DOWEL BEARING STRENGTH AND BOLTED CONNECTION BEHAVIOR OF ORIENTED STRAND LUMBER

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of PETER JOHN CATES find it satisfactory and recommend that it be accepted.

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Chair

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DOWEL BEARING STRENGTH AND BOLTED CONNECTION

BEHAVIOR OF ORIENTED STRAND LUMBER

Abstract

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Oriented strand lumber (OSL) is a relatively new commercial wood composite product with limited research data available in the public domain. This project looked at two aspects of connection behavior in OSL. The first part of the study addressed the effects of strand geometry and level of strand orientation on dowel bearing strength of the composite material. The second part of the study involved evaluation of bolted connection performance in OSL. In particular, European yield model (EYM) equations and end distance requirements were evaluated for effectiveness in predicting connection performance.

Dowel bearing strengths were determined for both the parallel to the strand orientation and the perpendicular to the strand orientation loading cases. Strand nominal lengths of 4, 8 and 12 inches and strand nominal widths of 0.50, 0.75 and 1.00 inches were used to determine the effect of strand geometry on dowel bearing strengths. The manufacturing process used to orient the strands consisted of vanes aligned in the direction of the length of the oscillating forming box. The mean strand angle was used to measure the degree of strand orientation consistency and was dependent on the vane spacing and strand length. A vane spacing of 3 inches was used

with each strand length and an additional vane spacing of 1.5 inches was used with the smaller strand lengths of 4 and 8 inches. Specific gravity and mean strand angle were measured for each of the finished OSL panels. From the analysis of the data collected, it was determined that strand geometry alone did not affect dowel bearing strength. However, level of strand orientation (mean strand angle) was found to affect the dowel bearing strength of specimens loaded perpendicular to the strand orientation. Specific gravity was also found to influence the dowel bearing strength in both the loading scenarios.

The European yield model (EYM) equations were analyzed using three different bolted connection configurations to determine if the EYM was an appropriate method in determining the yield load in connections made with OSL. End distance requirements currently specified in the National Design Specification (NDS) for solid sawn lumber were also investigated to determine if they are applicable for connections made with OSL. When using the EYM equations, actual test data for bolt bending yield strength and dowel bearing strength of the OSL were used in the calculations. Through the comparison of the EYM equations and tested OSL connections, it was determined that the EYM equations adequately model the yield behavior of bolted connections made with OSL. However, the 5 percent diameter offset method was found to be inadequate for determining connection yield load from test data. Based on the data from the connection tests with variable end distances, it was clear that in the Mode I_m and Mode III_s configured connection tests, the 5 percent diameter offset yield load was not affected by end distances as small as four times the fastener diameter (4D).

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EFFECT OF STRAND GEOMETRY ON DOWEL BEARING STRENGTH WHEN USING ORIENTED STRAND LUMBER

ABSTRACT

Oriented strand lumber (OSL) is a relatively new commercial wood composite product with limited research data available in the public domain. This project looked at the effects of strand geometry and level of strand orientation on dowel bearing strengths in OSL. Dowel bearing strengths were determined for both the parallel to the strand orientation and the perpendicular to the strand orientation loading cases. Strand nominal lengths of 4, 8 and 12 inches and strand nominal widths of 0.50, 0.75 and 1.00 inches were used to assess the effects of strand geometry on dowel bearing strengths. The manufacturing process used to orient the strands consisted of vanes aligned in the direction of the length of the oscillating forming box. The degree of overall strand orientation consistency was measured using the mean strand angle, which was dependent on the vane spacing and strand length. A vane spacing of 3 inches was used with each strand length and an additional vane spacing of 1.5 inches was used with the smaller strand lengths of 4 and 8 inches. Specific gravity and mean strand angle were measured for each of the finished OSL panels. From the analysis of the data collected, it was determined that strand geometry alone did not affect dowel bearing strength. However, level of strand orientation (mean strand angle) was found to affect the dowel bearing strength of specimens loaded perpendicular to the strand orientation. Specific gravity was also found to influence the dowel bearing strength in both the loading scenarios.

INTRODUCTION

Wood has been used as a building material for centuries. In the first part of the twentieth century, large diameter trees were abundant and readily harvested throughout North America. With large diameter trees abundant, large clear cross-section timbers and lumber were available to use in construction at an economical price. Toward the end of the twentieth century and into the twenty-first century, many of the large diameter trees had been harvested or protected in old-growth forests. The timber industry developed new wood-based products that would lessen the requirements for large diameter trees and utilize wood fiber more efficiently.

The timber industry has developed methods to produce wood composite products using smaller diameter trees and trees that can be grown more rapidly. Rather than using solid sawn lumber, smaller pieces (strands, particles, veneers, flakes, fiber, etc.) are produced from sawn logs, then coated with resin and pressed together forming a variety of composite products. Through quality control measures and gradual improvements in the manufacturing process, many composite products are able to surpass the strength characteristics of solid sawn lumber (FPL 1999).

Oriented strand lumber (OSL) is based on an earlier product called oriented strand board (OSB). OSB is produced when the plies of strand-based material are formed with the lengths of the strands oriented in the same direction within each ply. Strands in adjacent plies are then oriented perpendicular to one another. This produces a panel with nearly the same strength characteristics in both the length direction and width direction, which can be marketed as a replacement for plywood. For OSL the strands are typically longer than those used in OSB, which helps provide better orientation in some manufacturing processes. Also in OSL, all strands are oriented in the direction that will become the length of the board. Another difference

between OSL and OSB is that OSL panels are typically thicker than OSB panels since OSL is marketed as a replacement for solid sawn lumber. OSL panels are ripped parallel to the direction of the strand orientation to produce the desired dimensions for OSL boards.

Although some composite products have been in use for years and have been tested by both the manufacturers and public institutions, other products have not. OSL is one such product. Proprietary testing has been performed on OSL, but very little test data has been published in scientific journals. In particular, data on dowel bearing strengths for OSL material is needed.

OBJECTIVES

The overall goal of this project was to assess and document the effects of typical manufacturing parameters on the dowel bearing strength behavior of OSL. One specific goal of this project was to determine if strand geometry and level of strand orientation affect the dowel bearing strength of OSL when loaded either parallel or perpendicular to the strand orientation. Another specific goal of this project was to determine if the dowel bearing equations used for solid sawn lumber are appropriate for OSL.

BACKGROUND

When a double shear connection is designed in solid sawn lumber, the specific gravity (SG) of the lumber and the bolt diameter (D) are used in Equation 1-1 and Equation 1-2, to determine the dowel bearing strength (F_e) of the lumber members loaded either parallel or perpendicular to the grain (AF&PA 1997). The two dowel bearing strength equations are based on research performed at the U.S. Forest Products Laboratory (Wilkinson 1991). Wilkinson performed 240 tests on solid sawn lumber, using seven different species of wood and several

different diameters of bolts. Wilkinson concluded that the dowel bearing strength of wood could be calculated using specific gravity of the lumber and diameter of the bolt. Knowing the dowel bearing strength, bolt bending yield strength and geometry of the connection, nominal bolted connection design capacities can be calculated using a series of yield limit equations (AF&PA 1997). The bolted connection design capacity is taken as the lesser of the results from the series of yield limit equations.

$$F_{e_{\parallel}} = 11200\ SG \qquad \text{Equation 1-1}$$

$$F_{e_{\perp}} = \frac{6100\ SG^{1.45}}{\sqrt{D}} \qquad \text{Equation 1-2}$$

Current practice for designing bolted connections with OSL involves looking up an equivalent specific gravity (ESG) from information published by the manufacturer, then following the design procedures used for solid sawn lumber. One such manufacturer is Trus Joist, who produces a commercial OSL product called TimberStrand® LSL. Trus Joist publishes an equivalent specific gravity of 0.5 for their OSL product when loaded parallel to the direction of strand orientation and an increased equivalent specific gravity of 0.58 when bolts are loaded perpendicular to the direction of strand orientation (Trus Joist 2001). The ESG values are determined by determining the actual dowel bearing strength of the material, then back solving Equations 1-1 and 1-2 for specific gravity.

APA – The Engineered Wood Association also uses a form of the equivalent specific gravity procedure. The APA recommends that nail dowel bearing strength equal to that of Douglas-fir lumber from the 1991 NDS be used for OSB panels that bear the APA trademark

(APA 1997). To determine what species of wood to use when determining the nail dowel bearing strength of OSB, APA researchers performed nail dowel bearing tests on OSB and chose a species of wood that had slightly lower nail dowel bearing strength than that of the tested OSB. An average dowel bearing strength of 6084 psi was observed for the OSB tested at APA. Douglas-fir lumber was a common wood species that had a dowel bearing strength for nailed connections of 4650 psi and specific gravity of 0.5 as published in the 1991 NDS (AF&PA 1991). Therefore, OSB marked with the APA trademark uses an equivalent specific gravity of 0.50 for nailed connections.

Recent research has shown that both density and mean strand angle significantly influence the parallel elastic modulus (E) and the ultimate strength (σ_{ult}) for tension and compression in OSL (Meyers 2001). Meyers also showed that once mean strand angle was taken into account, strand length and strand width did not significantly influence E or σ_{ult}.

A slightly earlier study (Hoover et al. 1992) concluded that for varying strand dimensions there was not a significant difference in the OSB properties. Hoover et al. used strand thicknesses of 0.015 and 0.025 inches and strand lengths of 2 and 3 inches. OSB properties tested included: bending modulus of rupture (MOR) and modulus of elasticity (MOE), tensile modulus and strength, internal bond and several other tests.

By determining the parameters that influence strength characteristics the most, manufacturers can refine their manufacturing processes to develop desirable properties for composite products. Meyers' research suggested that manufacturers do not need to handle long strands if they are able to employ strand orientating processes that provide the same degree of orientation with shorter strands. Dowel bearing tests in this study were performed using OSL material from the same panels that Meyers tested.

MATERIALS

The OSL material used in this research was produced at the Washington State University Wood Materials and Engineering Laboratory. Strands were produced from aspen (*Populus tremuloides* Michx) trees that had been logged, debarked and sawn into boards. The aspen boards were then stranded, screened, dried and sprayed with a resin prior to forming a mat of oriented strands. The mat was formed using an oscillating forming box with a specified vane spacing. The oriented strand mats were then hot pressed at 360°F with a 15-minute press-schedule to produce the OSL panels (Meyers 2001).

Panels were created using several different strand geometries and vane spacings. Strand geometries were based on three different strand lengths and three different strand widths, with a constant thickness of approximately 0.03-inch. The strands used were nominally 4, 8 or 12 inches in length, with nominal widths of ½, ¾, or 1 inch. All combinations of strand length and width were formed using a vane spacing of 3 inches. In addition, the 4 and 8 inch strand length combinations also had panels formed with a 1.5 inch vane spacing. Three panels were produced for each combination of strand geometry and vane spacing, resulting in a total of 45 panels. All panels were produced with a nominal thickness of ¾ inch.

Six dowel bearing specimens were cut from each panel. Three specimens were cut such that their longest dimension was parallel to the strand orientation within the panel and the other three were cut with their longest dimension oriented perpendicular to the strand orientation. The specimens were cut from three different regions of the panel with one parallel and one perpendicular specimen coming from each region to produce three sets of specimens from each panel as shown in Figure 1-1. The overall dimensions of the panels were approximately 3.5 ft.

by 3 ft. with the longitudinal dimensions of the individual strands generally oriented in the 3.5 ft. direction.

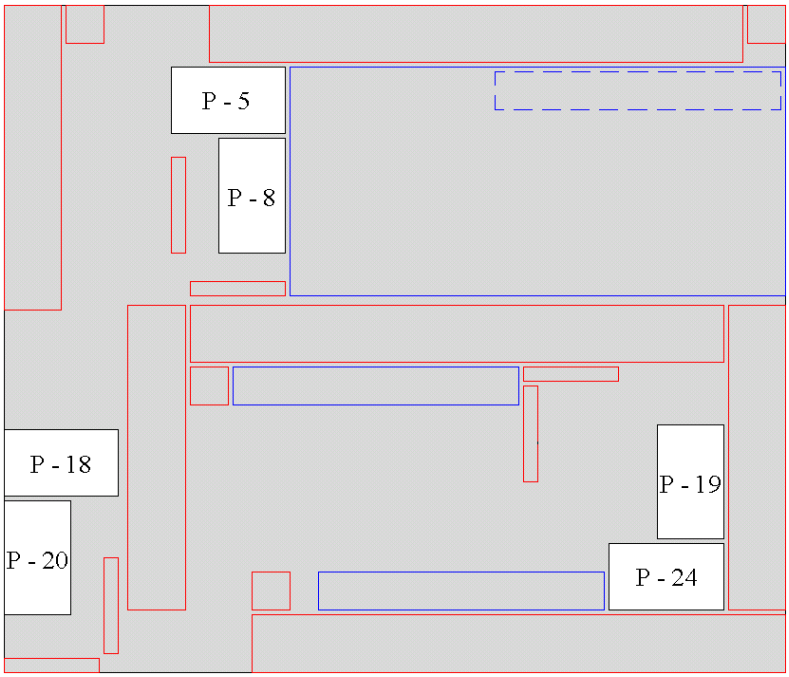

Figure 1-1: *Specimen Location and Orientation with Respect to the OSL Panel*

DENSITY PROFILE

Six density scans were performed on specimens from each of the OSL panels as part of another research project being performed at WSU (Meyers 2001). An x-ray density profiler was used to determine the vertical (through the thickness) density profiles. Specimens were 2 x 2 x 0.75 inches in size and the profiles were generally symmetrical as shown in Figure 1-2. In general, the face densities were approximately 1.5 times that of the core density. A vertical density profile of a commercial OSL product is shown in Figure 1-3. Commercial OSL specimens were 2 x 2 x 1.5 inches in size and the profiles were generally symmetrical and relatively constant.

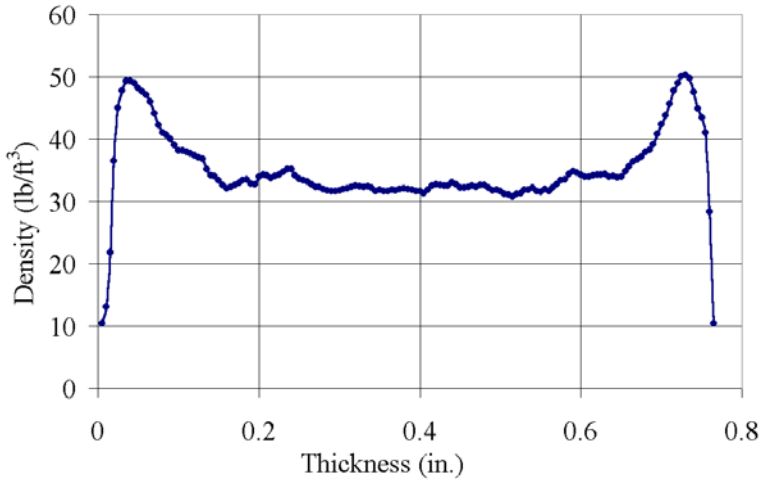

Figure 1-2: *Typical Vertical Density Profile of OSL (Aspen)*

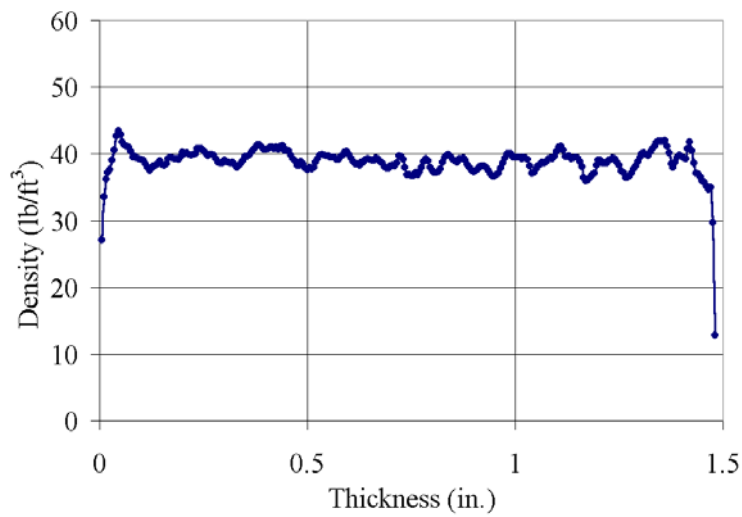

Figure 1-3: *Typical Vertical Density Profile of a Commercial OSL*

MOISTURE CONTENT AND SPECIFIC GRAVITY TESTS

All of the OSL specimens were conditioned to 85° F and 67% relative humidity. Moisture content and specific gravity tests were performed prior to the dowel bearing tests using ASTM D2395 Method A procedures. The calculated moisture content and specific gravity (oven-dry volume) were determined using equations given in ASTM D2395. The oven-dry

specific gravity matches the specific gravity basis used in the NDS (AF&PA 1997) and LRFD (AF&PA 1996) design standards. The average moisture content for the OSL specimens was 0.0881 with a standard deviation of 0.0021. The average specific gravity based on oven-dry weight was 0.60 with a standard deviation of 0.063(Appendix A, Cates 2002).

DOWEL BEARING TESTS

Half-hole dowel bearing tests were performed using the procedures in ASTM D5764-97a. The purpose of this test is to determine the load resistance and deformation characteristics of wood and wood-based products subjected to loads applied through fasteners. In this research, the test consisted of a load being applied to a ½ inch diameter dowel (bolt) placed horizontally in a half-hole drilled in the wood-based specimen.

In the case of the OSL used in this project, the panel was produced with a nominal thickness of 0.75 inches. However, the dowel bearing tests were intended to simulate 1.5 inch thick lumber. Therefore, the ¾ inch thick specimens were cut in half and then glued together using wood adhesive, as shown in Figure 1-4, to create the 1.5 inch thick desired specimen. This material was then drilled using a 9/16 inch spade drill bit and drill press to produce the dowel holes. This represents the use of an oversized bolt hole of 1/16 inch, corresponding to standard fabrication guidelines for bolted connections (AF&PA 1996; AF&PA 1997). The material was then cut through the center of the hole creating a dowel bearing test specimen with a half-hole.

The specimens were tested by applying a compressive load on a bolt resting in the half-hole of the dowel bearing specimen as shown in Figure 1-5. A load rate of 0.03 in/min was used with a 22 kip servo-hydraulic universal testing machine. The universal testing machine had two digital data acquisition devices to record the displacement of the actuator and the load applied. The displacement was measured using an internal linear variable differential transformer

(LVDT) and the load was measured using a 22 kip load cell. An MTS 407-Controller was used to control the rate of loading. The acquisition devices were connected to a computer where LabView software was used to collect the data. Load-displacement curves were created from the data collected (see Appendix A, Cates 2002).

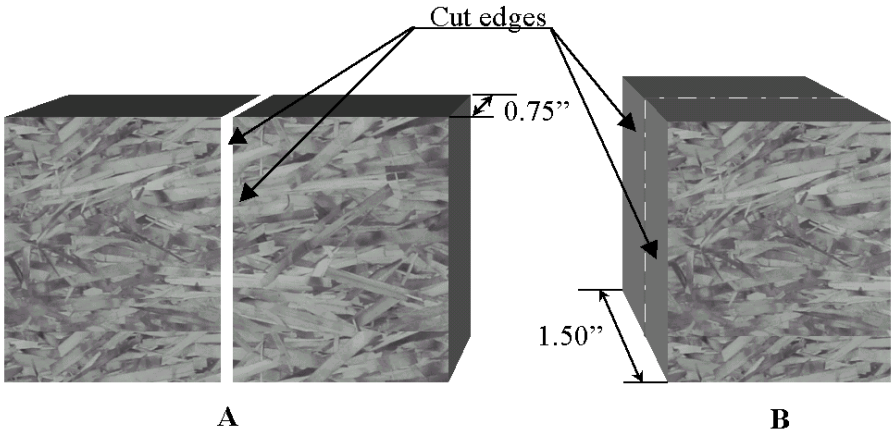

Figure 1-4: *Cutting panel specimens to create dowel bearing test specimens: (A) 0.75 inch thick panel specimen cut in half; (B) cut panel specimens glued together to form 1.5 inch thick material.*

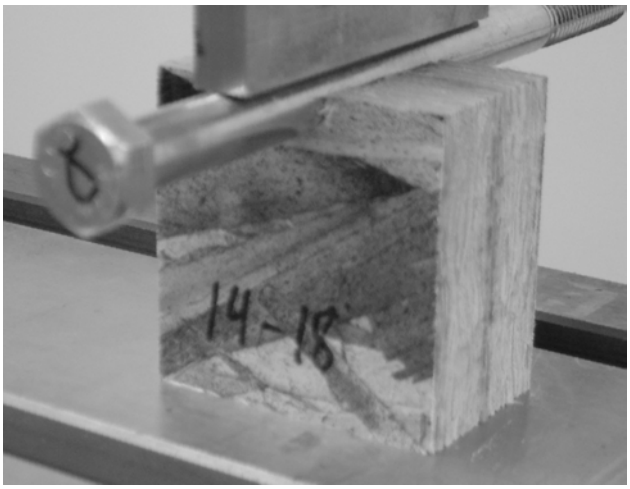

Figure 1-5: *Dowel Bearing Specimen Test Setup*

FIVE PERCENT DIAMETER OFFSET METHOD

From the load-displacement curves, a 5 percent diameter offset method was used to determine the yield loads in accordance with the provisions of ASTM D5764-97a. The 5 percent diameter offset method is accomplished by creating a line that is parallel to the first linear region of the load-displacement curve. The parallel line is drawn at a distance of 5 percent of the bolt diameter to the right of the linear region on the load-displacement curve. The yield load is read from the graph where the parallel 5 percent diameter offset line intersects the load-displacement curve. The method to determine the 5 percent diameter offset yield load is illustrated in Figure 1-6.

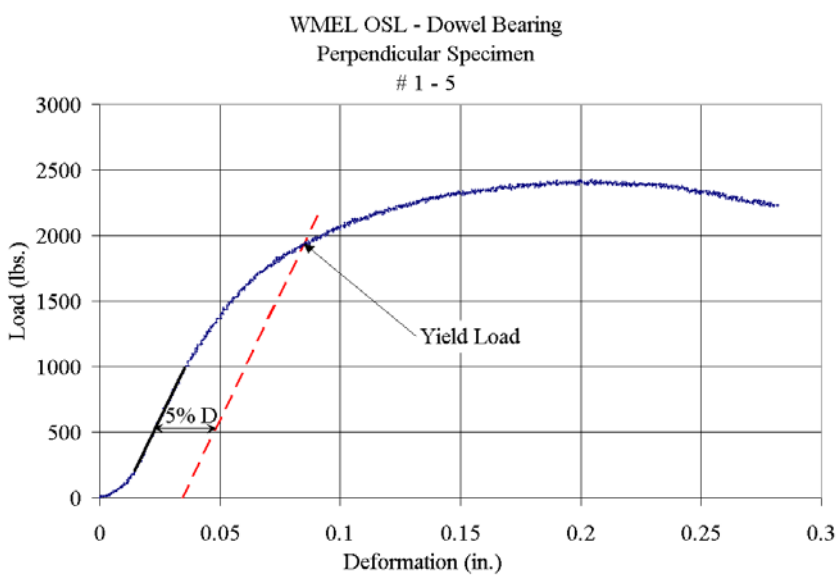

Figure 1-6: *Determining the Yield Load from a Load versus Displacement Curve*

RESULTS

Two different forms of ultimate failure were observed during the dowel bearing tests. In the specimens loaded parallel to the strand orientation, significant crushing occurred under the bolt in the half-hole prior to ultimate failure. For those specimens that were loaded well past

yield load and experienced an abrupt drop in load, cracks formed from the half-hole to the base of the specimen throughout the thickness. Splitting had a tendency to occur along the grain of the strands, which split the strands. By generally following the grain of the individual strands, the longitudinal cracks would propagate to the base of the specimen and appear as a jagged surface crack as shown in Figure 1-7. All of the specimens tested parallel to the strand orientation exhibited the same general behavior. Dowel bearing tests were also performed using a commercial OSL product loaded parallel to the strand orientation (Chapter 2, Cates 2002). The commercial product exhibited the same crushing behavior under the bolt and experienced the same general cracking behavior observed in the aspen-based OSLat ultimate failure.

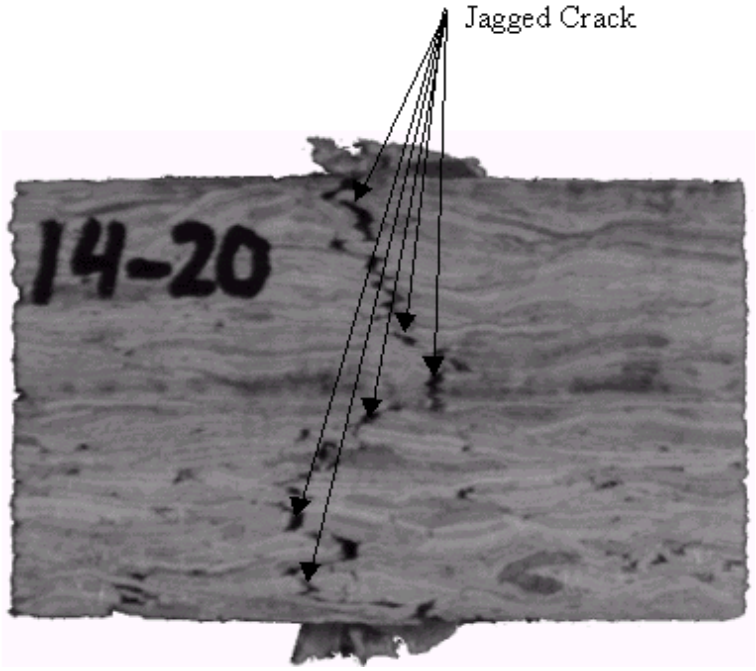

Figure 1-7: *Jagged Crack in the Base of a Dowel Bearing Specimen Loaded Parallel to the Strand Orientation*

In the specimens loaded perpendicular to the strand orientation, crushing was observed in the half-hole under the bolt, but cracks did not propagate through the thickness of the specimen. Instead the cracks or splitting tended to propagate through the width and height of the specimen

and might surface on any of the 1.5 inch thick edges of the specimen. Horizontal cracks occurred on the face of a few specimens due to buckling of surface strands. Figure 1-8 shows a dowel bearing specimen loaded perpendicular to strand orientation that experienced crushing beneath the bolt, splitting through the specimen width and permanent deformation of the top surface. The top surface of specimens loaded perpendicular to the strand orientation were typically observed to deform downward in the center as a simply supported beam might deform under a concentrated load applied at midspan. There was no significant deformation of the top surface in the specimens loaded parallel to the strand orientation.

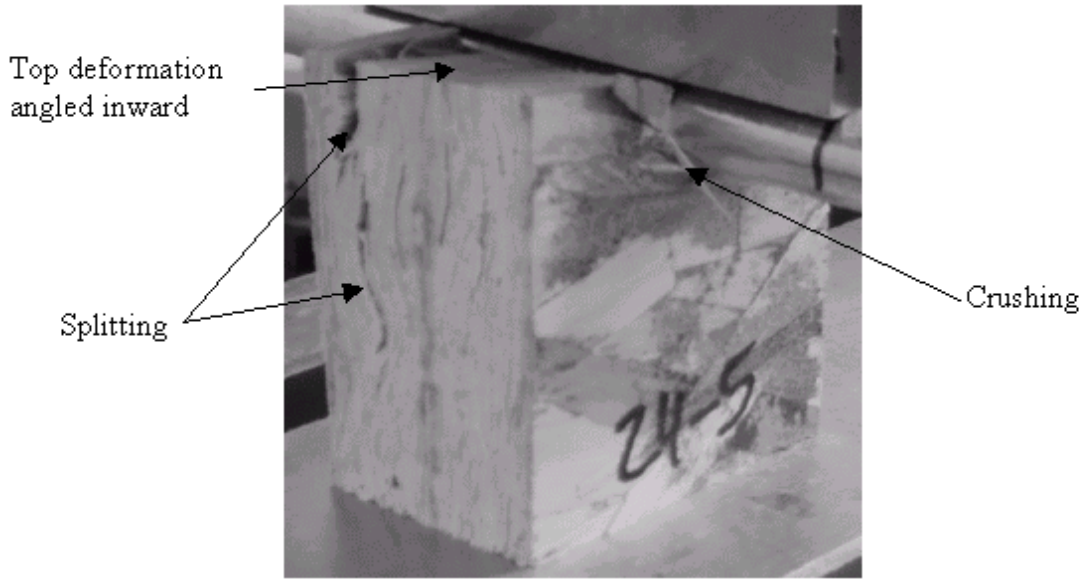

Figure 1-8: *Dowel Bearing Specimen Loaded Perpendicular to the Strand Orientation*

Dowel bearing specimens loaded perpendicular to strand orientation exhibited ultimate failure due to tension through the thickness of the specimens. This failure pattern may be associated with insufficient internal bond strength. Therefore, by increasing the internal bond strength of the material, the ultimate dowel bearing strength of the specimen should increase.

Dowel bearing strengths (F_e) were found using Equation 1-3 with the 5 percent diameter offset yield load (P_y), bolt diameter (D), and specimen thickness (t). Ultimate dowel bearing strengths (F_u) were calculated using Equation 1-3 with the ultimate load (P_u), bolt diameter and specimen thickness. The results were then grouped based on the strand geometry, vane spacing and loading direction for each specimen tested. The average dowel bearing strengths and average ultimate dowel bearing strengths for the grouped specimens that were loaded parallel to the strand orientation are given in Table 1-1. The average dowel bearing strengths and ultimate dowel bearing strengths for the grouped specimens that were loaded perpendicular to the strand orientation are shown in Table 1-2. Coefficient of variation (COV) of the two dowel bearing strengths are also provide in Table 1-1 and Table 1-2 for the grouped specimens.

$$F = \frac{P}{D\,t} \qquad \text{Equation 1-3}$$

Table 1-1: *Dowel Bearing Strengths (F_e) and Ultimate Dowel Bearing Strengths (F_u) for Specimens Loaded Parallel to Strand Orientation*

Vane Spacing (in.)	Nominal Strand Dimensions Length (in.)	Width (in.)	Mean F_e (psi)	COV of F_e (%)	Mean F_u (psi)	COV of F_u (%)
1.5	4	0.50	4975	13.0	5096	11.9
1.5	4	0.75	5077	10.0	5281	8.1
1.5	4	1.00	4574	17.6	4761	14.8
1.5	8	0.50	4403	12.6	4498	11.5
1.5	8	0.75	4661	17.1	4733	16.7
1.5	8	1.00	4412	19.6	4479	18.8
3.0	4	0.50	4822	16.4	5527	15.0
3.0	4	0.75	4426	21.7	5041	22.0
3.0	4	1.00	5013	23.8	5631	22.2
3.0	8	0.50	5094	26.7	5345	25.3
3.0	8	0.75	5332	22.4	5620	20.5
3.0	8	1.00	4904	19.1	5101	17.4
3.0	12	0.50	5366	11.8	5485	11.9
3.0	12	0.75	5307	27.6	5441	27.3
3.0	12	1.00	4680	19.4	4796	19.2

Table 1-2: *Dowel Bearing Strengths (F_e) and Ultimate Dowel Bearing Strengths (F_u) for Specimens Loaded Perpendicular to Strand Orientation*

Vane Spacing (in.)	Nominal Strand Dimensions Length (in.)	Width (in.)	Mean F_e (psi)	COV of F_e (%)	Mean F_e (psi)	COV of F_e (%)
1.5	4	0.50	3767	18.7	5221	11.2
1.5	4	0.75	3383	14.5	4919	13.1
1.5	4	1.00	3264	16.6	4574	14.9
1.5	8	0.50	3106	24.6	4534	20.7
1.5	8	0.75	2819	23.7	4255	30.3
1.5	8	1.00	2762	15.9	3665	10.9
3.0	4	0.50	3576	19.5	4903	22.7
3.0	4	0.75	3840	31.3	5023	16.0
3.0	4	1.00	3895	28.6	5629	12.8
3.0	8	0.50	3592	24.0	5141	20.7
3.0	8	0.75	3871	25.2	5154	27.4
3.0	8	1.00	3521	24.4	4780	16.0
3.0	12	0.50	3331	17.2	4126	16.7
3.0	12	0.75	3303	17.8	4374	17.1
3.0	12	1.00	3019	13.3	3981	9.4

The average dowel bearing strength from the all the specimens loaded parallel to the strand orientation is 4870 psi with a coefficient of variation of 19.6 percent. The average dowel bearing strength from the all the specimens loaded perpendicular to the strand orientation is 3403 psi with a coefficient of variation of 23.6 percent. The average ultimate dowel bearing strength from the all the specimens loaded parallel to the strand orientation is 5122 psi with a coefficient of variation of 19.1 percent. The average ultimate dowel bearing strength from the all the specimens loaded perpendicular to the strand orientation is 4683 psi with a coefficient of variation of 20.2 percent.

Table 1-3 provides a comparison of these dowel bearing strengths to published dowel bearing strengths. The data provided by AF&PA are the published design values for solid sawn lumber. Carstens' (1998) data comes from testing performed on a commercial OSL and on solid

sawn yellow poplar lumber. Trus Joist provides an equivalent specific gravity (ESG) that can be used with the Wilkinson equations (Equations 1-1 and 1-2) to determine the dowel bearing strength of their commercial OSL. Dowel bearing tests parallel to strand orientation were also performed on commercial OSL as part of this study.

Table 1-3: *Comparison of Dowel Bearing Strength*

Material	Loading Direction with respect to Strand Orientation	F_e (psi)	Source
OSL (aspen) - ½" bolts	Parallel	4870	
OSL (aspen) - ½" bolts	Perpendicular	3403	
Aspen - all bolt sizes	Parallel	4350	AF&PA 1997
Aspen - ½" bolts	Perpendicular	2200	AF&PA 1997
OSL (yellow poplar) - ½" bolts	Parallel	6278	Chapter 2, Cates 2002
OSL (yellow poplar) - ½" bolts	Parallel	7084	Carstens 1998
OSL (yellow poplar) - ½" bolts	Perpendicular	6379	Carstens 1998
OSL (yellow poplar) - all bolt sizes	Parallel	5600	ESG method, Trus Joist 2001
OSL (yellow poplar) - ½" bolts	Perpendicular	3916	ESG method, Trus Joist 2001
Yellow poplar - ½" bolts	Parallel	6830	Carstens 1998
Yellow poplar - ½" bolts	Perpendicular	2624	Carstens 1998
Yellow poplar - all bolt sizes	Parallel	4800	AF&PA 1997
Yellow poplar - ½" bolts	Perpendicular	2550	AF&PA 1997

It is clear from the comparison of the dowel bearing strengths in Table 1-3 that the OSL produced for this project with aspen strands had a larger dowel bearing strength then that of solid sawn aspen. The average dowel bearing strength of the aspen OSL specimens loaded parallel to strand orientation was 1.12 times the dowel bearing strength for solid sawn aspen loaded parallel to the grain. The aspen OSL specimens loaded perpendicular to strand orientation had a dowel bearing strength of 1.55 times the dowel bearing strength for solid sawn aspen loaded perpendicular to the grain. In the tests performed by the author, the average dowel bearing strength of the commercial yellow poplar OSL loaded parallel to the strand orientation was 1.31

times the dowel bearing strength of the published values for solid sawn yellow poplar and 1.12 times the value of dowel bearing strength determined by using the ESG published by Trus Joist. As shown in Table 1-3, the average dowel bearing strengths from Carstens' (1998) show similar trends.

The aspen-based OSL produced at WSU exhibited only a 12% increase in dowel bearing strengths when compared with the published dowel bearing strengths for solid sawn aspen lumber. In contrast, the commercial yellow poplar-based OSL exhibited a 31% increase in dowel bearing strengths when compared with the published dowel bearing strengths for solid sawn yellow poplar lumber. One possible reason for this difference was the vertical density profiles achieved in the manufacturing process. As shown in Figure 1-2 and Figure 1-3, the aspen-based OSL had face densities that were approximately 1.5 times that of the core density. When the aspen-based OSL was tested for dowel bearing strength, the highest density material would be expected to attract higher load concentrations, leading to nonuniform stress distribution through the thickness of the dowel bearing specimens. In contrast, the Commercial OSL however had nearly constant density throughout the thickness of the material and therefore exhibited more uniform stress distribution through the thickness of the specimens.

A statistical analysis of variance (ANOVA) was used to determine which variables had an influence on the dowel bearing strength of the specimens. Since the panels made with the 12 inch strands only had one vane spacing and the panels with the 4 and 8 inch strands had two different vane spacings, a general linear model (GLM) was found to be the best ANOVA procedure to use. In setting up the GLM, the strand width and strand length were available as factors affecting the dowel bearing strength. The specific gravity and mean strand angle values were available as covariates. The factors represent the variables that were controlled in the

manufacturing process and the covariates are variables that were measured for each specimen but were not controlled in the manufacturing process. The specific gravity values were measured for specimens from three different regions of each panel (see Appendix A, Cates 2002). Table 1-4 provides the average specific gravity for each OSL panel configuration.

Strand angles were determined using a digital image analysis technique. Digital photographs were taken of both faces of a panel. Approximately 170 randomly chosen individual strands from both faces of each panel were analyzed to determine the angle that individual strands formed with the longitudinal axis of the panel. The mean strand angle for each panel was calculated as the average of the absolute value of the individual strand angles. The analysis of the mean strand angle was performed as part of another research project utilizing the same OSL panels (Meyers 2001). Table 1-4 provides the average mean strand angle for each OSL panel configuration.

Since all of the dowel bearing specimens had nearly identical moisture content (Appendix A, Cates 2002), moisture content was not used as a covariate in the statistical analysis. Vane spacing was not used as a factor in the model because the primary purpose of vane spacing was to develop the mean strand angle. The strand length, which contributed to the mean strand angle, was included as a factor because it was assumed that the length of the individual strands might have additional influence on dowel bearing strength.

Table 1-4: *Specific Gravity and Mean Strand Angle for each Panel Configuration*

Vane Spacing (in.)	Target Strand Dimensions (in.) Length	Width	Specific Gravity Mean	COV (%)	Mean Strand Angle Mean (°)	COV (%)
1.5	4	0.50	0.61	6.6	17.97	4.0
1.5	4	0.75	0.54	11.1	19.03	7.4
1.5	4	1.00	0.59	8.0	17.77	3.4
1.5	8	0.50	0.61	9.0	11.81	1.6
1.5	8	0.75	0.63	10.7	12.65	9.5
1.5	8	1.00	0.60	10.1	13.40	4.2
3.0	4	0.50	0.57	9.8	28.70	7.2
3.0	4	0.75	0.57	10.0	28.42	4.4
3.0	4	1.00	0.56	10.4	28.25	6.6
3.0	8	0.50	0.60	8.4	19.00	6.5
3.0	8	0.75	0.62	7.7	17.78	6.5
3.0	8	1.00	0.64	10.2	18.31	3.8
3.0	12	0.50	0.58	8.9	18.51	6.3
3.0	12	0.75	0.64	15.5	17.09	10.6
3.0	12	1.00	0.60	11.4	14.46	3.7

The parameters that had an effect on the dowel bearing strength were determined from the results of the ANOVA for the dowel bearing strengths (Appendix A, Cates 2002). The results of the statistical analysis are shown in Table 1-5 and Table 1-6. It is clear that the specific gravity of the specimens exhibits a statistically significant influence on dowel bearing strength for both the parallel to strand orientation and perpendicular to strand orientation loading cases. This supports the equations determined by Wilkinson for dowel bearing strength in solid sawn lumber (Wilkinson 1991). It is also apparent that the mean strand angle exhibits a statistically significant influence on dowel bearing strength for the perpendicular to strand orientation loading case. However, the analysis shows that the mean strand angle is not statistically significant for specimens loaded parallel to the direction of strand orientation.

Table 1-5: *Dowel Bearing Strength Statistical Results for the Parallel Loading Case*

Source	F-Statistic	P-Value	Statistically
Specific Gravity	11.64	0.001	Significant
Mean Strand Angle	1.53	0.218	Not Significant
Strand Length	1.06	0.349	Not Significant
Strand Width	0.80	0.453	Not Significant

Table 1-6: *Dowel Bearing Strength Statistical Results for the Perpendicular Loading Case*

Source	F-Statistic	P-Value	Statistically
Specific Gravity	8.06	0.005	Significant
Mean Strand Angle	9.94	0.002	Significant
Strand Length	0.24	0.787	Not Significant
Strand Width	0.55	0.579	Not Significant

Scatter plots were created to show the relationship between the statistically significant variables and dowel bearing strength. Figure 1-9 shows the relationship between specific gravity and the dowel bearing strength for aspen OSL specimens loaded parallel to the strand orientation. The graph also shows the relationship between dowel bearing strength and specific gravity for a commercial yellow poplar-based OSL product (Chapter 2, Cates 2002). In addition, Figure 1-9 shows the NDS dowel bearing strength equation (Equation 1-1) developed by Wilkinson for solid sawn lumber loaded parallel to the grain. Figure 1-10 shows the relationship between specific gravity and dowel bearing strength for aspen OSL specimens loaded perpendicular to the strand orientation and specific gravity. The graph also shows the NDS dowel bearing strength equation (Equation 1-2) developed by Wilkinson for solid sawn lumber loaded perpendicular to the grain using a bolt diameter of 0.5 inches. Figure 1-11 shows the relationship between dowel bearing strength of each specimen loaded perpendicular to the strand orientation and the mean strand angle.

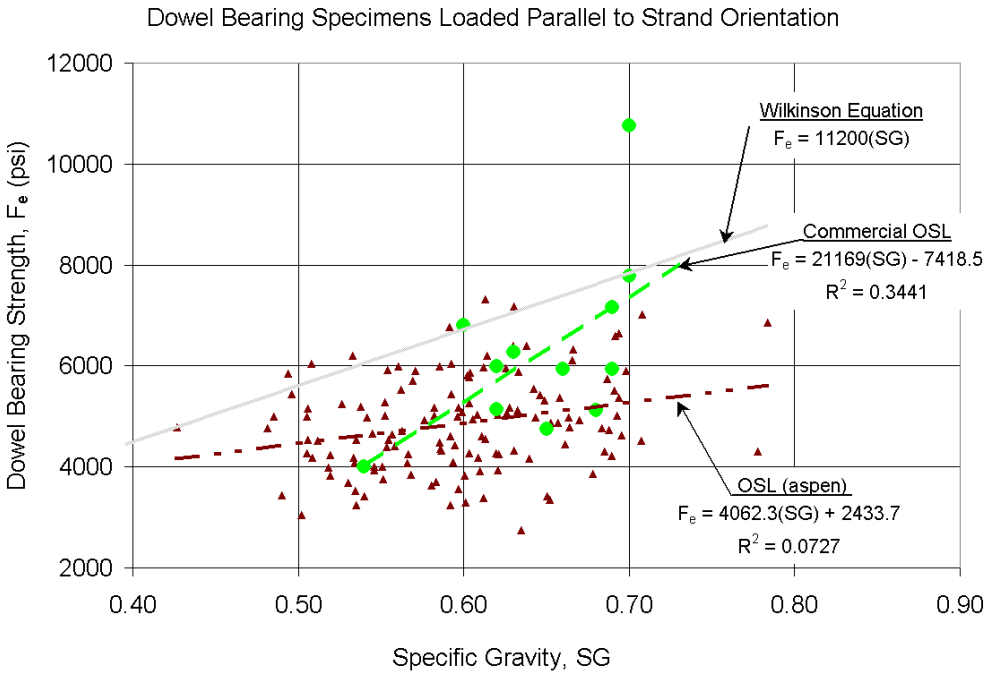

Figure 1-9: *Dowel Bearing Strength vs. Specific Gravity Scatter Plot for Dowel Bearing Specimens Loaded Parallel to the Strand Orientation*

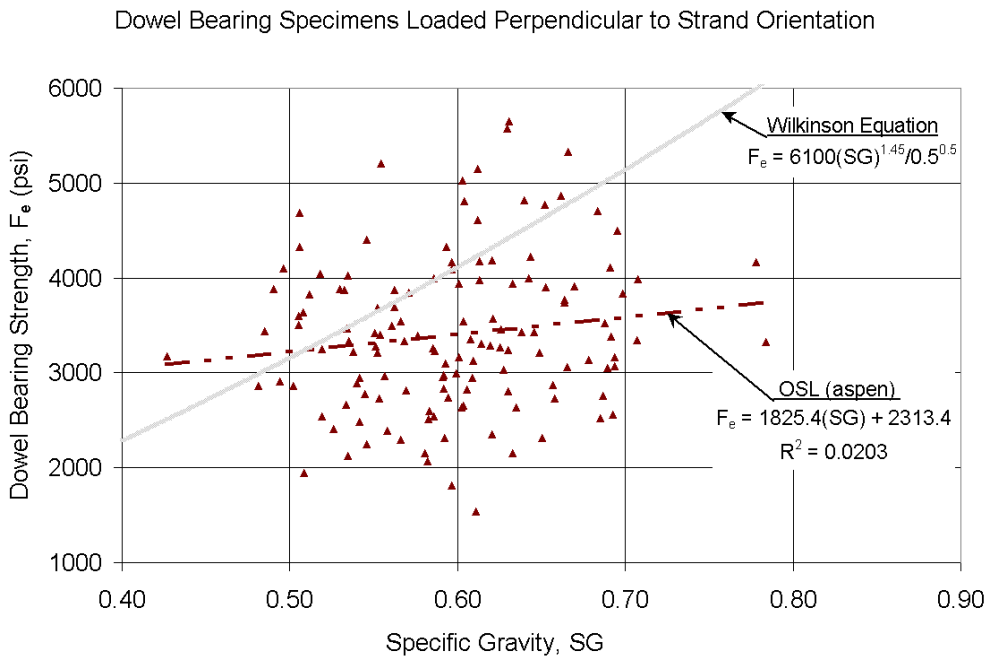

Figure 1-10: *Dowel Bearing Strength vs. Specific Gravity Scatter Plot for Dowel Bearing Specimens Loaded Perpendicular to the Strand Orientation*

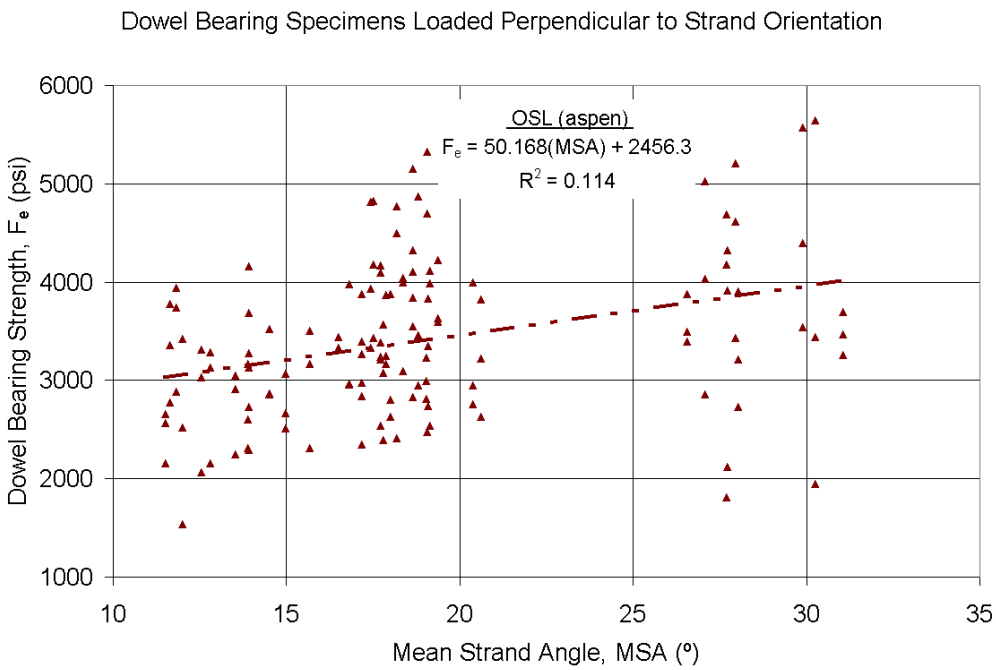

Figure 1-11: *Dowel Bearing Strength vs. Mean Strand Angle Scatter Plot for Dowel Bearing Specimens Loaded Perpendicular to the Strand Orientation*

The equations of the best-fit lines for the aspen-based OSL (aspen) show that the statistically significant variables from the ANOVA results are not strong indicators of the dowel bearing strength. The nearly horizontal best-fit regression line and low R-squared value shown in Figure 1-9 indicate that specific gravity is not a very strong predictor of dowel bearing strength for the OSL used in this study when loaded parallel to the strand orientation. Similarly, Figure 1-10 and Figure 1-11 indicate that specific gravity and mean strand angle are not strong predictors of OSL dowel bearing strength when loaded perpendicular to the strand orientation.

Since the ANOVA for the perpendicular loading case indicated that both specific gravity and mean strand angle were statistically significant to dowel bearing strength, a multiple regression was performed (Appendix A, Cates 2002). The adjusted R-squared value of the multiple regression was determined to be 0.151, which indicates that it is not much better than the single variable regressions, shown in the scatter plots, in predicting dowel bearing strength.

Wilkinson observed a strong correlation between specific gravity and dowel bearing strength for solid sawn lumber. In contrast, Figure 1-9 and Figure 1-10 indicate that there is not a strong correlation between specific gravity and dowel bearing strength for OSL members. One possible explanation for these different trends lies in the method of achieving higher density in OSL materials. During the production of OSL material, densification may be associated with damage to the strands during the heating and pressing process. The resulting resin crushed strands cannot be expected to perform in the same manner as undamaged wood fibers. Thus, while solid wood exhibits a strong directly proportional relationship between dowel bearing strength and specific gravity, OSL tends to exhibit only a slight increase in dowel bearing strength with increasing specific gravity.

CONCLUSIONS

Using an ANOVA that considered specimen specific gravity, mean strand angle, strand length and strand width, the dominant parameters that influenced dowel bearing strength in OSL were found. The only parameter found to exhibit a statistically significant affect on the dowel bearing strength in specimens loaded parallel to strand orientation was the specific gravity of the material. In the specimens loaded perpendicular to strand orientation, the specific gravity and mean strand angle were both found to affect the dowel bearing strength of the specimen. Based on dowel bearing tests performed on commercial OSL using a limited range of bolt diameters, there was some evidence to suggest that OSL dowel bearing strength loaded parallel to the strand orientation and perpendicular to the strand orientation might be influenced by the bolt diameter (Carstens 1998). Mean strand angle was found to only be significant for the perpendicular to strand orientation loading case for the range of angles measured in this project (between approximately 11 and 31 degrees). Manufacturers might find it possible to increase the

perpendicular to strand orientation dowel bearing strength by decreasing the level of strand orientation without decreasing the parallel to strand orientation dowel bearing strength.

For the range of strand lengths and widths used in this study, it was determined that the strand dimensions did not significantly effect the dowel bearing strengths of either the parallel or perpendicular to the strand orientation loading cases. It was determined that orientation did play a role in the perpendicular case, but strand dimensions were only one of several factors used to help orient the strands. If other factors in the orientation process were refined to allow 4 inch long strands to have the same mean strand angle as 12 inch long strands, then it is reasonable to conclude there would be no need to use the longer strands to achieve a desirable dowel bearing strength. It is up to the manufacturer to determine if it is more cost effective to develop a higher level of orientation through refining the orientation process or through the use of longer strands.

Scatter plots of dowel bearing strength versus specific gravity were created for both the parallel and perpendicular loading cases. The low R-squared value of the regression lines indicates that specific gravity is not a strong predictor of dowel bearing strength for either loading case. The scatter plot and corresponding R-squared value of dowel bearing strength versus mean strand angle for the perpendicular loading case indicates that mean strand angle is not a strong predictor of dowel bearing strength. The low adjusted R-squared value found by performing a multiple regression on the dowel bearing strength, specific gravity and mean strand angle of specimens loaded perpendicular to strand orientation indicated that the combined specific gravity and mean strand angle were also not strong indicators of dowel bearing strength. In general, it appears that dowel bearing strengths should be determined experimentally for each OSL product, regardless of variations in strand geometry, strand orientation and material density.

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CHAPTER 2:

DOUBLE SHEAR BOLTED CONNECTIONS IN ORIENTED STRAND LUMBER

ABSTRACT

Oriented strand lumber (OSL) is a relatively new commercial wood composite product with little research data available in the public domain. This project encompassed the testing and analysis of double shear bolted connections that were designed using commercial OSL. The European yield model (EYM) equations were analyzed using three different bolted connection configurations to determine if the EYM was an appropriate method in determining the yield load in connections made with OSL. End distance requirements currently specified in the National Design Specification (NDS) for solid sawn lumber were also investigated to determine if they are applicable for connections made with OSL. When using the EYM equations, actual test data for bolt bending yield strength and dowel bearing strength of the OSL were used in the calculations.

Modes I_m, III_s and IV connection configurations were tested in this project. Through the comparison of the EYM equations and tested OSL connections, it was determined that the EYM equations adequately model the yield behavior of bolted connections made with OSL. Based on the data from the connection tests with variable end distances, it was clear that in the Mode I_m and Mode III_s configured connection tests, the 5 percent diameter offset yield load was not affected by end distances as small as four times the fastener diameter (4D).

INTRODUCTION

Wood has been used as a building material for centuries. In the first part of the twentieth century, large diameter trees were abundant and readily harvested throughout North America. With large diameter trees abundant, large clear cross-section timbers and lumber were available

to use in construction at an economical price. Towards the end of the twentieth century and into the twenty-first century, many of the large diameter trees had been harvested or protected in old-growth forests. The timber industry developed new wood-based products that would lessen the requirements for large diameter trees and utilize wood fiber more efficiently.

The timber industry has developed methods to produce wood composite products using smaller diameter trees and trees that can be grown more rapidly. Rather than using solid sawn lumber, smaller pieces (strands, particles, veneers, flakes, fiber, etc.) are produced from sawn logs, then coated with resin and pressed together forming a variety of composite products. Through quality control measures and gradual improvements in the manufacturing process, many composite products were able to surpass the strength characteristics of solid sawn lumber (FPL 1999).

Oriented strand lumber (OSL) is based on an earlier product called oriented strand board (OSB). OSB is produced when the plies of strand-based material are formed with the lengths of the strands oriented in the same direction within each ply. Strands in adjacent plies are then oriented perpendicular to one another. This produces a panel product with nearly the same strength characteristics in both the length direction and width direction, which can be marketed as a replacement for plywood. For OSL, the strands are typically longer than those used in OSB, which helps provide better orientation in some manufacturing processes. Also in OSL, all strands are oriented in the direction that will become the length of the board. Another difference between OSL and OSB is that OSL panels are typically thicker than OSB panels since OSL is marketed as a replacement for solid sawn lumber. OSL panels are ripped parallel to the direction of the strand orientation to produce the desired OSL dimensions.

Although some of the composite products have been in use for years and have been tested by both the manufacturers and public institutions, other products have not. Oriented strand lumber (OSL) is one such product. Proprietary testing has been performed on OSL, but very little test data has been published in scientific journals. In particular, bolted connection tests to verify the use of the European yield model (EYM) and appropriate end distance requirements are needed.

OBJECTIVES

The overall goal of this project was to assess bolted connection behavior for OSL material. A specific goal of this project was to determine if the current NDS yield mode equations accurately predict the yield load of double shear bolted connections designed with commercial OSL materials. Another specific goal of this project is to determine whether the current end distance requirement for double shear bolted connections loaded in tension in solid sawn lumber is overly conservative when using OSL.

BACKGROUND

When a double shear connection is designed in solid sawn lumber, the specific gravity (SG) of the lumber and the bolt diameter (D) are used in Equation 2-1 and Equation 2-2, to determine the dowel bearing strength of the lumber members loaded either parallel or perpendicular to the grain (AF&PA 1997). The two dowel bearing strength (F_e) equations are based on research performed at the U.S. Forest Products Laboratory (Wilkinson 1991). Wilkinson performed 240 tests, using seven different species of wood and several different diameters of bolts. Wilkinson concluded that the dowel bearing strength of wood could be estimated based on specific gravity and bolt diameter. Knowing the dowel bearing strength, bolt

bending yield strength and geometry of the connection, the nominal bolted connection design capacity can be determined based on the theoretically derived yield limit equations (Equations 2-7 through 2-9).

$$F_{e_{\parallel}} = 11200\ S.G. \qquad \text{Equation 2-1}$$

$$F_{e_{\perp}} = \frac{6100\ S.G.^{1.45}}{\sqrt{D}} \qquad \text{Equation 2-2}$$

Determining the load at which material yielding (yield limit) will occur in a structural application is desirable because up until that point, the material exhibits elastic properties. If the loaded material stays in the elastic range, then after the load is removed the material should return to its undeformed shape. Once the material reaches loads above the yield point, then the material will become inelastic. Inelastically deformed material does not fully return to its original shape once applied loads are removed. The 5 percent diameter offset method is typically used to determine the yield limit for bolted connections in sawn lumber. Loads applied up to this level are assumed to cause only elastic deformation in the connection.

In an early research study, tests on bolted connections were performed and analyzed using a proportional-limit load (Trayer 1932). A proportional-limit load was the load at the upper end of the linear region of a load-displacement curve and was an alternate methods of defining the yield limit. Part of Trayer's study looked at repetitive loading and reloading of bolted connections. Trayer concluded that connection tests that were loaded as much as 25 percent greater load than the proportional-limit had slight increases to the proportional-limit load over the previous loads. The 5 percent diameter offset method typically predicts loads between the proportional-limit load and loads 25 percent greater than the proportional limit.

Current practice for designing bolted connections with OSL involves looking up an equivalent specific gravity from information published by the manufacturer, then applying the yield limit equations used for solid sawn lumber. One such manufacturer is Trus Joist, who produces a commercial OSL product called TimberStrand® LSL. Trus Joist publishes an equivalent specific gravity of 0.5 for their OSL product when loaded parallel to the direction of strand orientation and an increased equivalent specific gravity of 0.58 when bolts are loaded perpendicular to the direction of strand orientation (Trus Joist 2001).

Equivalent specific gravity for oriented strand composite products is determined by testing the dowel bearing strength of the material in both parallel and perpendicular directions. The parallel direction is generally in the direction of the strand length within the member. The perpendicular direction is perpendicular to the parallel direction. The average dowel bearing strengths are then used with either Equation 2-3 or Equation 2-4 to determine an equivalent specific gravity (ESG) for the particular loading case (ADTM D5456). Manufacturers typically publish equivalent specific gravity values for their proprietary composite products.

$$ESG_{\parallel} = \frac{F_{e_{\parallel}}}{11200} \qquad \text{Equation 2-3}$$

$$ESG_{\perp} = \left(\frac{F_{e_{\perp}} \sqrt{D}}{6100} \right)^{0.6897} \qquad \text{Equation 2-4}$$

Beginning with the 1991 National Design Specification for Wood Construction (NDS), engineers started designing bolted connections using yield limit equations based on the European yield model (EYM). The yield limit equations were based on European research and have been confirmed with testing performed in North America on solid sawn lumber from domestic species (AF&PA 1997). Connections using composite material are typically designed using the same

equations that were developed and verified with solid sawn lumber. End and edge distance requirements for solid sawn lumber are also typically applied to strand-based material such as OSL.

End distance requirements in the NDS were based on early research performed by Trayer at the U.S. Forest Products Laboratory and have been in the Specification since the 1944 edition (AF&PA 1997). Trayer performed several hundred bolted connection tests using lumber from five different species of coniferous and deciduous wood (Trayer 1932). Trayer determined the proportional-limit loads and maximum loads from the bolted connection tests and recommended the end distance requirements currently used in the NDS for "full design value". Unfortunately, it is unclear whether Trayer's end distance recommendations were based on reductions in the proportional-limit loads or maximum loads for the various connection configurations. Table 2-1 gives the NDS minimum end distance requirements for bolted connections (AF&PA 1997).

The "7D" in the table for softwood bolted connections loaded parallel to the grain in tension represents an end distance requirement of 7 times the diameter of the bolt. If the end distance requirement of 7D is not met, the load capacity of the connection must be reduced. If the 3.5D end distance requirement for "reduced design value" is not met, then the connection is not permitted to carry any structural load.

Table 2-1: *NDS End Distance Requirements for Bolts*

Direction of Loading	Minimum End Distances for: Reduced Design Value	Full Design Value
Perpendicular to Grain	2D	4D
Parallel to Grain, Compression: (bolt bearing away from member end)	2D	4D
Parallel to Grain, Tension: (bolt bearing toward from member end)		
for softwoods	3.5D	7D
for hardwoods	2.5D	5D

MATERIALS

The wood based material used in the double shear bolted connections was a yellow poplar (*Liriodendron tulipifera* L.) based OSL. This material was produced commercially and was part of a shipment used for prior research conducted at Washington State University (Carstens 1998; Sattabongkot 2000). The OSL was stored in a controlled environment for over a year prior to testing and had cross sectional dimensions of 1.5 by 5.5 inches (nominally 2 x 6).

Three different sets of bolts were used in the connection tests. Two sets of ½ inch diameter bolts with lengths of 7-3/8 inches and 11 inches were used for the Mode III_s and Mode IV connections respectfully, and a third set of ¾ inch diameter bolts was used for the Mode I_m connections. All bolts were ASTM A307 Grade A bolts. To reduce variability, each set of bolts came from a single lot.

DENSITY PROFILE

Density scans were performed on samples from nine randomly selected OSL boards. An x-ray density profiler was used to determine the vertical density profiles on the nine specimens. Specimens were 2 inches square by 1.5 inches thick and the profiles were generally symmetrical as shown in Figure 2-1. Density was relatively constant through the thickness of each of the specimens.

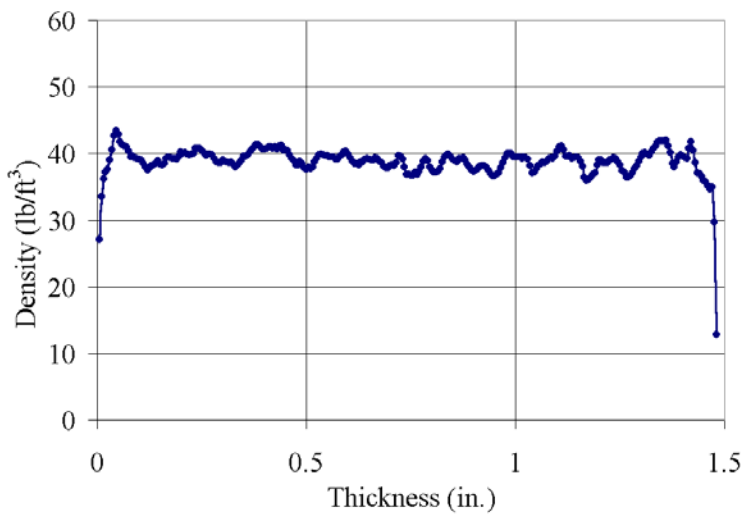

Figure 2-1: *Typical Vertical Density Profile for an OSL Specimen*

MOISTURE CONTENT AND SPECIFIC GRAVITY TESTS

OSL specimens were not conditioned to a specific moisture content. Instead, moisture content and specific gravity tests were performed at the time of the double shear bolted connection tests using ASTM D2395 Method A procedures. The moisture content and specific gravity (oven-dry volume) were determined using equations given in ASTM D2395.

The moisture content and specific gravity tests were performed on randomly selected OSL boards from the sample population of 127 boards. A sample size of 18 was used to determine the overall moisture content and specific gravity of the OSL material following its storage in a controlled environment for over one year. The results are shown in Appendix A (Cates 2002). The average moisture content was determined to be 5.84 percent with a coefficient of variation of 4.4 percent and the average specific gravity was determined to be approximately 0.65 with a coefficient of variation of 7.4 percent. Specific gravity tests were not necessary for all OSL specimens since dowel bearing strength tests were conducted for every OSL board from the sample population.

BOLT BENDING YIELD STRENGTH

The average bolt bending yield strength (F_{yb}) was determined by testing twelve bolts from each group. The bolts were tested using ASTM F1575-95 as a guideline. There is no current ASTM method to determine the bending yield strength of bolts, however ASTM F1575-95 is used to determine the bending yield strength of nails. This procedure was modified for bolts as shown in Figure 2-2.

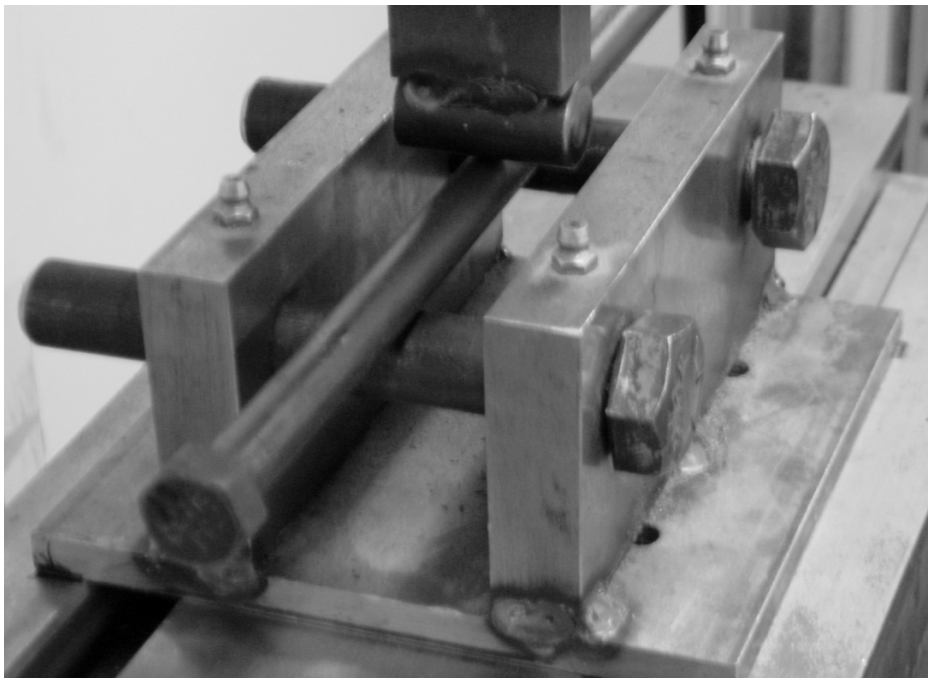

Figure 2-2: *Bolt Bending Yield Test*

The bolts were tested at a load rate of 0.25 in/min using a 22 kip servo-hydraulic universal testing machine. The universal testing machine had two digital data acquisition devices. One was used to record the displacement of the movable crosshead and the other was used to record the load applied. The displacement was measured using an internal linear variable differential transformer (LVDT) and the load was measured using a 22 kip load cell. An MTS

407-Controller was used to control the rate of loading. The acquisition devices were connected to a computer where LabView software was used to collect the data.

Load-displacement curves were created from the bolt bending yield tests. These curves were analyzed and the 5% diameter offset yield value was determined for each bolt. For prismatic bolts and a bearing point spacing of 4 inches, the bending yield strength equation from ASTM F1575, was simplified to the form shown in Equation 2-5. The results for each of the tests are shown in Appendix B with a summary of the results shown in Table 2-2 (Cates 2002). The average bolt bending yield strength was used in the calculations to determine the predicted yield strength of the individual connections.

$$F_{yb} = \frac{6\,(5\%\ Diameter\ Yield\ Load)}{D^3} \qquad \text{Equation 2-5}$$

Table 2-2: *Bolt Bending Yield Strength*

Bolt Diameter (in.)	Bolt Length (in.)	Bolt Bending Yield Strength, F_{yb} Average (psi)	COV (%)
0.75	5.375	68826	1.68
0.50	7.375	62426	1.74
0.50	11.000	57769	2.73

DOWEL BEARING TESTS

Half-hole dowel bearing tests were performed using the guidelines found in ASTM D5764-97a. The purpose of this test is to determine the load resistance and deformation characteristics in wood and wood-based products. The test consists of a load being applied through a dowel (bolt) that is placed horizontally on or through the wood-based specimen.

Two sets of dowel bearing tests were performed on the commercial OSL product. One set of tests used ¾ inch bolts and the other set used ½ inch bolts. This was done to reflect the use

of two different bolt diameters in the bolted connection tests. All dowel bearing specimens were loaded parallel to the direction of strand orientation. The commercially produced OSL had a thickness of 1.5 inches and width of 5.5 inches. When producing the dowel bearing specimens the thickness and width of the commercial product were not changed. The center of the bolt hole was drilled at a distance of six times the bolt diameter from the base of the specimen. The hole was drilled using a spade drill bit and drill press to produce an oversized hole of 1/16 inch. The oversized bolt hole was created to correspond with standard fabrication provisions for bolted connections. The material was then cut through the center of the hole to create the half-hole specimen used for dowel bearing tests.

The specimens were tested at a load rate of 0.03 in/min using a 22 kip servo-hydraulic universal testing machine. The universal testing machine had two digital data acquisition devices used to record the displacement of the actuator and the applied load. The displacement was measured using an internal linear variable differential transformer (LVDT) and the load was measured using a 22 kip load cell. An MTS 407-Controller was used to control the rate of loading. The data acquisition devices were connected to a computer where LabView software was used to collect the data.

Load-displacement curves were created from the data. From the curves, the 5% diameter offset yield load was determined, and the dowel bearing strength was calculated using Equation 2-6. The results of the dowel bearing calculations are shown in Table 2-3 and Table 2-4. The average dowel bearing strength of the specimens tested with a ½ inch diameter bolt was 6278 psi with a coefficient of variation of 21.7 percent. The specimens tested with a ¾ inch diameter bolt had an average dowel bearing strength of 7545 psi with a coefficient of variation of 19.1 percent. The dowel bearing strength of a particular board was used later in the corresponding yield limit

equations to determine the predicted yield strength of each bolted connection (Appendix B, Cates 2002).

$$F_e = \frac{5\%\ Diameter\ Yield\ Load}{(Specimen\ Thickness)(Bolt\ Diameter)} \qquad \text{Equation 2-6}$$

Table 2-3: *Dowel Bearing Strength of OSL Boards using ½ inch Bolts*

Board ID	F_e (psi)	Board ID	F_e (psi)	Board ID	F_e (psi)
K007	7218	K121	5980	K160	5810
K013	7558	K122	4233	K161	4932
K018	7290	K124	6016	K163	5426
K026	7924	K126	7006	K164	4563
K037	5544	K128	5667	K165	5938
K046	5966	K129	5764	K168	7164
K053	5537	K130	5472	K169	5788
K056	6391	K132	4898	K170	9025
K063	7264	K133	5692	K171	5944
K065	4307	K134	6394	K174	6134
K076	5093	K135	5117	K175	10964
K097	7765	K136	5138	K178	7465
K099	6077	K137	5416	K179	10758
K103	5359	K138	5962	K181	7484
K104	6807	K139	5069	K182	6699
K105	5593	K141	6428	K183	7778
K106	5266	K142	5160	K185	8536
K107	3277	K143	5227	K187	5665
K109	5966	K144	4920	K192	6199
K110	7070	K145	6108	K193	8225
K112	5819	K146	6031	K196	8019
K113	5327	K148	4753	K197	5311
K114	5624	K149	5001	K198	6010
K115	6853	K151	4006	K207	6924
K116	5466	K152	6278	K214	7364
K117	6105	K153	5224	K215	9283
K118	5272	K155	5411	K217	7313
K119	6534	K156	6128	K219	8266
K120	5992	K157	7858	K223	8535
				Average =	6278
				COV =	21.7%

Table 2-4: *Dowel Bearing Strength of OSL Boards using ¾ inch Bolts*

Board ID	F_e (psi)	Board ID	F_e (psi)	Board ID	F_e (psi)
K005	9237	K102	6360	K194	7715
K010	7926	K108	6238	K199	7360
K025	8619	K123	5866	K200	6578
K047	9258	K125	5649	K202	7636
K055	8567	K140	7963	K204	8437
K060	5663	K150	6742	K205	8681
K071	5948	K154	6072	K208	8667
K073	4853	K158	7495	K209	7552
K077	7265	K159	5945	K210	6733
K087	6763	K166	6996	K211	6181
K088	7789	K172	8939	K220	6186
K096	8010	K177	8876	K221	8212
K100	7736	K180	10622	K222	11988
		K184	8475		
				Average =	7545
				COV =	19.1%

BOLTED SHEAR CONNECTION TESTS

Double shear bolted connection tests were performed using the guidelines presented in ASTM 5652-95. The purpose of this test is to determine the strength and stiffness of bolted connections in wood and wood based products. The double shear connection tests consist of a main member sandwiched between two side members. A bolt passes through all three members restricting the movement of the main member with respect to the side members. For the tension tests, the main member was pulled in one direction while the side members were pulled in the opposite direction as shown in Figure 2-3.

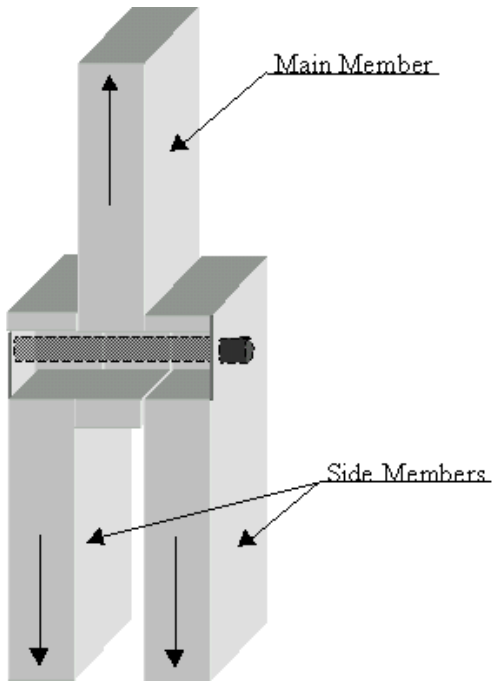

Figure 2-3: *Double Shear Bolted Connection Test Setup*

Three different connection configurations were tested to verify the ability of the EYM equations to predict the yield load of connections produced with oriented strand lumber (OSL). Double shear bolted connection specimens were created to produce yield modes I_m, III_s and IV. Specimens were designed to exhibit various yield modes by specifying various member thicknesses and bolt diameters for the connection. The connection yield loads for each configuration were predicted based on the bolt bending yield strength tests and dowel bearing strengths tests performed earlier in this research project. Connections designed to produce Mode I_m behavior included 1.5 inch thick members and a 0.75 inch diameter bolt. Mode III_s specimens were designed with 1.5 inch thick members and a 0.50 inch diameter bolt. Mode IV connection specimens were designed with 3 inch thick members and a 0.50 inch diameter bolt. All of the double shear connections tested for validation of the yield limit equations used a single ASTM A307 Grade A steel bolt located at seven diameters (7D) away from the end of the member.

Mode I_m and Mode III_s tests had a sample size of 12 while Mode IV had a sample size of 14. All connections were loaded parallel to the strand orientation in tension.

In order to evaluate the effect of reduced end distance on connection yield loads, connections using two different bolt diameters and varying end distances were tested. Since Mode I_m and Mode III_s connections used bolts with two different diameters, these test configurations were also used with varying end distances for this part of the research project. The Mode I_m and Mode III_s connections were also selected because they exhibit relatively brittle (Mode I_m) and relatively ductile (Mode III_s) connection behavior. The Mode I_m and Mode III_s tests performed in the first part of the research project had an end distance equal to seven diameters (7D) and were used as the baseline for subsequent end distance tests. The 7D represents the NDS minimum end distance requirement for full design value for bolts loaded parallel to the grain in tension for solid sawn softwood lumber (AF&PA 1997). Three additional end distances were used to evaluate an appropriate end distance requirement for OSL bolted connections loaded parallel to the direction of strand orientation. Since the OSL in the project was composed of yellow poplar strands, the end distance requirements for hardwood lumber was also of interest. The 5D end distance represents the minimum NDS requirement for full design value for bolts loaded parallel to the grain in tension for solid sawn hardwood lumber (AF&PA 1997). The 3D end distance was selected because it represents the average NDS minimum end distance requirements for reduced design value for bolts loaded parallel to the grain in tension for softwood and hardwood lumber (AF&PA 1997). The final end distance used was determined after the initial testing and analysis was completed. It was decided to test the final set of connections using an end distance of 4D for the Mode I_m connection tests and an end distance of 2D for the Mode III_s connection tests. This last set of end distances provided data to better

pinpoint a minimum end distance requirement. All connection tests with reduced end distances were performed using a sample size of 12 and were loaded parallel to strand orientation in tension.

OSL boards were randomly assigned to be used in Mode I_m, Mode III_s and Mode IV configured connection tests. A specimen from each board was removed and tested for dowel bearing strength as previously discussed. All boards used in the tests were cut to length to form connection members. Mode IV members were glued together to produce the desired double thick members. All double thick members were composed of adjacent specimens form the same board. All bolt holes were drilled using a 1/16 inch oversized spade drill bit and drill press. Connections were then assembled and tested. In assembling the connections, the side members for a connection were taken from the same OSL board.

In order to achieve connection failure in 5 – 20 minutes, ASTM D5652-95 recommends a testing rate of 0.04 in/min. The Mode I_m and Mode III_s connection tests were tested at the loading rate of 0.04 in/min while the Mode IV tests had a varying load rate. Due to the large deformation exhibited by Mode IV connections prior to failure, an initial loading rate of 0.06 in/min was used. After the Mode IV tests went well beyond the 5% diameter offset yield load, the loading rate was increased to 0.15 in/min in order to achieve connection failure within 20 minutes. All of the double shear bolted connections were tested using a 22 kip servo-hydraulic universal testing machine. The universal testing machine had two digital data acquisition devices used to record the displacement of the movable crosshead and the load applied. The displacement was measured using an internal linear variable differential transformer (LVDT) and the load was measured using a 22 kip load cell. As illustrated in ASTM D5652-95, two external LVDTs were also used to measure the displacement. The use of two external LVDTs allowed

the relative displacement between connection side members and main member to be isolated and measured. An MTS 407-Controller was used to control the rate of loading. The data acquisition devices and external LVDTs were connected to a computer where LabView software was used to collect the data. This data was used to create load-displacement curves for each connection (see Appendix B, Cates 2002).

The 5 percent diameter offset method was used to determine the connection yield loads from the load-displacement curves in accordance with the provisions of ASTM D5652-95. The 5 percent diameter offset method is accomplished by creating a line that is parallel to the first linear region of the load-displacement curve. The parallel line is drawn at a distance of 5 percent of the bolt diameter to the right of the linear region on the load-displacement curve. The yield load is read from the graph where the parallel 5 percent diameter offset line intersects the load-displacement curve. The method to determine the 5 percent diameter offset yield load is illustrated in Figure 2-4.

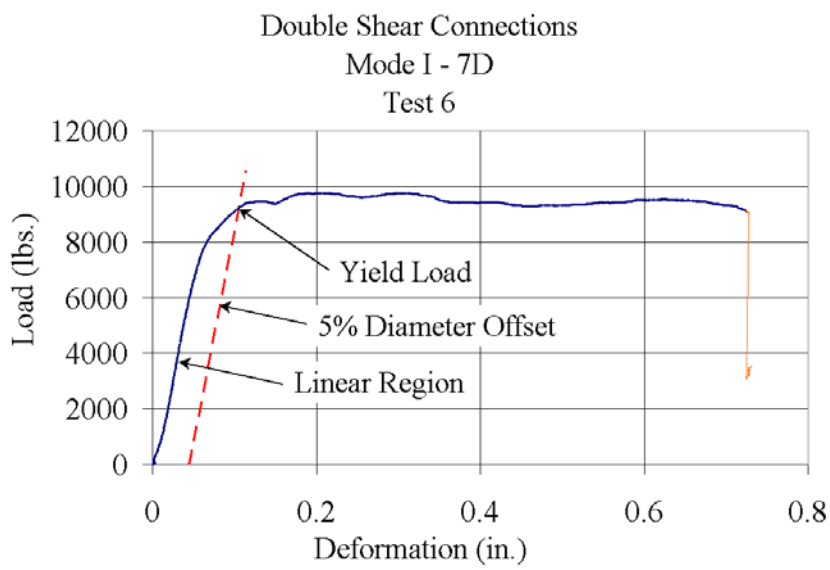

Figure 2-4: *Determining the Yield Load from a Load versus Displacement Curve*

Using the bolt bending yield strength, the dowel bearing strength of each OSL member and the thickness of each member, the predicted yield loads were calculated for each test. The predicted yield loads for the bolted connections were calculated using Equations 2-7 through 2-9 (McLain and Thangjitham 1983). These equations are equivalent to NDS and LRFD equations for Modes I_m, III_s, and IV connections, but without safety and load duration adjustments (AF&PA 1996 and 1997).

Mode I_m: $$F_y = D\, t_m\, F_{em}$$ Equation 2-7

Mode III_s: $$F_y = \frac{2\, D\, t_s\, F_{em}}{\beta + 2}\left[-1 + \sqrt{\frac{2(1+\beta)}{\beta} + \frac{2\, F_{yb}(2+\beta) D^2}{3\, F_{em}\, t_s^2}}\right]$$ Equation 2-8

Mode IV: $$F_y = 2\, D^2 \sqrt{\frac{2\, F_{em}\, F_{yb}}{3(1+\beta)}}$$ Equation 2-9

Where:

F_y = yield load for respective mode (lb.)

$$\beta = \frac{F_{em}}{F_{es}}$$

D = bolt diameter (in.)

t_m = thickness of main member (in.)

t_s = thickness of one side member (in.)

F_{em} = dowel bearing strength of main member (psi)

F_{es} = dowel bearing strength of side members (psi)

F_{yb} = bending yield strength of bolt (psi)

RESULTS

Verifying European Yield Model Equations

The behavior of three different bolted connection yield modes was investigated to assess the adequacy of the EYM equations to predict the actual yield capacities for connections made with OSL. The three connection yield modes investigated were Mode I_m, Mode III_s and Mode IV. Cut away cross sections of actual test specimens depicting the three mode types are shown in Figure 2-5 through Figure 2-7.

Figure 2-5 shows that the side member on the right of the figure is bearing on the threads of the bolt. This is not allowed in ASTM D5652-95 and is normally not done. It was decided that this was not a problem in this case. There was no observed difference in the deformation of the OSL member between the area that came in contact with the threads and the area that came into contact with the bolt shank. Also, since the main member failed in all Mode I_m connections, and the bolt did not deform, the presence of threads in the side member did not affect the connection behavior.

In Figure 2-6 and Figure 2-7 it appears that the unthreaded portion of the bolt is too long. To tighten the bolts used the Mode III_s and Mode IV configured connection tests, a sleeve and additional washer were used. The sleeve was cut from a pipe that allowed it to slide over the threads and that had an outside diameter approximately equal to the outside diameter of the nut being used. A washer was placed under the head of the bolt prior to it being put in the connection. Another washer was then placed next to the OSL member on the threaded end of the bolt. The sleeve was placed on to the bolt next to the washer. Finally, another washer and a nut were placed on the end of the bolt. The nut was finger tightened completing the connection.

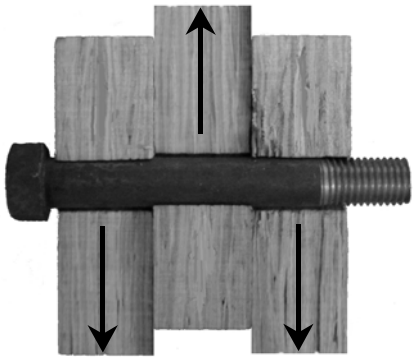

Figure 2-5: *Cross Section of a Mode I_m Bolted Connection*

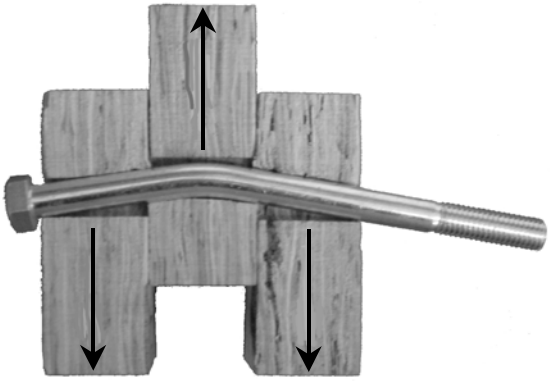

Figure 2-6: *Cross Section of a Mode III_s Bolted Connection*

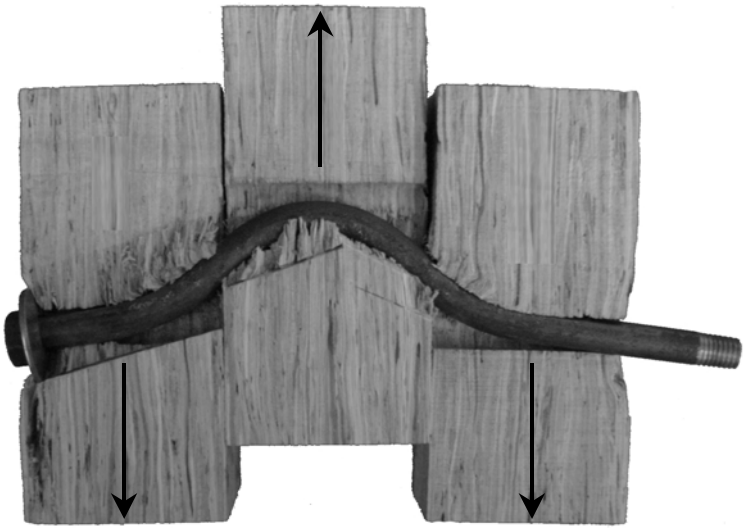

Figure 2-7: *Cross Section of a Mode IV Bolted Connection*

From the connection cross sections shown in Figure 2-5 through Figure 2-7 and test observations, it is clear that the type of material behavior predicted by the EYM equations occurred in the OSL connection tests. Mode I_m connection tests experienced crushing in the main member and no deformation or rotation of the bolt was observed. In the Mode III_s connection tests, single curvature deformation was observed in the bolt. Bolts used in the Mode IV connection tests experienced double curvature deformation. Since the material behavior predicted by the EYM equations were observed in the double shear bolted connection tests, it implies that the theoretical basis for the EYM equations is clearly applicable for the OSL material. However, the 5 percent diameter offset method of determining the yield limit for a tested connection needs to be analyzed.

It should be noted that the EYM equations were developed for bolted connections without oversized bolt holes. When bolts fit snuggly in a connection that exhibits Mode IV behavior, curvature bending of the bolt within the main member and reverse curvature bending of the bolt within the side members occurs simultaneously. When oversized bolt holes are used, the bolt is able to deflect in the center of the main member prior to the bolt coming in contact with the outer edges of the side members. This allows for curvature bending of the bolt within the main member to occur prior to the reverse curvature bending of the bolt within the side members.

The predicted yield loads were compared with the yield loads determined from the individual connection tests. The predicted yield loads based on the European Yield Mode equations were compared with the actual yield loads using a paired t-test for each mode type (Appendix B, Cates 2002). The paired t-test was used because both the predicted and tested yield loads were specific to the individual connection. Each yield load was calculated using the

dowel bearing strengths for the specific OSL boards used in the connection. As shown in Table 2-5, the Mode I_m data confirms that there was no statistical difference between the population means of the predicted and actual yield loads. This clearly supports the use of the EYM based equations and the 5 percent diameter offset method for determining yield load for Mode I_m connections in OSL. However, the results for Mode IIIs and Mode IV show that there was a statistical difference between the population means of the predicted and actual yield loads. Since the deformed bolt shapes in the Mode IIIs and Mode IV connections matched the overall predictions from the yield limit equations, this implies that the 5 percent offset method may not be an appropriate method for determining connection yield load. Further analysis of the data collected was needed to assess the use of the 5 percent diameter offset method for Mode IIIs and Mode IV using OSL.

Table 2-5: *Results of Paired T-Tests between Predicted and Actual Yield Loads*

Yield Mode	Predicted Yield Load (lbs) Mean	Predicted Yield Load (lbs) Std Dev	Tested Yield Load (lbs) Mean	Tested Yield Load (lbs) Std Dev	T-statistic	P-value	Statistically
I_m	6935	1175	7405	1607	-0.98	0.350	Not Different
III_s	4561	300	3835	343	5.31	< 0.0005	Different
IV	5211	314	5564	458	-3.89	0.002	Different

Another method for assessing the EYM equations and the 5 percent diameter offset method to accurately predict the tested yield loads in OSL bolted connections involved looking at the ratio of tested to predicted yield loads. The ratios were evaluated for each mode type and the mean and standard deviation for each mode type were determined. The mean, standard deviation and number of tests performed for each mode are shown in Table 2-6. The results from the Mode I_m and Mode IV yield ratios seem reasonable approximations that are slightly

conservative. However, the Mode III_s average yield ratio is approximately 15 percent unconservative and therefore does not appear to be as reasonable.

Initially the Mode IV tests results did not appear to be as reasonable as those shown in Table 2-5 and Table 2-6. The Mode IV connection tests were initially analyzed using a 5% diameter offset based on the first linear region of the load-displacement curve. When the tested yield load was compared to the predicted yield load, an average yield load ratio of 0.76 with a standard deviation of 0.059 was found. It was not until a 5% diameter offset was applied to the second linear region of the Mode IV load-displacement curve, that the yield ratio shown in Table 2-6 was found. Figure 2-8 shows the yielding region on a load-displacement curve for a Mode IV connection test. This method of using the second linear region for the 5 percent diameter offset line is different from the procedures given in ASTM D5652-95.

Recent research performed on wood plastic composite solid and hollow sections has also led to questions regarding the 5 percent diameter offset method for determining connection yield (Balma 1999; Parsons 2001). Balma (1999) performed bolted connection tests for wood plastic composites with solid and hollow sections using an oversized bolt hole of 1/16 inch. Balma found that the average experimental value for yield was 76 percent of the predicted yield load for low-density polyethylene (LDPE) Mode III_s connections, was between 86 percent and 96 percent of the predicted yield load for high-density polyethylene (HDPE) Mode III_s connections, and was 98 percent of the predicted yield load for a set of LDPE Mode I connections. Parsons (2001) performed connection tests on hollow wood plastic composite sections with bolt holes that were not oversized. Parsons found that the average experimental value of yield was 97 percent of the predicted yield load for polyvinyl chloride (PVC) Mode I_m connections, 104 percent of the predicted yield load for HDPE Mode I_m connections, 86 percent of the predicted yield load for

PVC Mode III_s connections, 77 percent of the predicted yield load for HDPE Mode III_s connections, 88 percent of the predicted yield load for PVC Mode IV connections, and 82 percent of the predicted yield load for HDPE Mode IV connections.

Table 2-6: *Results of Tested to Predicted Yield Load Ratio*

Yield Mode	Sample Size (N)	Tested to Predicted Yield Load Ratio Mean	Std. Dev.
I_m	12	1.08	0.226
III_s	12	0.84	0.095
IV	14	1.07	0.066

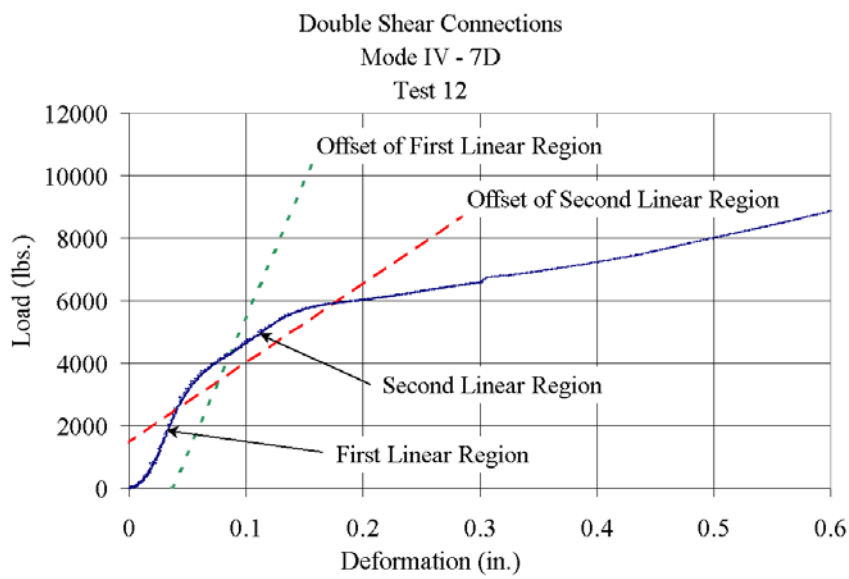

Figure 2-8: *Yield Region on the Load-displacement Curve for a Mode IV Connection*

In tests performed on Douglas-fir glulam beams with oversized hole connections exhibiting Mode I_m and Mode III_s behavior, the experimental yield load was lower than the predicted yield load (Wilkinson 1993). Wilkinson reported that for oversized bolt holes of 1/16 inch, there was a decrease in the experimental yield load of up to 21 percent compared with the predicted yield load. The decrease that Wilkinson found is similar to the reduction that was

observed in the Mode III_s connections in this study. The Mode IV connections analyzed with the first linear region of the load-displacement curve also exhibited the decrease that Wilkinson observed. However, it is interesting to note that by plotting the EYM yield loads and the tested yield loads, Wilkinson concluded that the EYM equations adequately predicted the yield load for bolted connections with oversize bolts in glulam beams.

End Distance Requirements

In addition to the tests performed to assess the EYM equations, six other sets of bolted connection tests using OSL were performed with varying end distances. Three sets of tests were based on the Mode I_m configuration and three sets of test were based on the Mode III_s configuration. Unfortunately, there was insufficient OSL material to provide matched specimens for each set of end distance connection tests. Therefore, one method that the connection test results were analyzed was by comparing the tested yield load to the predicted yield load of the connections. The tested yield loads were determined using the 5 percent diameter offset method and the predicted yield loads were calculated using the EYM equations.

The EYM equations do not take end distance values into account. Therefore the tested to predicted yield load ratio should not change unless a change in end distance affects the yield load of the connection. If the EYM equations perfectly predict the connection yield load using the 5 percent offset method, then the ratio of tested to predicted yield will be 1.0. If it does not perfectly predict the yield load, then the ratio may be greater than or less than 1.0. In either case, the ratio should not change significantly unless the connection yield load is affected by the reduced end distance.

The connection test results were also analyzed by comparing ultimate to yield load ratios (reserve ratio). Analyzing the reserve ratio is a tool to quantify the reserve capacity of the

connection after yield has been reached. As shown in the load-displacement curves for each of the connection tests (see Appendix B, Cates 2002), reserve ratios tend to be much higher for Mode III_s and Mode IV connections, than for Mode I_m connections. Where the reserve ratio is greater than 1.0, it can be concluded that the yield load was reached prior to failure and the yield load was not affected by the reduced end distance. However, one must be careful with this method as reserve ratio values approach 1.0. Connections that failed prior to reaching the 5 percent diameter offset were assigned a yield load equal to the ultimate load of the connection, in accordance with provisions in ASTM D5652-95. This results in a reserve ratio of 1.0 when the yield load is affected by the reduced end distance. Therefore with shorter end distances, the reserve ratio approaches a value of 1.0 asymptotically.

The effect of end distance on connection yield load was addressed by comparing the tested and predicted yield loads by calculating ratios of the tested to predicted yield load. An analysis of variance (ANOVA) using a General Linear Model (GLM) was used to compare the means between the ratios from the four sets of data collected for each of the two yield mode configured tests. The bolted connection tests with an end distance of 7D were used as a control and the tests using smaller end distances were compared to them. Several different techniques within GLM were used to compare the means of the data sets, as presented in Appendix B (Cates 2002). The Dunnett method appeared to be the most appropriate method to compare the means, because it produced the tightest confidence intervals of the methods performed. The results of the Dunnett method are shown in Table 2-7 for the Mode I_m configured connection tests and in Table 2-8 for the Mode III_s configured connection tests.

Table 2-7: *Results from the Dunnett Method for Mode I_m Configured End Distance Tests*

End Distance (Control of 7D)	Test/Predicted Means	Difference of Means	T-Value	P-Value	Statistically
7D	1.08	Control			
5D	1.15	0.0692	0.804	0.7606	Not Different
4D	1.13	0.0475	0.552	0.9023	Not Different
3D	1.02	-0.0683	-0.795	0.7669	Not Different

Table 2-8: *Results from the Dunnett Method for Mode III_s Configured End Distance Tests*

End Distance (Control of 7D)	Test/Predicted Means	Difference of Means	T-Value	P-Value	Statistically
7D	0.84	Control			
5D	0.83	-0.0158	-0.402	0.9580	Not Different
3D	0.83	-0.0108	-0.275	0.9856	Not Different
2D	0.65	-0.1933	-4.914	<0.00005	Different

It was observed from the load versus displacement curves (see Appendix B, Cates 2002) that for both the Mode I_m configured tests with an end distance of 3D and the Mode III_s configured tests with an end distance of 2D, that in some of the tests the connection failed prior to reaching the 5 percent diameter offset. From the results of the statistical comparison of means method, it does not appear that there was any statistical difference between the Mode I_m configured tests with an end distance of 7D and those tests with other end distances. The Mode III_s configured tests however, showed that ratios of test yield to yield are statistically different for end distances of 7D and 2D.

In the end distance connection tests where the connection failed prior to reaching a 5 percent diameter offset, the test to predicted yield load ratio was expected to be statistically different than those that did not fail prior to reaching the 5 percent diameter offset. The Mode III_s configured connection tests performed as expected, but the Mode I_m configured connection

tests did not. One possible explanation why the Mode I_m configured connection tests with an end distance of 3D was not considered statistically different, was that the end distance used was approximately equal to the "critical end distance" of the member. The end distance at which the connection fails upon reaching the yield load could be considered the "critical end distance". Another possible reason for observing no statistical difference in the Mode I_m connections was that the yield mode of the connection did not change. The statistical analysis results of the Mode I_m connection tests appear to suggest that the end distance of 3D was approximately equal to the "critical end distance" of the Mode I_m connection configuration.

In the Mode III_s connection tests a statistical difference was found between the tests with an end distance of 7D and 2D. In the Mode III_s connection tests with an end distance of 2D, 10 of the 12 connections failed due to crushing of the wood. There was no evidence of bolt bending in these 10 connections. Therefore, the Mode III_s configured connection tests with an end distance of 2D behaved like Mode I_m connections. The statistical analysis results of the Mode III_s connection tests suggests that the end distance of 2D was below the "critical end distance" of the Mode III_s connection configuration.

Dividing the ultimate load by the yield load for a particular connection test results in an estimate of "reserve capacity" beyond connection yield. The estimate of the "reserve capacity" can be thought of as a reserve ratio. The reserve ratio can then be analyzed to determine the effect of decreasing the end distance of a bolted OSL connection test. The reserve ratio means and standard deviations are shown in Table 2-9 for each connection configuration. Reserve ratios were also calculated for the 7D Mode IV connection tests as shown in Appendix B (Cates 2002). The average reserve ratio for Mode IV connections was 2.69 with a standard deviation of 0.212. As stated previously, in some cases the connection failed prior to the 5 percent diameter

offset yield load being reached. When this occurred, the yield load was taken to be equal to the maximum load attained. The ultimate load was also assigned this value resulting in a reserve ratio of 1.0.

Table 2-9: *Reserve Ratios for Mode I_m and Mode III_s Configured Bolted Connection Tests*

	Mode I_m		Mode III_s	
End Distance	Mean	Std. Dev.	Mean	Std. Dev.
7D	1.23	0.146	1.85	0.437
5D	1.15	0.076	1.66	0.211
4D	1.09	0.091	N/A	N/A
3D	1.01	0.025	1.39	0.284
2D	N/A	N/A	1.01	0.019

To visually represent the data found in Table 2-9, a graph was created to show the decrease in the reserve ratio as the end distance in OSL bolted connection decreases. The graph, shown in Figure 2-9, displays the reserve ratio for both the Mode I_m and Mode III_s configured connection tests. The reserve ratios from each mode configuration were connected with a trend line. Only the connection tests with the three largest end distances from each mode configuration were used to determine the trend line. A linear trend line was used to prevent unjustified confidence in relationship between the reserve ratio and end distance of the connections. Curved trend lines can be developed using polynomials, logarithmic functions and power series that connect three points nearly perfectly without representing the true relationship of the data. Connection tests using the smallest end distance were excluded due to the common occurrence of test specimens reaching failure prior to reaching the 5 percent diameter offset yield load. Ten of the twelve Mode I_m connection tests with an end distance of 3D failed prior to reaching yield. Six of the twelve Mode IIIs connection tests with and end distance of 2D failed prior to reaching yield. The error bars represent one standard deviation above and below the

reserve ratio means. Figure 2-9 displays how the Mode III_s configured connection tests using an end distance of 2D had a reserve ratio well below the trend line connecting the rest of the tests with that configuration. The Mode I_m configured connection test data also showed that the connections with the smallest end distance were slightly below the trend of the other Mode I_m configured tests.

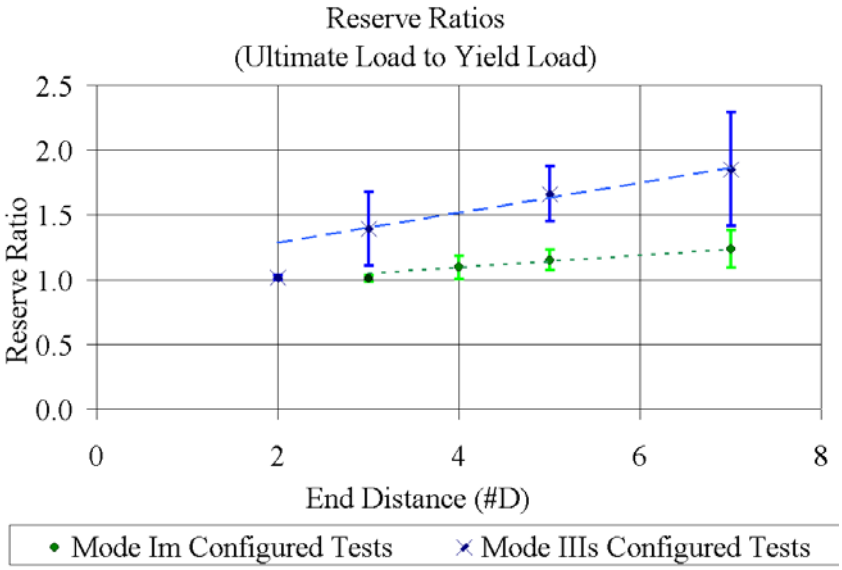

Figure 2-9: *Reserve Ratio versus End Distance*

Data from several other research projects that reported yield and ultimate capacity of double shear bolted connection tests were analyzed to determine the reserve ratio using traditional wood materials. One project used ½, ¾ and 1 inch bolts with Douglas-fir glulam beams as the main members and steel side members (Wilkinson 1992). Another project used ½ inch bolts with Southern Pine lumber for members (Pollock 1997). A third project reported data using ½ and ¾ inch bolts with Southern Pine and Ponderosa pine used as members (Galloway 2000). Results of the average yield and ultimate loads from the above projects were used to calculate reserve ratios for each of the tests. All tests were loaded parallel to the grain and had

end distances of 7D or greater. The results from the three studies are shown in Table 2-10. Using the sample size for each test, each reserve ratio was weighted and used to determine an average reserve ratio for each mode. Equation 2-10 shows how the average reserve ratio is calculated. The average reserve ratio was found to be 1.06 for Mode I_m, 1.73 for Mode III_s and 1.54 for Mode IV, based on the data provided in Table 2-10.

Table 2-10: *Reserve Ratios Calculated from Cited Research*

Mode	Source	Members	Sample Size (N)	Bolt Diameter (in)	Average Yield Load (lb)	Average Ult.Load (lb)	Reserve Ratio
I_m	Wilkinson	Douglas-fir	20	0.50	4560	4850	1.06
I_m	Wilkinson	Douglas-fir	20	0.75	8020	8830	1.10
I_m	Wilkinson	Douglas-fir	20	1.00	13630	13710	1.01
III_s	Wilkinson	Douglas-fir	20	0.50	6450	7940	1.23
III_s	Wilkinson	Douglas-fir	20	0.50	5460	11970	2.19
III_s	Wilkinson	Douglas-fir	20	0.50	5700	14800	2.60
III_s	Wilkinson	Douglas-fir	20	0.75	12540	17960	1.43
III_s	Wilkinson	Douglas-fir	20	0.75	13040	24580	1.88
III_s	Wilkinson	Douglas-fir	20	0.75	13030	28260	2.17
III_s	Wilkinson	Douglas-fir	20	1.00	24550	31560	1.29
III_s	Wilkinson	Douglas-fir	20	1.00	22350	38190	1.71
III_s	Wilkinson	Douglas-fir	20	1.00	26320	39950	1.52
III_s	Pollock	Southern Pine	41	0.50	4392	7261	1.65
III_s	Galloway	Southern Pine	32	0.50	4118	6460	1.57
IV	Galloway	Ponderosa Pine	32	0.75	9593	14806	1.54

$$\text{Ave Reserve Ratio} = \frac{\sum_{i=1}^{n}(N_i)(Ratio_i)}{\sum_{i=1}^{n}(N_i)} \qquad \text{Equation 2-10}$$

Where:

N_i = sample size in the ith data set

n = number of data sets for a specified connection yield mode

In comparing the reserve ratios between connections created with OSL and those shown in Table 2-10, it appears that the Mode I_m connections made with OSL and having an end distance of 7D exhibited a higher reserve ratio than those in the Douglas-fir glulam connection tests. In fact, even the OSL Mode I_m connections having an end distance of 4D had a reserve ratio of 1.09 which was comparable to the three Mode I_m connections tests performed by Wilkinson with end distances of 7.5D. The OSL Mode III_s connection tests with an end distance of 7D appear to be comparable to those shown in Table 2-10. The average reserve ratio of the 7D OSL connections was slightly higher than the mean of those shown in the table, but several of Wilkinson's tests had an even greater mean than the OSL tests. In the Mode IV connection tests it was difficult to assess the reserve ratios because only one set of tests was found for comparison. However, based on the limited data from Galloway's study, it appears that OSL had a much larger reserve ratio than the connections made with Ponderosa Pine.

DISCUSSION OF RESULTS

From the bolted connection tests with end distances of 7D, it can be concluded that the EYM equations predict overall yield mode behavior in OSL quite well. The EYM equations predicted which connections exhibited crushing of the main member, single curvature deformation of the bolt and double curvature deformation of the bolt. For the Mode I_m connections, the 5 percent diameter offset method used to determine the yield load provided accurate results. The predicted and tested connection yield loads were within 8% of each other. For Modes III_s and IV, the 5 percent diameter offset method did not work well for determining connection yield. The predicted and tested connection loads differ by 16% for Mode III_s connections and by 24% for Mode IV connections. When the Mode IV connection tests were

analyzed using the 5 percent diameter offset of the second linear region on the load-displacement curves, the predicted and tested connection loads were found to differ by only 7%. Other researchers have obtained similar trends for oversized holes in solid sawn lumber (Wilkinson 1993) and for bolted connections in wood-plastic material (Balma 1999; Parsons 2001).

If a more accurate prediction of yield load is required, one must ask what part of the process needs refinement. It is apparent from the Mode IV bolted connection tests, that the process used to determine the yield load from experimental data greatly affects the results. Using the second linear region to determine the yield load produced results that were much more representative of the yield loads calculated by the equations, and accurately predicted the transition point to the final low-slope region of load-displacement curve. Similarly, a more appropriate process to determine the yield load might be needed for Mode III_s connection tests.

The first linear region in the load-displacement curves for Mode IV connections appears to be caused by single curvature bending of the bolt and crushing of the wood near the shear planes between the members. This is similar to the yielding behavior exhibited in Mode IIIs connections. The second linear region in the load-displacement curves for Mode IV connections appears to be caused by the second curvature (reverse curvature) bending and additional crushing in the main member and side members. This behavior is what distinguishes yield Mode IV from Mode III_s.

There are several alternate methods that can be considered when determining the yield load from load-displacement curves of tested bolted connections. Early work used a proportional limit as discussed earlier (Trayer 1932). More recent research used both larger offsets (e.g. – 10% of the fastener diameter offset) and specified displacements on the load-displacement curves to determine yield loads of connections (Balma 1999). Balma considered using four

different offset percentages ranging from 5% to 12% and four different displacements limits ranging from approximately 0.05 inches to approximately 0.30 inches in analyzing the load-displacement curves. Another possible method to determine the yield load of a connection from load-displacement curves is to use a numerical approximation technique to determine the second derivative of the load-displacement curve. To use a second derivative method, a smoothing technique needs to be applied to the data points prior to determining the slope of the lines connection adjacent points. Once a slope has been determined for the lines connection adjacent points, these slopes need to be matched with the corresponding displacements, thus creating the first derivative data points. The slope of the first derivative data points can then be obtained in the same manner as the slope of the original data set. The resulting data corresponds to the second derivative on the original load-displacement curve. The maximum value of the second derivative data set should be the location of maximum curvature on the load-displacement curve.

The connection tests with varying end distances clearly illustrate that the yield load of an OSL connection is not affected by the end distance until it becomes much smaller than the current design requirements for full connection design values require. While the ultimate capacity of a connection decreased as the end distance of a connection decreased, this did not affect connection yield capacities, which are the basis for current connection design provisions.

In the Mode I_m configured connection tests, it was observed that yield loads from the tests with an end distance of 3D were affected by the reduced end distances. Yield loads from Mode I_m connection tests using end distances of 4D and larger were not affected. This suggests that the "critical" end distance for Mode I_m connections made with the OSL used in this study was between 3D and 4D.

In the Mode III_s configured connection tests, it was clear that yield loads were greatly affected by the smallest end distance of 2D. The average tested to predicted yield load ratios for the Mode III_s connection tests with an end distance of 7D, 5D and 3D were all approximately 0.83. The average tested to predicted yield load ratio for the Mode III_s connection tests with an end distance of 2D was 0.65. This can be considered a yield capacity loss of approximately 22%. In the Mode III_s connection tests with end distances of 3D and larger, the yield load was not affected by the reduced end distance. It was clear that the "critical" end distance for Mode III_s connection tests falls between 2D and 3D.

It appears that the yield load of Mode I_m and Mode III_s are both affected by end distances of approximately 3D and smaller. Although the analysis of the data from the connection tests support a smaller end distance requirement for OSL Mode III_s connections than for Mode I_m connections, this could complicate the current design procedures. A single end distance requirement for OSL connections is more reasonable. Based on the results of this study, it appears that the an end distance requirement of 4D would be sufficient for full connection design values in OSL loaded in tension parallel to the strand orientation.

The NDS currently permits a reduced bolted connection design capacity for end distances less than the full design requirement (AF&PA 1997). The reduced design capacity is calculated by multiplying the full design capacity by the ratio of actual end distance to required end distance for full design value. The minimum end distance allowed is equal to one-half of the full design end distance requirement. Since this project included only two data sets with end distances below the "critical end distance", there is not sufficient data to adequately assess the use of reduced design capacities for each end distance less than 4D. However, these two data sets give indications that the current reduced design capacity relationship may be sufficient.

The end distance requirement for full design capacity can conservatively be taken as 4D for bolted connections using OSL. Following the current reduced design capacity method for solid sawn lumber the minimum end distance allowed will be 2D. The only mode configuration to be tested with an end distance of 2D is the Mode III_s configuration. From Table 2-8, the average tested to predicted yield load ratio is 0.65 for the Mode III_s configured connection tests with an end distance of 2D. This tested to predicted yield load ratio is greater than the reduced design capacity value (2D/4D = 0.5). Out of the 12 Mode III_s configured connection tests with an end distance of 2D, only one test had a tested to predicted yield load ratio value below 0.50 (tests #43, ratio of 0.47) (Appendix B, Cates 2002). Therefore, the current method of determining reduced design capacity appears appropriate for the Mode III_s OSL connections. The Mode I_m connections tests however, did not include end distance tests of 2D. It is unclear how the yield limit of Mode I_m connections would be affected when tested with end distances of less than 3D. However, from Table 2-7, the average tested to predicted yield load ratio is 1.02 for the Mode I_m configured connection tests with an end distance of 3D. This tested to predicted yield load ratio is greater than the reduced design capacity value (3D/4D = 0.75). Out of the 12 Mode I_m configured connection tests with an end distance of 3D, only one test had a tested to predicted yield load ratio value below 0.75 (tests #27, ratio of 0.58) (Appendix B, Cates 2002).

Additional tests will need to be performed to verify that the tested to predicted yield load ratios for the different mode configurations are at least 0.5 for end distances of 2D.

CONCLUSIONS

From bolted connection tests exhibiting yield Modes I_m, III_s and IV, it was determined that the European yield model (EYM) adequately models the yield behavior in OSL double shear

bolted connections. However, the 5 percent diameter offset method was not found to be particularly effective in estimating yield loads.

A reduced end distance of 4D was recommended for OSL bolted connections based on tests of yield Modes I_m and III_s performed in this study. Mode I_m connection tests exhibited reduced connection yield loads at end distances less than 4D. Mode III_s connection tests exhibited reduced connection yield loads at end distances less than 3D. For design simplicity and conservatism, an end distance requirement of 4D was recommended for bolted connections in OSL loaded parallel to strand orientation in tension.

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CHAPTER 3:

SUMMARY AND CONCLUSIONS

Based on the results of a statistical ANOVA, it was determined that specific gravity exhibits a statistically significant influence on dowel bearing strength of OSL material loaded either parallel or perpendicular to the strand orientation. Mean strand angle was also found to exhibit a statistically significant influence on dowel bearing strength for specimens loaded perpendicular to the strand orientation. The low R-squared values obtained from the scatter plots and multiple regression however, indicate that neither specific gravity nor mean strand angle are strong predictors of dowel bearing strength in either the parallel or perpendicular loading cases. As a result, the Wilkinson dowel bearing strength equations used for solid sawn lumber are not directly applicable for OSL. Since the OSL tested in this study does not exhibit a strong correlation with specific gravity it is important that manufacturers determine dowel bearing strength values for each OSL product and verify those values any time the manufacturing process is changed.

Based on bolted connection tests exhibiting yield Modes I_m, III_s and IV, it was determined that the European yield model (EYM) adequately models the yield behavior in OSL double shear bolted connections. However, the 5 percent diameter offset method was not found to be particularly effective in estimating yield loads. Inadequacy in the 5 percent diameter offset method was at least partially attributed to the use of 1/16 inch oversized bolt holes. Similar trends have been observed in sawn lumber (Wilkinson 1993) and in wood plastic composites (Balma 1999). Inadequacy in the 5 percent diameter offset method was also observed in wood plastic composite hollow sections without oversized bolts (Parsons 2001).

A reduced end distance of 4D was recommended for OSL bolted connections based on tests of yield Modes I_m and III_s performed in this study. Mode I_m connection tests exhibited reduced connection yield loads at end distances less than 4D. Mode III_s connection tests exhibited reduced connection yield loads at end distances less than 3D. For design simplicity and conservatism, an end distance requirement of 4D was recommended for bolted connections in OSL loaded parallel to strand orientation in tension.

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APPENDIX A:

ORIENTED STRAND LUMBER PRODUCED AT WSU

STRAND GEOMETRY AND ORIENTATION

Strand geometry and vane spacing were varied during the production of the oriented strand lumber (OSL) panels at the Washington State University Wood Materials and Engineering Laboratory. Vane spacing combined with strand geometry directly affects the level of strand orientation within the panels. Table A-1 shows the strand geometry and vane spacing for each of the 45 panels used in this research project.

Table A-1: *Strand Geometry and Vane Spacing of OSL*

PANELS	STRAND		VANE SPACING (in.)
	LENGTH (in.)	WIDTH (in.)	
1 to 3	12	0.75	3.0
4 to 6	12	0.50	3.0
7 to 9	12	1.00	3.0
10 to 12	8	1.00	1.5
13 to 15	8	0.75	1.5
16 to 18	8	0.50	1.5
19 to 21	4	1.00	1.5
22 to 24	4	0.50	1.5
25 to 27	4	0.75	1.5
28 to 30	4	0.50	3.0
31 to 33	4	0.75	3.0
34 to 36	4	1.00	3.0
37 to 39	8	1.00	3.0
40 to 42	8	0.50	3.0
43 to 45	8	0.75	3.0

MEAN STRAND ANGLES

The mean strand angle for each panel was determined as part of another research project performed at Washington State University (Meyers 2001). The mean strand angle results from Meyers' research is shown in Table A-2. The mean strand angles from the table were rounded off to the nearest whole angle, prior to being used as a covariate in the ANOVA analysis.

Table A-2: *Results of Mean Strand Angles*

Panel	Mean Strand Angle (°)	Panel	Mean Strand Angle (°)	Panel	Mean Strand Angle (°)
1	19.13	16	11.81	31	27.68
2	16.48	17	11.63	32	29.87
3	15.65	18	12.00	33	27.70
4	19.35	19	17.78	34	26.54
5	17.17	20	17.16	35	27.95
6	19.02	21	18.36	36	30.25
7	13.91	22	17.70	37	19.08
8	14.49	23	17.42	38	17.70
9	14.97	24	18.79	39	18.16
10	13.51	25	18.64	40	18.00
11	13.89	26	17.85	41	18.63
12	12.79	27	20.59	42	20.37
13	13.90	28	27.06	43	19.05
14	12.54	29	31.04	44	17.50
15	11.50	30	28.01	45	16.79

SPECIMEN LOCATION

Each specimen was identified by a label consisting of the panel and location numbers separated by a hyphen. The panel number indicated which panel the specimen came from, thereby indicating the strand geometry and level of strand orientation. The location number indicated the area of the panel from which the specimen was cut. The location number also indicated the strand orientation of the specimen in relation to the strand orientation of the panel. Figure A-1 shows the layout of the panels. The overall dimensions of the panels were approximately 3.5 feet by 3 feet with the longitudinal dimensions of the individual strands generally oriented in the 3.5 feet direction. All panels were produced with a nominal thickness of ¾ inch. The shaded areas in Figure A-1 represent material that was used for other research projects at Washington State University.

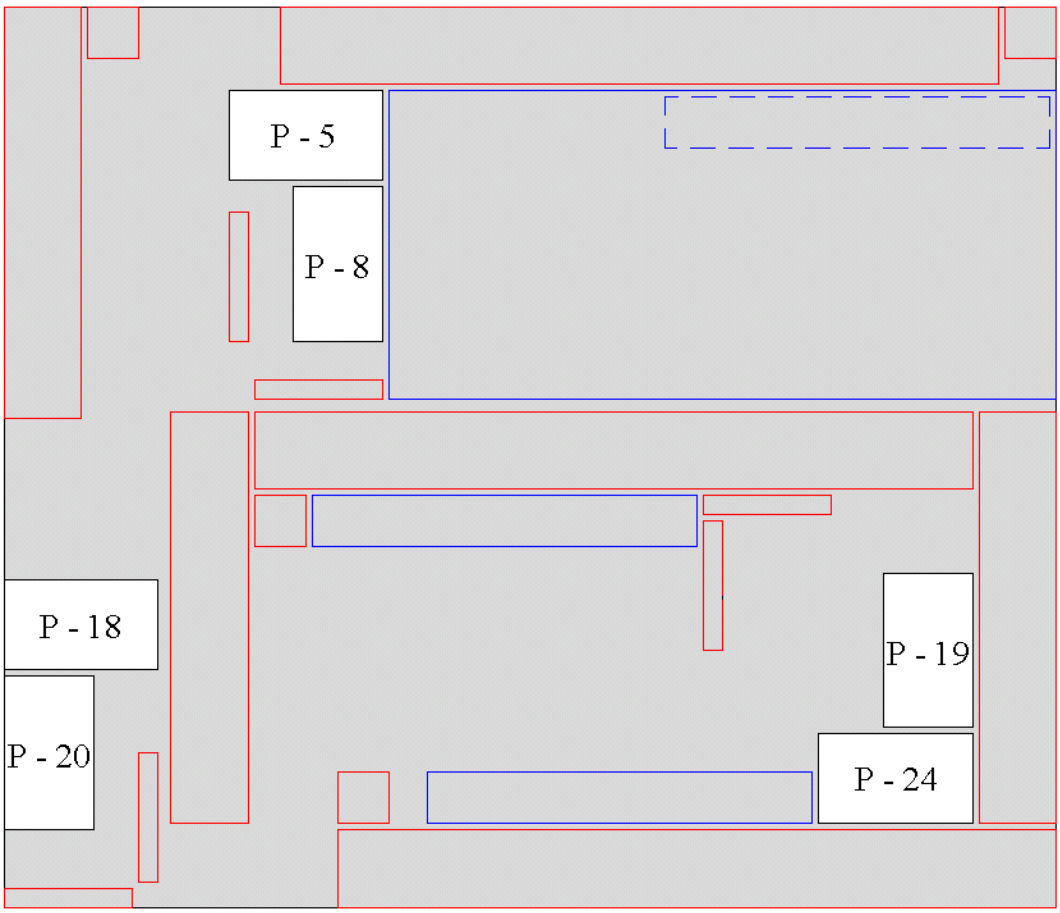


Figure A-1: *Specimen Location and Orientation with Respect to the OSL Panel*

MOISTURE CONTENT AND SPECIFIC GRAVITY

Moisture content and specific gravity tests were performed on specimens taken from the same general location as the dowel bearing specimens. As previously shown in Figure A-1, one parallel and one perpendicular specimen used in the dowel bearing tests were taken from the same area. In almost all cases, one of the two dowel bearing specimens (P – 8, P – 19 and P – 20) from each set, was slightly larger than the other (P – 5, P – 18 and P – 24). Since all dowel bearing specimens were to have the same general dimensions, the extra material was used for moisture content and specific gravity tests. The results from these tests can be found on the

following pages with the exception of panel two. Panel two did not include sufficient material from specimen 2 – 20 for the moisture content (MC) and specific gravity (S.G.) tests to be performed for that location.

In the tables, two specific gravity values are displayed. The first specific gravity value ($S.G._a$) is the specific gravity based on oven-dried weight and volume at the moisture content at which the dowel bearing specimens were tested. The second specific gravity value ($S.G._d$) is the specific gravity based on oven-dried weight and volume.

Specimen	Average Dimensions (in) Length	Thickness	Height	Volume (in^3)	Initial Wt. (g)	Final Wt. (g)	MC (%)	$S.G._a$	$S.G._d$
1-8	5.141	1.865	1.865	7.534	66.97	61.59	8.74	0.50	0.52
1-19	3.479	1.180	1.180	3.329	38.87	35.80	8.58	0.66	0.69
1-20	3.594	2.110	2.110	6.117	73.03	67.29	8.53	0.67	0.71
2-8	5.141	1.876	1.876	7.887	76.42	70.29	8.72	0.54	0.57
2-19	3.483	1.168	1.168	3.124	41.05	37.95	8.17	0.74	0.78
2-20									
3-8	5.141	1.898	1.898	7.621	83.90	77.45	8.33	0.62	0.65
3-19	3.489	1.179	1.179	3.230	37.82	34.88	8.43	0.66	0.69
3-20	3.603	2.107	2.107	6.066	52.57	48.29	8.86	0.49	0.51
4-8	5.139	1.866	1.866	7.625	65.98	60.73	8.64	0.49	0.50
4-19	3.495	1.170	1.170	3.118	34.01	31.34	8.52	0.61	0.64
4-20	3.603	2.115	2.115	6.004	52.29	48.02	8.89	0.49	0.51
5-8	5.141	1.883	1.883	7.380	77.79	71.63	8.60	0.59	0.62
5-19	3.493	1.162	1.162	3.232	34.32	31.60	8.61	0.60	0.63
5-20	3.603	2.112	2.112	5.646	51.46	47.29	8.82	0.51	0.53
6-8	5.133	1.896	1.896	7.784	77.78	71.51	8.77	0.56	0.59
6-19	3.487	1.184	1.184	3.190	30.98	28.49	8.74	0.54	0.57
6-20	3.550	2.116	2.116	6.021	61.43	56.40	8.92	0.57	0.60
7-8	5.134	1.899	1.899	7.742	72.98	67.00	8.93	0.53	0.55
7-19	3.489	1.169	1.169	3.139	34.98	32.20	8.63	0.63	0.66
7-20	3.613	2.120	2.120	6.068	57.32	52.57	9.04	0.53	0.55
8-8	5.167	1.880	1.880	7.802	90.65	83.55	8.50	0.65	0.69
8-19	3.492	1.169	1.169	3.067	34.12	31.40	8.66	0.62	0.66
8-20	3.601	2.117	2.117	6.131	52.86	48.43	9.15	0.48	0.50
9-8	5.130	1.878	1.878	7.572	75.16	69.09	8.79	0.56	0.58
9-19	3.490	1.190	1.190	3.220	36.26	33.42	8.50	0.63	0.67
9-20	3.598	2.117	2.117	6.131	56.02	51.36	9.07	0.51	0.53
10-8	5.144	1.868	1.868	7.632	64.77	59.40	9.04	0.47	0.49
10-19	3.492	1.187	1.187	3.209	37.38	34.44	8.54	0.65	0.69
10-20	3.598	2.114	2.114	6.134	57.30	52.52	9.10	0.52	0.55
11-8	5.134	1.877	1.877	7.762	78.25	72.02	8.65	0.57	0.59
11-19	3.493	1.179	1.179	3.144	32.13	29.59	8.58	0.57	0.60
11-20	3.634	2.125	2.125	6.300	62.66	57.52	8.94	0.56	0.58
12-8	5.136	1.876	1.876	7.471	80.22	73.83	8.66	0.60	0.63
12-19	3.493	1.186	1.186	3.207	36.79	33.85	8.69	0.64	0.68
12-20	3.613	2.122	2.122	6.052	63.75	58.55	8.88	0.59	0.62

Specimen	Average Dimensions (in) Length	Thickness	Height	Volume (in^3)	Initial Wt. (g)	Final Wt. (g)	MC (%)	$S.G._a$	$S.G._d$
13-8	5.137	1.877	1.877	7.529	72.79	66.85	8.89	0.54	0.57
13-19	3.488	1.191	1.191	3.163	41.28	38.09	8.37	0.73	0.78
13-20	3.621	2.120	2.120	6.054	62.79	57.68	8.86	0.58	0.61
14-8	5.139	1.877	1.877	7.570	80.69	74.22	8.72	0.60	0.63
14-19	3.492	1.181	1.181	3.121	30.97	28.48	8.74	0.56	0.58
14-20	3.611	2.125	2.125	6.126	63.98	58.76	8.88	0.59	0.61
15-8	5.138	1.887	1.887	7.775	79.84	73.42	8.74	0.58	0.60
15-19	3.489	1.194	1.194	3.212	37.59	34.61	8.61	0.66	0.69
15-20	3.606	2.127	2.127	6.236	61.78	56.68	9.00	0.55	0.58
16-8	5.149	1.866	1.866	7.638	78.08	71.83	8.70	0.57	0.60
16-19	3.492	1.179	1.179	3.138	35.26	32.46	8.63	0.63	0.66
16-20	3.612	2.122	2.122	6.176	57.09	52.37	9.01	0.52	0.54
17-8	5.135	1.890	1.890	7.856	73.21	67.24	8.88	0.52	0.54
17-19	3.492	1.174	1.174	3.116	35.05	32.22	8.78	0.63	0.66
17-20	3.603	2.124	2.124	6.266	64.84	59.53	8.92	0.58	0.61
18-8	5.126	1.891	1.891	7.595	71.53	65.64	8.97	0.53	0.55
18-19	3.490	1.170	1.170	3.168	36.70	33.75	8.74	0.65	0.68
18-20	3.535	2.119	2.119	5.997	62.35	57.21	8.98	0.58	0.61
19-8	5.153	1.890	1.890	7.535	79.52	73.13	8.74	0.59	0.62
19-19	3.489	1.181	1.181	3.213	37.66	34.66	8.66	0.66	0.69
19-20	3.601	2.120	2.120	6.134	58.27	53.97	7.97	0.54	0.56
20-8	5.150	1.884	1.884	7.653	77.16	70.94	8.77	0.57	0.59
20-19	3.495	1.163	1.163	3.132	31.57	29.04	8.71	0.57	0.59
20-20	3.606	2.119	2.119	6.166	60.58	55.65	8.86	0.55	0.58
21-8	5.120	1.898	1.898	7.692	76.82	70.58	8.84	0.56	0.59
21-19	3.483	1.172	1.172	3.190	28.32	26.00	8.92	0.50	0.52
21-20	3.601	2.119	2.119	6.073	61.32	56.34	8.84	0.57	0.59
22-8	5.136	1.881	1.881	7.627	71.99	66.14	8.84	0.53	0.55
22-19	3.485	1.170	1.170	3.218	32.70	30.05	8.82	0.57	0.60
22-20	3.601	2.118	2.118	6.060	64.87	59.60	8.84	0.60	0.63
23-8	5.153	1.890	1.890	7.387	67.61	62.13	8.82	0.51	0.53
23-19	3.487	1.168	1.168	3.273	33.65	30.90	8.90	0.58	0.60
23-20	3.604	2.120	2.120	5.884	63.22	58.16	8.70	0.60	0.63
24-8	5.141	1.886	1.886	7.661	81.45	74.87	8.79	0.60	0.63
24-19	3.478	1.165	1.165	3.148	35.28	32.44	8.75	0.63	0.66
24-20	3.521	2.108	2.108	6.013	62.27	57.23	8.81	0.58	0.61

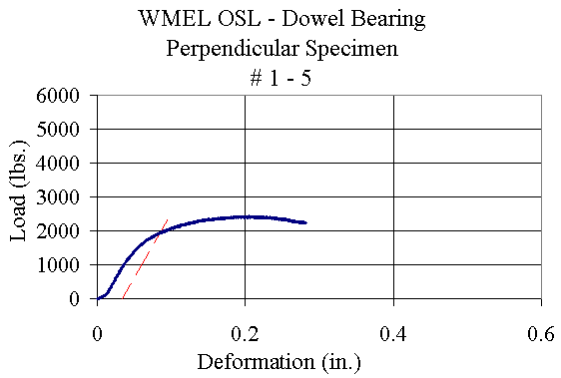
Specimen	Average Dimensions (in) Length	Thickness	Height	Volume (in^3)	Initial Wt. (g)	Final Wt. (g)	MC (%)	$S.G._a$	$S.G._d$
25-8	5.138	1.852	1.852	7.501	63.94	58.61	9.09	0.48	0.50
25-19	3.486	1.167	1.167	3.120	32.05	29.44	8.87	0.58	0.60
25-20	3.603	2.113	2.113	6.131	63.22	57.99	9.02	0.58	0.61
26-8	5.144	1.864	1.864	7.529	55.52	50.85	9.18	0.41	0.43
26-19	3.476	1.165	1.165	3.128	30.06	27.56	9.07	0.54	0.56
26-20	3.599	2.111	2.111	6.133	54.61	50.06	9.09	0.50	0.52
27-8	5.137	1.874	1.874	7.355	67.75	62.12	9.06	0.52	0.54
27-19	3.483	1.169	1.169	3.194	28.05	25.72	9.06	0.49	0.51
27-20	3.597	2.125	2.125	5.997	61.50	56.47	8.91	0.57	0.60
28-8	5.142	1.862	1.862	7.558	69.21	63.48	9.03	0.51	0.53
28-19	3.482	1.163	1.163	3.162	32.44	29.85	8.68	0.58	0.60
28-20	4.452	2.112	2.112	7.710	63.80	58.57	8.93	0.46	0.48
29-8	5.147	1.869	1.869	7.765	77.54	71.09	9.07	0.56	0.59
29-19	3.492	1.162	1.162	3.103	29.82	27.38	8.91	0.54	0.56
29-20	3.598	2.111	2.111	6.253	57.21	52.44	9.10	0.51	0.53
30-8	5.140	1.857	1.857	7.455	82.51	75.83	8.81	0.62	0.65
30-19	3.492	1.154	1.154	3.140	29.69	27.28	8.83	0.53	0.55
30-20	3.595	2.112	2.112	6.062	66.73	61.27	8.91	0.62	0.65
31-8	5.145	1.878	1.878	7.706	81.36	74.61	9.05	0.59	0.62
31-19	3.487	1.167	1.167	3.156	27.40	25.14	8.99	0.49	0.51
31-20	3.587	2.106	2.106	6.190	62.95	57.73	9.04	0.57	0.60
32-8	5.141	1.878	1.878	7.755	82.99	76.20	8.91	0.60	0.63
32-19	3.488	1.179	1.179	3.198	29.83	27.41	8.83	0.52	0.55
32-20	3.587	2.106	2.106	6.013	58.14	53.32	9.04	0.54	0.57
33-8	5.147	1.890	1.890	7.717	87.50	80.46	8.75	0.64	0.67
33-19	3.486	1.167	1.167	3.167	27.47	25.25	8.79	0.49	0.51
33-20	3.589	2.106	2.106	6.100	55.90	51.21	9.16	0.51	0.53
34-8	5.135	1.883	1.883	7.856	75.27	69.07	8.98	0.54	0.56
34-19	3.489	1.158	1.158	3.096	29.29	26.95	8.68	0.53	0.55
34-20	3.588	2.105	2.105	6.109	51.47	47.20	9.05	0.47	0.49
35-8	5.131	1.879	1.879	7.741	83.83	77.09	8.74	0.61	0.64
35-19	3.490	1.158	1.158	3.129	29.63	27.25	8.73	0.53	0.55
35-20	3.590	2.110	2.110	6.180	64.36	59.09	8.92	0.58	0.61
36-8	5.123	1.888	1.888	7.559	80.90	74.43	8.69	0.60	0.63
36-19	3.489	1.165	1.165	3.138	26.14	24.03	8.78	0.47	0.48
36-20	3.577	2.113	2.113	5.931	51.75	47.43	9.11	0.49	0.51

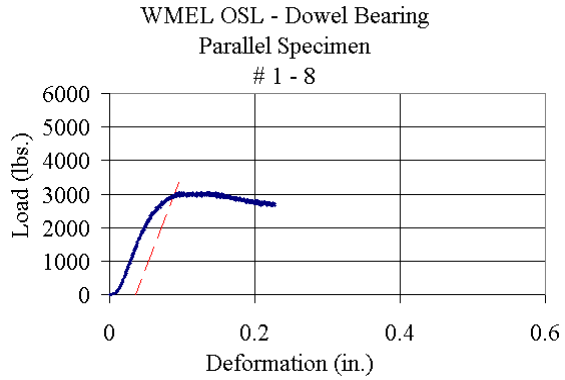
Specimen	Average Dimensions (in) Length	Thickness	Height	Volume (in^3)	Initial Wt. (g)	Final Wt. (g)	MC (%)	$S.G._a$	$S.G._d$
37-8	5.153	1.903	1.903	7.708	78.02	71.79	8.68	0.57	0.59
37-19	3.489	1.197	1.197	3.215	37.90	34.93	8.50	0.66	0.70
37-20	3.582	2.121	2.121	6.142	73.29	67.47	8.63	0.67	0.71
38-8	5.138	1.879	1.879	7.455	74.33	68.45	8.59	0.56	0.59
38-19	3.489	1.187	1.187	3.247	37.93	34.98	8.43	0.66	0.69
38-20	3.589	2.112	2.112	5.849	59.51	54.46	9.27	0.57	0.60
39-8	5.161	1.885	1.885	7.792	86.07	79.22	8.65	0.62	0.65
39-19	3.489	1.168	1.168	3.132	28.22	25.92	8.87	0.50	0.53
39-20	3.588	2.111	2.111	6.222	73.10	67.19	8.80	0.66	0.70
40-8	5.159	1.899	1.899	7.846	84.54	77.74	8.75	0.60	0.63
40-19	3.490	1.164	1.164	3.122	28.33	26.01	8.92	0.51	0.53
40-20	3.593	2.111	2.111	6.191	66.33	60.86	8.99	0.60	0.63
41-8	5.158	1.900	1.900	7.926	80.15	73.61	8.88	0.57	0.59
41-19	3.487	1.177	1.177	3.139	32.68	30.04	8.79	0.58	0.61
41-20	3.586	2.110	2.110	6.224	60.70	55.65	9.07	0.55	0.57
42-8	5.150	1.887	1.887	7.963	73.87	67.68	9.15	0.52	0.54
42-19	3.487	1.167	1.167	3.171	36.82	33.89	8.65	0.65	0.69
42-20	3.586	2.109	2.109	6.349	69.23	63.56	8.92	0.61	0.64
43-8	5.149	1.873	1.873	7.679	88.81	81.65	8.77	0.65	0.68
43-19	3.482	1.167	1.167	3.198	36.04	33.21	8.52	0.63	0.67
43-20	3.602	2.112	2.112	6.202	57.51	52.72	9.09	0.52	0.54
44-8	5.151	1.882	1.882	7.831	84.97	78.24	8.60	0.61	0.64
44-19	3.488	1.188	1.188	3.153	32.85	30.21	8.74	0.58	0.61
44-20	3.581	2.112	2.112	6.258	68.59	62.99	8.89	0.61	0.65
45-8	5.150	1.885	1.885	7.684	73.11	67.08	8.99	0.53	0.56
45-19	3.489	1.178	1.178	3.147	31.71	29.14	8.82	0.56	0.59
45-20	3.587	2.119	2.119	6.243	65.14	59.73	9.06	0.58	0.61
						Mean =	8.81	0.57	0.60
						Std. Dev =	0.208	0.058	0.063
						COV =	2.4%	10.2%	10.6%

DOWEL BEARING

Load vs. Displacement Curves

Dowel bearing tests were performed on 270 specimens. Each panel contributed three parallel and three perpendicular dowel bearing specimens to the overall number of specimens tested. Load-displacement curves were created for each of the dowel bearing tests and can be found on the following pages. Curves are labeled as "WMEL OSL – Dowel Bearing" with the direction of load applied with respect to panel orientation, followed by the specimen label. "WMEL" represents the location where the OSL was produced (Wood Materials and Engineering Laboratory at Washington State University).


WMEL OSL - Dowel Bearing
Perpendicular Specimen
1 - 5
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
1 - 8
Load (lbs.)
6000
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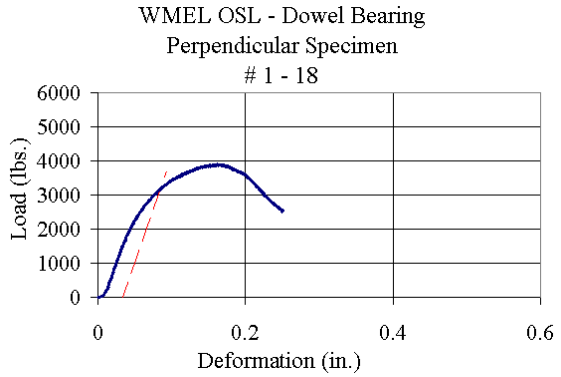
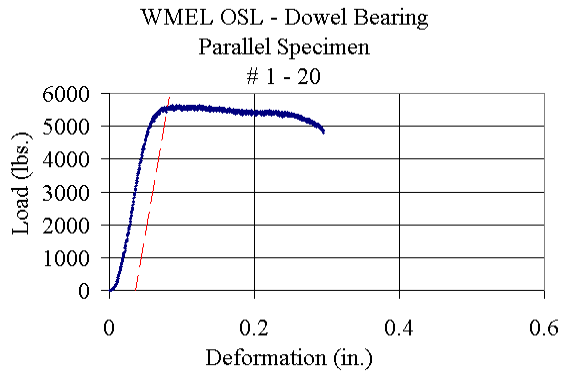
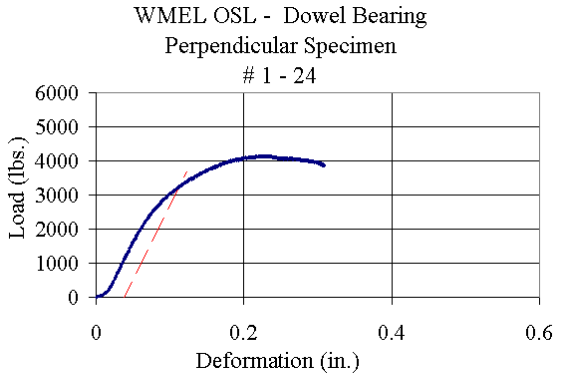
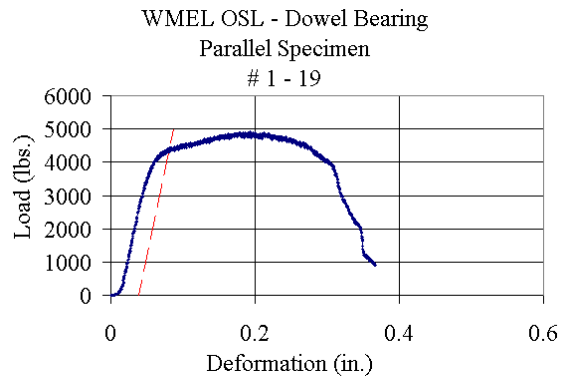
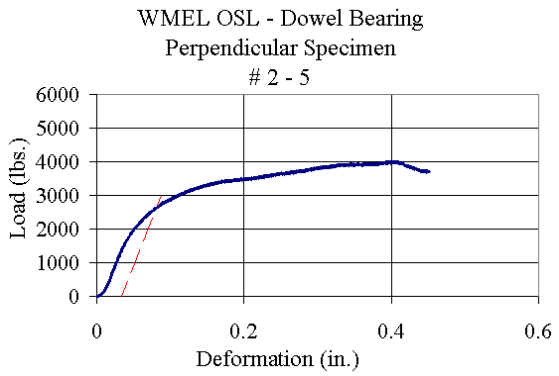
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
1 - 18
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
1 - 20
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
1 - 24
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
1 - 19
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
2 - 5
Load (lbs.)
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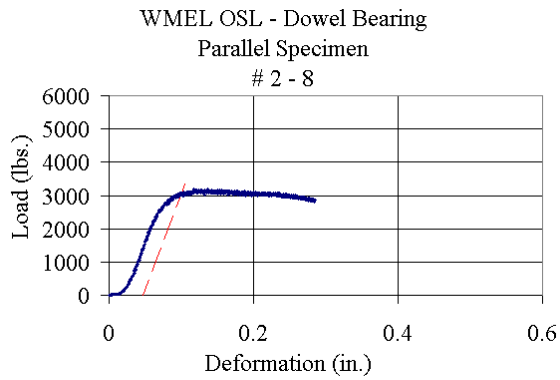
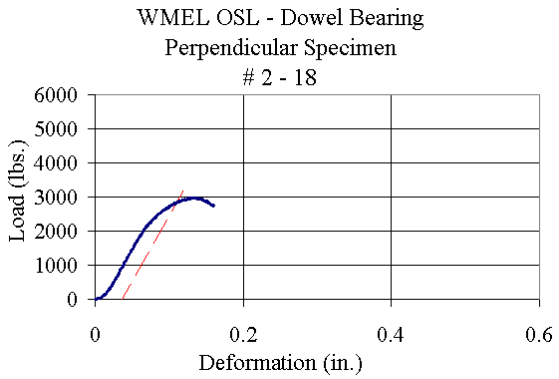
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
2 - 8
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
2 - 18
Load (lbs.)
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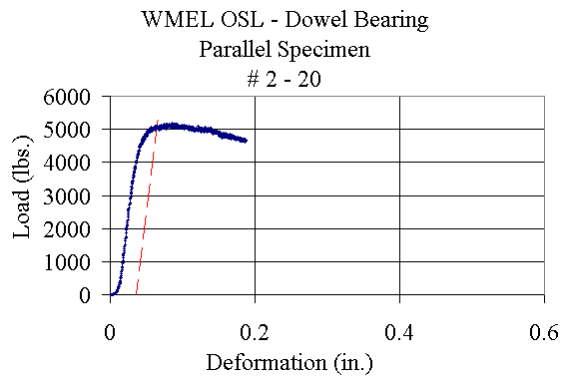
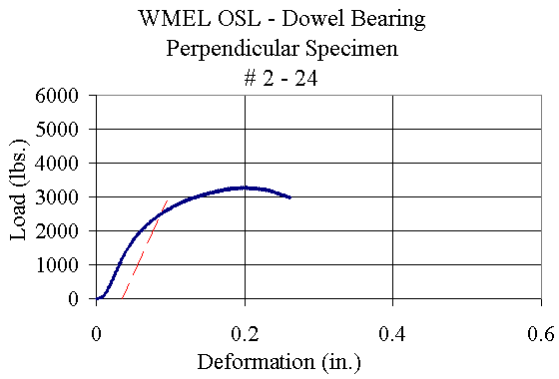
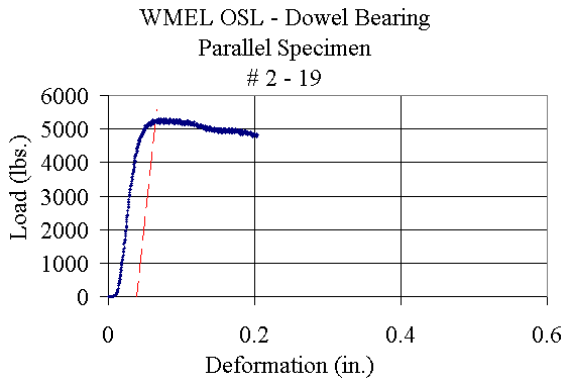
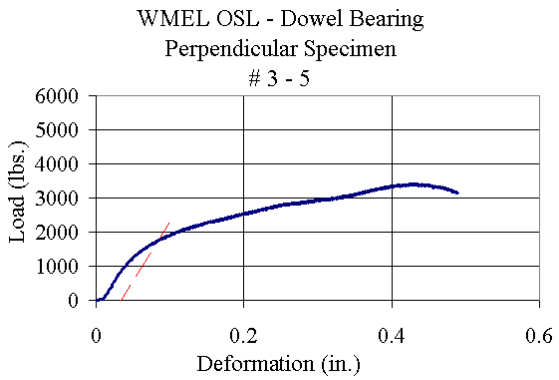
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
2 - 20
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
2 - 24
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
2 - 19
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
3 - 5
Load (lbs.)
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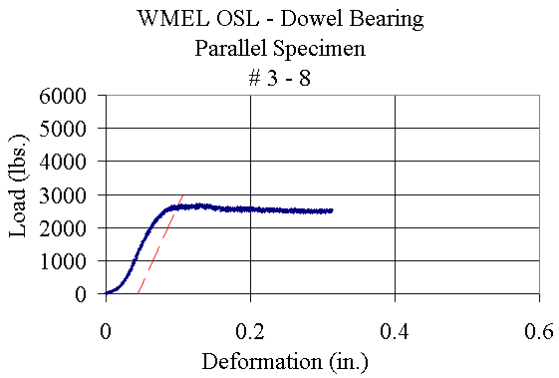
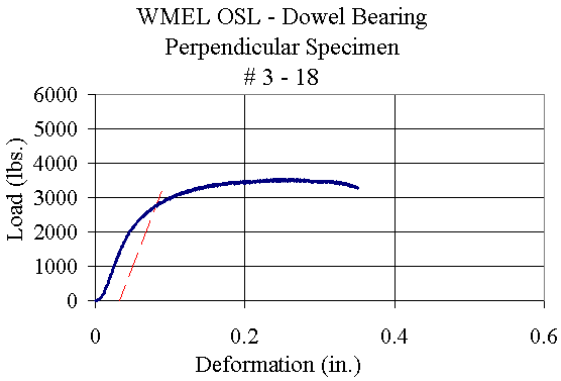
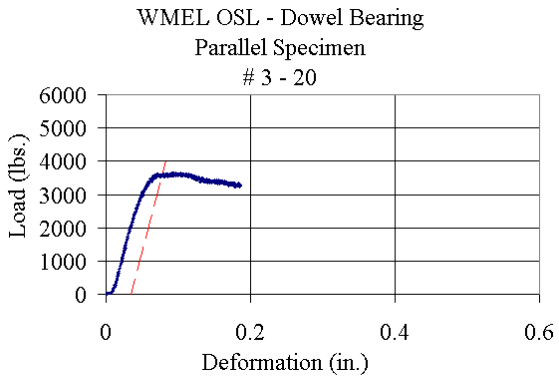
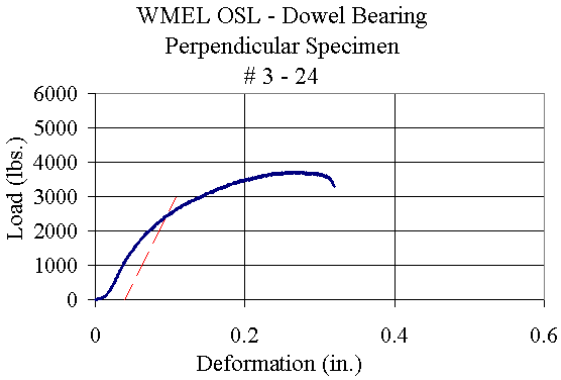
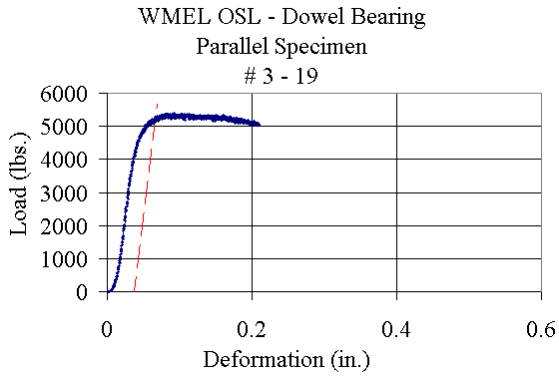
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

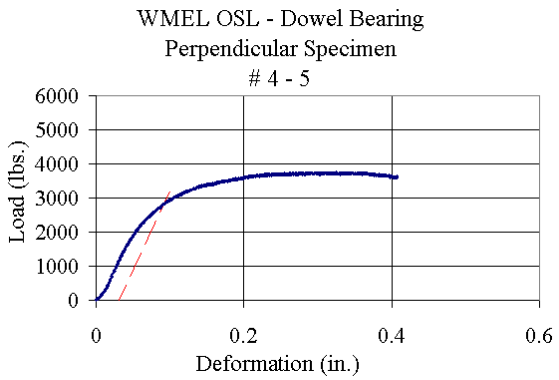

WMEL OSL - Dowel Bearing
Parallel Specimen
3 - 8
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

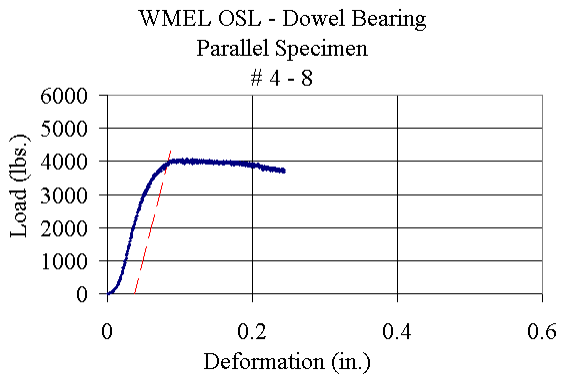

WMEL OSL - Dowel Bearing
Perpendicular Specimen
3 - 18
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

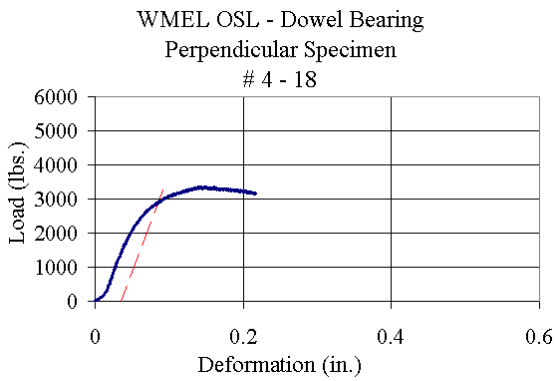

WMEL OSL - Dowel Bearing
Parallel Specimen
3 - 20
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

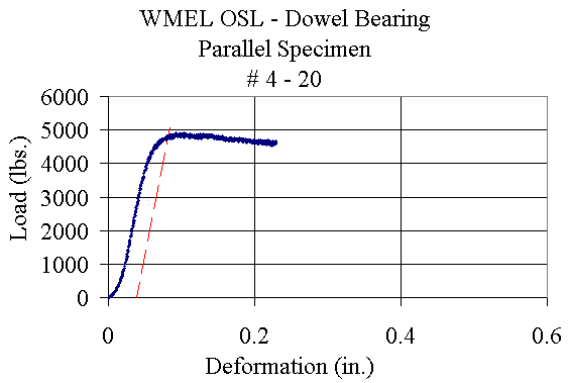

WMEL OSL - Dowel Bearing
Perpendicular Specimen
3 - 24
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

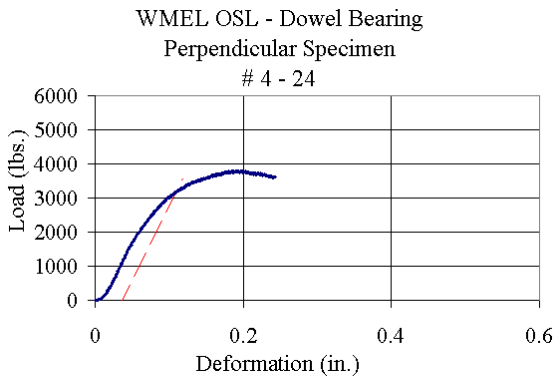

WMEL OSL - Dowel Bearing
Parallel Specimen
3 - 19
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

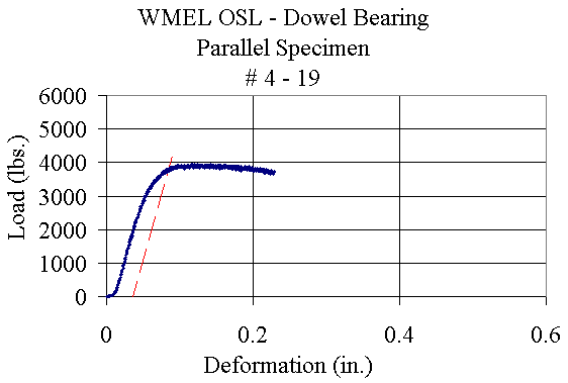

WMEL OSL - Dowel Bearing
Perpendicular Specimen
4 - 5
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

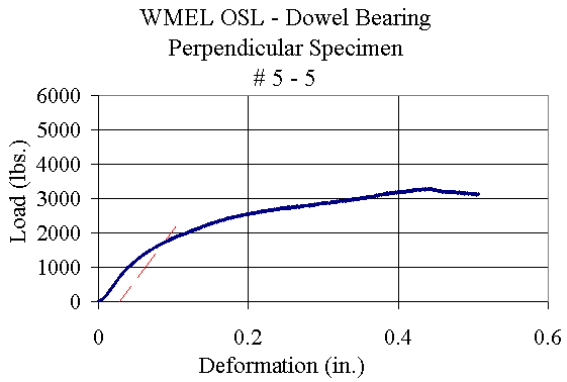

WMEL OSL - Dowel Bearing
Parallel Specimen
4 - 8
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
4 - 18
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
4 - 20
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
4 - 24
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
4 - 19
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
5 - 5
Load (lbs.)
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1000
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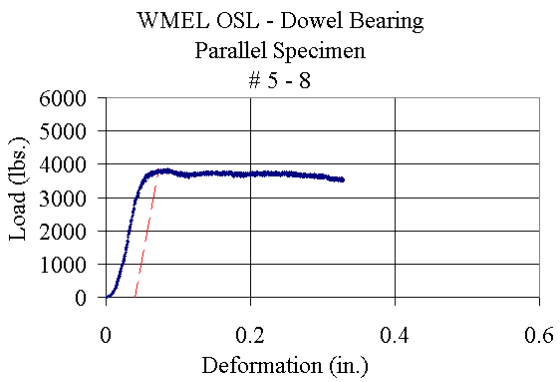
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
5 - 8
Load (lbs.)
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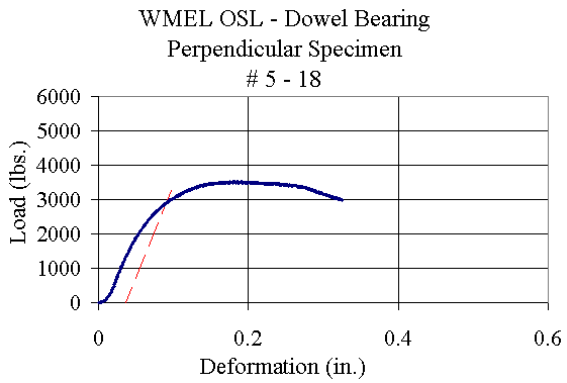
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
5 - 18
Load (lbs.)
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5000
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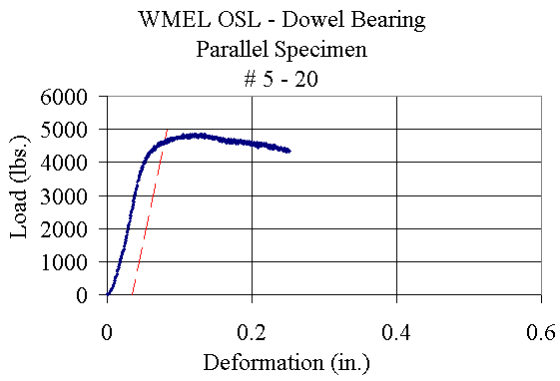
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
5 - 20
Load (lbs.)
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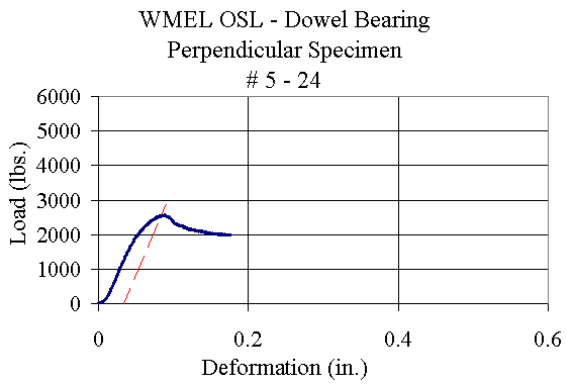
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
5 - 24
Load (lbs.)
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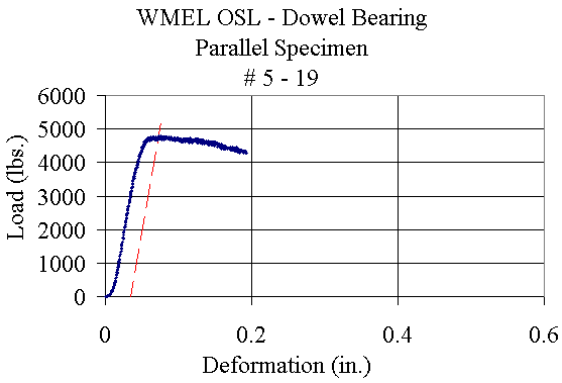
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
5 - 19
Load (lbs.)
6000
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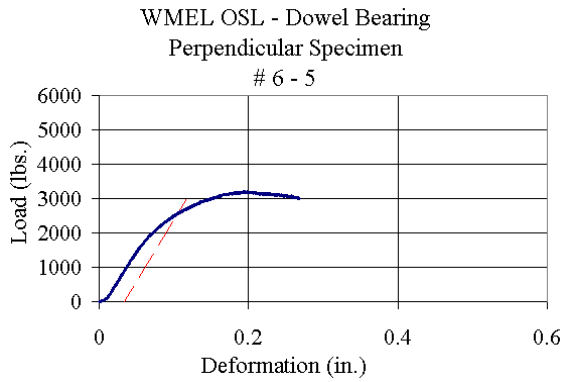
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
6 - 5
Load (lbs.)
6000
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4000
3000
2000
1000
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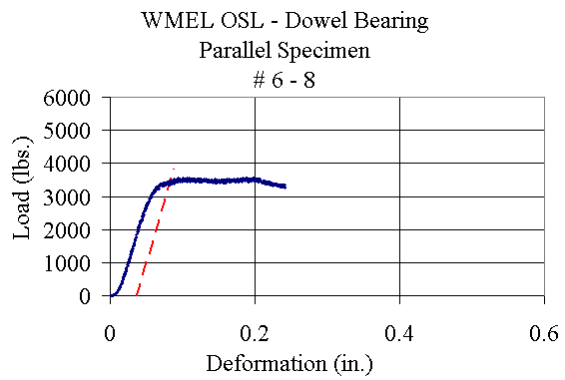
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
6 - 8
Load (lbs.)
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1000
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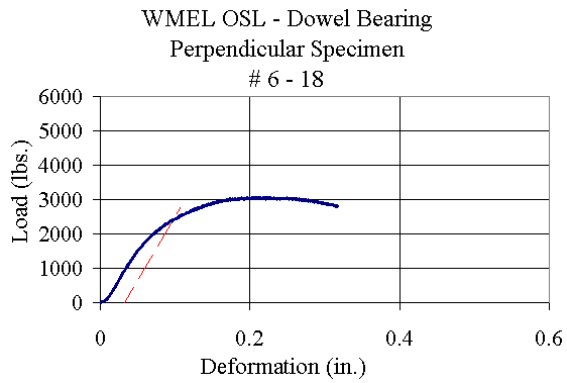
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
6 - 18
Load (lbs.)
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1000
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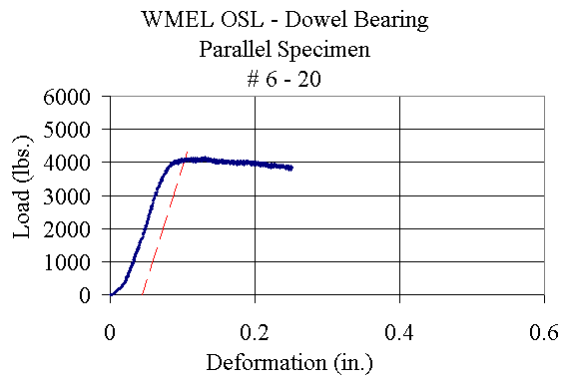
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
6 - 20
Load (lbs.)
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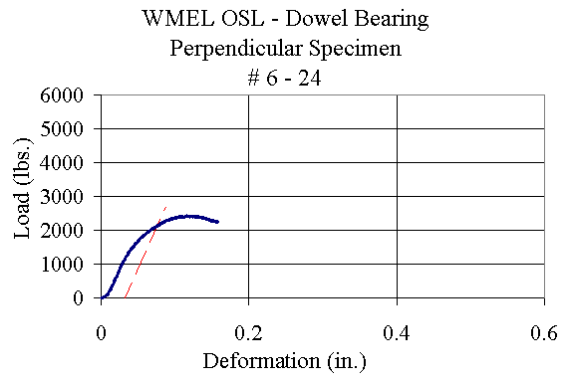
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
6 - 24
Load (lbs.)
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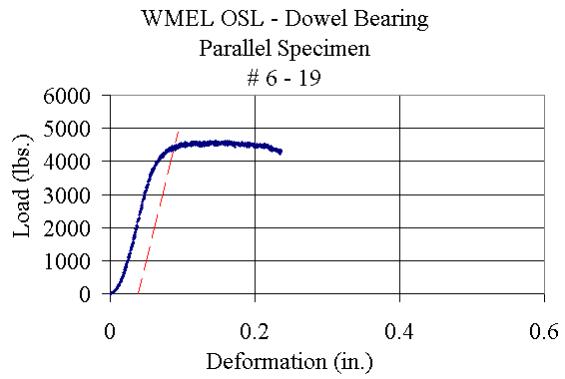
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
6 - 19
Load (lbs.)
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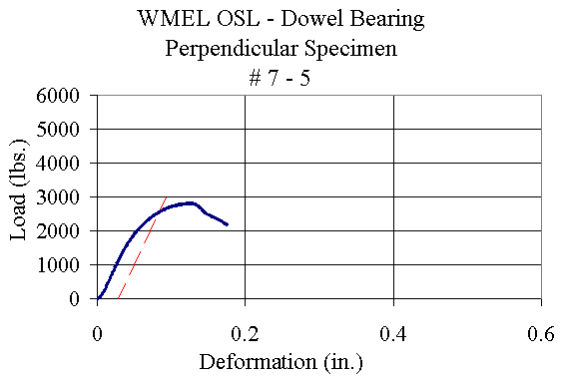
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
7 - 5
Load (lbs.)
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3000
2000
1000
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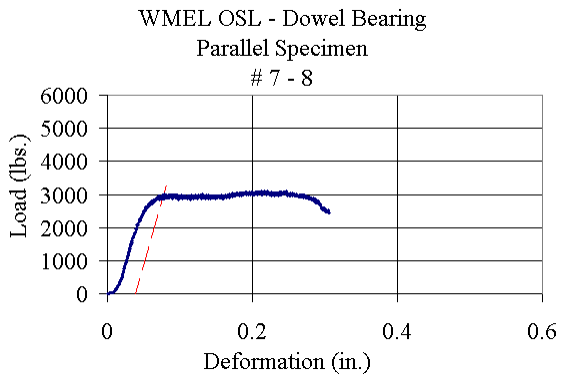
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
7 - 8
Load (lbs.)
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1000
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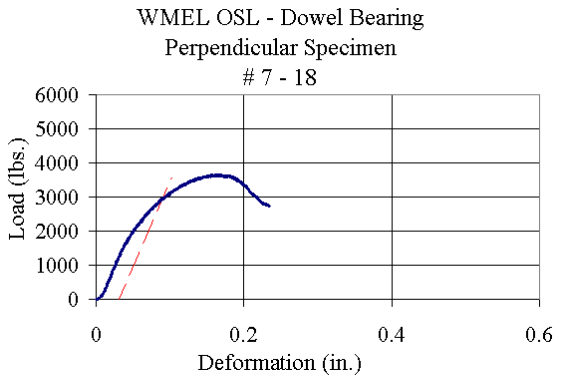
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
7 - 18
Load (lbs.)
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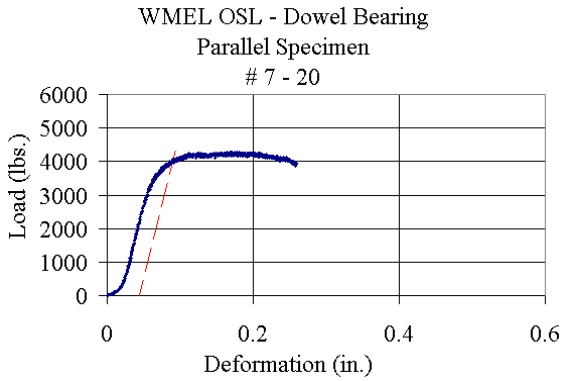
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
7 - 20
Load (lbs.)
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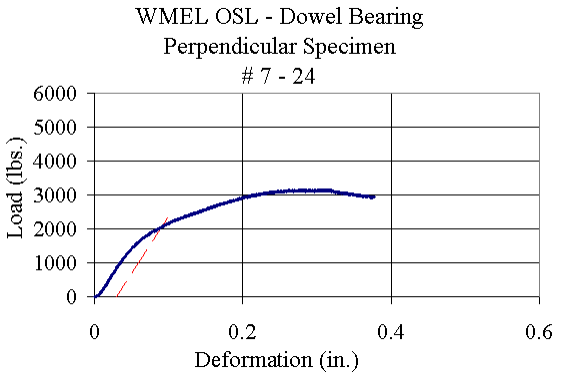
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
7 - 24
Load (lbs.)
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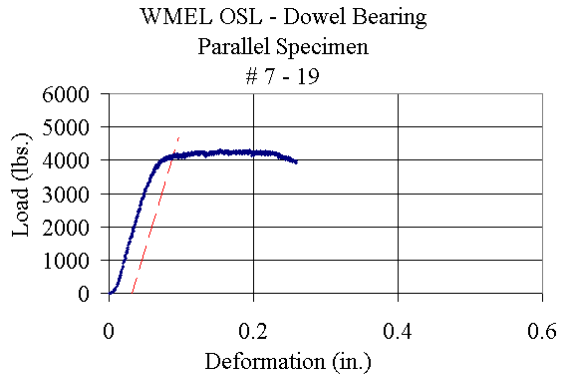
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
7 - 19
Load (lbs.)
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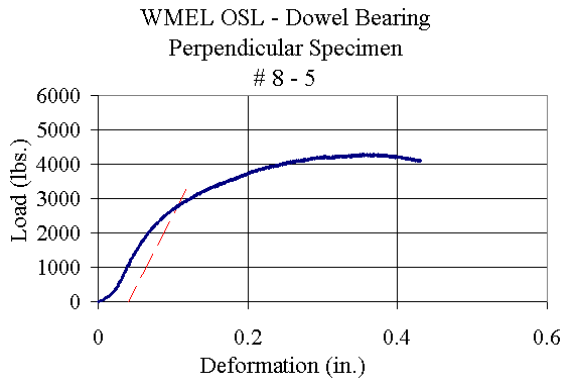
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
8 - 5
Load (lbs.)
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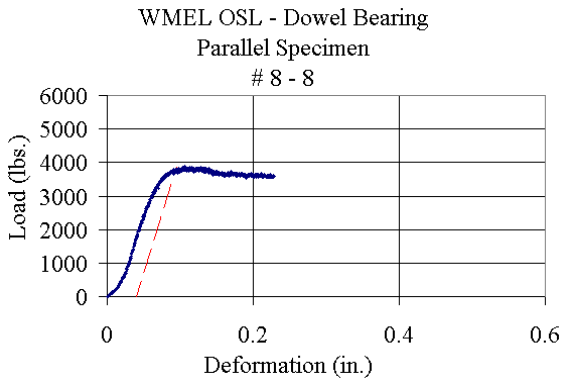
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
8 - 8
Load (lbs.)
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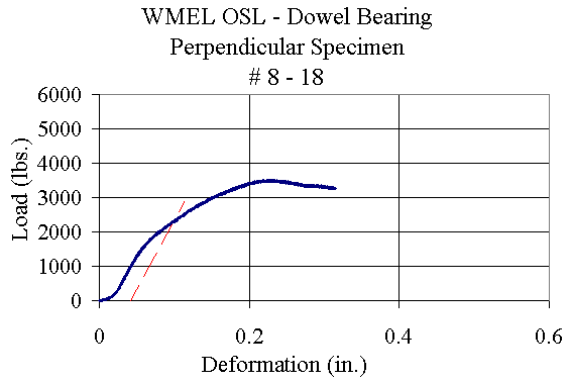
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
8 - 18
Load (lbs.)
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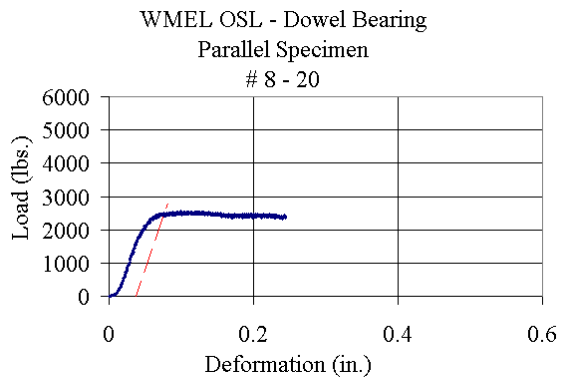
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
8 - 20
Load (lbs.)
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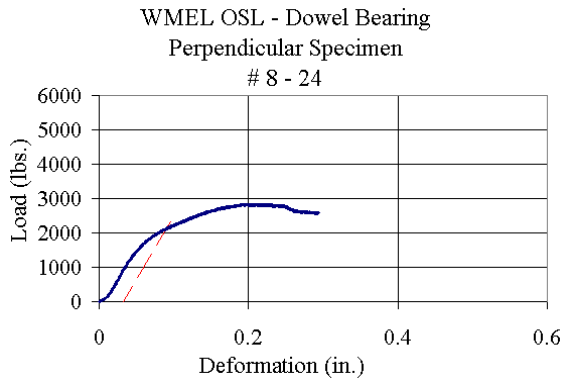
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
8 - 24
Load (lbs.)
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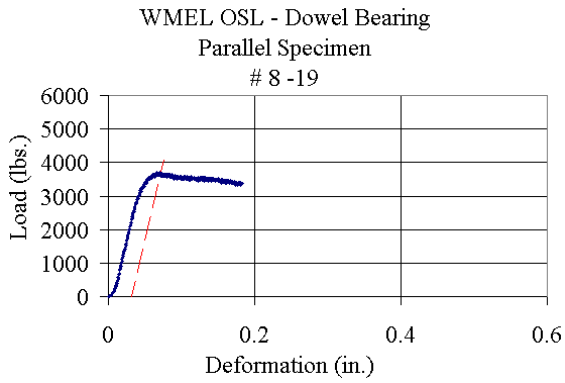
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
8 -19
Load (lbs.)
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4000
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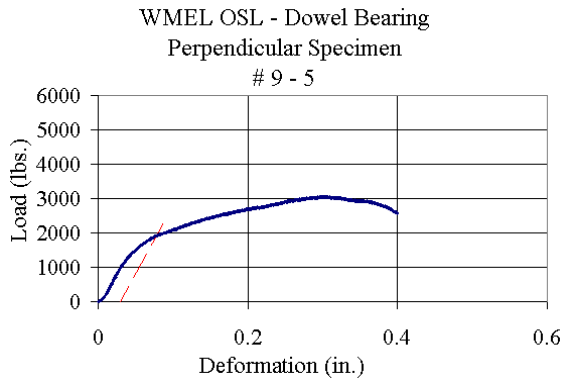
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
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Load (lbs.)
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2000
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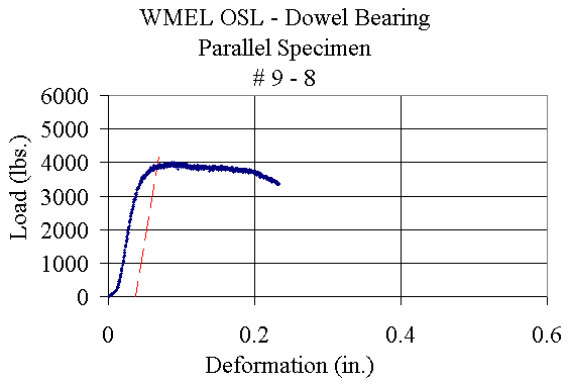
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
9 - 8
Load (lbs.)
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3000
2000
1000
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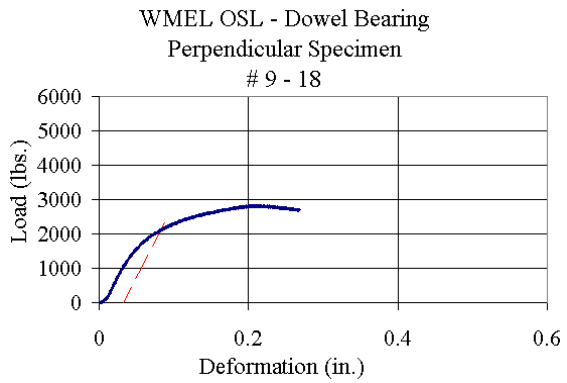
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
9 - 18
Load (lbs.)
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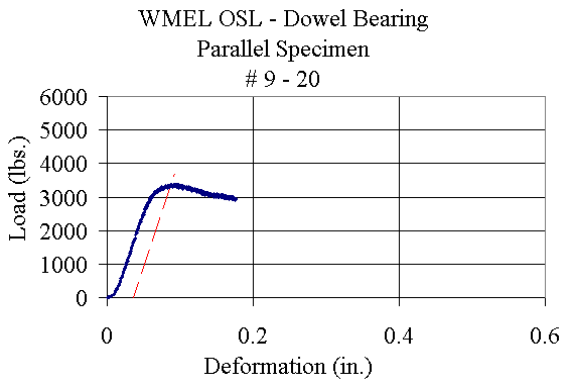
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
9 - 20
Load (lbs.)
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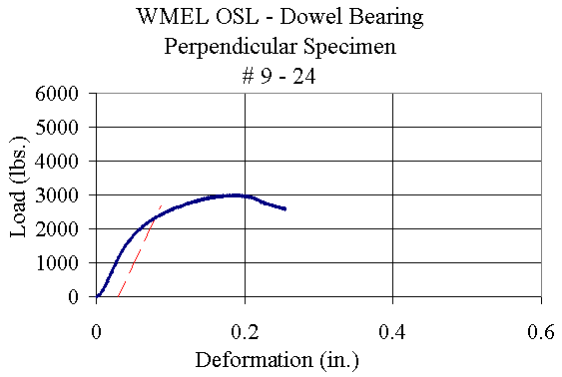
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
9 - 24
Load (lbs.)
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2000
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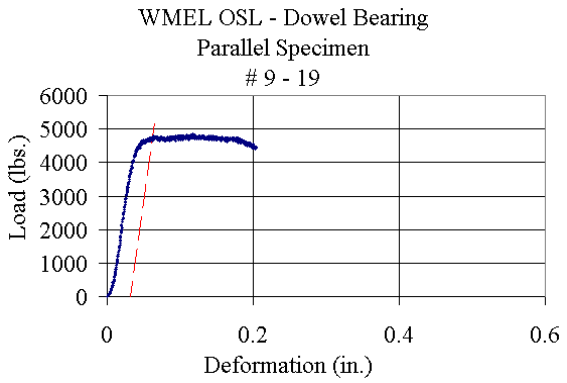
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
9 - 19
Load (lbs.)
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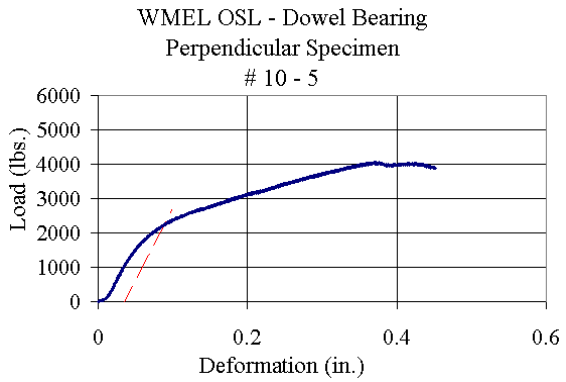
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
10 - 5
Load (lbs.)
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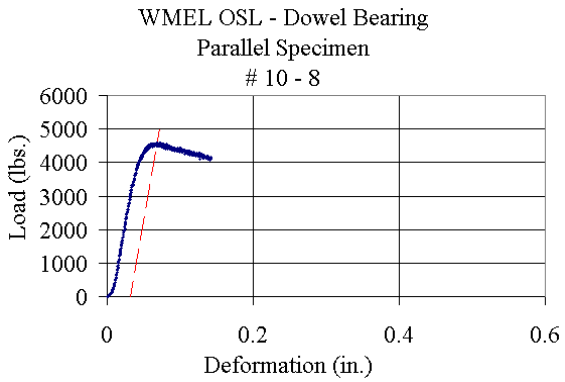
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
10 - 8
Load (lbs.)
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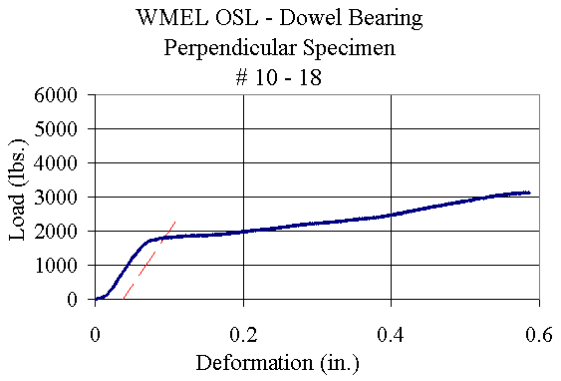
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
10 - 18
Load (lbs.)
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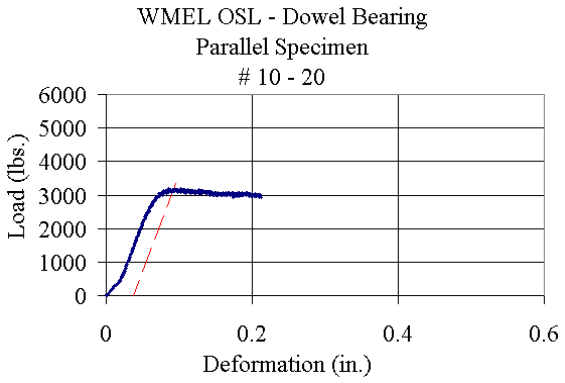
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
10 - 20
Load (lbs.)
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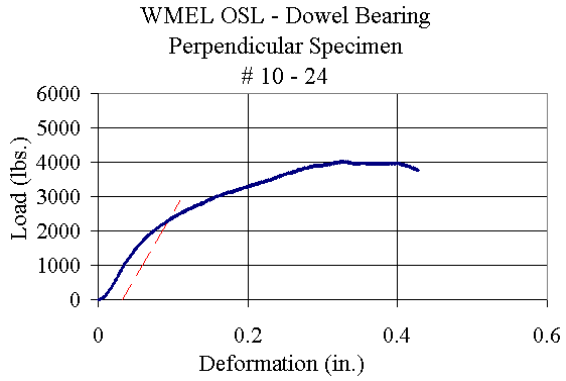
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
10 - 24
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
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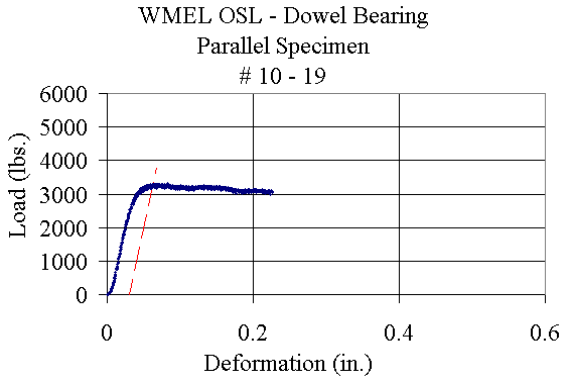
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
10 - 19
Load (lbs.)
6000
5000
4000
3000
2000
1000
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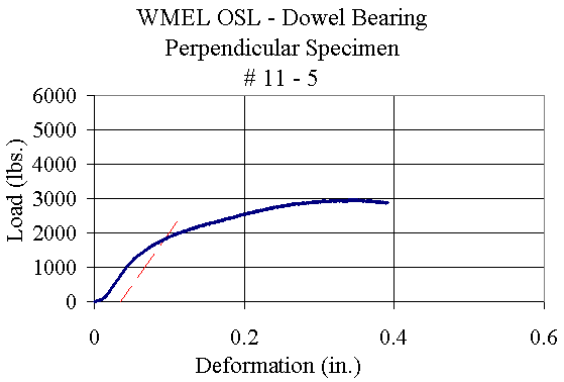
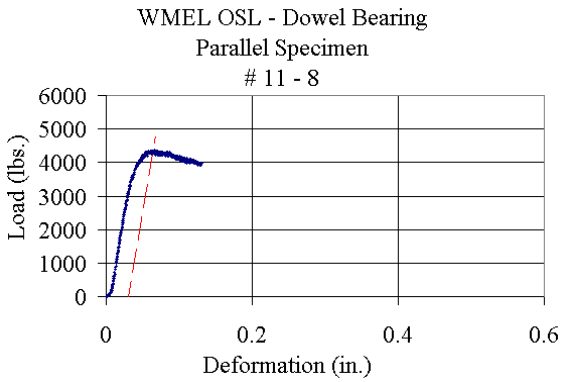
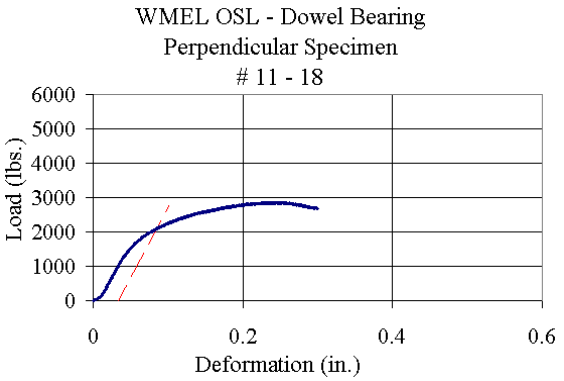
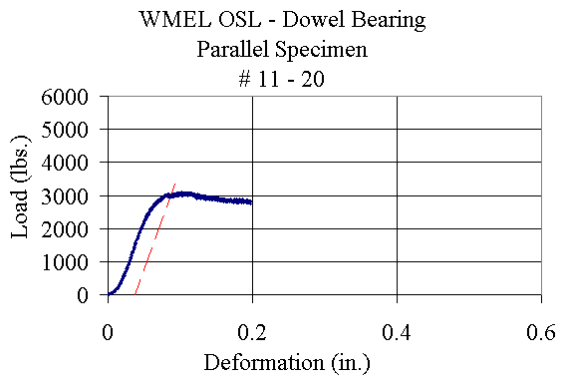
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
11 - 5
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
11 - 8
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
11 - 18
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
11 - 20
Load (lbs.)
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5000
4000
3000
2000
1000
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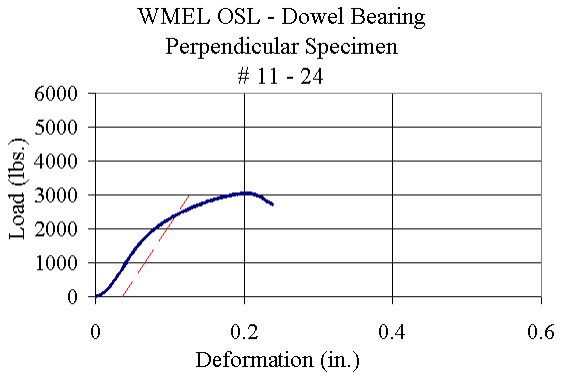
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
11 - 24
Load (lbs.)
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4000
3000
2000
1000
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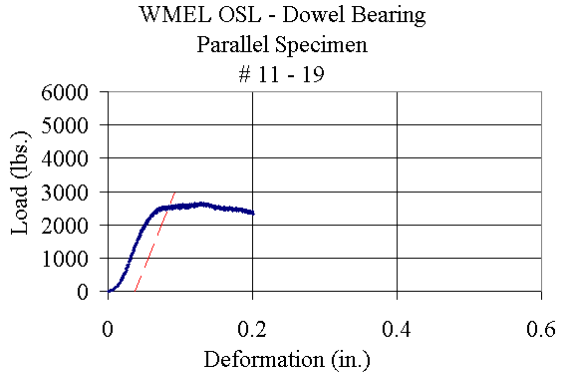
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
11 - 19
Load (lbs.)
6000
5000
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1000
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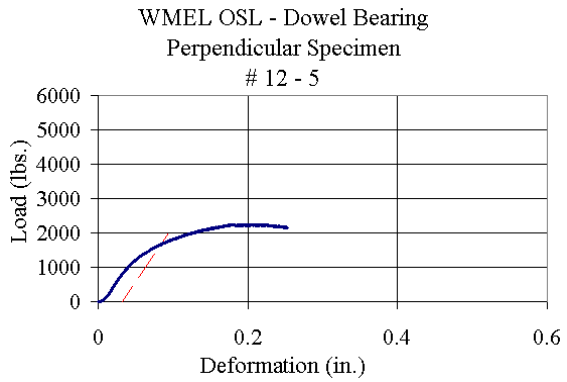
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
12 - 5
Load (lbs.)
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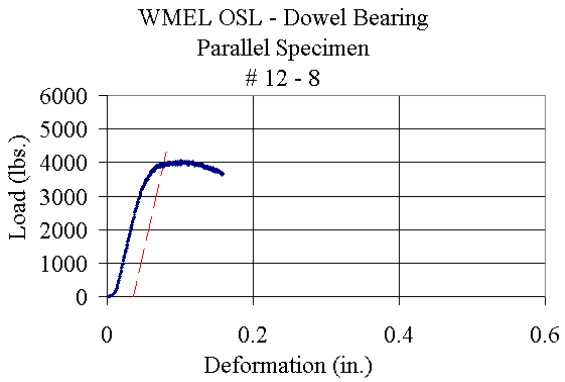
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
12 - 8
Load (lbs.)
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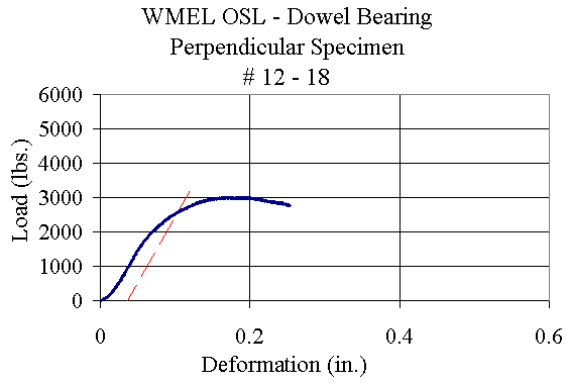
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
12 - 18
Load (lbs.)
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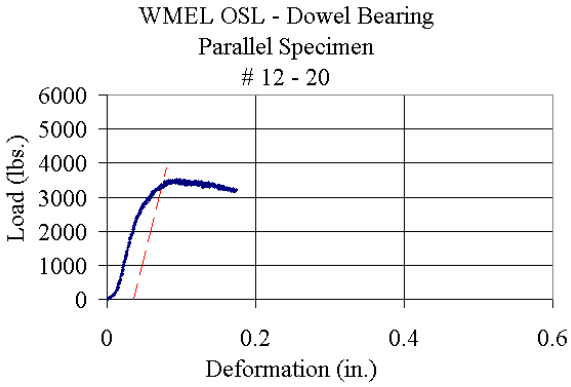
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
12 - 20
Load (lbs.)
6000
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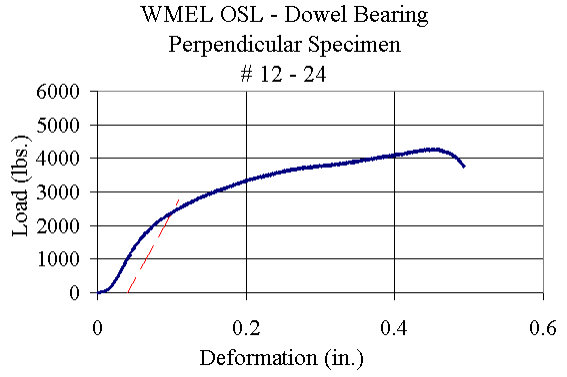
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
12 - 24
Load (lbs.)
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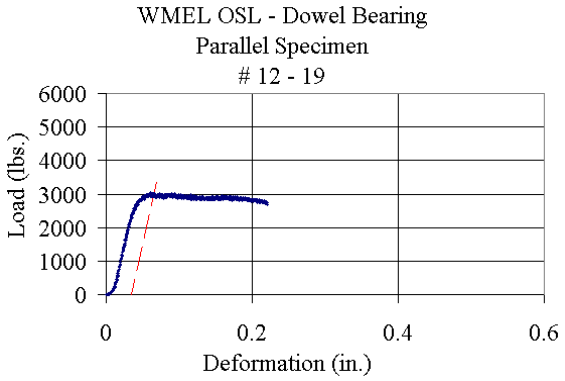
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
12 - 19
Load (lbs.)
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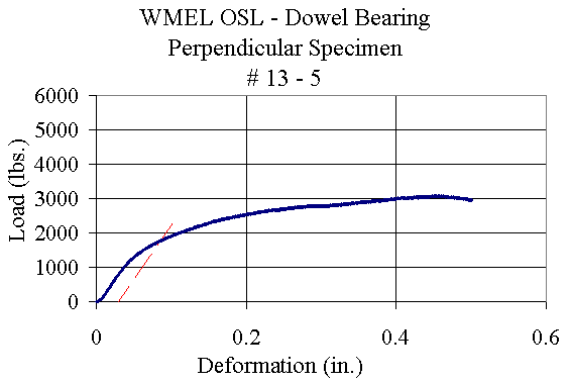
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
13 - 5
Load (lbs.)
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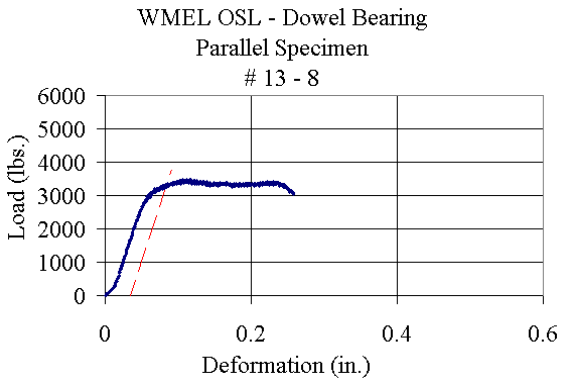
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
13 - 8
Load (lbs.)
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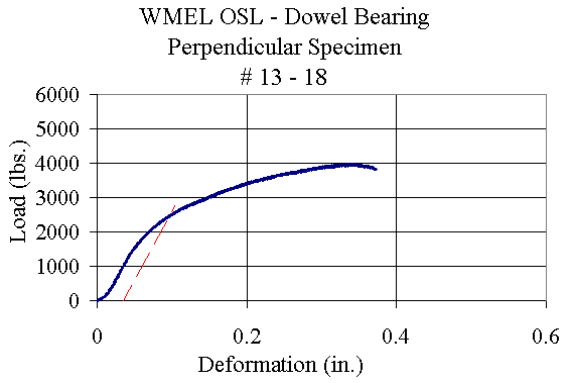
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
13 - 18
Load (lbs.)
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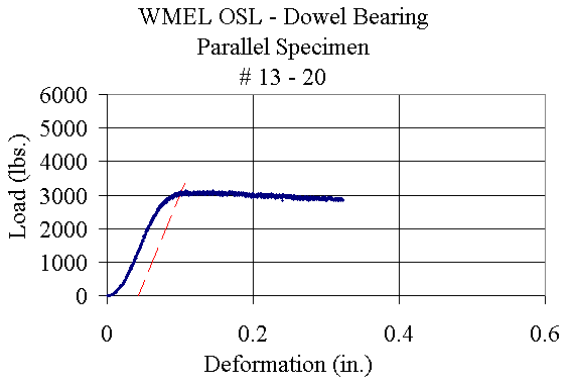
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
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Load (lbs.)
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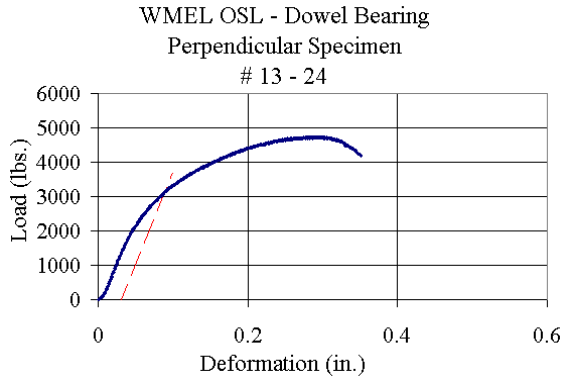
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
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Load (lbs.)
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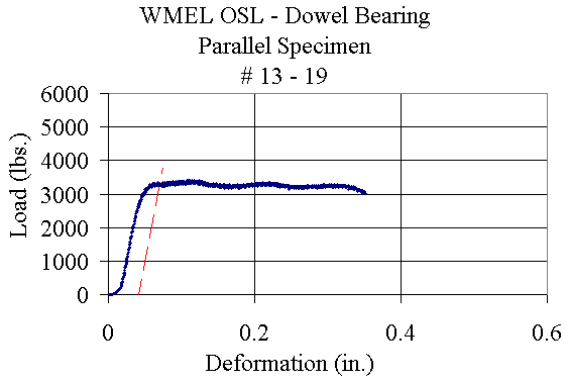
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
13 - 19
Load (lbs.)
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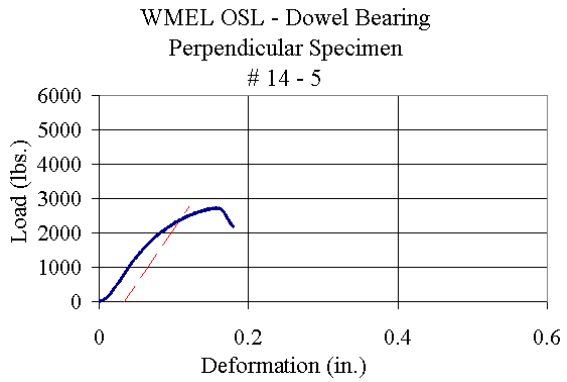
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
14 - 5
Load (lbs.)
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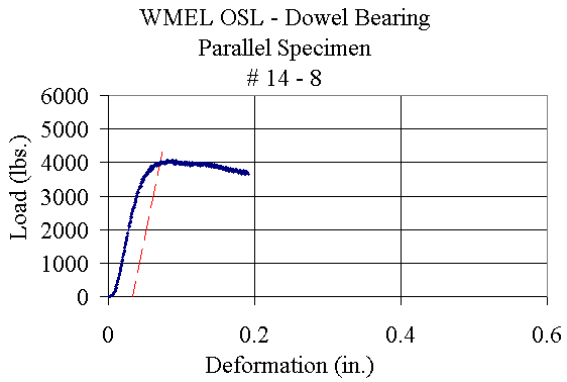
0.6
Deformation (in.)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Parallel Specimen
14 - 8
Load (lbs.)
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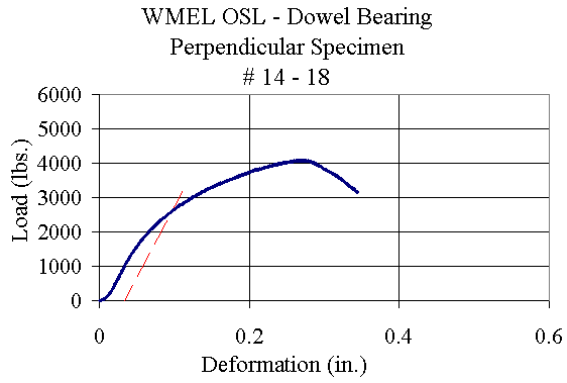
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
14 - 18
Load (lbs.)
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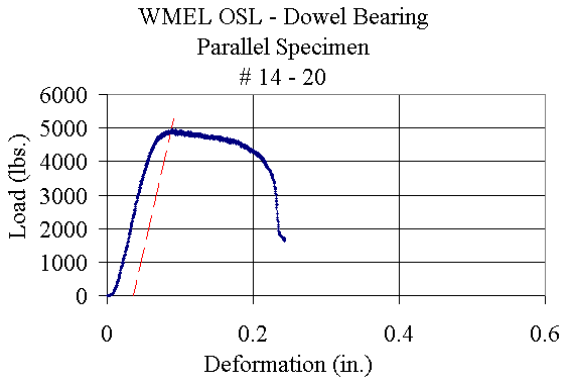
0.6
Deformation (in.)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Parallel Specimen
14 - 20
Load (lbs.)
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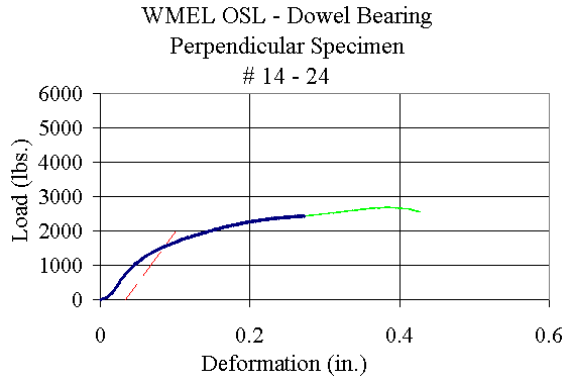
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
14 - 24
Load (lbs.)
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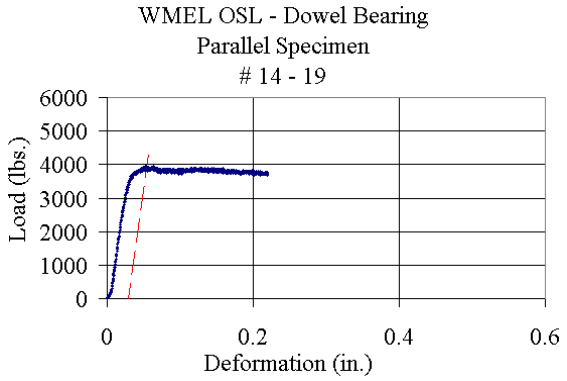
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
14 - 19
Load (lbs.)
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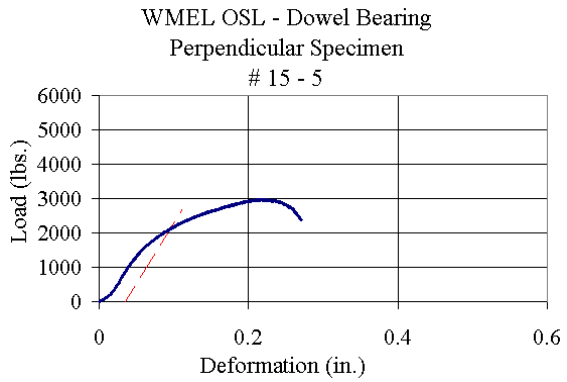
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
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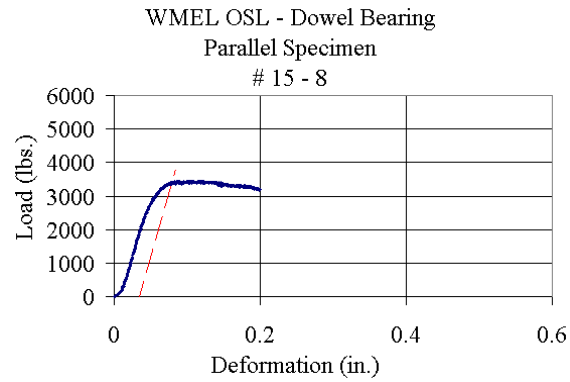
Deformation (in.)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Parallel Specimen
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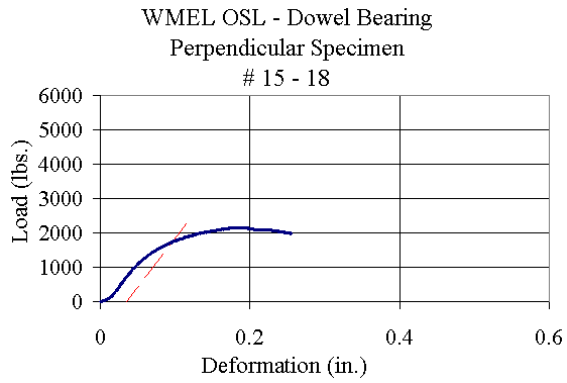
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
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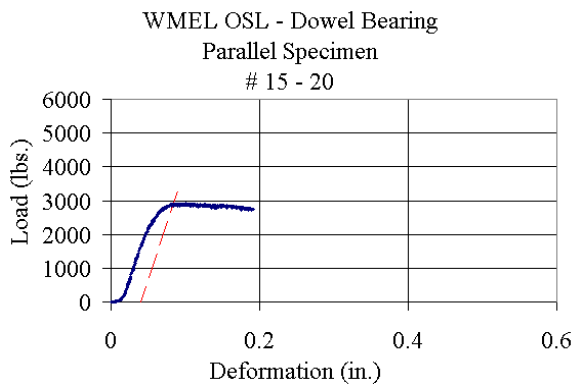
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
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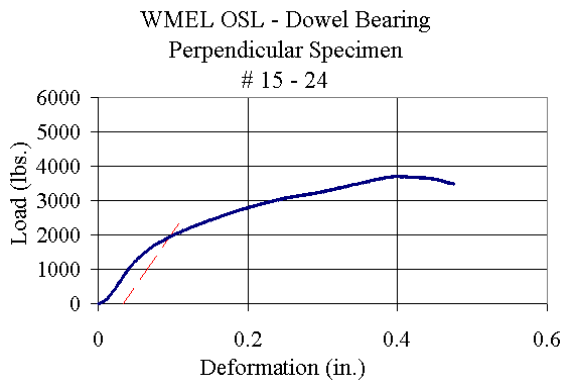
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
15 - 24
Load (lbs.)
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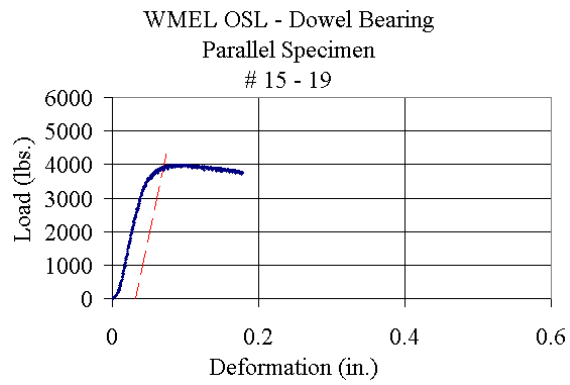
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
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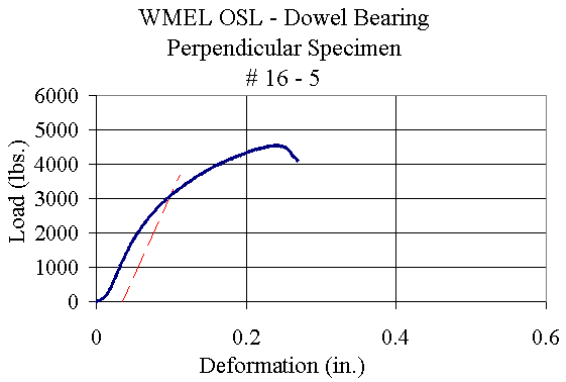
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
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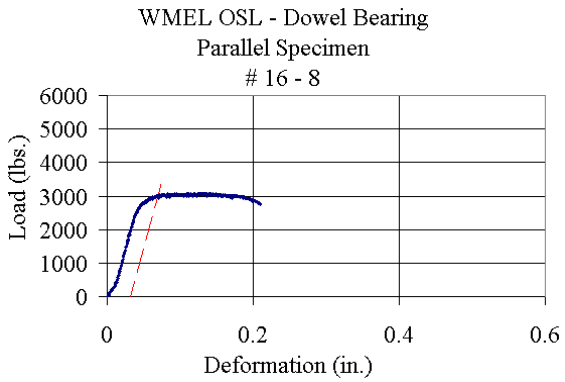
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
16 - 8
Load (lbs.)
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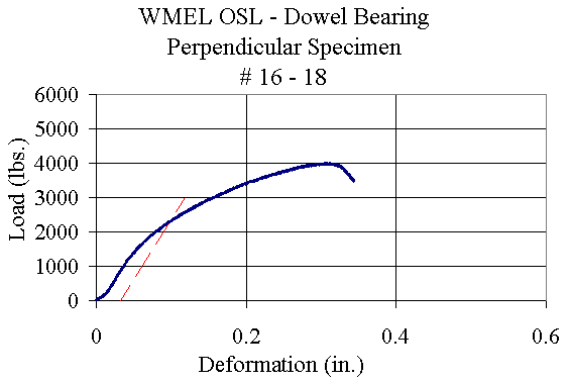
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
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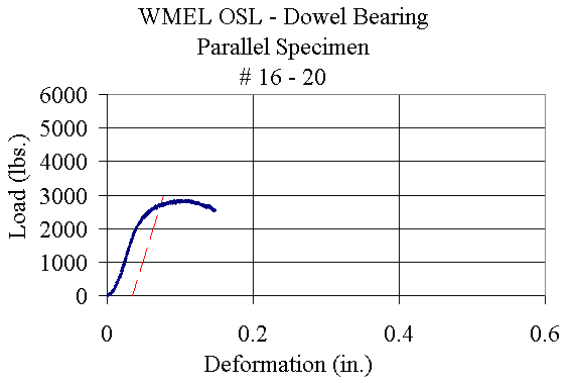
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
16 - 20
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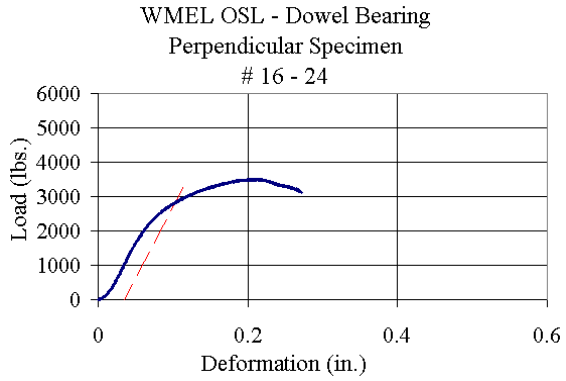
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
16 - 24
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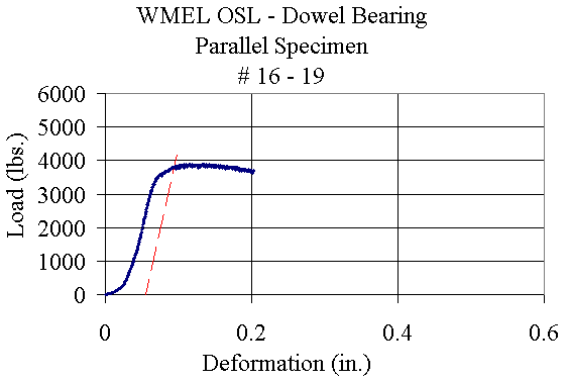
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
16 - 19
Load (lbs.)
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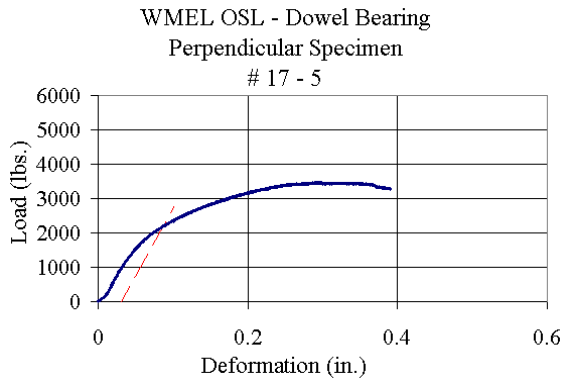
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
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Load (lbs.)
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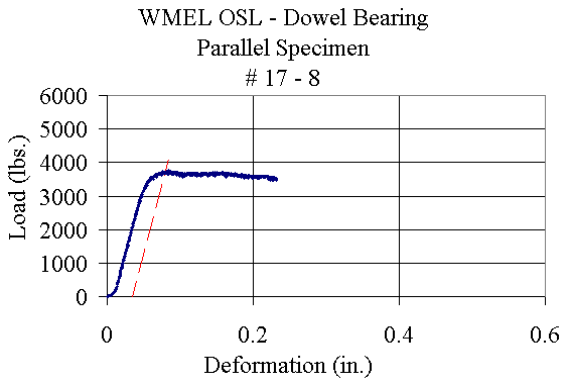
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
17 - 8
Load (lbs.)
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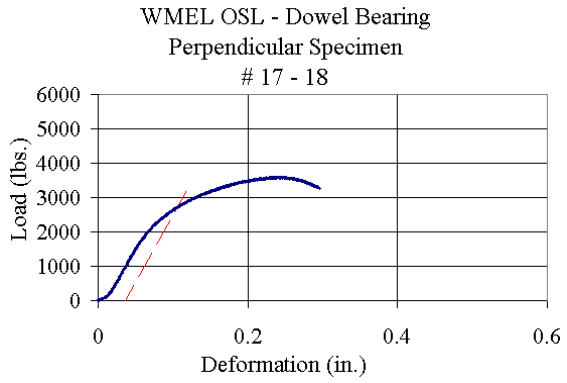
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
17 - 18
Load (lbs.)
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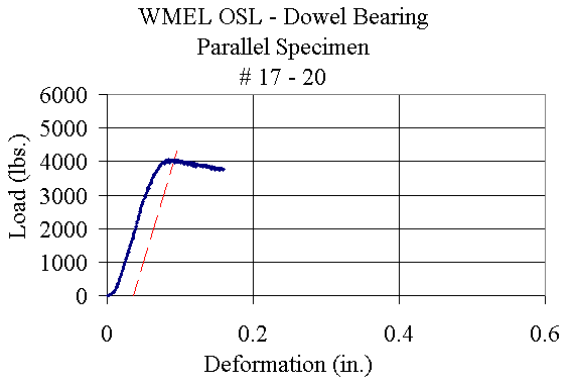
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
17 - 20
Load (lbs.)
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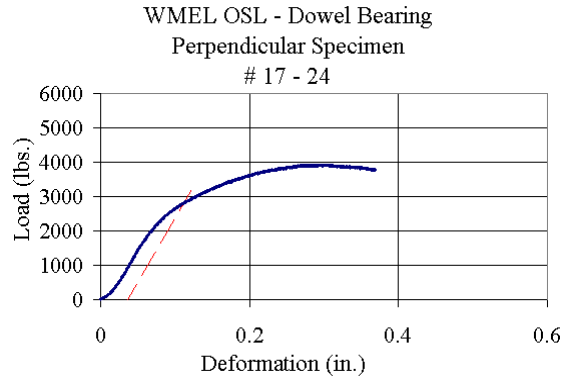
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
17 - 24
Load (lbs.)
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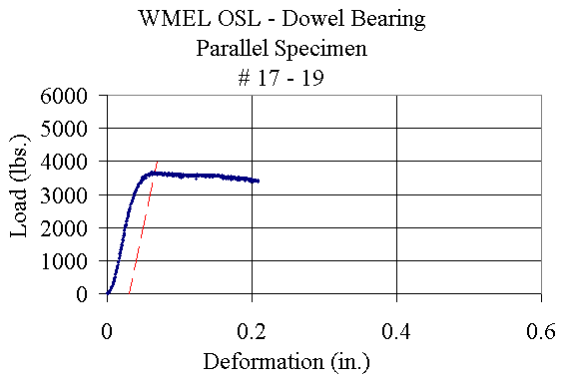
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
17 - 19
Load (lbs.)
6000
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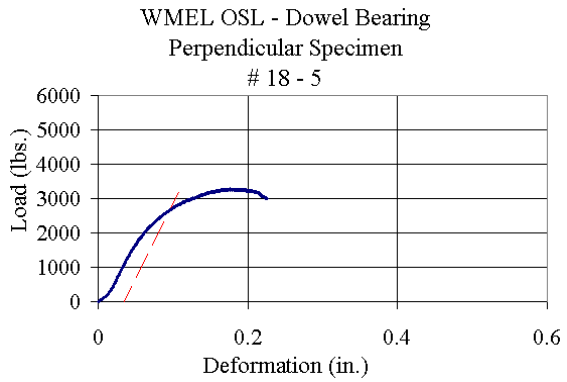
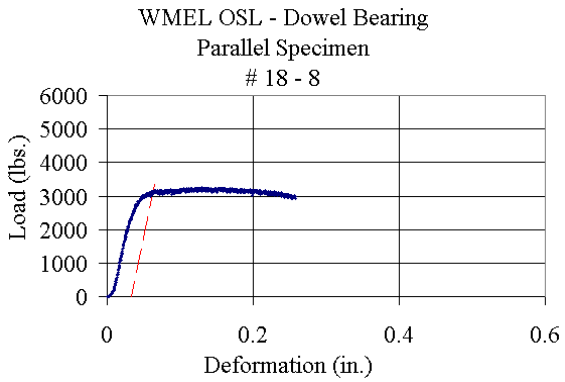
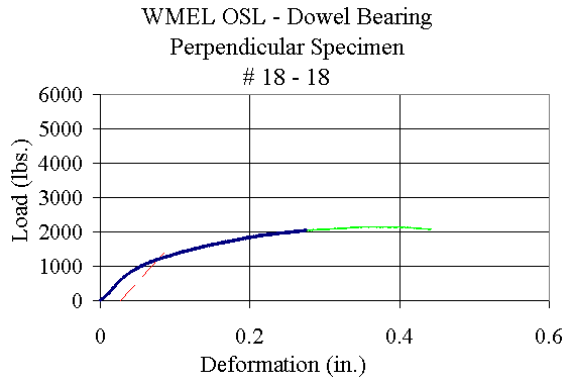
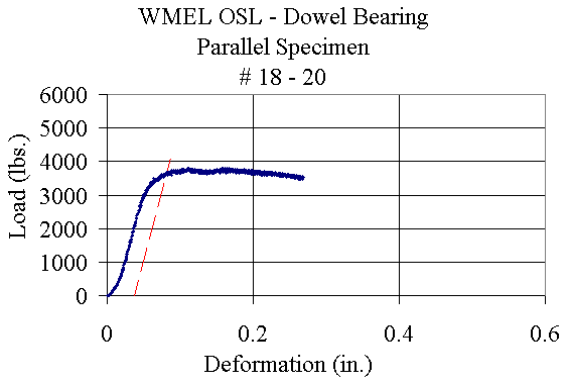
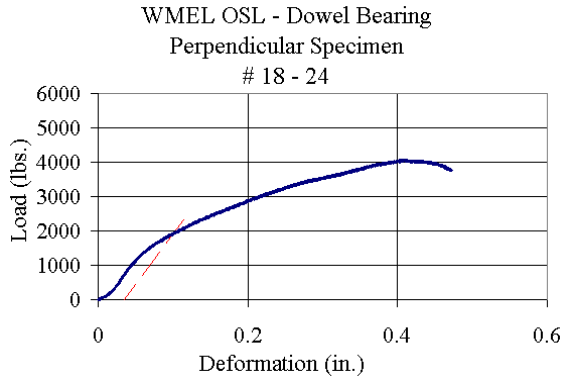
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
18 - 5
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
18 - 8
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
18 - 18
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
18 - 20
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
18 - 24
Load (lbs.)
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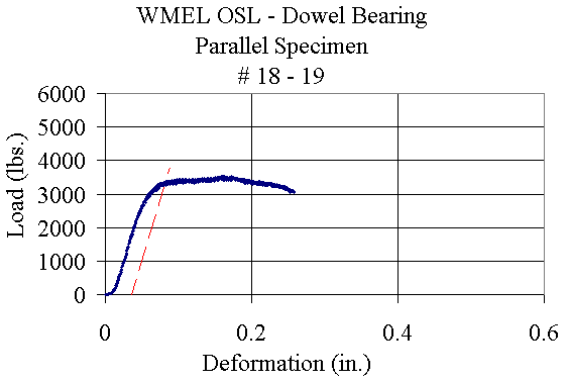
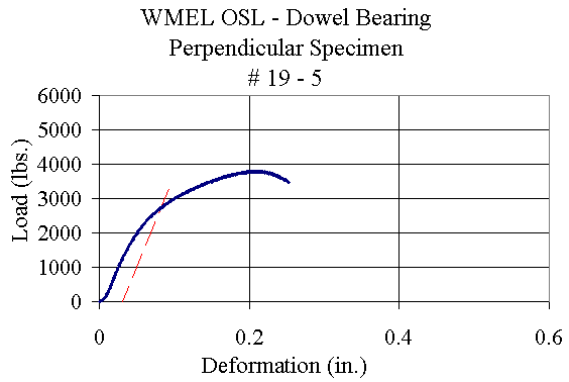
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
18 - 19
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
19 - 5
Load (lbs.)
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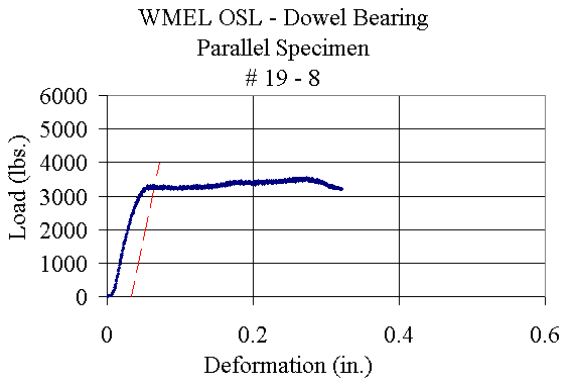
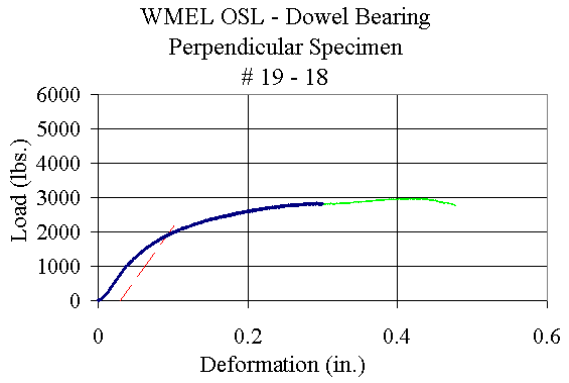
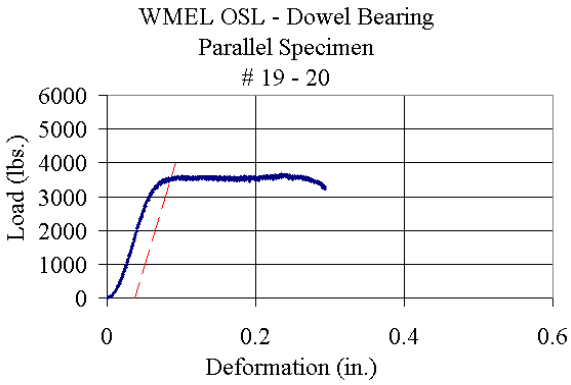
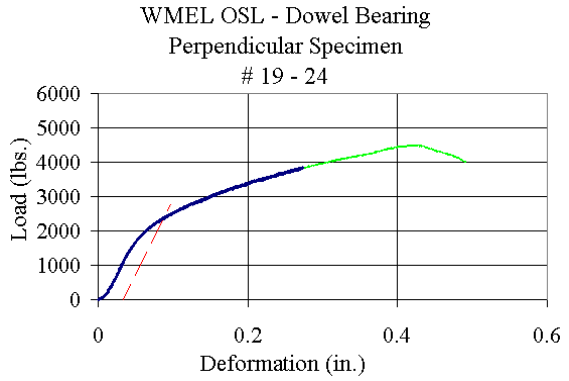
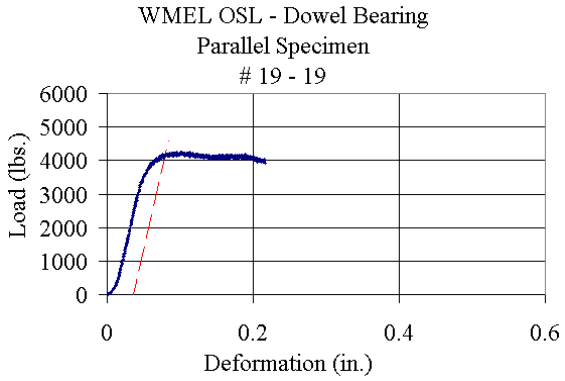
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

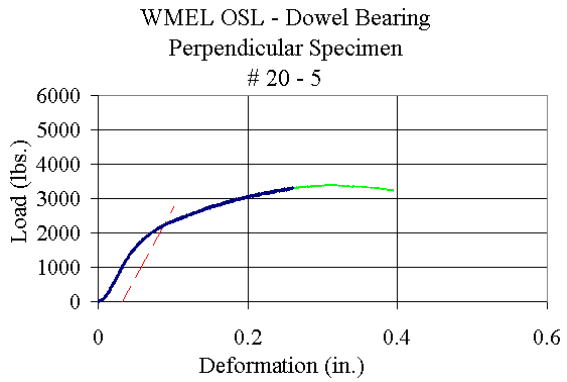

WMEL OSL - Dowel Bearing
Parallel Specimen
19 - 8
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

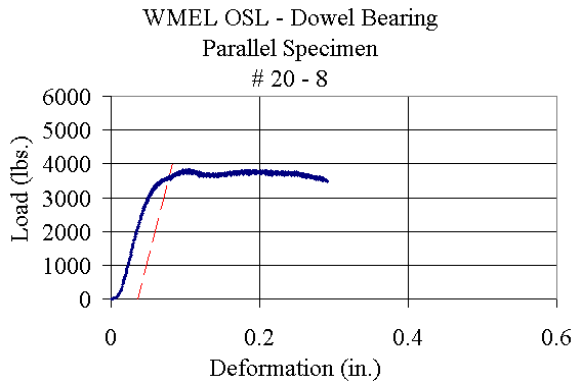

WMEL OSL - Dowel Bearing
Perpendicular Specimen
19 - 18
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

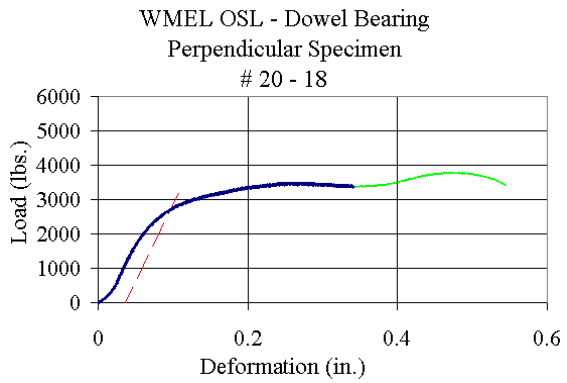

WMEL OSL - Dowel Bearing
Parallel Specimen
19 - 20
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

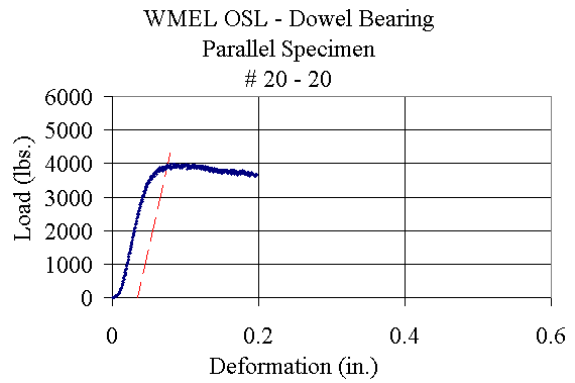

WMEL OSL - Dowel Bearing
Perpendicular Specimen
19 - 24
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

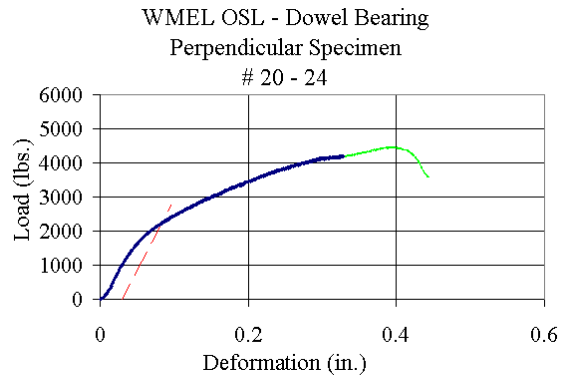

WMEL OSL - Dowel Bearing
Parallel Specimen
19 - 19
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

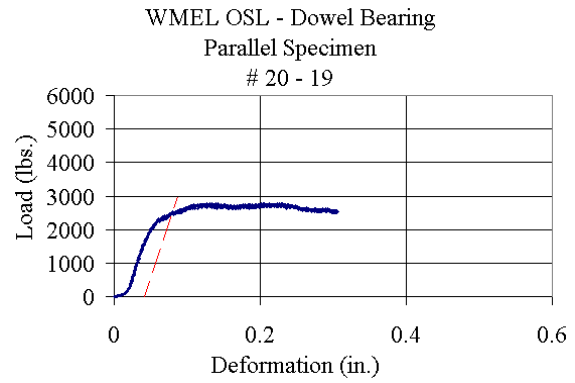

WMEL OSL - Dowel Bearing
Perpendicular Specimen
20 - 5
Load (lbs.)
Deformation (in.)

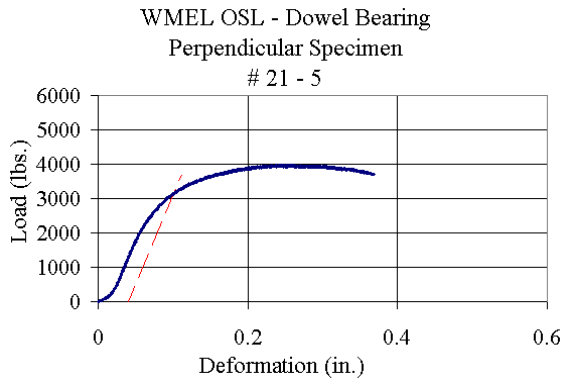

WMEL OSL - Dowel Bearing
Parallel Specimen
20 - 8
Load (lbs.)
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
20 - 18
Load (lbs.)
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
20 - 20
Load (lbs.)
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
20 - 24
Load (lbs.)
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
20 - 19
Load (lbs.)
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
21 - 5
Load (lbs.)
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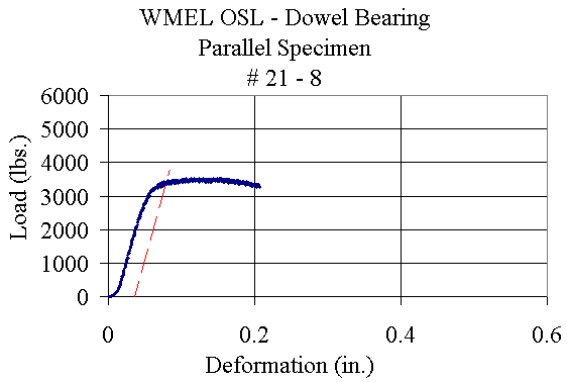
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
21 - 8
Load (lbs.)
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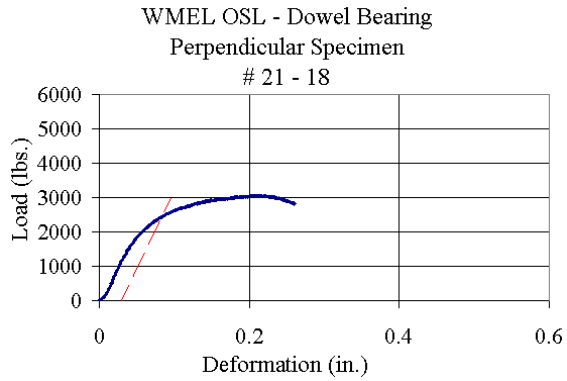
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
21 - 18
Load (lbs.)
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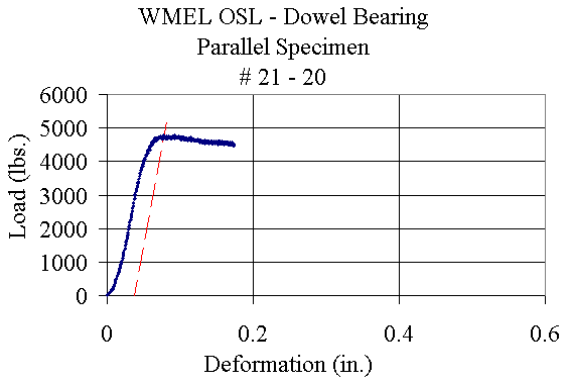
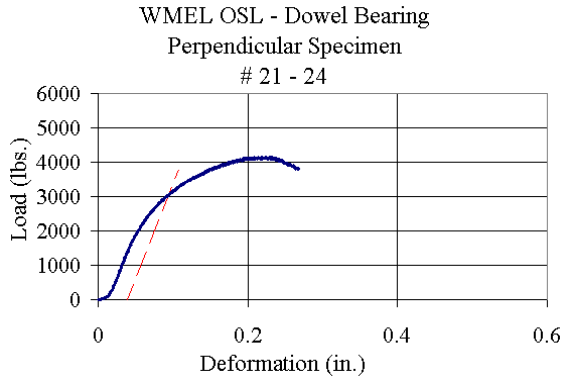
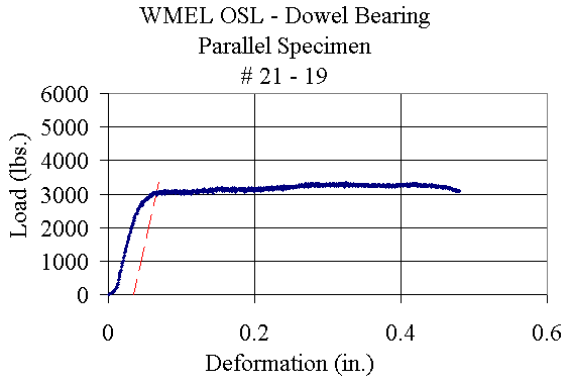
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
21 - 20
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
21 - 24
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
21 - 19
Load (lbs.)
6000
5000
4000
3000
2000
1000
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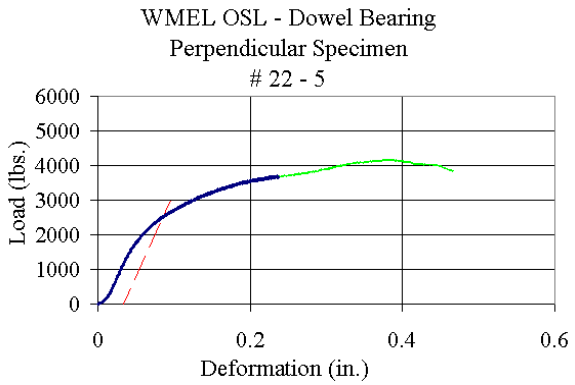
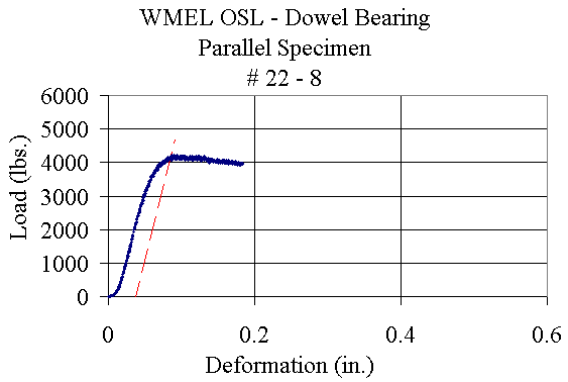
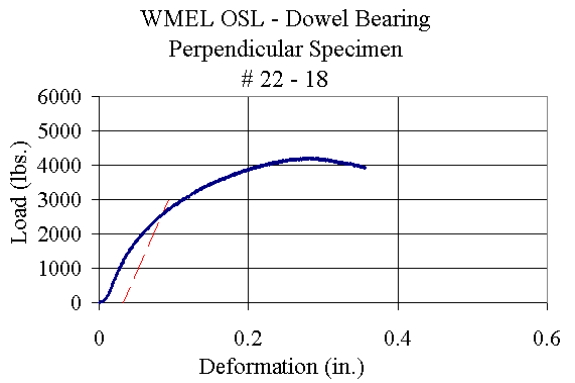
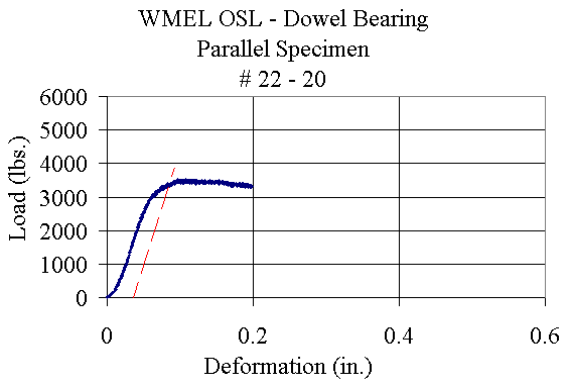
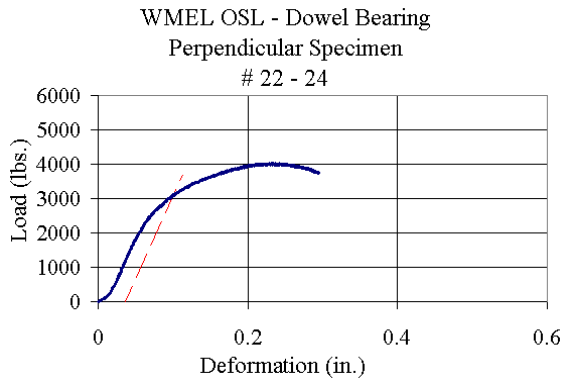
0
0.2
0.4
0.6
Deformation (in.)

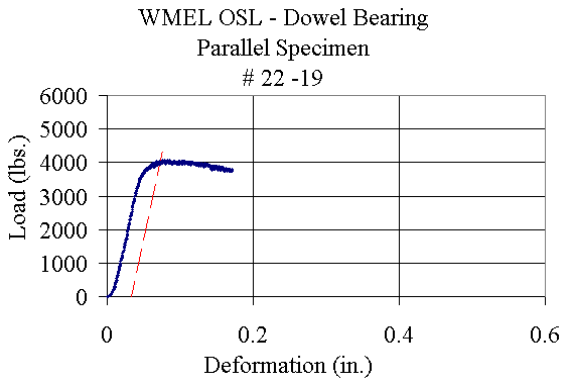

WMEL OSL - Dowel Bearing
Perpendicular Specimen
22 - 5
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

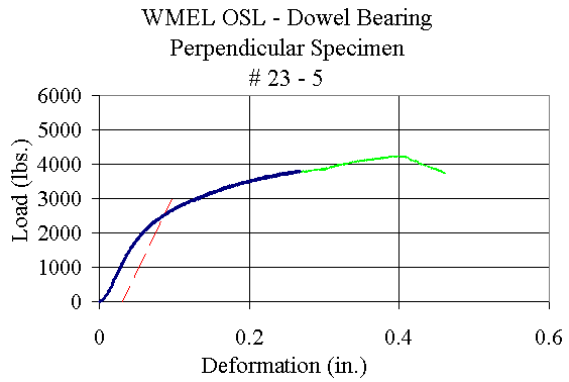

WMEL OSL - Dowel Bearing
Parallel Specimen
22 - 8
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

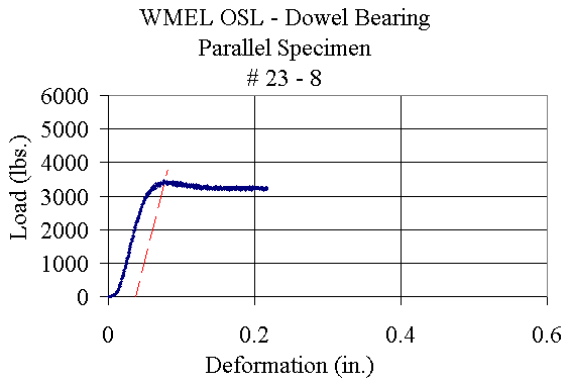

WMEL OSL - Dowel Bearing
Perpendicular Specimen
22 - 18
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

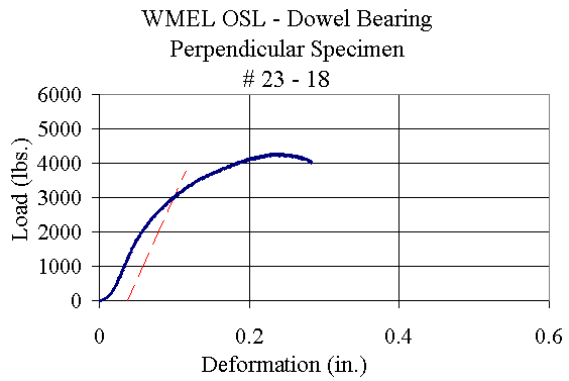

WMEL OSL - Dowel Bearing
Parallel Specimen
22 - 20
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

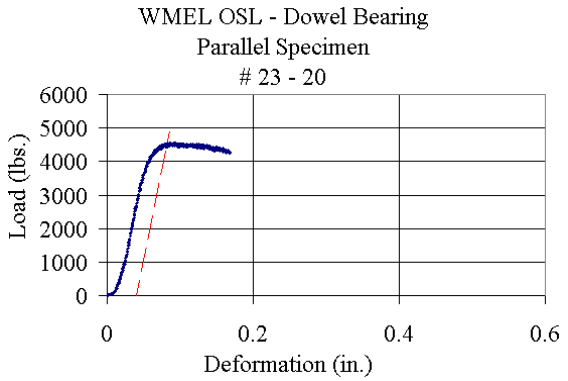

WMEL OSL - Dowel Bearing
Perpendicular Specimen
22 - 24
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

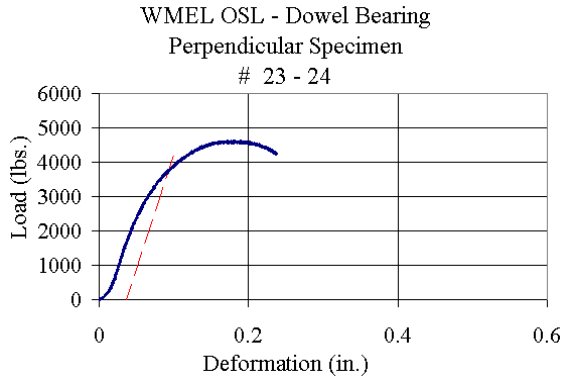

WMEL OSL - Dowel Bearing
Parallel Specimen
22 -19
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

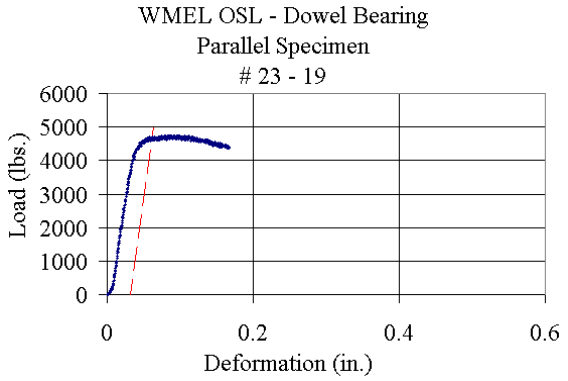

WMEL OSL - Dowel Bearing
Perpendicular Specimen
23 - 5
Load (lbs.)
Deformation (in.)

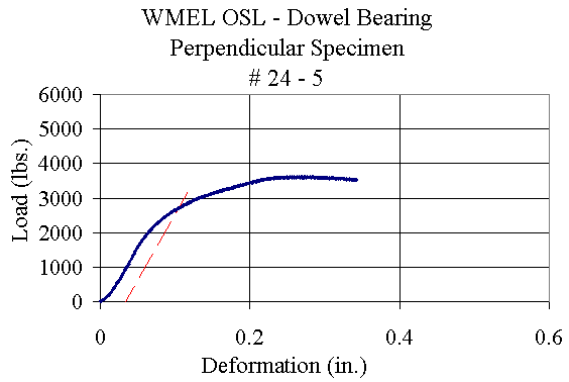

WMEL OSL - Dowel Bearing
Parallel Specimen
23 - 8
Load (lbs.)
Deformation (in.)

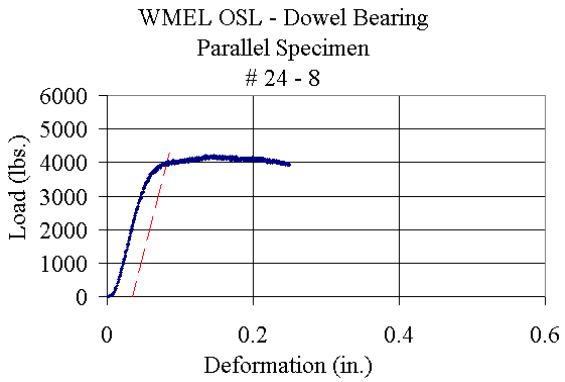

WMEL OSL - Dowel Bearing
Perpendicular Specimen
23 - 18
Load (lbs.)
Deformation (in.)

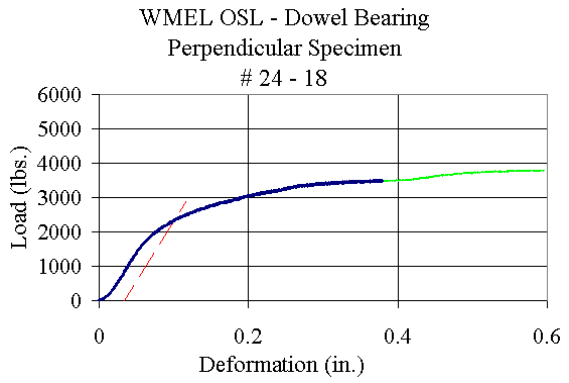

WMEL OSL - Dowel Bearing
Parallel Specimen
23 - 20
Load (lbs.)
Deformation (in.)

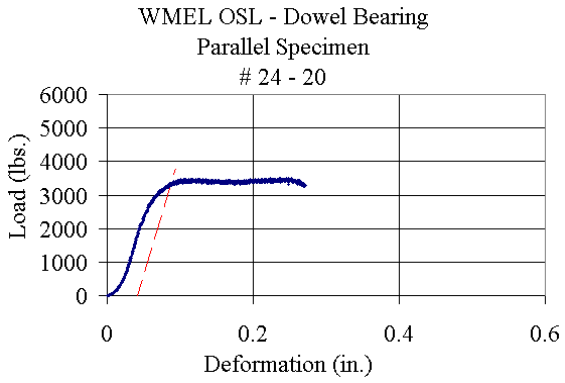

WMEL OSL - Dowel Bearing
Perpendicular Specimen
23 - 24
Load (lbs.)
Deformation (in.)

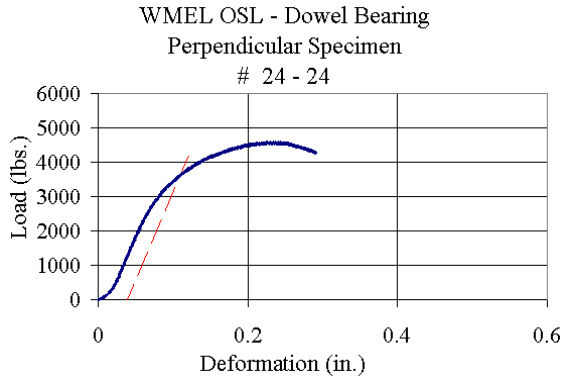

WMEL OSL - Dowel Bearing
Parallel Specimen
23 - 19
Load (lbs.)
Deformation (in.)

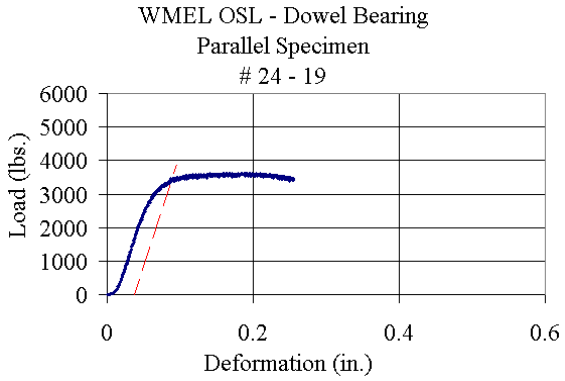

WMEL OSL - Dowel Bearing
Perpendicular Specimen
24 - 5
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

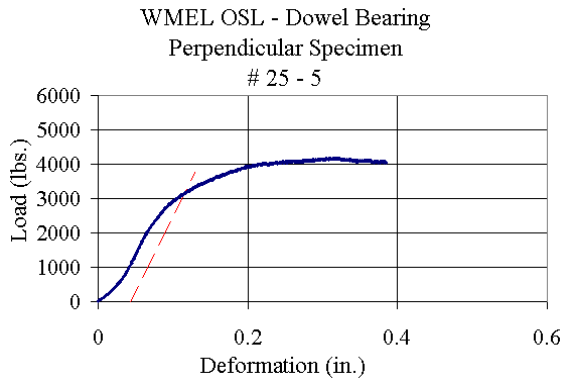

WMEL OSL - Dowel Bearing
Parallel Specimen
24 - 8
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

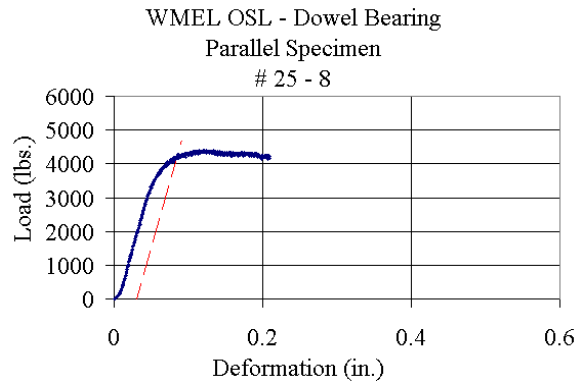

WMEL OSL - Dowel Bearing
Perpendicular Specimen
24 - 18
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

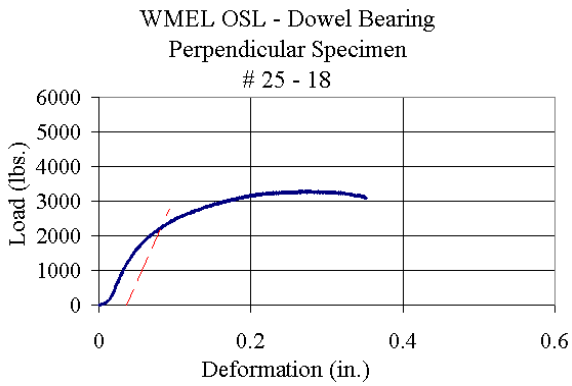

WMEL OSL - Dowel Bearing
Parallel Specimen
24 - 20
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

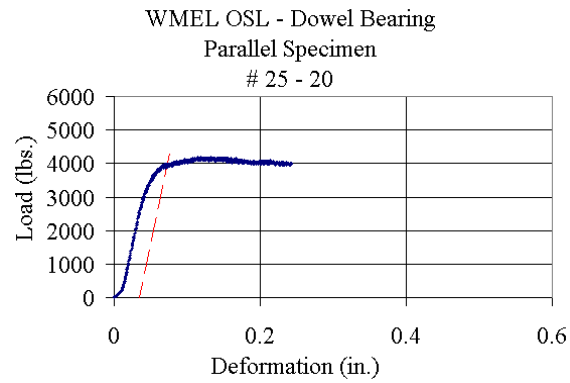

WMEL OSL - Dowel Bearing
Perpendicular Specimen
24 - 24
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

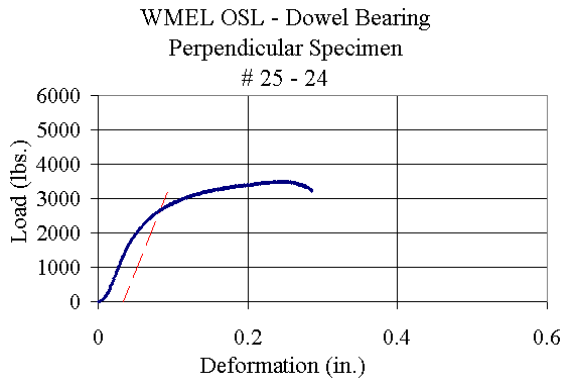

WMEL OSL - Dowel Bearing
Parallel Specimen
24 - 19
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
25 - 5
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
25 - 8
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
25 - 18
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
25 - 20
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
25 - 24
Load (lbs.)
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5000
4000
3000
2000
1000
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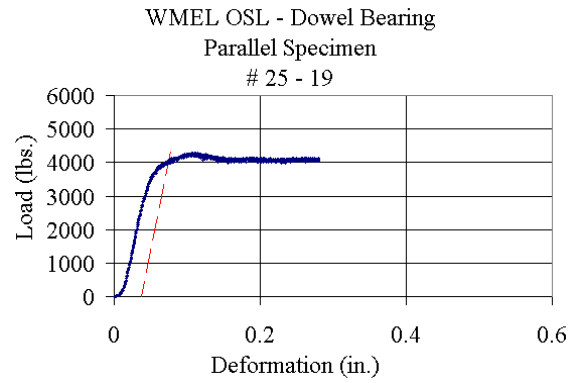
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
25 - 19
Load (lbs.)
6000
5000
4000
3000
2000
1000
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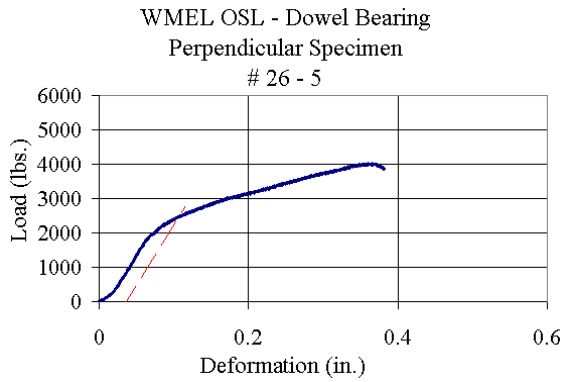
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
26 - 5
Load (lbs.)
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5000
4000
3000
2000
1000
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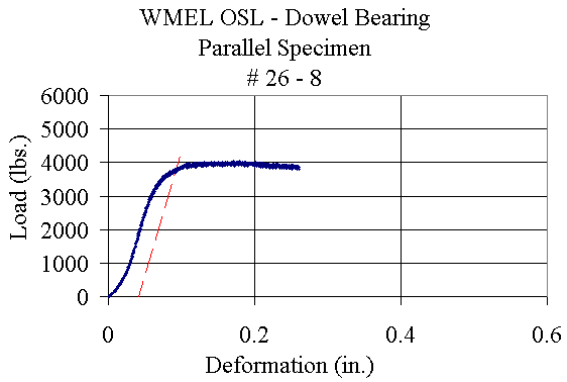
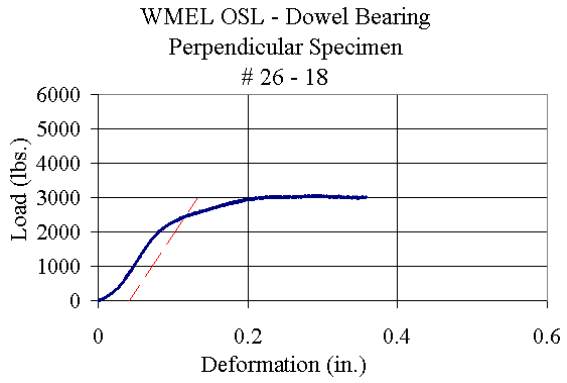
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
26 - 8
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
26 - 18
Load (lbs.)
6000
5000
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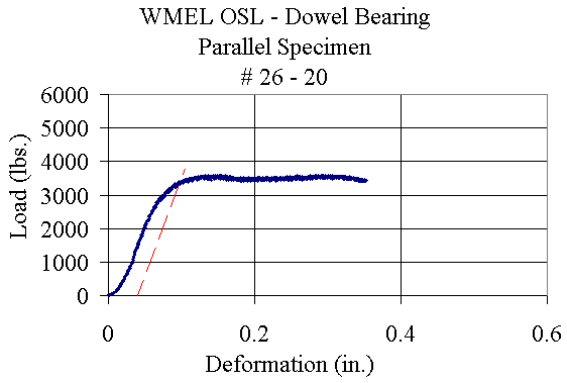
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
26 - 20
Load (lbs.)
6000
5000
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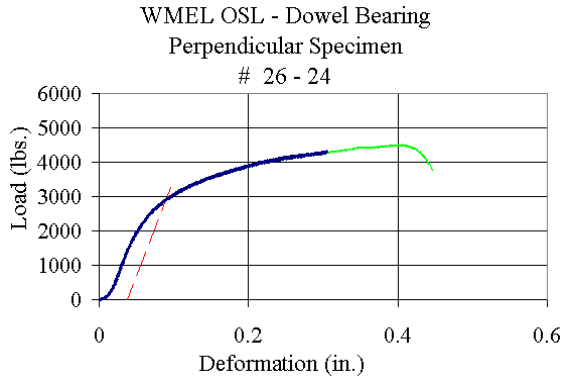
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
26 - 24
Load (lbs.)
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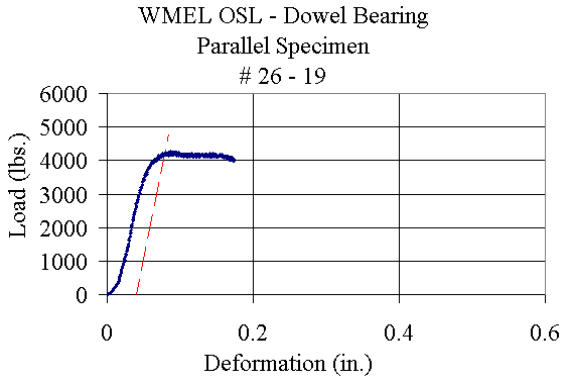
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
26 - 19
Load (lbs.)
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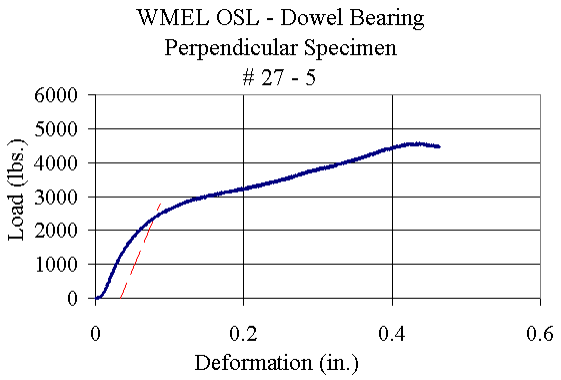
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
27 - 5
Load (lbs.)
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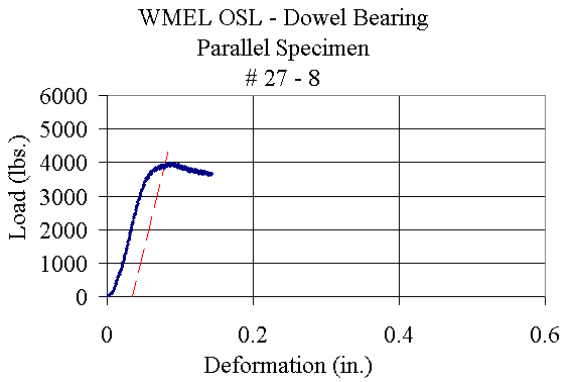
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
27 - 8
Load (lbs.)
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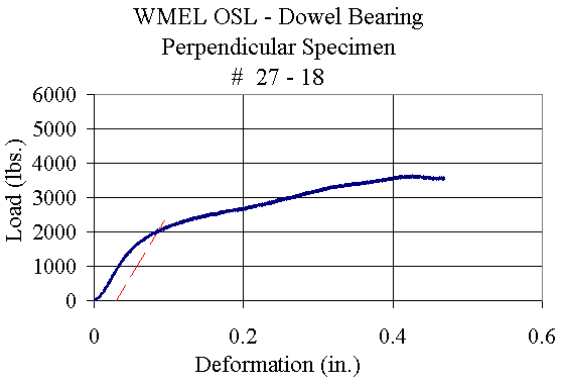
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
27 - 18
Load (lbs.)
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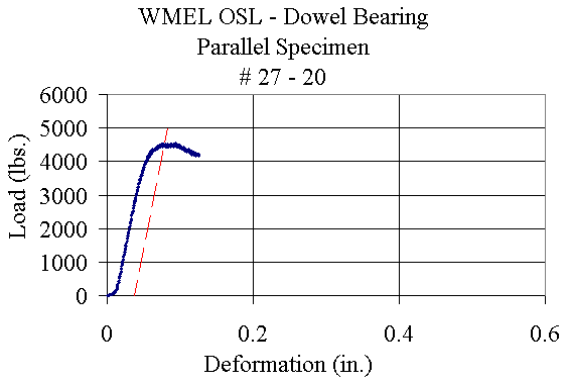
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
27 - 20
Load (lbs.)
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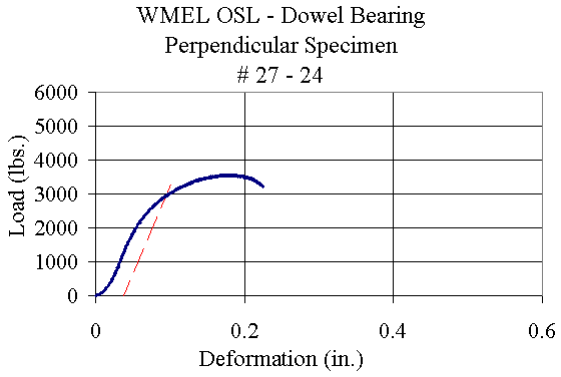
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
27 - 24
Load (lbs.)
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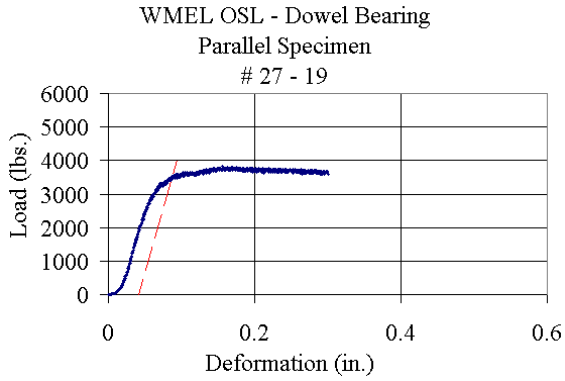
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
27 - 19
Load (lbs.)
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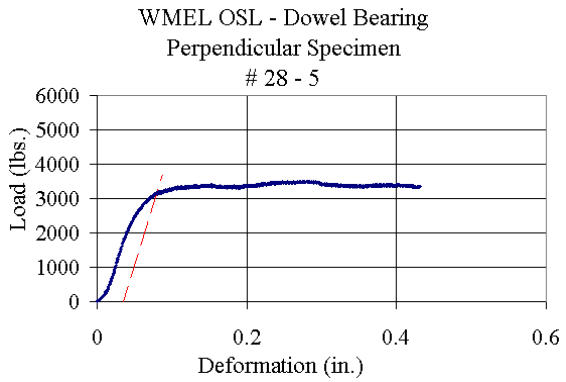
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
28 - 5
Load (lbs.)
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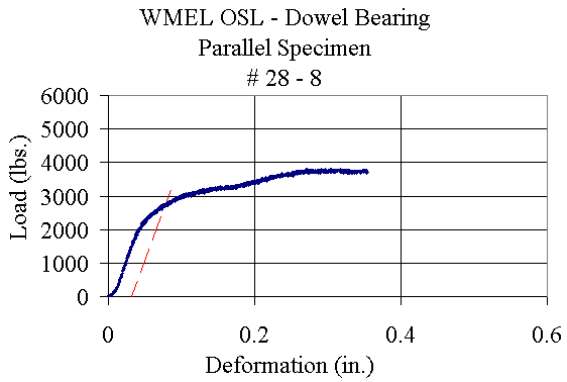
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
28 - 8
Load (lbs.)
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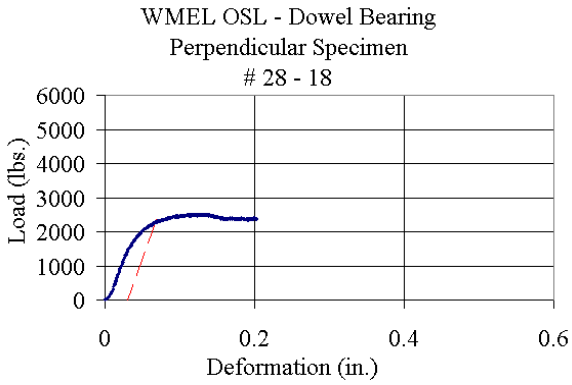
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
28 - 18
Load (lbs.)
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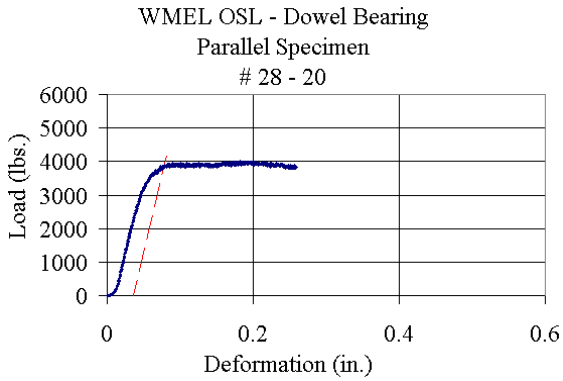
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
28 - 20
Load (lbs.)
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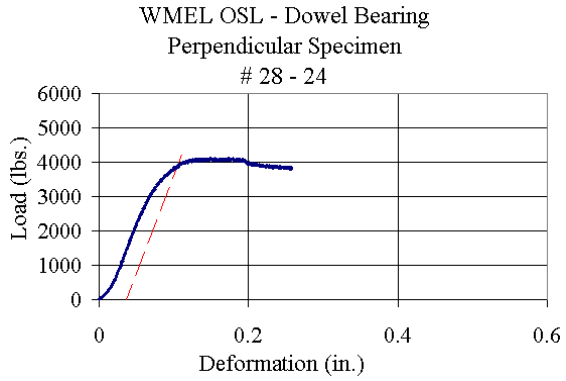
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
28 - 24
Load (lbs.)
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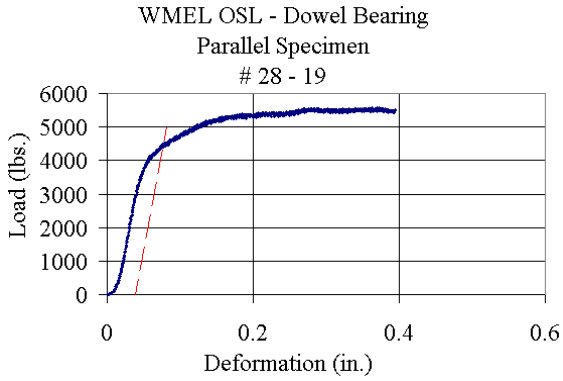
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
28 - 19
Load (lbs.)
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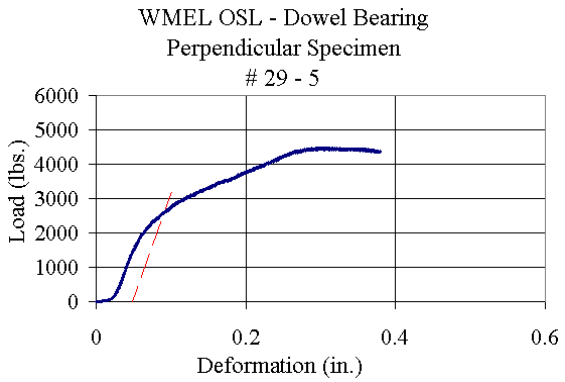
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
29 - 5
Load (lbs.)
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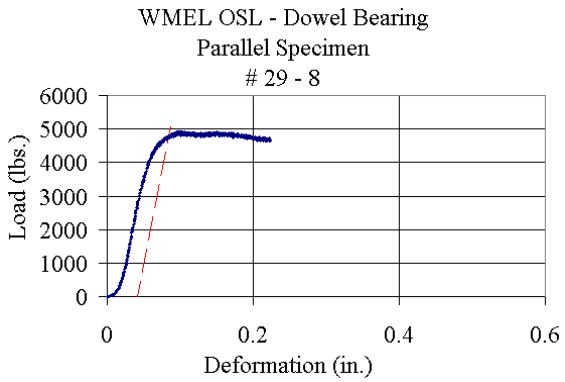
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
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Load (lbs.)
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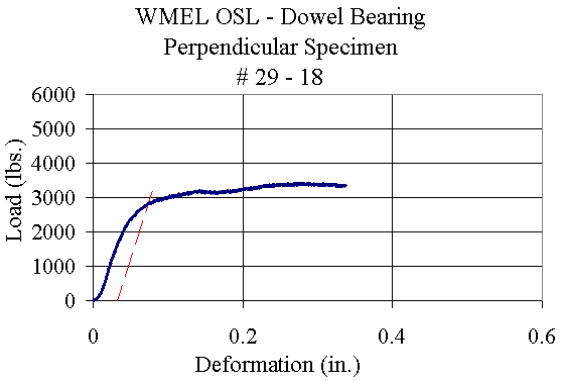
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
29 - 18
Load (lbs.)
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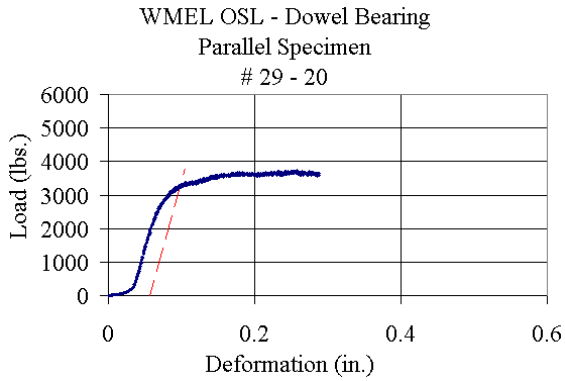
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
29 - 20
Load (lbs.)
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1000
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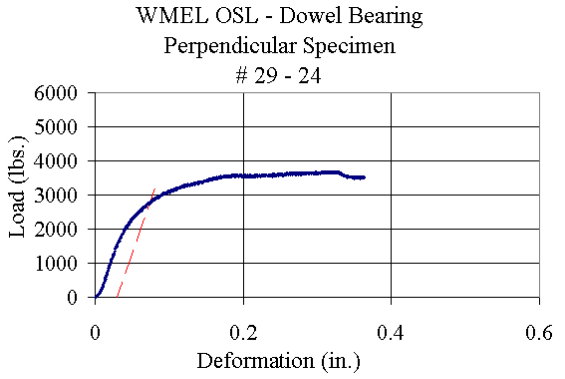
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
29 - 24
Load (lbs.)
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3000
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1000
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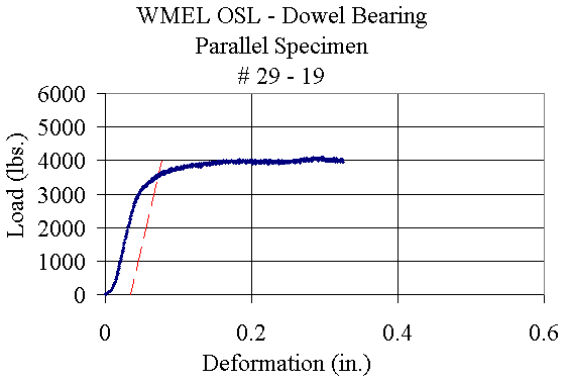
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
29 - 19
Load (lbs.)
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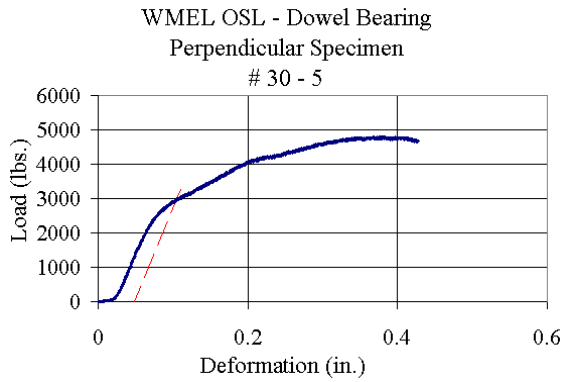
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
30 - 5
Load (lbs.)
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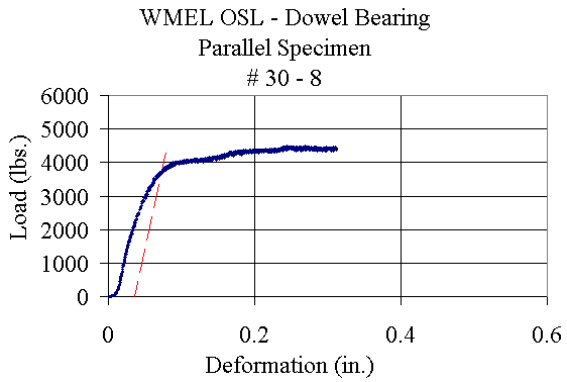
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
30 - 8
Load (lbs.)
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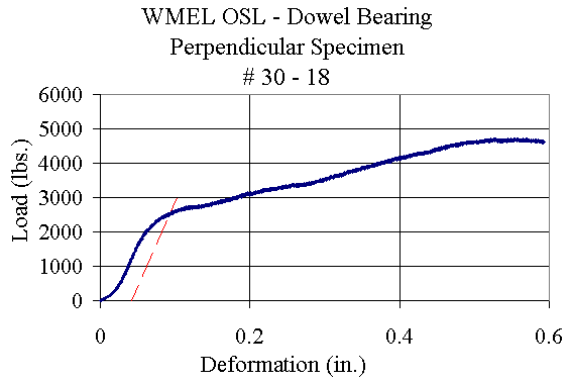
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
30 - 18
Load (lbs.)
6000
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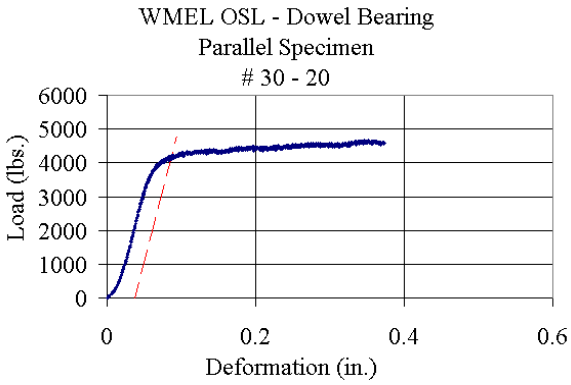
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
30 - 20
Load (lbs.)
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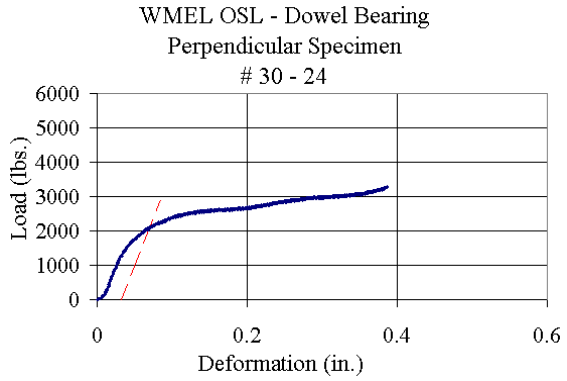
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
30 - 24
Load (lbs.)
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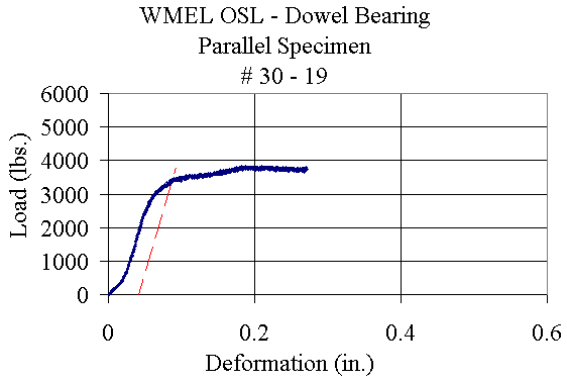
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
30 - 19
Load (lbs.)
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0.2
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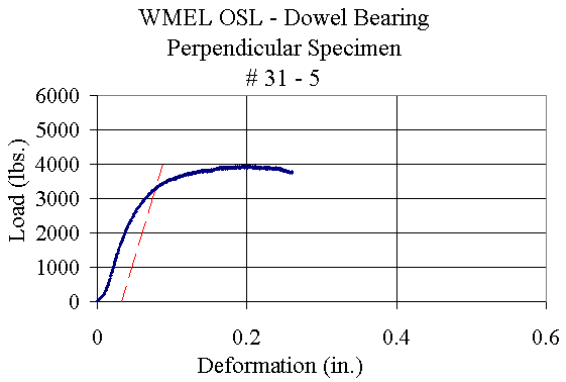
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
31 - 5
Load (lbs.)
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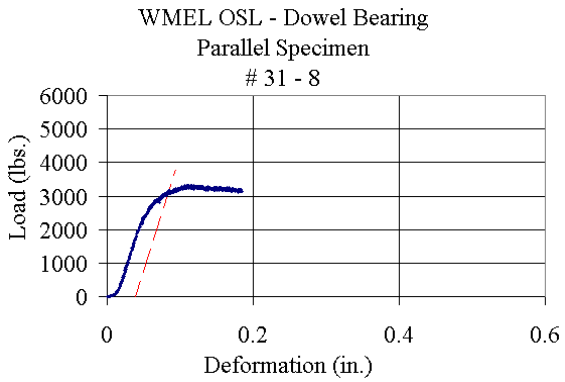
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
31 - 8
Load (lbs.)
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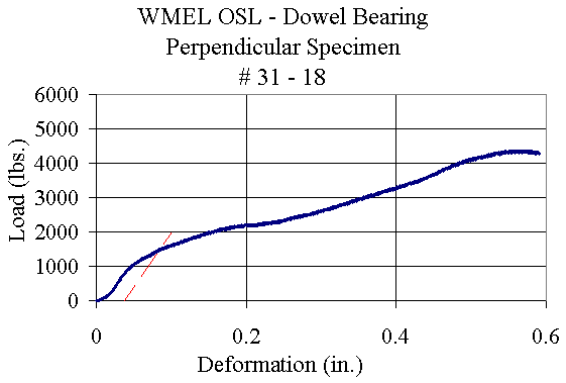
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
31 - 18
Load (lbs.)
6000
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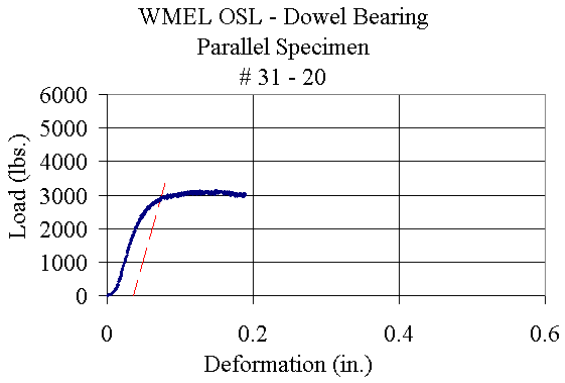
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
31 - 20
Load (lbs.)
6000
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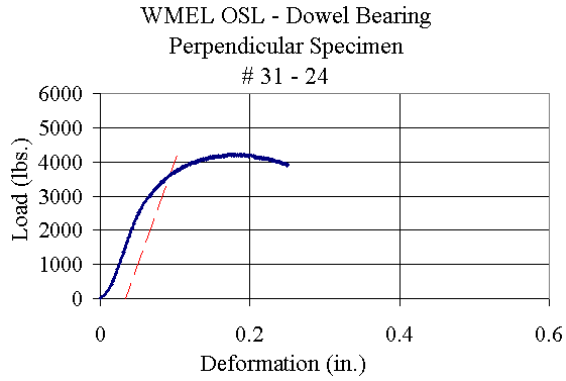
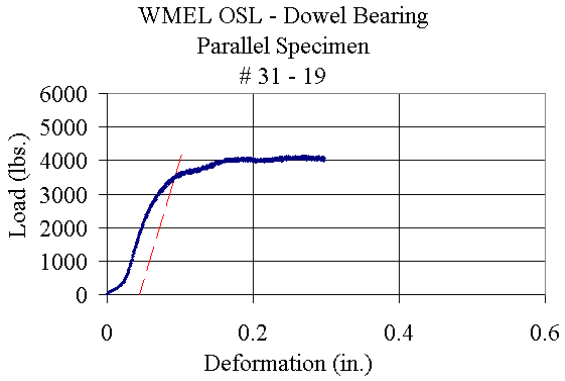
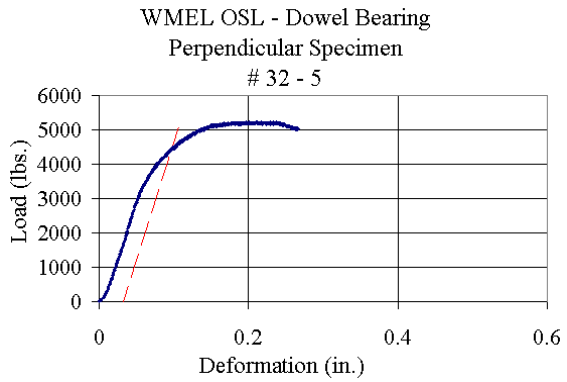
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
31 - 24
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
31 - 19
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
32 - 5
Load (lbs.)
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3000
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1000
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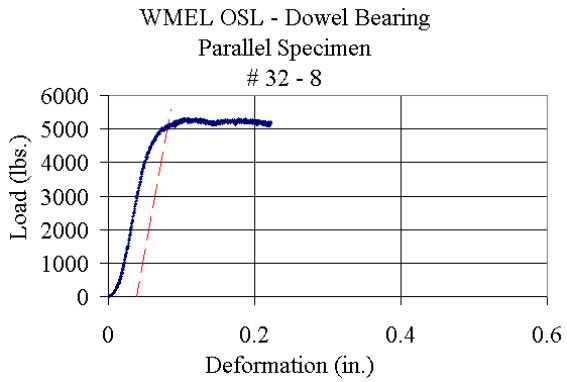
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
32 - 8
Load (lbs.)
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5000
4000
3000
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1000
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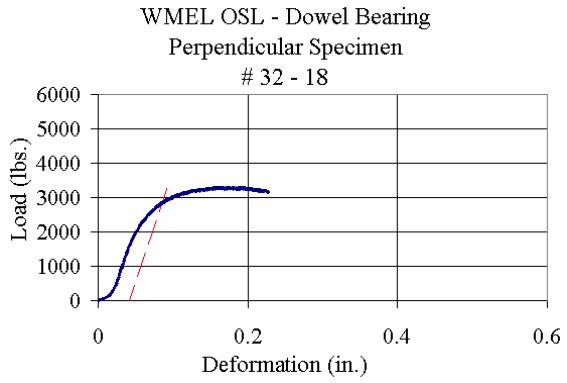
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
32 - 18
Load (lbs.)
6000
5000
4000
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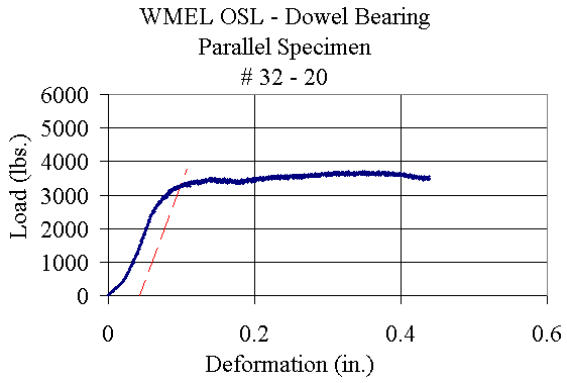
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
32 - 20
Load (lbs.)
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0.2
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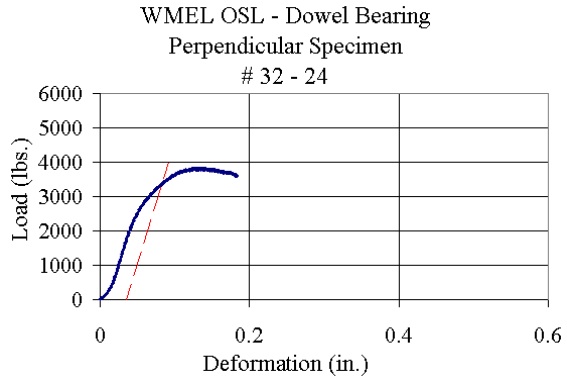
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
32 - 24
Load (lbs.)
6000
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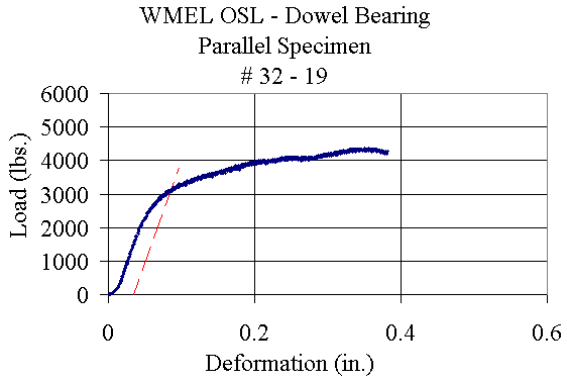
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
32 - 19
Load (lbs.)
6000
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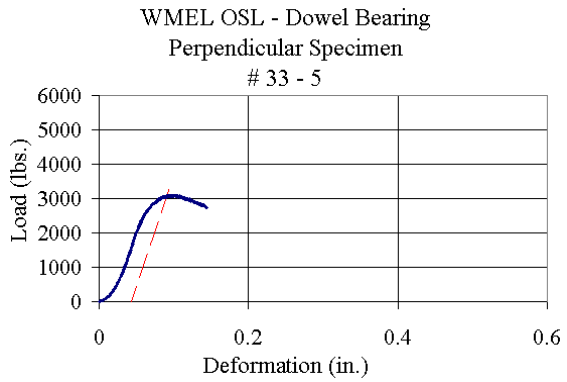
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
33 - 5
Load (lbs.)
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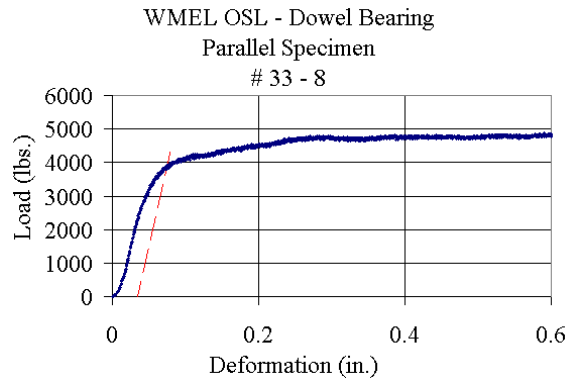
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
33 - 8
Load (lbs.)
6000
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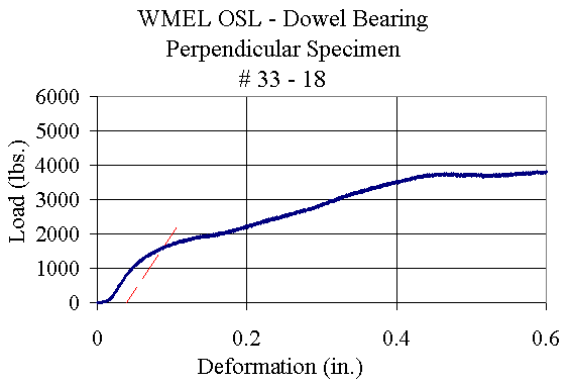
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
33 - 18
Load (lbs.)
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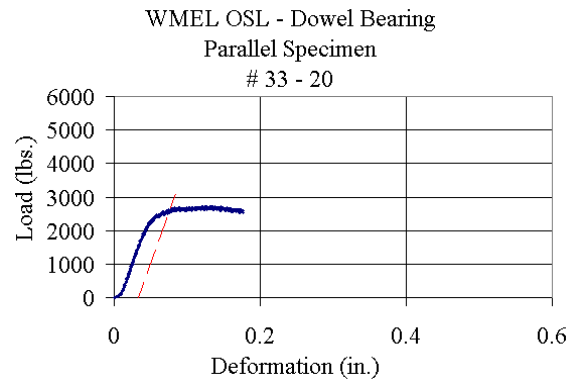
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
33 - 20
Load (lbs.)
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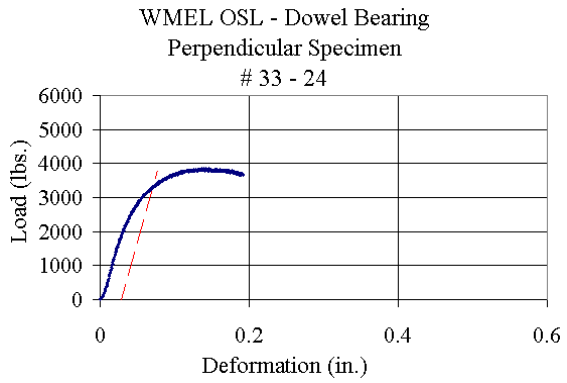
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
33 - 24
Load (lbs.)
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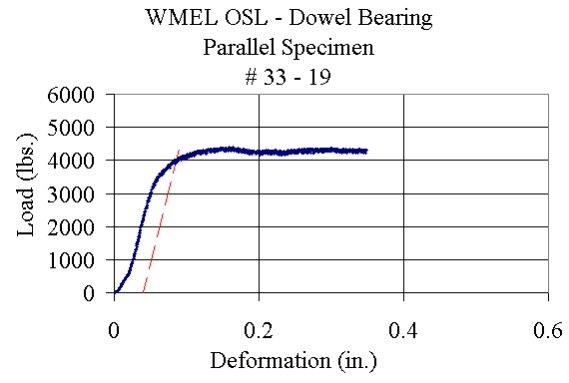
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
33 - 19
Load (lbs.)
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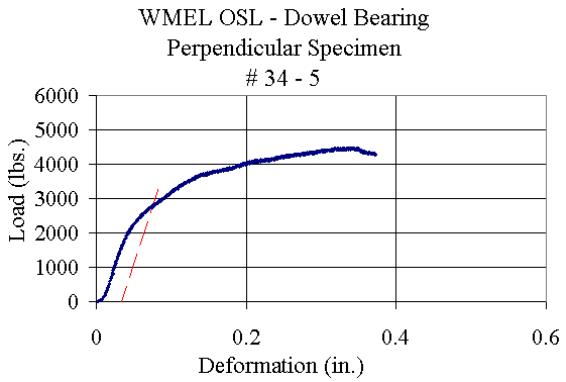
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
34 - 5
Load (lbs.)
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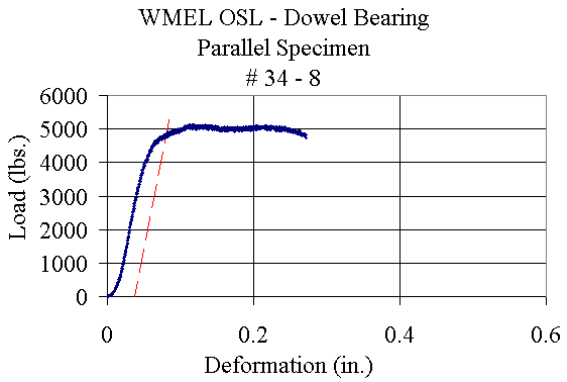
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
34 - 8
Load (lbs.)
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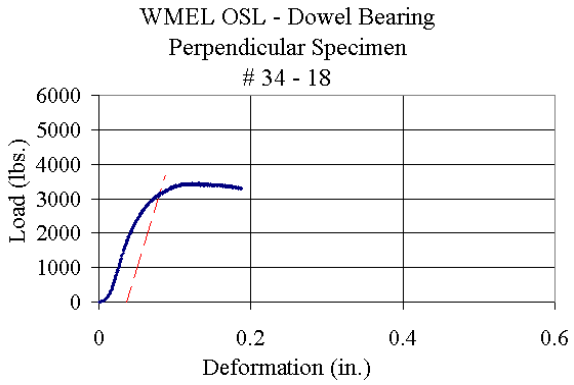
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
34 - 18
Load (lbs.)
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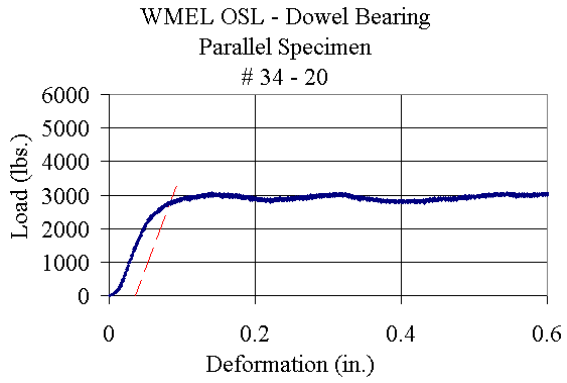
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
34 - 20
Load (lbs.)
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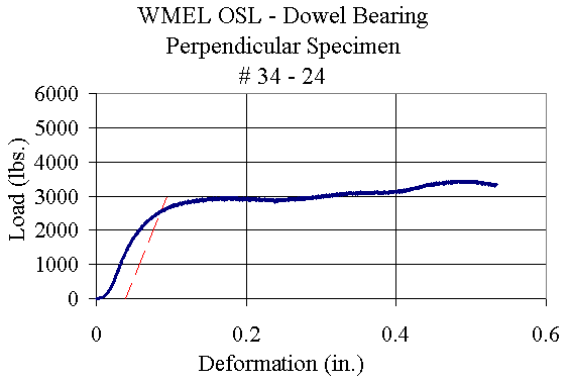
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
34 - 24
Load (lbs.)
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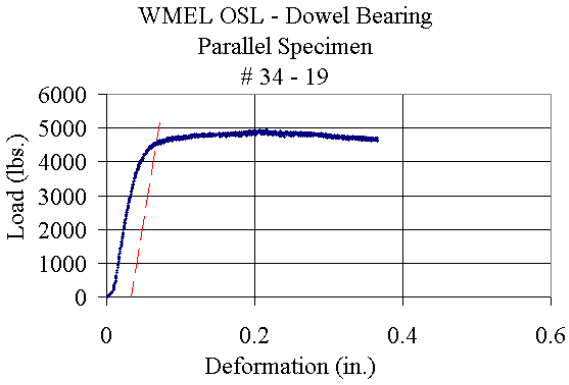
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
34 - 19
Load (lbs.)
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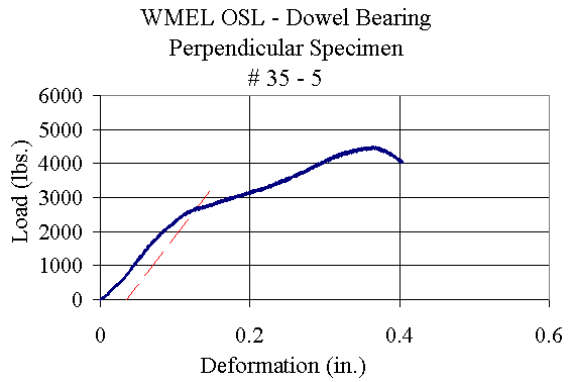
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
35 - 5
Load (lbs.)
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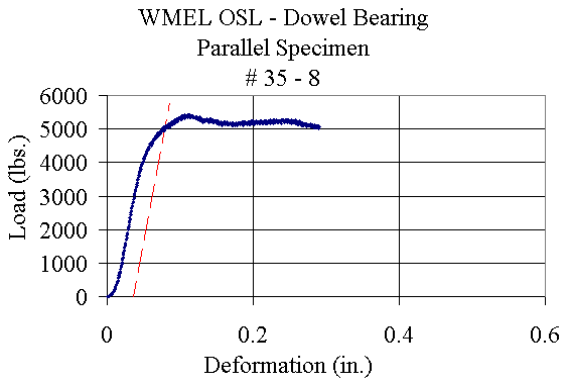
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
35 - 8
Load (lbs.)
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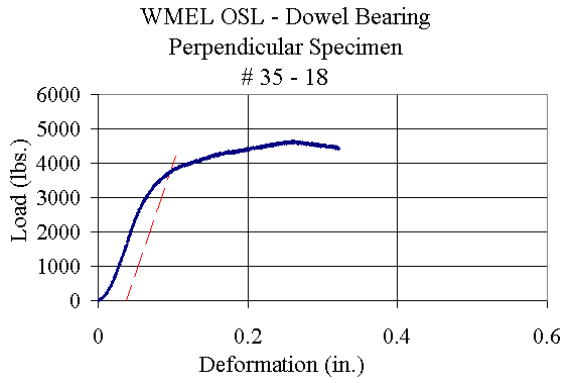
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
35 - 18
Load (lbs.)
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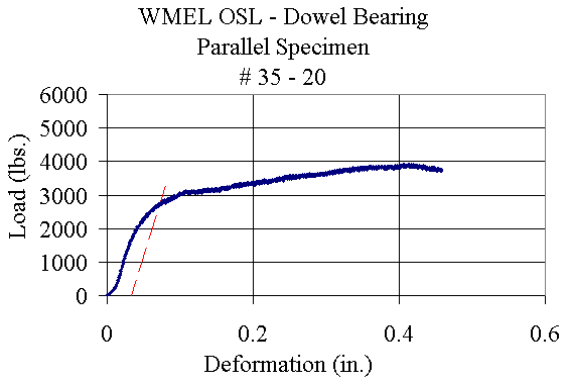
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
35 - 20
Load (lbs.)
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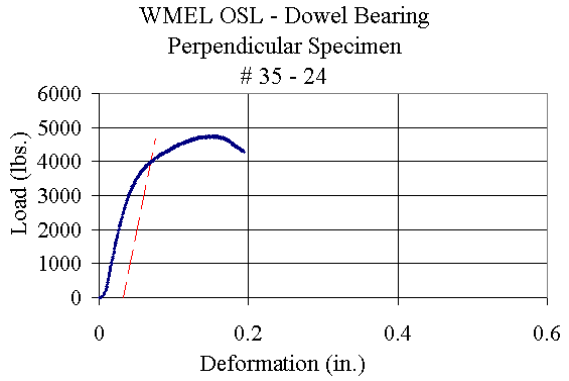
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
35 - 24
Load (lbs.)
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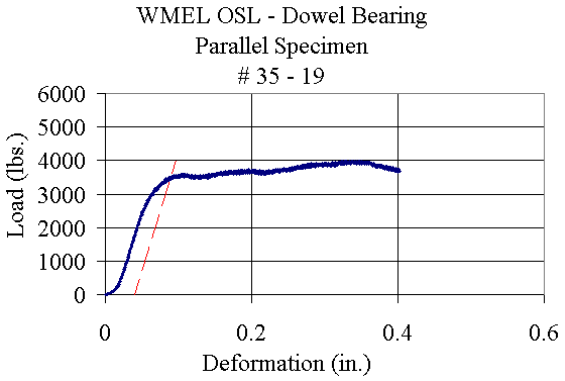
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
35 - 19
Load (lbs.)
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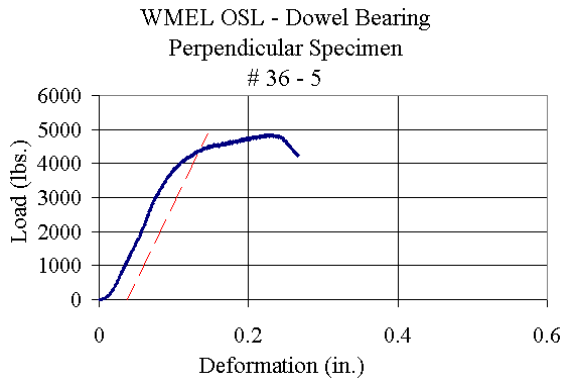
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
36 - 5
Load (lbs.)
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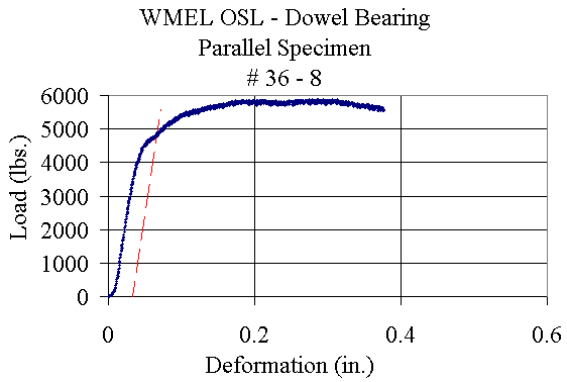
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
36 - 8
Load (lbs.)
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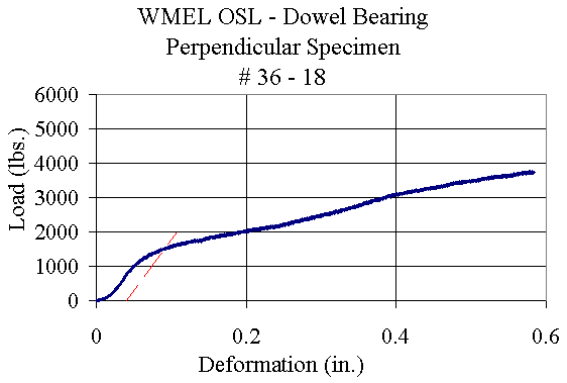
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
36 - 18
Load (lbs.)
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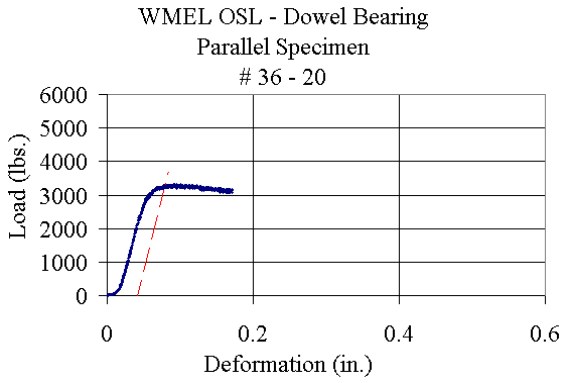
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
36 - 20
Load (lbs.)
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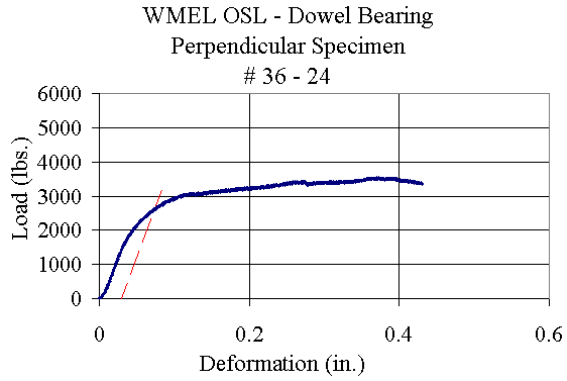
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
36 - 24
Load (lbs.)
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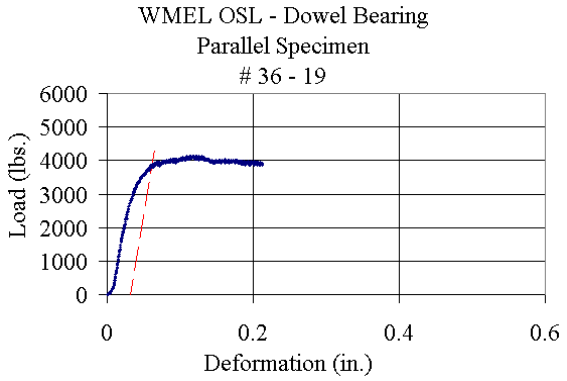
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
36 - 19
Load (lbs.)
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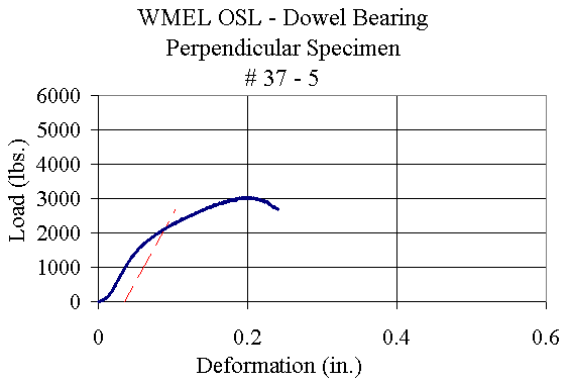
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
37 - 5
Load (lbs.)
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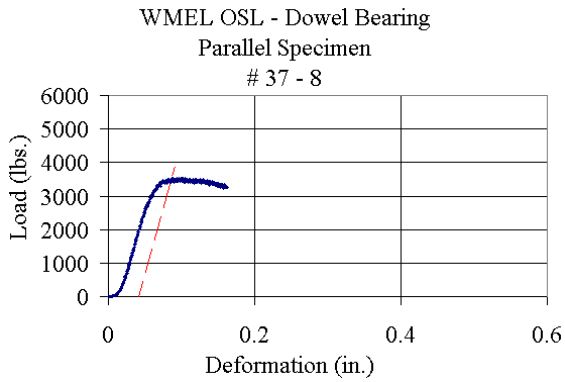
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
37 - 8
Load (lbs.)
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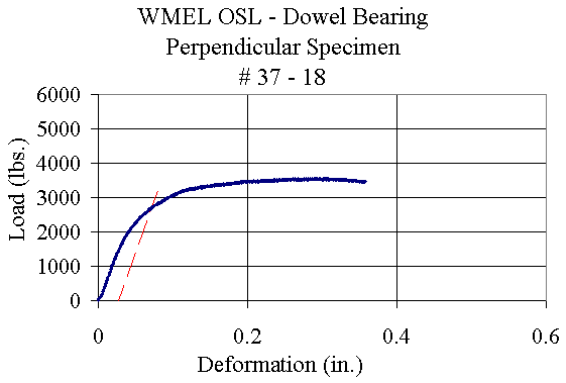
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
37 - 18
Load (lbs.)
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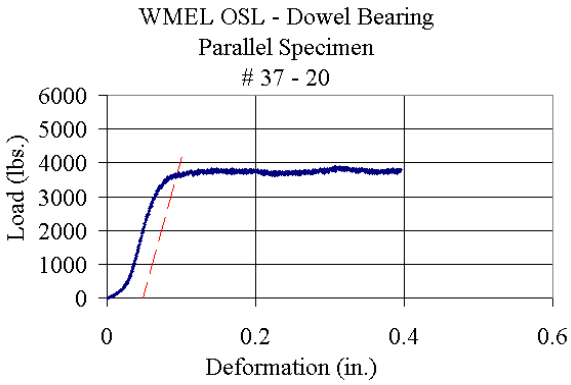
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
37 - 20
Load (lbs.)
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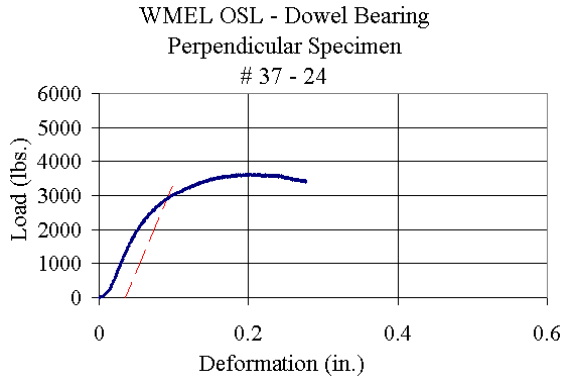
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
37 - 24
Load (lbs.)
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5000
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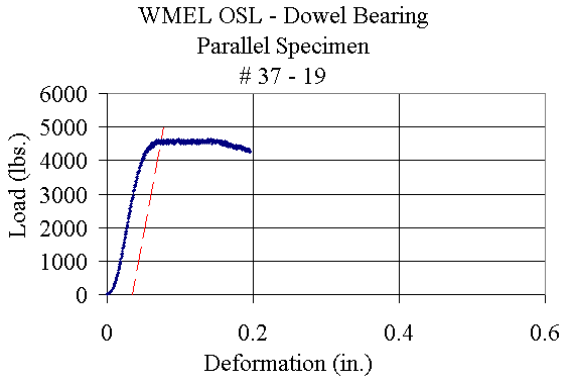
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
37 - 19
Load (lbs.)
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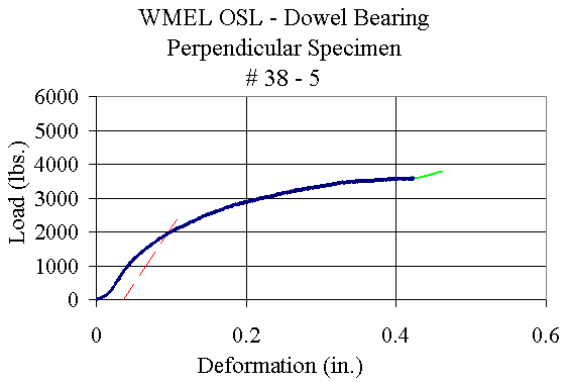
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
38 - 5
Load (lbs.)
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5000
4000
3000
2000
1000
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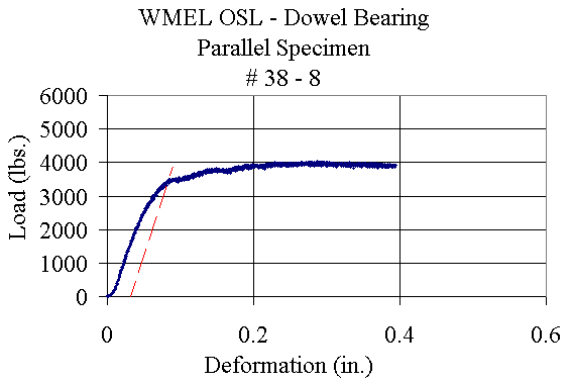
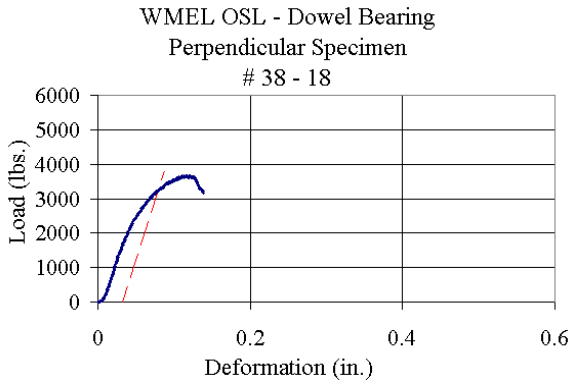
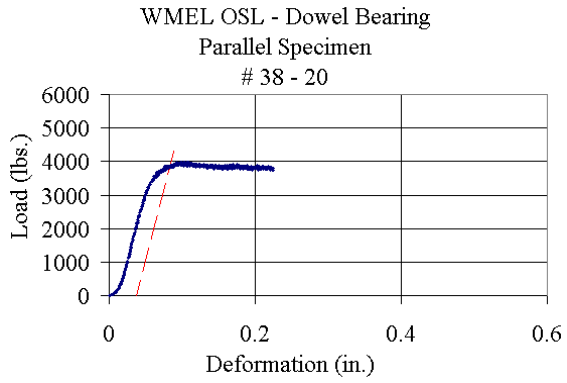
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
38 - 8
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
38 - 18
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
38 - 20
Load (lbs.)
6000
5000
4000
3000
2000
1000
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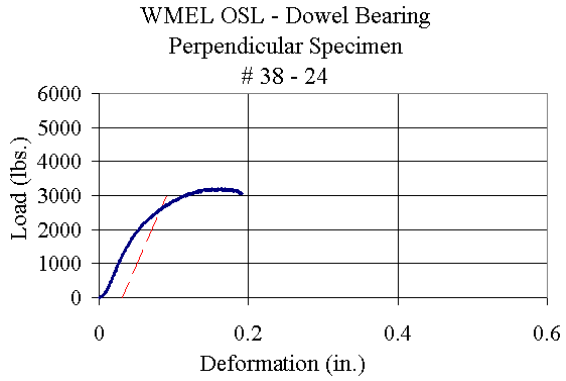
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
38 - 24
Load (lbs.)
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5000
4000
3000
2000
1000
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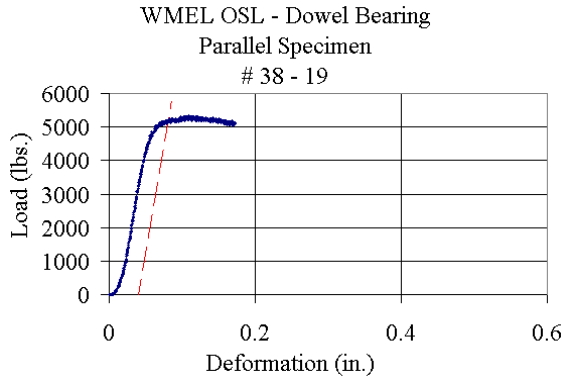
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
38 - 19
Load (lbs.)
6000
5000
4000
3000
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1000
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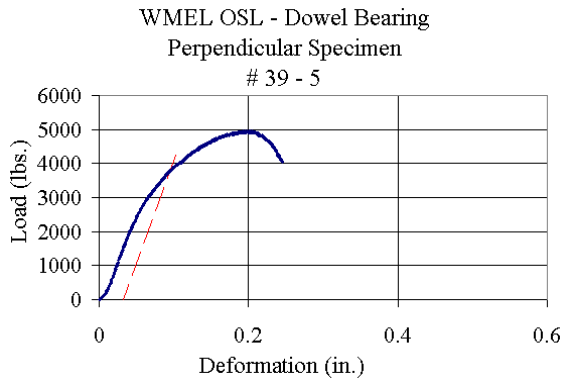
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
39 - 5
Load (lbs.)
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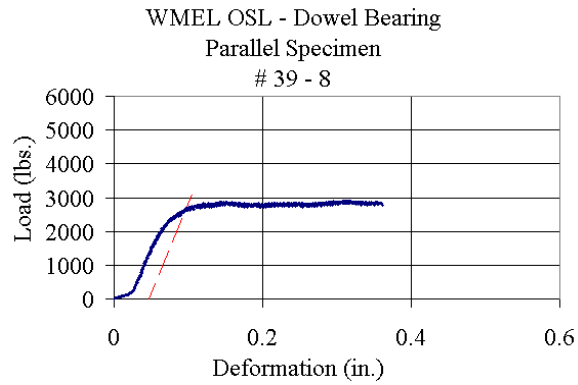
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
39 - 8
Load (lbs.)
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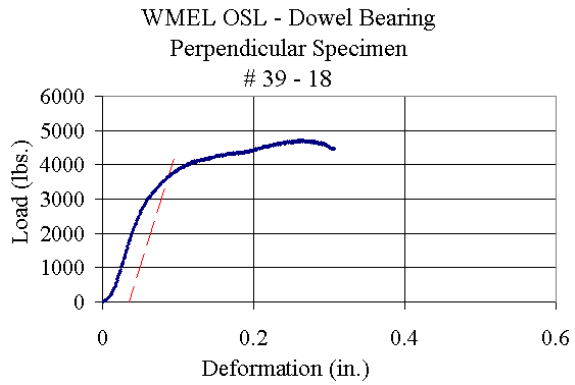
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
39 - 18
Load (lbs.)
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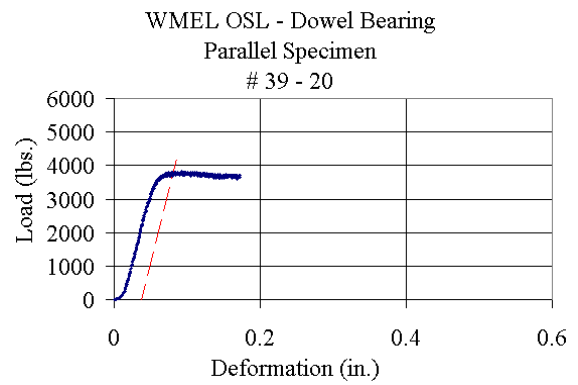
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
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Load (lbs.)
6000
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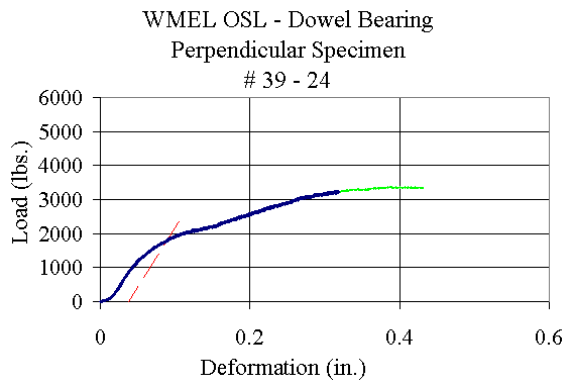
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
39 - 24
Load (lbs.)
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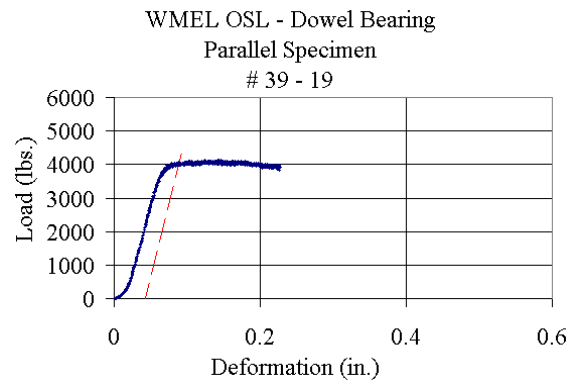
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
39 - 19
Load (lbs.)
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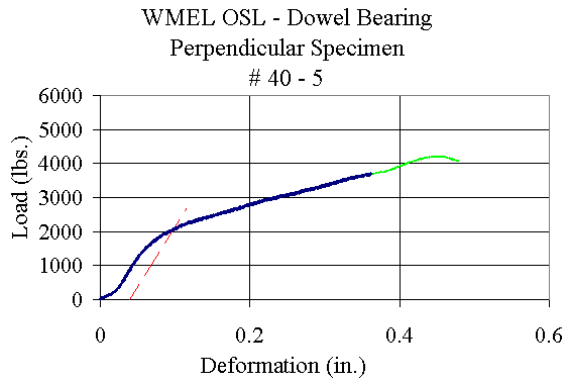
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
40 - 5
Load (lbs.)
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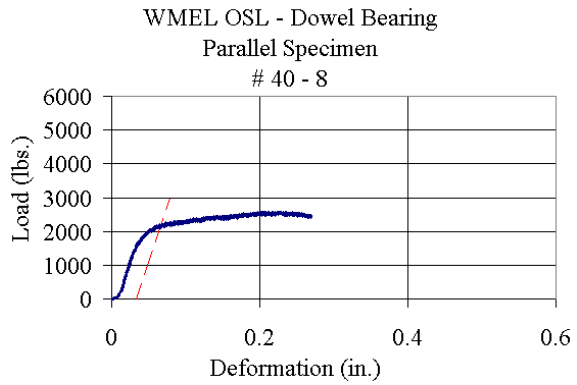
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
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Load (lbs.)
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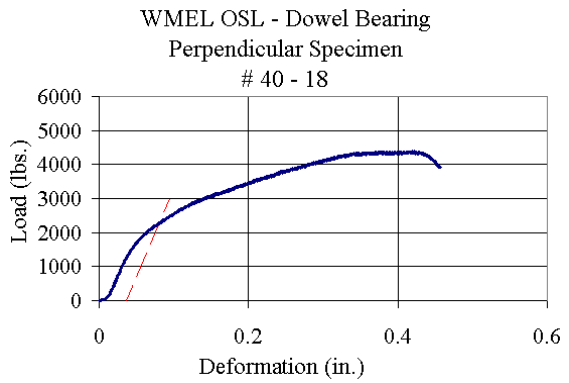
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
40 - 18
Load (lbs.)
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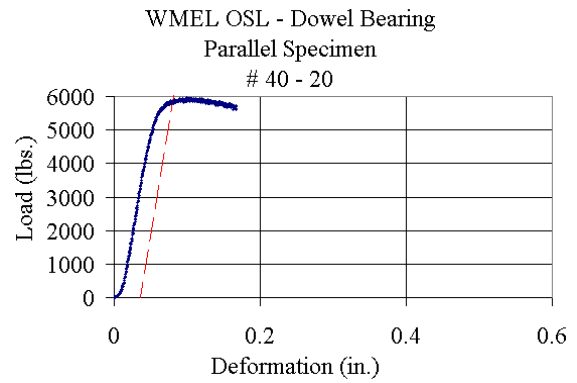
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
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Load (lbs.)
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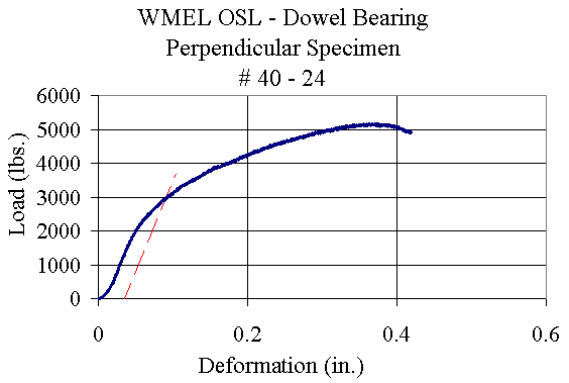
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
40 - 24
Load (lbs.)
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1000
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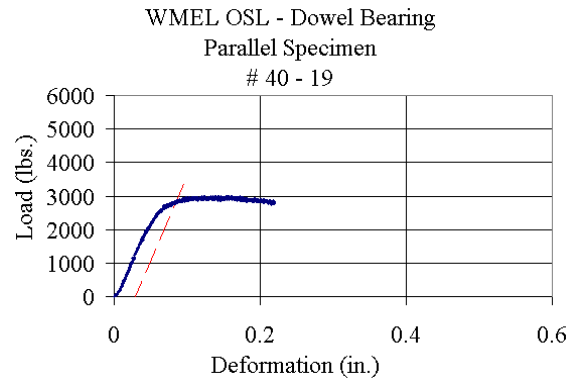
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
40 - 19
Load (lbs.)
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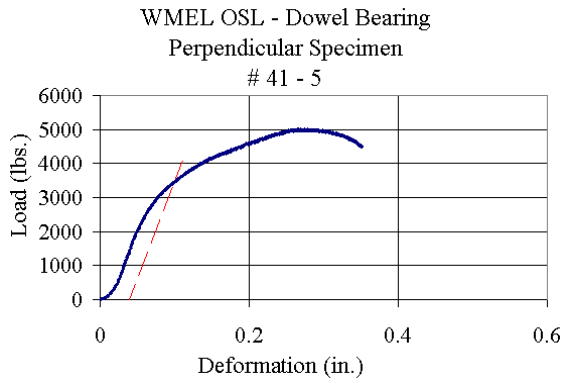
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
41 - 5
Load (lbs.)
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5000
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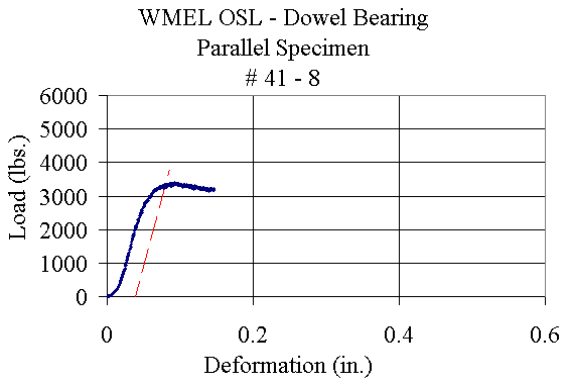
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
41 - 8
Load (lbs.)
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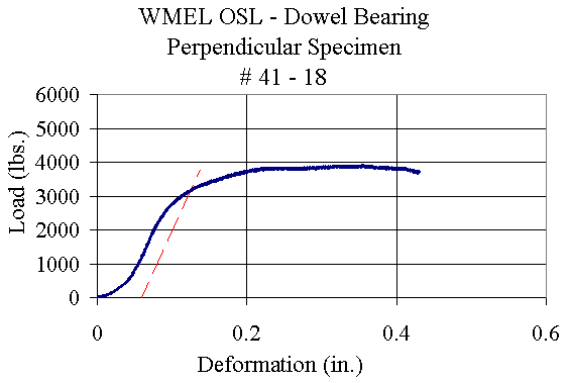
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
41 - 18
Load (lbs.)
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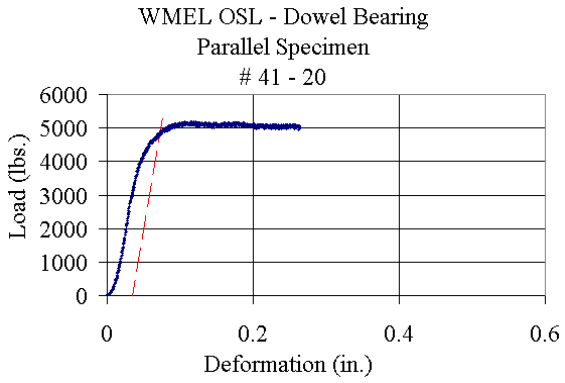
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
41 - 20
Load (lbs.)
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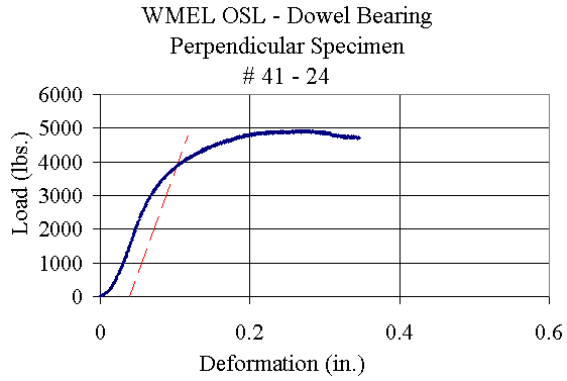
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
41 - 24
Load (lbs.)
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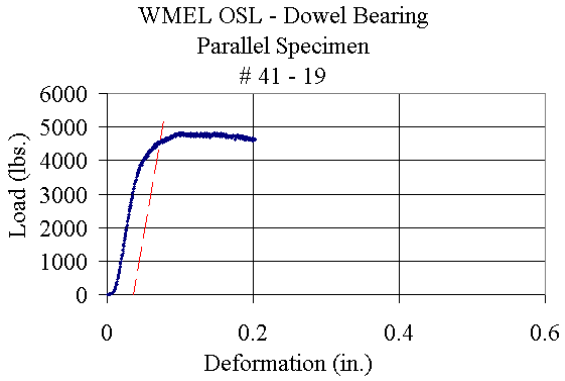
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
41 - 19
Load (lbs.)
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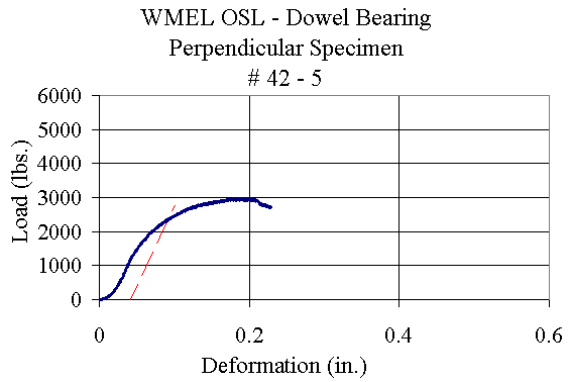
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
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Load (lbs.)
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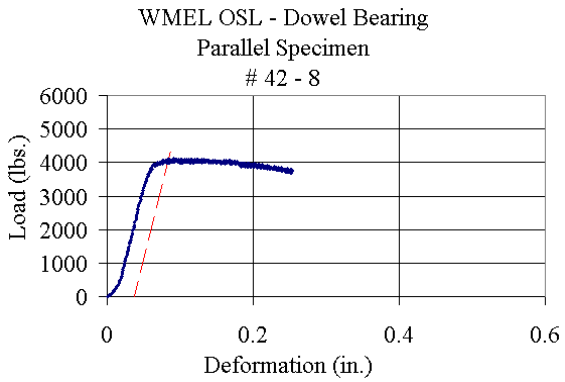
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
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Load (lbs.)
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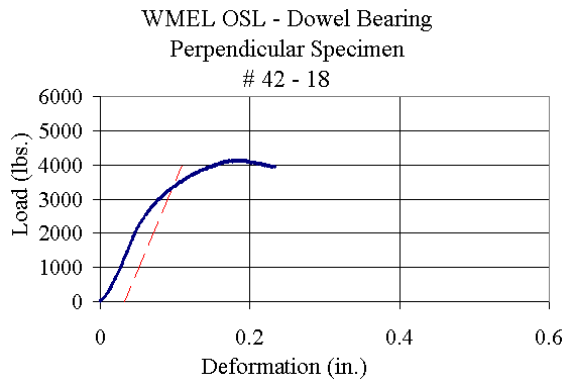
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
42 - 18
Load (lbs.)
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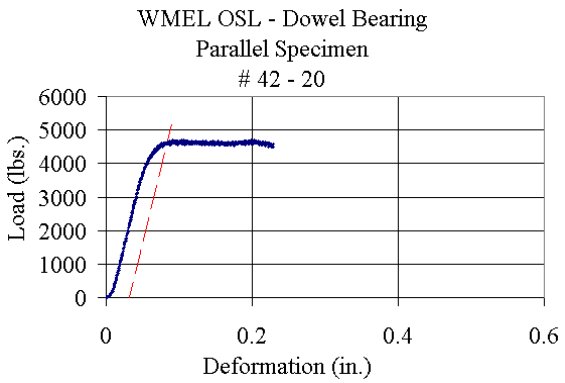
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
42 - 20
Load (lbs.)
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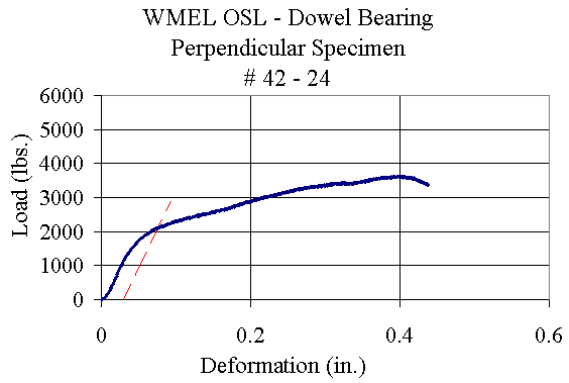
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
42 - 24
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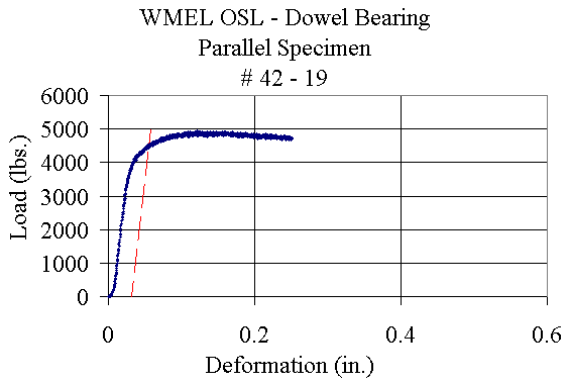
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
42 - 19
Load (lbs.)
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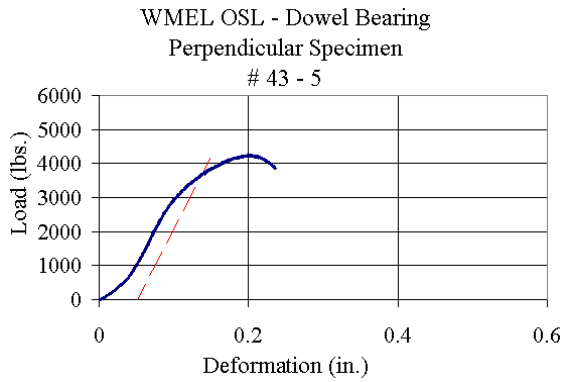
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
43 - 5
Load (lbs.)
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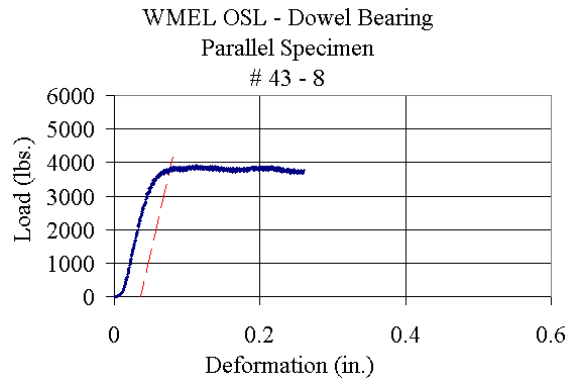
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
43 - 8
Load (lbs.)
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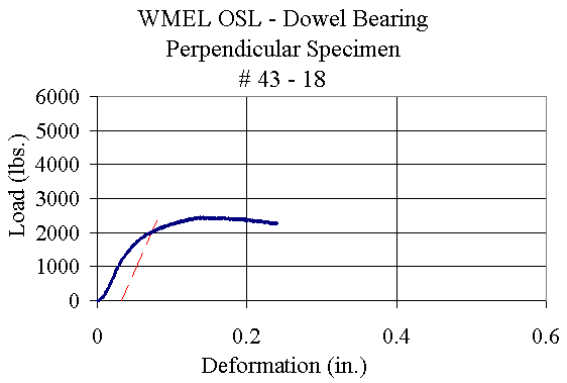
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
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Load (lbs.)
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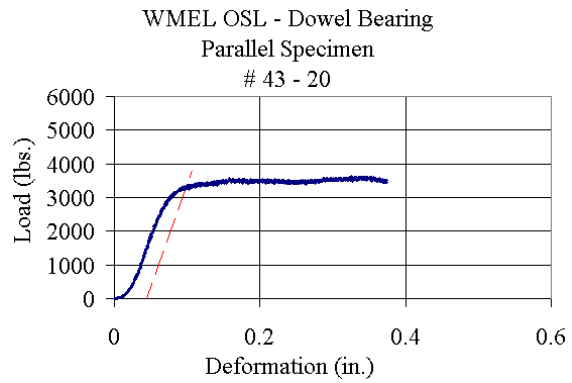
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
43 - 20
Load (lbs.)
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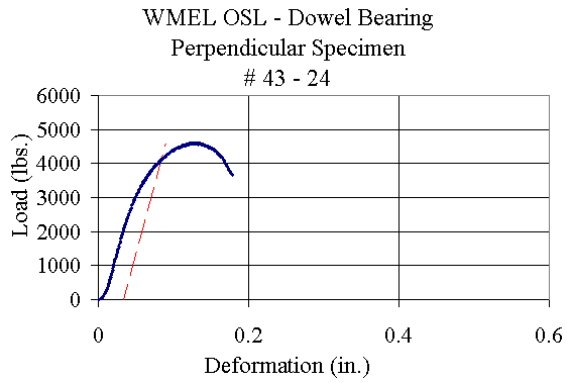
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
43 - 24
Load (lbs.)
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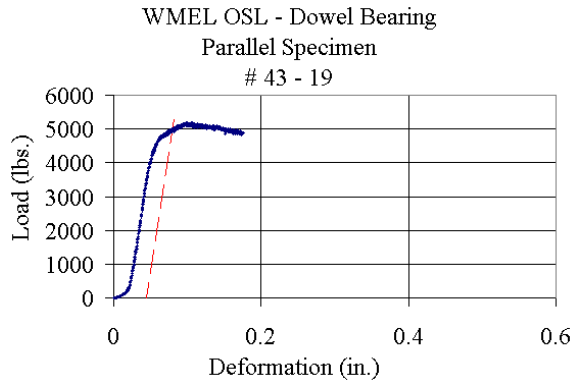
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
43 - 19
Load (lbs.)
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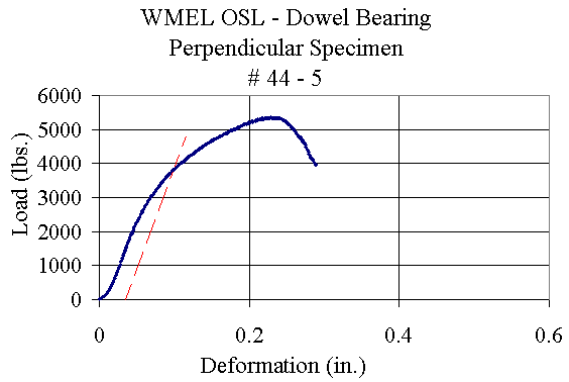
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
44 - 5
Load (lbs.)
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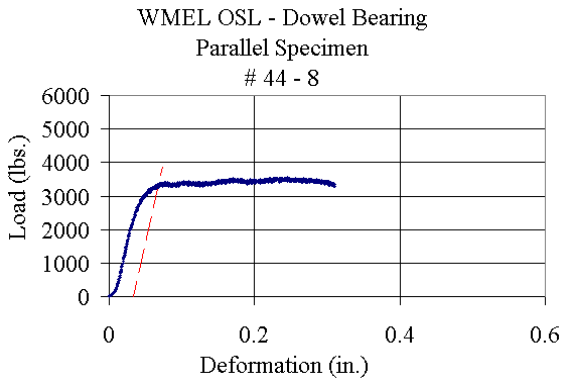
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
44 - 8
Load (lbs.)
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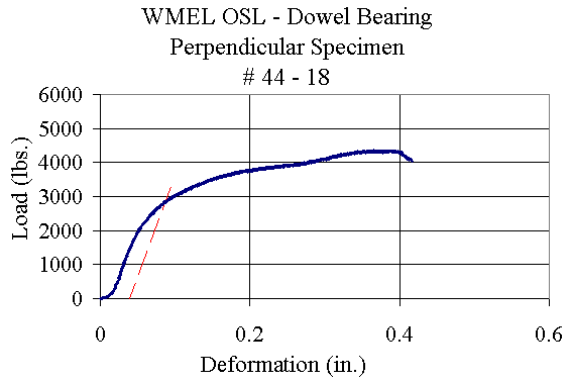
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
44 - 18
Load (lbs.)
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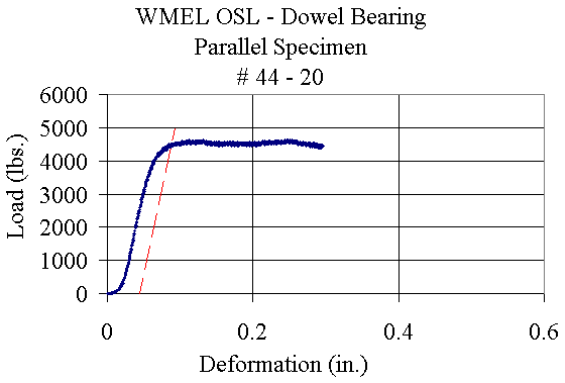
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
44 - 20
Load (lbs.)
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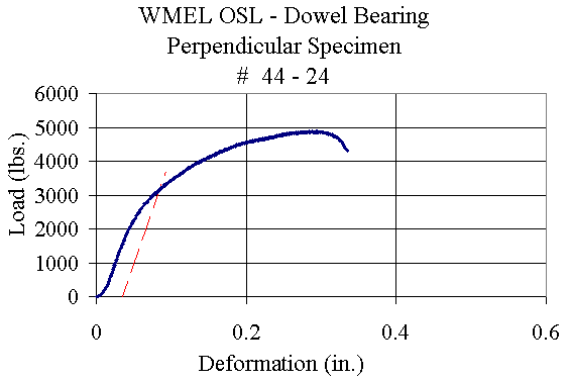
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
44 - 24
Load (lbs.)
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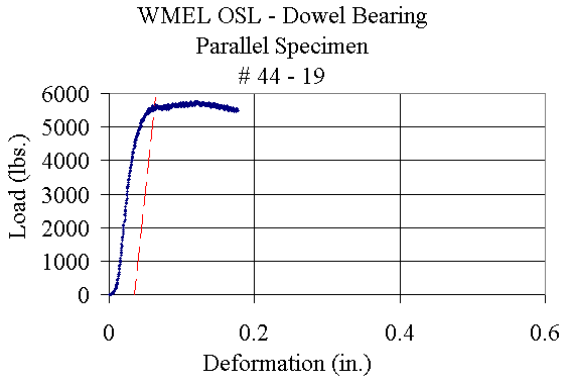
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
44 - 19
Load (lbs.)
6000
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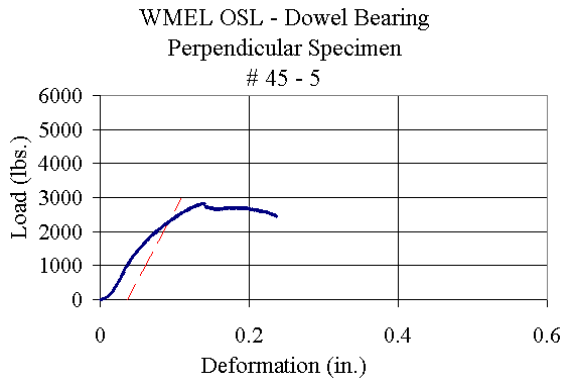
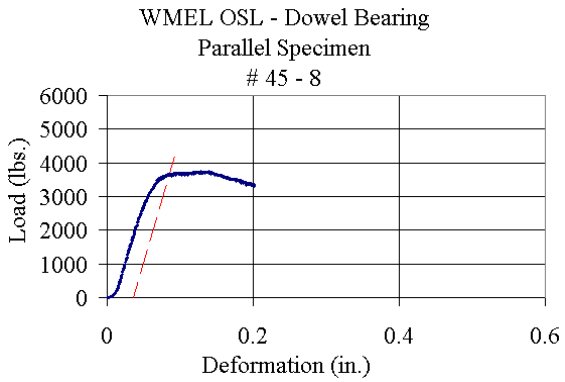
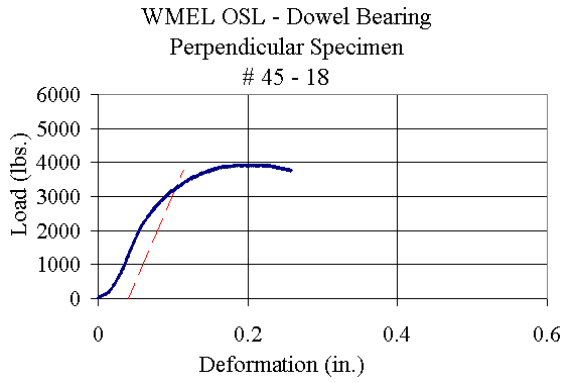
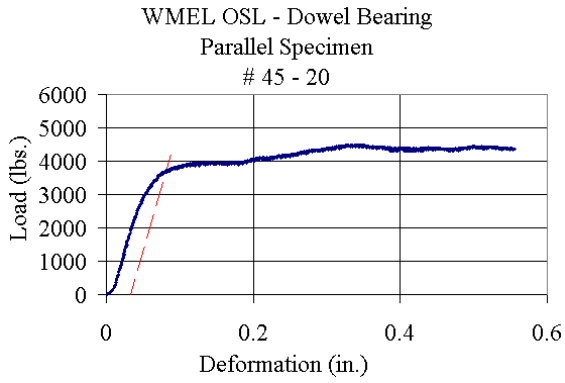
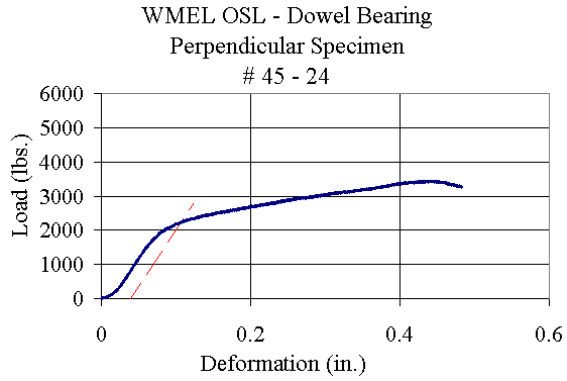
0.6
Deformation (in.)

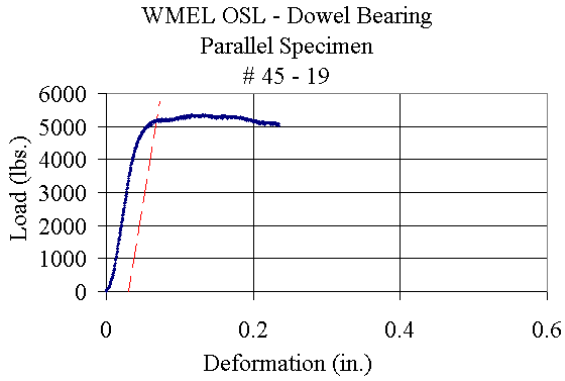

WMEL OSL - Dowel Bearing
Perpendicular Specimen
45 - 5
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
45 - 8
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
45 - 18
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
45 - 20
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Perpendicular Specimen
45 - 24
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)


WMEL OSL - Dowel Bearing
Parallel Specimen
45 - 19
Load (lbs.)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
Deformation (in.)

Dowel Bearing Strength

The 5 percent diameter offset load was determined for each of the specimens from the load-displacement curves created from the dowel bearing tests. These values were used with the bolt diameter and the specimen thickness to determine dowel bearing strength. The dowel bearing strengths, along with the specimen dimensions, can be found on the following pages. Specimens loaded parallel to strand orientation are listed first, with perpendicular to strand orientation specimens following. Some of the perpendicular to strand orientation tests are marked with an asterisk. The asterisk in these tables signifies that loading mechanism impacted the test specimen following significant specimen deformation, as shown in Figure A-2. In some of the specimens that were impacted by the loading mechanism, the approximate load at which impact occurred was observed. In these cases, the load-displacement curve was shaded lighter after the observed load was reached (for example, see specimen 14 – 24). In many cases, this observation was not made until well after initial impact occurred and the curve was not shaded differently. It should be noted however that the observed impact never occurred prior to the 5 percent offset region of the graph being reached and in the unobserved cases, it is not believed to occur prior to this region.

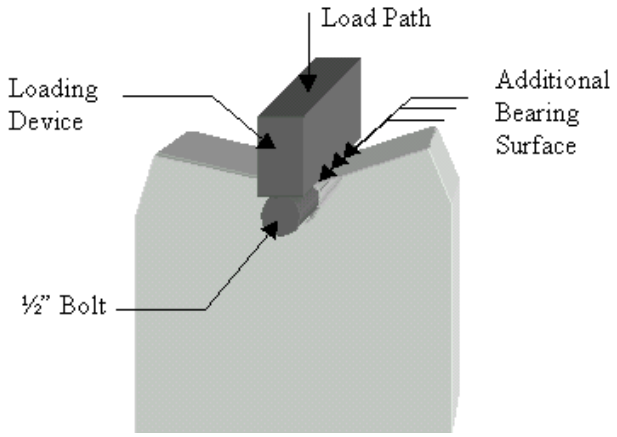


Figure A-2: *Perpendicular dowel bearing specimen with additional bearing surface*

Parallel Specimens:

Panel	Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	5% Diameter Offset Load (lbs.)	F_e (psi)
1	1-8	0.495	1.553	2.590	2.561	2948	3830
	1-19	0.495	1.608	2.472	2.536	4385	5510
	1-20	0.495	1.601	2.484	2.571	5556	7010
2	2-8	0.495	1.605	2.484	2.563	3052	3840
	2-19	0.495	1.541	2.490	2.557	5233	6860
	2-20	0.495	1.601	2.484	2.571	5050	6370
3	3-8	0.495	1.535	2.485	2.548	2604	3430
	3-19	0.495	1.578	2.485	2.544	5189	6640
	3-20	0.495	1.692	2.492	2.565	3573	4270
4	4-8	0.495	1.586	2.485	2.572	3916	4990
	4-19	0.495	1.534	2.485	2.537	3781	4980
	4-20	0.495	1.607	2.470	2.566	4801	6040
5	5-8	0.495	1.521	2.492	2.563	3783	5020
	5-19	0.495	1.605	2.478	2.546	4734	5960
	5-20	0.495	1.503	2.491	2.568	4611	6200
6	6-8	0.495	1.603	2.489	2.533	3427	4320
	6-19	0.495	1.563	2.491	2.545	4411	5700
	6-20	0.495	1.616	2.490	2.553	4073	5090
7	7-8	0.495	1.574	2.476	2.559	2927	3760
	7-19	0.495	1.546	2.489	2.571	4107	5370
	7-20	0.495	1.611	2.493	2.571	3994	5010
8	8-8	0.495	1.598	2.480	2.563	3741	4730
	8-19	0.495	1.512	2.487	2.563	3652	4880
	8-20	0.495	1.628	2.479	2.558	2457	3050
9	9-8	0.495	1.557	2.481	2.554	3867	5020
	9-19	0.495	1.554	2.476	2.550	4709	6120
	9-20	0.495	1.613	2.487	2.563	3343	4190
10	10-8	0.495	1.568	2.479	2.552	4542	5850
	10-19	0.495	1.552	2.477	2.567	3241	4220
	10-20	0.495	1.615	2.500	2.567	3142	3930
11	11-8	0.495	1.605	2.475	2.545	4316	5430
	11-19	0.495	1.544	2.495	2.548	2516	3290
	11-20	0.495	1.632	2.490	2.558	2997	3710

Panel	Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	5% Diameter Offset Load (lbs.)	F_e (psi)
12	12-8	0.495	1.552	2.486	2.545	3940	5130
	12-19	0.495	1.554	2.485	2.554	2976	3870
	12-20	0.495	1.567	2.493	2.549	3314	4270
13	13-8	0.495	1.562	2.473	2.544	3284	4250
	13-19	0.495	1.541	2.485	2.553	3287	4310
	13-20	0.495	1.571	2.482	2.559	3047	3920
14	14-8	0.495	1.560	2.478	2.545	3989	5170
	14-19	0.495	1.522	2.475	2.545	3896	5170
	14-20	0.495	1.587	2.493	2.543	4879	6210
15	15-8	0.495	1.603	2.475	2.545	3392	4270
	15-19	0.495	1.569	2.493	2.550	3896	5020
	15-20	0.495	1.600	2.481	2.557	2878	3630
16	16-8	0.495	1.582	2.483	2.555	2996	3830
	16-19	0.495	1.537	2.484	2.563	3792	4980
	16-20	0.495	1.597	2.479	2.568	2707	3420
17	17-8	0.495	1.609	2.490	2.560	3707	4650
	17-19	0.495	1.542	2.486	2.557	3652	4780
	17-20	0.495	1.619	2.485	2.539	4033	5030
18	18-8	0.495	1.559	2.468	2.565	3090	4000
	18-19	0.495	1.560	2.491	2.555	3326	4310
	18-20	0.495	1.593	2.481	2.564	3637	4610
19	19-8	0.495	1.555	2.488	2.556	3274	4250
	19-19	0.495	1.561	2.478	2.566	4147	5370
	19-20	0.495	1.618	2.479	2.566	3526	4400
20	20-8	0.495	1.574	2.483	2.550	3589	4610
	20-19	0.495	1.545	2.475	2.549	2477	3240
	20-20	0.495	1.595	2.473	2.547	3887	4920
21	21-8	0.495	1.576	2.483	2.536	3397	4350
	21-19	0.495	1.538	2.479	2.550	3034	3990
	21-20	0.495	1.581	2.486	2.551	4723	6040
22	22-8	0.495	1.581	2.482	2.558	4138	5290
	22-19	0.495	1.558	2.472	2.552	3994	5180
	22-20	0.495	1.573	2.490	2.547	3361	4320
23	23-8	0.495	1.516	2.489	2.559	3397	4530
	23-19	0.495	1.598	2.472	2.561	4646	5870
	23-20	0.495	1.544	2.492	2.555	4503	5890

Panel	Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	5% Diameter Offset Load (lbs.)	F_e (psi)
24	24-8	0.495	1.583	2.490	2.547	3975	5070
	24-19	0.495	1.546	2.480	2.544	3407	4450
	24-20	0.495	1.605	2.491	2.543	3319	4180
25	25-8	0.495	1.560	2.482	2.538	4204	5440
	25-19	0.495	1.544	2.486	2.552	4023	5260
	25-20	0.495	1.618	2.474	2.571	3955	4940
26	26-8	0.495	1.590	2.471	2.568	3764	4780
	26-19	0.495	1.533	2.485	2.551	4190	5520
	26-20	0.495	1.602	2.497	2.558	3357	4230
27	27-8	0.495	1.516	2.488	2.542	3891	5190
	27-19	0.495	1.563	2.485	2.552	3489	4510
	27-20	0.495	1.559	2.491	2.544	4484	5810
28	28-8	0.495	1.569	2.487	2.538	2731	3520
	28-19	0.495	1.555	2.489	2.543	4445	5770
	28-20	0.495	1.625	2.492	2.542	3838	4770
29	29-8	0.495	1.606	2.477	2.553	4758	5990
	29-19	0.495	1.526	2.488	2.555	3554	4700
	29-20	0.495	1.623	2.479	2.544	3270	4070
30	30-8	0.495	1.548	2.495	2.569	3727	4860
	30-19	0.495	1.558	2.492	2.549	3387	4390
	30-20	0.495	1.581	2.487	2.571	4161	5320
31	31-8	0.495	1.592	2.469	2.557	3103	3940
	31-19	0.495	1.559	2.498	2.561	3495	4530
	31-20	0.495	1.647	2.486	2.563	2902	3560
32	32-8	0.495	1.603	2.494	2.558	5081	6400
	32-19	0.495	1.569	2.483	2.547	3103	4000
	32-20	0.495	1.612	2.485	2.561	3254	4080
33	33-8	0.495	1.589	2.490	2.542	3872	4920
	33-19	0.495	1.557	2.483	2.554	3979	5160
	33-20	0.495	1.607	2.486	2.558	2584	3250
34	34-8	0.495	1.620	2.478	2.554	4804	5990
	34-19	0.495	1.549	2.482	2.555	4532	5910
	34-20	0.495	1.624	2.478	2.542	2758	3430
35	35-8	0.495	1.587	2.482	2.545	5032	6410
	35-19	0.495	1.545	2.480	2.550	3475	4540
	35-20	0.495	1.630	2.483	2.548	2726	3380

Panel	Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	5% Diameter Offset Load (lbs.)	F_e (psi)
36	36-8	0.495	1.557	2.483	2.560	4836	6270
	36-19	0.495	1.556	2.484	2.545	3847	4990
	36-20	0.495	1.571	2.476	2.542	3256	4190
37	37-8	0.495	1.579	2.479	2.541	3462	4430
	37-19	0.495	1.557	2.491	2.546	4552	5910
	37-20	0.495	1.620	2.488	2.559	3626	4520
38	38-8	0.495	1.549	2.476	2.540	3436	4480
	38-19	0.495	1.585	2.485	2.573	5168	6590
	38-20	0.495	1.558	2.493	2.546	3857	5000
39	39-8	0.495	1.601	2.483	2.553	2653	3350
	39-19	0.495	1.547	2.499	2.559	4018	5250
	39-20	0.495	1.643	2.472	2.547	3754	4620
40	40-8	0.495	1.590	2.485	2.560	2163	2750
	40-19	0.495	1.548	2.472	2.543	2826	3690
	40-20	0.495	1.643	2.489	2.562	5832	7170
41	41-8	0.495	1.626	2.492	2.575	3299	4100
	41-19	0.495	1.534	2.476	2.542	4537	5980
	41-20	0.495	1.657	2.492	2.560	4841	5900
42	42-8	0.495	1.640	2.491	2.576	4047	4990
	42-19	0.495	1.575	2.477	2.549	4470	5730
	42-20	0.495	1.679	2.492	2.544	4606	5540
43	43-8	0.495	1.596	2.476	2.548	3759	4760
	43-19	0.495	1.588	2.490	2.565	4968	6320
	43-20	0.495	1.652	2.490	2.542	3309	4050
44	44-8	0.495	1.610	2.483	2.541	3314	4160
	44-19	0.495	1.539	2.480	2.546	5571	7310
	44-20	0.495	1.670	2.497	2.549	4484	5420
45	45-8	0.495	1.588	2.475	2.538	3652	4650
	45-19	0.495	1.545	2.484	2.544	5179	6770
	45-20	0.495	1.643	2.478	2.548	3698	4550
					Max =	5832	7310
					Min =	2163	2750
					Average =	3808	4870
					Std Dev =	744	955
					COV =	19.5%	19.6%

Perpendicular Specimens:

Panel	Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	5% Diameter Offset Load (lbs.)	F_e (psi)
1	1-5	0.495	1.532	2.492	2.514	1929	2540
	1-18	0.495	1.612	2.488	2.537	3182	3990
	1-24	0.495	1.582	2.489	2.543	3221	4110
2	* 2-5	0.495	1.597	2.487	2.534	2634	3330
	2-18	0.495	1.665	2.494	2.606	2839	3440
	2-24	0.495	1.505	2.487	2.553	2477	3320
3	* 3-5	0.495	1.523	2.492	2.526	1743	2310
	3-18	0.495	1.590	2.492	2.533	2761	3510
	3-24	0.495	1.544	2.490	2.549	2418	3160
4	4-5	0.495	1.583	2.478	2.562	2820	3600
	4-18	0.495	1.606	2.485	2.518	2888	3630
	4-24	0.495	1.509	2.472	2.519	3152	4220
5	* 5-5	0.495	1.482	2.493	2.564	1723	2350
	5-18	0.495	1.506	2.498	2.524	2888	3870
	5-24	0.495	1.568	2.482	2.576	2536	3270
6	6-5	0.495	1.604	2.492	2.494	2565	3230
	6-18	0.495	1.618	2.481	2.559	2399	2990
	6-24	0.495	1.534	2.484	2.555	2134	2810
7	7-5	0.495	1.577	2.494	2.559	2555	3270
	7-18	0.495	1.605	2.495	2.551	2927	3680
	* 7-24	0.495	1.521	2.484	2.553	2056	2730
8	* 8-5	0.495	1.596	2.487	2.547	2780	3520
	8-18	0.495	1.626	2.498	2.550	2301	2860
	8-24	0.495	1.483	2.490	2.550	2105	2870
9	9-5	0.495	1.538	2.480	2.558	1909	2510
	9-18	0.495	1.597	2.490	2.554	2105	2660
	9-24	0.495	1.536	2.480	2.558	2330	3060
10	* 10-5	0.495	1.548	2.486	2.548	2232	2910
	10-18	0.495	1.620	2.496	2.560	1801	2250
	* 10-24	0.495	1.537	2.497	2.554	2320	3050
11	11-5	0.495	1.593	2.494	2.549	1821	2310
	11-18	0.495	1.628	2.491	2.548	2095	2600
	11-24	0.495	1.523	2.494	2.554	2389	3170

Panel	Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	5% Diameter Offset Load (lbs.)	F_e (psi)
	12-5	0.495	1.546	2.497	2.562	1650	2160
12	12-18	0.495	1.581	2.489	2.552	2569	3280
*	12-24	0.495	1.533	2.486	2.564	2379	3140
*	13-5	0.495	1.551	2.487	2.558	1762	2300
13	13-18	0.495	1.582	2.488	2.555	2450	3130
	13-24	0.495	1.511	2.482	2.543	3113	4160
	14-5	0.495	1.573	2.479	2.540	2363	3030
14	14-18	0.495	1.595	2.493	2.554	2614	3310
*	14-24	0.495	1.504	2.490	2.547	1537	2060
	15-5	0.495	1.601	2.495	2.554	2104	2650
15	15-18	0.495	1.610	2.492	2.557	1718	2160
*	15-24	0.495	1.528	2.483	2.553	1938	2560
	16-5	0.495	1.588	2.487	2.560	3096	3940
16	16-18	0.495	1.617	2.492	2.559	2313	2890
	16-24	0.495	1.520	2.489	2.549	2814	3740
	17-5	0.495	1.605	2.486	2.552	2203	2770
17	17-18	0.495	1.638	2.489	2.567	2722	3360
	17-24	0.495	1.504	2.491	2.549	2810	3770
	18-5	0.495	1.567	2.490	2.543	2656	3420
18 *	18-18	0.495	1.582	2.498	2.544	1204	1540
*	18-24	0.495	1.528	2.490	2.551	1909	2520
	19-5	0.495	1.549	2.490	2.558	2736	3570
19 *	19-18	0.495	1.602	2.490	2.562	1896	2390
*	19-24	0.495	1.552	2.488	2.551	2362	3070
*	20-5	0.495	1.576	2.486	2.554	2212	2840
20 *	20-18	0.495	1.609	2.499	2.542	2702	3390
*	20-24	0.495	1.523	2.498	2.563	2242	2970
	21-5	0.495	1.579	2.483	2.543	3127	4000
21	21-18	0.495	1.586	2.484	2.546	2433	3100
*	21-24	0.495	1.527	2.470	2.550	3055	4040
*	22-5	0.495	1.581	2.484	2.566	2516	3210
22	22-18	0.495	1.587	2.499	2.560	2544	3240
	22-24	0.495	1.531	2.485	2.545	3102	4090
*	23-5	0.495	1.528	2.484	2.558	2523	3340
23	23-18	0.495	1.542	2.488	2.551	3004	3940
	23-24	0.495	1.575	2.493	2.556	3752	4810

Panel		Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	5% Diameter Offset Load (lbs.)	F_e (psi)
		24-5	0.495	1.579	2.485	2.552	2702	3460
24	*	24-18	0.495	1.613	2.488	2.565	2353	2950
		24-24	0.495	1.511	2.489	2.558	3640	4870
		25-5	0.495	1.559	2.488	2.549	3165	4100
25		25-18	0.495	1.598	2.489	2.531	2236	2830
		25-24	0.495	1.512	2.494	2.550	2654	3550
	*	26-5	0.495	1.572	2.491	2.549	2467	3170
26	*	26-18	0.495	1.507	2.495	2.553	2424	3250
	*	26-24	0.495	1.513	2.475	2.564	2898	3870
	*	27-5	0.495	1.501	2.490	2.547	2394	3220
27	*	27-18	0.495	1.551	2.487	2.556	2021	2630
		27-24	0.495	1.549	2.493	2.557	2934	3830
	*	28-5	0.495	1.578	2.484	2.566	3147	4030
28		28-18	0.495	1.616	2.484	2.564	2288	2860
		28-24	0.495	1.554	2.491	2.550	3868	5030
		29-5	0.495	1.607	2.480	2.556	2594	3260
29		29-18	0.495	1.638	2.492	2.553	2810	3470
		29-24	0.495	1.512	2.496	2.552	2768	3700
		30-5	0.495	1.545	2.487	2.562	2985	3900
30	*	30-18	0.495	1.590	2.496	2.560	2528	3210
	*	30-24	0.495	1.538	2.488	2.553	2078	2730
		31-5	0.495	1.590	2.491	2.569	3292	4180
31	*	31-18	0.495	1.629	2.499	2.561	1462	1810
		31-24	0.495	1.548	2.494	2.558	3593	4690
		32-5	0.495	1.610	2.484	2.572	4444	5580
32		32-18	0.495	1.616	2.489	2.549	2833	3540
		32-24	0.495	1.546	2.488	2.544	3368	4400
		33-5	0.495	1.583	2.480	2.568	3064	3910
33		33-18	0.495	1.516	2.480	2.486	1593	2120
		33-24	0.495	1.541	2.485	2.554	3298	4320
		34-5	0.495	1.606	2.494	2.549	2776	3490
34		34-18	0.495	1.630	2.482	2.558	3130	3880
	*	34-24	0.495	1.515	2.476	2.543	2549	3400
		35-5	0.495	1.568	2.477	2.579	2664	3430
35		35-18	0.495	1.638	2.488	2.553	3741	4610
		35-24	0.495	1.548	2.493	2.550	3992	5210

Panel		Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	5% Diameter Offset Load (lbs.)	F_e (psi)
		36-5	0.495	1.566	2.497	2.553	4377	5650
36	*	36-18	0.495	1.566	2.491	2.559	1507	1940
	*	36-24	0.495	1.546	2.485	2.548	2634	3440
		37-5	0.495	1.562	2.490	2.564	2118	2740
37		37-18	0.495	1.620	2.485	2.562	2684	3350
		37-24	0.495	1.524	2.502	2.549	2893	3830
	*	38-5	0.495	1.540	2.488	2.546	1934	2540
38		38-18	0.495	1.576	2.485	2.546	3250	4170
		38-24	0.495	1.554	2.483	2.543	2604	3390
		39-5	0.495	1.597	2.487	2.558	3772	4770
39		39-18	0.495	1.640	2.495	2.530	3650	4500
	*	39-24	0.495	1.510	2.482	2.541	1801	2410
	*	40-5	0.495	1.583	2.497	2.543	2064	2630
40	*	40-18	0.495	1.640	2.496	2.560	2274	2800
	*	40-24	0.495	1.531	2.495	2.563	2942	3880
		41-5	0.495	1.618	2.487	2.551	3462	4320
41		41-18	0.495	1.656	2.492	2.561	3150	3840
		41-24	0.495	1.522	2.493	2.554	3882	5150
		42-5	0.495	1.623	2.485	2.546	2366	2950
42		42-18	0.495	1.689	2.487	2.557	3338	3990
	*	42-24	0.495	1.543	2.490	2.549	2104	2750
		43-5	0.495	1.576	2.498	2.553	3668	4700
43		43-18	0.495	1.636	2.497	2.558	2008	2480
		43-24	0.495	1.557	2.492	2.554	4108	5330
		44-5	0.495	1.604	2.491	2.542	3828	4820
44	*	44-18	0.495	1.669	2.484	2.548	2834	3430
		44-24	0.495	1.522	2.486	2.556	3145	4170
		45-5	0.495	1.571	2.491	2.552	2304	2960
45		45-18	0.495	1.641	2.493	2.538	3229	3980
	*	45-24	0.495	1.530	2.480	2.548	2241	2960
						Max =	4444	5650
						Min =	1204	1540
						Average =	2645	3403
						Std Dev =	630	804
						COV =	23.8%	23.6%

Ultimate Dowel Bearing Strength

The ultimate load was determined for each of the specimens from load-displacement curves created from the dowel bearing tests. These values were used with the bolt diameter and the specimen thickness to determine an ultimate dowel bearing strength. The ultimate dowel bearing strengths, along with the specimen dimensions, can be found on the following pages. Specimens loaded parallel to strand orientation are listed first, with specimens loaded perpendicular to strand orientation following. Some of the perpendicular to strand orientation tests were marked with an asterisk. The asterisk in these tables signifies that the loading mechanism impacted the test specimen following significant specimen deformation, as discussed earlier. If the point at which load mechanism contact occurred was not observed, the ultimate dowel bearing strength was not calculated and the ultimate load is marked “n/a”. If the point of contact was observed, the ultimate dowel bearing strength was calculated using the ultimate load on the load-displacement curve prior to reaching the point of load mechanism bearing.

Parallel Specimens:

Panel	Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	Ultimate Load (lbs.)	F_u (psi)
1	1-8	0.495	1.553	2.590	2.561	3006	3910
	1-19	0.495	1.608	2.472	2.536	4836	6076
	1-20	0.495	1.601	2.484	2.571	5580	7041
2	2-8	0.495	1.605	2.484	2.563	3133	3943
	2-19	0.495	1.541	2.490	2.557	5267	6905
	2-20	0.495	1.601	2.484	2.571	5120	6461
3	3-8	0.495	1.535	2.485	2.548	2663	3505
	3-19	0.495	1.578	2.485	2.544	5326	6819
	3-20	0.495	1.692	2.492	2.565	3613	4314
4	4-8	0.495	1.586	2.485	2.572	4024	5126
	4-19	0.495	1.534	2.485	2.537	3906	5144
	4-20	0.495	1.607	2.470	2.566	4866	6117
5	5-8	0.495	1.521	2.492	2.563	3808	5058
	5-19	0.495	1.605	2.478	2.546	4748	5976
	5-20	0.495	1.503	2.491	2.568	4817	6475
6	6-8	0.495	1.603	2.489	2.533	3524	4441
	6-19	0.495	1.563	2.491	2.545	4562	5896
	6-20	0.495	1.616	2.490	2.553	4102	5128
7	7-8	0.495	1.574	2.476	2.559	3064	3933
	7-19	0.495	1.546	2.489	2.571	4268	5577
	7-20	0.495	1.611	2.493	2.571	4239	5316
8	8-8	0.495	1.598	2.480	2.563	3808	4814
	8-19	0.495	1.512	2.487	2.563	3661	4892
	8-20	0.495	1.628	2.479	2.558	2516	3122
9	9-8	0.495	1.557	2.481	2.554	3955	5132
	9-19	0.495	1.554	2.476	2.550	4748	6172
	9-20	0.495	1.613	2.487	2.563	3358	4206
10	10-8	0.495	1.568	2.479	2.552	4542	5852
	10-19	0.495	1.552	2.477	2.567	3250	4230
	10-20	0.495	1.615	2.500	2.567	3142	3930
11	11-8	0.495	1.605	2.475	2.545	4327	5446
	11-19	0.495	1.544	2.495	2.548	2624	3433
	11-20	0.495	1.632	2.490	2.558	3064	3793

Panel	Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	Ultimate Load (lbs.)	F_u (psi)
12	12-8	0.495	1.552	2.486	2.545	4024	5238
	12-19	0.495	1.554	2.485	2.554	2996	3895
	12-20	0.495	1.567	2.493	2.549	3485	4493
13	13-8	0.495	1.562	2.473	2.544	3446	4457
	13-19	0.495	1.541	2.485	2.553	3378	4428
	13-20	0.495	1.571	2.482	2.559	3074	3953
14	14-8	0.495	1.560	2.478	2.545	4053	5249
	14-19	0.495	1.522	2.475	2.545	3896	5171
	14-20	0.495	1.587	2.493	2.543	4905	6244
15	15-8	0.495	1.603	2.475	2.545	3427	4319
	15-19	0.495	1.569	2.493	2.550	3975	5118
	15-20	0.495	1.600	2.481	2.557	2898	3659
16	16-8	0.495	1.582	2.483	2.555	3064	3913
	16-19	0.495	1.537	2.484	2.563	3867	5083
	16-20	0.495	1.597	2.479	2.568	2820	3567
17	17-8	0.495	1.609	2.490	2.560	3720	4671
	17-19	0.495	1.542	2.486	2.557	3652	4785
	17-20	0.495	1.619	2.485	2.539	4033	5032
18	18-8	0.495	1.559	2.468	2.565	3201	4148
	18-19	0.495	1.560	2.491	2.555	3485	4513
	18-20	0.495	1.593	2.481	2.564	3759	4767
19	19-8	0.495	1.555	2.488	2.556	3505	4554
	19-19	0.495	1.561	2.478	2.566	4210	5448
	19-20	0.495	1.618	2.479	2.566	3632	4535
20	20-8	0.495	1.574	2.483	2.550	3789	4863
	20-19	0.495	1.545	2.475	2.549	2731	3571
	20-20	0.495	1.595	2.473	2.547	3936	4985
21	21-8	0.495	1.576	2.483	2.536	3505	4493
	21-19	0.495	1.538	2.479	2.550	3309	4346
	21-20	0.495	1.581	2.486	2.551	4738	6054
22	22-8	0.495	1.581	2.482	2.558	4171	5330
	22-19	0.495	1.558	2.472	2.552	4033	5229
	22-20	0.495	1.573	2.490	2.547	3485	4476
23	23-8	0.495	1.516	2.489	2.559	3417	4553
	23-19	0.495	1.598	2.472	2.561	4709	5953
	23-20	0.495	1.544	2.492	2.555	4533	5931

Panel	Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	Ultimate Load (lbs.)	F_u (psi)
24	24-8	0.495	1.583	2.490	2.547	4180	5334
	24-19	0.495	1.546	2.480	2.544	3593	4695
	24-20	0.495	1.605	2.491	2.543	3466	4363
25	25-8	0.495	1.560	2.482	2.538	4376	5667
	25-19	0.495	1.544	2.486	2.552	4239	5546
	25-20	0.495	1.618	2.474	2.571	4161	5195
26	26-8	0.495	1.590	2.471	2.568	3985	5063
	26-19	0.495	1.533	2.485	2.551	4229	5573
	26-20	0.495	1.602	2.497	2.558	3564	4494
27	27-8	0.495	1.516	2.488	2.542	3955	5270
	27-19	0.495	1.563	2.485	2.552	3769	4871
	27-20	0.495	1.559	2.491	2.544	4513	5848
28	28-8	0.495	1.569	2.487	2.538	3769	4853
	28-19	0.495	1.555	2.489	2.543	5541	7199
	28-20	0.495	1.625	2.492	2.542	3965	4929
29	29-8	0.495	1.606	2.477	2.553	4885	6145
	29-19	0.495	1.526	2.488	2.555	4063	5379
	29-20	0.495	1.623	2.479	2.544	3691	4594
30	30-8	0.495	1.548	2.495	2.569	4454	5813
	30-19	0.495	1.558	2.492	2.549	3789	4913
	30-20	0.495	1.581	2.487	2.571	4631	5917
31	31-8	0.495	1.592	2.469	2.557	3299	4186
	31-19	0.495	1.559	2.498	2.561	4112	5328
	31-20	0.495	1.647	2.486	2.563	3103	3806
32	32-8	0.495	1.603	2.494	2.558	5287	6663
	32-19	0.495	1.569	2.483	2.547	4337	5584
	32-20	0.495	1.612	2.485	2.561	3671	4601
33	33-8	0.495	1.589	2.490	2.542	4846	6161
	33-19	0.495	1.557	2.483	2.554	4357	5653
	33-20	0.495	1.607	2.486	2.558	2692	3384
34	34-8	0.495	1.620	2.478	2.554	5110	6372
	34-19	0.495	1.549	2.482	2.555	4915	6410
	34-20	0.495	1.624	2.478	2.542	3123	3885
35	35-8	0.495	1.587	2.482	2.545	5394	6866
	35-19	0.495	1.545	2.480	2.550	3955	5171
	35-20	0.495	1.630	2.483	2.548	3887	4818

Panel	Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	Ultimate Load (lbs.)	F_u (psi)
36	36-8	0.495	1.557	2.483	2.560	5845	7584
	36-19	0.495	1.556	2.484	2.545	4112	5339
	36-20	0.495	1.571	2.476	2.542	3289	4229
37	37-8	0.495	1.579	2.479	2.541	3505	4484
	37-19	0.495	1.557	2.491	2.546	4601	5970
	37-20	0.495	1.620	2.488	2.559	3847	4797
38	38-8	0.495	1.549	2.476	2.540	3985	5197
	38-19	0.495	1.585	2.485	2.573	5287	6739
	38-20	0.495	1.558	2.493	2.546	3945	5115
39	39-8	0.495	1.601	2.483	2.553	2878	3632
	39-19	0.495	1.547	2.499	2.559	4082	5331
	39-20	0.495	1.643	2.472	2.547	3779	4647
40	40-8	0.495	1.590	2.485	2.560	2555	3246
	40-19	0.495	1.548	2.472	2.543	2966	3871
	40-20	0.495	1.643	2.489	2.562	5923	7283
41	41-8	0.495	1.626	2.492	2.575	3358	4172
	41-19	0.495	1.534	2.476	2.542	4807	6331
	41-20	0.495	1.657	2.492	2.560	5150	6279
42	42-8	0.495	1.640	2.491	2.576	4092	5041
	42-19	0.495	1.575	2.477	2.549	4895	6279
	42-20	0.495	1.679	2.492	2.544	4660	5607
43	43-8	0.495	1.596	2.476	2.548	3877	4907
	43-19	0.495	1.588	2.490	2.565	5150	6552
	43-20	0.495	1.652	2.490	2.542	3593	4394
44	44-8	0.495	1.610	2.483	2.541	3515	4411
	44-19	0.495	1.539	2.480	2.546	5737	7531
	44-20	0.495	1.670	2.497	2.549	4601	5566
45	45-8	0.495	1.588	2.475	2.538	3730	4745
	45-19	0.495	1.545	2.484	2.544	5336	6977
	45-20	0.495	1.643	2.478	2.548	4474	5501
					Max =		7584
					Min =		3122
					Average =		5122
					Std Dev =		977
					COV =		19.1%

Perpendicular Specimens:

Panel	Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	Ultimate Load (lbs.)	F_u (psi)
1	1-5	0.495	1.532	2.492	2.514	2408	3175
	1-18	0.495	1.612	2.488	2.537	3887	4871
	1-24	0.495	1.582	2.489	2.543	4141	5288
2	* 2-5	0.495	1.597	2.487	2.534	n/a	
	2-18	0.495	1.665	2.494	2.606	2966	3599
	2-24	0.495	1.505	2.487	2.553	3260	4376
3	* 3-5	0.495	1.523	2.492	2.526	n/a	
	3-18	0.495	1.590	2.492	2.533	3515	4466
	3-24	0.495	1.544	2.490	2.549	3701	4842
4	4-5	0.495	1.583	2.478	2.562	3740	4773
	4-18	0.495	1.606	2.485	2.518	3338	4199
	4-24	0.495	1.509	2.472	2.519	3779	5059
5	* 5-5	0.495	1.482	2.493	2.564	n/a	
	5-18	0.495	1.506	2.498	2.524	3515	4715
	5-24	0.495	1.568	2.482	2.576	2555	3292
6	6-5	0.495	1.604	2.492	2.494	3182	4008
	6-18	0.495	1.618	2.481	2.559	3045	3802
	6-24	0.495	1.534	2.484	2.555	2418	3184
7	7-5	0.495	1.577	2.494	2.559	2810	3600
	7-18	0.495	1.605	2.495	2.551	3642	4584
	* 7-24	0.495	1.521	2.484	2.553	n/a	
8	* 8-5	0.495	1.596	2.487	2.547	n/a	
	8-18	0.495	1.626	2.498	2.550	3495	4342
	8-24	0.495	1.483	2.490	2.550	2820	3842
9	9-5	0.495	1.538	2.480	2.558	3045	4000
	9-18	0.495	1.597	2.490	2.554	2820	3567
	9-24	0.495	1.536	2.480	2.558	2988	3930
10	* 10-5	0.495	1.548	2.486	2.548	n/a	
	10-18	0.495	1.620	2.496	2.560	3123	3895
	* 10-24	0.495	1.537	2.497	2.554	n/a	
11	11-5	0.495	1.593	2.494	2.549	2957	3750
	11-18	0.495	1.628	2.491	2.548	2849	3535
	11-24	0.495	1.523	2.494	2.554	3054	4051

Panel		Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	Ultimate Load (lbs.)	F_u (psi)
12		12-5	0.495	1.546	2.497	2.562	2242	2930
		12-18	0.495	1.581	2.489	2.552	2996	3828
	*	12-24	0.495	1.533	2.486	2.564	n/a	
13	*	13-5	0.495	1.551	2.487	2.558	n/a	
		13-18	0.495	1.582	2.488	2.555	3955	5051
		13-24	0.495	1.511	2.482	2.543	4729	6323
14		14-5	0.495	1.573	2.479	2.540	2722	3496
		14-18	0.495	1.595	2.493	2.554	4092	5183
	*	14-24	0.495	1.504	2.490	2.547	2448	3288
15		15-5	0.495	1.601	2.495	2.554	2966	3743
		15-18	0.495	1.610	2.492	2.557	2154	2703
	*	15-24	0.495	1.528	2.483	2.553	n/a	
16		16-5	0.495	1.588	2.487	2.560	4552	5791
		16-18	0.495	1.617	2.492	2.559	3985	4979
		16-24	0.495	1.520	2.489	2.549	3495	4645
17		17-5	0.495	1.605	2.486	2.552	3446	4337
		17-18	0.495	1.638	2.489	2.567	3593	4431
		17-24	0.495	1.504	2.491	2.549	3916	5260
18		18-5	0.495	1.567	2.490	2.543	3270	4216
	*	18-18	0.495	1.582	2.498	2.544	2046	2613
	*	18-24	0.495	1.528	2.490	2.551	n/a	
19		19-5	0.495	1.549	2.490	2.558	3789	4942
	*	19-18	0.495	1.602	2.490	2.562	2820	3556
	*	19-24	0.495	1.552	2.488	2.551	3840	4998
20	*	20-5	0.495	1.576	2.486	2.554	3300	4230
	*	20-18	0.495	1.609	2.499	2.542	3456	4339
	*	20-24	0.495	1.523	2.498	2.563	4200	5571
21		21-5	0.495	1.579	2.483	2.543	3965	5073
		21-18	0.495	1.586	2.484	2.546	3045	3879
	*	21-24	0.495	1.527	2.470	2.550	n/a	
22	*	22-5	0.495	1.581	2.484	2.566	3701	4729
		22-18	0.495	1.587	2.499	2.560	4200	5346
		22-24	0.495	1.531	2.485	2.545	4014	5297
23	*	23-5	0.495	1.528	2.484	2.558	3789	5010
		23-18	0.495	1.542	2.488	2.551	4259	5580
		23-24	0.495	1.575	2.493	2.556	4601	5902

Panel	Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	Ultimate Load (lbs.)	F_u (psi)
	24-5	0.495	1.579	2.485	2.552	3613	4623
24 *	24-18	0.495	1.613	2.488	2.565	3505	4390
	24-24	0.495	1.511	2.489	2.558	4572	6113
	25-5	0.495	1.559	2.488	2.549	4171	5405
25	25-18	0.495	1.598	2.489	2.531	3270	4134
	25-24	0.495	1.512	2.494	2.550	3495	4670
*	26-5	0.495	1.572	2.491	2.549	n/a	
26 *	26-18	0.495	1.507	2.495	2.553	n/a	
*	26-24	0.495	1.513	2.475	2.564	4298	5739
*	27-5	0.495	1.501	2.490	2.547	n/a	
27 *	27-18	0.495	1.551	2.487	2.556	n/a	
	27-24	0.495	1.549	2.493	2.557	3564	4648
*	28-5	0.495	1.578	2.484	2.566	n/a	
28	28-18	0.495	1.616	2.484	2.564	2496	3120
	28-24	0.495	1.554	2.491	2.550	4092	5320
	29-5	0.495	1.607	2.480	2.556	4465	5613
29	29-18	0.495	1.638	2.492	2.553	3397	4190
	29-24	0.495	1.512	2.496	2.552	3681	4918
	30-5	0.495	1.545	2.487	2.562	4787	6259
30 *	30-18	0.495	1.590	2.496	2.560	n/a	
*	30-24	0.495	1.538	2.488	2.553	n/a	
	31-5	0.495	1.590	2.491	2.569	3926	4988
31 *	31-18	0.495	1.629	2.499	2.561	n/a	
	31-24	0.495	1.548	2.494	2.558	4220	5507
	32-5	0.495	1.610	2.484	2.572	5208	6535
32	32-18	0.495	1.616	2.489	2.549	3289	4112
	32-24	0.495	1.546	2.488	2.544	3818	4989
	33-5	0.495	1.583	2.480	2.568	3084	3936
33	33-18	0.495	1.516	2.480	2.486	3818	5088
	33-24	0.495	1.541	2.485	2.554	3838	5031
	34-5	0.495	1.606	2.494	2.549	4464	5615
34	34-18	0.495	1.630	2.482	2.558	3436	4259
*	34-24	0.495	1.515	2.476	2.543	n/a	
	35-5	0.495	1.568	2.477	2.579	4474	5764
35	35-18	0.495	1.638	2.488	2.553	4631	5712
	35-24	0.495	1.548	2.493	2.550	4738	6183

Panel		Test	Bolt Diameter (in.)	Thickness (in.)	Length (in.)	Height (in.)	Ultimate Load (lbs.)	F_u (psi)
		36-5	0.495	1.566	2.497	2.553	4836	6239
36	*	36-18	0.495	1.566	2.491	2.559	n/a	
	*	36-24	0.495	1.546	2.485	2.548	n/a	
		37-5	0.495	1.562	2.490	2.564	3025	3912
37		37-18	0.495	1.620	2.485	2.562	3554	4432
		37-24	0.495	1.524	2.502	2.549	3613	4789
	*	38-5	0.495	1.540	2.488	2.546	3583	4700
38		38-18	0.495	1.576	2.485	2.546	3642	4669
		38-24	0.495	1.554	2.483	2.543	3192	4150
		39-5	0.495	1.597	2.487	2.558	4934	6242
39		39-18	0.495	1.640	2.495	2.530	4709	5801
	*	39-24	0.495	1.510	2.482	2.541	3231	4323
	*	40-5	0.495	1.583	2.497	2.543	3691	4710
40	*	40-18	0.495	1.640	2.496	2.560	n/a	
	*	40-24	0.495	1.531	2.495	2.563	n/a	
		41-5	0.495	1.618	2.487	2.551	5003	6247
41		41-18	0.495	1.656	2.492	2.561	3887	4742
		41-24	0.495	1.522	2.493	2.554	4915	6524
		42-5	0.495	1.623	2.485	2.546	2947	3668
42		42-18	0.495	1.689	2.487	2.557	4141	4953
	*	42-24	0.495	1.543	2.490	2.549	n/a	
		43-5	0.495	1.576	2.498	2.553	4239	5434
43		43-18	0.495	1.636	2.497	2.558	2438	3011
		43-24	0.495	1.557	2.492	2.554	4601	5970
		44-5	0.495	1.604	2.491	2.542	5355	6745
44	*	44-18	0.495	1.669	2.484	2.548	n/a	
		44-24	0.495	1.522	2.486	2.556	4866	6459
		45-5	0.495	1.571	2.491	2.552	2829	3638
45		45-18	0.495	1.641	2.493	2.538	3916	4821
	*	45-24	0.495	1.530	2.480	2.548	n/a	
						Max =		6745
						Min =		2613
						Average =		4683
						Std Dev =		944
						COV =		20.2%

Analysis of Variance (ANOVA) Results

Dowel Bearing Specimens Loaded Parallel to Strand Orientation

Homogeneity of Variance

Response Fe
Factors Length Width

Levene's Test (any continuous distribution)
Test Statistic: 1.554
P-Value : 0.145

General Linear Model

Factor	Type	Levels	Values
Length	fixed	3	12 4 8
Width	fixed	3	1 1/2 ¾

Analysis of Variance for Fe, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SG	1	8717632	9742771	9742771	11.64	0.001
Angle	1	1771809	1284921	1284921	1.53	0.218
Length	2	1795397	1778374	889187	1.06	0.349
Width	2	1335839	1335839	667920	0.80	0.453
Error	127	106319623	106319623	837162		
Total	133	119940299				

Term	Coef	StDev	T	P
Constant	1732.1	891.7	1.94	0.054
SG	4515	1324	3.41	0.001
Angle	25.03	20.21	1.24	0.218
Length				
12	198.1	139.1	1.42	0.157
4	-95.7	151.2	-0.63	0.528
Width				
1	-140.3	112.0	-1.25	0.212
1/2	85.0	111.9	0.76	0.449

Means for Covariates

Covariate	Mean	StDev
SG	0.5967	0.06311

Angle	18.9328	5.43339

Least Squares Means for Fe

Length	Mean	StDev
12	5098	185.8
4	4805	156.6
8	4798	143.8
Width		
1	4760	140.1
1/2	4985	139.1
3/4	4956	141.4

Dowel Bearing Specimens Loaded Perpendicular to Strand Orientation

Homogeneity of Variance

Response Fe
Factors Length Width

Levene's Test (any continuous distribution)
Test Statistic: 1.032
P-Value : 0.415

General Linear Model

Factor	Type	Levels	Values
Length	fixed	3	12 4 8
Width	fixed	3	0.5 0.75 1

Analysis of Variance for Fe, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SG	1	1745463	4538850	4538850	8.06	0.005
Angle	1	12391702	5597045	5597045	9.94	0.002
Length	2	245053	270324	135162	0.24	0.787
Width	2	618150	618150	309075	0.55	0.579
Error	127	71523051	71523051	563174		
Total	133	86523419				

Term	Coef	StDev	T	P
Constant	559.0	731.4	0.76	0.446
SG	3082	1086	2.84	0.005
Angle	52.25	16.57	3.15	0.002
Length				
12	-76.4	114.1	-0.67	0.504
4	68.4	124.0	0.55	0.582
Width				

0.5	71.97	91.77	0.78	0.434
0.75	19.16	92.15	0.21	0.836

Means for Covariates

Covariate	Mean	StDev
SG	0.5967	0.06311
Angle	18.9328	5.43339

Least Squares Means for Fe

Length	Mean	StDev
12	3311	152.4
4	3456	128.4
8	3395	118.0
Width		
0.5	3459	114.1
0.75	3406	116.0
1	3296	114.9

Multiple Regression Analysis

Dowel Bearing Specimens Loaded Perpendicular to Strand Orientation
The regression equation is
Fe = 525 + 2988 SG + 57.8 Angle

134 cases used 1 cases contain missing values

Predictor	Coef	StDev	T	P	VIF
Constant	525.4	720.5	0.73	0.467	
SG	2988	1051	2.84	0.005	1.1
Angle	57.81	12.21	4.74	0.000	1.1

S = 743.3 R-Sq = 16.3% R-Sq(adj) = 15.1%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	14137165	7068583	12.79	0.000
Residual Error	131	72386254	552567		
Lack of Fit	97	55751765	574760	1.17	0.303
Pure Error	34	16634489	489250		
Total	133	86523419			

72 rows with no replicates

Source	DF	Seq SS
SG	1	1745463
Angle	1	12391702

APPENDIX B:

COMMERCIAL ORIENTED STRAND LUMBER

MOISTURE CONTENT AND SPECIFIC GRAVITY

Moisture content and specific gravity tests were performed prior to the dowel bearing and the bolted connections tests. A sample size of 18 specimens was used for both the moisture content and specific gravity tests. The results from these tests can be found below. The moisture content was found to be approximately 6% and the oven-dried specific gravity was approximately 0.65.

Specimen	Width	Average (in) Thickness	Length	Volume (in^3)	Initial Wt. (g)	Final Wt. (g)	MC (%)	$S.G._a$	$S.G._d$
K010	5.498	1.473	2.045	16.558	182.38	171.87	6.12	0.63	0.66
K088	5.499	1.497	2.034	16.739	202.65	190.70	6.27	0.69	0.72
K102	5.502	1.484	2.049	16.729	171.56	161.98	5.91	0.59	0.61
K104	5.506	1.489	2.038	16.707	167.29	158.09	5.82	0.58	0.60
K120	5.502	1.485	2.048	16.729	174.98	165.08	6.00	0.60	0.62
K123	5.494	1.479	2.037	16.558	162.12	152.87	6.05	0.56	0.58
K125	5.496	1.482	2.046	16.670	187.67	177.07	5.99	0.65	0.67
K135	5.497	1.479	2.045	16.625	188.39	177.83	5.94	0.65	0.68
K136	3.412	1.475	1.992	10.025	104.87	99.37	5.53	0.60	0.62
K148	5.499	1.491	2.030	16.639	182.76	172.48	5.96	0.63	0.65
K151	3.401	1.482	1.991	10.033	91.25	86.42	5.59	0.53	0.54
K152	3.404	1.481	1.987	10.014	105.82	100.27	5.54	0.61	0.63
K165	3.396	1.485	1.994	10.051	110.70	104.65	5.78	0.64	0.66
K168	3.400	1.491	1.985	10.059	116.42	110.09	5.75	0.67	0.69
K171	5.498	1.463	2.062	16.586	192.64	182.35	5.64	0.67	0.69
K179	3.390	1.473	1.995	9.956	116.07	110.23	5.30	0.68	0.70
K183	5.490	1.460	2.058	16.494	192.91	182.49	5.71	0.67	0.70
K208	5.493	1.473	2.024	16.379	186.76	175.90	6.17	0.66	0.68
						Mean =	5.84	0.63	0.65
						Std Dev =	0.254	0.045	0.048
						COV =	4.4%	7.2%	7.4%

BOLT BENDING YIELD STRENGTH

Load-displacement curves were created from the bolt bending yield tests. These curves were analyzed and the 5% diameter offset yield value was determined for each bolt. With a bearing point spacing of 4 inches, the bending yield strength equation was simplified to the form shown in Equation B-1. The results from the tests are shown in Table B-1 through Table B-3.

$$F_{yb} = \frac{6\,(5\%\ Diameter\ Yield\ Load)}{D^3} \qquad \text{Equation B-1}$$

Table B-1: *Mode I_m and End Distance Tests with ¾ inch Bolts*

¾ inch Diameter Bolts – 5 3/8 inches in length

Test	Diameter (in)	5% D Offset load (lbs.)	F_{yb} (psi)
Bolt 37	0.747	4861	69964
Bolt 38	0.745	4821	69953
Bolt 39	0.750	4818	68523
Bolt 40	0.753	4879	68571
Bolt 41	0.747	4748	68346
Bolt 42	0.749	4865	69469
Bolt 43	0.749	4766	68056
Bolt 44	0.753	4706	66131
Bolt 45	0.750	4806	68353
Bolt 46	0.750	4812	68440
Bolt 47	0.751	4931	69852
Bolt 48	0.749	4920	70254

Average = 68826 psi
Std. Dev. = 1155 psi
COV = 1.68 %

Table B-2: *Mode III_s and End Distance Tests with ½ inch Bolts*

½ inch Diameter Bolts - 7 3/8 inches in length

Test	Diameter (in)	5% D Offset load (lbs.)	F_{yb} (psi)
Bolt 1	0.493	1253	62749
Bolt 2	0.494	1259	62654
Bolt 3	0.493	1217	60923
Bolt 4	0.494	1293	64359
Bolt 5	0.495	1290	63794
Bolt 6	0.495	1266	62620
Bolt 7	0.494	1260	62716
Bolt 8	0.493	1226	61390
Bolt 9	0.493	1215	60864
Bolt 10	0.493	1235	61848
Bolt 11	0.493	1237	61925
Bolt 12	0.493	1264	63274

Average = 62426 psi
Std. Dev. = 1086 psi
COV = 1.74 %

Table B-3: *Mode IV Bolts*

½ inch diameter bolts – 11 inches in length

Test	Diameter (in)	5% D Offset load (lbs.)	F_{yb} (psi)
Bolt 13	0.502	1185	56184
Bolt 14	0.500	1224	58740
Bolt 15	0.500	1204	57800
Bolt 16	0.500	1234	59210
Bolt 17	0.500	1224	58740
Bolt 18	0.502	1185	56184
Bolt 19	0.502	1175	55719
Bolt 20	0.499	1264	61046
Bolt 21	0.504	1194	55976
Bolt 22	0.502	1224	58041
Bolt 23	0.501	1206	57543
Bolt 24	0.502	1224	58041

Average = 57769 psi
Std. Dev. = 1577 psi
COV = 2.73 %

DOWEL BEARING

Load vs. Displacement Curves

A dowel bearing test was performed on a specimen from each 2 x 6 OSL board. Boards were randomly assigned to either the one-half inch or three-quarter inch bolted connection tests. Once assigned, the dowel bearing specimen from a particular board was tested using the appropriate bolt size. Load-displacement curves were created for each of the dowel bearing tests. An example load-displacement curve is shown in Figure B-1.

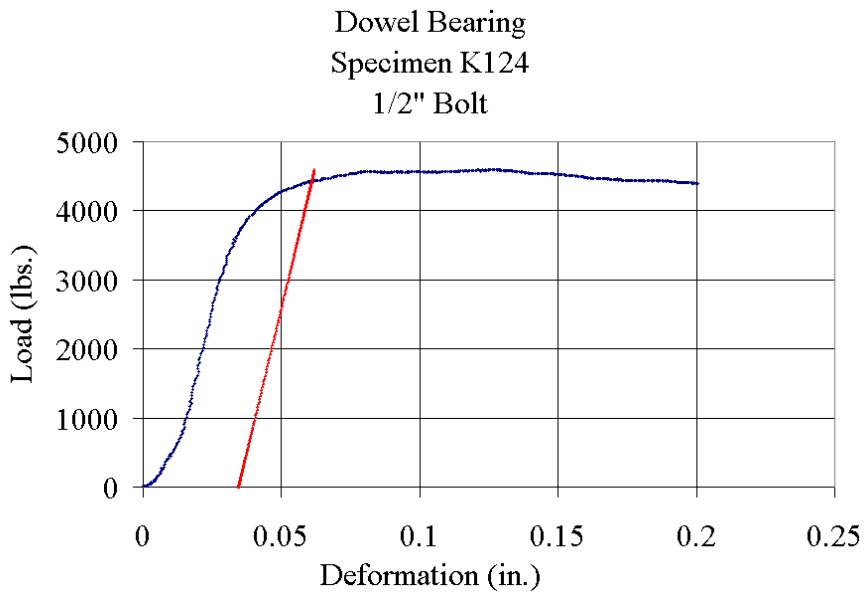


Figure B-1: *Dowel Bearing Load vs. Displacement Curve*

Dowel Bearing Strength

From the dowel bearing curves, the 5 percent diameter offset load was determined for each of the specimens. These values have been used with the bolt diameter and the specimen thickness to determine a dowel bearing strength. The results along with the specimen dimensions can be found on the following pages. The average thickness value in the tables is the average of two thickness measurements. Measurement were taken on either side of the half-hole and were labeled “A” and “B”.

1/2 inch Diameter Dowel Bearing Tests

Test	Diameter (in.)	Thickness A (in.)	Thickness B (in.)	Ave. Thickness (in.)	5% D Offset Load (lbs.)	F_e (psi)
K007	0.495	1.476	1.478	1.477	5277	7218
K013	0.495	1.472	1.464	1.468	5492	7558
K018	0.495	1.470	1.482	1.476	5326	7290
K026	0.495	1.480	1.480	1.480	5805	7924
K037	0.495	1.471	1.468	1.470	4033	5544
K046	0.495	1.461	1.464	1.463	4319	5966
K053	0.495	1.479	1.486	1.483	4063	5537
K056	0.495	1.470	1.469	1.470	4649	6391
K063	0.495	1.490	1.484	1.487	5347	7264
K065	0.495	1.480	1.496	1.488	3172	4307
K076	0.495	1.484	1.467	1.476	3720	5093
K097	0.495	1.494	1.491	1.493	5737	7765
K099	0.495	1.489	1.491	1.490	4482	6077
K103	0.495	1.491	1.469	1.480	3926	5359
K104	0.495	1.489	1.498	1.494	5032	6807
K105	0.495	1.488	1.490	1.489	4122	5593
K106	0.495	1.490	1.480	1.485	3871	5266
K107	0.495	1.481	1.495	1.488	2414	3277
K109	0.495	1.489	1.488	1.489	4396	5966
K110	0.495	1.492	1.494	1.493	5225	7070
K112	0.495	1.496	1.482	1.489	4289	5819
K113	0.495	1.465	1.490	1.478	3896	5327
K114	0.495	1.477	1.449	1.463	4073	5624
K115	0.495	1.490	1.491	1.491	5056	6853
K116	0.495	1.493	1.488	1.491	4033	5466
K117	0.495	1.488	1.486	1.487	4494	6105
K118	0.495	1.472	1.487	1.480	3861	5272
K119	0.495	1.454	1.476	1.465	4738	6534
K120	0.495	1.489	1.493	1.491	4422	5992
K121	0.495	1.487	1.483	1.485	4396	5980
K122	0.495	1.487	1.488	1.488	3117	4233
K124	0.495	1.489	1.483	1.486	4425	6016
K126	0.495	1.471	1.476	1.474	5110	7006
K128	0.495	1.479	1.484	1.482	4156	5667
K129	0.495	1.493	1.499	1.496	4268	5764
K130	0.495	1.484	1.490	1.487	4028	5472
K132	0.495	1.486	1.486	1.486	3603	4898
K133	0.495	1.491	1.483	1.487	4190	5692
K134	0.495	1.495	1.487	1.491	4719	6394
K135	0.495	1.476	1.492	1.484	3759	5117

Test	Diameter (in.)	Thickness A (in.)	Thickness B (in.)	Ave. Thickness (in.)	5% D Offset Load (lbs.)	F_e (psi)
K136	0.493	1.471	1.474	1.473	3730	5138
K137	0.495	1.485	1.488	1.487	3985	5416
K138	0.495	1.493	1.482	1.488	4390	5962
K139	0.495	1.493	1.488	1.491	3740	5069
K141	0.495	1.485	1.490	1.488	4733	6428
K142	0.495	1.476	1.487	1.482	3784	5160
K143	0.495	1.483	1.484	1.484	3838	5227
K144	0.495	1.482	1.477	1.480	3603	4920
K145	0.495	1.496	1.490	1.493	4514	6108
K146	0.495	1.481	1.497	1.489	4445	6031
K148	0.495	1.495	1.492	1.494	3514	4753
K149	0.495	1.486	1.488	1.487	3681	5001
K151	0.493	1.477	1.467	1.472	2907	4006
K152	0.493	1.475	1.478	1.477	4570	6278
K153	0.495	1.487	1.496	1.492	3857	5224
K155	0.495	1.483	1.482	1.483	3971	5411
K156	0.495	1.479	1.490	1.485	4503	6128
K157	0.495	1.490	1.470	1.480	5757	7858
K160	0.495	1.490	1.485	1.488	4278	5810
K161	0.495	1.497	1.495	1.496	3652	4932
K163	0.495	1.487	1.487	1.487	3994	5426
K164	0.495	1.485	1.497	1.491	3368	4563
K165	0.493	1.479	1.476	1.478	4325	5938
K168	0.493	1.490	1.492	1.491	5266	7164
K169	0.495	1.466	1.473	1.470	4210	5788
K170	0.495	1.458	1.465	1.462	6529	9025
K171	0.495	1.448	1.460	1.454	4278	5944
K174	0.495	1.470	1.464	1.467	4454	6134
K175	0.495	1.462	1.471	1.467	7959	10964
K178	0.495	1.472	1.474	1.473	5443	7465
K179	0.493	1.471	1.473	1.472	7807	10758
K181	0.495	1.472	1.472	1.472	5453	7484
K182	0.495	1.465	1.471	1.468	4868	6699
K183	0.495	1.453	1.466	1.460	5619	7778
K185	0.495	1.464	1.471	1.468	6201	8536
K187	0.495	1.464	1.469	1.467	4112	5665
K192	0.495	1.467	1.468	1.468	4503	6199
K193	0.495	1.467	1.468	1.468	5975	8225
K196	0.495	1.479	1.476	1.478	5865	8019
K197	0.495	1.469	1.473	1.471	3867	5311
K198	0.495	1.470	1.472	1.471	4376	6010

Test	Diameter (in.)	Thickness A (in.)	Thickness B (in.)	Ave. Thickness (in.)	5% D Offset Load (lbs.)	F_e (psi)
K207	0.495	1.475	1.473	1.474	5052	6924
K214	0.495	1.474	1.467	1.471	5360	7364
K215	0.495	1.472	1.465	1.469	6748	9283
K217	0.495	1.477	1.476	1.477	5345	7313
K219	0.495	1.471	1.477	1.474	6031	8266
K223	0.495	1.478	1.474	1.476	6236	8535
				Max =	7959	10964
				Min =	2414	3277
				Average =	4595	6278
				Std Dev =	981	1360
				COV =	21.3%	21.7%

3/4 inch Diameter Dowel Bearing Tests

Test	Diameter (in.)	Thickness A (in.)	Thickness B (in.)	Ave. Thickness (in.)	5% D Offset Load (lbs.)	F_e (psi)
K005	0.748	1.472	1.481	1.477	10201	9237
K010	0.748	1.474	1.472	1.473	8733	7926
K025	0.748	1.463	1.474	1.469	9467	8619
K047	0.748	1.456	1.466	1.461	10117	9258
K055	0.748	1.475	1.474	1.475	9449	8567
K060	0.748	1.469	1.485	1.477	6256	5663
K071	0.748	1.491	1.486	1.489	6623	5948
K073	0.748	1.488	1.479	1.484	5385	4853
K077	0.748	1.494	1.484	1.489	8091	7265
K087	0.748	1.497	1.487	1.492	7548	6763
K088	0.748	1.480	1.501	1.491	8684	7789
K096	0.748	1.488	1.499	1.494	8948	8010
K100	0.748	1.486	1.478	1.482	8576	7736
K102	0.748	1.494	1.490	1.492	7098	6360
K108	0.748	1.486	1.489	1.488	6941	6238
K123	0.748	1.481	1.491	1.486	6520	5866
K125	0.748	1.477	1.493	1.485	6275	5649
K140	0.748	1.488	1.487	1.488	8860	7963
K150	0.748	1.484	1.486	1.485	7489	6742
K154	0.748	1.486	1.493	1.490	6765	6072
K158	0.748	1.488	1.484	1.486	8331	7495
K159	0.748	1.501	1.480	1.491	6628	5945
K166	0.748	1.487	1.490	1.489	7789	6996
K172	0.748	1.470	1.470	1.470	9829	8939
K177	0.748	1.481	1.471	1.476	9800	8876

Test	Diameter (in.)	Thickness A (in.)	Thickness B (in.)	Ave. Thickness (in.)	5% D Offset Load (lbs.)	F_e (psi)
K180	0.748	1.464	1.476	1.470	11680	10622
K184	0.748	1.471	1.457	1.464	9281	8475
K194	0.748	1.474	1.473	1.474	8503	7715
K199	0.748	1.469	1.476	1.473	8106	7360
K200	0.748	1.477	1.460	1.469	7225	6578
K202	0.748	1.471	1.467	1.469	8390	7636
K204	0.748	1.468	1.467	1.468	9261	8437
K205	0.748	1.475	1.474	1.475	9575	8681
K208	0.748	1.465	1.466	1.466	9501	8667
K209	0.748	1.472	1.471	1.472	8312	7552
K210	0.748	1.471	1.472	1.472	7411	6733
K211	0.748	1.472	1.467	1.470	6794	6181
K220	0.748	1.476	1.465	1.471	6804	6186
K221	0.748	1.469	1.473	1.471	9036	8212
K222	0.748	1.482	1.468	1.475	13226	11988
				Max =	13226	11988
				Min =	5385	4853
				Average =	8338	7545
				Std Dev =	1567	1439
				COV =	18.8%	19.1%

DOUBLE SHEAR BOLTED CONNECTIONS

Three different connection configurations were created to produce the behavior of yield Modes I_m, III_s and IV. Mode I_m connection tests were designed with a ¾ inch bolt and 1.5 inch OSL members. Mode III_s tests were also designed with 1.5inch members, but used a ½ inch bolt to produce the desired behavior. Mode IV connection tests were designed with 3 inch members and a ½ inch bolt. Equations based on the EYM were used to calculate predicted yield values for each of the tests. Connections were then tested and compared with the predicted values.

Predicted Yield Values

Predicted values for each of the tests were calculated using the average bolt bending strength for that lot of bolts and the dowel bearing strength of the OSL board for each member. The results from these calculations are shown on the following pages

Mode I_m Bolted Connection Calculations

Test #	End Distance	D_{ave} (in)	$t_{m\ ave}$ (in)	$t_{s\ ave}$ (in)	F_{yb} (psi)	F_{em} (psi)	F_{es} (psi)	k_3	R_e	Predicted Yield Load (lbs)
1	7D	0.740	1.483	1.469	68826	4853	5663	2.345	0.857	5328
2	7D	0.746	1.482	1.481	68826	4853	5945	2.348	0.816	5368
3	7D	0.752	1.475	1.475	68826	4853	6072	2.374	0.799	5381
4	7D	0.743	1.485	1.465	68826	7963	8939	1.920	0.891	8782
5	7D	0.740	1.482	1.471	68826	5649	6186	2.190	0.913	6190
6	7D	0.744	1.470	1.477	68826	6181	6742	2.111	0.917	6761
7	7D	0.740	1.488	1.476	68826	6360	7736	2.091	0.822	7003
8	7D	0.742	1.456	1.467	68826	6578	8212	2.082	0.801	7107
9	7D	0.740	1.460	1.465	68826	6733	8437	2.062	0.798	7275
10	7D	0.746	1.483	1.466	68826	6996	8681	2.040	0.806	7736
11	7D	0.745	1.468	1.467	68826	7360	10622	2.036	0.693	8049
12	7D	0.743	1.468	1.470	68826	7552	11988	2.043	0.630	8240
13	5D	0.749	1.475	1.486	68826	5663	6238	2.192	0.908	6256
14	5D	0.747	1.488	1.494	68826	5945	6763	2.135	0.879	6603
15	5D	0.747	1.472	1.483	68826	6072	7265	2.135	0.836	6674
16	5D	0.748	1.487	1.472	68826	8010	9258	1.924	0.865	8905
17	5D	0.749	1.477	1.460	68826	5649	6186	2.229	0.913	6250
18	5D	0.744	1.467	1.487	68826	6181	6238	2.095	0.991	6744
19	5D	0.744	1.488	1.480	68826	6360	7736	2.095	0.822	7039
20	5D	0.746	1.469	1.461	68826	6578	8212	2.096	0.801	7202
21	5D	0.746	1.465	1.457	68826	6733	8437	2.082	0.798	7353
22	5D	0.751	1.486	1.468	68826	6996	8681	2.049	0.806	7801
23	5D	0.745	1.466	1.473	68826	7360	10622	2.031	0.693	8039
24	5D	0.744	1.466	1.468	68826	7552	11988	2.047	0.630	8240
25	3D	0.747	1.475	1.462	68826	6742	7715	2.066	0.874	7429
26	3D	0.747	1.488	1.481	68826	6763	7789	2.041	0.868	7514
27	3D	0.753	1.481	1.471	68826	7265	7926	2.003	0.917	8102
28	3D	0.747	1.470	1.467	68826	8619	9237	1.862	0.933	9461
29	3D	0.748	1.481	1.480	68826	5649	5866	2.198	0.963	6256
30	3D	0.749	1.464	1.482	68826	6181	5948	2.112	1.039	6775
31	3D	0.750	1.487	1.478	68826	6360	7495	2.106	0.849	7093
32	3D	0.748	1.468	1.468	68826	6578	7636	2.083	0.861	7220
33	3D	0.748	1.473	1.456	68826	6733	8475	2.090	0.794	7416
34	3D	0.746	1.488	1.464	68826	6996	8567	2.041	0.817	7766
35	3D	0.748	1.461	1.466	68826	7360	8667	1.996	0.849	8036
36	3D	0.750	1.466	1.461	68826	7552	8876	1.986	0.851	8300

Test #	End Distance	D_{ave} (in)	$t_{m\ ave}$ (in)	$t_{s\ ave}$ (in)	F_{yb} (psi)	F_{em} (psi)	F_{es} (psi)	k_3	R_e	Predicted Yield Load (lbs)
37	4D	0.745	1.471	1.483	68826	7715	7963	1.920	0.969	8455
38	4D	0.745	1.480	1.489	68826	7789	8010	1.906	0.972	8585
39	4D	0.749	1.469	1.468	68826	7926	8619	1.929	0.920	8722
40	4D	0.748	1.463	1.470	68826	8939	9237	1.830	0.968	9782
41	4D	0.744	1.481	1.482	68826	5649	5866	2.184	0.963	6222
42	4D	0.747	1.448	1.483	68826	6181	5948	2.105	1.039	6683
43	4D	0.746	1.480	1.484	68826	6360	7495	2.091	0.849	7023
44	4D	0.749	1.473	1.466	68826	6578	7636	2.086	0.861	7254
45	4D	0.747	1.468	1.465	68826	6733	8475	2.076	0.794	7380
46	4D	0.746	1.484	1.475	68826	6996	8567	2.030	0.817	7746
47	4D	0.753	1.457	1.471	68826	7360	8667	2.001	0.849	8072
48	4D	0.746	1.452	1.465	68826	7552	8876	1.973	0.851	8176

Mode III_s Bolted Connection Calculations

Test #	End Distance	D_{ave} (in)	$t_{m\ ave}$ (in)	$t_{s\ ave}$ (in)	F_{yb} (psi)	F_{em} (psi)	F_{es} (psi)	k_3	R_e	Predicted Yield Load (lbs)
1	7D	0.493	1.482	1.484	62426	7006	4898	1.377	1.430	4118
2	7D	0.494	1.475	1.480	62426	7070	5001	1.377	1.414	4167
3	7D	0.493	1.470	1.482	62426	7313	5327	1.363	1.373	4316
4	7D	0.493	1.452	1.479	62426	7364	5466	1.364	1.347	4380
5	7D	0.493	1.462	1.478	62426	7484	5593	1.358	1.338	4442
6	7D	0.494	1.461	1.489	62426	7778	5692	1.333	1.366	4528
7	7D	0.493	1.475	1.488	62426	7858	5819	1.330	1.350	4577
8	7D	0.493	1.459	1.481	62426	8225	5980	1.312	1.375	4664
9	7D	0.494	1.465	1.475	62426	8536	6031	1.297	1.415	4723
10	7D	0.493	1.475	1.479	62426	8535	6128	1.297	1.393	4756
11	7D	0.494	1.457	1.481	62426	9025	6428	1.274	1.404	4937
12	7D	0.494	1.457	1.487	62426	9283	6807	1.265	1.364	5123
13	5D	0.494	1.483	1.485	62426	7006	4898	1.377	1.430	4124
14	5D	0.493	1.485	1.479	62426	7070	5001	1.377	1.414	4162
15	5D	0.494	1.471	1.479	62426	7313	5327	1.365	1.373	4323
16	5D	0.493	1.461	1.478	62426	7364	5466	1.365	1.347	4379
17	5D	0.493	1.466	1.483	62426	7484	5593	1.355	1.338	4447
18	5D	0.493	1.458	1.486	62426	7778	5692	1.335	1.366	4520
19	5D	0.493	1.475	1.489	62426	7858	5819	1.330	1.350	4578
20	5D	0.494	1.455	1.477	62426	8225	5980	1.316	1.375	4680
21	5D	0.493	1.463	1.481	62426	8536	6031	1.293	1.415	4719
22	5D	0.493	1.475	1.485	62426	8535	6128	1.293	1.393	4764
23	5D	0.494	1.458	1.480	62426	9025	6428	1.274	1.404	4935
24	5D	0.493	1.464	1.488	62426	9283	6807	1.263	1.364	5114
25	3D	0.494	1.478	1.479	62426	7006	4932	1.381	1.421	4132
26	3D	0.493	1.486	1.469	62426	7070	5272	1.389	1.341	4257
27	3D	0.493	1.480	1.469	62426	7313	5359	1.372	1.365	4321
28	3D	0.494	1.469	1.456	62426	7364	5665	1.384	1.300	4439
29	3D	0.493	1.471	1.485	62426	7484	5667	1.356	1.321	4474
30	3D	0.493	1.462	1.483	62426	7778	5764	1.337	1.349	4540
31	3D	0.494	1.477	1.480	62426	7858	5966	1.339	1.317	4637
32	3D	0.494	1.469	1.481	62426	8225	5992	1.314	1.373	4684
33	3D	0.493	1.466	1.460	62426	8536	6134	1.308	1.392	4741
34	3D	0.492	1.476	1.457	62426	8535	6199	1.309	1.377	4743
35	3D	0.494	1.456	1.464	62426	9025	6699	1.289	1.347	5023
36	3D	0.494	1.468	1.482	62426	9283	6853	1.269	1.355	5135

Test #	End Distance	D_{ave} (in)	$t_{m\ ave}$ (in)	$t_{s\ ave}$ (in)	F_{yb} (psi)	F_{em} (psi)	F_{es} (psi)	k_3	R_e	Predicted Yield Load (lbs)
37	2D	0.494	1.477	1.481	62426	7006	4932	1.380	1.421	4134
38	2D	0.493	1.467	1.472	62426	7070	5272	1.388	1.341	4264
39	2D	0.493	1.474	1.473	62426	7313	5359	1.369	1.365	4320
40	2D	0.492	1.467	1.463	62426	7364	5665	1.377	1.300	4426
41	2D	0.492	1.466	1.478	62426	7484	5667	1.359	1.321	4456
42	2D	0.492	1.461	1.477	62426	7778	5764	1.339	1.349	4524
43	2D	0.492	1.464	1.478	62426	7858	5966	1.338	1.317	4609
44	2D	0.492	1.471	1.484	62426	8225	5992	1.310	1.373	4667
45	2D	0.492	1.469	1.452	62426	8536	6134	1.311	1.392	4715
46	2D	0.491	1.456	1.465	62426	8535	6199	1.303	1.377	4742
47	2D	0.492	1.460	1.464	62426	9025	6699	1.286	1.347	4991
48	2D	0.492	1.466	1.479	62426	9283	6853	1.267	1.355	5103

Mode IV Bolted Connection Calculations

Test #	End Distance	D_{ave} (in)	$t_{m\ ave}$ (in)	$t_{s\ ave}$ (in)	F_{yb} (psi)	F_{em} (psi)	F_{es} (psi)	k_3	R_e	Predicted Yield Load (lbs)
1	7D	0.501	2.977	2.963	57769	4307	5411	1.286	0.796	4818
2	7D	0.501	2.972	2.970	57769	4307	5416	1.286	0.795	4832
3	7D	0.501	2.960	2.968	57769	4920	5426	1.203	0.907	4998
4	7D	0.503	2.969	2.946	57769	4920	5624	1.223	0.875	5080
5	7D	0.503	2.964	2.928	57769	5069	5944	1.233	0.853	5201
6	7D	0.503	2.971	2.973	57769	5069	5810	1.218	0.872	5174
7	7D	0.500	2.955	2.966	57769	5117	5962	1.223	0.858	5149
8	7D	0.503	2.962	2.965	57769	5117	6016	1.229	0.851	5215
9	7D	0.500	2.962	2.971	57769	5160	6105	1.229	0.845	5196
10	7D	0.501	2.964	2.976	57769	5160	6394	1.252	0.807	5264
11	7D	0.503	2.978	2.928	57769	5224	7465	1.334	0.700	5513
12	7D	0.501	2.970	2.955	57769	5224	7924	1.366	0.659	5535
13	7D	0.499	2.971	2.955	57769	7164	4006	0.924	1.788	4960
14	7D	0.498	2.921	2.962	57769	10758	5938	0.868	1.812	6021

Load vs. Displacement Curves

A total of 110 double shear bolted connection tests were conducted. Mode I_m and Mode III_s tests were conducted on 48 connection specimens each. Twelve tests were performed for each of four sets of connection specimens with each of the two different mode configurations. The four sets of connection specimens each had a different end distance. In Mode I_m configuration, end distances of 7D, 5D, 4D and 3D were used. For the Mode III_s configuration, end distances of 7D, 5D, 3D and 2D were used. The remaining 14 tests were conducted on Mode IV specimens with a consistent end distance of 7D.

Displacement was measured using linear variable differential transformers (LVDTs). External LVDTs were used to measure the displacement of the connection and an internal LVDT was used to measure the movement of the actuator with respect to the crosshead of the testing apparatus. The preferred method was to use the external LVDTs so that the relative displacement between structural elements of the actual connection was being measured. In Mode I_m and Mode IV configuration tests, there were instances where the external LVDTs became unreliable. In a few of the tests, one or both of the external LVDTs ran out of stroke or became loose due to excessive vibration of the test specimens. Problems with the external LVDTs nearly always occurred after the yield load of the connection was reached. In these cases, the internal LVDT was used from the point just before the external LVDT measurements became unreliable, through the end of the tests. Where the internal LVDT measurements were used in a curve, that region of the curve is shaded lighter than the region of the curve where the external LVDTs are used (for example, see Mode I, test 1 graph). Since displacement was not a factor in determining the ultimate load, using the internal LVDT to determine displacement after the yield point did not present a problem. In the single case that the external LVDTs were not

connected properly to the connection and the internal LVDT had to be used to determine the displacement (see Mode I, test 41), the yield value was not significantly affected (see discussion for Mode IIIs configured tests below)

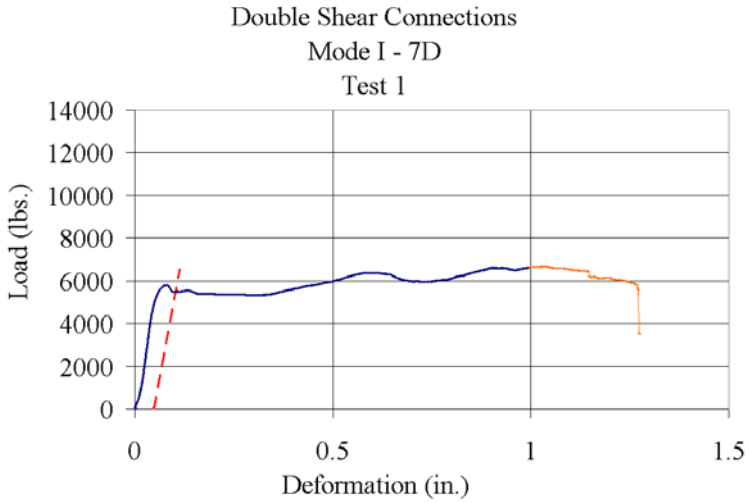
In the case of the Mode III_s configuration, all the displacements were measured using the internal LVDT and therefore the graphs are not shown in a lighter color. There were several tests that had unreliable external LVDT readings prior to reaching yield loads. Preferring to be able to use the same method to determine yield load for all the Mode III_s configured connection tests, 6 connections tests were plotted using two different methods and then analyzed. The first method used the average of the two external LVDTs to determine the displacement of the connection. The second method used the internal LVDT to determine displacement of the connection. The 5 percent diameter offset yield load for each of these methods is shown in Table B-4. From the percent difference values, it is clear that using the internal LVDT is comparable to using the average of the two external LVDTs when determining yield load. A paired t-test was also conducted on the yield load data in Table B-4 from the two different methods and found to be statistically the same with a p-value of 0.975.

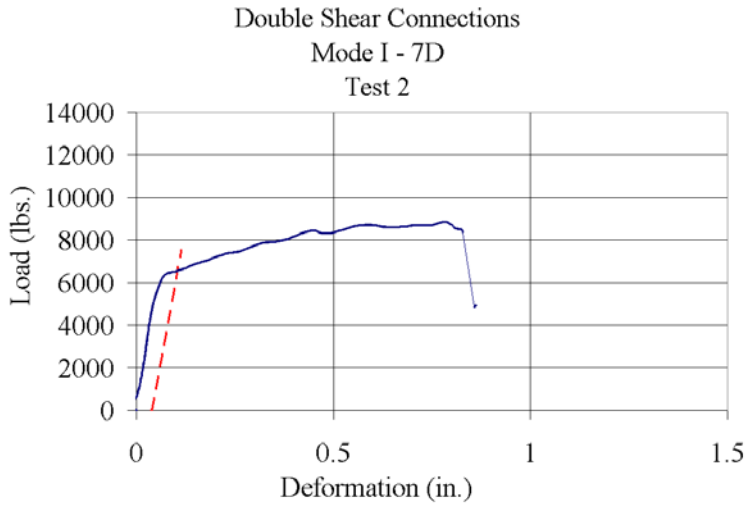
Table B-4: *Comparing External and Internal LVDT Results*

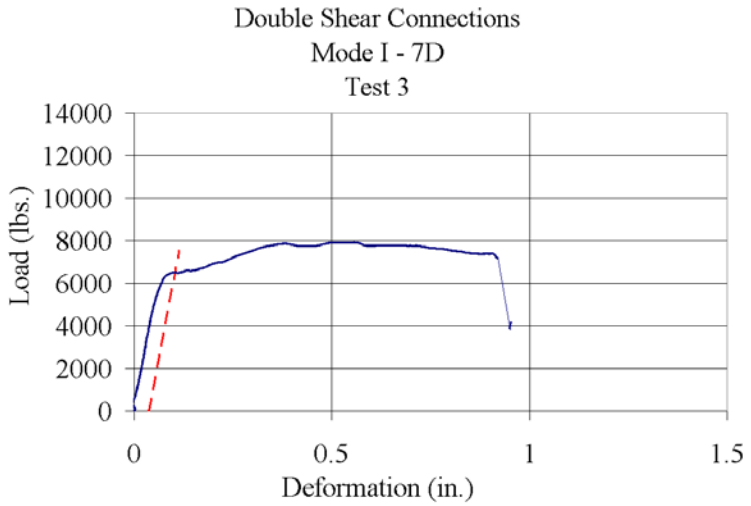
Test Number	Yield Load (lbs) Average of External LVDTs	Internal LVDT	Percent Difference (%)
7	4025	4082	1.42%
8	3926	3784	-3.62%
9	3853	3945	2.39%
10	3560	3420	-3.93%
11	3309	3353	1.33%
12	3857	3955	2.54%

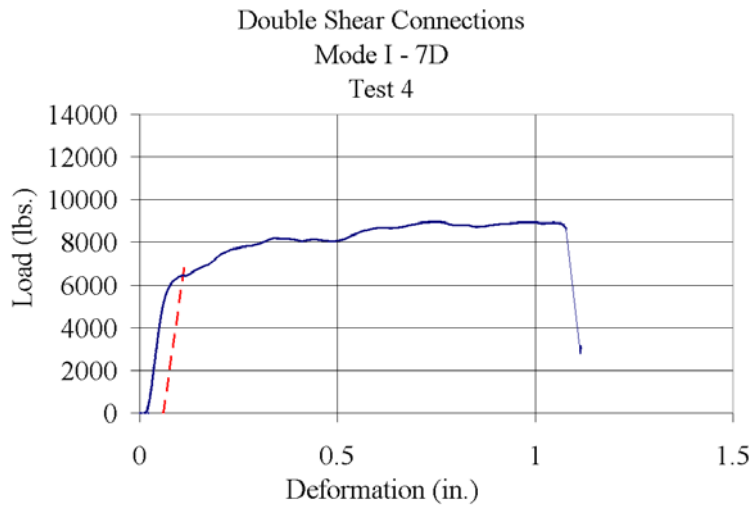
Load-displacement curves are shown on the following pages with the Mode I_m configured tests first, followed by the Mode III_s configured tests and finishing with Mode IV tests. Within each mode, tests are shown from largest end distance to smallest end distance.

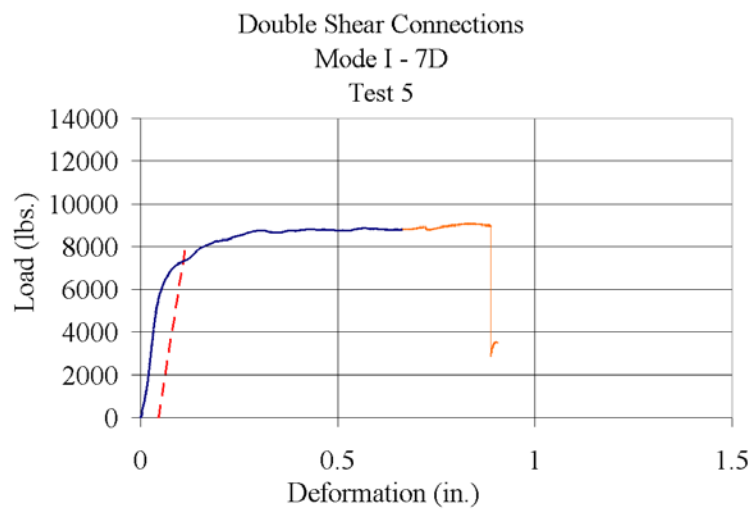
Mode I_m Bolted Connection Tests



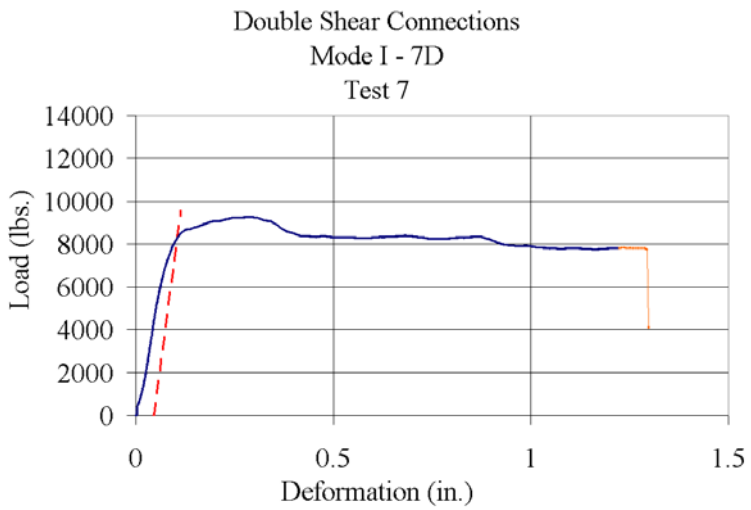


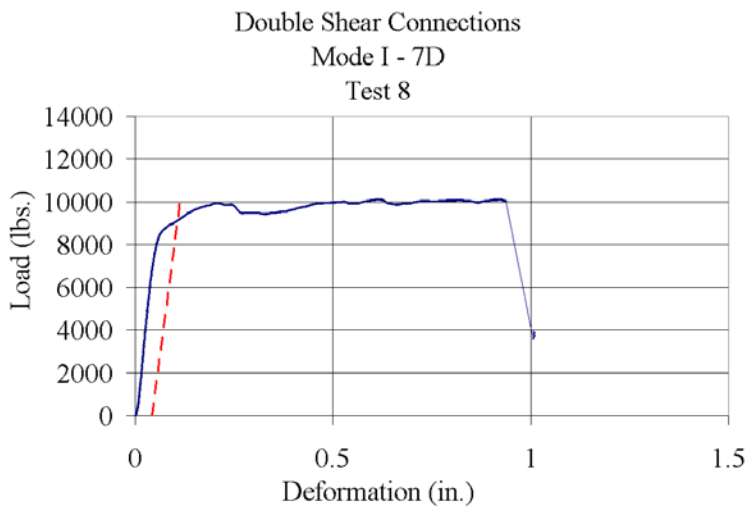


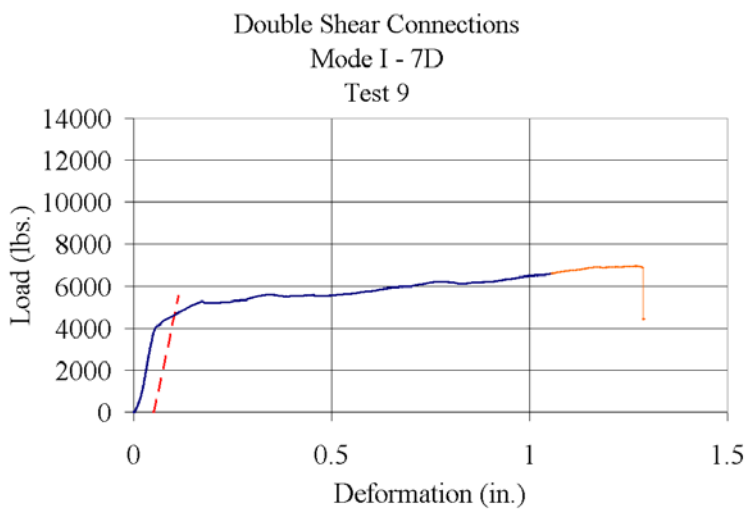

Double Shear Connections
Mode I - 7D
Test 4
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

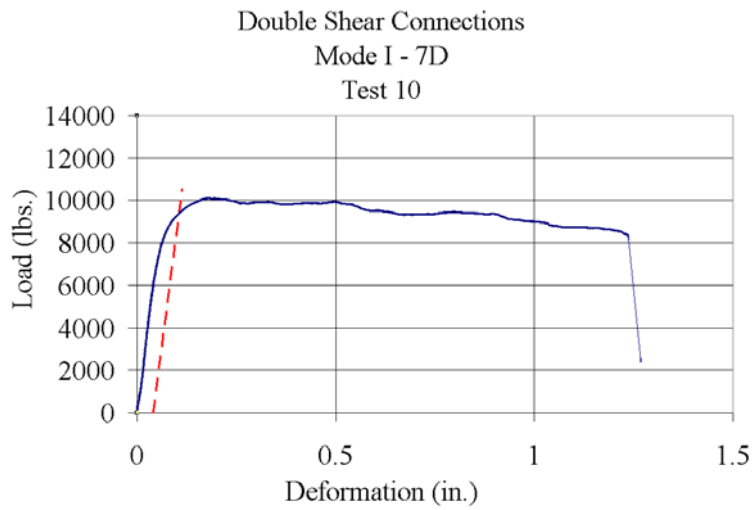

Double Shear Connections
Mode I - 7D
Test 5
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

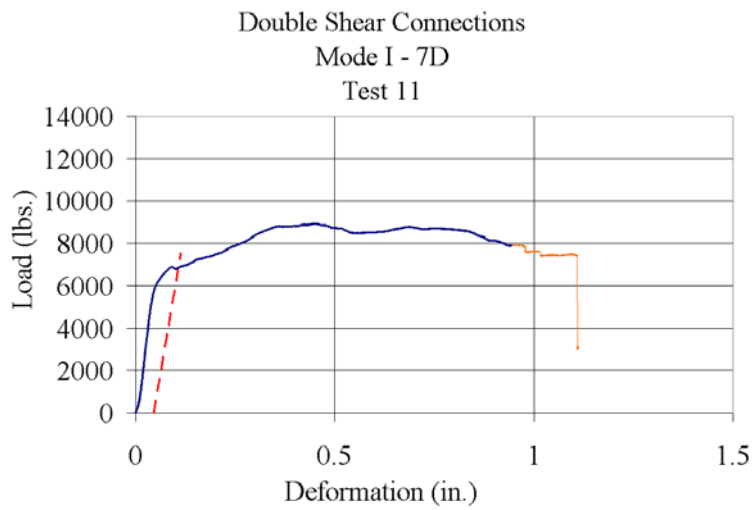

Double Shear Connections
Mode I - 7D
Test 6
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

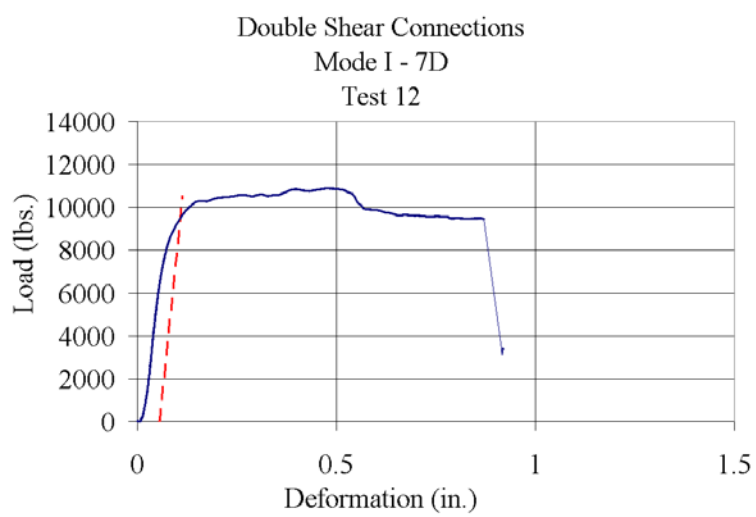

Double Shear Connections
Mode I - 7D
Test 7
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

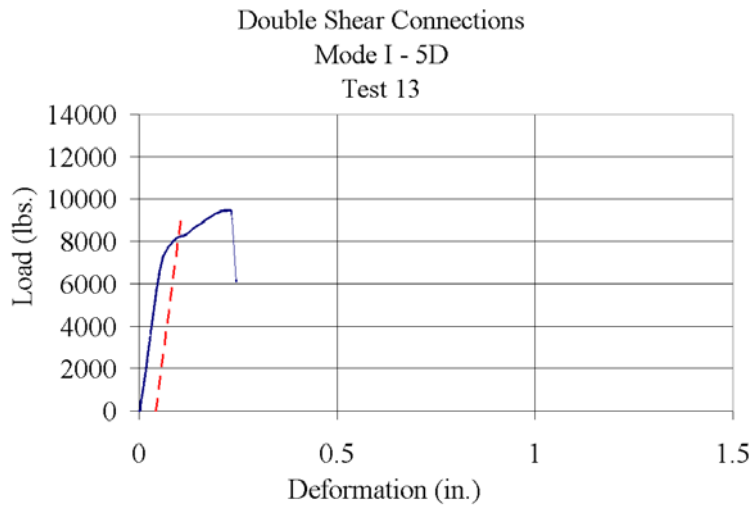

Double Shear Connections
Mode I - 7D
Test 8
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

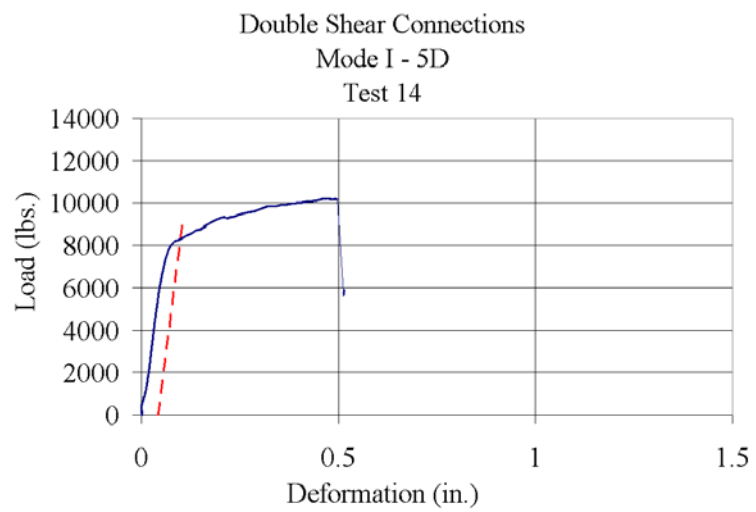

Double Shear Connections
Mode I - 7D
Test 9
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

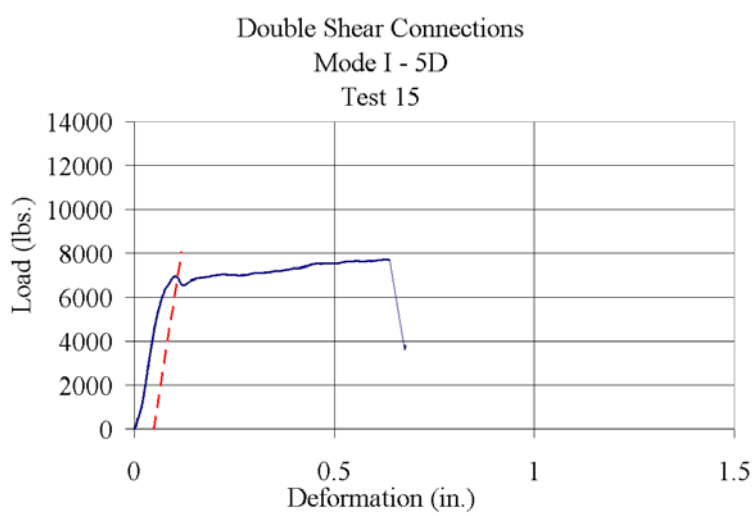

Double Shear Connections
Mode I - 7D
Test 10
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

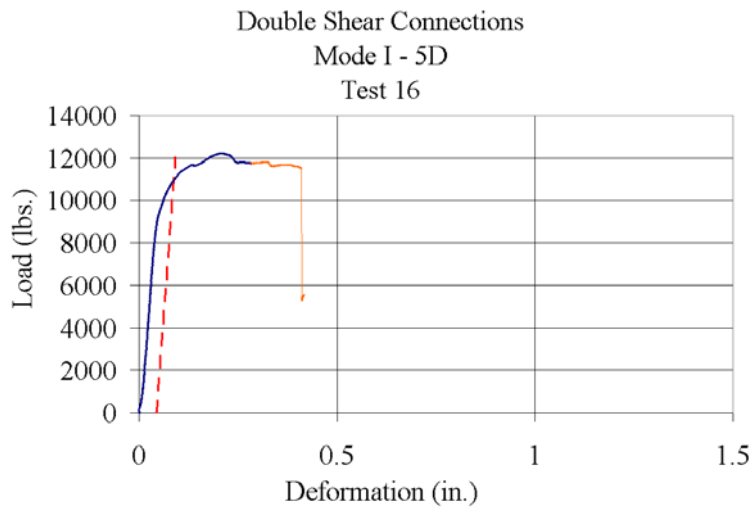

Double Shear Connections
Mode I - 7D
Test 11
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

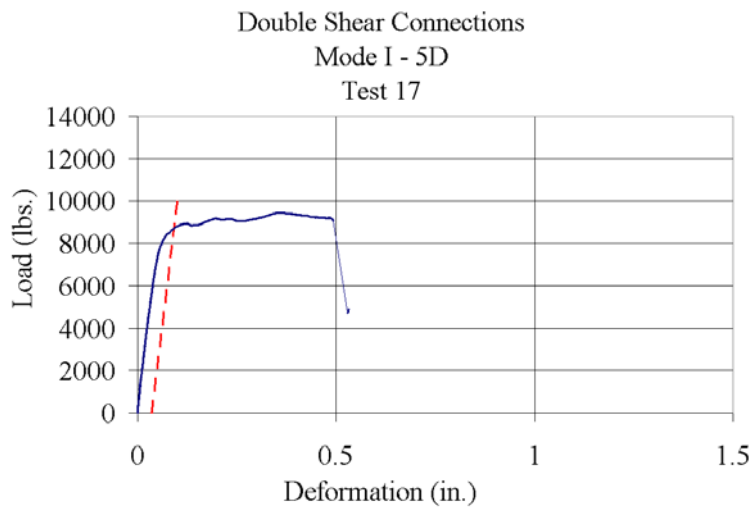

Double Shear Connections
Mode I - 7D
Test 12
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

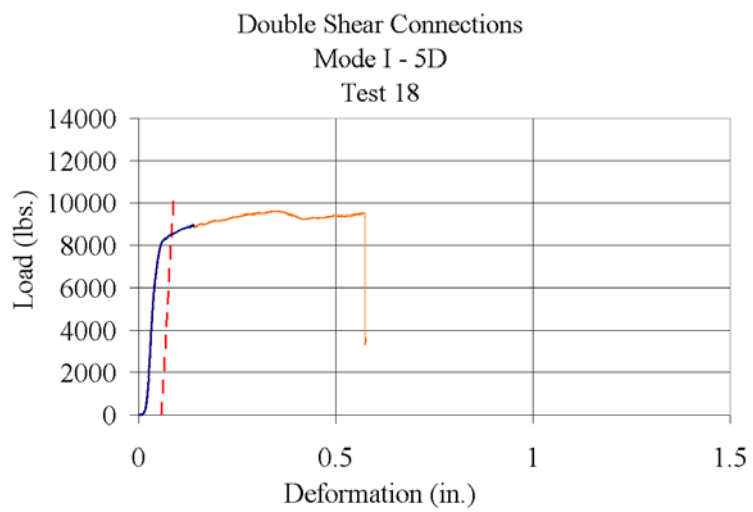

Double Shear Connections
Mode I - 5D
Test 13
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

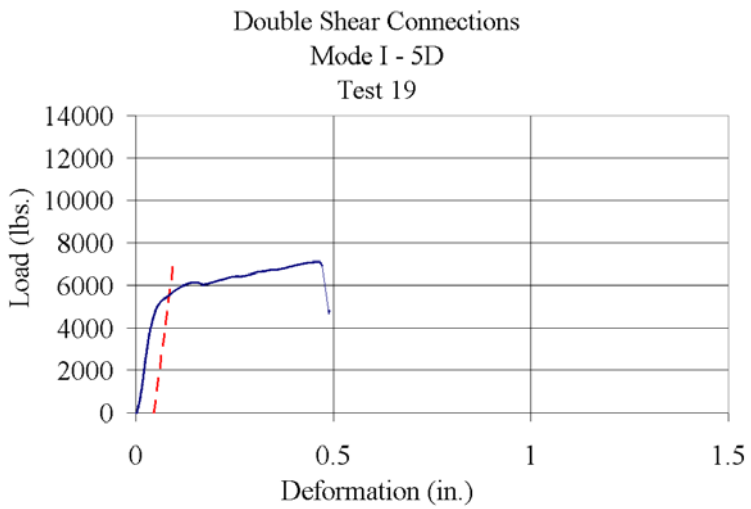

Double Shear Connections
Mode I - 5D
Test 14
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

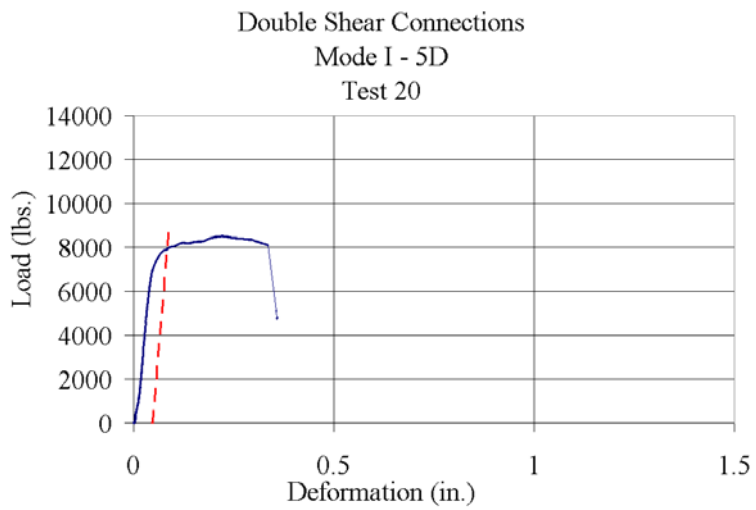

Double Shear Connections
Mode I - 5D
Test 15
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

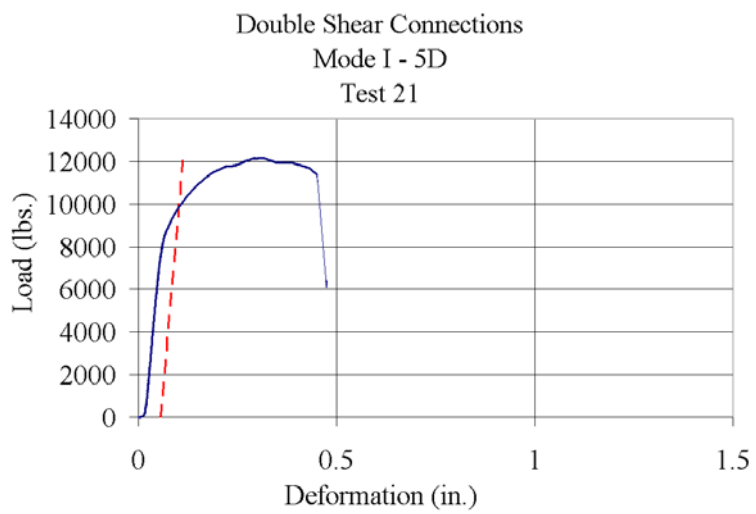

Double Shear Connections
Mode I - 5D
Test 16
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

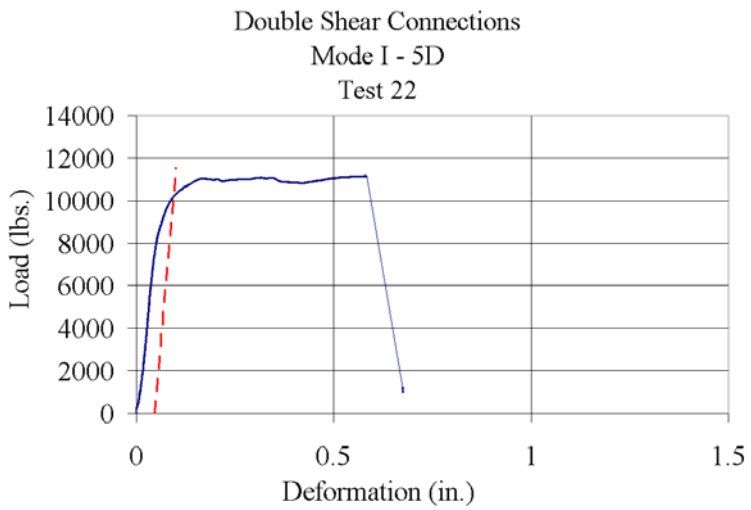

Double Shear Connections
Mode I - 5D
Test 17
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

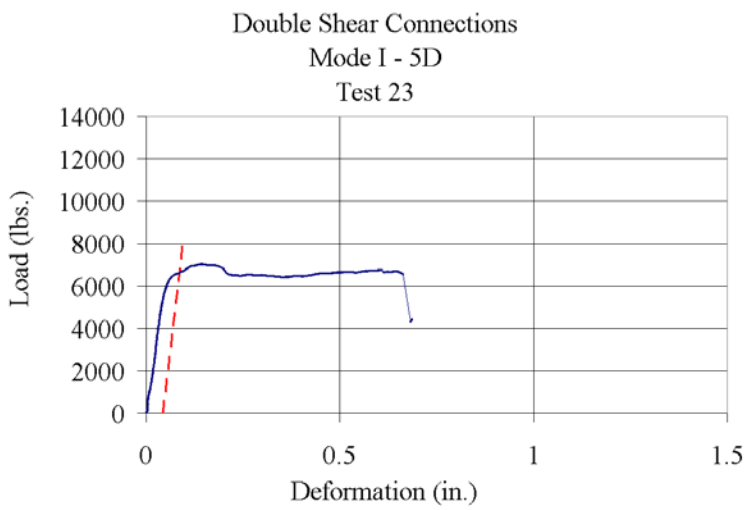

Double Shear Connections
Mode I - 5D
Test 18
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

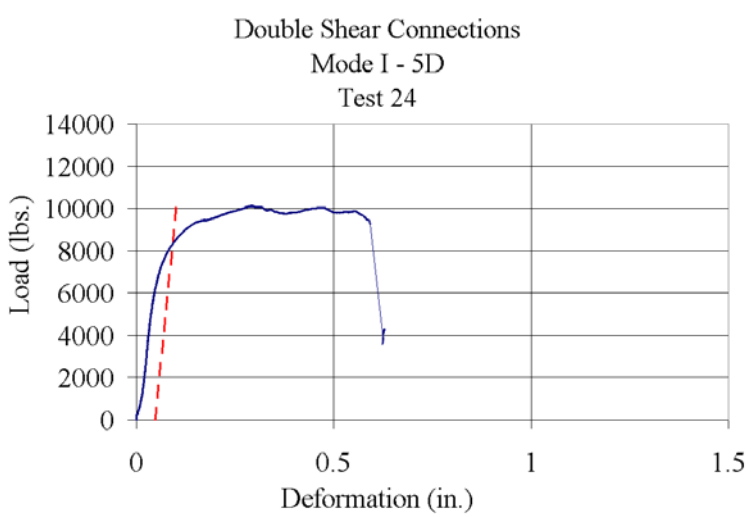

Double Shear Connections
Mode I - 5D
Test 19
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

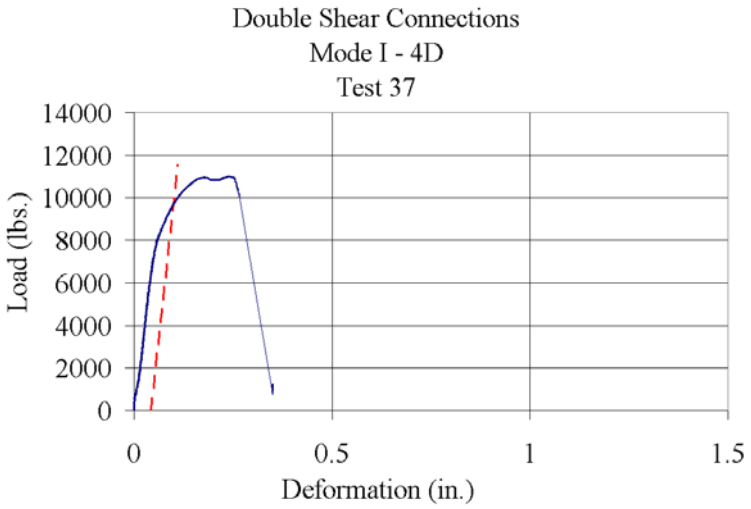

Double Shear Connections
Mode I - 5D
Test 20
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

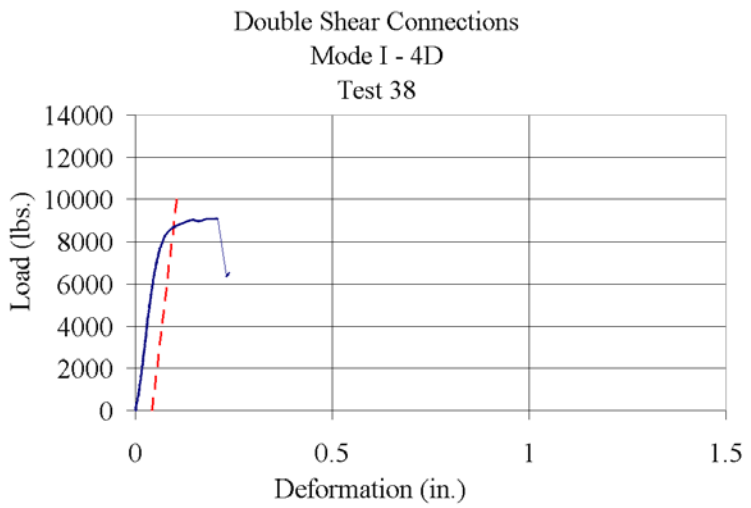

Double Shear Connections
Mode I - 5D
Test 21
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

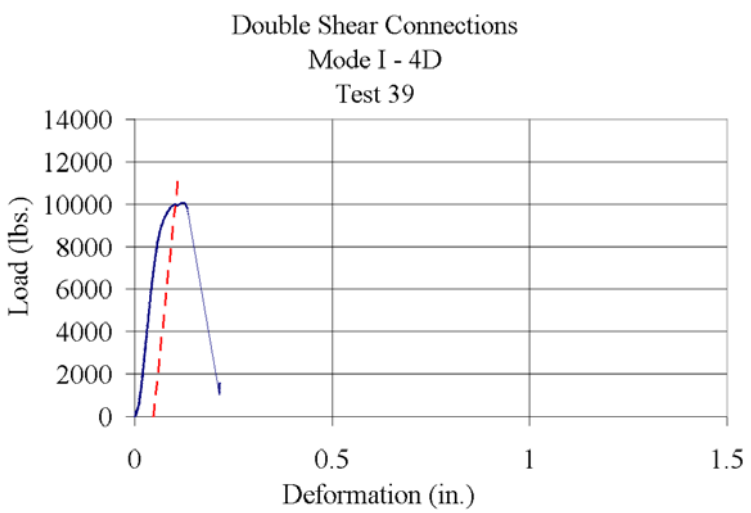

Double Shear Connections
Mode I - 5D
Test 22
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

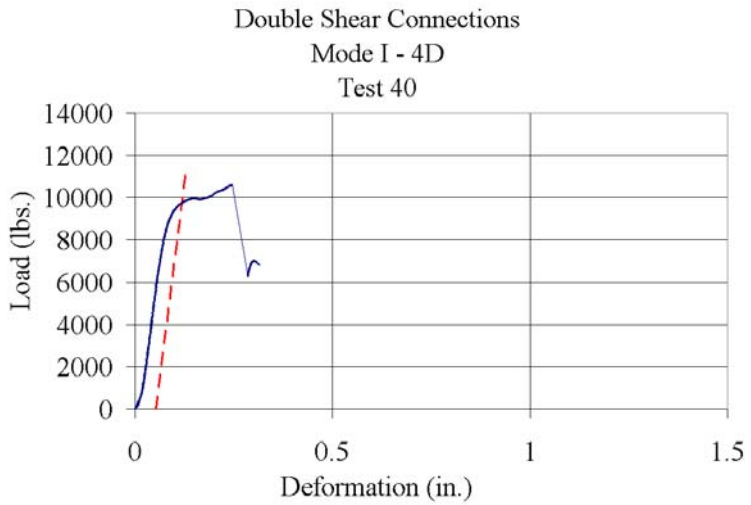

Double Shear Connections
Mode I - 5D
Test 23
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

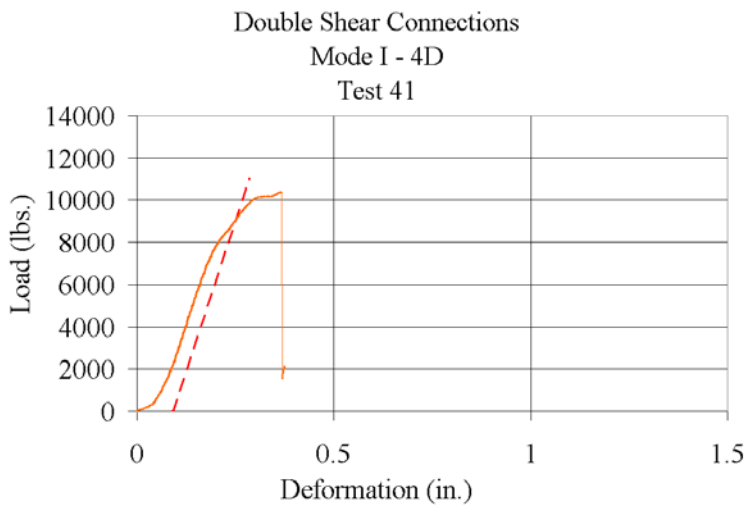

Double Shear Connections
Mode I - 5D
Test 24
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

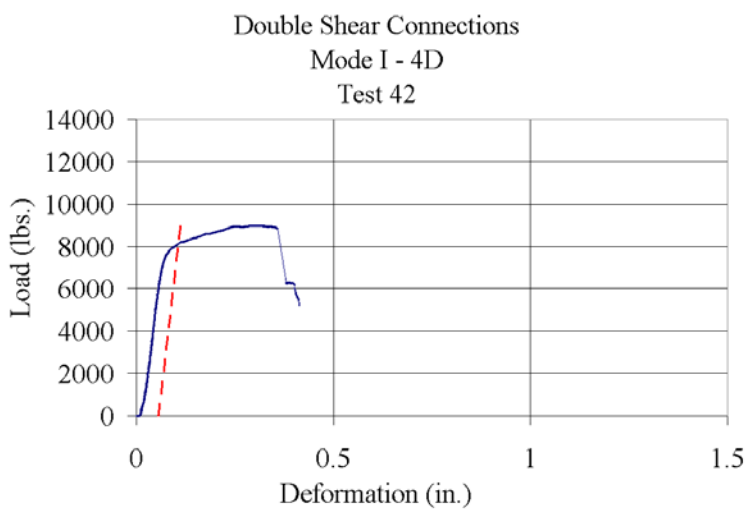

Double Shear Connections
Mode I - 4D
Test 37
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

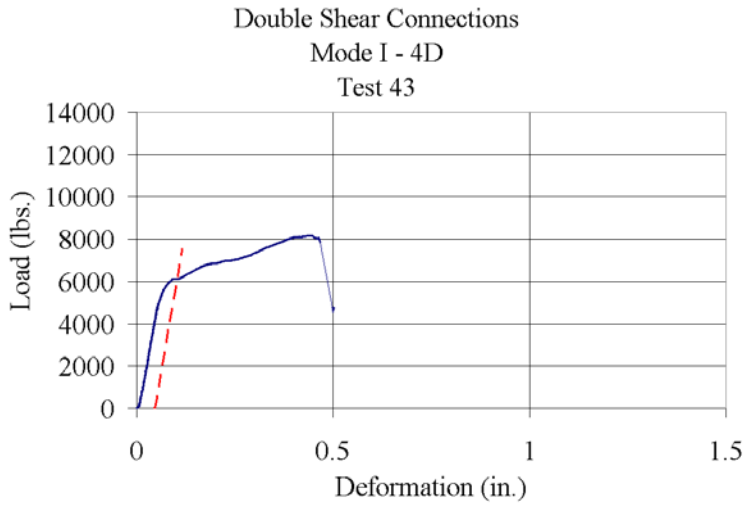

Double Shear Connections
Mode I - 4D
Test 38
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

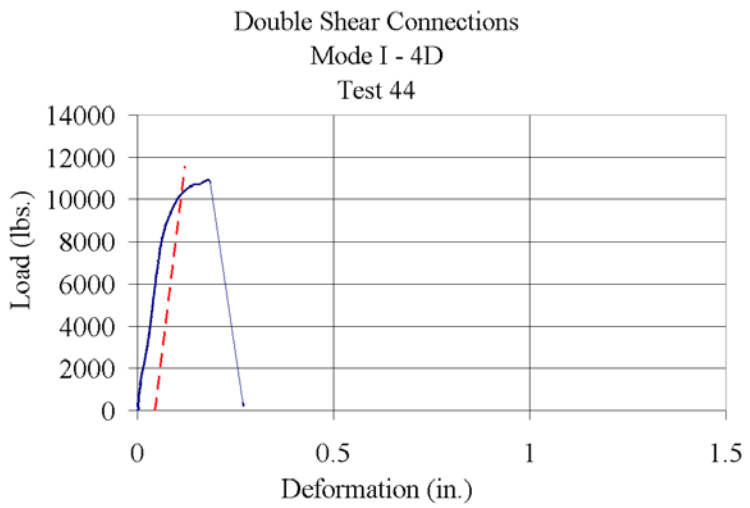

Double Shear Connections
Mode I - 4D
Test 39
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

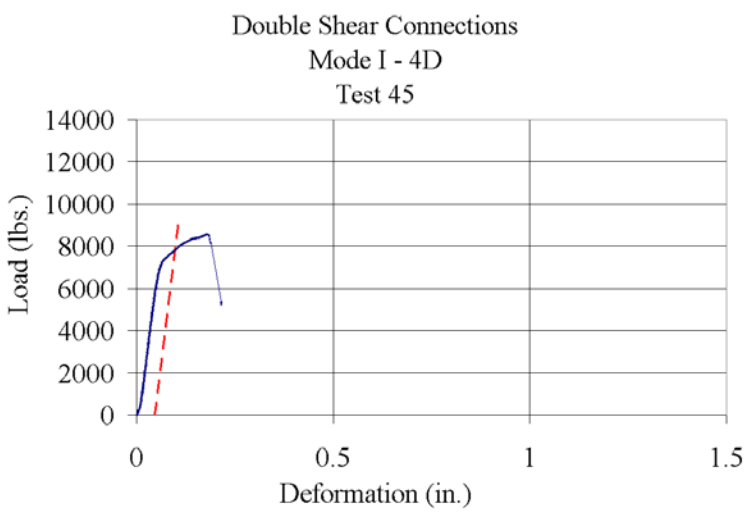

Double Shear Connections
Mode I - 4D
Test 40
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

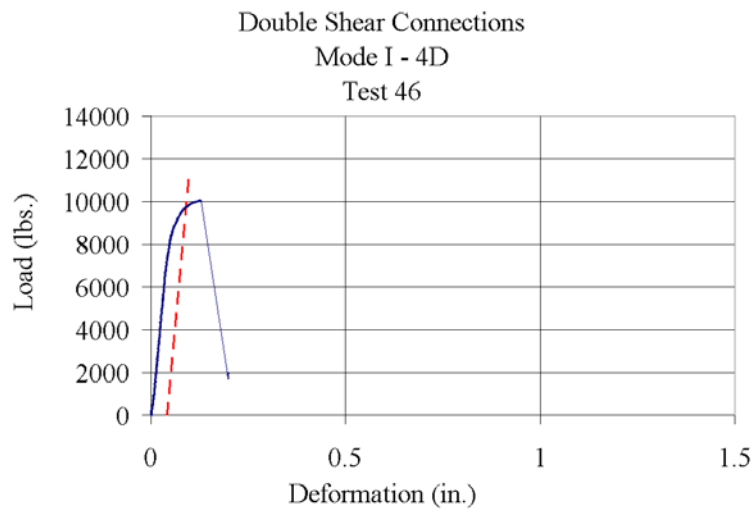

Double Shear Connections
Mode I - 4D
Test 41
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

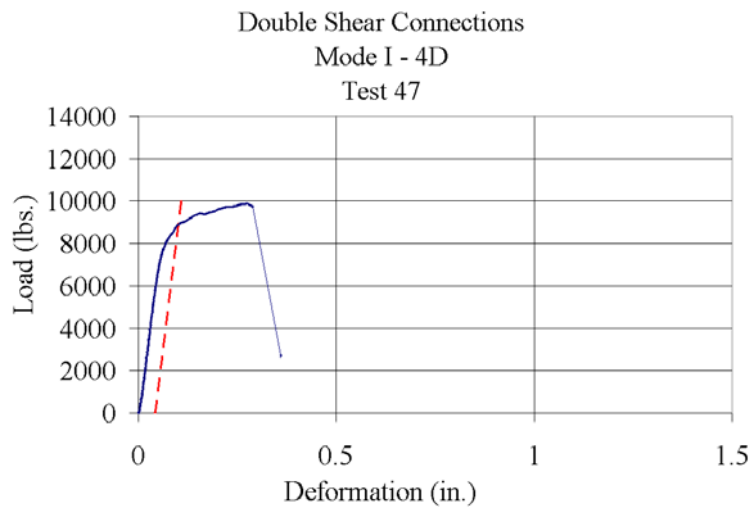

Double Shear Connections
Mode I - 4D
Test 42
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

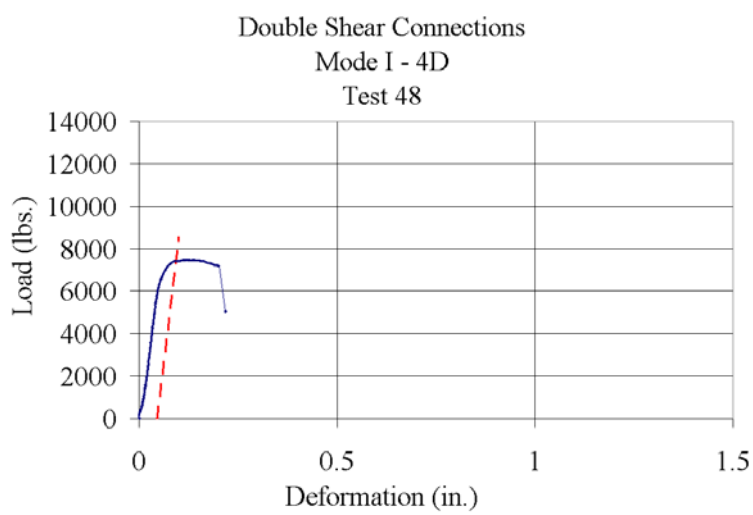

Double Shear Connections
Mode I - 4D
Test 43
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

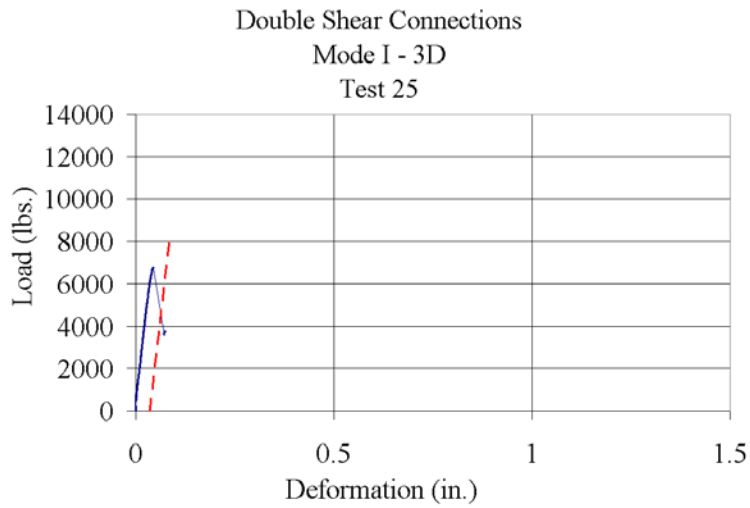

Double Shear Connections
Mode I - 4D
Test 44
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

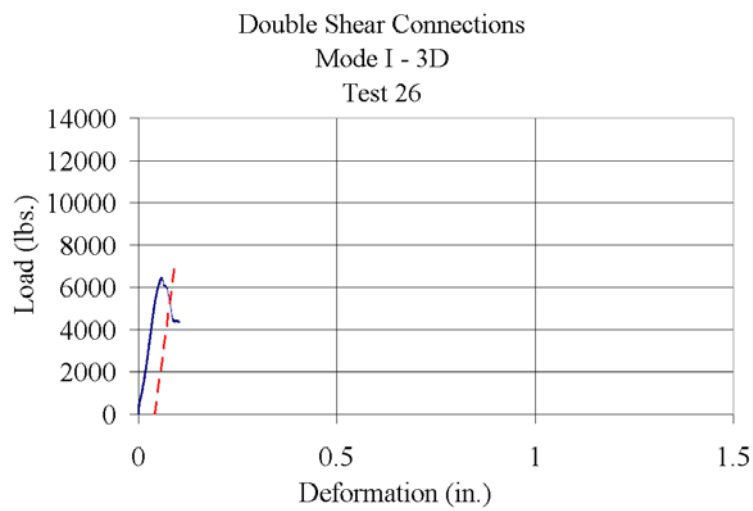

Double Shear Connections
Mode I - 4D
Test 45
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

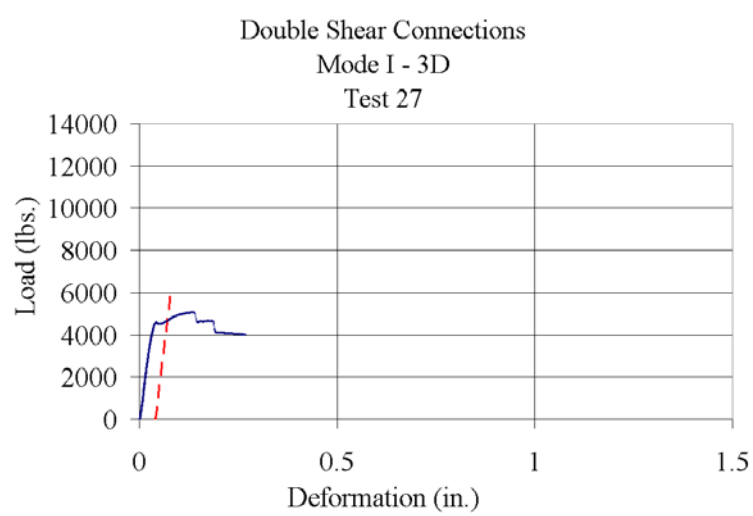

Double Shear Connections
Mode I - 4D
Test 46
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

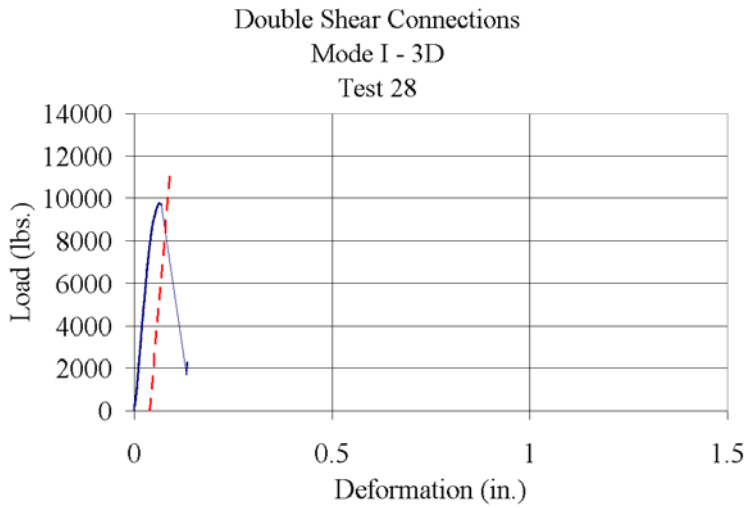

Double Shear Connections
Mode I - 4D
Test 47
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

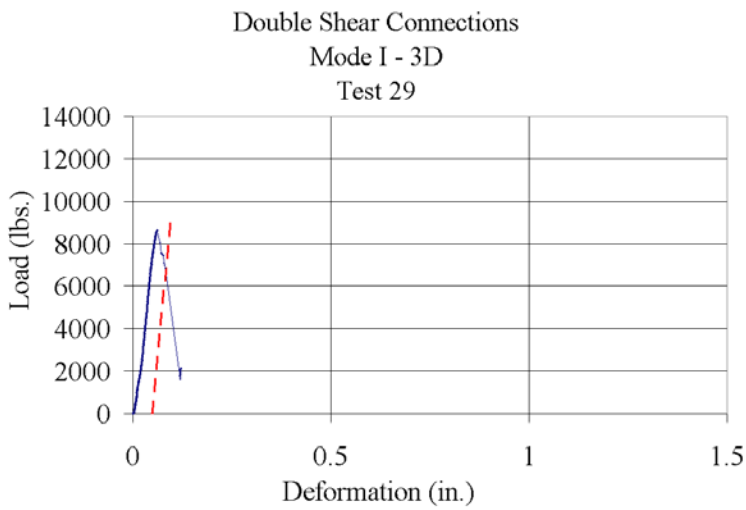

Double Shear Connections
Mode I - 4D
Test 48
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

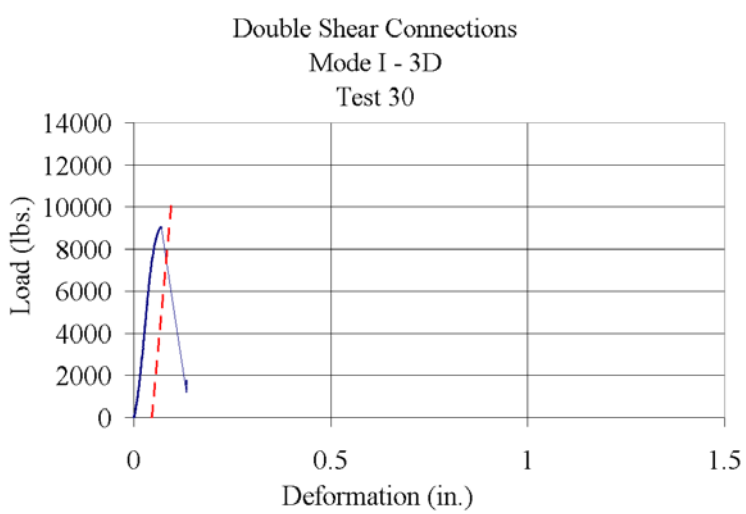

Double Shear Connections
Mode I - 3D
Test 25
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

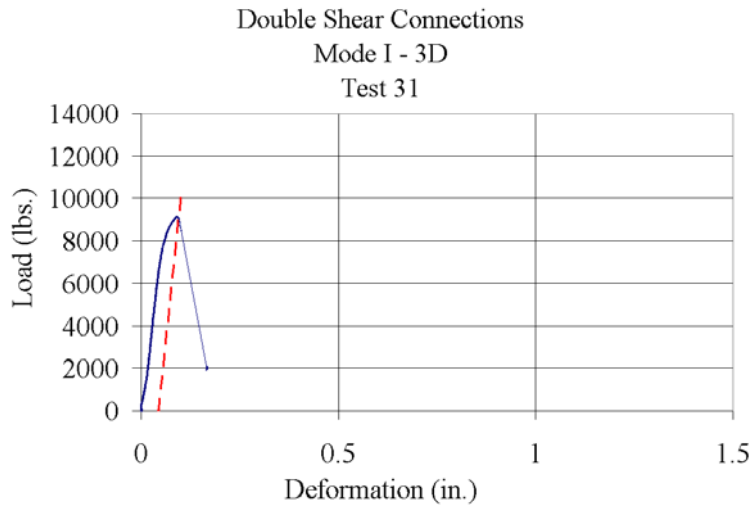

Double Shear Connections
Mode I - 3D
Test 26
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

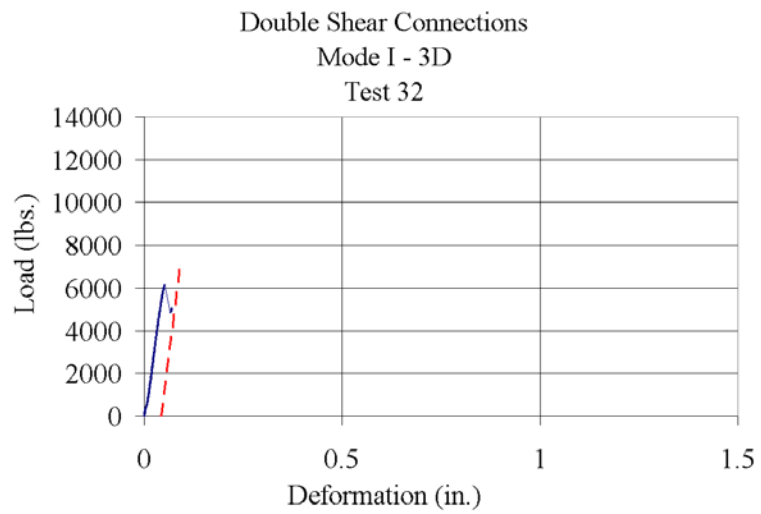

Double Shear Connections
Mode I - 3D
Test 27
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

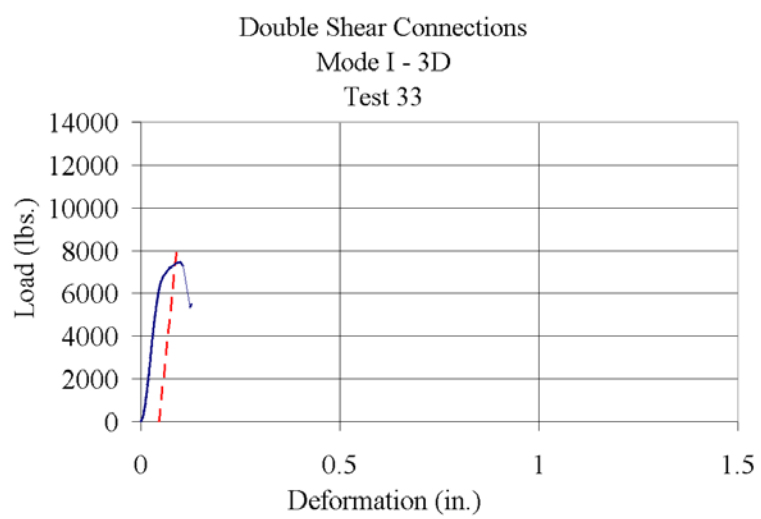

Double Shear Connections
Mode I - 3D
Test 28
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

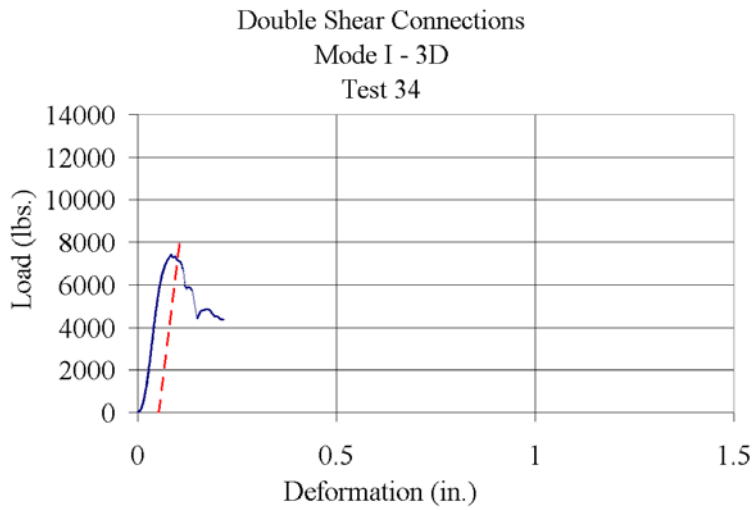

Double Shear Connections
Mode I - 3D
Test 29
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

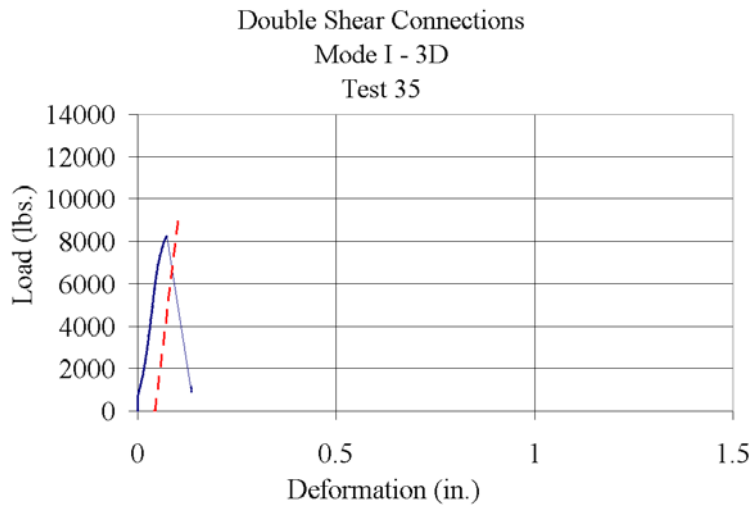

Double Shear Connections
Mode I - 3D
Test 30
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

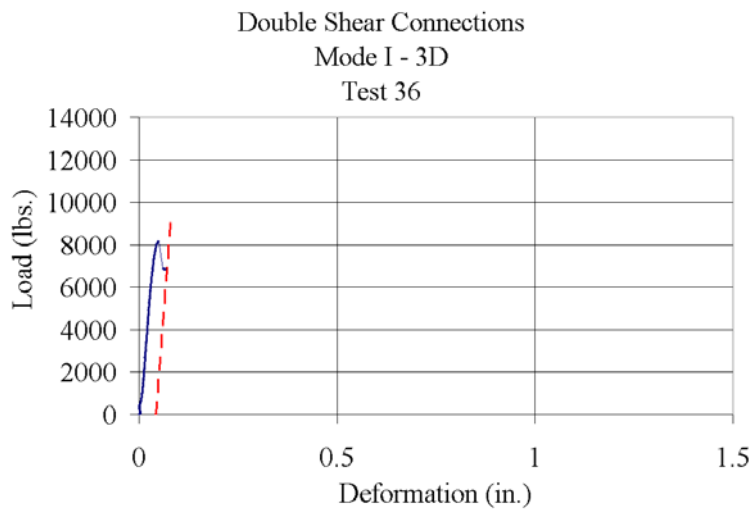

Double Shear Connections
Mode I - 3D
Test 31
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)


Double Shear Connections
Mode I - 3D
Test 32
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

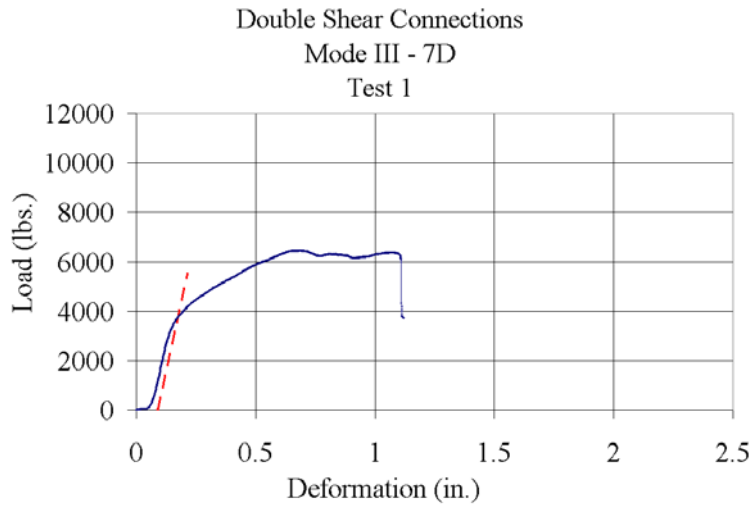

Double Shear Connections
Mode I - 3D
Test 33
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

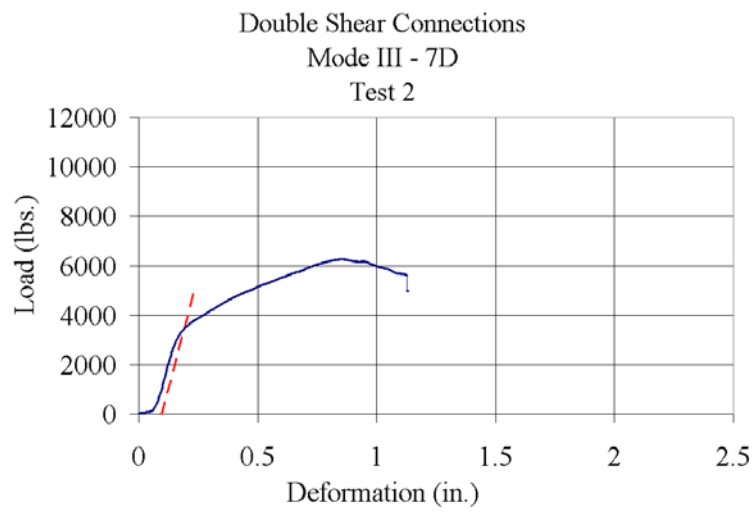

Double Shear Connections
Mode I - 3D
Test 34
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

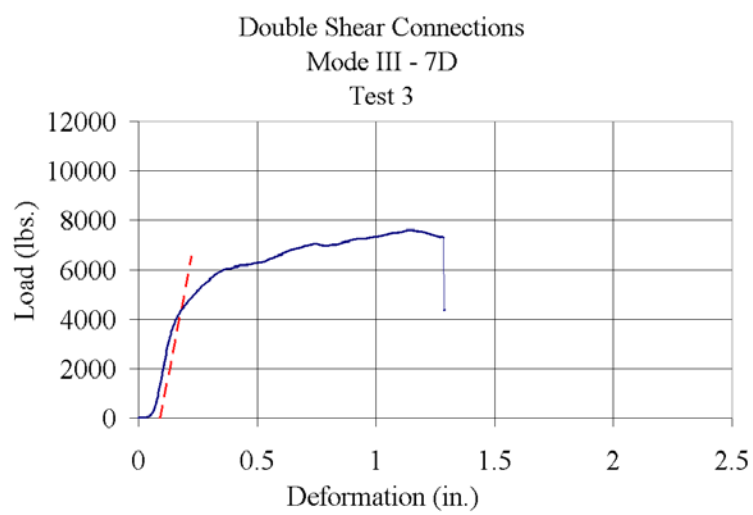

Double Shear Connections
Mode I - 3D
Test 35
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

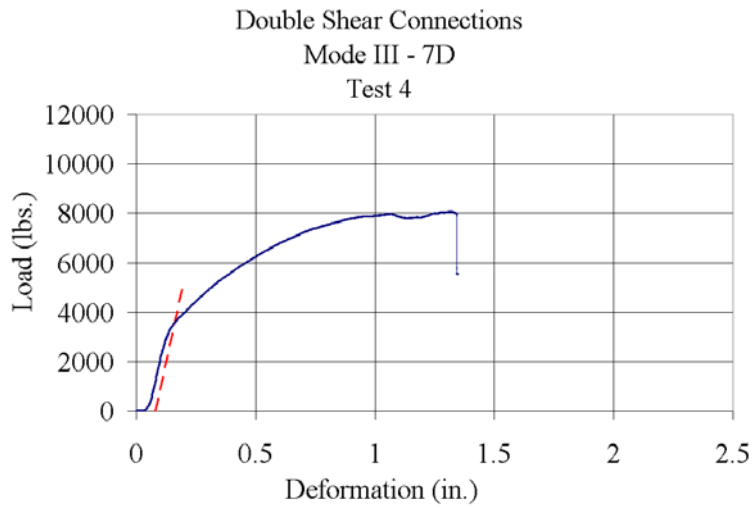

Double Shear Connections
Mode I - 3D
Test 36
Load (lbs.)
14000
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
Deformation (in.)

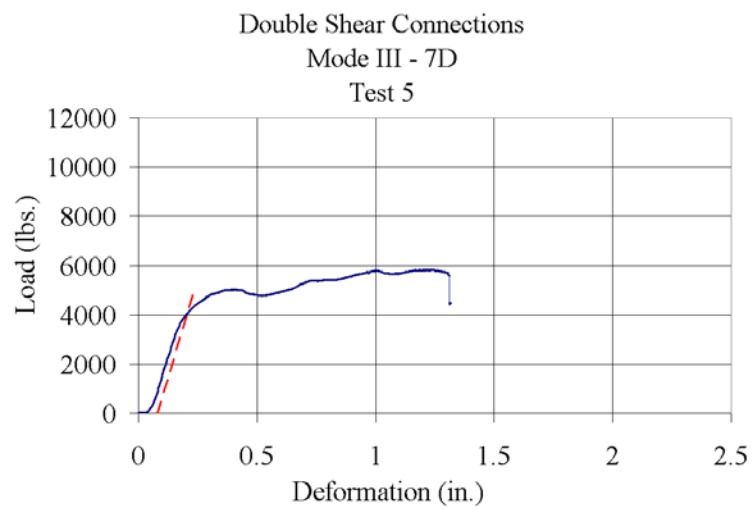
Mode III_s Bolted Connection Tests

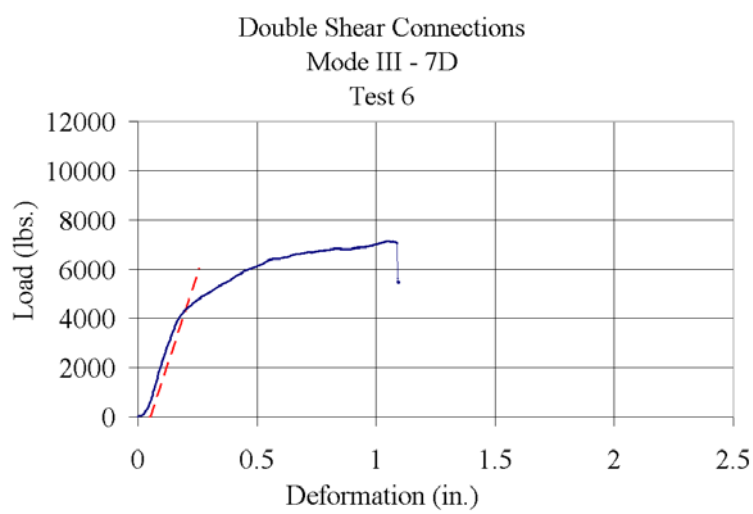


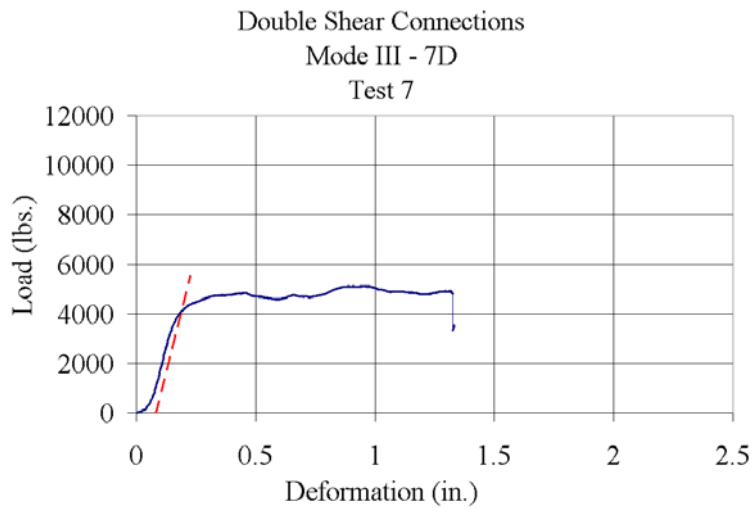


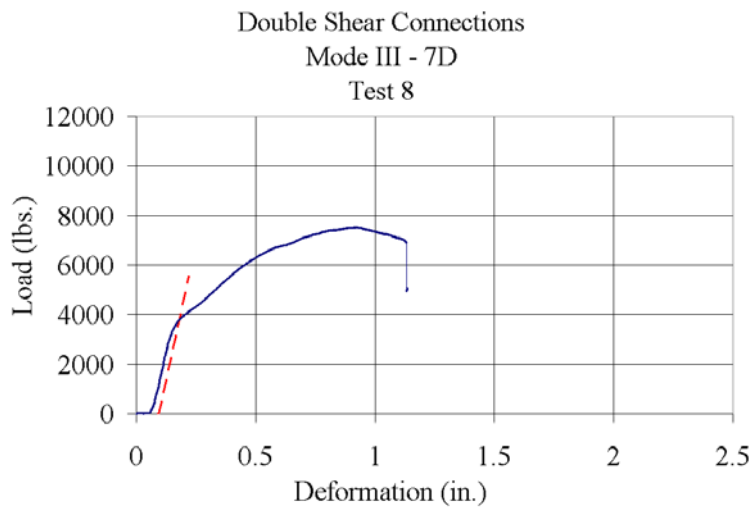


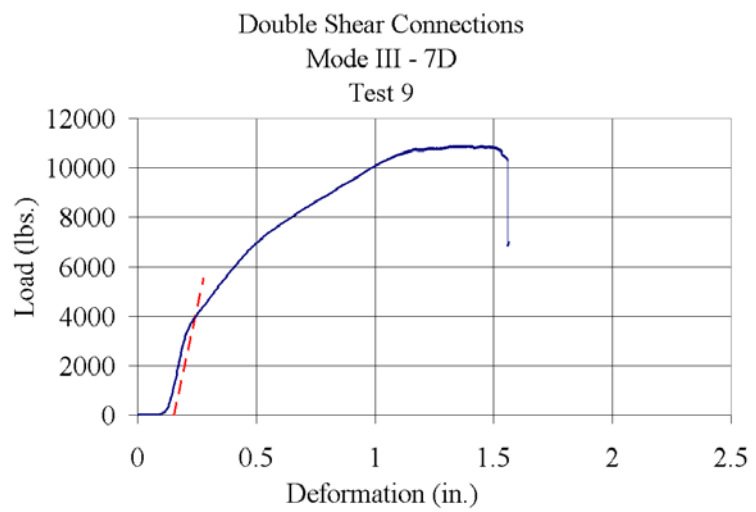

Double Shear Connections
Mode III - 7D
Test 4
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

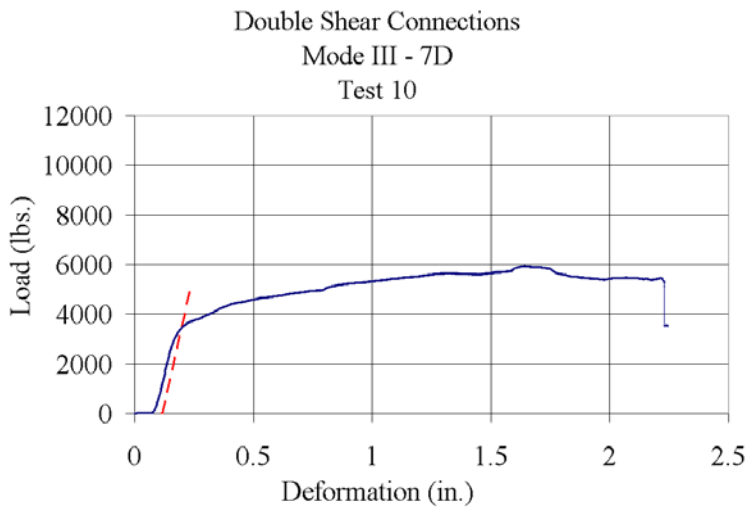

Double Shear Connections
Mode III - 7D
Test 5
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

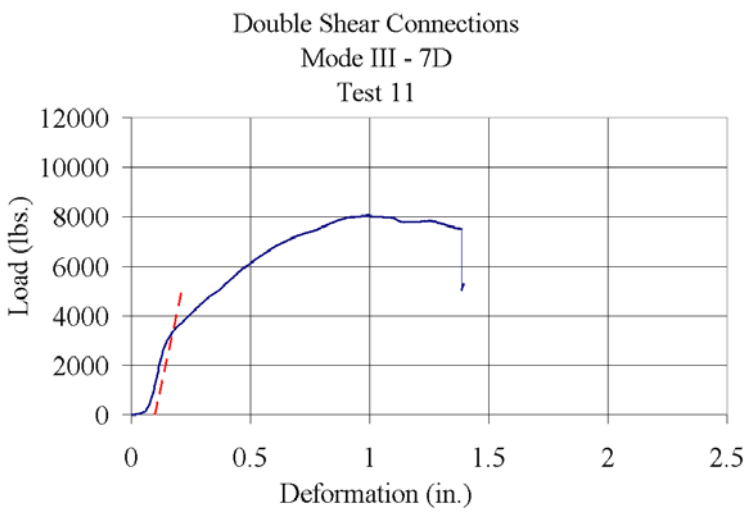

Double Shear Connections
Mode III - 7D
Test 6
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

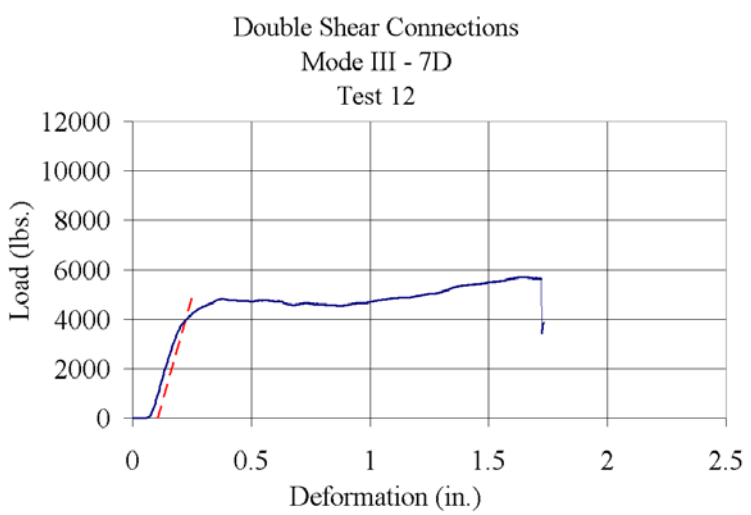

Double Shear Connections
Mode III - 7D
Test 7
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

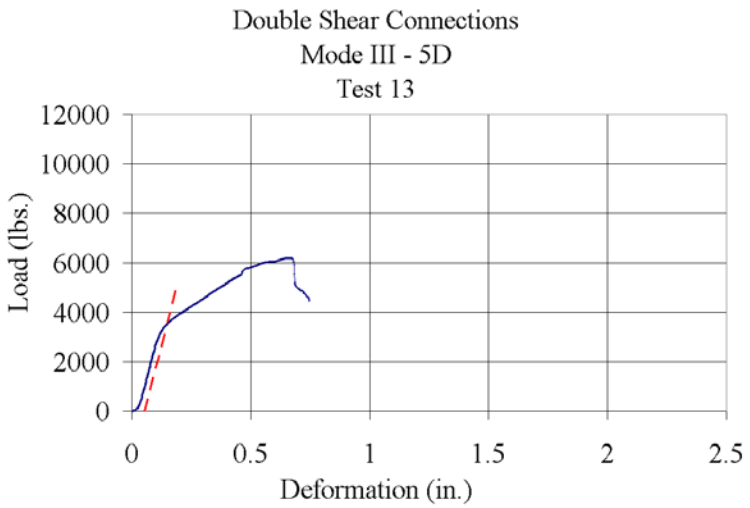

Double Shear Connections
Mode III - 7D
Test 8
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

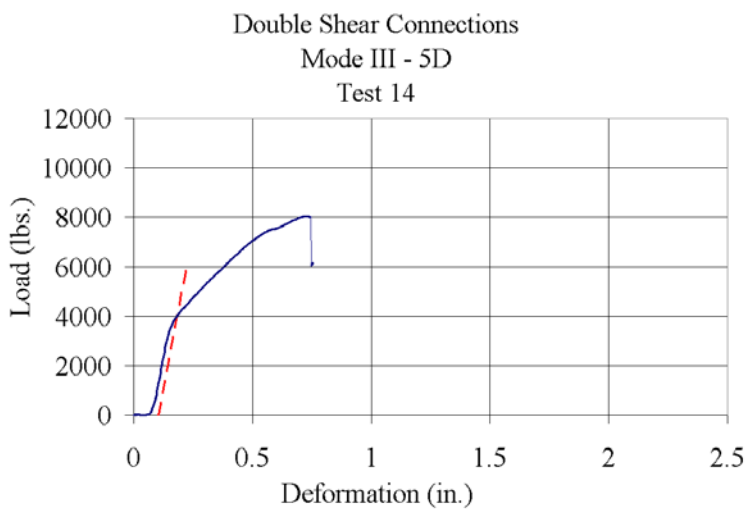

Double Shear Connections
Mode III - 7D
Test 9
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

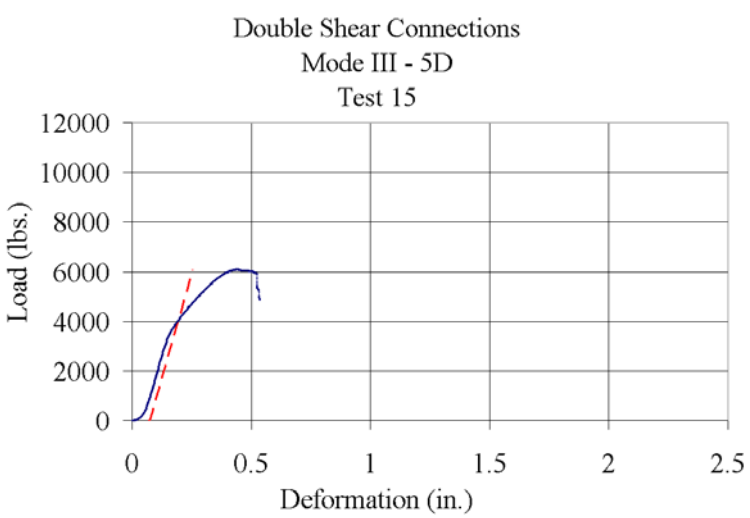

Double Shear Connections
Mode III - 7D
Test 10
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

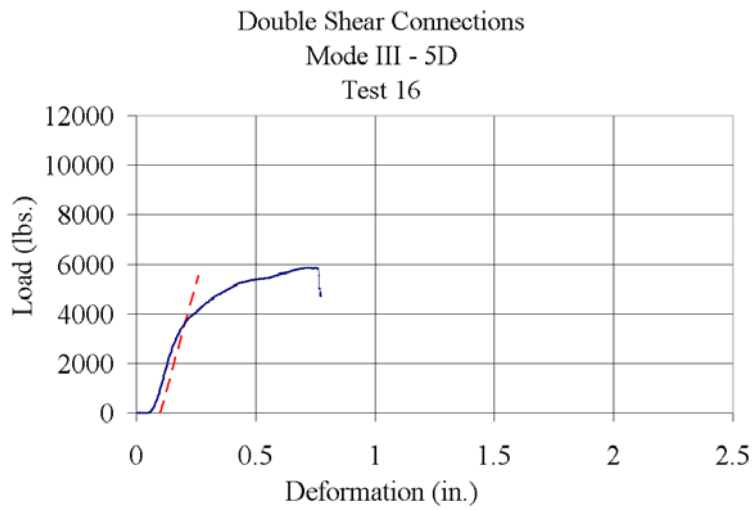

Double Shear Connections
Mode III - 7D
Test 11
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

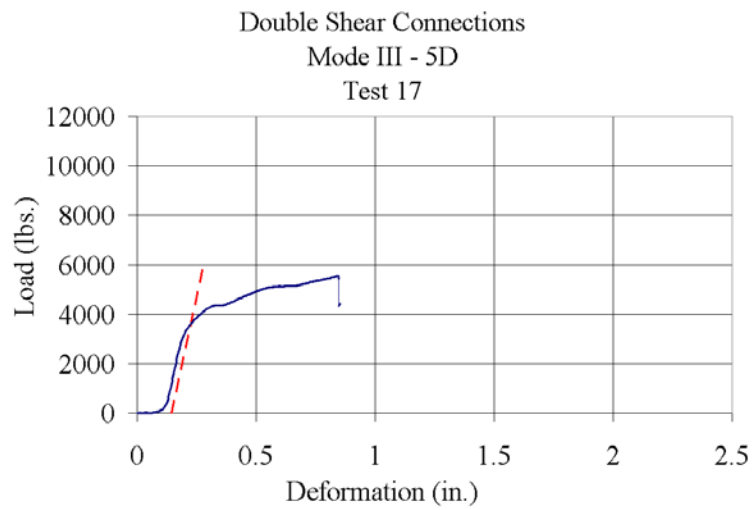

Double Shear Connections
Mode III - 7D
Test 12
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

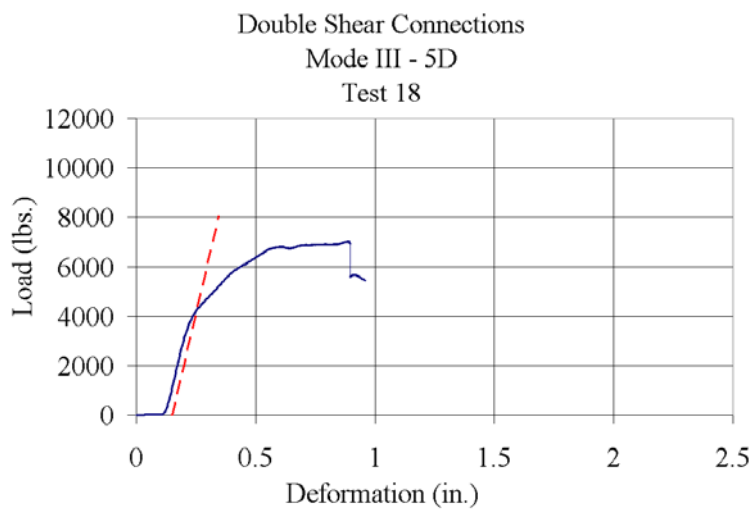

Double Shear Connections
Mode III - 5D
Test 13
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

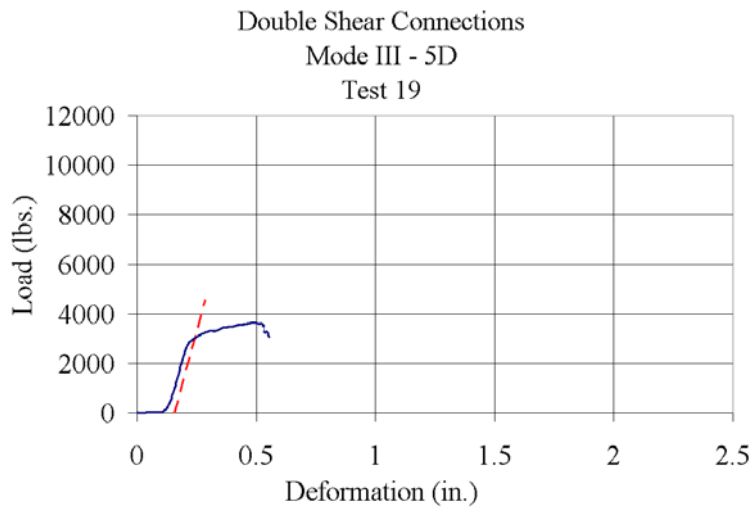

Double Shear Connections
Mode III - 5D
Test 14
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

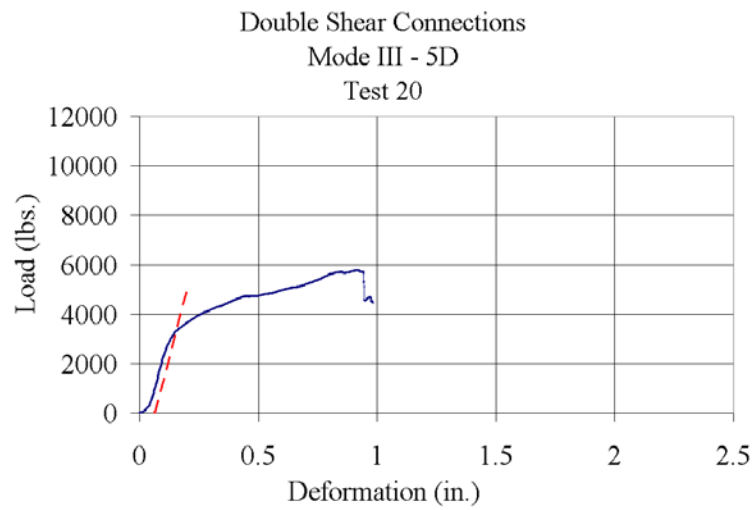

Double Shear Connections
Mode III - 5D
Test 15
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

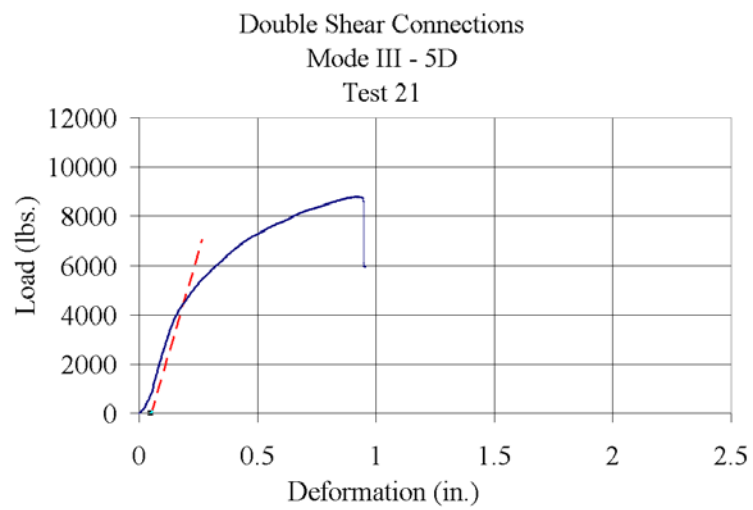

Double Shear Connections
Mode III - 5D
Test 16
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

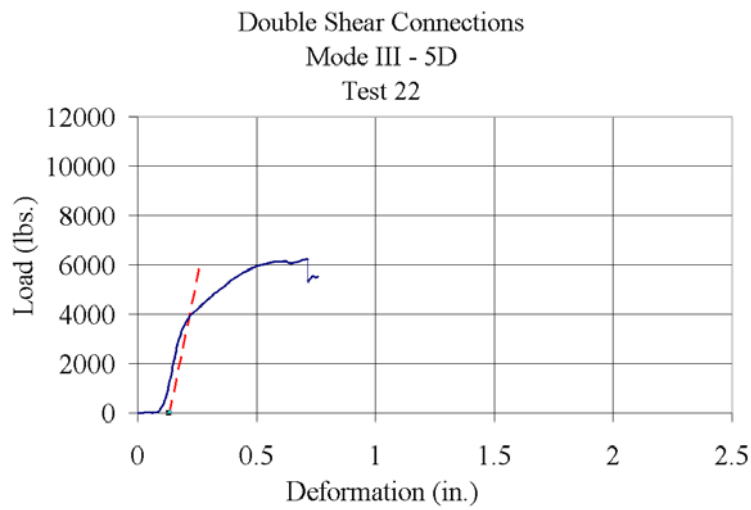

Double Shear Connections
Mode III - 5D
Test 17
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

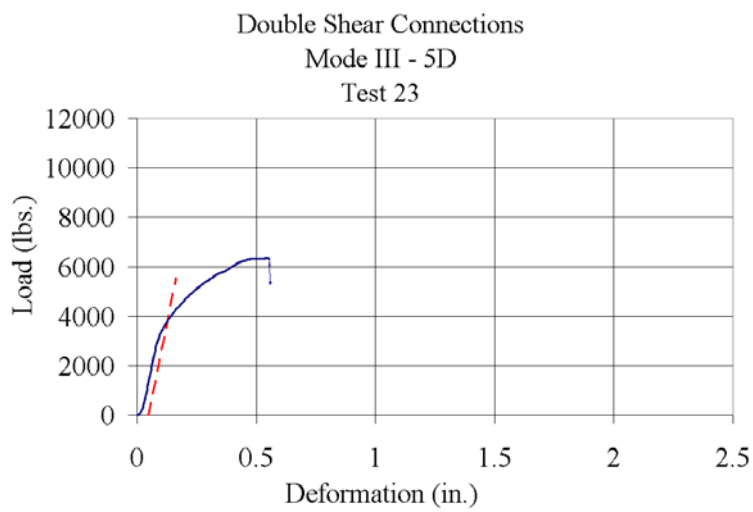

Double Shear Connections
Mode III - 5D
Test 18
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

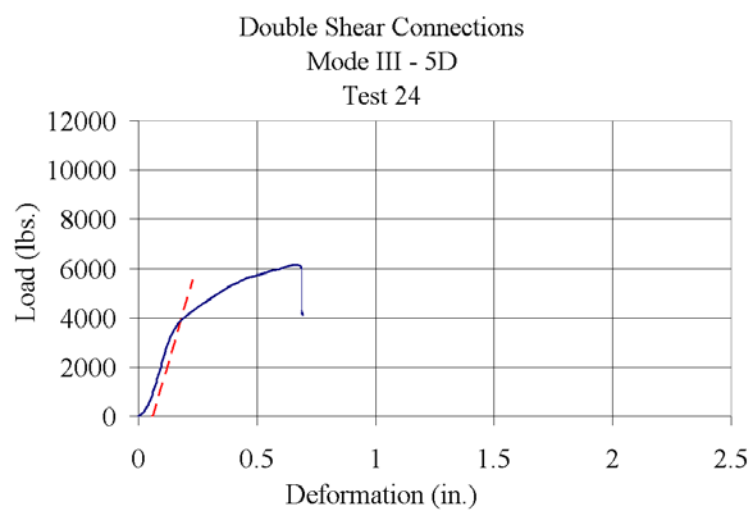

Double Shear Connections
Mode III - 5D
Test 19
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

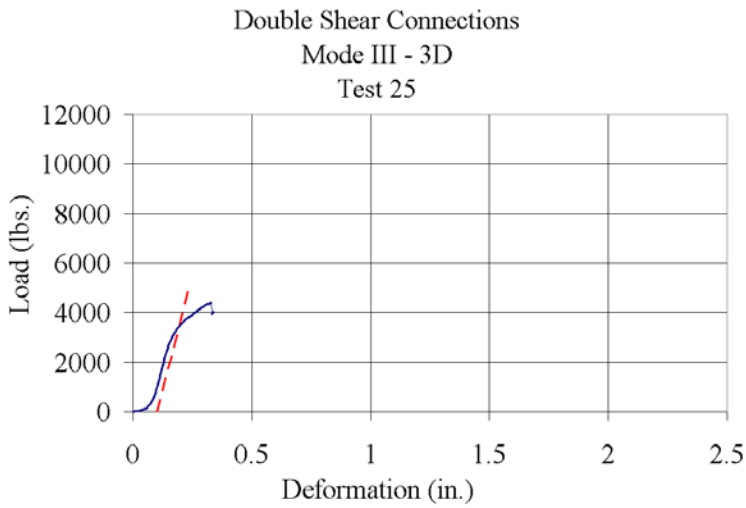

Double Shear Connections
Mode III - 5D
Test 20
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

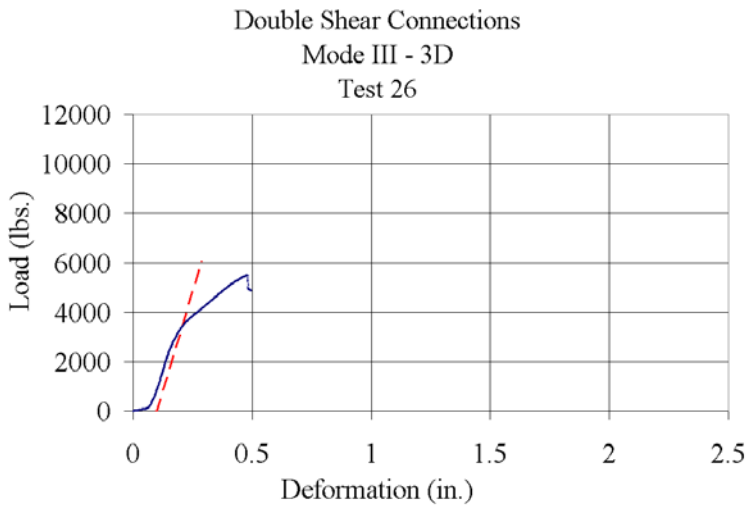

Double Shear Connections
Mode III - 5D
Test 21
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

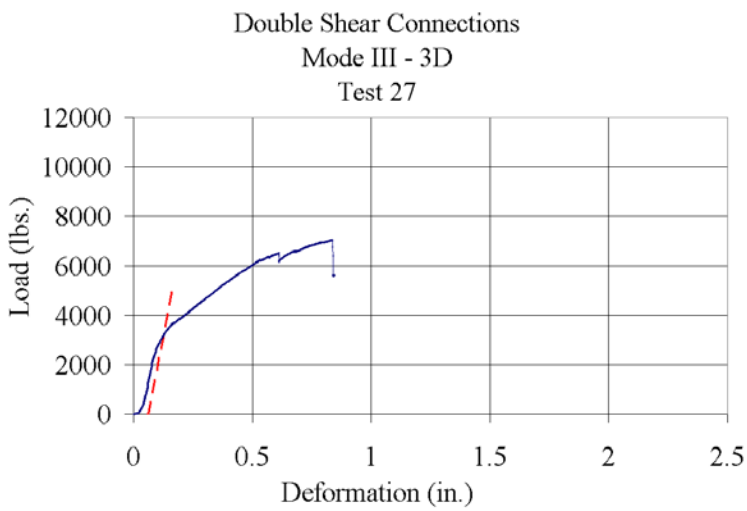

Double Shear Connections
Mode III - 5D
Test 22
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

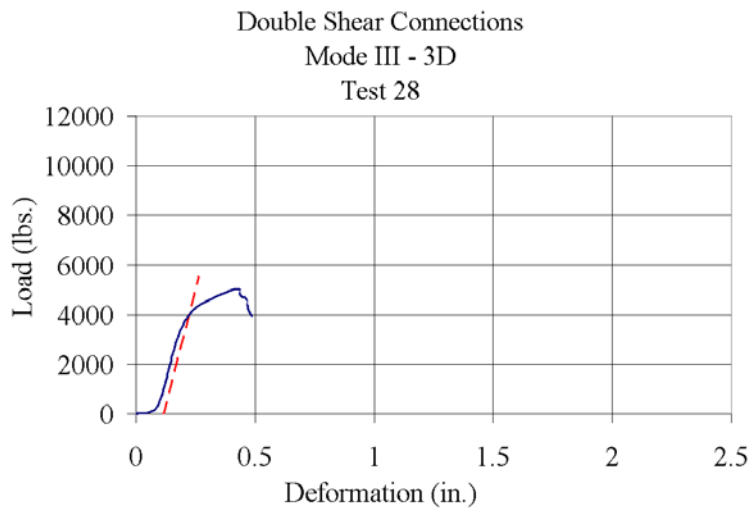

Double Shear Connections
Mode III - 5D
Test 23
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

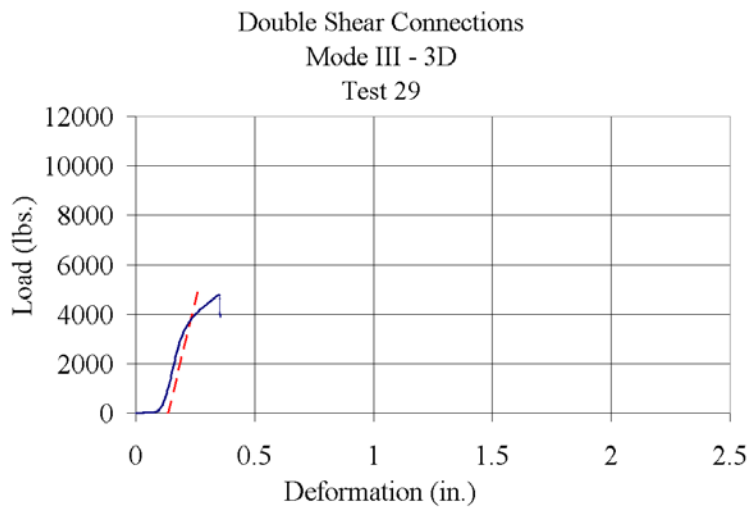

Double Shear Connections
Mode III - 5D
Test 24
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

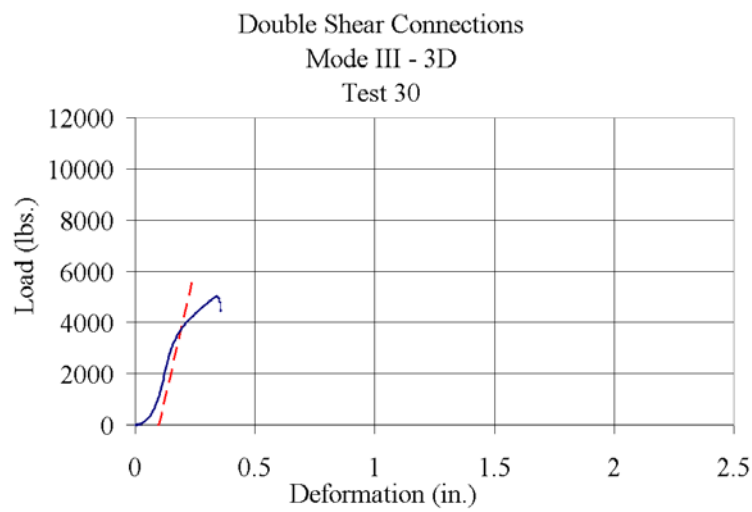

Double Shear Connections
Mode III - 3D
Test 25
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

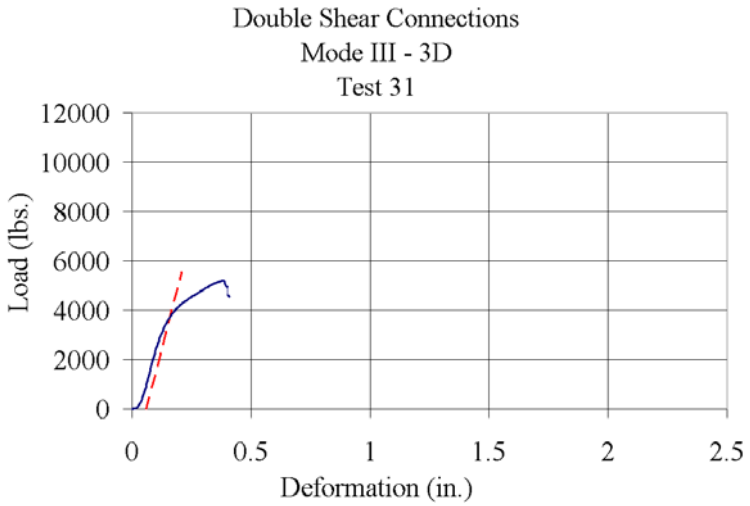

Double Shear Connections
Mode III - 3D
Test 26
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

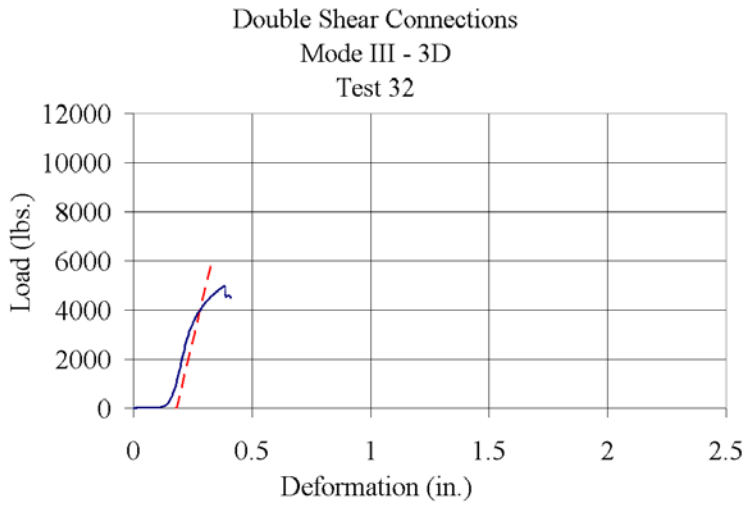

Double Shear Connections
Mode III - 3D
Test 27
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

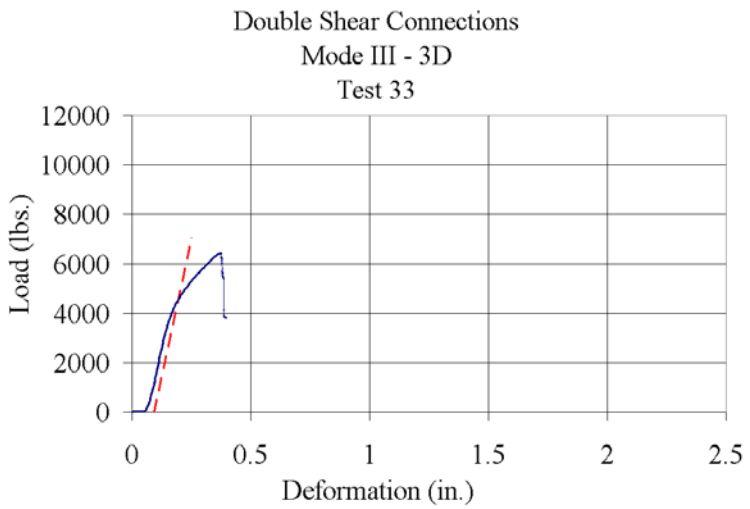

Double Shear Connections
Mode III - 3D
Test 28
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

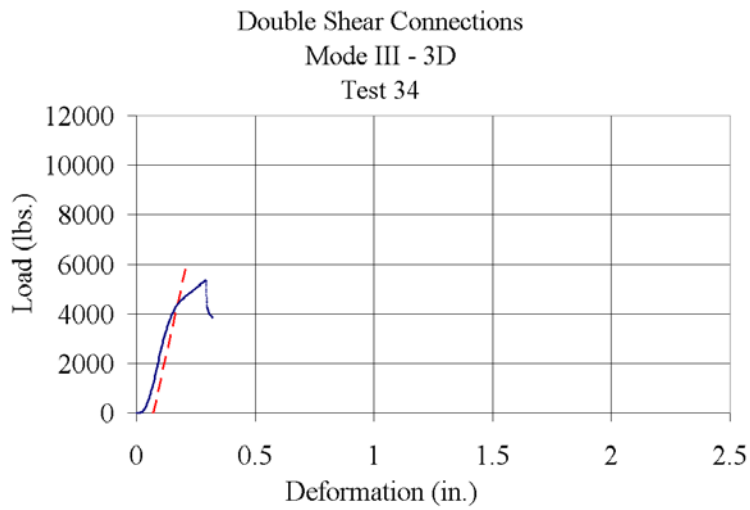

Double Shear Connections
Mode III - 3D
Test 29
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

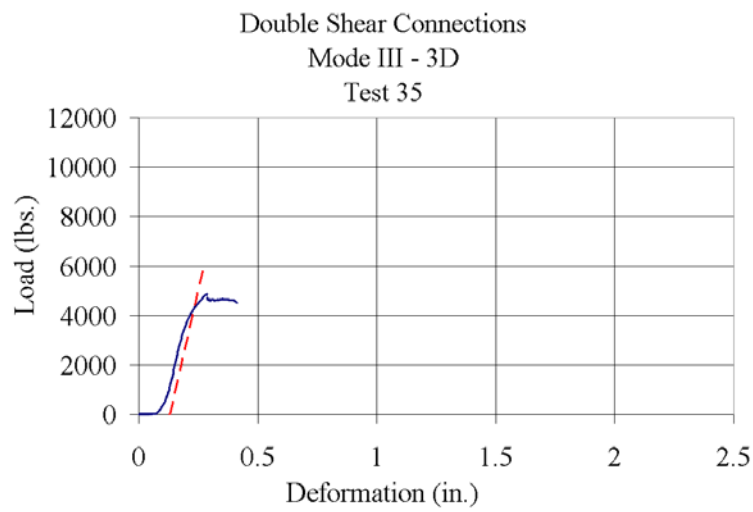

Double Shear Connections
Mode III - 3D
Test 30
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

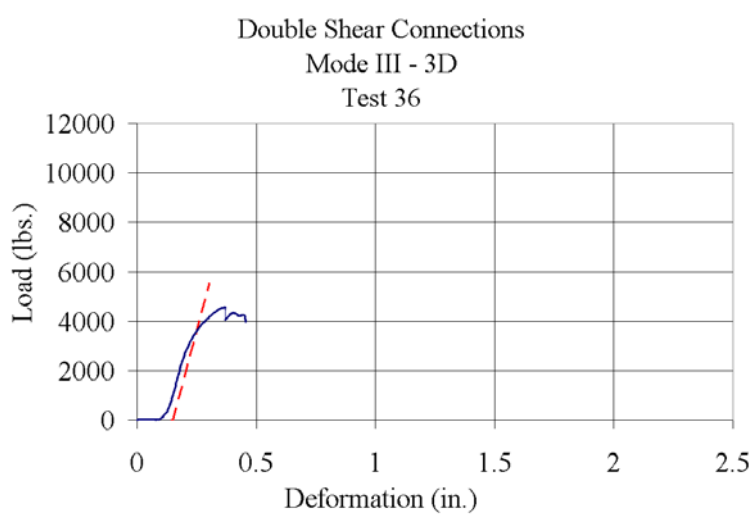

Double Shear Connections
Mode III - 3D
Test 31
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

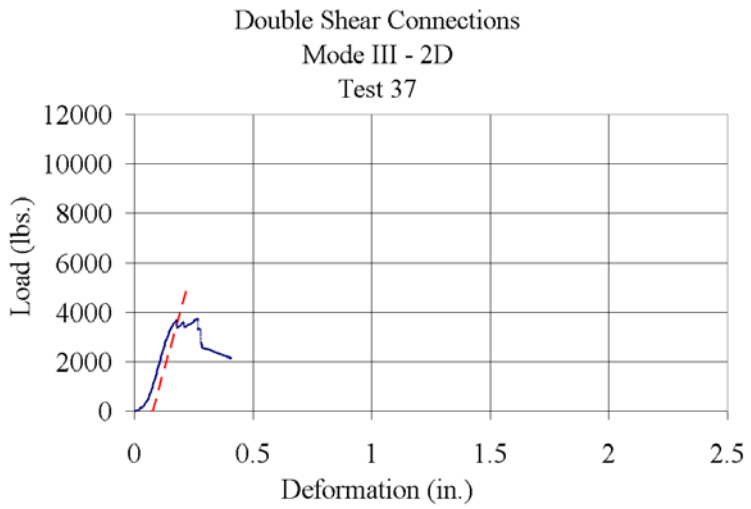

Double Shear Connections
Mode III - 3D
Test 32
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

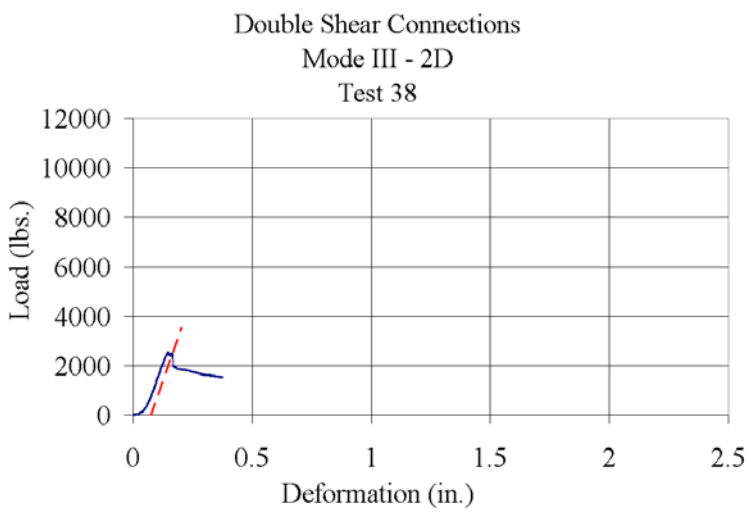

Double Shear Connections
Mode III - 3D
Test 33
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

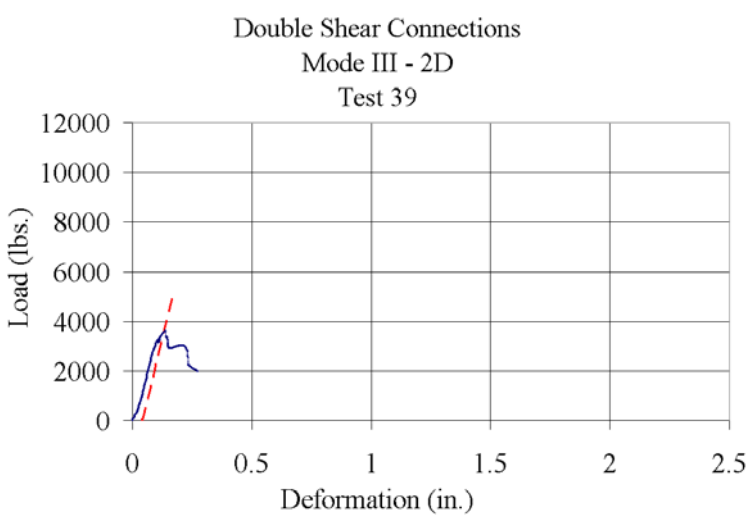

Double Shear Connections
Mode III - 3D
Test 34
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

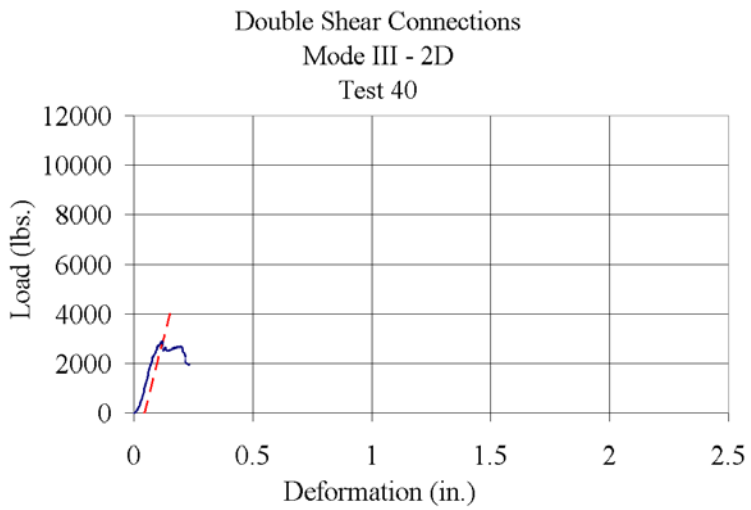

Double Shear Connections
Mode III - 3D
Test 35
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

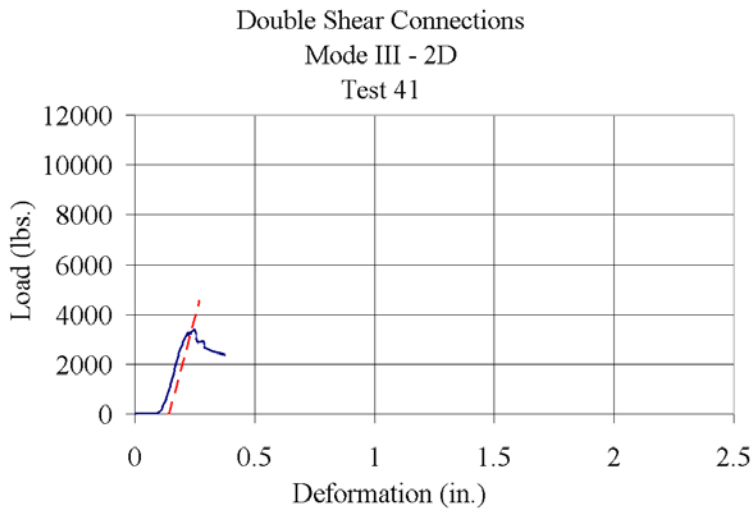

Double Shear Connections
Mode III - 3D
Test 36
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

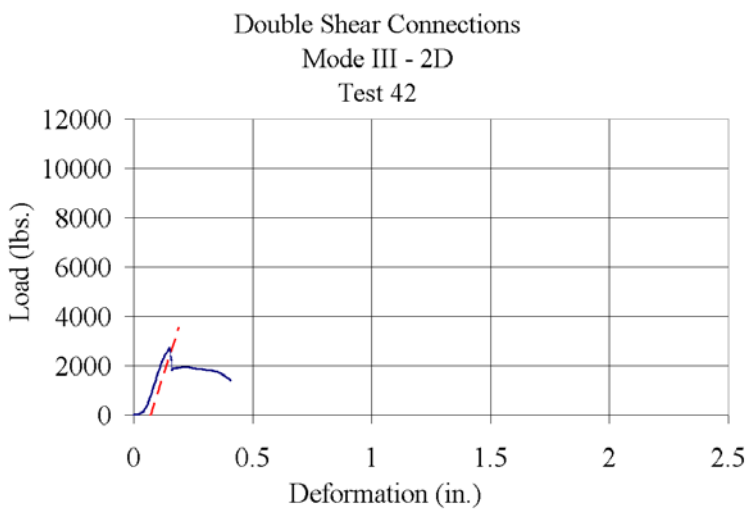

Double Shear Connections
Mode III - 2D
Test 37
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

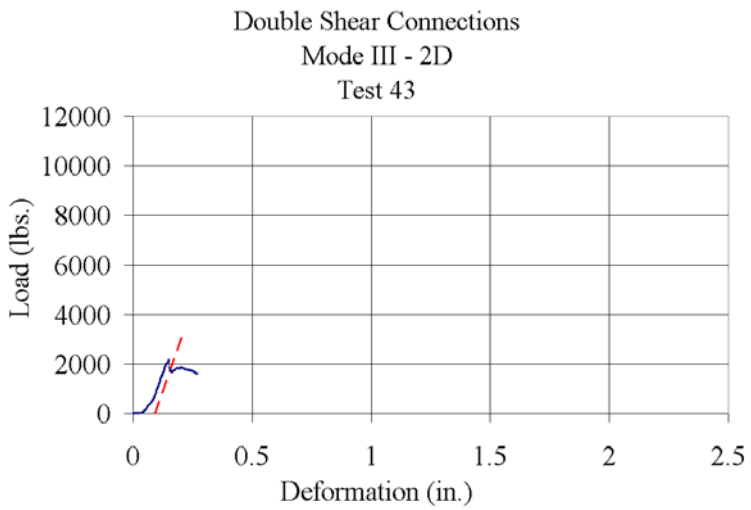

Double Shear Connections
Mode III - 2D
Test 38
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

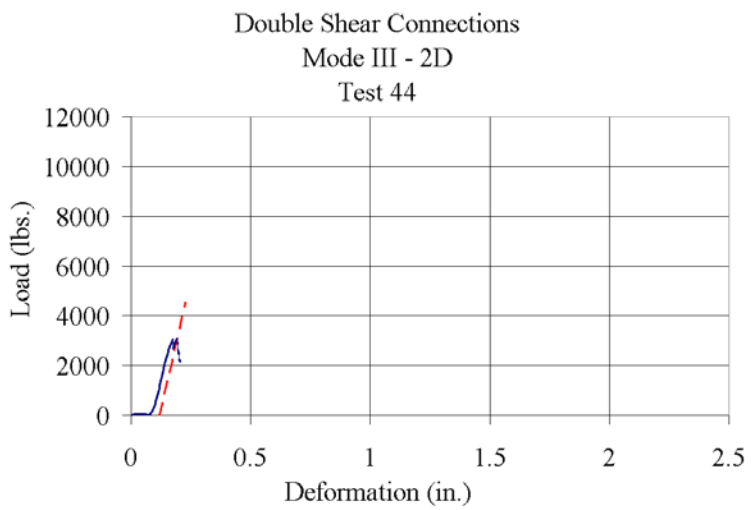

Double Shear Connections
Mode III - 2D
Test 39
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

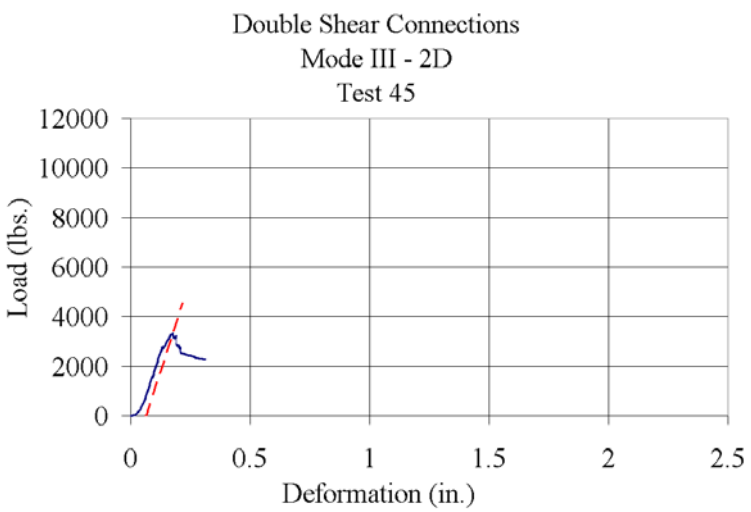

Double Shear Connections
Mode III - 2D
Test 40
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

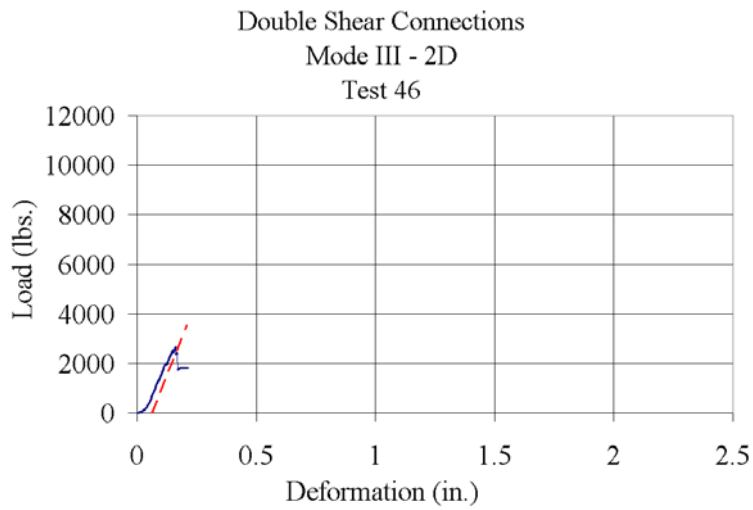

Double Shear Connections
Mode III - 2D
Test 41
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

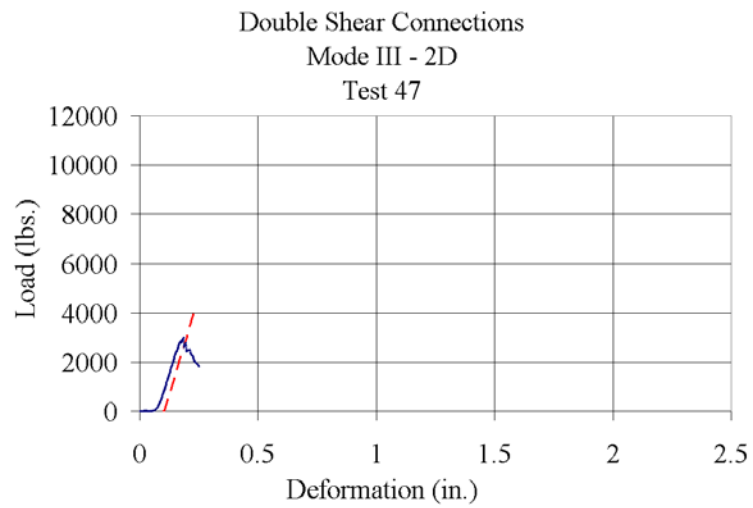

Double Shear Connections
Mode III - 2D
Test 42
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

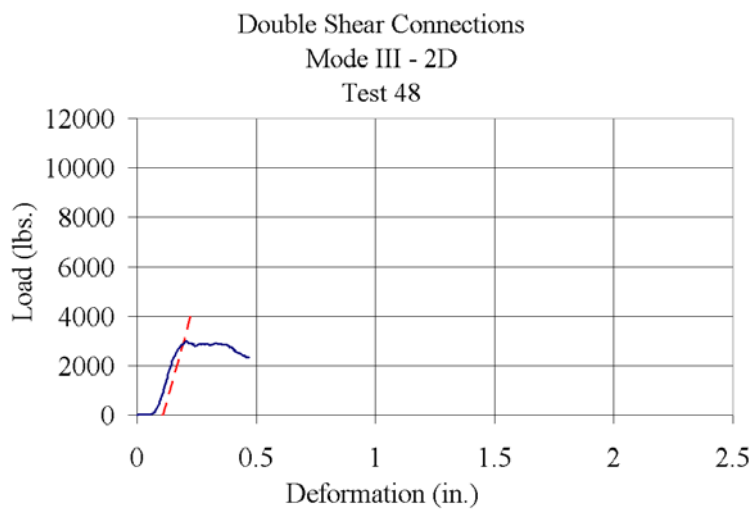

Double Shear Connections
Mode III - 2D
Test 43
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)


Double Shear Connections
Mode III - 2D
Test 44
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)


Double Shear Connections
Mode III - 2D
Test 45
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

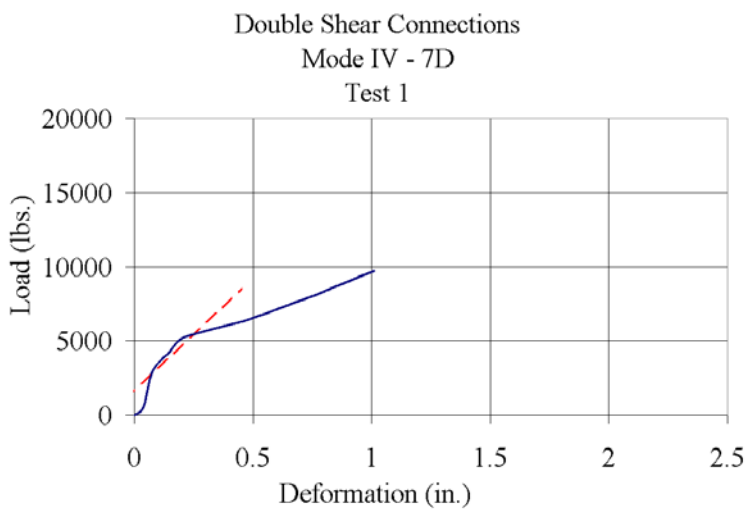

Double Shear Connections
Mode III - 2D
Test 46
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

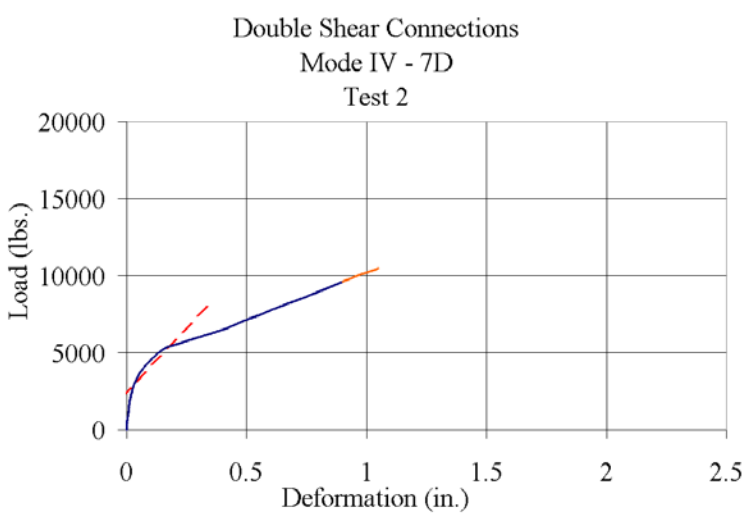

Double Shear Connections
Mode III - 2D
Test 47
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

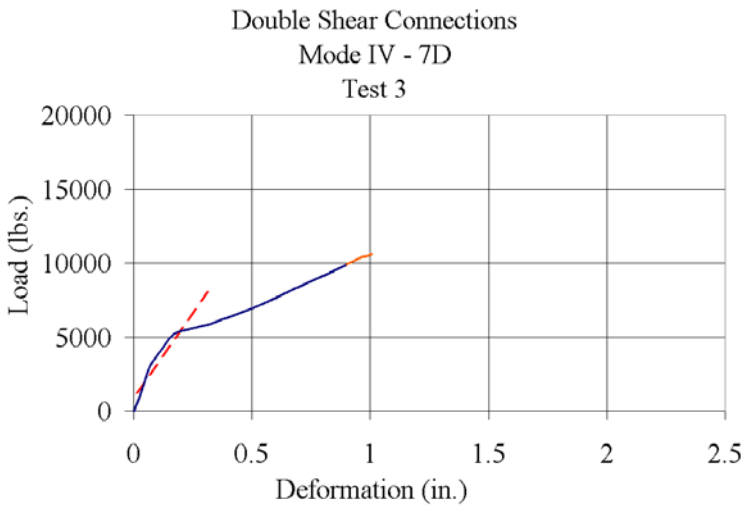

Double Shear Connections
Mode III - 2D
Test 48
Load (lbs.)
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

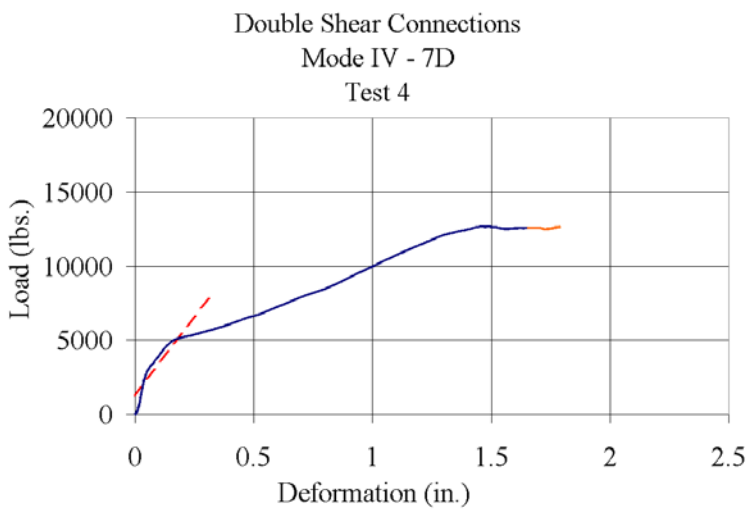
Mode IV Bolted Connection Tests

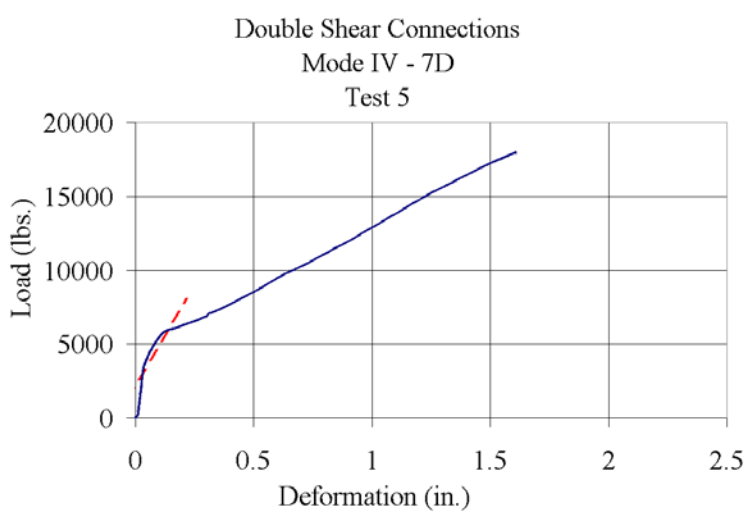
It should be noted that not all of the Mode IV bolted connection tests were loaded to their ultimate capacity. Test number 1, 2 and 3 were stopped after the LVDT ran out of stroke. In the other tests where the LVDTs ran out of stroke, load-displacement curves were generated using the crosshead displacement. Where the crosshead displacement is used, the graph is shaded a lighter color. Test number 5 was also stopped prematurely. In this case, a limiting load level of 18,000 lbs. was detected by the MTS 407-controller. For the remainder of the tests the load limit was raised to 20,000 lbs.

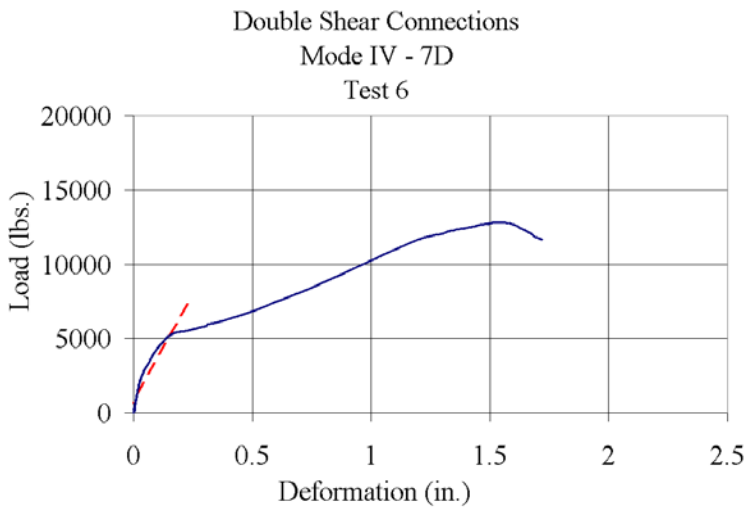


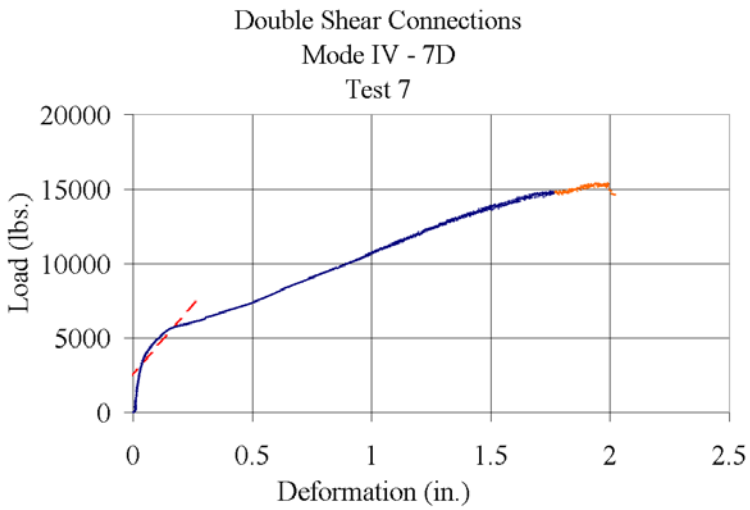


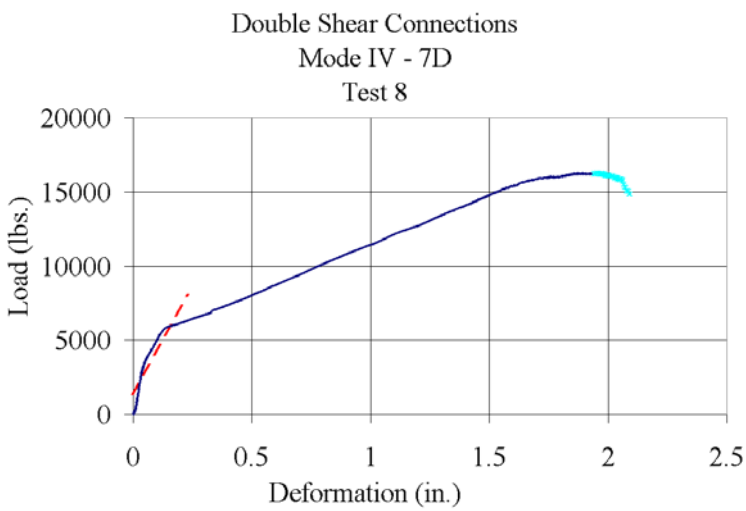

Double Shear Connections
Mode IV - 7D
Test 3
Load (lbs.)
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

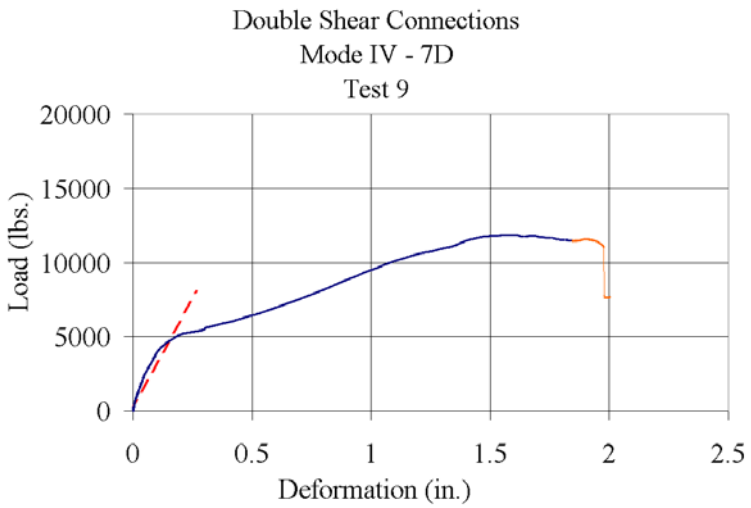

Double Shear Connections
Mode IV - 7D
Test 4
Load (lbs.)
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

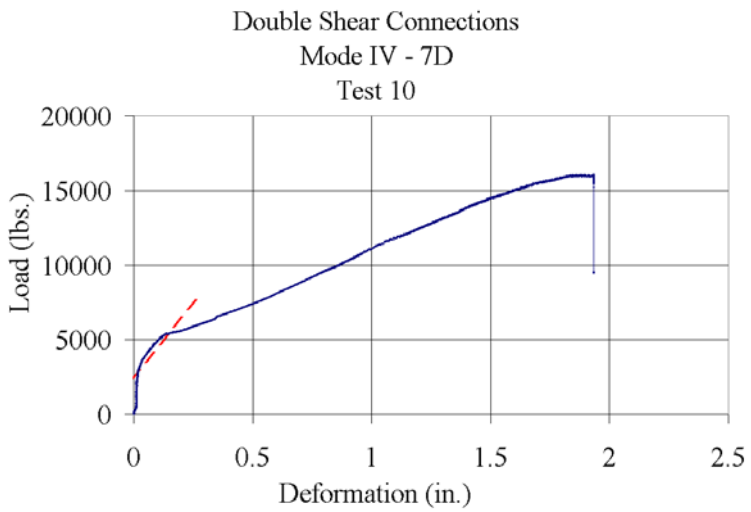

Double Shear Connections
Mode IV - 7D
Test 5
Load (lbs.)
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

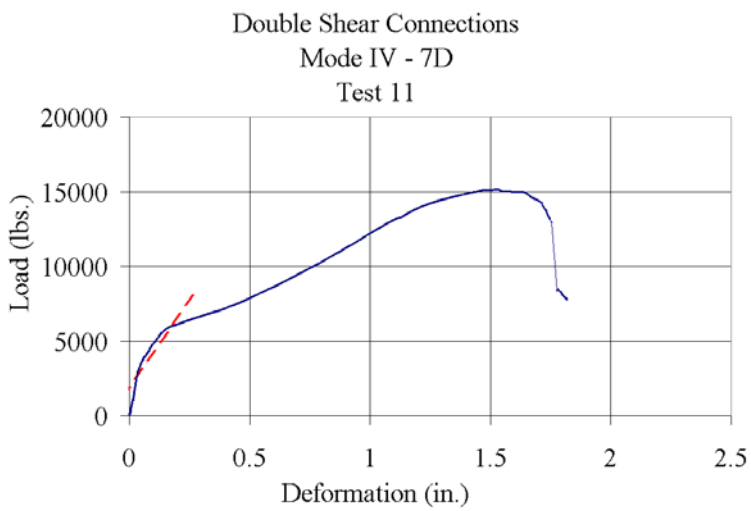

Double Shear Connections
Mode IV - 7D
Test 6
Load (lbs.)
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

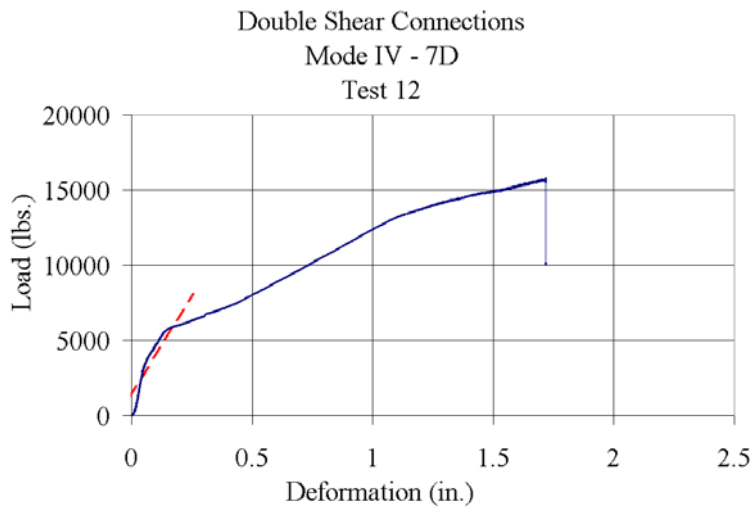

Double Shear Connections
Mode IV - 7D
Test 7
Load (lbs.)
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

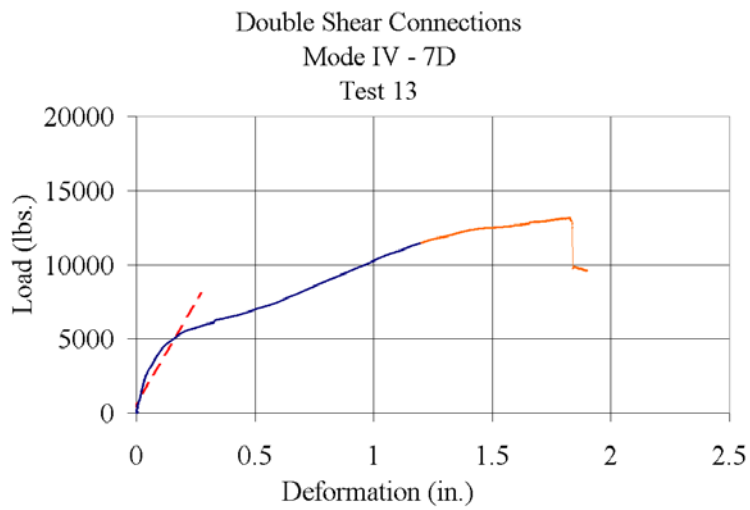

Double Shear Connections
Mode IV - 7D
Test 8
Load (lbs.)
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

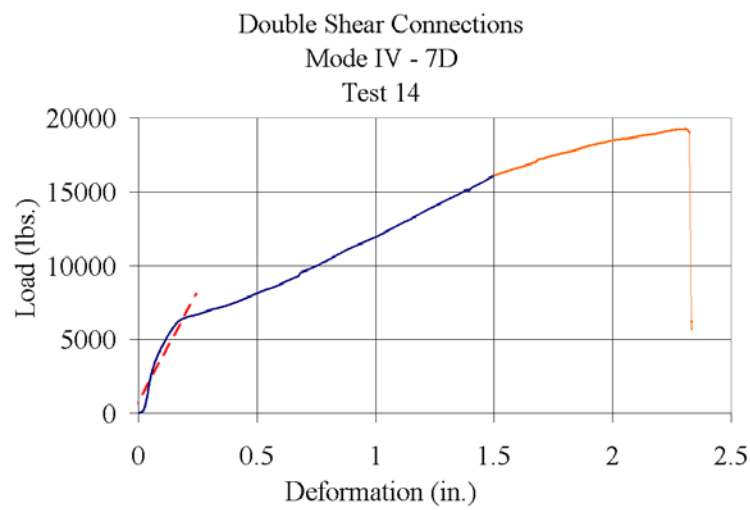

Double Shear Connections
Mode IV - 7D
Test 9
Load (lbs.)
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)


Double Shear Connections
Mode IV - 7D
Test 10
Load (lbs.)
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)


Double Shear Connections
Mode IV - 7D
Test 11
Load (lbs.)
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)


Double Shear Connections
Mode IV - 7D
Test 12
Load (lbs.)
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)


Double Shear Connections
Mode IV - 7D
Test 13
Load (lbs.)
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)


Double Shear Connections
Mode IV - 7D
Test 14
Load (lbs.)
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
Deformation (in.)

Results

Mode I_m Bolted Connection Tests

End Distance of 7D:

Test Number	Predicted Yield Load (lbs)	Tested Yield Load (lbs)	Tested/Predicted Yield Load Ratio	Ultimate Load (lbs)	Ultimate/Yield Load Ratio
1	5328	5688	1.07	6687	1.18
2	5368	6490	1.21	8870	1.37
3	5381	6510	1.21	7930	1.22
4	8782	6413	0.73	8978	1.40
5	6190	7108	1.15	9056	1.27
6	6761	9115	1.35	9761	1.07
7	7003	8566	1.22	9271	1.08
8	7107	8929	1.26	10113	1.13
9	7275	4523	0.62	6971	1.54
10	7736	9193	1.19	10103	1.10
11	8049	6833	0.85	8938	1.31
12	8240	9487	1.15	10896	1.15
		Mean =	1.08	Mean =	1.23
		Std Dev =	0.226	Std Dev =	0.146

End Distance of 5D:

Test Number	Predicted Yield Load (lbs)	Tested Yield Load (lbs)	Tested/Predicted Yield Load Ratio	Ultimate Load (lbs)	Ultimate/Yield Load Ratio
13	6256	8214	1.31	9476.8	1.15
14	6603	8282	1.25	10201.2	1.23
15	6674	6912	1.04	7724.3	1.12
16	8905	10936	1.23	12227.8	1.12
17	6250	8713	1.39	9447.4	1.08
18	6744	8517	1.26	9613.8	1.13
19	7039	5507	0.78	7127.1	1.29
20	7202	7920	1.10	8517.3	1.08
21	7353	9829	1.34	12159.2	1.24
22	7801	10191	1.31	11160.6	1.10
23	8039	6628	0.82	7039	1.06
24	8240	8312	1.01	10122.9	1.22
		Mean =	1.15	Mean =	1.15
		Std Dev =	0.203	Std Dev =	0.076

End Distance of 4D:

Test Number	Predicted Yield Load (lbs)	Tested Yield Load (lbs)	Tested/Predicted Yield Load Ratio	Ultimate Load (lbs)	Ultimate/Yield Load Ratio
37	8455	9673	1.14	11004	1.14
38	8585	8694	1.01	9114.5	1.05
39	8722	9986	1.14	10064.2	1.01
40	9782	9741	1.00	10592.8	1.09
41	6222	9095	1.46	10387.2	1.14
42	6683	8126	1.22	8977.5	1.10
43	7023	6119	0.87	8174.7	1.34
44	7254	10260	1.41	10395.5	1.01
45	7380	7803	1.06	8566.3	1.10
46	7746	9741	1.26	10054.4	1.03
47	8072	8880	1.10	9887.9	1.11
48	8176	7421	0.91	7479.6	1.01
		Mean =	1.13	Mean =	1.09
		Std Dev =	0.183	Std Dev =	0.091

End Distance of 3D:

Test Number	Predicted Yield Load (lbs)	Tested Yield Load (lbs)	Tested/Predicted Yield Load Ratio	Ultimate Load (lbs)	Ultimate/Yield Load Ratio
25	7429	6765	0.91	6764.9	1.00
26	7514	6471	0.86	6471.2	1.00
27	8102	4670	0.58	5081	1.09
28	9461	9800	1.04	9799.8	1.00
29	6256	8645	1.38	8644.6	1.00
30	6775	9036	1.33	9036.2	1.00
31	7093	9154	1.29	9153.7	1.00
32	7220	6119	0.85	6118.8	1.00
33	7416	7372	0.99	7469.8	1.01
34	7766	7411	0.95	7411.1	1.00
35	8036	8243	1.03	8243.2	1.00
36	8300	8175	0.98	8174.7	1.00
		Mean =	1.02	Mean =	1.01
		Std Dev =	0.228	Std Dev =	0.025

Mode III_s Bolted Connection Tests

End Distance of 7D:

Test Number	Predicted Yield Load (lbs)	Tested Yield Load (lbs)	Tested/Predicted Yield Load Ratio	Ultimate Load (lbs)	Ultimate/Yield Load Ratio
1	4118	3740	0.91	6461	1.73
2	4167	3427	0.82	6266	1.83
3	4316	4308	1.00	7597	1.76
4	4380	3573	0.82	8067	2.26
5	4442	4082	0.92	5825	1.43
6	4528	4352	0.96	7137	1.64
7	4577	4082	0.89	5110	1.25
8	4664	3784	0.81	7529	1.99
9	4723	3945	0.84	10887	2.76
10	4756	3420	0.72	5933	1.73
11	4937	3353	0.68	8057	2.40
12	5123	3955	0.77	5698	1.44
		Mean =	0.84	Mean =	1.85
		Std Dev =	0.095	Std Dev =	0.437

End Distance of 5D:

Test Number	Predicted Yield Load (lbs)	Tested Yield Load (lbs)	Tested/Predicted Yield Load Ratio	Ultimate Load (lbs)	Ultimate Load / Yield Load Ratio
13	4124	3500	0.85	6187	1.768
14	4162	4004	0.96	8047	2.010
15	4323	4039	0.93	6099	1.510
16	4379	3617	0.83	5854	1.619
17	4447	3583	0.81	5551	1.549
18	4520	4249	0.94	7020	1.652
19	4578	3015	0.66	3642	1.208
20	4680	3309	0.71	5776	1.746
21	4719	4455	0.94	8801	1.976
22	4764	3867	0.81	6256	1.618
23	4935	3759	0.76	6344	1.687
24	5114	3857	0.75	6148	1.594
		Mean =	0.83	Mean =	1.66
		Std Dev =	0.100	Std Dev =	0.211

End Distance of 3D:

Test Number	Predicted Yield Load (lbs)	Tested Yield Load (lbs)	Tested/Predicted Yield Load Ratio	Ultimate Load (lbs)	Ultimate/Yield Load Ratio
25	4132	3417	0.83	4396	1.29
26	4257	3427	0.80	5502	1.61
27	4321	3182	0.74	7039	2.21
28	4439	3965	0.89	5042	1.27
29	4474	3759	0.84	4778	1.27
30	4540	3730	0.82	5042	1.35
31	4637	3750	0.81	5208	1.39
32	4684	3975	0.85	4973	1.25
33	4741	4552	0.96	6413	1.41
34	4743	4347	0.92	5345	1.23
35	5023	4269	0.85	4875	1.14
36	5135	3603	0.70	4562	1.27
		Mean =	0.83	Mean =	1.39
		Std Dev =	0.071	Std Dev =	0.284

End Distance of 2D:

Test Number	Predicted Yield Load (lbs)	Tested Yield Load (lbs)	Tested/Predicted Yield Load Ratio	Ultimate Load (lbs)	Ultimate Load / Yield Load Ratio
37	4134	3652	0.88	3720	1.02
38	4264	2545	0.60	2545	1.00
39	4320	3544	0.82	3622	1.02
40	4426	2888	0.65	2888	1.00
41	4456	3270	0.73	3417	1.04
42	4524	2722	0.60	2722	1.00
43	4609	2164	0.47	2164	1.00
44	4667	3064	0.66	3094	1.01
45	4715	3270	0.69	3319	1.01
46	4742	2653	0.56	2653	1.00
47	4991	3006	0.60	3006	1.00
48	5103	2839	0.56	2996	1.06
		Mean =	0.65	Mean =	1.01
		Std Dev =	0.115	Std Dev =	0.019

Mode IV Bolted Connection Tests

It should be noted that the "n/a" term in the "Ultimate Load" column of the table below represents the fact that the corresponding connection was not loaded to failure. These tests were stopped prematurely, when the external LVDTs ran out of stroke and is unrelated to load capacity. In the tests after the first three, the external LVDTs were adjusted to allow for more stroke and the internal LVDT was used once the external LVDTs could no longer measure the displacement of the connection. It should be further noted that the "Ultimate Load" value in the table for test number 5 is a minimum ultimate load. This test did not reach its ultimate capacity either, however in this case the test was stopped when it reached the upper boundary of the safety interlocks assigned for load. The connection may have been close to failure in which case, the ultimate to yield load ratio would be correct. On the other hand, it may have been able to carry significantly more load in which case, the ultimate to yield load ratio would be on the low side.

End Distance of 7D:

Test Number	Predicted Yield Load (lbs)	Tested Yield Load (lbs)	Tested/Predicted Yield Load Ratio	Ultimate Load (lbs)	Ultimate/Yield Load Ratio
1	4818	5443	1.13	n/a	
2	4832	5424	1.12	n/a	
3	4998	5385	1.08	n/a	
4	5080	5120	1.01	12650	2.47
5	5201	5982	1.15	18000	3.01
6	5174	5248	1.01	12815	2.44
7	5149	5757	1.12	15341	2.66
8	5215	5962	1.14	16232	2.72
9	5196	4729	0.91	11865	2.51
10	5264	5424	1.03	16000	2.95
11	5513	6011	1.09	15165	2.52
12	5535	5913	1.07	15700	2.66
13	4960	5081	1.02	13158	2.59
14	6021	6413	1.07	19257	3.00
		Mean =	1.07	Mean =	2.69
		Std Dev =	0.066	Std Dev =	0.212

Statistical Analysis

Comparing Predicted and Actual Bolted Connection Yield Loads

Paired T-Tests and Confidence Intervals

Paired T for Mode I Predicted - Mode I Tested

	N	Mean	StDev	SE Mean
Mode I Predicted	12	6935	1175	339
Mode I Tested	12	7405	1607	464
Difference	12	-470	1665	481

95% CI for mean difference: (-1528, 589)
T-Test of mean difference = 0 (vs not = 0): T-Value = -0.98 P-Value = 0.350

Paired T for Mode III Predicted - Mode III Tested

	N	Mean	StDev	SE Mean
Mode III Predicted	12	4560.9	300.3	86.7
Mode III Tested	12	3835.1	342.6	98.9
Difference	12	726	473	137

95% CI for mean difference: (425, 1026)
T-Test of mean difference = 0 (vs not = 0): T-Value = 5.31 P-Value = 0.000

Paired T for Mode IV Predicted - Mode IV Tested

	N	Mean	StDev	SE Mean
Mode IV Predicted	14	5211	314	84
Mode IV Tested	14	5564	458	122
Difference	14	-352.6	339.5	90.7

95% CI for mean difference: (-548.6, -156.6)
T-Test of mean difference = 0 (vs not = 0): T-Value = -3.89 P-Value = 0.002

Comparing Results From End Distance Tests

General Linear Model (Mode I_m)

Factor	Type	Levels	Values
End Dist	fixed	4	3D 4D 5D 7D

Analysis of Variance for Tested/Predicted, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
End Dist	3	0.13351	0.13351	0.04450	1.00	0.401
Error	44	1.95282	1.95282	0.04438		
Total	47	2.08632				

Bonferroni 95.0% Simultaneous Confidence Intervals
Response Variable Tested/Predicted
Comparisons with Control Level
End Dist = 7D subtracted from:

End Dist	Lower	Center	Upper
3D	-0.2824	-0.06833	0.1457
4D	-0.1666	0.04750	0.2616
5D	-0.1449	0.06917	0.2832

```
--------+---------+---------+--------
(-------------*------------)
          (------------*------------)
           (------------*-------------)
--------+---------+---------+--------
      -0.16      0.00      0.16
```

Bonferroni Simultaneous Tests
Response Variable Tested/Predicted
Comparisons with Control Level
End Dist = 7D subtracted from:

Level End Dist	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3D	-0.06833	0.08601	-0.7945	1.000
4D	0.04750	0.08601	0.5523	1.000
5D	0.06917	0.08601	0.8042	1.000

Sidak 95.0% Simultaneous Confidence Intervals
Response Variable Tested/Predicted
Comparisons with Control Level
End Dist = 7D subtracted from:

End Dist	Lower	Center	Upper	--------+---------+---------+--------
3D	-0.2818	-0.06833	0.1451	(----------*----------)
4D	-0.1660	0.04750	0.2610	(----------*----------)
5D	-0.1443	0.06917	0.2826	(----------*----------)
				--------+---------+---------+--------
				-0.16 0.00 0.16

Sidak Simultaneous Tests
Response Variable Tested/Predicted
Comparisons with Control Level
End Dist = 7D subtracted from:

Level End Dist	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3D	-0.06833	0.08601	-0.7945	0.8159
4D	0.04750	0.08601	0.5523	0.9278
5D	0.06917	0.08601	0.8042	0.8105

Dunnett 95.0% Simultaneous Confidence Intervals
Response Variable Tested/Predicted
Comparisons with Control Level
End Dist = 7D subtracted from:

End Dist	Lower	Center	Upper	--------+---------+---------+--------
3D	-0.2776	-0.06833	0.1409	(----------*----------)
4D	-0.1617	0.04750	0.2567	(----------*----------)
5D	-0.1401	0.06917	0.2784	(----------*----------)
				--------+---------+---------+--------
				-0.16 0.00 0.16

Dunnett Simultaneous Tests
Response Variable Tested/Predicted
Comparisons with Control Level
End Dist = 7D subtracted from:

Level End Dist	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3D	-0.06833	0.08601	-0.7945	0.7669
4D	0.04750	0.08601	0.5523	0.9023
5D	0.06917	0.08601	0.8042	0.7606

General Linear Model (Mode III_s)

Factor	Type	Levels	Values
End Dist	fixed	4	2D 3D 5D 7D

Analysis of Variance for Tested/Predicted, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
End Dist	3	0.30775	0.30775	0.10258	11.05	0.000
Error	44	0.40865	0.40865	0.00929		
Total	47	0.71640				

Bonferroni 95.0% Simultaneous Confidence Intervals
Response Variable Tested/Predicted
Comparisons with Control Level
End Dist = 7D subtracted from:

End Dist	Lower	Center	Upper
2D	-0.2913	-0.1933	-0.09541
3D	-0.1088	-0.0108	0.08709
5D	-0.1138	-0.0158	0.08209

```
-----+---------+---------+---------+-
  (-------*-------)
                  (-------*-------)
                  (-------*-------)
-----+---------+---------+---------+-
   -0.24     -0.12      0.00      0.12
```

Bonferroni Simultaneous Tests
Response Variable Tested/Predicted
Comparisons with Control Level
End Dist = 7D subtracted from:

Level End Dist	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2D	-0.1933	0.03934	-4.914	0.0000
3D	-0.0108	0.03934	-0.275	1.0000
5D	-0.0158	0.03934	-0.402	1.0000

Sidak 95.0% Simultaneous Confidence Intervals
Response Variable Tested/Predicted
Comparisons with Control Level
End Dist = 7D subtracted from:

```
End Dist    Lower   Center    Upper  -----+---------+---------+---------+-
2D       -0.2910  -0.1933  -0.09568    (-------*-------)
3D       -0.1085  -0.0108   0.08682                    (-------*-------)
5D       -0.1135  -0.0158   0.08182                    (-------*-------)
                                     -----+---------+---------+---------+-
                                        -0.24     -0.12      0.00      0.12
```

Sidak Simultaneous Tests
Response Variable Tested/Predicted
Comparisons with Control Level
End Dist = 7D subtracted from:

Level End Dist	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2D	-0.1933	0.03934	-4.914	0.0000
3D	-0.0108	0.03934	-0.275	0.9900
5D	-0.0158	0.03934	-0.402	0.9700

Dunnett 95.0% Simultaneous Confidence Intervals
Response Variable Tested/Predicted
Comparisons with Control Level
End Dist = 7D subtracted from:

```
End Dist    Lower   Center    Upper  -----+---------+---------+---------+-
2D       -0.2891  -0.1933  -0.09761    (-------*-------)
3D       -0.1066  -0.0108   0.08489                    (-------*-------)
5D       -0.1116  -0.0158   0.07989                    (-------*-------)
                                     -----+---------+---------+---------+-
                                        -0.24     -0.12      0.00      0.12
```

Dunnett Simultaneous Tests
Response Variable Tested/Predicted
Comparisons with Control Level
End Dist = 7D subtracted from:

Level End Dist	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2D	-0.1933	0.03934	-4.914	0.0000
3D	-0.0108	0.03934	-0.275	0.9856
5D	-0.0158	0.03934	-0.402	0.9580