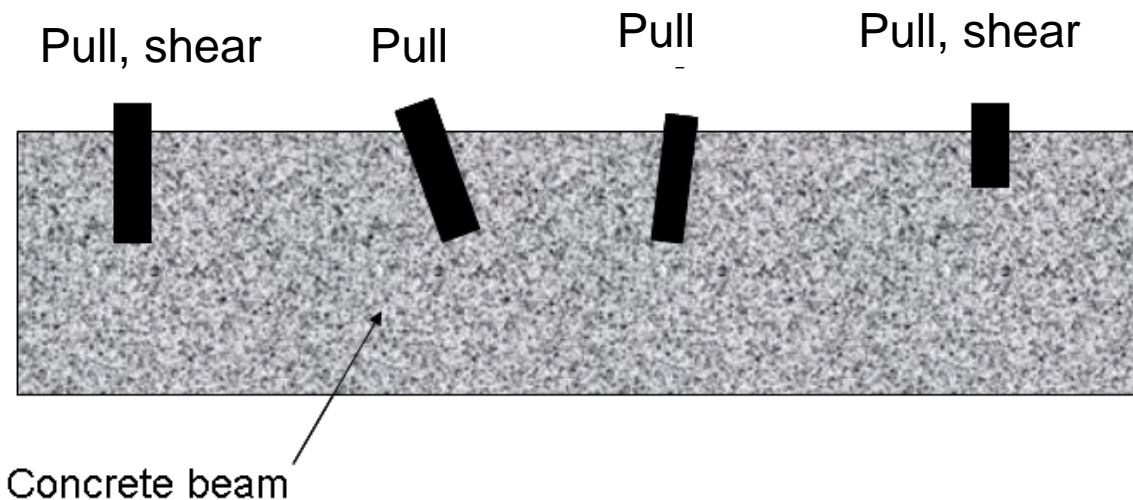


Figure C.13. Testing procedures for individual dowels in a beam.

In the first series of tests, eight beams were tested. However, since the initial shear pull testing resulted in interesting preliminary findings with respect to the effect of misalignment on shear stiffness and ultimate strength, an additional series of eight beams was tested. The additional individual dowel testing was designed to achieve the following:

1. Validate the test results from the first eight beams and conduct repeatability testing
2. Test additional combinations of misalignment levels
3. Test reduced diameter dowels (1.25 in.)
4. Learn more about stiffness using repeated loading for the shear pull testing

The following information details the purpose of the additional individual dowel testing:

1. Validation of the previous test results and repeatability testing.

Important observations were made based on the results of the initial test beams. However, there was a concern that natural variability in the testing affected the results. Possible sources of variability in the laboratory testing include the concrete mix, measurement error, and the installation process. Great care was taken to create concrete beams that exhibited similar properties from test to test. This included a consistent concrete mix proportion, vibration/consolidation, dowel greasing, and concrete beam curing procedure, to minimize the effect of variability of concrete properties from beam to beam. Care also was taken to ensure that the LVDTs and load cells were calibrated within a suitable precision. As noted earlier, beam rotation had caused problems in past dowel testing. Special clamping mechanisms were put in place to minimize the rotation of the beam, as well as to decrease the slippage or machine compliance of the system. Several tests were implemented to observe the affect of variability in the laboratory testing. These included repeated tests for the misalignment levels already tested to learn more about the confidence level that can be placed in the test results. The additional tests were performed for the following purposes:

- Validation of significant findings
- Evaluation of the ultimate shear repeatability and collection of more precise measurements of shear stiffness

2. Testing of additional combinations of misalignment levels.

A larger data set was designed to allow for a better understanding of the effect of dowel misalignment on dowel performance. The following misalignment levels were designed to add a dimension to the data set that previously had not been tested:

- While the effect of extreme rotation (2 in.) and reduced embedment length was tested, the combination of both was not examined in the previous data set. This case was examined in the extended misalignment cases.
- Significant vertical tilt (1 in.) caused only a slight decrease in ultimate shear strength. The additional testing evaluated if moderate vertical tilt (0.5 in.) had a similar effect.
- Reduction in embedment length to 3 in. caused a decrease in ultimate shear and stiffness. The additional testing was designed to find the threshold in which the reduced embedment length creates extreme reduction in ultimate shear and stiffness.

3. Testing misalignment levels with 1.25- in. dowel diameters.

One of the limitations of the original test program was that only 1.5-in. dowel diameters were tested. Additional dowel testing addressed that limitation and provided valuable information for calibration of the analytical models, and formulating the equivalent dowel diameter concept.

4. Use repeated loading for the shear pull testing.

While the original test results gave useful data on initial shear stiffness and ultimate strength, repeated loading was designed to provide information to learn more about how dowel misalignment affects the pavement performance in fatigue.

C.6 Data Analysis

The following section presents a detailed analysis of the laboratory testing results.

C.6.1 Modified Pullout Testing

Each dowel was tested individually by pulling it vertically with respect to the concrete beam. The dowels were pulled in a displacement-controlled mode at a rate of 0.003 in./sec until the dowel translated 0.25 inches in the vertical direction with respect to the concrete beam. A list of the tested dowels, along with their prescribed alignments, was presented in Table C.1.

During the testing, the pullout force and displacement were recorded continuously. Figure C.14 shows an example of the two types of curves experienced. Throughout the pullout testing, a majority of the dowels showed a more traditional curve as shown by the solid black line, while others showed a more unstable curve like the . The unstable curves were characterized as “static-slip” because they seem to slip once the dowel experiences enough force to exceed the static friction.

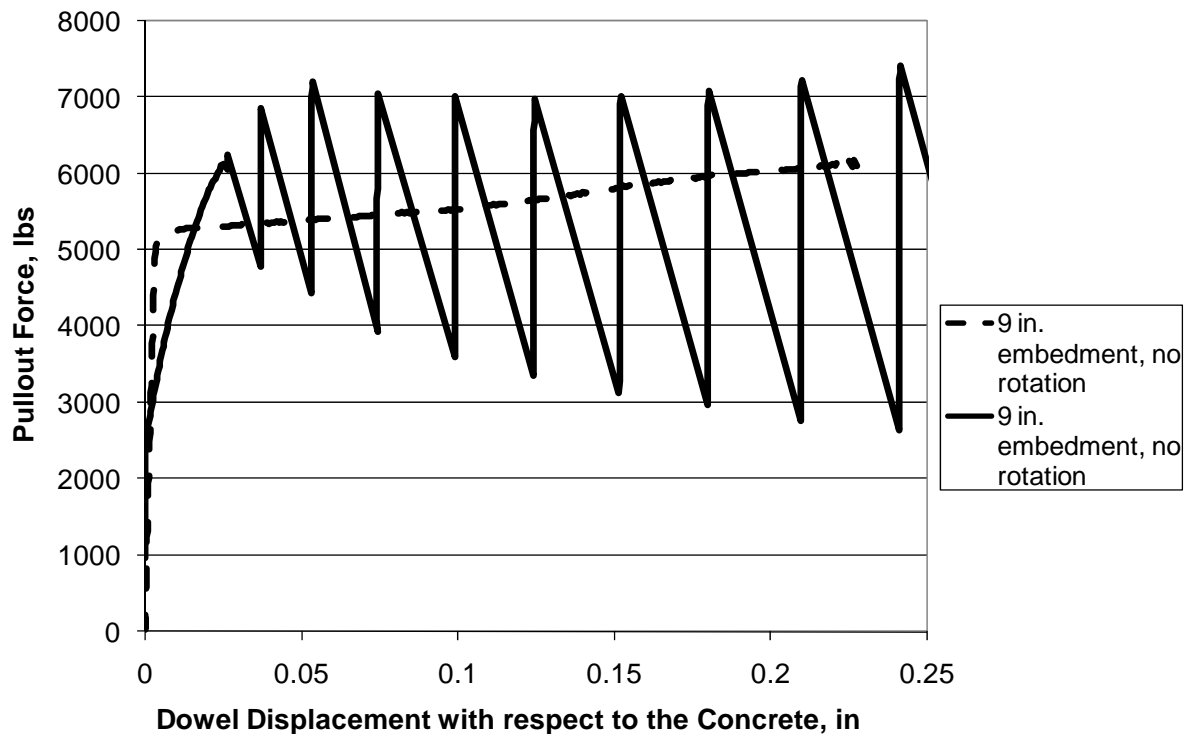


Figure C.14. The two types of curves from the pullout testing.

One of the concerns associated with the experiments conducted in this study is the possible effect of variations in concrete properties from different beams. The compressive strengths of the first three beams, as well as the ninth and tenth beams, were tested to ensure that the concrete properties were similar. Table C.2 shows the measured 7 day compressive strengths of concrete cylinders from the batches of those beams. It can be observed that the compressive strength was consistently close to the targeted value of 5000 psi.

Table C.2. Compressive strength measured for selected beams.

Beam	Specimen	Force (lb)	Compressive Strength [fc'](psi)		
1	1	130,690	4624.558		
	2	137,030	4848.903	Avg. [fc']	st dev
	3	129,210	4572.187	4681.883	146.9951
2	1	131,450	4651.451		
	2	135,720	4802.548	Avg. [fc']	st dev
	3	156,830	5549.54	5001.18	480.8659
3	1	158770	5618.188		
	2	151110	5347.134	Avg. [fc']	st dev
	3	144950	5129.158	5364.827	244.9948
9	1	140860	4984.43		
	2	144950	5129.158	Avg. [fc']	st dev
	3	147980	5236.377	5116.655	126.4376
15	1	144180	5101.911		
	2	136230	4820.594	Avg. [fc']	st dev
	3	128060	4531.493	4818	285.2176

As stated above, all water-cured beams contained one non-greased perfectly aligned dowel with an embedment length of 6 in. Comparison of the pullout force obtained for these dowels permits evaluation of the repeatability of the test.

Table C.3 summarizes the maximum pullout forces for the non-greased dowels in beams 2 through 6, along with the basic statistics (mean, standard deviation, and coefficient of variation). Considering the complex nature of dowel-concrete interaction behavior, the coefficient of variation of 7% indicates that repeatability of the test is reasonably good and the effect of variation in concrete properties is not significant.

Table C.3. Maximum pullout force for the 6 inch ungreased dowel in each beam.

Dowel	Maximum pullout force (lb)
B2D3	11,469
B3D3	10,757
B4D3	13,083
B5D2	11,619
B6D3	11,544
mean	11,694
std	849
Coefficient of Variation	0.07

The characteristics of the pullout force vs. dowel traditional displacement curves can be classified into two categories:

- Stiffness of the static friction leading to the initial slip
- Stiffness of the kinetic friction after the initial slip

As shown in Figure C.15, the dowel from the supplemental beam was almost completely stiff before the initial slip, while the dowel from beam 8 lost some stiffness leading up to the complete initial slip. After the initial slip, the pullout force required to pull the dowel out from the supplemental beam remained fairly constant, while the dowel from beam 8 required less pullout force as the dowel displaced.

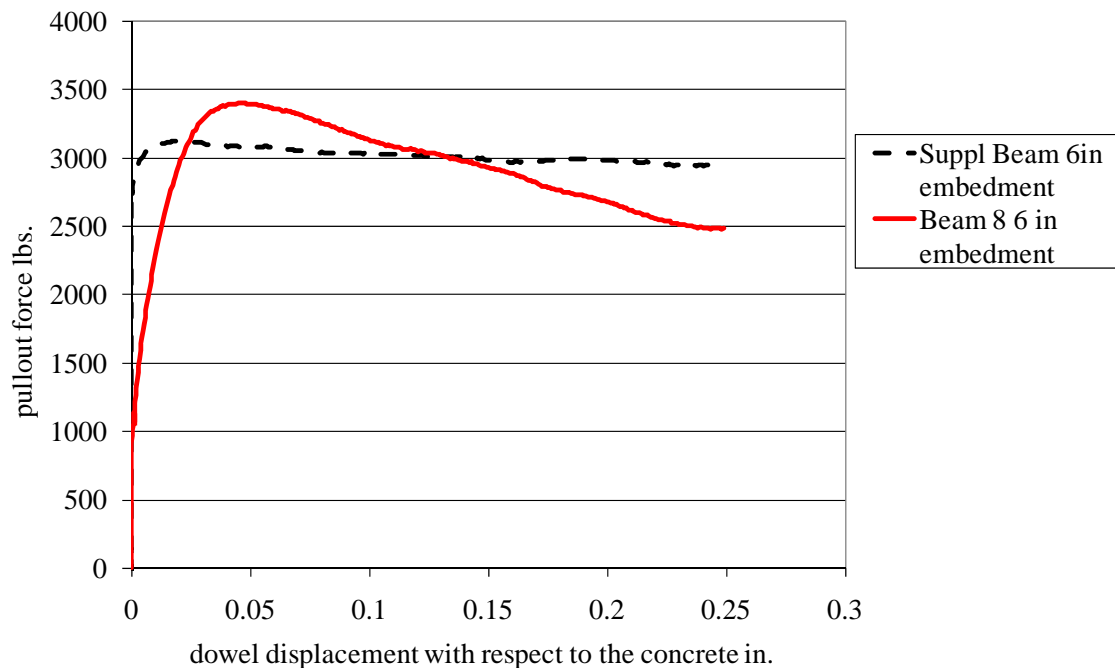


Figure C.15. The curve characteristics for two dowels with the same alignment and similar maximum pullout force.

The analysis also showed that the shape of the curve can be different depending on the magnitude of the misalignment. Figure C.16 shows an example of dowels with reduced embedment lengths of 3 and 6 in. While both misalignment levels showed similar stiffness after the initial slip, the stiffness before the initial slip is lower for the 3-in. embedded dowel.

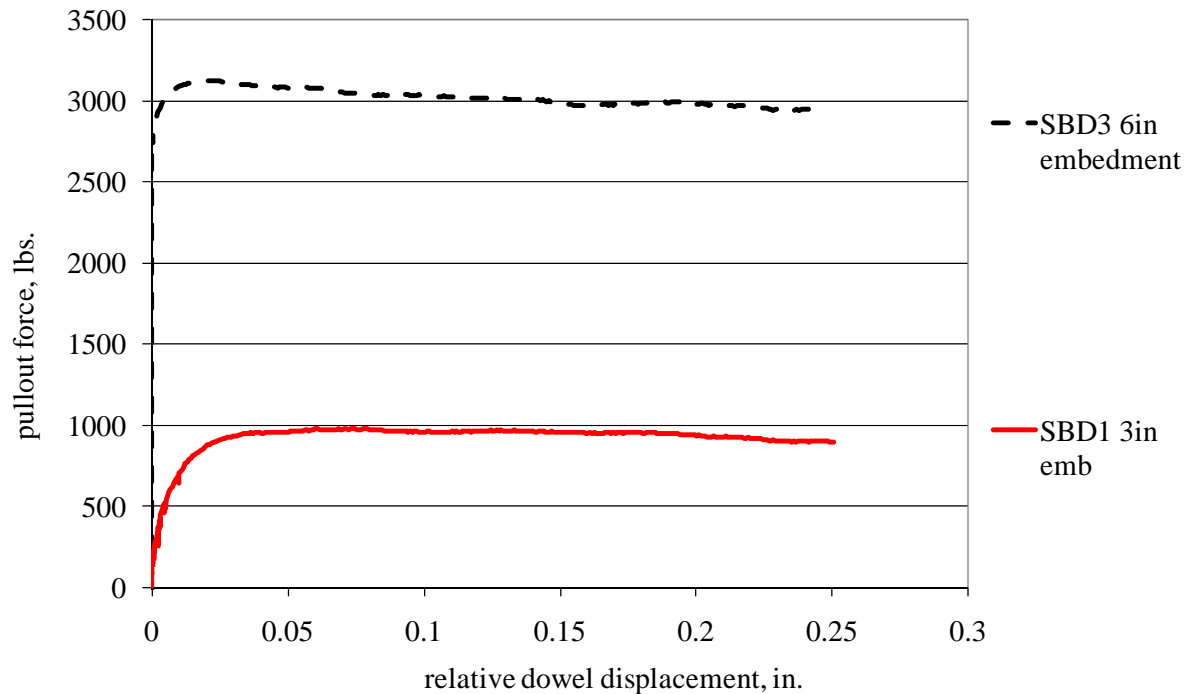


Figure C.16. The curve characteristics for two dowels in the same beam with different magnitudes of reduced embedment length.

C.6.1.1 Modified Pullout Data Overview

It was observed that the effect of greasing or not greasing the dowels was greater than the effect of rotation or vertical translation on pullout testing. Figure C.17 shows the pullout force versus displacement for a greased and ungreased 6-in. embedded dowel in the same beam. It can be observed that the ungreased dowel has a significantly higher pullout force required.

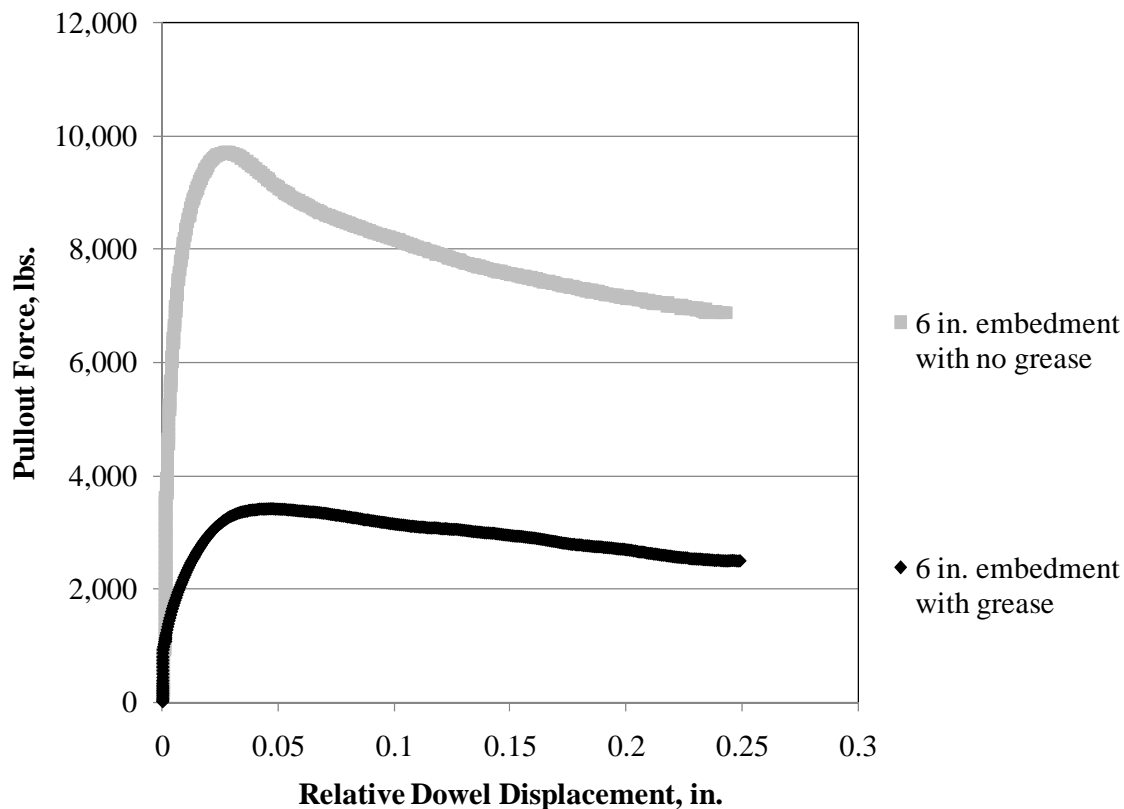


Figure C.17. The effect of greasing dowels on pullout force.

After each pullout test, the interface between the dowel and concrete was inspected on the surface. Slight surface paste chipping occurred for 1-in. tilted dowels, while spalling damage was observed for 2-in. rotation of the dowels after pullout testing.

Figure C.18 shows a distribution of the maximum force required to pull out each type and level of misalignment. The group to the furthest left shows the 6-in. embedded ungreased dowels. The next three groups (from left to right) are the dowels with 9-in. embedment separated by no rotation, 1-in. rotation, and 2-in. rotation. The next three groups are the dowels with 6-in. embedment separated by no rotation, 1-in. rotation, and 2-in. rotation. This is followed by the 4-in. through 2-in. embedment groups.

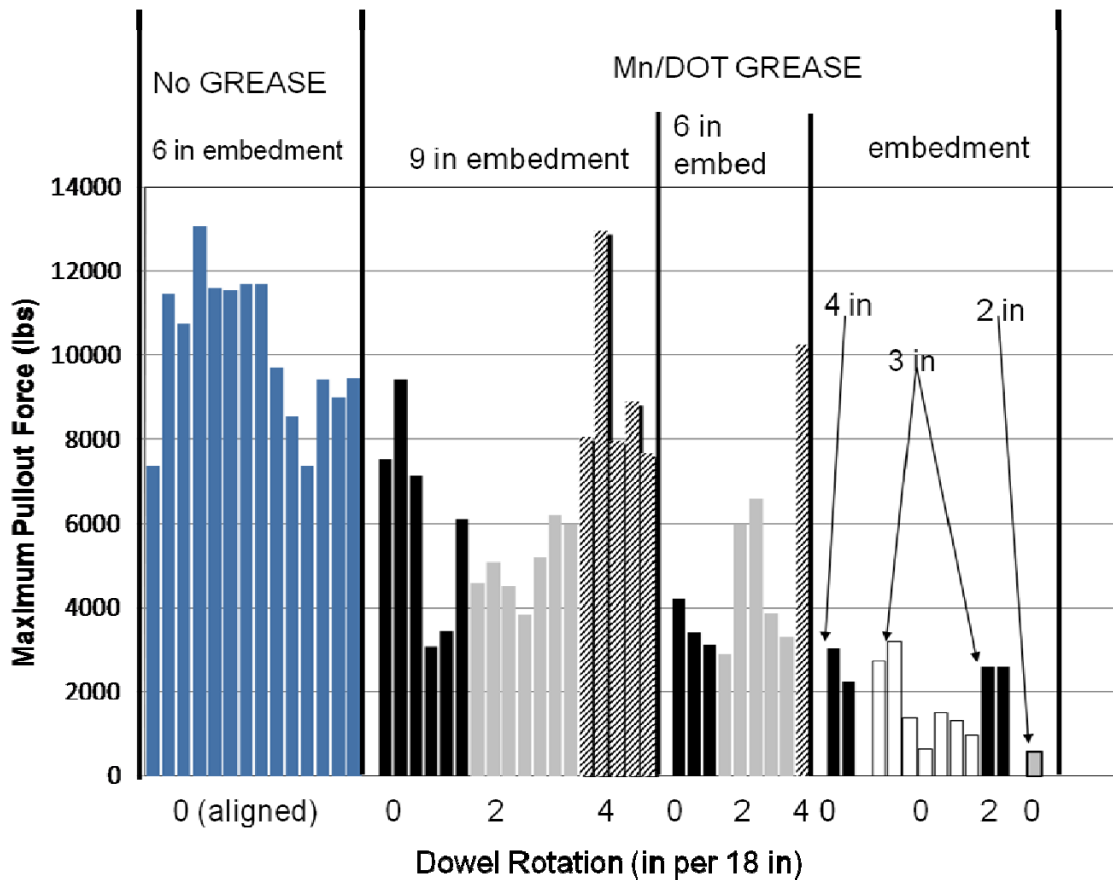


Figure C.18. Distribution of maximum pullout force required for greased and ungreased dowels at different misalignment levels.

C.6.1.2 Modified Pullout Trends

To test for statistical differences in pullout forces between the various groups of dowels, Student's t-tests were conducted. The details of all of the t-tests are shown in Tables C.4 through C.6. Comparison of the pullout forces for the 6-in. greased versus ungreased dowels shows that the lack of proper greasing significantly increases the required pullout forces and has a more pronounced effect than dowel misalignment.

Figure C.18 shows that greased 6-in. embedded dowels have a significantly lower pullout force than the ungreased dowels. The t-test results confirmed the significance of this difference. In fact, it can be stated with over 99% confidence that even 9-in. embedded greased dowels have a lower mean pullout force than the 6-in. embedded ungreased dowels.

A few observations can be made by initial analysis of the distribution. Looking at the 6-in. greased versus ungreased dowels, it can be observed that the lack of proper greasing significantly increases the required pullout forces and has a more pronounced effect than dowel misalignment. Table C.4 shows the t-tests between ungreased and greased 6-in. dowels, as well as ungreased 6-in. dowels versus greased 9-in. dowels. The greased 6-in. embedded dowels have a significantly lower pullout force than the ungreased dowels. In

fact, it can be stated with over 99% confidence that even 9-in. embedded greased dowels have a lower mean pullout force than the 6-in. embedded ungreated dowels.

Table C.4. Greased versus ungreated t-test for means.

6in no grease vs grease		
t-Test: Two-Sample Assuming Unequal Variances		
	<i>6 in no grease</i>	<i>6 in grease</i>
Mean	10203.42857	3582.333333
Variance	3065326.264	319521.3333
Observations	14	3
Hypothesized Mean Difference	0	
df	11	
t Stat	11.60597687	
P(T<=t) one-tail	8.1915E-08	
t Critical one-tail	1.795884814	
P(T<=t) two-tail	1.6383E-07	
t Critical two-tail	2.200985159	
6 in no grease vs 9 in grease		
t-Test: Two-Sample Assuming Unequal Variances		
	<i>6 in no grease</i>	<i>9 in grease</i>
Mean	10203.42857	6126.666667
Variance	3065326.264	6087066.667
Observations	14	6
Hypothesized Mean Difference	0	
df	7	
t Stat	3.670728697	
P(T<=t) one-tail	0.003978287	
t Critical one-tail	1.894578604	
P(T<=t) two-tail	0.007956574	
t Critical two-tail	2.364624251	

Table C.5 shows a t-test for aligned versus rotated dowels. Looking at the different rotation levels, it can be observed that rotation up to 1 in. does not have a significant effect on required pullout force, while the required pullout force is increased for 2-in. rotation. This suggests that dowels that are not properly greased or dowels that experience extreme rotation could cause problems with increased longitudinal restraint at the joints.

Table C.5. Aligned versus rotated maximum pullout force comparison.

aligned vs 1 in rotation		
t-Test: Two-Sample Assuming Unequal Variances		
	<i>Aligned</i>	<i>1 in rotation</i>
Mean	6126.666667	5059.714286
Variance	6087066.667	692864.5714
Observations	6	7
Hypothesized Mean Difference	0	
df	6	
t Stat	1.011117279	
P(T<=t) one-tail	0.175491881	
t Critical one-tail	1.943180274	
P(T<=t) two-tail	0.350983763	
t Critical two-tail	2.446911846	
aligned vs 2 in rotation		
t-Test: Two-Sample Assuming Unequal Variances		
	<i>Aligned</i>	<i>2 in rotation</i>
Mean	6126.666667	9126.4
Variance	6087066.667	4853316.8
Observations	6	5
Hypothesized Mean Difference	0	
df	9	
t Stat	-2.129037486	
P(T<=t) one-tail	0.031059295	
t Critical one-tail	1.833112923	
P(T<=t) two-tail	0.062118591	
t Critical two-tail	2.262157158	

Also, as should be expected for the reduced dowel-concrete contact area, the required pullout force becomes lower for the reduced embedment lengths. Table C.6 shows a t-test between 9-in. embedded dowels and 3-in. embedded dowels. It can be observed that the larger dowels have a significantly larger required pullout force.

Table C.6. Comparison of the required pullout force for aligned dowels versus dowels with reduced diameter.

9 in vs 3 in embedded dowels		
t-Test: Two-Sample Assuming Unequal Variances		
	<i>9 inch</i>	<i>3 inch</i>
Mean	6126.666667	1659.714286
Variance	6087066.667	864387.9048
Observations	6	7
Hypothesized Mean Difference	0	
df	6	
t Stat	4.187367975	
P(T<=t) one-tail	0.002883042	
t Critical one-tail	1.943180274	
P(T<=t) two-tail	0.005766084	
t Critical two-tail	2.446911846	

Although some premature cracking has been attributed to joint lockup due to dowel misalignment in the past, laboratory analysis of the pullout testing has shown that moderate dowel misalignments have not had a significant effect on increasing the maximum required pullout force. At the same time, quality of greasing was found to have a pronounced effect on the magnitude of the pullout force.

C.6.2 Shear Pull Testing

After all four dowels in a beam were subjected to pullout testing, the two outer dowels were tested in shear (see Figure C.19). The dowels were pulled in a displacement-controlled mode (while monitoring the applied load) until the specimen displayed visible distresses after failure. Table C.7 summarizes the maximum shear forces for each dowel tested in the shear pull test. A more detailed data analysis of the test results is presented below.

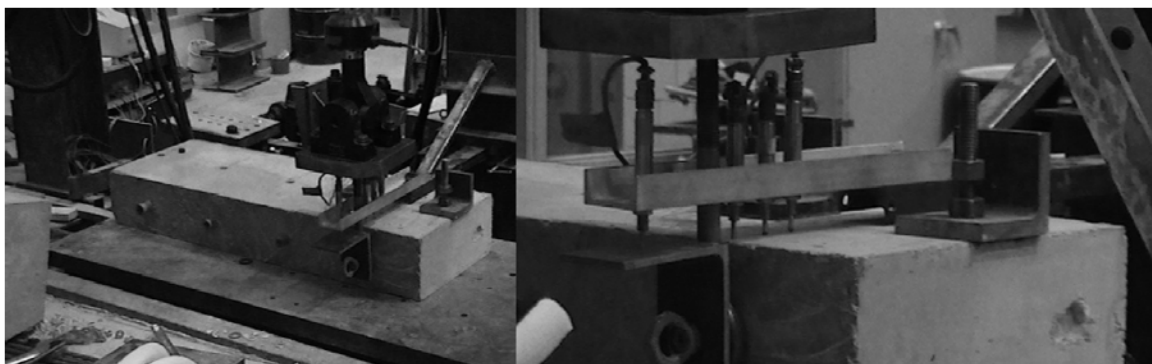


Figure C.19. Shear pull setup.

Table C.7. Ultimate dowel shear capacity for each dowel tested in one-time shear pull.

Dowel ID	Alignment Type	Rotational Misalignment (in./9-in. embedment)	Embedment Length (in.)	Vertical Translation (in.)	Dowel Diameter	Max. Shear Force (kips)
B1D1	A	0	9	0	1.5	9.0
B1D4	HS	1	9	0		7.7
B2D1	VT	1	9	0	1.5	7.0
B2D4	A	0	6	0		8.3
B3D1	A	0	4	2	1.5	2.9
B3D4	A	0	3	2		2.7
B4D1	A	0	9	2	1.5	4.2
B4D4	A	0	3	0		7.3
B5D1	VT	1	3	0	1.5	5.1
B5D4	VT	2	9	0		4.4
B6D1	A	0	9	0	1.5	9.6
B6D3	A	0	6	0		9.8
B7D1	HS	2	9	0	1.5	7.9
B7D4	VT	1	6	0		8.3
B8D1	VT	1	9	0	1.5	8.3
B8D4	A	0	6	0		8.4
B9D1	A	0	9	2	1.5	4.7
B9D4	A	0	3	0		6.7
B10D1	VT	1	6	0	1.5	7.2
B10D4	A	0	3	2		2.6
B11D1	VT	0.5	9	0	1.5	8.3
B11D4	A	0	2	0		5.4
B14D1	A	0	9	0	1.25	8.2
B14D4	VT	1	9	0		7.4
B15D1	A	0	3	0	1.25	5.3

Dowel ID	Alignment Type	Rotational Misalignment (in./9-in. embedment)	Embedment Length (in.)	Vertical Translation (in.)	Dowel Diameter	Max. Shear Force (kips)
B15D4	A	0	9	2		4.1
SBD1	A	0	3	0	1.5	5.9
SBD4	A	0	9	2		3.9

C.6.2.1 Shear Pull Results Interpretation

Figure C.20 shows the displacement locations that were recorded continuously. LVDT1 measures the displacement of the metal angle above the dowel giving the absolute dowel displacement. LVDT2 measures the displacement at the edge of the concrete beam closest to the dowel. LVDT3 measures the displacement of the beam 2 in. from the edge LVDT along the dowel. LVDT4 measures the displacement of the beam 4 in. from the edge LVDT along the dowel.

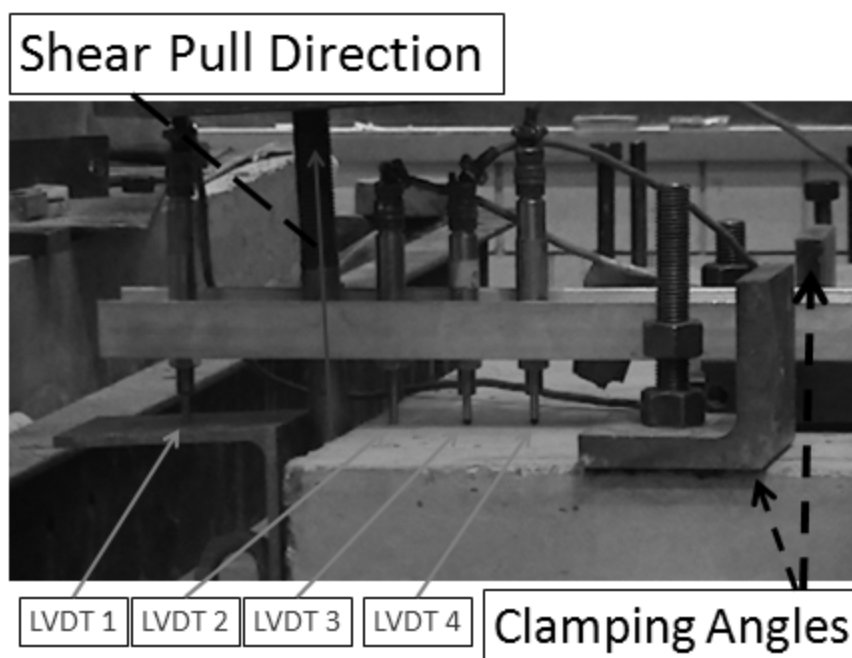


Figure C.20. Locations on the dowel and concrete where displacement was measured.

The shear pull force, displacement of the dowel, and displacements at three locations on the beam were recorded during testing (see Figure C.20). Figure C.21 shows an example of the

recorded displacements and shear force for a dowel tilted vertically 1 in. per 9 in. of embedment length.

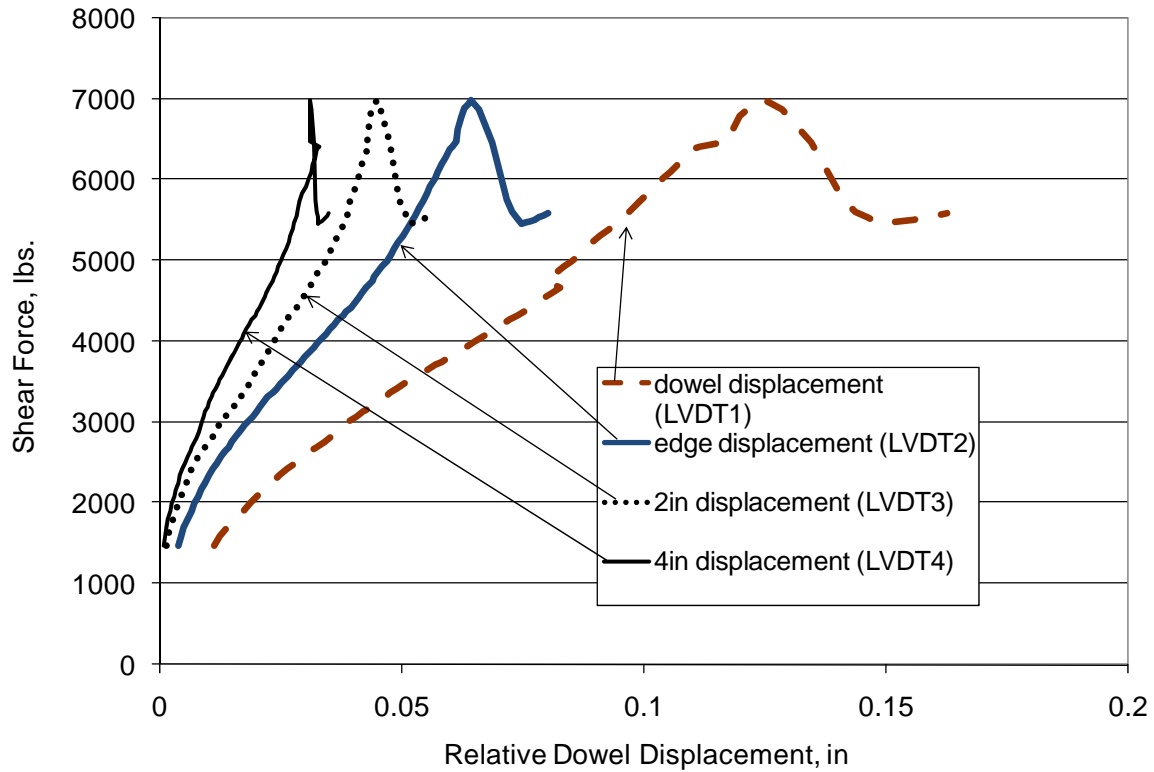


Figure C.21. Measured values for the shear testing of dowel B2D1.

To conduct analysis of the effect of dowel misalignment on the stiffness of dowel/concrete interaction, a relative vertical displacement of the dowel end with respect to the surrounding concrete was estimated. The relative dowel displacement was found by subtracting the calculated dowel displacement due to the rigid body rotation of the beam from the actual dowel displacement. The calculated dowel displacement was found using the displacements of LVDT2 and LVDT4 (Figure C.20) and the specimen geometry. These displacements were used to calculate the slope of the rigid body motion of the beam.

$$\frac{\partial_2 - \partial_4}{l_{24}} = \Delta_{rb}$$

l_{24} – The distance between LVDT₁ and LVDT₂

∂_2 – The vertical displacement measured by the LVDT located at the edge of the beam (LVDT2)

∂_4 – The vertical displacement measured by the LVDT located 4 inches from the edge (LVDT4)

Δ_{rb} – The slope of the rigid body motion of the beam

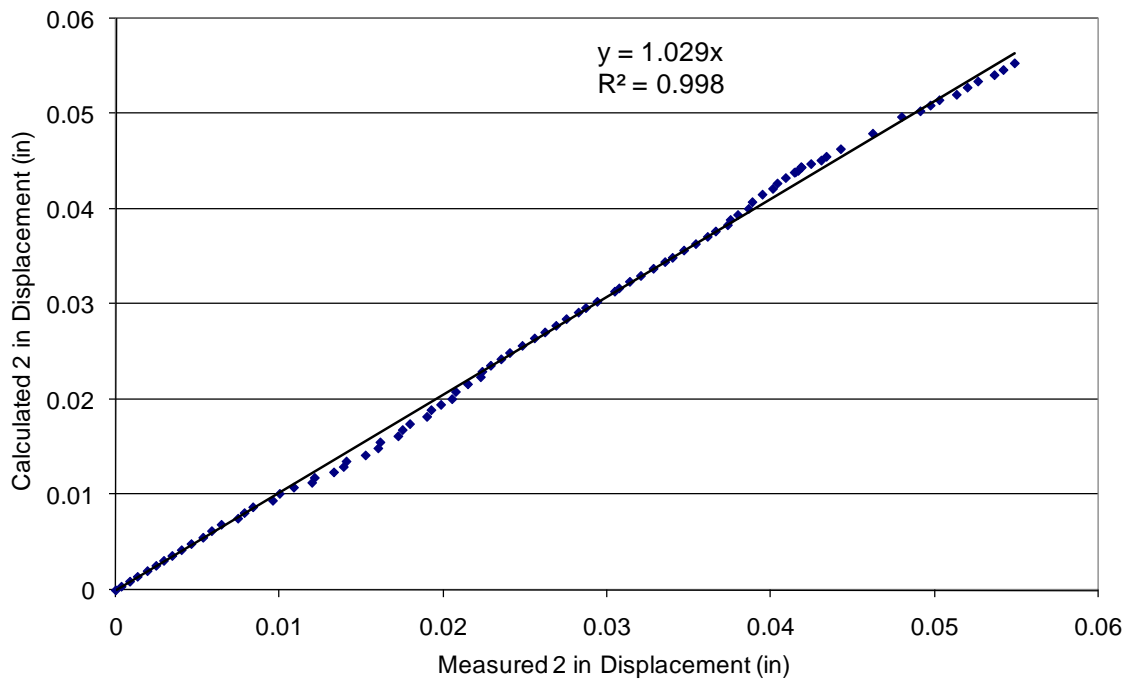
The slope of the rigid body could then be used to calculate the position that the dowel would be in assuming rigid body motion (i.e., rotated from its original position together with the beam without bending).

$$\Delta_{rb} l_{14} + \partial_4 = \partial_{calc}$$

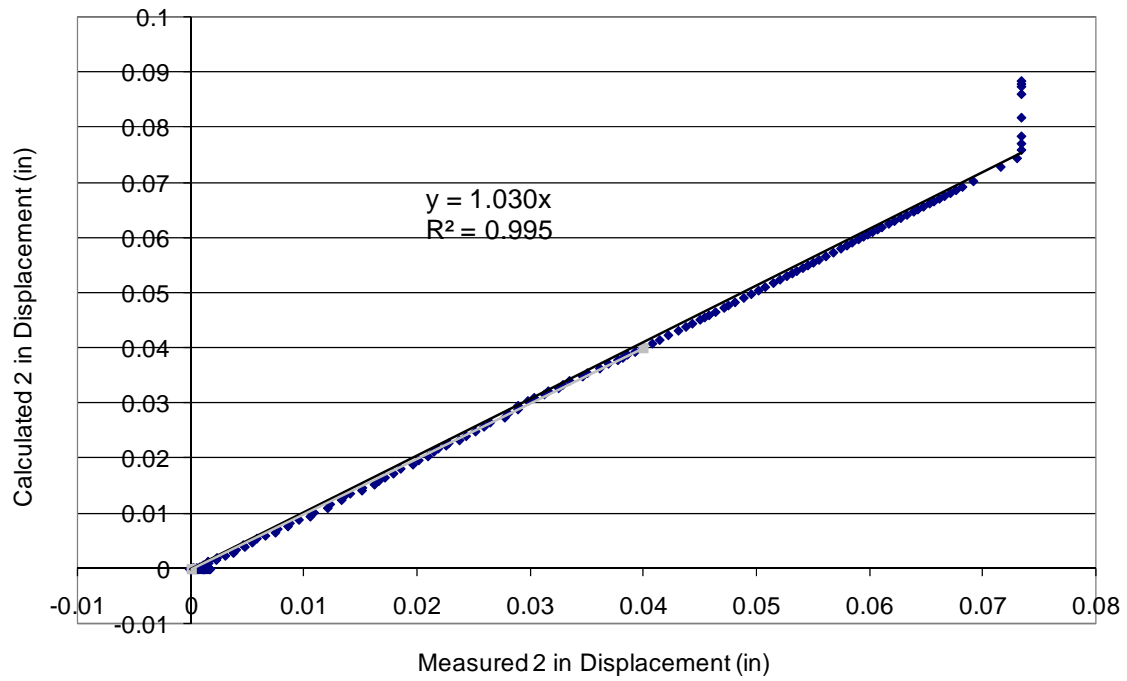
l_{14} – The distance between the dowel LVDT (LVDT₁) and the dowel located 4 inches from the edge (LVDT₄)

∂_{calc} – Calculated dowel displacement assuming rigid body motion.

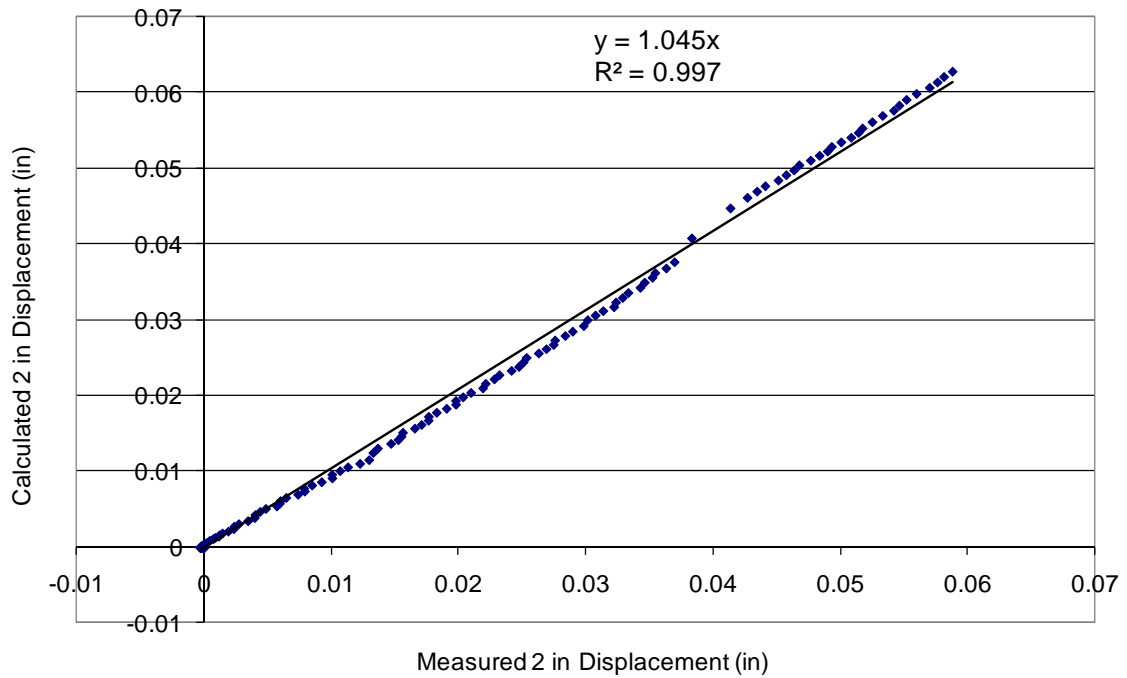
Also, to check the accuracy of the rigid body motion calculation, the displacement at LVDT2 was calculated and compared to the actual measurement. Figure C.22 shows examples of the calculated versus measured displacement at the 2-in. location for beams with various types and levels of misalignments. These plots are representative of the agreement observed for the tested beams, and shows that the rigid body assumption for the rotation of the concrete beam is appropriate.



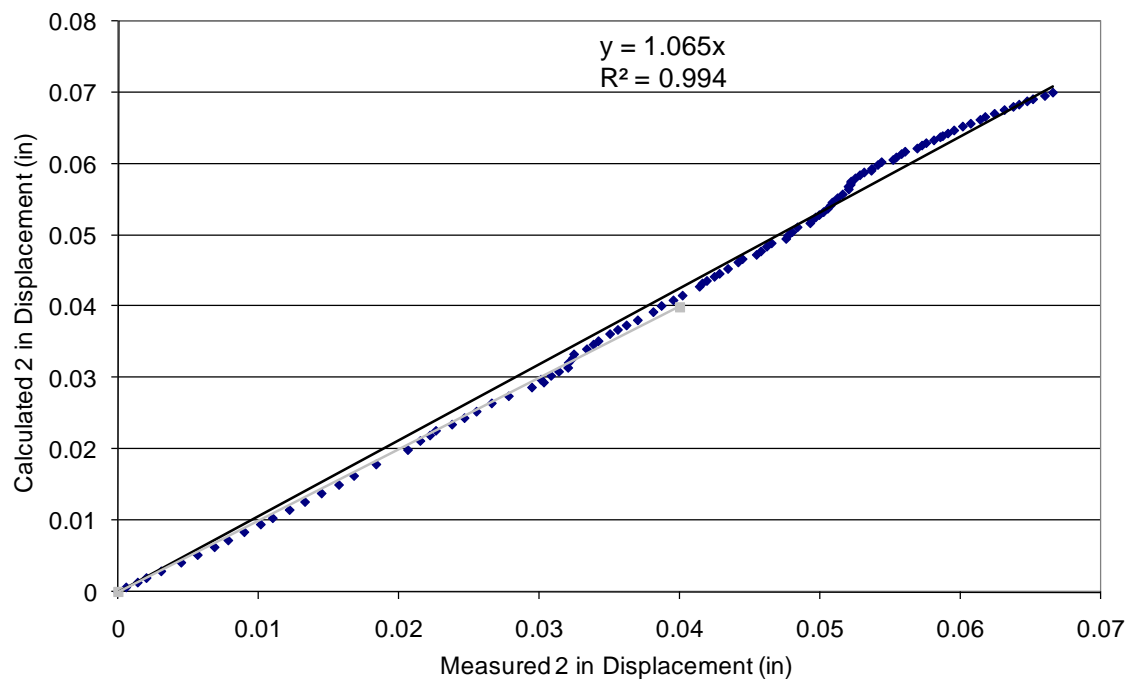
(a) 1 inch vertically tilted dowel in beam 2.



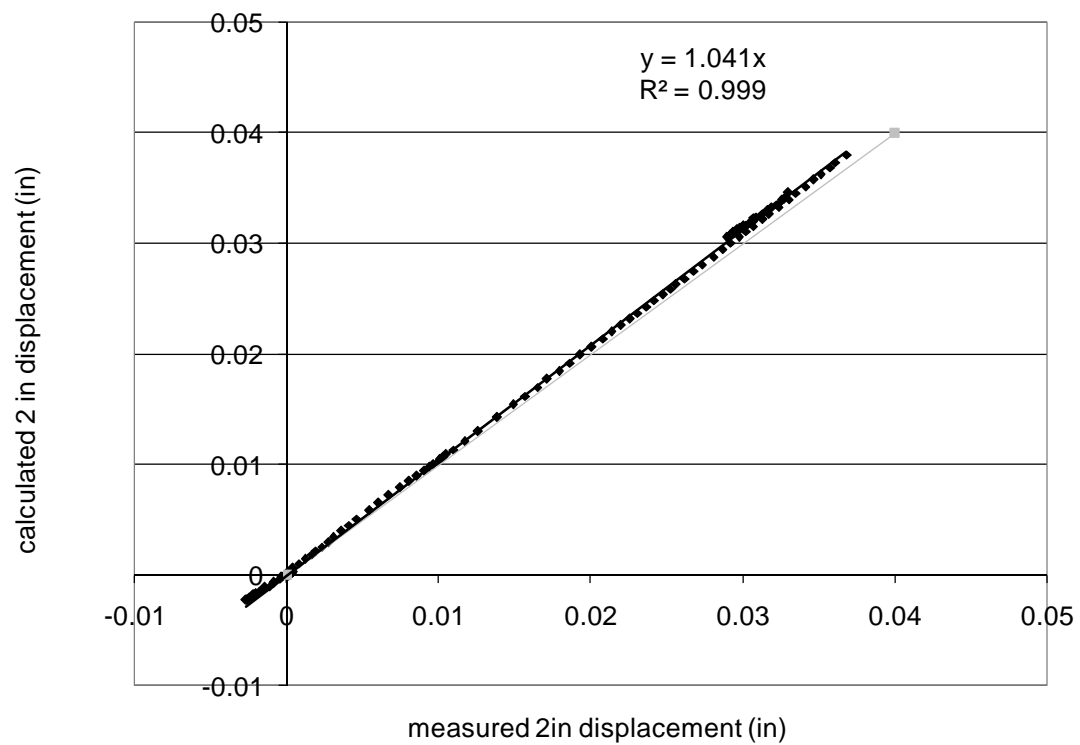
(b) 6 inch embedded dowel in beam 6. (b)



(c) 1 in horizontal tilted dowel in beam 1



(d) 3 inch embedded dowel with 1.25 inches of concrete cover



(e) 2 inch embedded dowel in beam 11

Figure C.22. Verification of the rigid body slope for beams shown in a, b, c, d, and e.

Figure C.23 shows the example from Figure C.21 with the calculated values added to the same test. The plot shows that while the beam surface displacements can be described as rigid body motion, the dowel exhibits additional displacements with respect to the concrete beam surface.

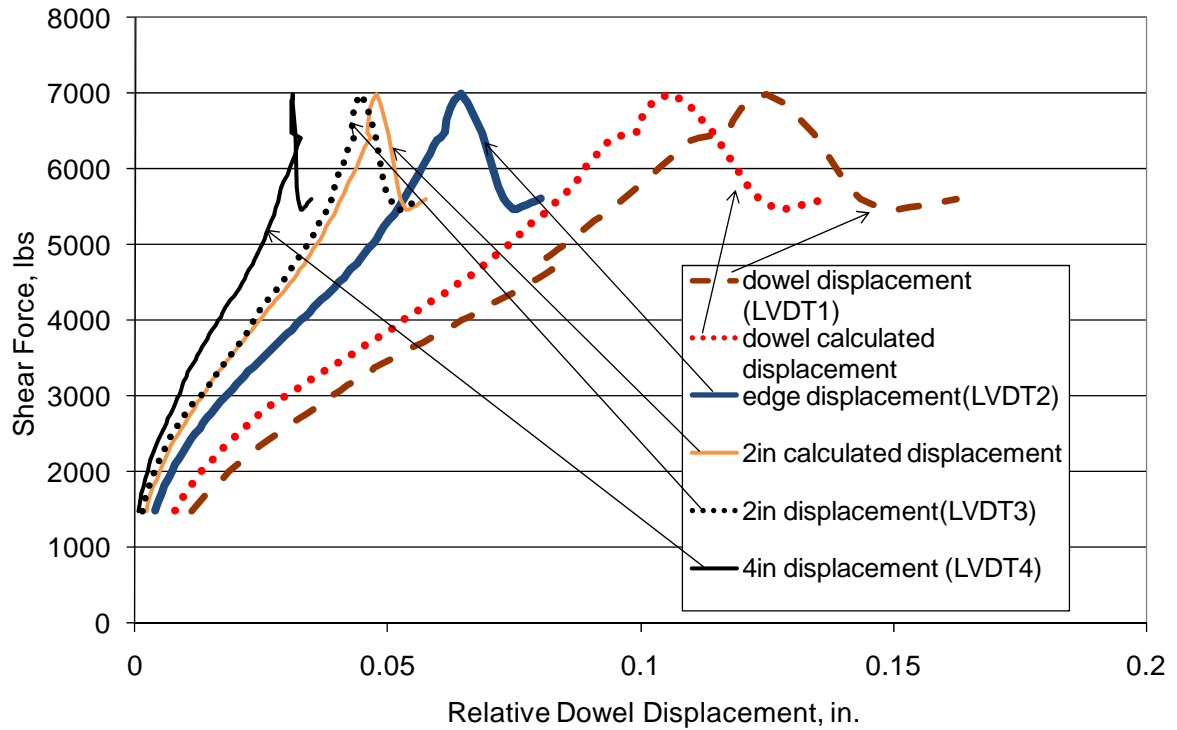


Figure C.23. Measured and calculated values for dowel B2D1.

By subtracting this calculated dowel displacement from the measured dowel displacement, the relative dowel displacement can be found.

$$\partial_{rel} = \partial_{meas} - \partial_{calc}$$

∂_{meas} – The dowel displacement measured by LVDT1

∂_{rel} – The dowel displacement due to failure found by subtracting the calculated rigid body displacement from the actual dowel displacement

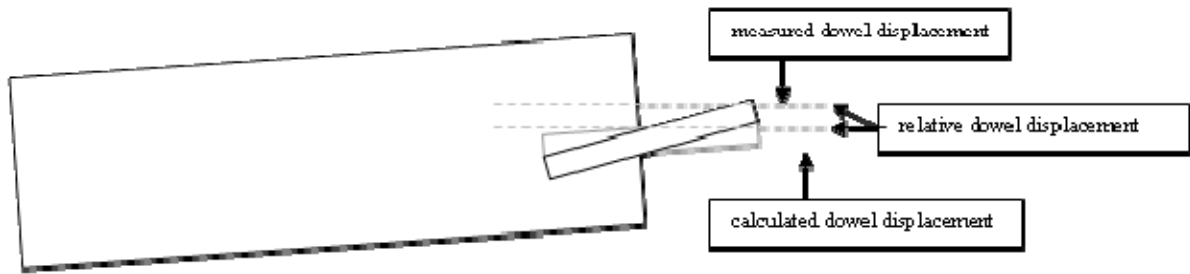


Figure C.24. Relative displacement gives the displacement of the dowel due to shear failure.

Figure C.25 shows a plot of relative dowel displacement versus applied shear force, as well as an illustration of how this curve is analyzed. The maximum shear force applied to fail the concrete surrounding the dowel was considered the ultimate shear strength of the specimen. The ultimate shear value gives information about the ability to sustain overloading and maintain stiffness for the different types of misalignments. Also, the slope of the curve characterized the stiffness of each dowel alignment tested in shear. The stiffness associated with each alignment type and magnitude gave direct information about how the LTE might be affected. In this manner, the relative dowel displacement was used to estimate the degree of deformation of the concrete during testing.

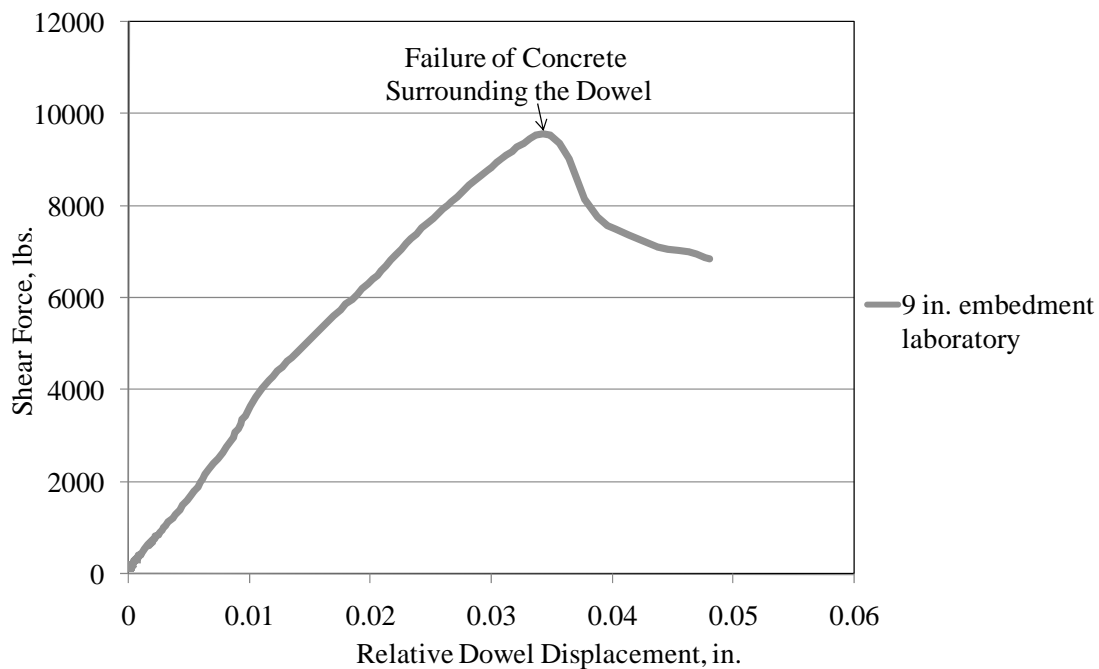


Figure C.25. Example relative displacement versus shear force curve.

Figure C.26 shows the relative dowel displacement versus shear force for dowels with 2, 4, and 9 in. of embedment. The Figure shows how the two types of performance measures (shear stiffness and ultimate shear capacity) can be affected by misalignment. As the plot shows, the typical 9-in. dowel has a higher ultimate shear force than the dowels with lower

embedment length. However, there is no loss in shear stiffness in the dowel with 4-in. embedment until failure at about 7 kips. In the 2-in. embedment case, the dowel not only has a lower ultimate shear at about 5 kips, but there is a loss in stiffness before failure.

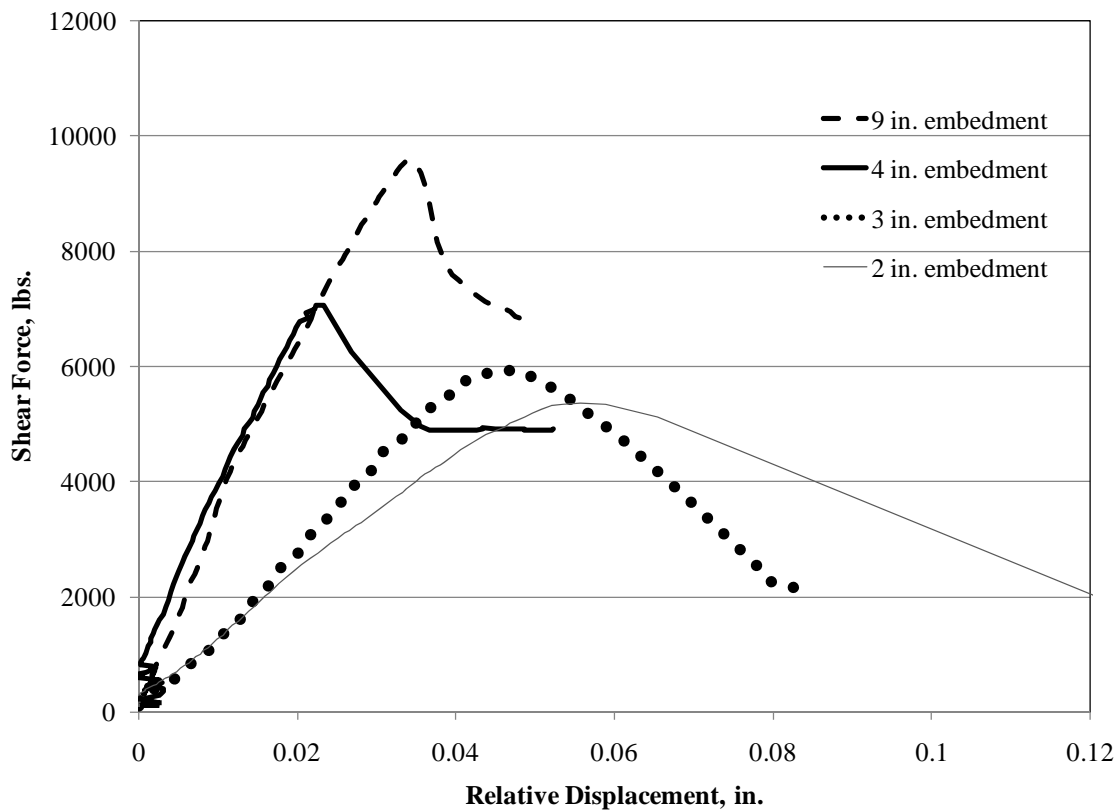


Figure C.26. Example of reduced ultimate shear and loss in stiffness curves.

The effect of misalignment on repeated shear loading also was analyzed. The following test parameters were selected for the repeated shear testing:

- Magnitude of loading: 3 kip.
- Load frequency: 2 Hz. This frequency provided sufficient productivity but did not cause instability in the measurements.
- Rest period: 0.5 seconds. To reduce the residual effect (“bouncing”), a seating static load of 500 lb was added between loading cycles.
- Measurement frequency: every 0.1 seconds.
- Number of load cycles: at least 10,000.

The laboratory setup was the same for the repeated load testing as for the previous shear test. The only change was that the dowels were not tested in displacement controlled mode until

failure, but rather, in repeated 3 kip loads for more than 10,000 load cycles. In this manner, the effect of a one-time load to failure on strength and stiffness could be related to the effect of a repeated load fatigue test.

As with the pullout testing, one of the concerns associated with the shear pull testing was the possible effect of variations in concrete properties from different beams. To analyze the effect of dowel misalignment on shear testing, the variability in the shear test needed to be estimated. Figures A.27 through A.29 show the shear force versus relative dowel displacement for dowels with the same level of misalignment. With the exception of reduced concrete cover, there is a small difference in stiffness and ultimate shear due to natural variability in shear testing. Although the repeatability of the ultimate shear was similar for reduced concrete cover, this extreme case of low concrete cover appears to have an effect on the shear stiffness measurements. Therefore, when analyzing the stiffness and ultimate shear capacity of the different misalignment types and levels, discrepancies within this natural variability were not considered significant.

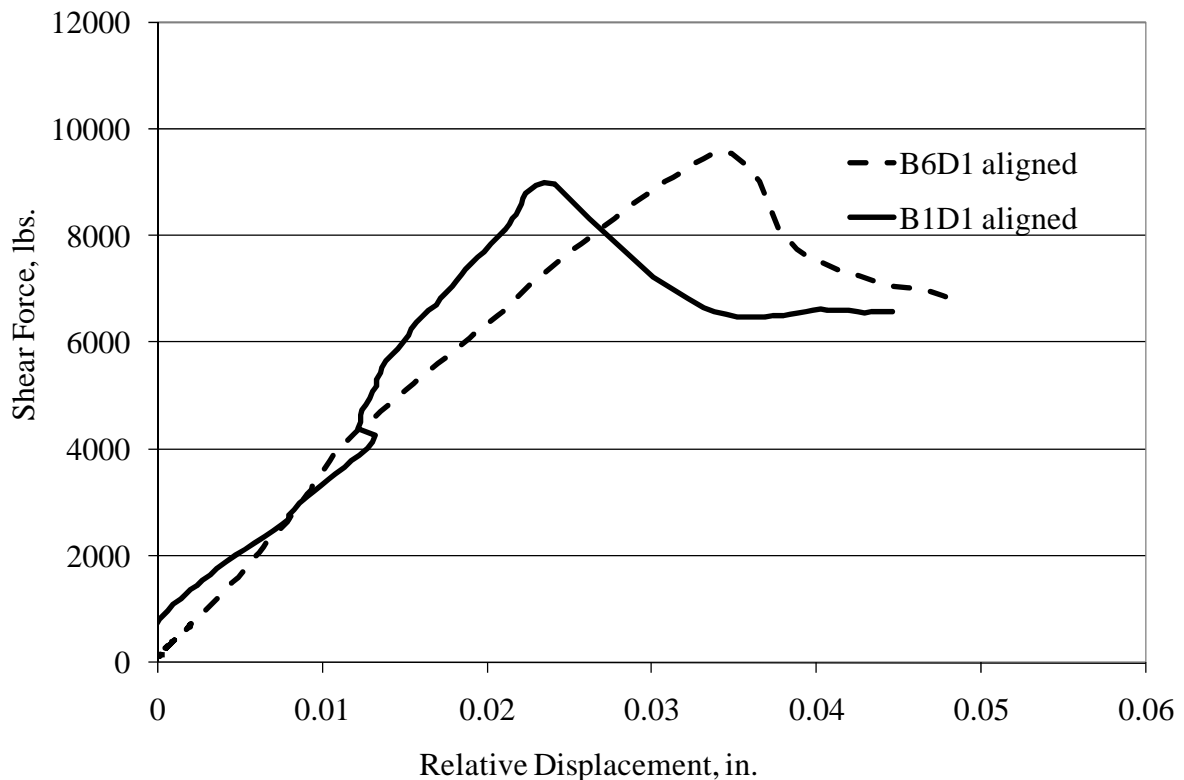


Figure C.27. Shear test curves for two aligned dowels.

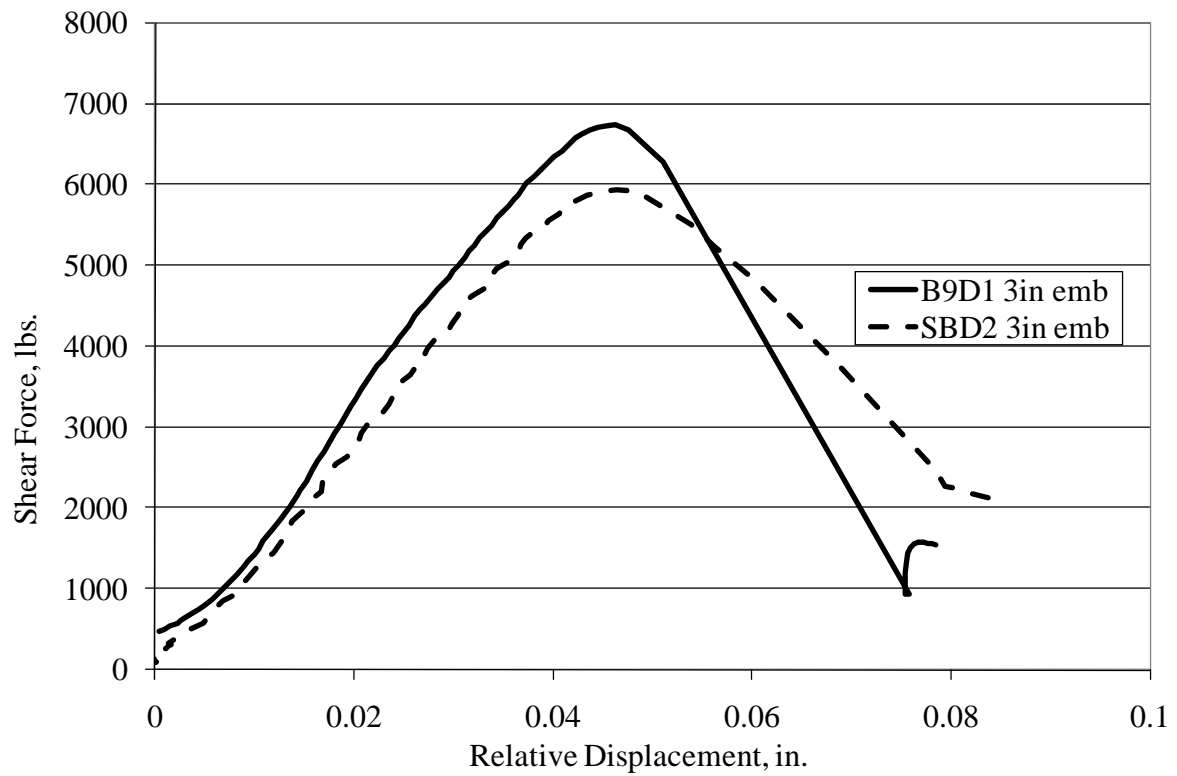


Figure C.28. Shear test curves for two dowels with 3-in. embedment.

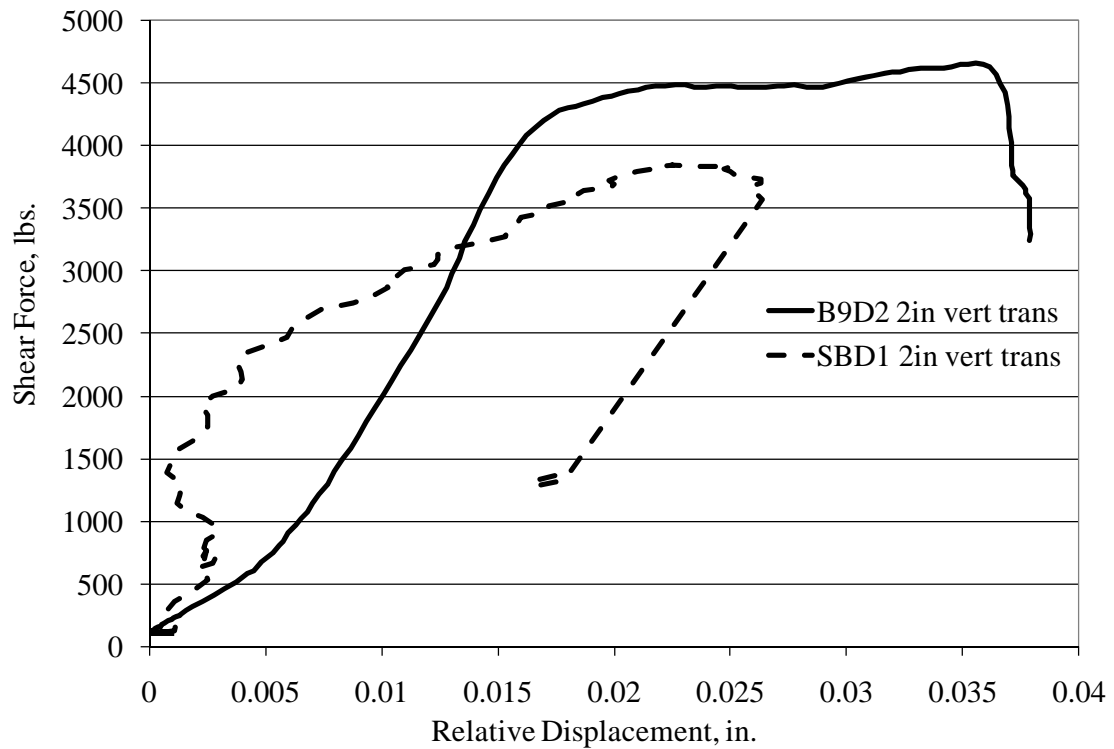


Figure C.29. Shear test curves for two dowels with 1.25-in. concrete cover.

C.6.2.2 Shear Pull Trends

By analyzing the performance measures (shear stiffness, ultimate shear capacity) of each dowel tested in shear, comparisons between different dowels can be made. These shear performance measures were compared for the different types and levels of misalignments from the shear laboratory testing.

As shown by Figure C.30, vertical tilt of up to 1 in. did not have a very large effect on shear stiffness or ultimate shear, while 2-in. vertical tilt greatly reduced the shear stiffness and ultimate shear. This suggests that, for the laboratory testing conditions, the shear capacity is between 1 and 2 inches of vertical tilt. It should be noted that the extreme loss in stiffness experienced by the 2-in. vertically tilted dowel was caused by the damage in the pullout test before shear testing.

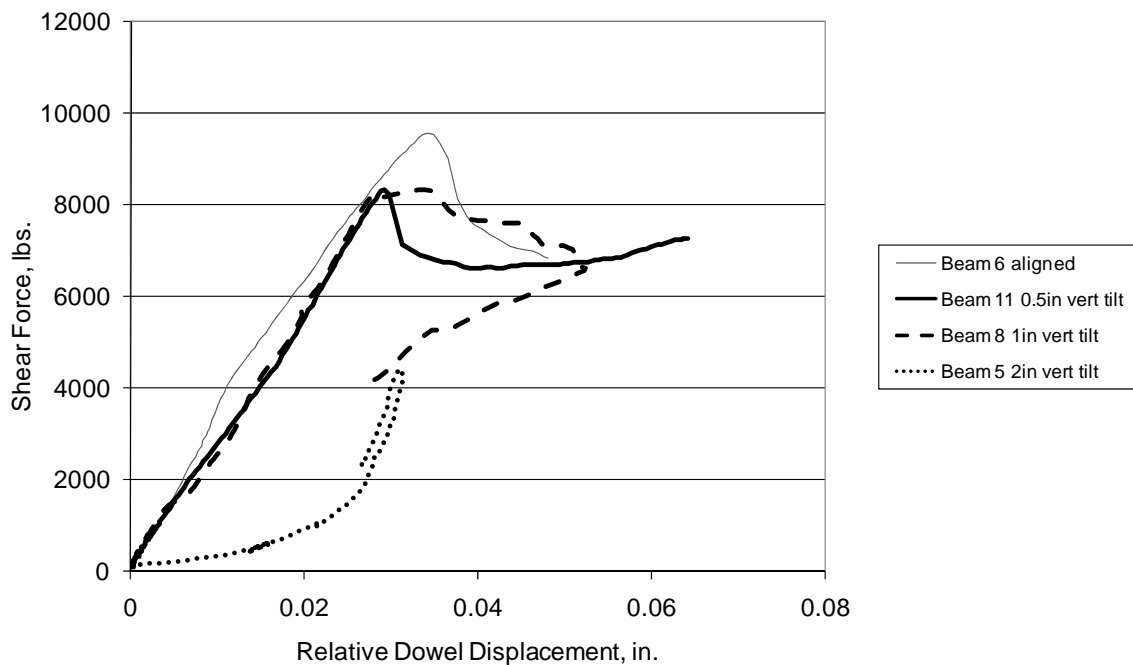


Figure C.30. Vertical tilt shear pull shear capacity.

Figure C.31 displays the shear force versus relative dowel displacement curves for aligned dowels with various embedment lengths. Comparison of the curves for dowels of 9 and 6 inches of embedment show that a reduction in embedment length to 6 in. did not have much of an effect on shear behavior. Conversely, comparing the dowels with embedment lengths of 3 and 2 inches shows that, for dowel embedment lengths reduced to 3 in. or less, the stiffness and ultimate shear capacity were reduced significantly. The 4-in. embedment length exhibited the same stiffness as the dowels with 6- and 9-in. embedment lengths, but lower ultimate shear capacity.

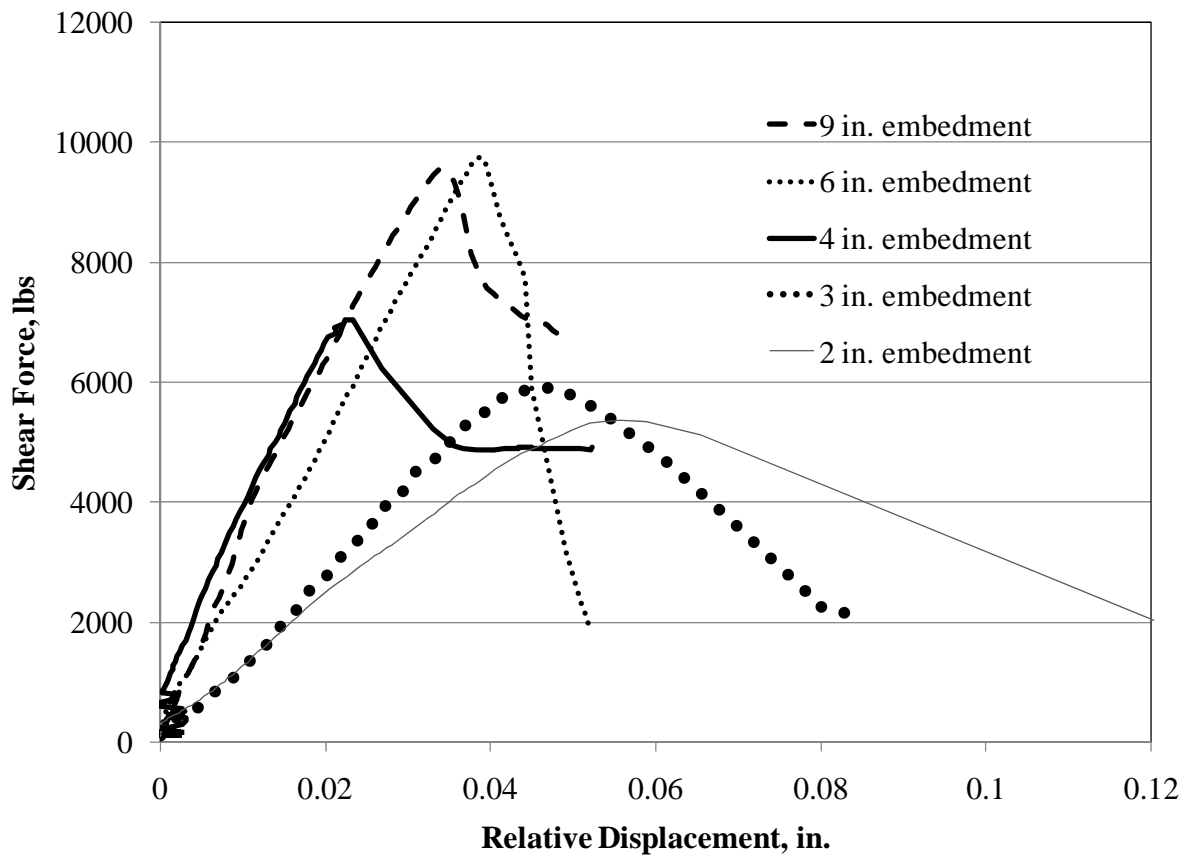


Figure C.31. Effect of embedment length on shear pull shear capacity.

Figure C.32 shows the effect of reduced concrete cover on dowel shear capacity. It can be observed that dowel vertical translation by 2 in. and resulting concrete cover of 1.25 in. reduced ultimate shear capacity by more than half.

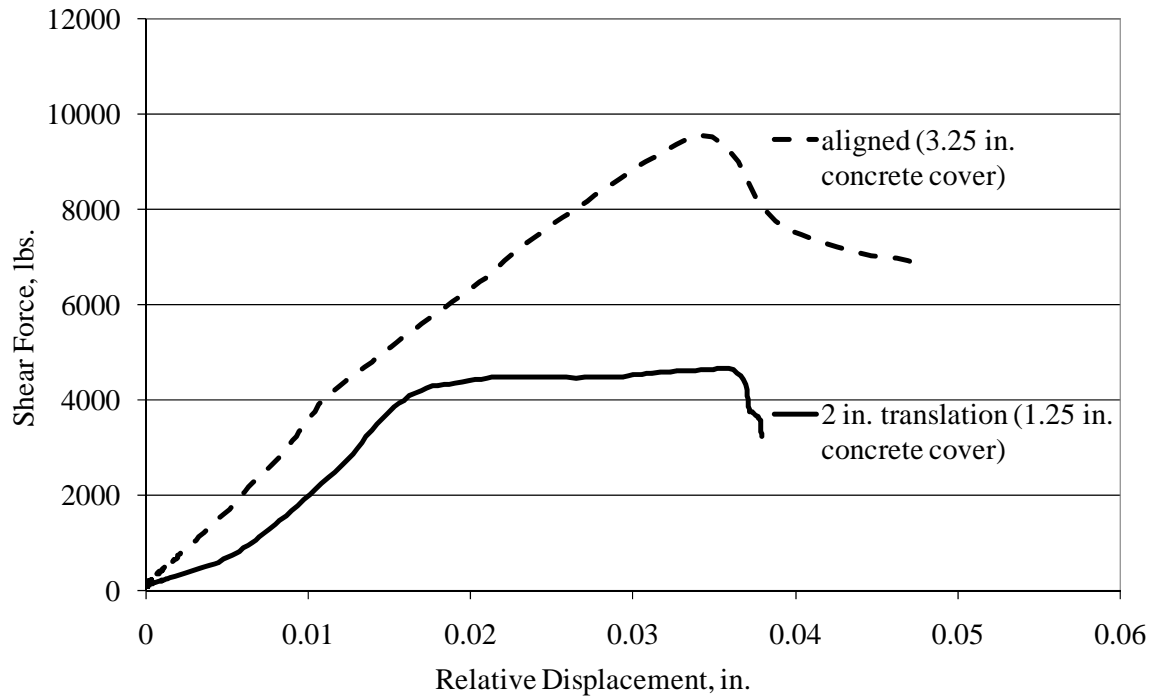


Figure C.32. Effect of reduced concrete cover on shear testing.

Figure C.33 displays the shear force versus relative dowel displacements for an aligned dowel, reduced embedment length, reduced concrete cover, as well as a combination of both. As discussed earlier, a 2-in. decrease in concrete cover created a large decrease on ultimate shear, while a reduction to 3 inches in embedment length reduces the stiffness. It can be observed that a combination of the two misalignments has compounding effect, resulting in decreases the ultimate shear capacity and shear stiffness.

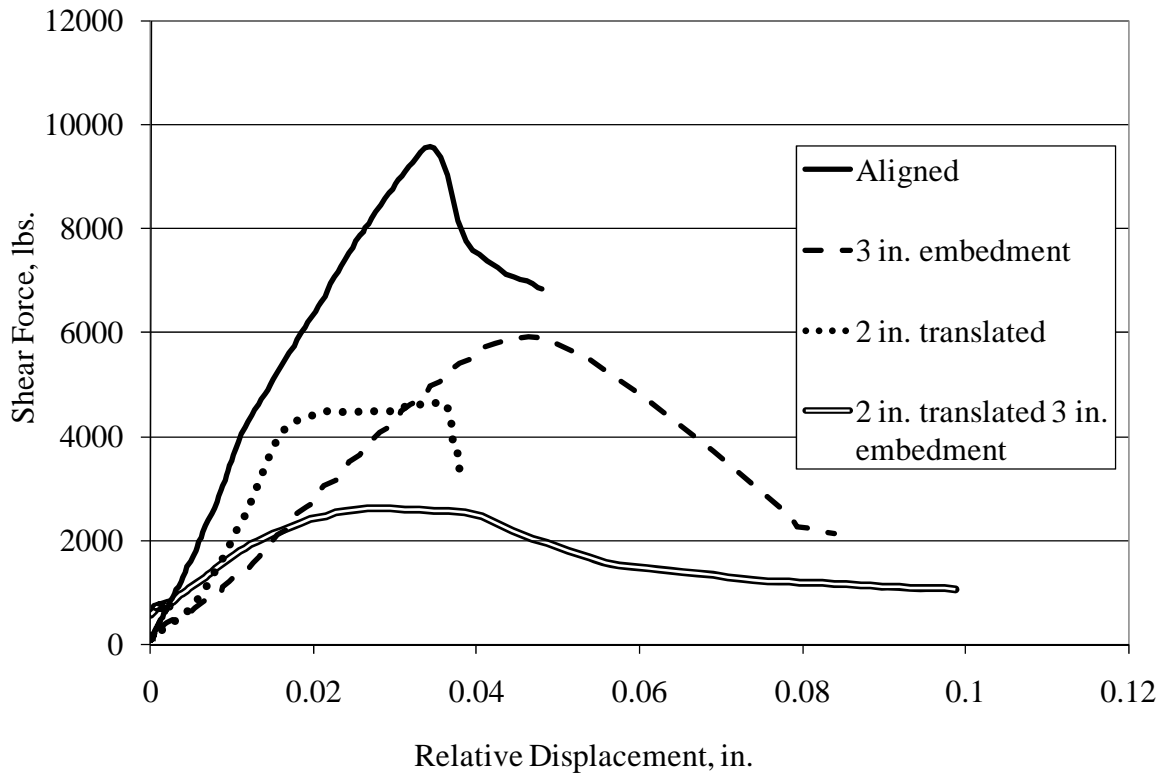


Figure C.33. Effect of the combination of reduced concrete cover and embedment length.

Figure C.34 displays the shear force versus relative dowel displacements for an aligned dowel, 1-in. vertically tilted dowel, reduced embedment length dowel, as well as a combination of both. It can be observed that a combination of the vertical tilt and reduced embedment length has compounding effect, resulting in decreases the ultimate shear capacity and shear stiffness from the two misalignments.

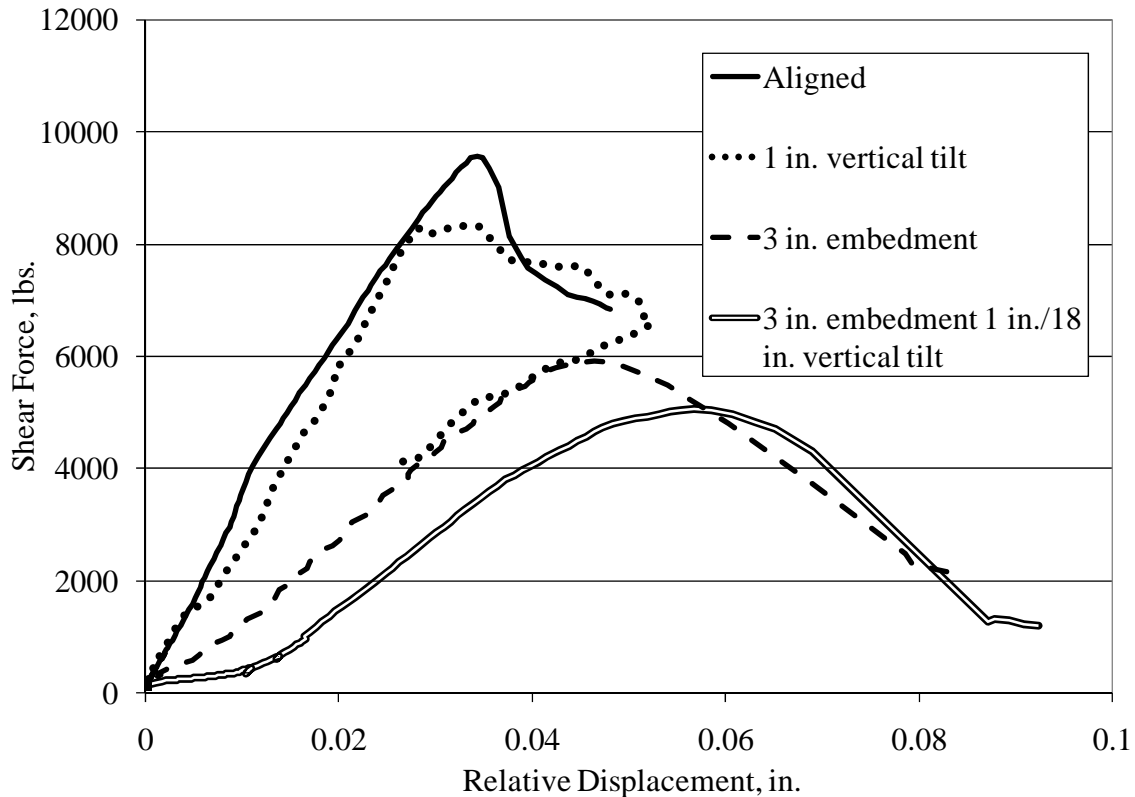


Figure C.34. Combined effect of vertical tilt and 3-in. embedment.

The repeated shear load testing also revealed some interesting phenomena. The shear capacity of a dowel subjected to repeated loading was significantly lower than the ultimate shear in a one-time displacement controlled loading. Therefore, the dowel misalignment can also cause lower performance in fatigue, as well as initial strength and stiffness. To illustrate this effect, the performance of a 2-in. vertically translated dowel causing 1.25 in. concrete cover and an aligned dowel under repeated loading was compared.

Figure C.35 shows the relative displacement versus shear load of an aligned dowel and a dowel with reduced concrete cover of 1.25 in. The plot shows the curves for both dowels after the initial few cycles, as well as after 14,000 load cycles. The stiffness decreased for both dowels after 14,000 load cycles. However, the stiffness of the 2-in. vertically translated dowel had a more significant decrease in stiffness close to the 3 kip level after 14,000 cycles. This suggests that the dowel with reduced concrete cover was beginning to fail at 3 kips after being fatigued by multiple load applications. This failure load at 3 kips is significantly lower than the failure of the one-time displacement controlled load application of about 4.7 kips.

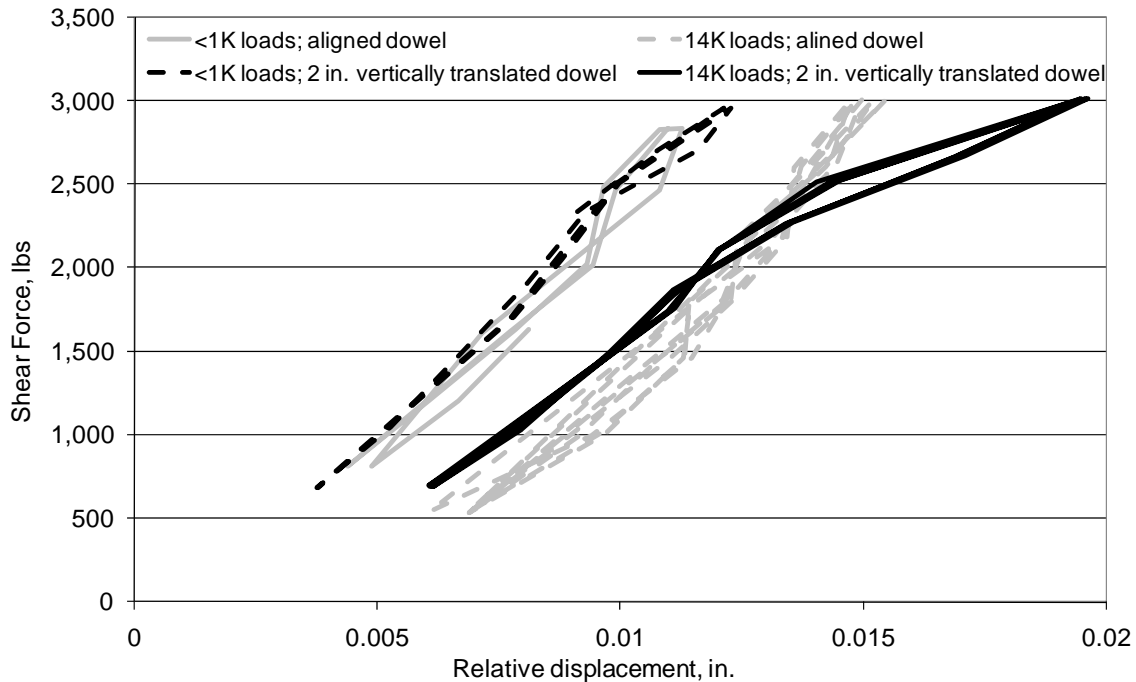


Figure C.35. Effect of the number of load cycles on low concrete cover.

Also, the effect of misalignment for a dowel diameter of 1.25 in. was tested. Data analysis of the shear pull testing shows that reduced dowel diameter causes lower shear stiffness. Figure C.36 compares the shear performance of aligned dowels with 1.5 in. and 1.25 in. diameters. Figure C.37 compares performance of dowels with 1.5 in. and 1.25 in. diameters, with reduced concrete covers. Figure C.38 compares performance of dowels with 1.5 in. and 1.25 in. diameters, with reduced embedment lengths. Figure C.39 compares performance of dowels with 1.5 in. and 1.25 in. diameters, with 1 in. of vertical tilt. As expected, shear performance of the thinner dowels was worse than the performance of the thicker dowels with the same level of alignment.

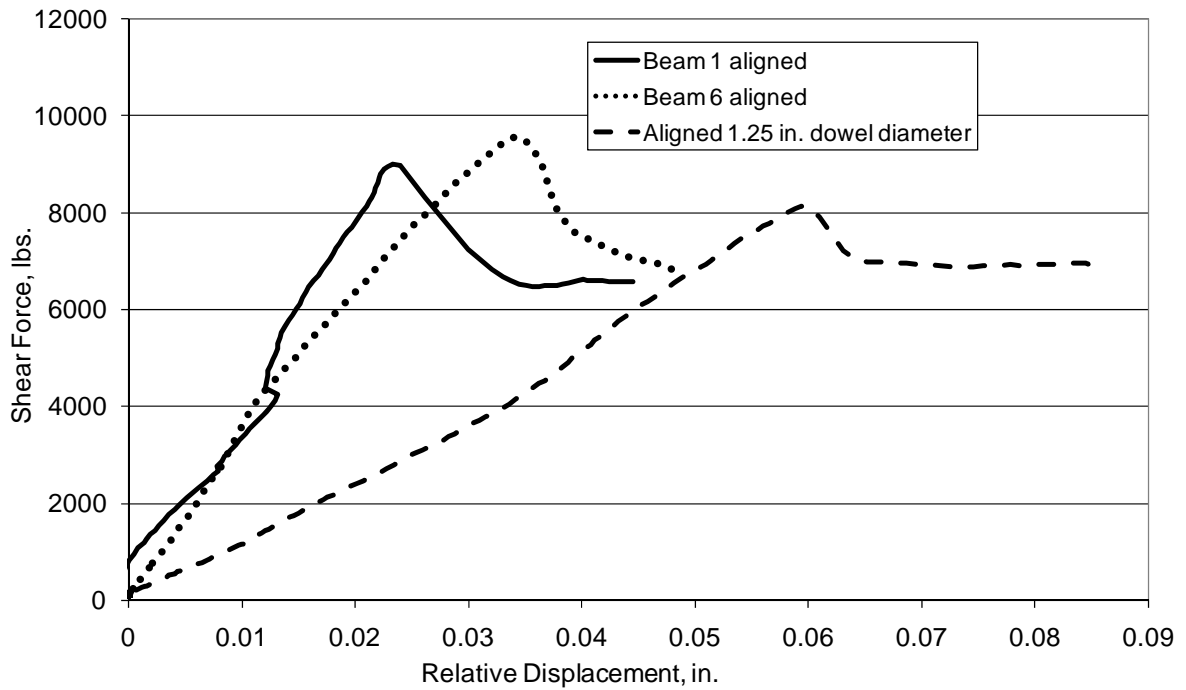


Figure C.36. Effect of reduced dowel diameter for aligned dowels in shear.

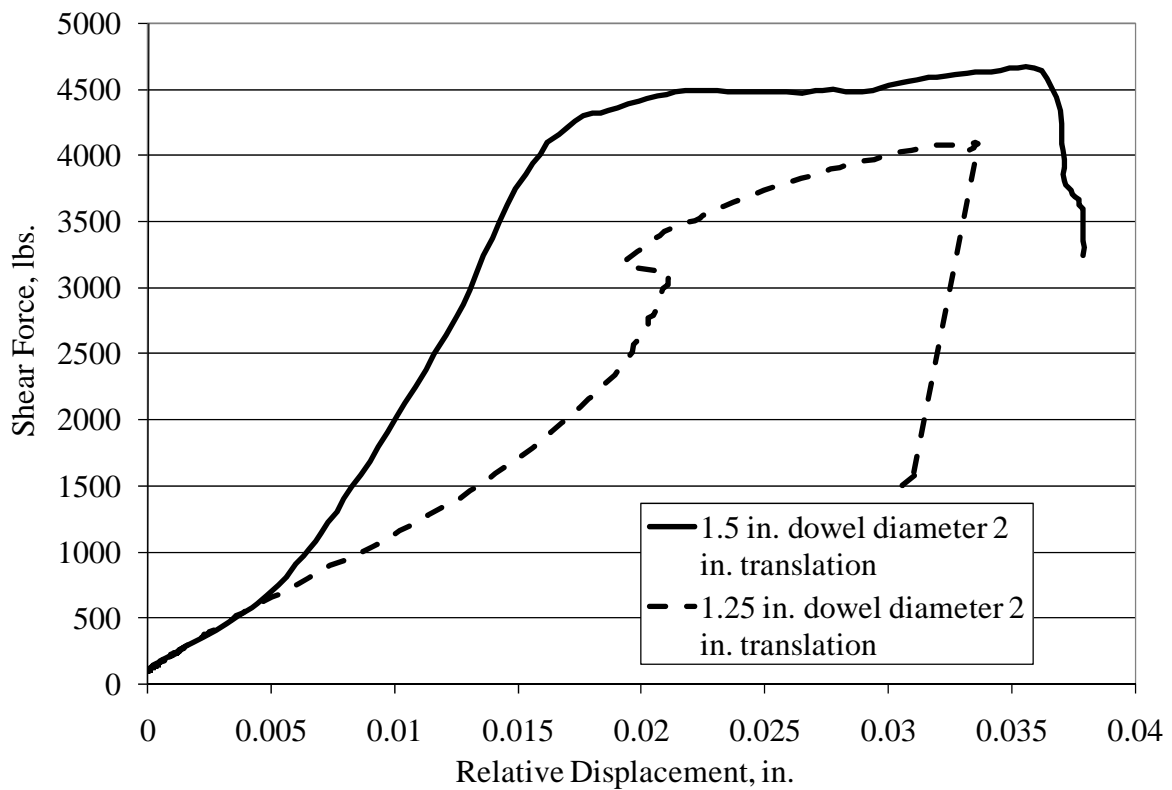


Figure C.37. Reducing the dowel diameter from 1.5 in. to 1.25 in. caused a drop in shear stiffness.

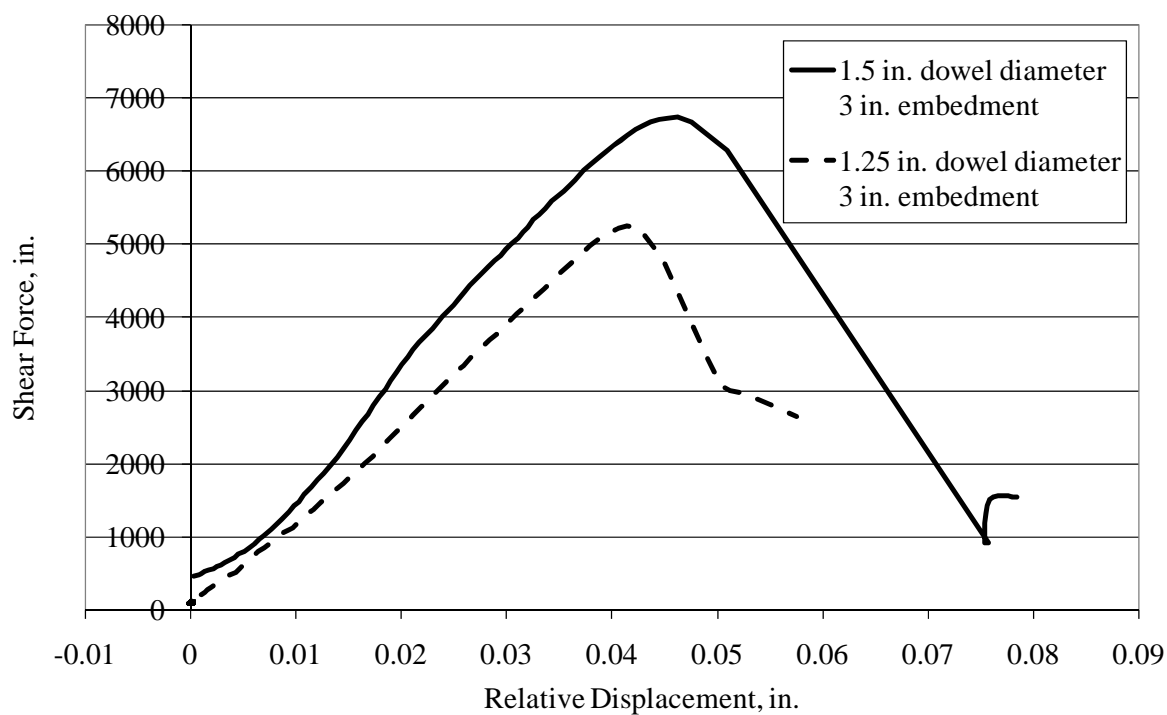


Figure 38. Effect of reduced dowel diameter on low embedment length.

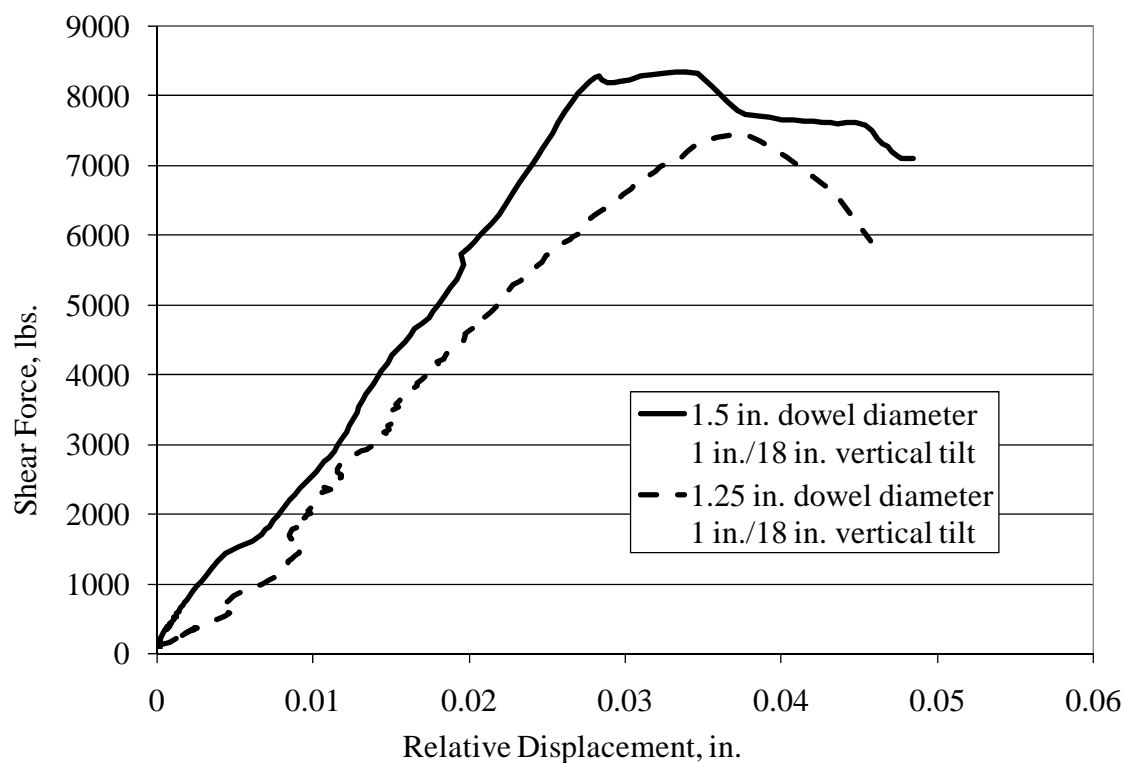


Figure 39. Effect of reduced dowel diameter for a vertically tilted dowel.

To summarize, the following effects of dowel misalignment on performance were observed in the laboratory study:

- Presence of greasing had a significantly higher effect on pullout force than dowel misalignment
- Dowel rotation does not affect dowel shear capacity unless the rotation is as extreme as 2 in. per 9-in. embedment
- Reduction in dowel embedment length of up to 6 in. does not affect dowel performance, while reduction in embedment length to 3 in. and lower significantly affects shear capacity
- Reduction in concrete cover from 3.25 in. to 1.25 in. causes severe reduction in ultimate shear force
- Combinations of misalignments have a compounding effect on shear performance

C.7 References

Khazanovich, L., N. Buch, and A. Gotlif. "Mechanistic Evaluation of Vertical Misalignment of Dowel Bars and their Effect on Joint Performance," *Proceedings, Seventh International Conference on Concrete Pavement*, September 9-13, Lake Buena Vista, FL, 2001, pp. 525-538,

Tayabji, S.D., "Dowel Placement Tolerances for Concrete Pavements," *Transportation Research Record No. 1062*. Transportation Research Board of the National Academies, Washington, DC, 1986.