Field Measurements of Plow Loads During Ice Removal Operations

Iowa Department of Transportation Project HR 334

Final Report

by
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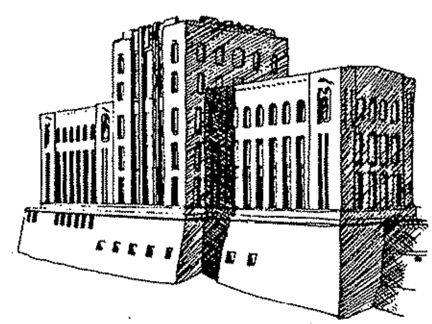

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ABSTRACT

One of the more severe winter hazards is ice or compacted snow on roadways. While three methods are typically used to combat ice (salting, sanding and scraping), relatively little effort has been applied to improve methods of scraping ice from roads. In this project, a new test facility has been developed , comprising a truck with an underbody blade, which has been instrumented such that the forces to scrape ice from a pavement can be measured. A test site has been used, which is not accessible to the public, and ice covers have been sprayed onto the pavement and subsequently scraped from it, while the scraping loads have been recorded. Three different cutting edges have been tested for their ice scraping efficiency. Two of the blades are standard (one with a carbide insert, the other without) while the third blade was designed under the SHRP H-204A project.

Results from the tests allowed two parameters to be identified. The first is the scraping efficiency which is the ratio of vertical to horizontal force. The lower this ratio, the more efficiently ice is being removed. The second parameter is the scraping effectiveness, which is related (in some as yet unspecified manner) to the horizontal load. The higher the horizontal load, the more ice is being scraped. The ideal case is thus to have as high a horizontal load as possible, combined with the lowest possible vertical load. Results indicate that the SHRP blade removed ice more effectively than the other two blades under equivalent conditions, and furthermore, did so with greater efficiency and thus more control. Furthermore, blade angles close to 0° provide for the most efficient scraping for all three blades.

The study has shown that field testing of plow blades is possible in controlled situations, and that blades can be evaluated using this system. The system is available for further tests as are deemed appropriate.

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I. INTRODUCTION

Maintaining safe driving conditions in winter weather can be a difficult task. There are three main methods used to remove snow and ice from the road surface. The first is to use salt, or some other chemical, to depress the freezing point and thus melt the snow and ice from the road surface. The second method is to use sand to increase the friction of an ice covered road and thereby make the road more driveable. Many times this method is combined with the first by applying a mix of salt and sand to the road. This creates an immediate improvement in traction caused by the presence of the sand and allows for the salt to melt the ice over time. The third method is to remove the snow and ice mechanically by means of a plow. This can be extremely effective in heavy snow falls, but much less effective when ice or compacted snow is present on the pavement surface. These materials can form very strong bonds with the road surface and prove to be rather hard to remove by scraping.

To remove ice from roadways, salting is probably the most widely used method, but also poses a number of problems. Salt can cause serious degradation of bridges and pavements, as well as corrosive damage to automobiles. Environmental concerns, such as contamination of the ground water and damage to vegetation, are also associated with the use of salt. Furthermore, the use of sand may give rise to hazardous levels of airborne particulates. Given these concerns over the use of salt and sand, it seems prudent to investigate methods of improving ice removal by scraping.

Recent studies have shown that the shape of the blade used on a plow blade is very important in determining the loads acting on the plow. These studies, which were part of the Strategic Highway Research Program (SHRP), examined the effect of a number of parameters on the forces required to remove ice from a sample of pavement in the laboratory (Nixon 1993; Nixon et al., 1993). Some of the parameters studied included clearance angle, attack angle, rake angle, and blade flat width, are shown in figure 1. It was found that if a blade had a non zero clearance angle (specifically, in this series of experiments, if the clearance angle was 2° or greater) then the forces on the blade were reduced by a factor of twenty when compared to a blade with a zero degree clearance angle. It was also found that the scraping forces increased when the blade flat width was more than 3/8 of an inch.

The tests performed in the laboratory were under somewhat more ideal conditions than those found on true road surfaces and on a much smaller scale. Because there is a lack of data on the loads experienced by a snow plow during ice removal, the need for full scale tests with current snow removal equipment became apparent.

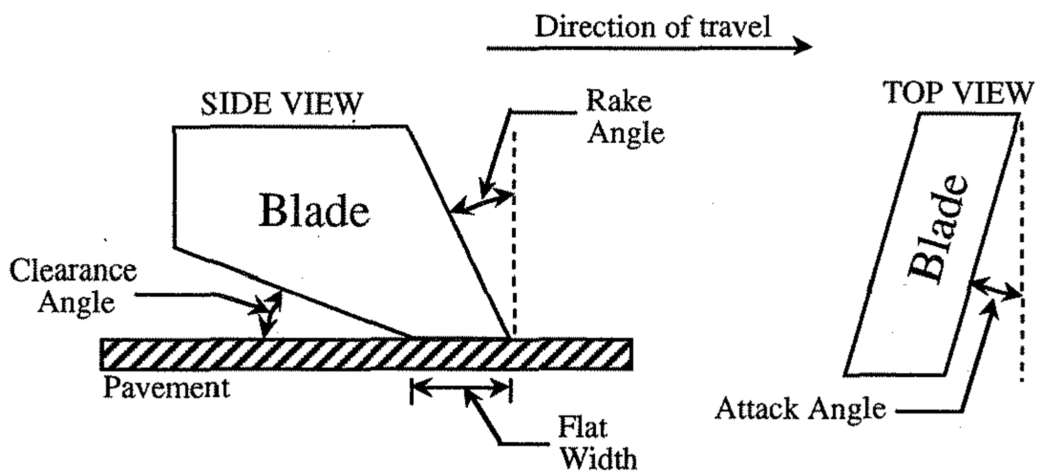


Figure 1. Definition of terms used in SHRP study.

The purpose of the project described herein was to develop a method to measure the forces on an underbody plow during the removal of ice from pavement and to compare different blade types under a variety of conditions. The tests performed used two different commercially available blades and a prototype blade developed under SHRP project H-204. The blades were tested at angles of 0°, 15°, and 30° at low and high download conditions.

II. EXPERIMENTAL DESCRIPTION

A. Underbody Plow. The tests were performed using a 1975 International Fleetstar 2050 25 ton gross vehicle weight (GVW) dump truck on loan from the Iowa Department of Transportation (IDoT). The truck (IDoT # A20607) was fitted with a Wausau truck grader (model HH8-7983-5) hereafter referred to as an underbody plow. The underbody plow was bolted to the truck's frame midway between the front and rear axles (see figure 2). Five hydraulic control levers in the truck's cab allowed the operator full use of the underbody plow. The driver was able to control the left and right vertical position (and thus download), the blade angle, cast angle, and cast angle lock.

The most significant benefit of an underbody plow is the ability to place a variable download on the cutting edge or blade of the plow. This cannot be accomplished with standard front mount blades or "skippers" as they are called. Blades of this type have only their own weight for a download force. Underbody plows on the other hand can have download forces that approach the truck weight.

1. Range of motion. The blade could be moved vertically approximately 8 inches by the extension of two hydraulic cylinders and a linkage system. Figure 3 shows the left side cylinder and linkage system. Extension of the hydraulic cylinder causes the triangular shaped links to rotate and in turn lower the blade. The two cylinders allow the operator to control the vertical position or download to the left or right side of the blade independently. The vertical range allows for the download pressure on the blade to be varied. Download was accomplished by transferring the weight of the truck from the tires to the blade by lowering the blade with the two hydraulic cylinders. The more the blade was forced down the more weight was taken away from the tires and placed on the blade.

In addition to the variable download abilities, the blade angle could be adjusted over an 80 degree range. The blade angle was defined as the angle the blade made with the perpendicular of the road surface as shown in figure 4. This range of motion allowed the blade to be positioned anywhere between a point nearly perpendicular to the road surface to a point that placed the blade nearly parallel to the road surface. Blade angle was set by

Figure 2. IDoT truck used for the test series.

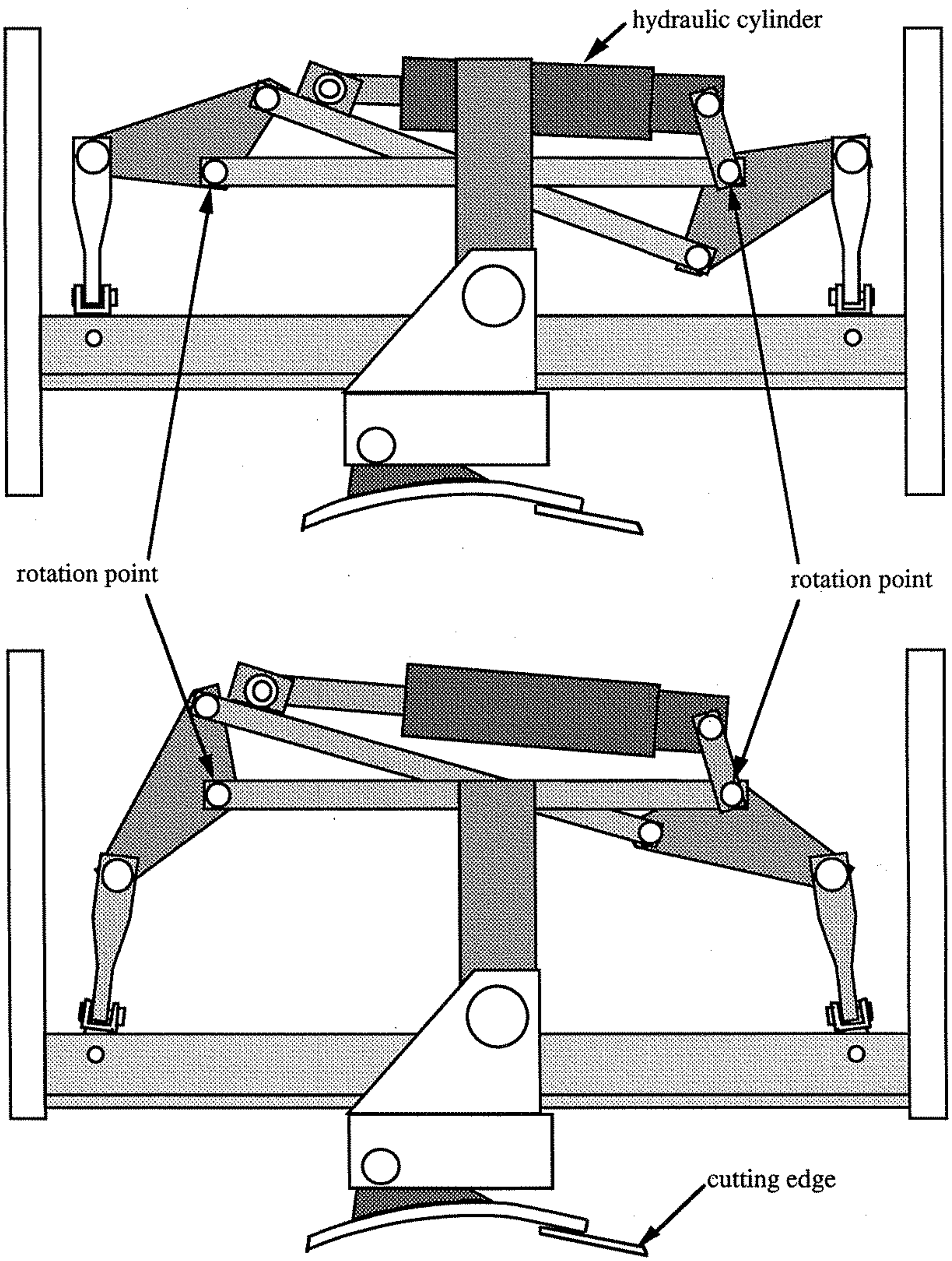


Figure 3. Side view of underbody plow's vertical motion.

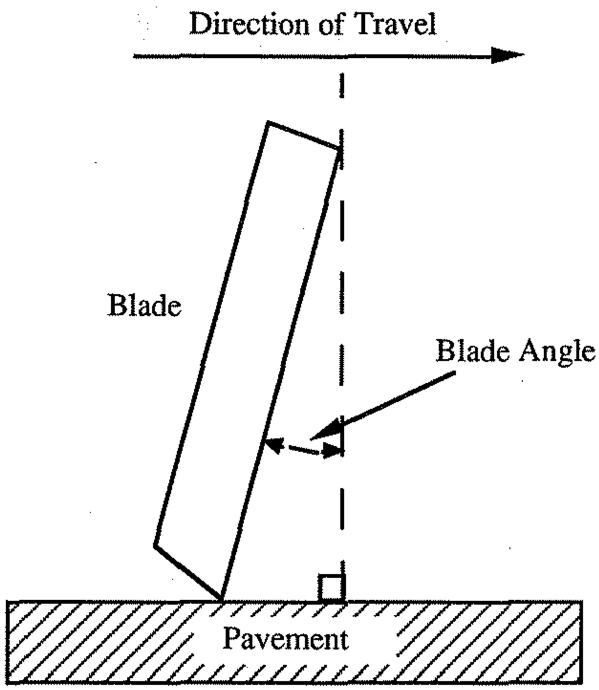


Figure 4. Definition of blade angle.

two hydraulic cylinders that act in parallel to rotate the blade. The rotation of the blade can be seen in figure 5, which shows the left side view of the plow mechanism.

To prevent damage to the blade arising from irregularities in the road such as protruding concrete joints, bridge expansion joints, and manhole covers, the hydraulic system is equipped with a shock accumulator. When a high spot in the road is encountered the blade will rotate back causing the cylinders to retract. This in turn requires that the hydraulic oil be displaced from the cylinders to the shock accumulator. The shock accumulator is in series with the extending side of the cylinders and consists of a cylinder with a spring loaded piston inside. The spring is strong enough to keep the blade in place firmly, but allows fluid to collect when irregularities in the road are encountered minimizing damage to the plow and the road.

The cast angle of the blade could also be adjusted. The cast angle was defined as the angle the blade makes with the perpendicular to the direction of travel as shown in figure 6. This allows the snow and ice debris to be directed to the left or right side of the road. The cast angle could range from 30 degrees left to 30 degrees right. To insure the blade stayed at the selected cast angle during scraping two hydraulically powered locking pins, located above the blade mount, locked into notches on the plow carriage.

2. Cutting Edges. The cutting edge or blade was bolted to the blade support to allow for easy replacement. For this series of tests three different blades were tested. The first of which was a standard steel blade that came with the truck. This blade was 3/4 x 5 x 96 inches. The other two blades both had carbide inserts. The first was a commercially available blade, built by Kennametal, part number PB748H. The second was a custom designed and built blade. This blade was designed under the Strategic Highway Research Program (SHRP) project H-204A, and built for use with this truck. The geometries of the blades are shown in figure 7. The second and third blades were nearly the same dimensions as the original blade, except that each was made of two sections that were 48 inches long.

3. Instrumentation. Forces on the blade were measured using pressure gages in the hydraulic lines to the cylinders responsible for the download force or vertical displacement and the rotation of the blade. For this three International Pressure Products ST-420 0 - 3000 psi gages were used; one gage for each side of the vertical motion and one for the pair of cylinders that rotate the blade angle. Each gage had a self contained signal conditioner that converts the pressure measurements into a voltage signal, which was recorded by a computer. After calibration of the system the vertical and horizontal forces on the blade were determined from the pressure gage data.

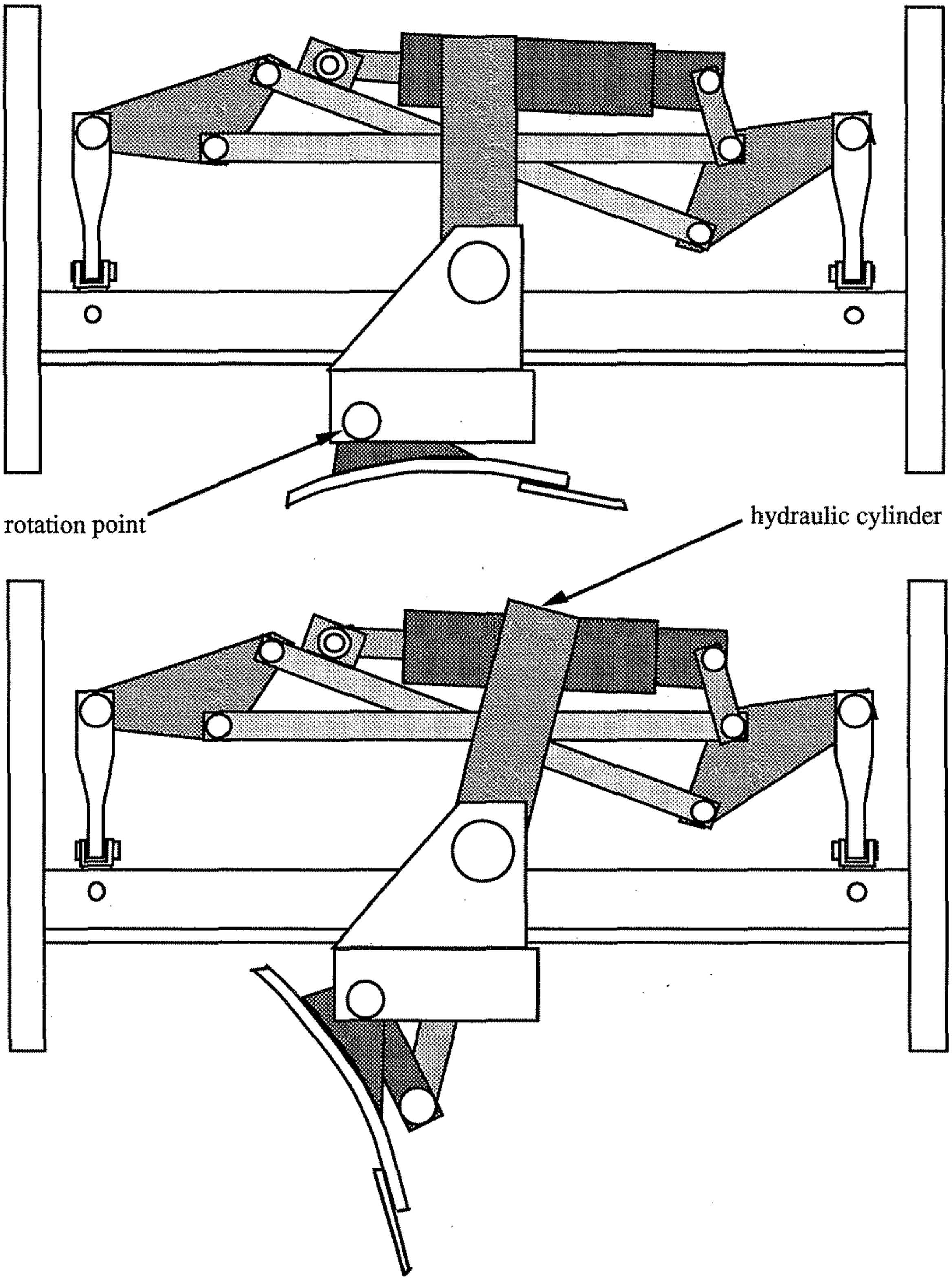
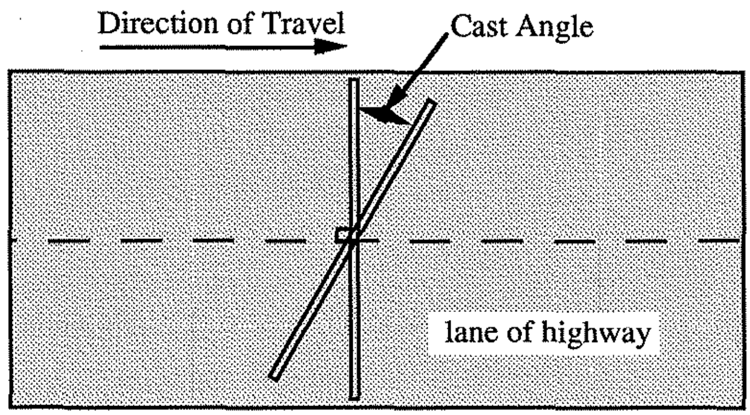


Figure 5. Side view of underbody plow's blade angle motion.



Top View of the Blade

Figure 6. Definition of cast angle.

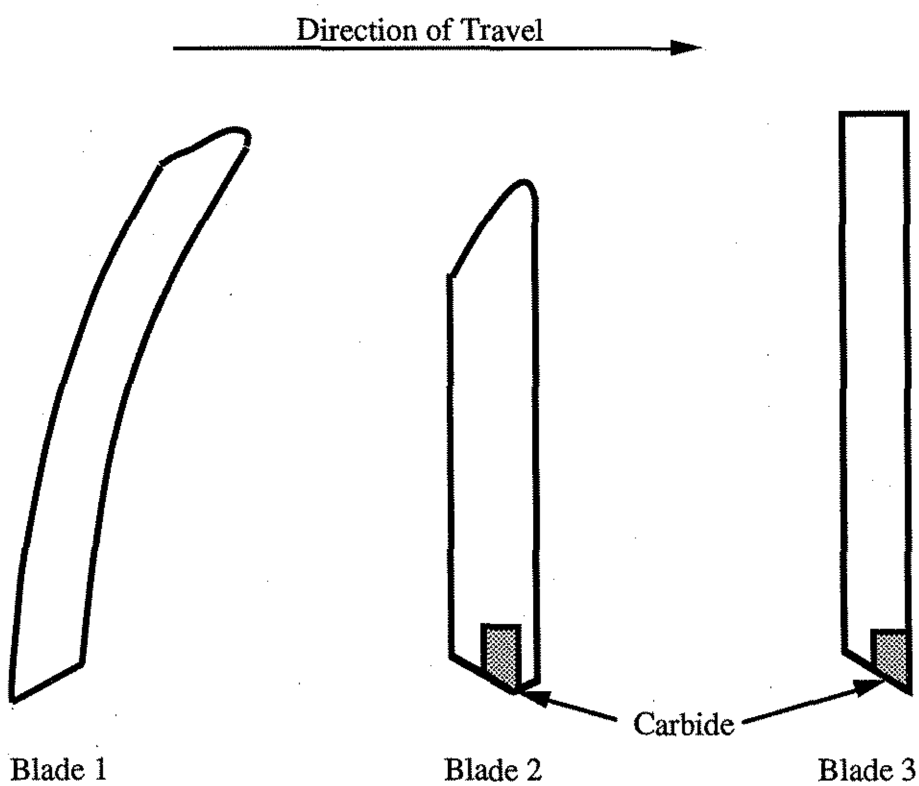


Figure 7. Side view of cutting edges used in experiment.

The angle that the blade had with the pavement was measured with an inclinometer. A Schaevitz Angle Star Protractor System was used for this task. The inclinometer was located on the left side of the blade in a protective box shown in figure 8. The velocity of the truck was determined by a fifth wheel located at the rear of the truck and shown in figure 9. This fifth wheel used a DC tachometer generator that provided a linear relationship of the speed to voltage. This allowed the speed to be determined with an accuracy of 0.1 mph.

Also on the truck was a load cell used to measure the force required to pull a weighted sled behind the truck. This provided information about the friction changes in the ice after the ice had been scraped by the blade. The sled, shown in figure 10, had a total weight of 330 pounds and was pulled at a constant velocity across the ice both before and after a test. This method of measuring the change in friction of the ice proved unreliable and will require further development.

Data signals from the sensors were collected on a portable PC. For these tests a Kontron IP Lite was used. This PC was chosen because it was shock rated for operation up to 5 gravities. This shock rating was needed to guarantee normal data acquisition because the truck bounced greatly during testing. An analog to digital circuit board in the PC allowed the software to collect and store the data. A Metrabyte DAS-8 analog to digital board was used along with the CODAS data acquisition software by Dataq Instruments. Data was written to the PC's hard drive during testing and then analyzed after testing at the Iowa Institute of Hydraulic Research (IIHR) ice laboratory. Power for the computer and sensors was obtained from the truck batteries through a power inverter and filter system built at IIHR. The computer and power supply are shown in testing configuration in figure 11.

B. Water Tank and Spray System. A 750 gallon tank of water in the truck was used to create the ice necessary for the testing. A 3 hp pump at the back of the tank delivered the water at 60 psi to a spray nozzle located on a boom offset from the truck as shown in figure 12. The spray nozzle allowed the water to be sprayed uniformly over the pavement with a 25 ft wide spread. The spray system was also equipped with solenoid valves that allowed the driver to turn the water flow on or off from the cab of the truck.

C. Experimental Procedure. All tests were performed at the spillway apron of the Coralville Reservoir located approximately five miles north of Iowa City. This site was chosen because it was flat and inaccessible to the public during the winter months.

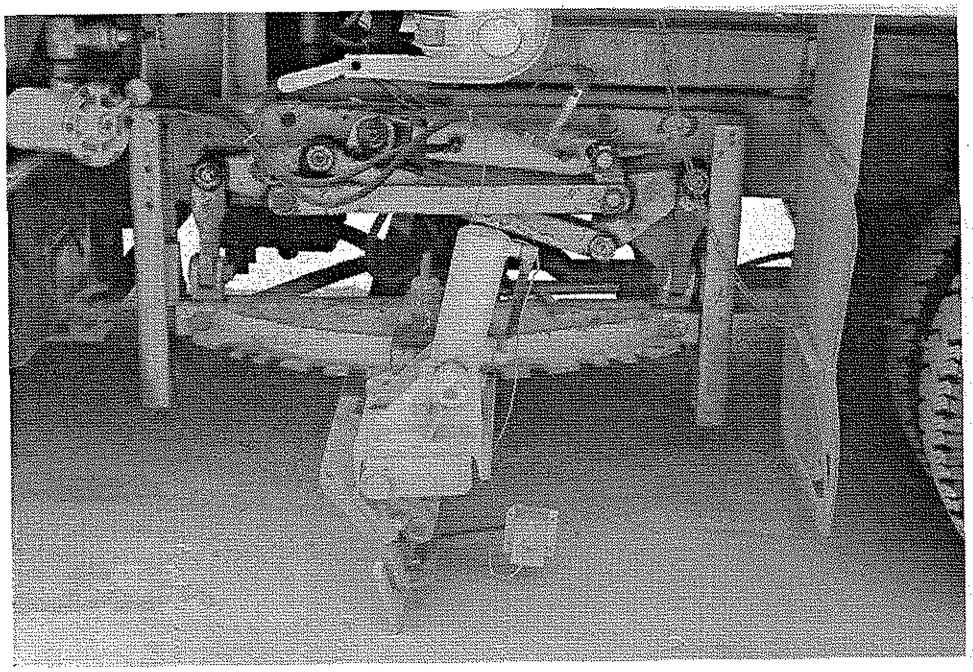


Figure 8. Side view of underbody plow showing instrumentation.

Figure 9. Fifth wheel used to record truck's speed during tests.

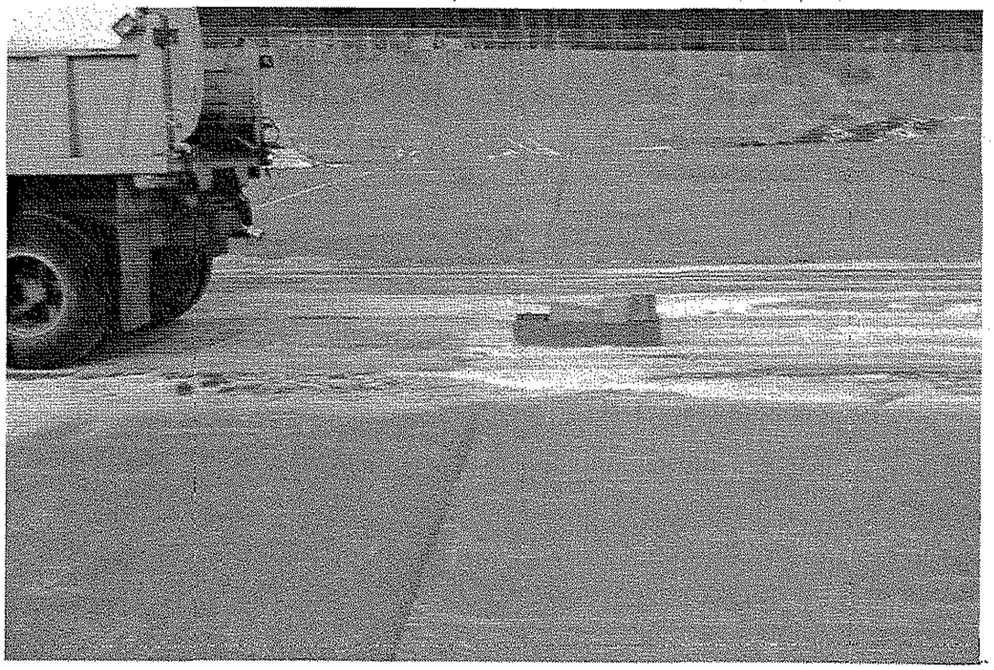


Figure 10. Friction sled pulled behind truck to measure change of road conditions.

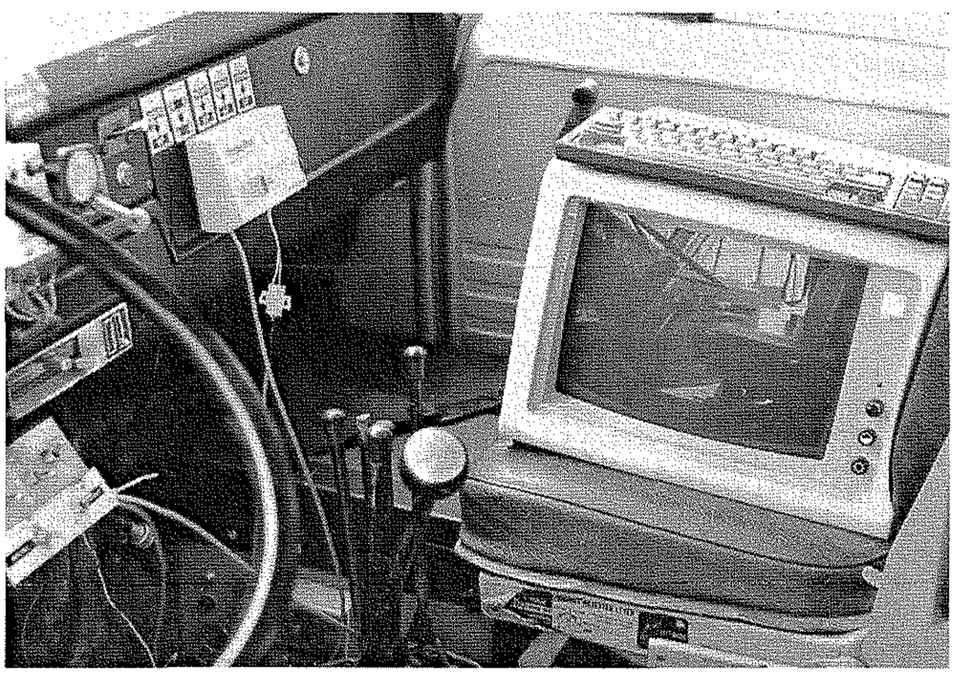


Figure 11. Computer system in testing configuration.

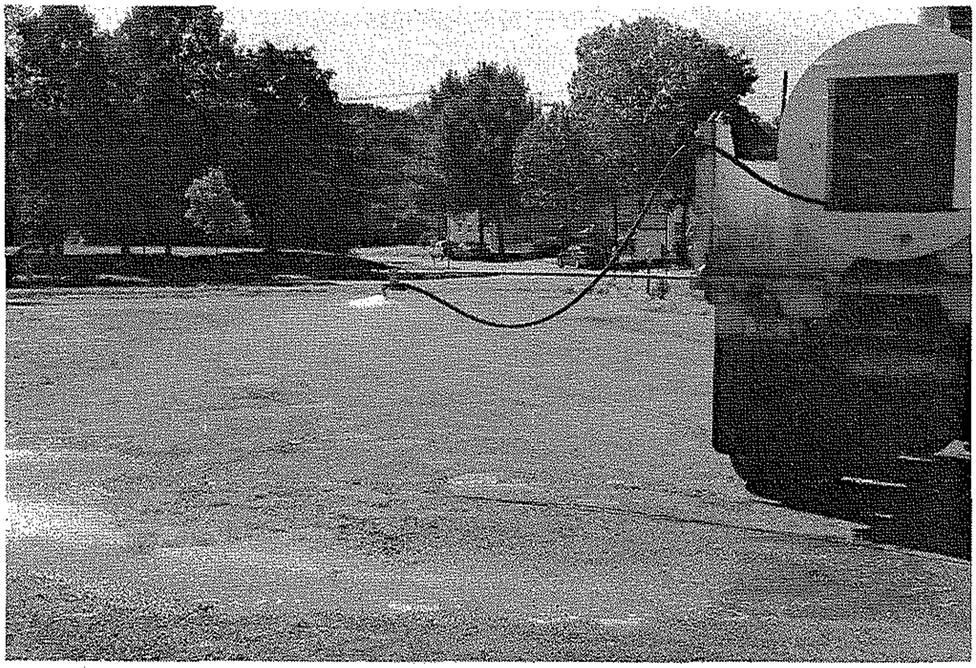


Figure 12. Spray system used to make ice sheet for tests.

1. Meteorological requirements. It was found that the overnight low temperature had to be no more than 20 ° F to insure a good quality ice sheet. A study of the temperature history of Iowa City was conducted to provide an idea as to the number of testing days to be expected for a winter. The temperature records for Iowa City over the last 100 years were examined indicating that testing would most likely begin in mid November and run through mid March. It was found that the possible number of testing days ranged from as many as 93 days to as few as 33 days. Sunny days with highs in the mid to upper twenties and lows in the teens proved to be the optimum weather conditions. Such weather conditions melted post test ice by sunset and a new sheet could usually be started by 10 PM. Warmer days pushed ice making times later into the night with 2 AM being a limit as to how late ice could be made. After 2 AM there was not adequate hardening time for the ice sheet and the ice had a more slush like consistency.

2. Preparation of ice sheet. Water used to make the test ice was obtained from the University of Iowa Water Treatment Plant and taken to the testing site where the temperature of the water and the air were recorded. The water was then sprayed on the concrete using the previously mentioned spray system. The water was applied by driving back and forth over the testing area. The area covered was approximately 25 X 180 feet. The truck traveled at approximately 2 ft/s during the spraying process. Provided the temperature was low enough the water was generally frozen within two minutes, and the entire 750 gallon was sprayed in 40 minutes. The ice was then left to harden overnight and the testing would take place the following morning. The ice sheet formed was 1/4 to 1/2 inch thick.

Water temperature had an effect on the hardening time for the ice. Because the Water Plant's source was the Iowa River, water temperature throughout much of the winter is from 33 to 35 °F. This allowed for the fastest hardening times for the ice throughout most of the testing season. However, near the beginning and end of the testing season the river temperature can be upwards of 50 °F. Water of this temperature caused very long hardening times for the ice, and could prevent testing altogether. When this occurred chilled water was obtained from the IIHR ice laboratory so that more tests could be conducted.

3. Scraping procedure. To provide better traction of the tires during testing the area around the tank in the box of the truck was filled with gravel, and the tank was filled with water. This gave the truck a total weight of 44,000 pounds with a full tank of water. Air temperature at the concrete surface, ice thickness, and ice condition were recorded prior to testing. The truck was positioned in line with the ice sheet approximately 150 feet from the ice. This allowed enough distance for the truck to accelerate to the desired testing velocity of 15 mph. The angle of the blade was set using the display of the inclinometer in the cab. When the truck began to drive on the ice, the download on the blade was applied until the desired pressure was indicated on the computer screen in the cab of the truck.

The ice sheet was examined after each test and photos were taken. The overall effectiveness of the blade was determined by the amount of ice that the blade removed from the pavement. Some tests were also videotaped to provide a visual record of the blade performance during the test and to allow for replay of the test for closer inspection. Videotaped tests allowed for the dynamic action of the blade to be examined more carefully and to observe the scraping process in slow motion.

4. Calibration of sensors. The pressure gages were calibrated by means of a set of calibrated hydraulic jacks. The blade was first set in position, the jacks were then used to push against the blade at known increments and the voltage from each pressure gage was recorded by the computer at each increment. The known pressures of the jacks could then be used to relate the voltage directly to a force and the calibration coefficient was thus be calculated. This was performed for both horizontal and vertical components of the blade force.

Vertical force on the blade could be calculated from the two pressure gages on the hydraulic cylinders for the vertical motion. Horizontal forces were determined from the pressure in the cylinders that rotate the blade angle. This pressure however, includes a vertical component that is a function of the blade angle. As the blade angle increased, the amount of pressure in the cylinders due to the vertical component also increased. From recording the pressure due to a known vertical load over a range of angles, the relation between angle and vertical load was determined. Calibrating in this way took into account the change in the lever arm length of the blade mechanism, or how the mechanical advantage changed with angle. Once the vertical component was known for a given download, as a function of the blade angle, the horizontal force on the blade could then be determined.

Calibration of the inclinometer required measuring the blade angle with a protractor level for various angles and determining the calibration coefficient. The fifth wheel was calibrated by recording the time it took the truck to travel a known distance at different constant velocities and thus determining the calibration coefficient. The load cell for the friction sled was calibrated using a load cell calibration stand at IIHR.

5. Test matrix. The testing parameters studied were the blade, down pressure, and angle of blade. For each of the three blades previously described the down pressure was tested at a low (500 psi) and high (1200 psi) value. These pressures were the value of the pressure in the hydraulic cylinders responsible for the download. The angle of the blade was set to 0°, 15°, or 30°. A schematic of the test matrix, shown in figure 13, indicates the possible test configurations. Due to the physical limitations of the system, it was not possible to achieve the 0° blade angle for blade 2 and 3.

III. RESULTS

A. Conversion of Raw Data. An example of raw data as obtained from the sensors on the truck are shown in figures 14 and 15. For this particular test (number 28) blade 3 was used with a low download pressure and a blade angle of 30°. Figure 14 displays the voltage from the left and right download sensors and from the speed wheel indicated as channel 1,2 and 5 respectively. Figure 15 displays the horizontal loading cylinders and the blade angle sensor, indicated as channel 3 and channel 4 respectively.

The raw data can then be transformed to show the loads, blade angle and speed of the truck as shown in figures 16 and 17. The vertical force is the sum of channels 1 and 2 and the horizontal force is the difference of channel 3's recorded force less the force due to the vertical loading as determined from the calibration of the system. It should be noted that all values are plotted against the distance traveled from the beginning of the test. The starting point was taken as the point where the raw data of channel 1 and channel 2 leveled off indicating that the download pressure was no longer being increased. A summary of the data values for all the tests is given in appendix A. The results from all the tests in graphical form are presented in appendix B.

B. Definition of Effectiveness and Efficiency. One aim of this project was to maximize the quantity of ice removed by scraping. The more ice removed by the blade, the greater is the effectiveness of the blade. From the test results it appears that the quantity of ice removed is directly proportional to the horizontal load. Accordingly, in this study, it has been assumed that the horizontal force is a measure of the effectiveness of the blade, with a higher horizontal force indicating a higher effectiveness. It should be noted, however, that it is not clear how well effectiveness is consistent from blade to blade. Thus a horizontal force of 10,000 lbs on blade 1 may not be as effective (i.e. may not remove as much ice) as a 10,000 lb horizontal force developed by blade 3. Further work is required to develop this correlation. Nonetheless, a high horizontal load is desirable.

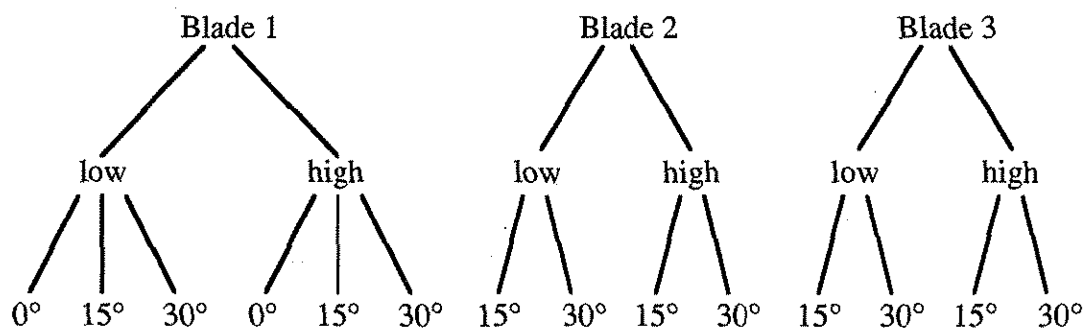


Figure 13. Schematic representation of the test matrix.

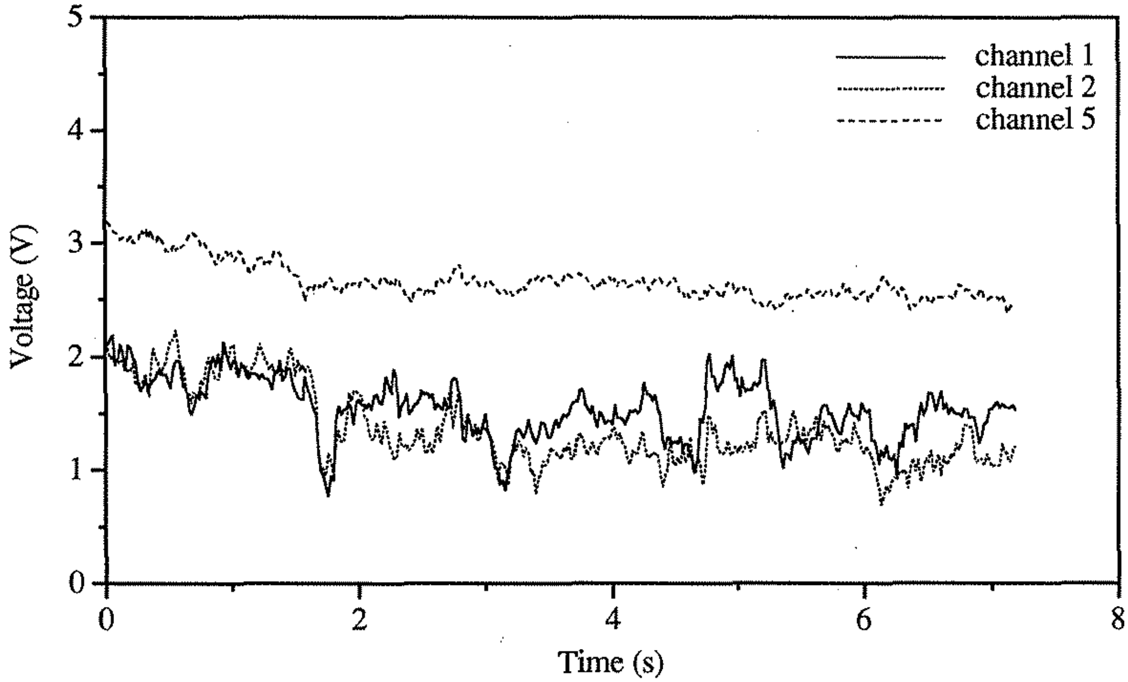


Figure 14. Raw data from sensors for test number 28.

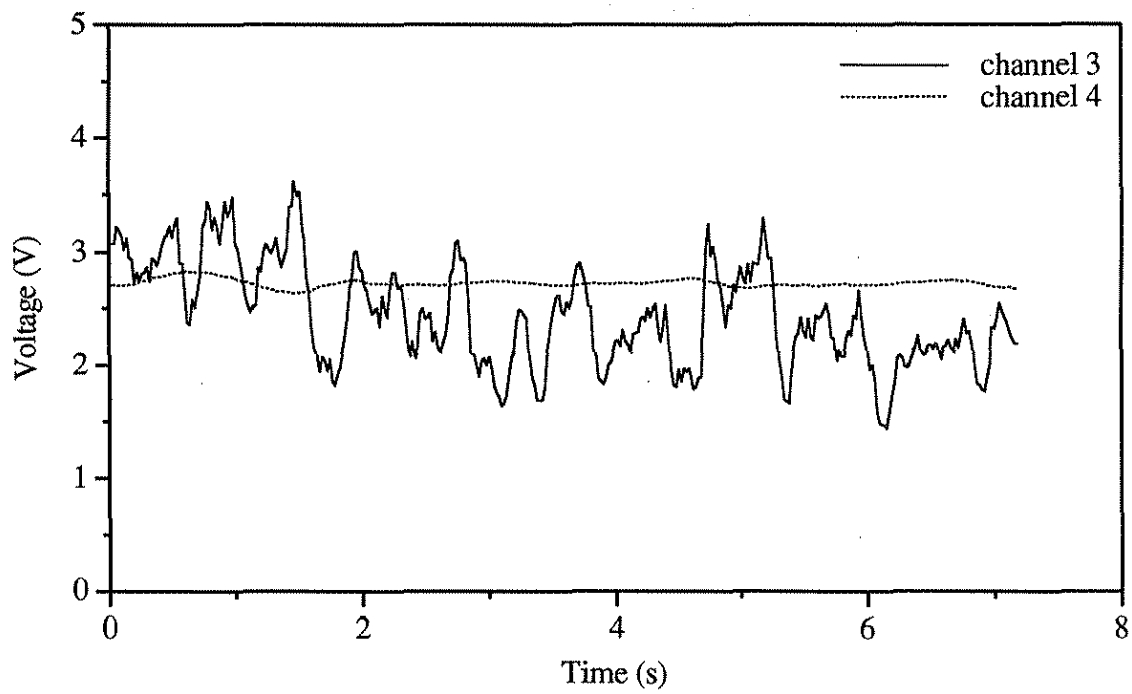


Figure 15. Raw data from sensors for test number 28.

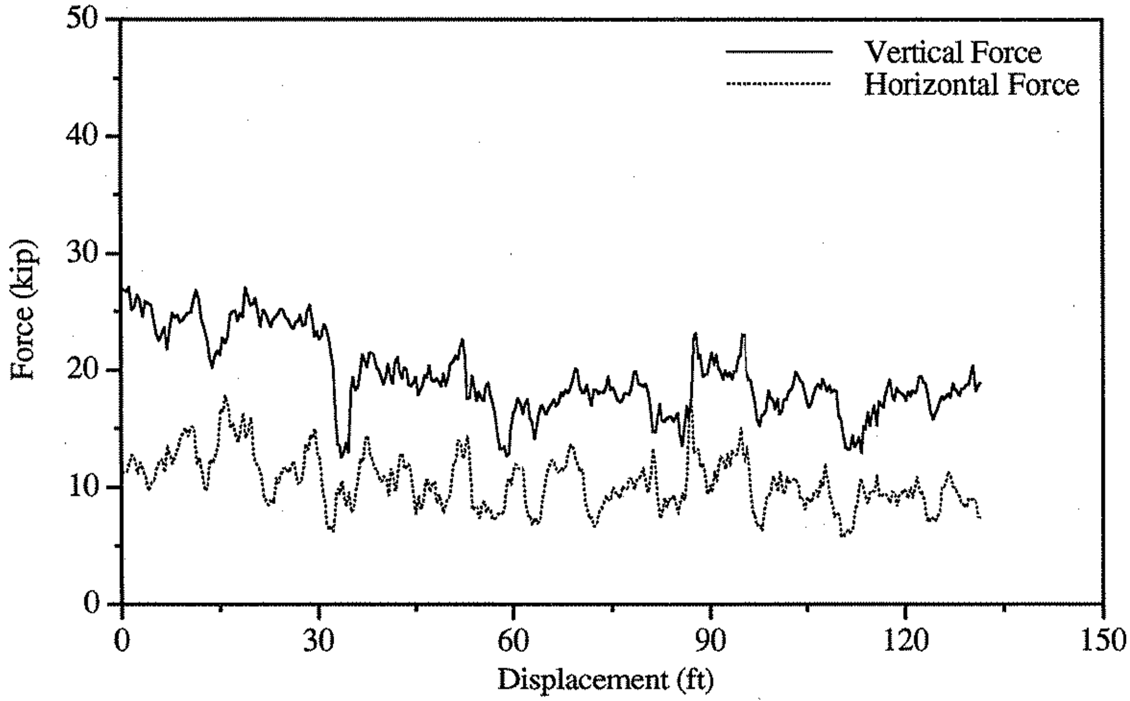


Figure 16. Vertical and horizontal forces on blade for test number 28.

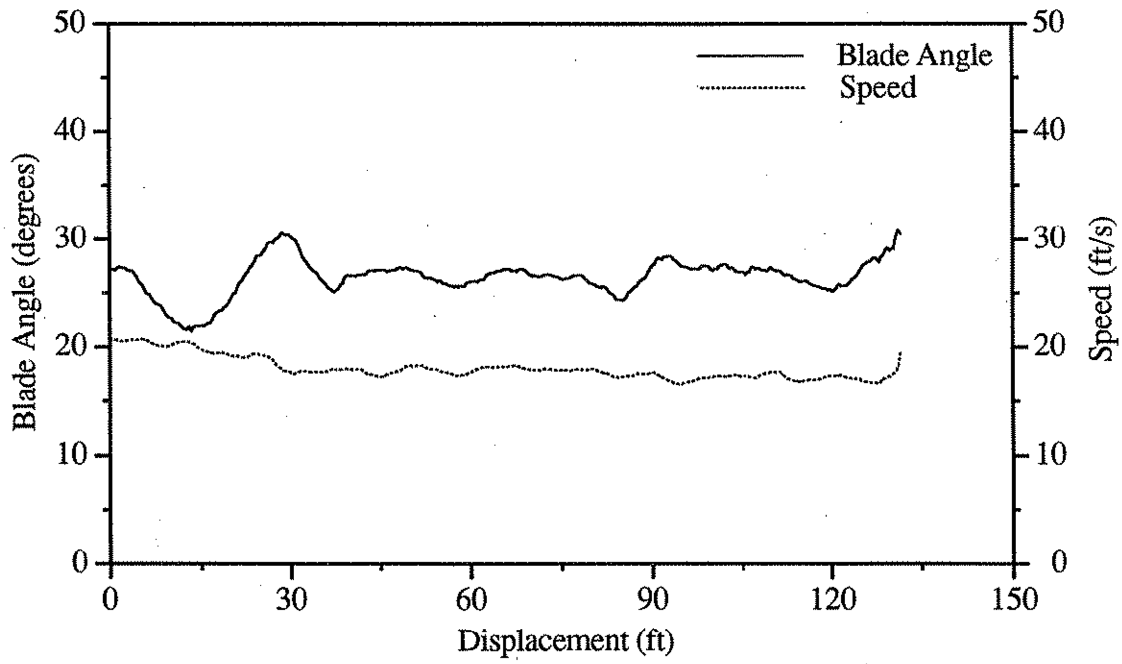


Figure 17. Blade angle and speed of truck for test number 28.

Working against the benefit of a high horizontal load is the tendency of the blade to ride up onto the top of the ice surface, thus cutting no ice. To counteract this tendency to ride up, a vertical download is applied to the blade essentially forcing it into the ice. This vertical load is not directly beneficial to the scraping process, other than forcing the blade into the ice. Further, a high vertical download is cause for concern because it removes traction from the trucks axles, and makes the truck rest predominantly on the cutting edge. Accordingly, the most desirable condition for ice scraping is a high horizontal load (implying much ice removal) and a low vertical load (implying the truck is supported on its axles, rather than on the blade). Thus the ratio of vertical to horizontal force provides a good measure of what might be termed scraping efficiency. However, some care must be taken in the use of this force ratio, because when both vertical and horizontal loads are very low, and thus no ice is being cut, very low values of the force ratio may be observed, apparently implying excellent scraping efficiency, when in fact no ice is being scraped at all. As the value of the force ratio gets larger it indicates the condition of the blade riding across the surface of the ice as opposed to scraping of the ice. The ideal situation for ice removal is thus a low efficiency ratio and a high effectiveness (horizontal force).

C. Efficiency Results. Using the efficiency ratio allows a comparison to be made between the three blades. The results of the tests for all the blades are shown in figure 18 through figure 20. As previously mentioned there were no tests performed at 0° for blade 2 and blade 3 because of the limits of the underbody plow and due to the shape of the blades. It should be noted that the data has been offset about the tested blade angles to provide for clearer presentation of results. The average value of all the tests and the standard deviations are plotted for each blade. It was found that there was in some cases significant scatter in the data. This will be discussed further in the next chapter. The results obtained for blade 3 have been separated into two groups. This was due to a high amount of wear that the blade experienced from removing snow and ice deposited on the test site during a storm. This point will be discussed further in the next chapter.

By plotting the average values of the force ratio for all the test conditions in ascending order, a comparison of the three blades can be made (see figure 21). The notation used for the categories along the x-axis in figure 21 is as follows, blade number, blade angle, low or high download, and for blade 3 tests before wear occurred (b) or after wear occurred (a). Blade 3 had the lowest force ratio for the first four cases followed closely by blade 1 and then blade 2.

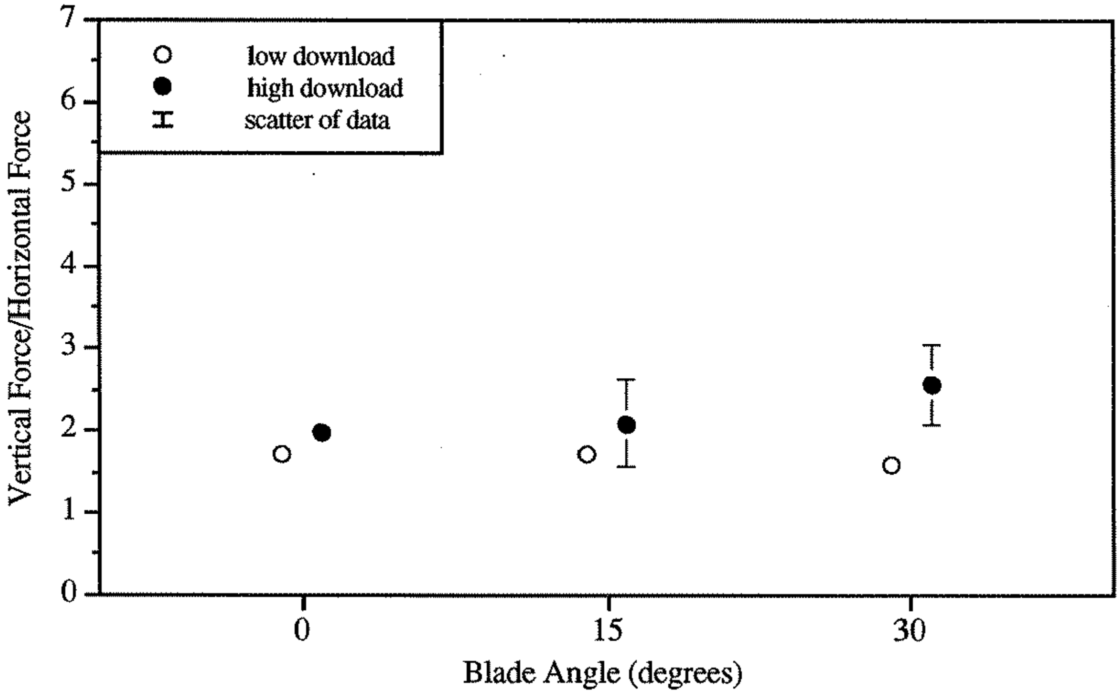


Figure 18. Average force ratio values for test series performed on blade 1.

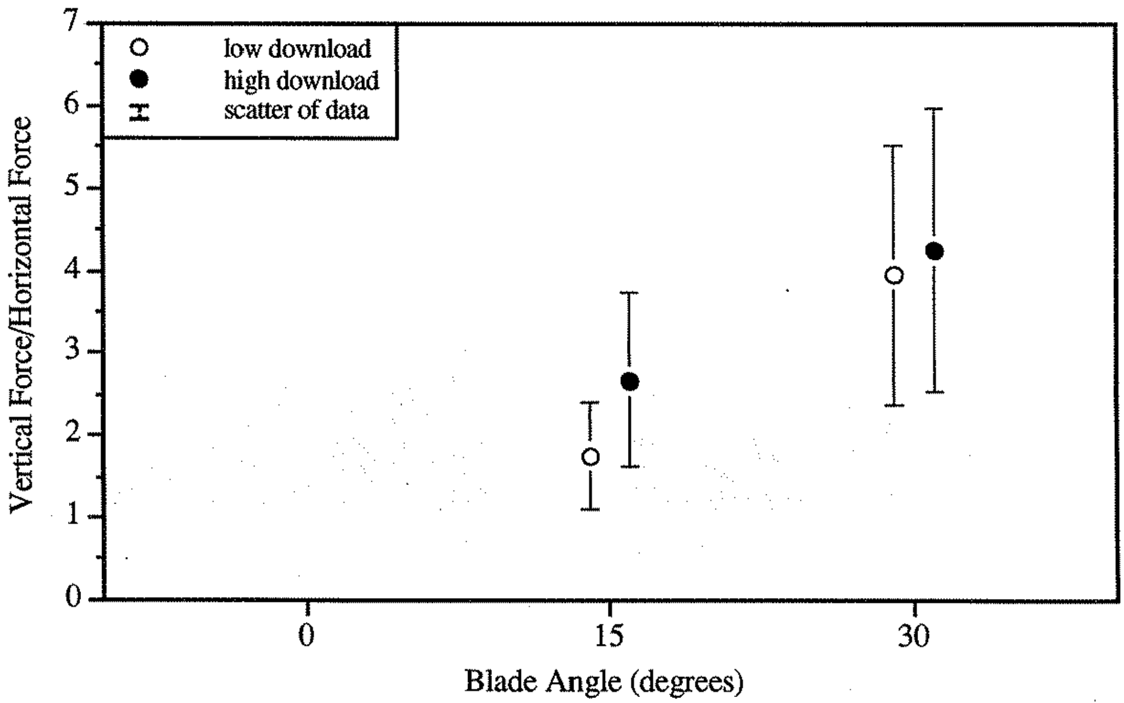


Figure 19. Average force ratio values for test series performed on blade 2.

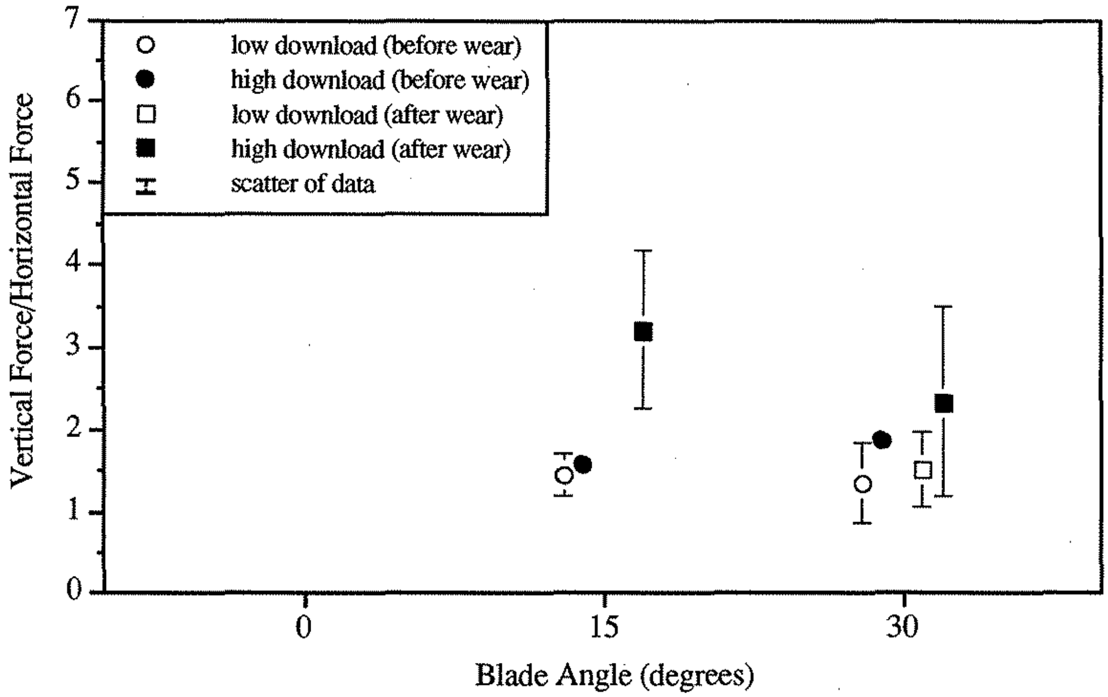


Figure 20. Average force ratio values for test series performed on blade 3.

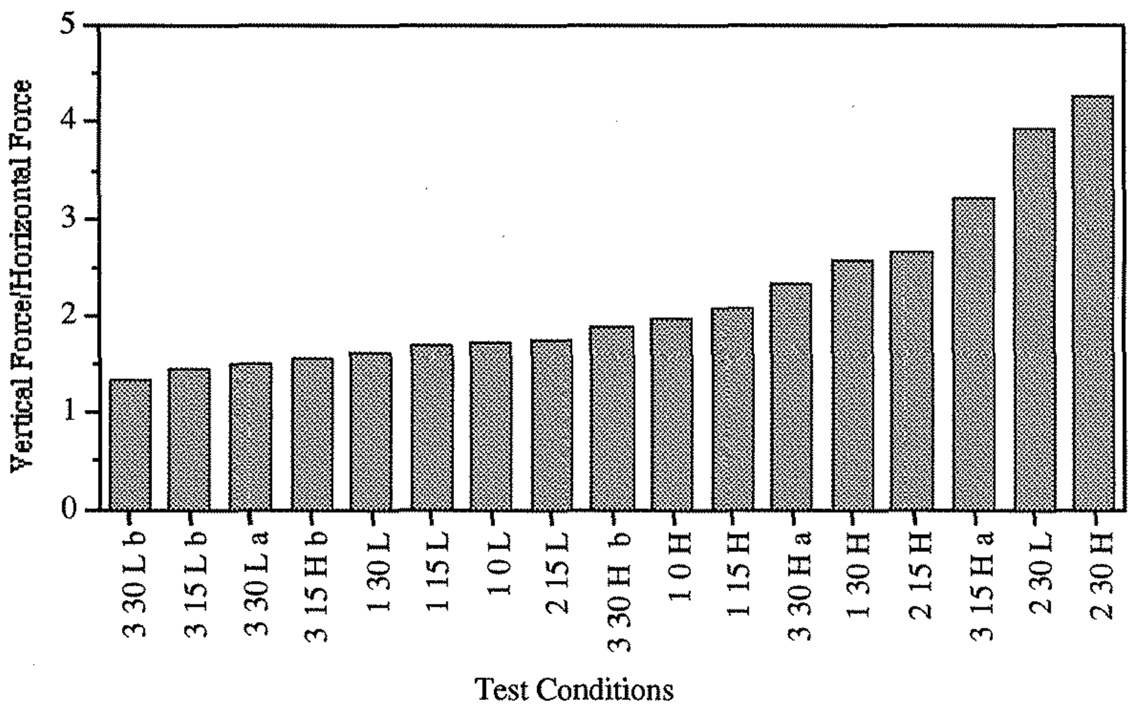


Figure 21. Average ordered force ratio values for all testing configurations.

1. Air temperature effects on efficiency. One of the variables beyond the control of the tests was the temperature. It was observed that for tests performed on warmer days (> 23 °F) more ice was removed than on very cold test days. By plotting the force ratio against the air temperature it was hoped to show any relationship to the amount of ice removed as a function of the air temperature. Plots of the force ratio versus the air temperature for each blade and test conditions are shown in figure 22 through figure 25.

2. Effects of wear on efficiency. Another factor of the tests was the wear the blade experiences through repeated testing. The force ratio vs. the test chronology was plotted for each blade in attempts to indicate the effect the wear of the blade had on the tests. These results are presented in figure 26 through 28.

D. Effectiveness Results. The horizontal force experienced by the blade during testing allows a comparison to be made between the three blades scraping effectiveness. The results of the tests for all the blades are shown in figure 29 through figure 31. Again the data has been offset about the tested blade angles for clarity. The average values and the standard deviations are plotted for each blade.

By plotting the average values of the horizontal force for all the test conditions in descending order, a comparison of the three blades can be made (see figure 32). The same notation is used for the categories along the x-axis as in figure 21. Blade 3 had the highest horizontal force for the first case followed closely by blade 1 and then blade 2.

1. Air temperature effects on effectiveness. Again to investigate the effects of air temperature on the amount of ice removed, the horizontal force is plotted against the air temperature. Figures 33 through 37 show the results of air temperature on the average horizontal force on the blade.

2. Effects of wear on effectiveness. The horizontal force was plotted against the test chronology for each blade in attempts to indicate the effect the wear of the blade had on the tests. These results are presented in figures 38 through 40.

E. Visual Results. The differences in each blades ability to remove ice from the pavement can be seen visually. Figure 41 - 42 show the ice sheet after a test using blade 1. Figures 43 and 44 show the results with blade 2 and likewise figures 45 and 46 show the results of blade 3. Figure 47 shows the amount of ice removed using blade 3 at 15° with a high download.

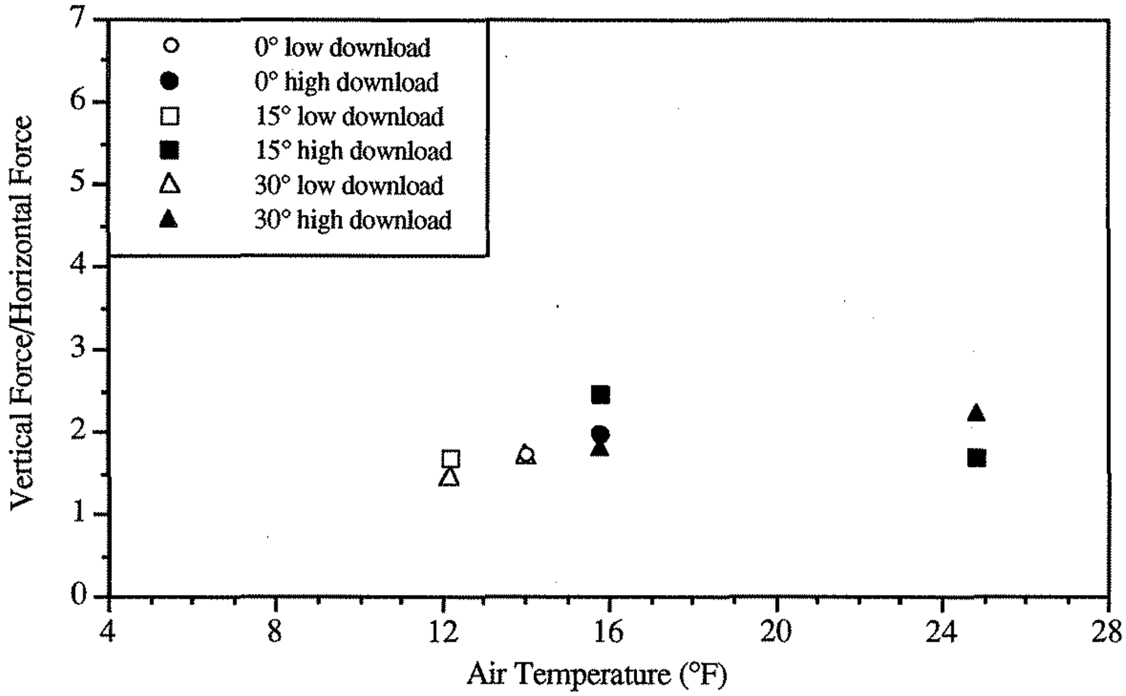


Figure 22. Air temperature effects of force ratio for all blade 1 tests.

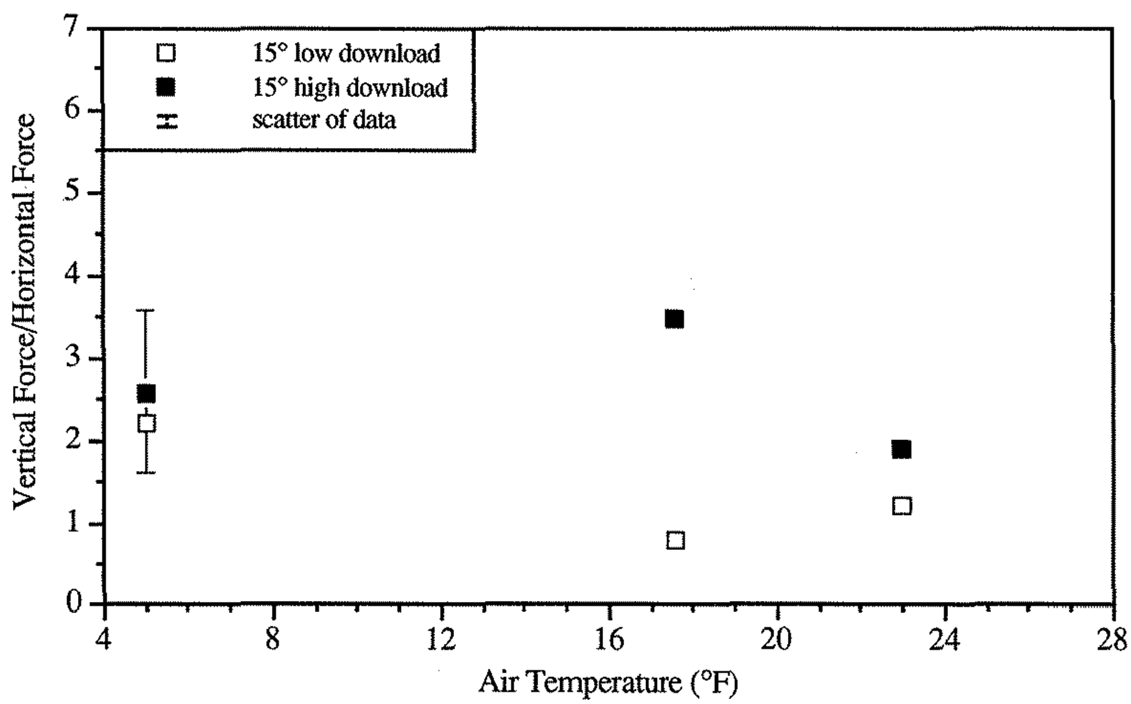


Figure 23. Air temperature effects of force ratio for blade 2 tests at 15° blade angle.

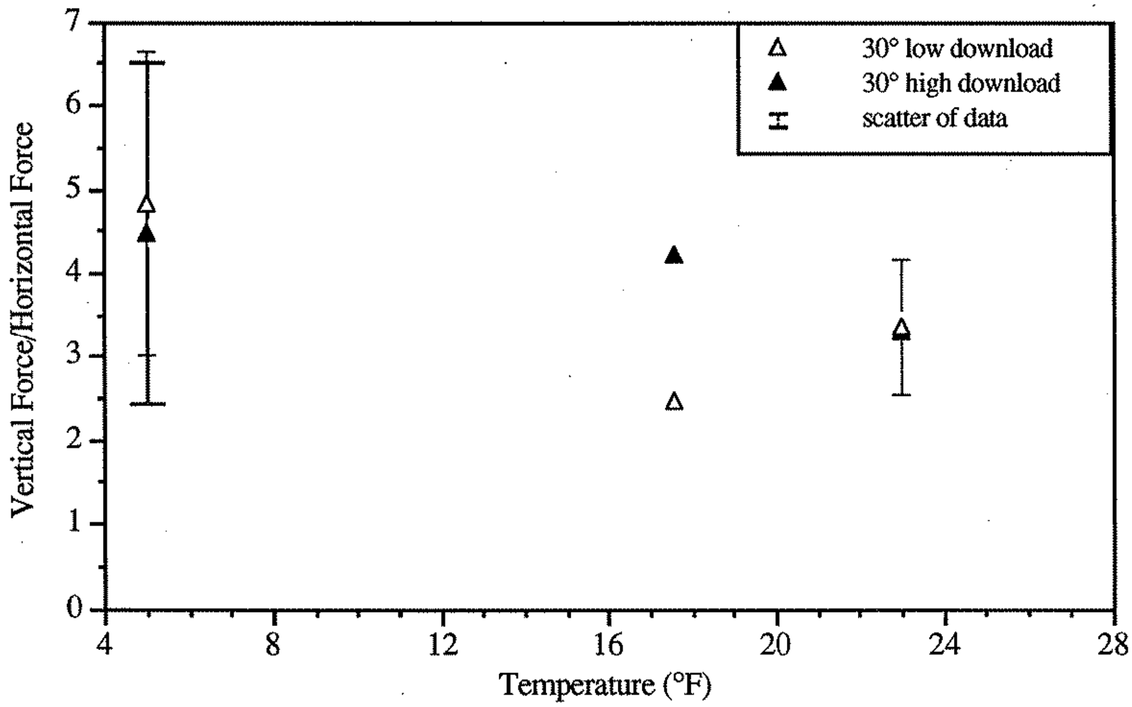


Figure 24. Air temperature effects of force ratio for blade 2 tests at 30° blade angle.

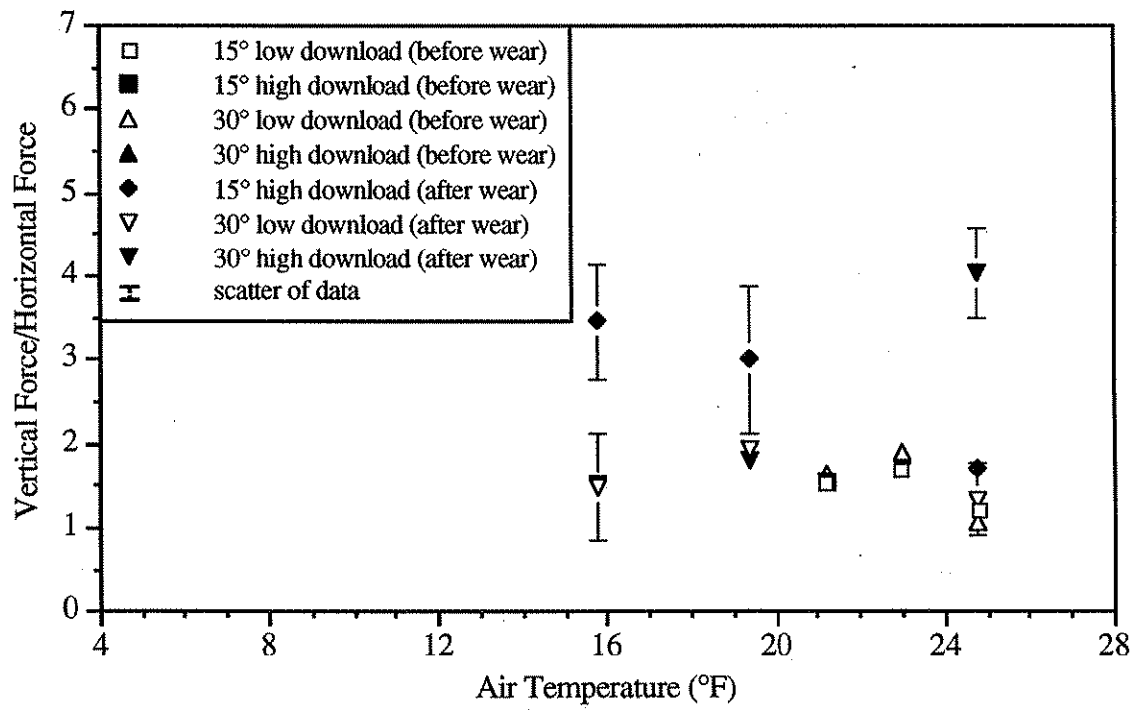


Figure 25. Air temperature effects of force ratio for all blade 3 tests.

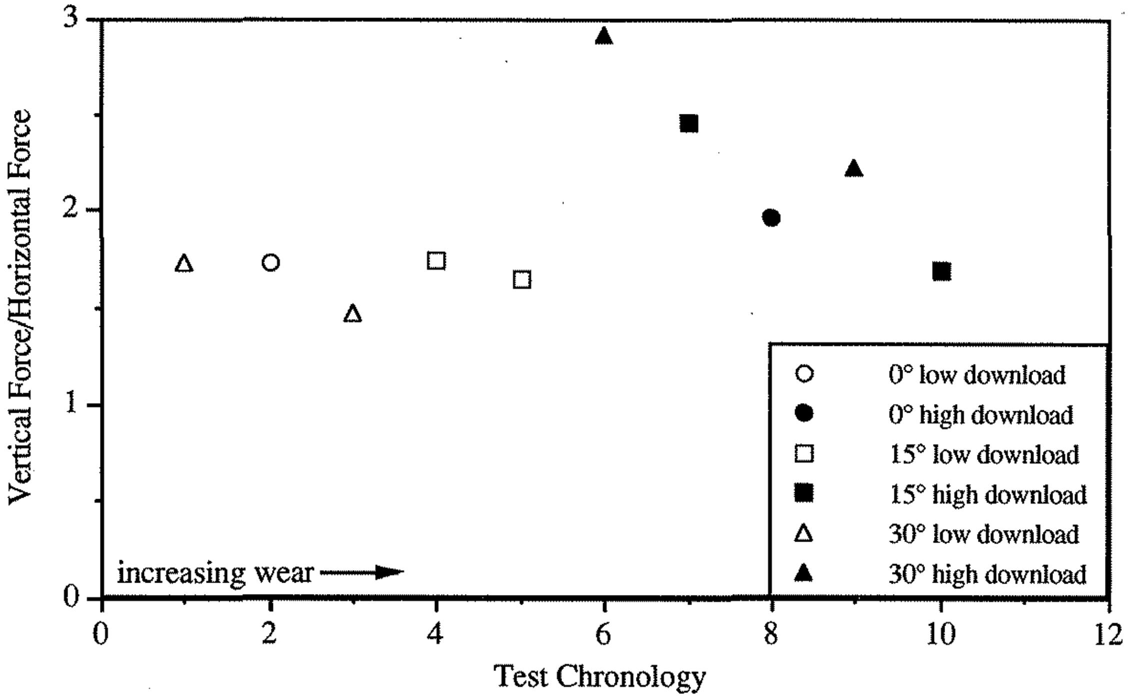


Figure 26. Effects of wear on the force ratio for blade 1 tests.

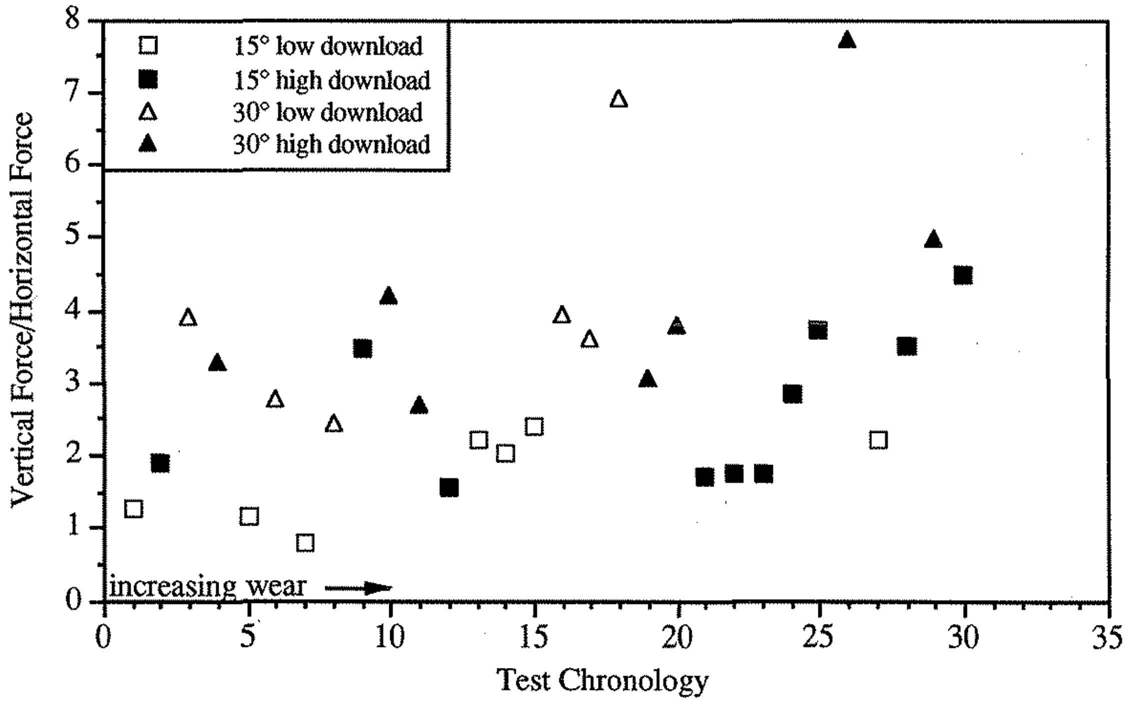


Figure 27. Effects of wear on the force ratio for blade 2 tests.

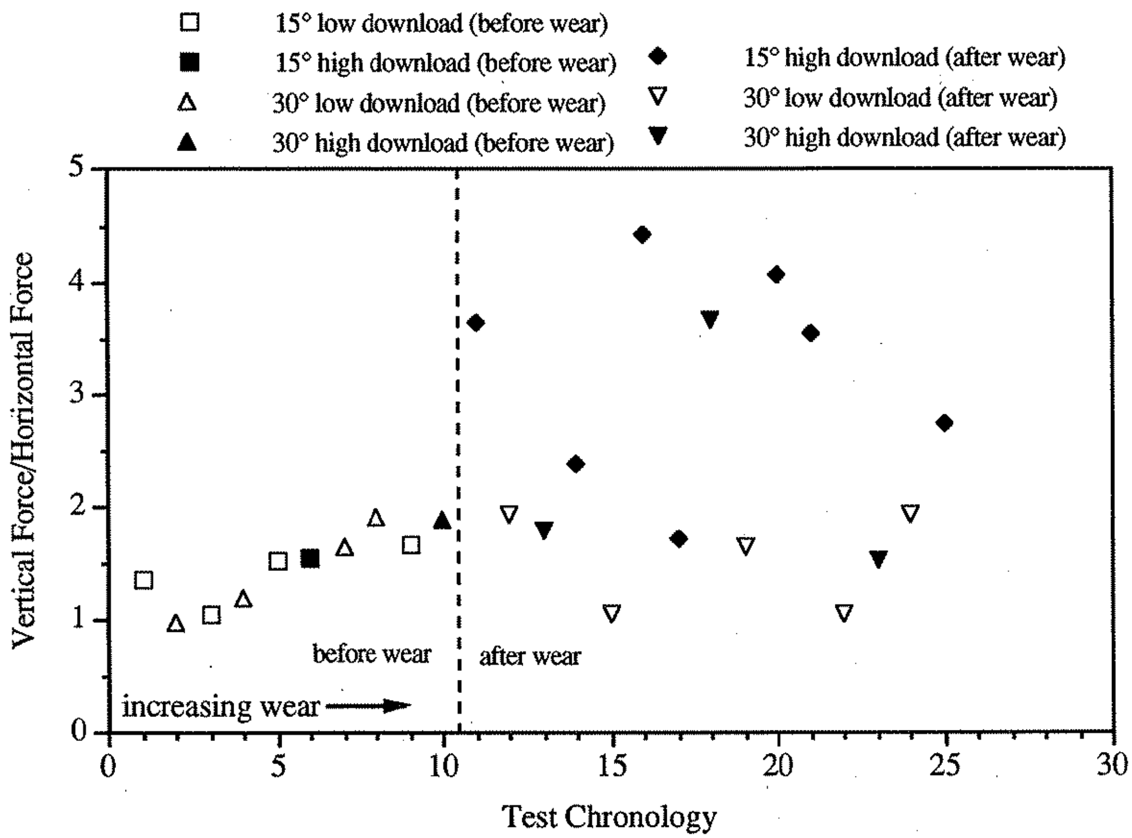


Figure 28. Effects of wear on the force ratio for blade 3 tests.

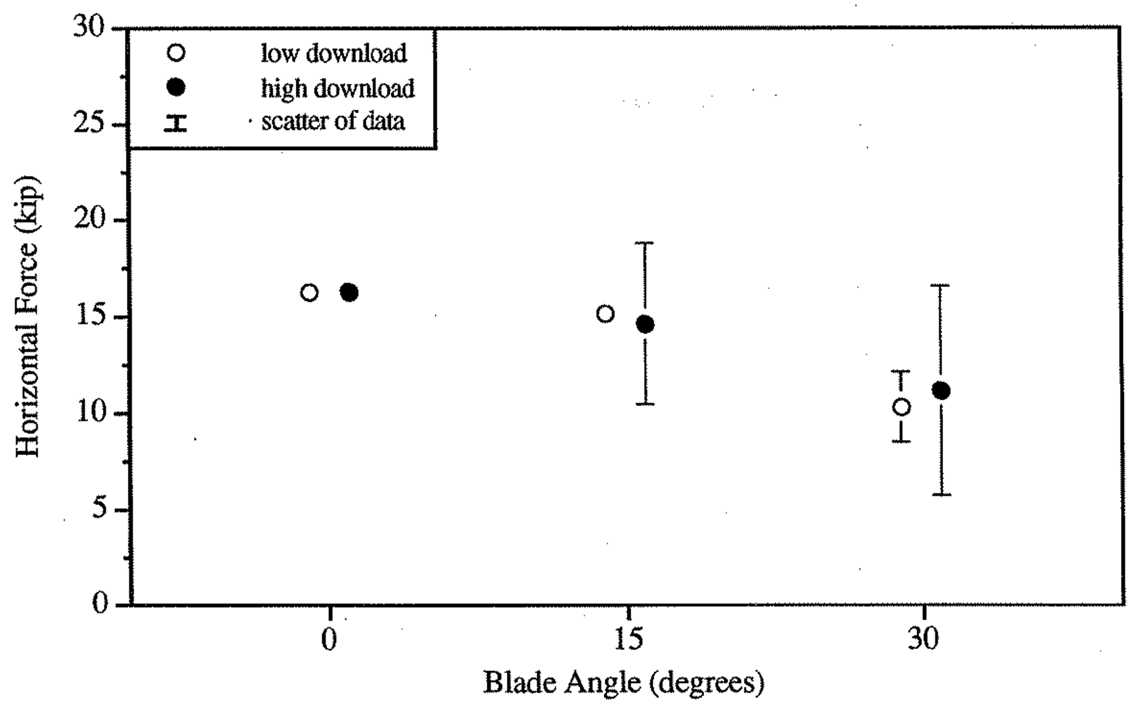


Figure 29. Average horizontal force values for test series performed on blade 1.

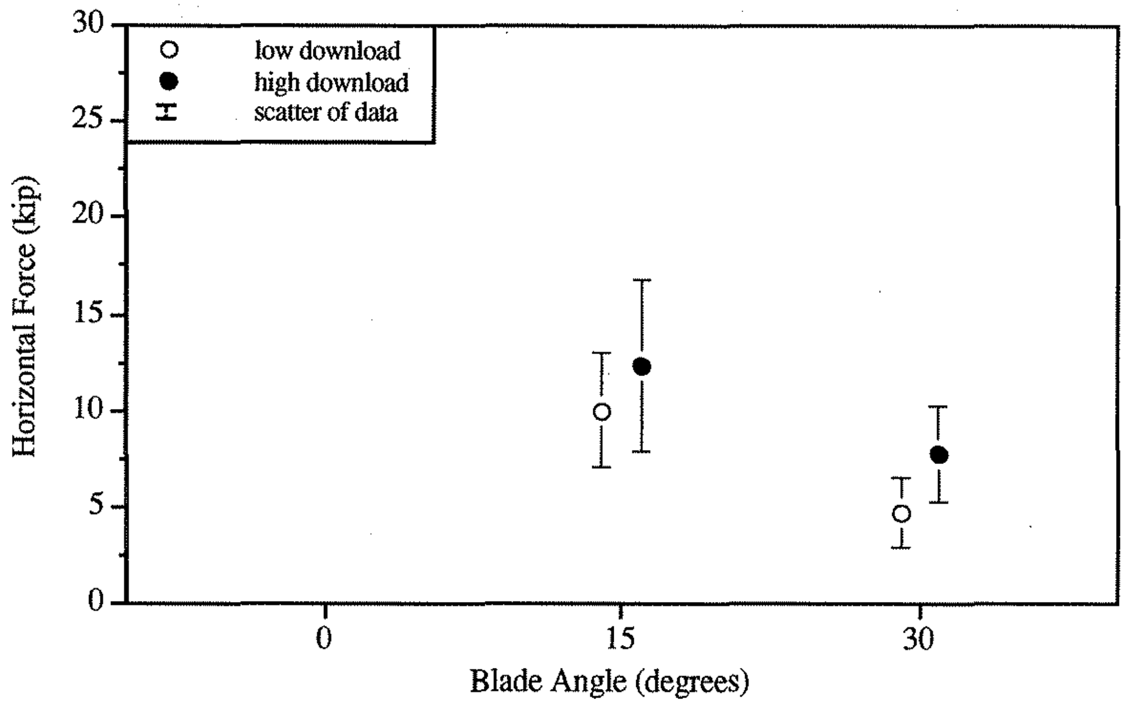


Figure 30. Average horizontal force values for test series performed on blade 2.

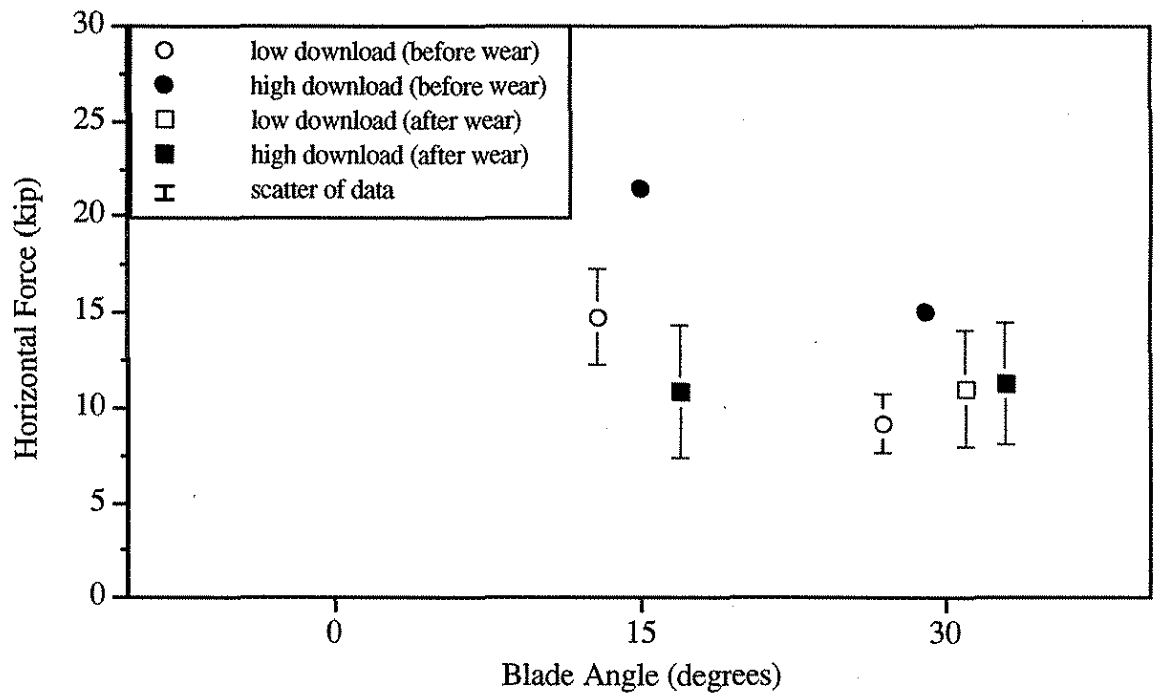


Figure 31. Average horizontal force values for test series performed on blade 3.

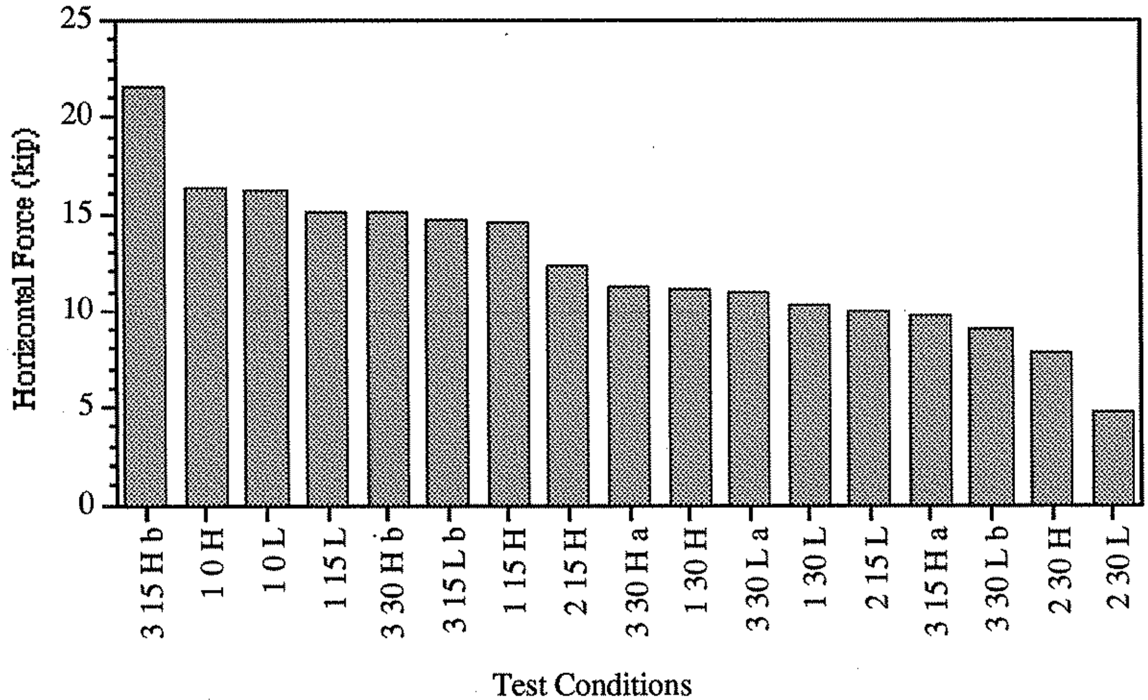


Figure 32. Average ordered horizontal force values for all testing configurations.

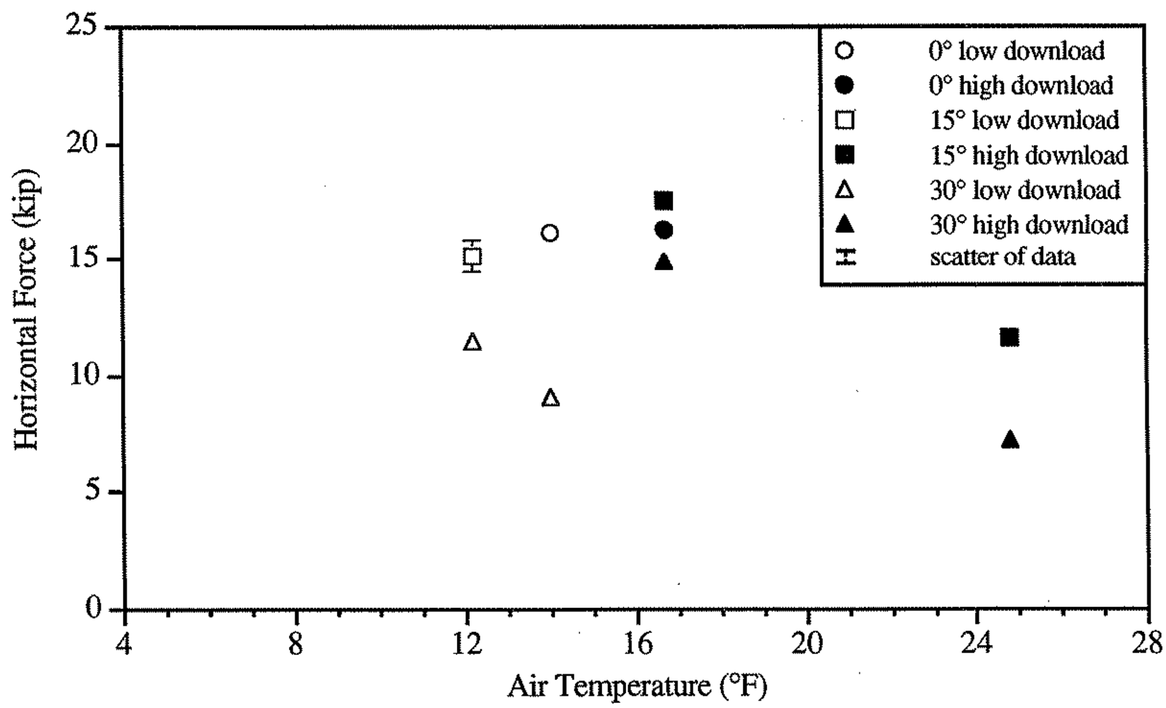


Figure 33. Air temperature effects of horizontal force for all blade 1 tests.

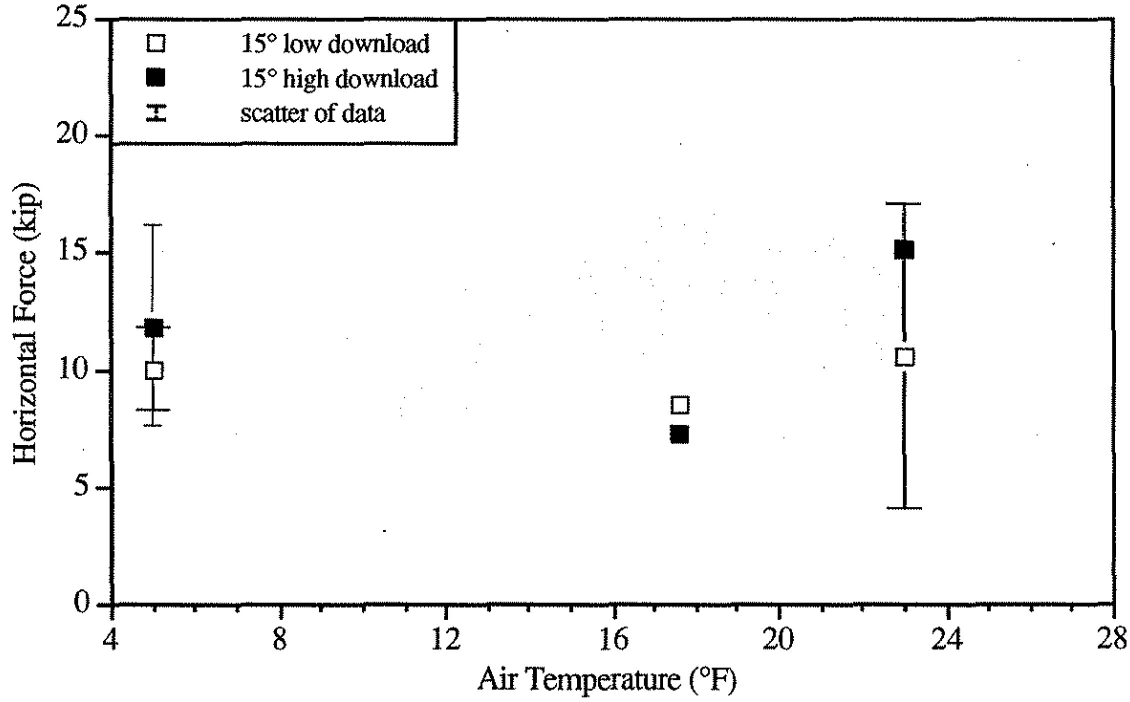


Figure 34. Air temperature effects of horizontal force for blade 2 tests at 15° blade angle.

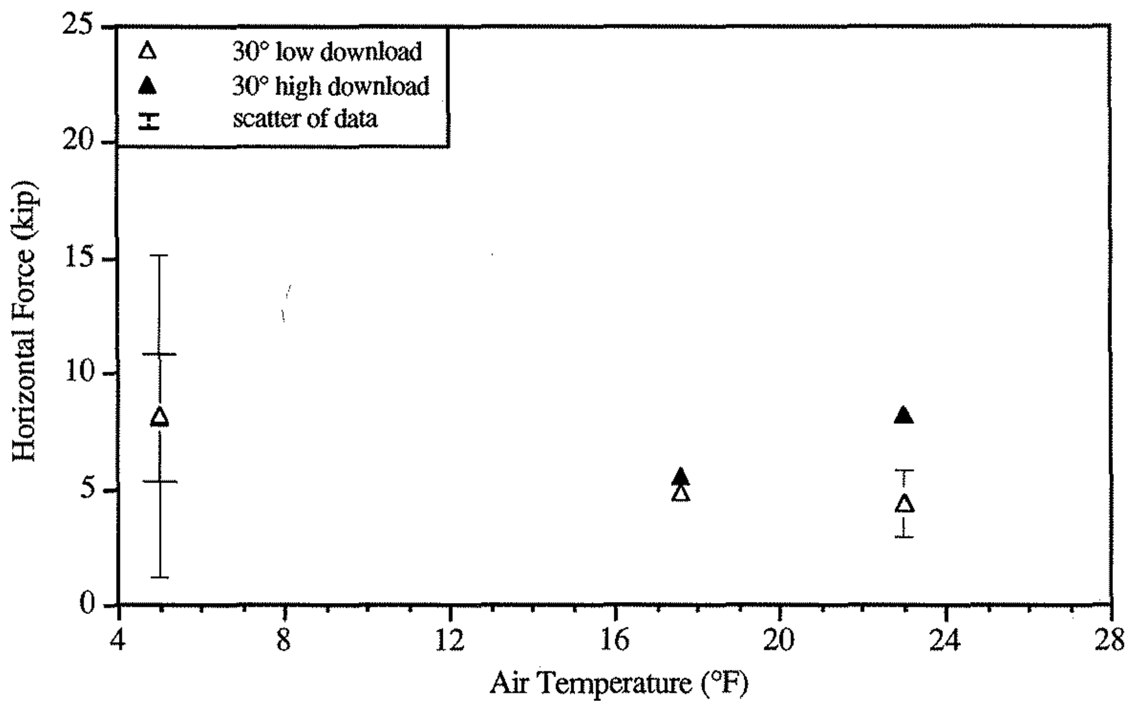


Figure 35. Air temperature effects of horizontal force for blade 2 tests at 30° blade angle.

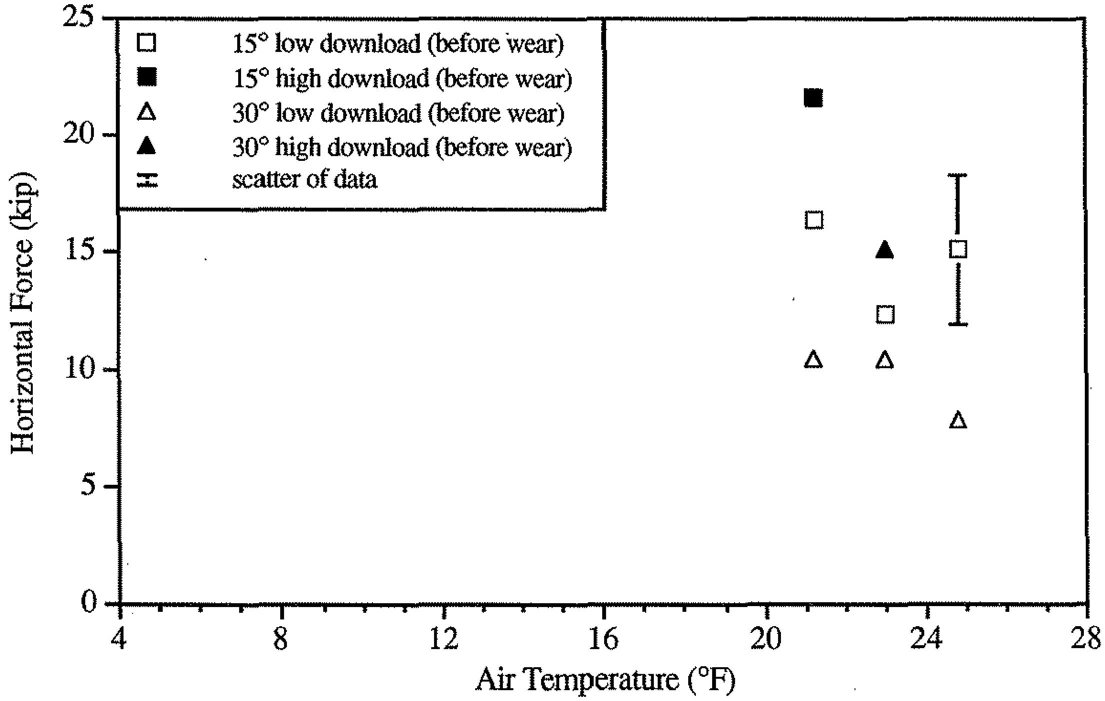


Figure 36. Air temperature effects of horizontal force for blade 3 tests before wear.

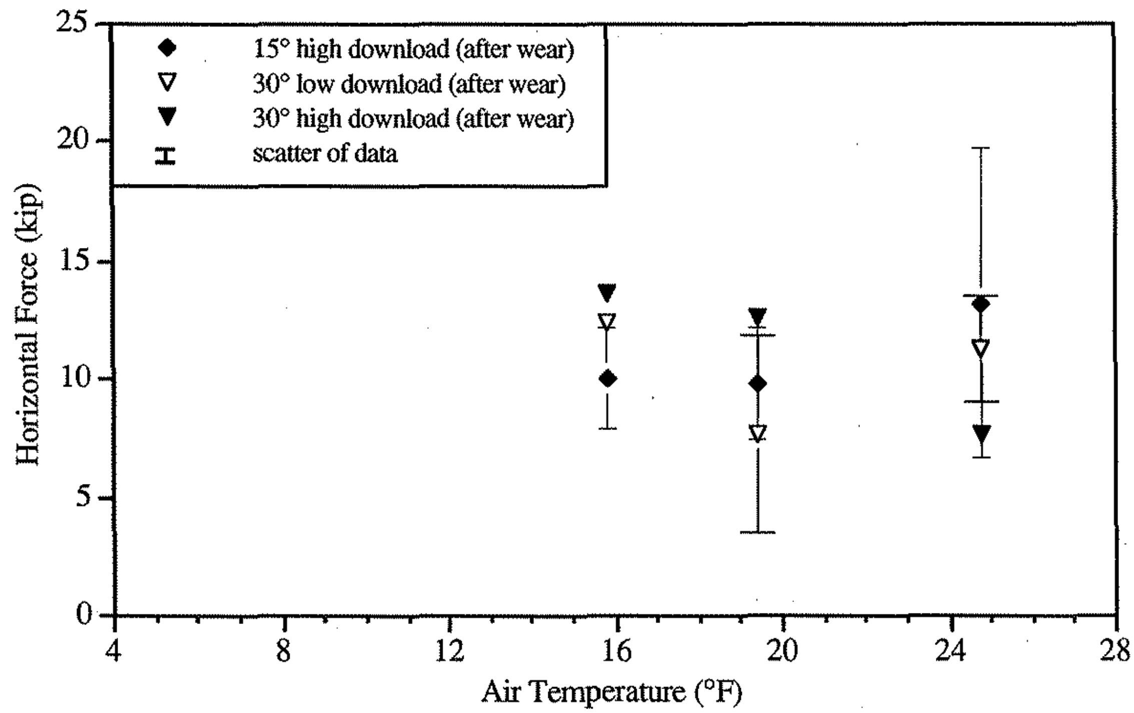


Figure 37. Air temperature effects of horizontal force for blade 3 tests after wear.

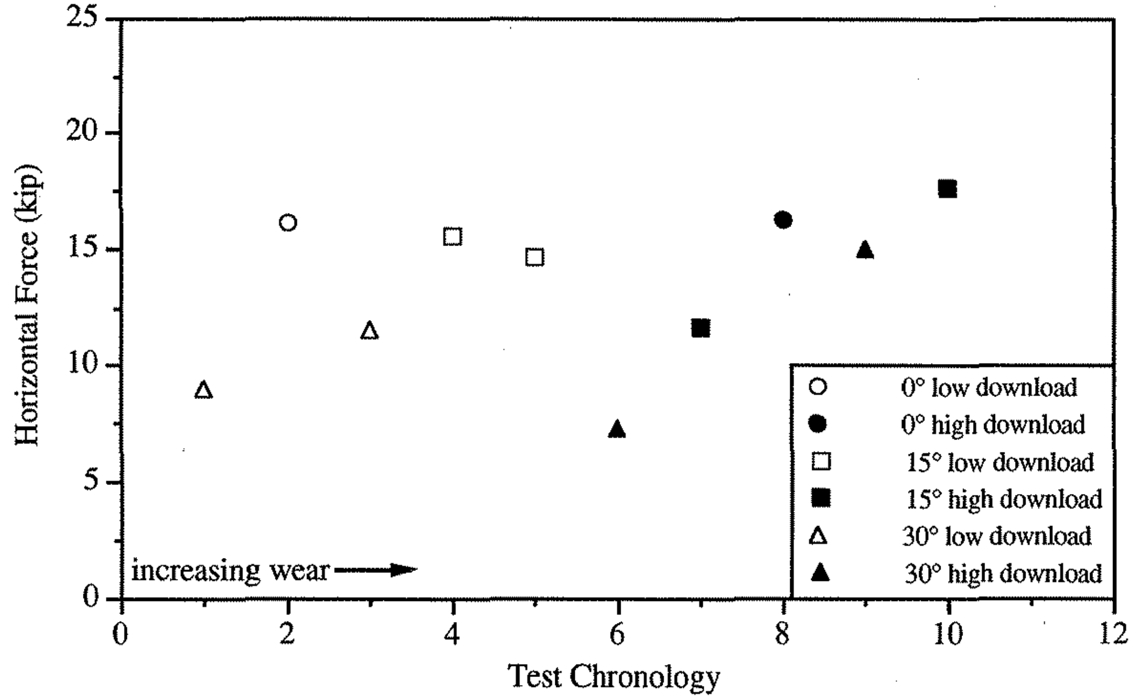


Figure 38. Effects of wear on the horizontal force for blade 1 tests.

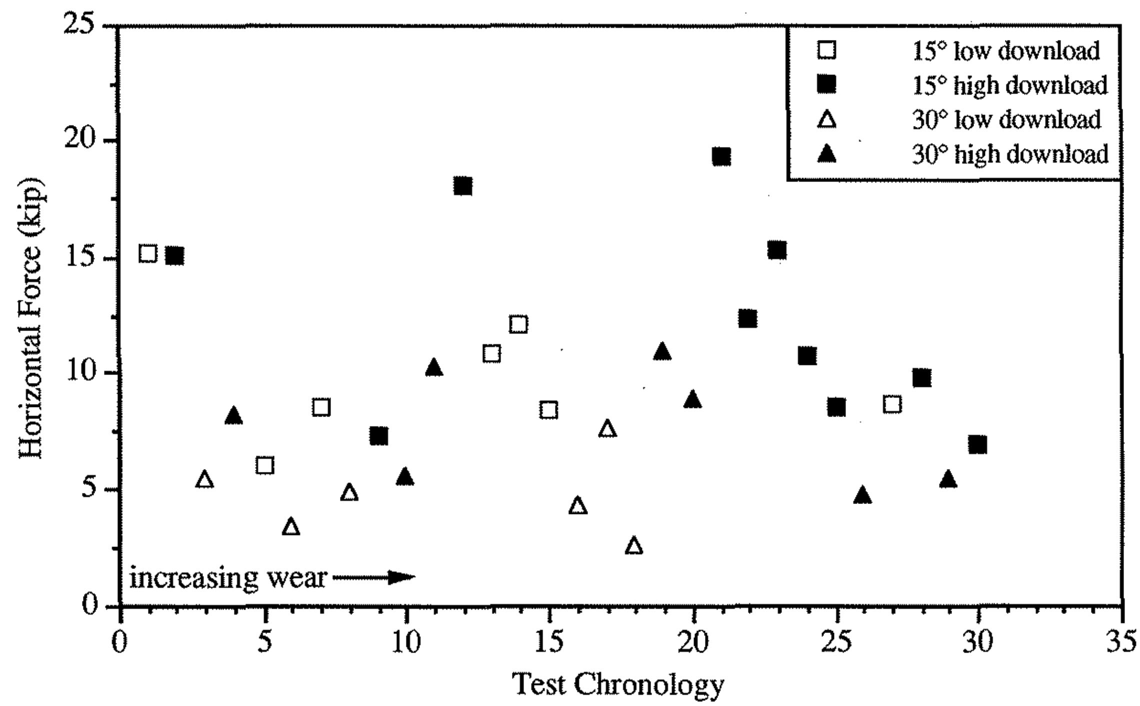


Figure 39. Effects of wear on the horizontal force for blade 2 tests.

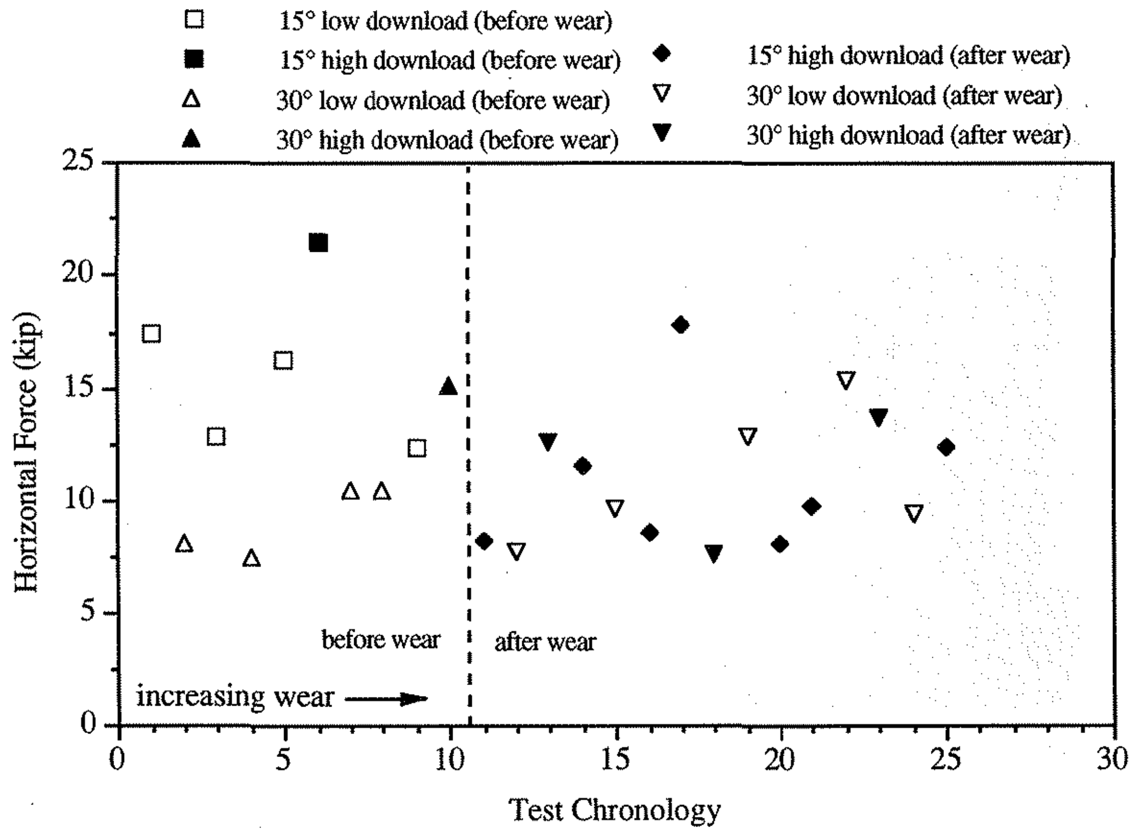


Figure 40. Effects of wear on the horizontal force for blade 3 tests.

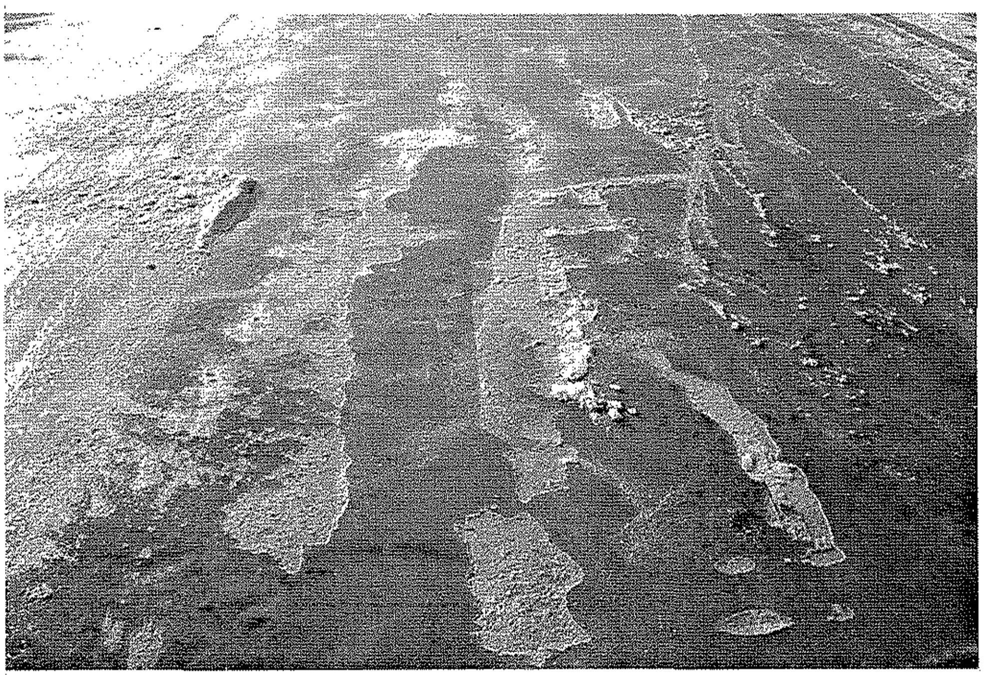


Figure 41. Ice sheet after test number 2 with blade 1, low download, 0° blade angle.

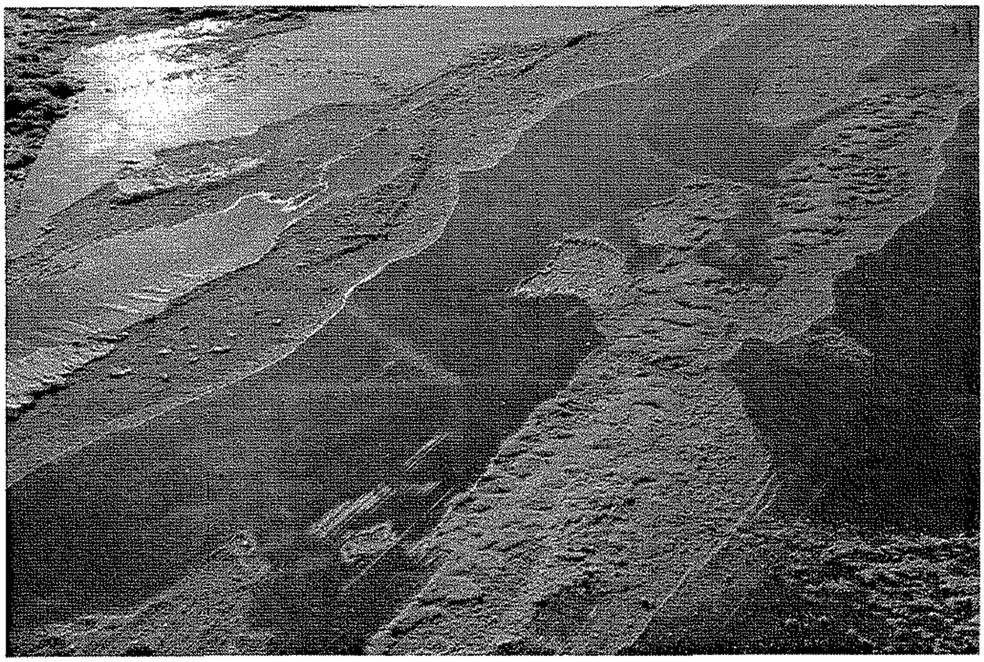


Figure 42. Ice sheet after test number 2 with blade 1, low download, 0° blade angle.

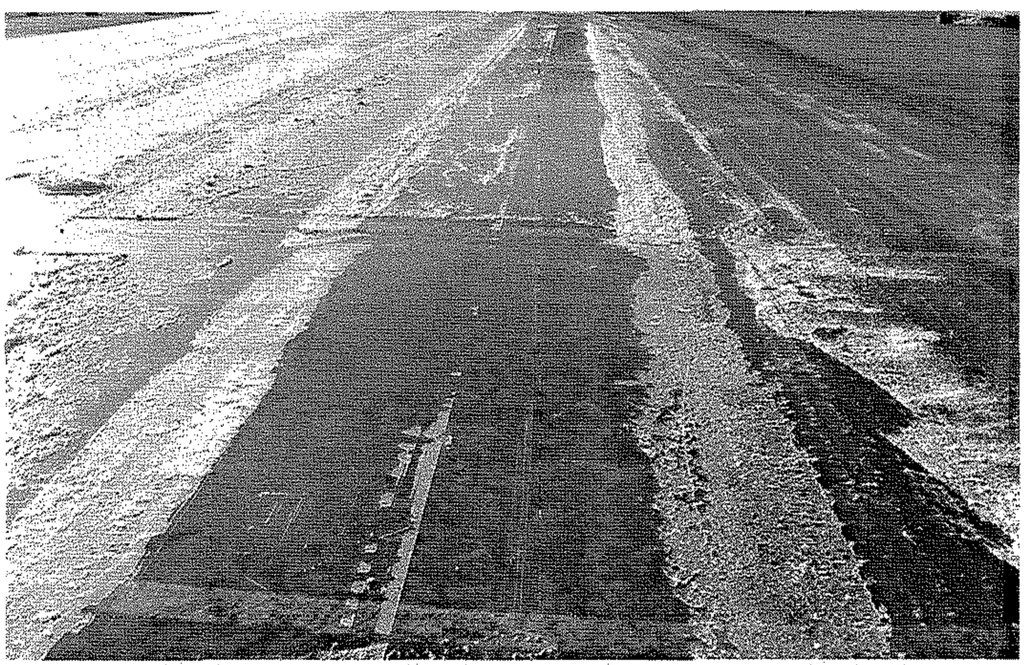


Figure 43. Ice sheet after test number 14 with blade 2, high download, 30° blade angle.

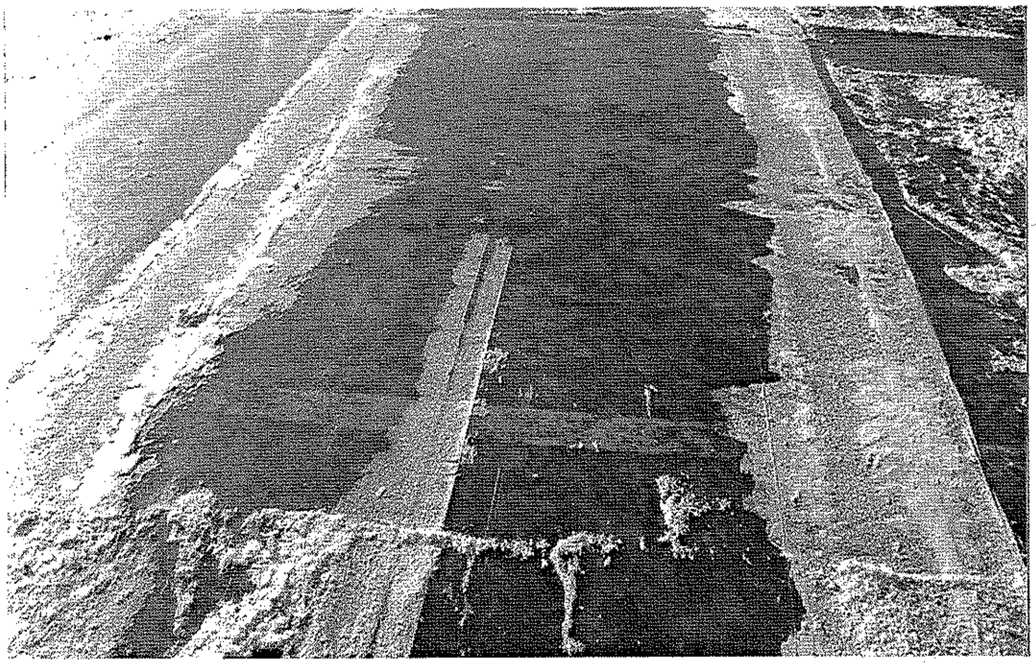


Figure 44. Ice sheet after test number 12 with blade 2, high download, 15° blade angle.

Figure 45. Ice sheet after test number 22 with blade 3, low download, 30° blade angle.

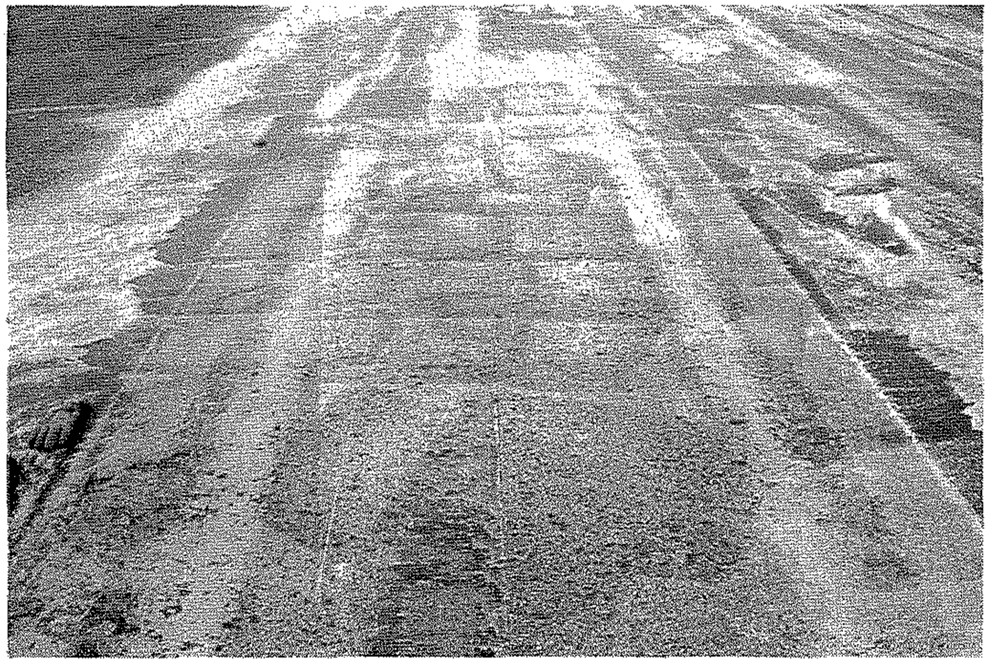


Figure 46. Ice sheet after test number 26 with blade 3, high download, 15° blade angle.

Figure 47. Depth of ice removed for test number 26 with blade 3, high download, 15° blade angle.

IV. DISCUSSION

A. Variability of the Test Conditions. Examination of the results for each test (see appendix B) indicates that there can be a large amount of variation from test to test, even for nominally identical testing conditions. This was attributed to the fact that the equipment used for the tests was not designed to be a precision test machine, but a practical machine used to remove snow and ice from roadways. It was noticed that the blade support of the underbody plow had been completely worn through the bolt holes used to attach the blade and that a new piece of steel had been welded to the remaining support. This caused some unevenness in the blade when it was mounted to the blade support. Also the blade mount itself was not of true shape, most likely caused by the years of service the plow had seen.

The amount of download could not be consistently repeated from test to test because the only indication of download was by the amount of pressure in the hydraulic system as observed on the computer screen. Given the amount of truck bounce experienced, and the difficulty of reading from a computer screen while driving the truck, it was not possible to apply the correct pressure repeatedly from test to test. For further experiments, a digital display will be used to give a more easily read measure of the down pressure applied. In these tests, however, there was a range of download that was achieved for both low and high download tests. Similarly the blade angle also varied from test to test (i.e. in 15° tests, the blade angle might in reality vary between 20° and 10°). Figure 48 indicates the average download and average blade angle for all the tests. It can be seen that most tests that were set for low download fall in a range from 5 kip to 20 kip and that the high download tests are in a range from 20 kip to 35 kip. The blade angle had a range of 10° to 20° for tests at 15° and varied from 20° to 30° for the tests performed at 30°.

From looking at the test results in appendix B, for example test number 23, it can be seen that for some tests the download changed abruptly. This was caused by the decrease in download pressure to prevent the speed of the truck from decreasing due to loss of traction or lack of power. Another possibility is the download may have been reduced during the test because it was observed that the download was too high for that particular test condition and was reduced. Similarly in some tests the blade angle was increased, thus lowering the download force and hence maintaining the testing speed. An example of this is test number 37 (see appendix B).

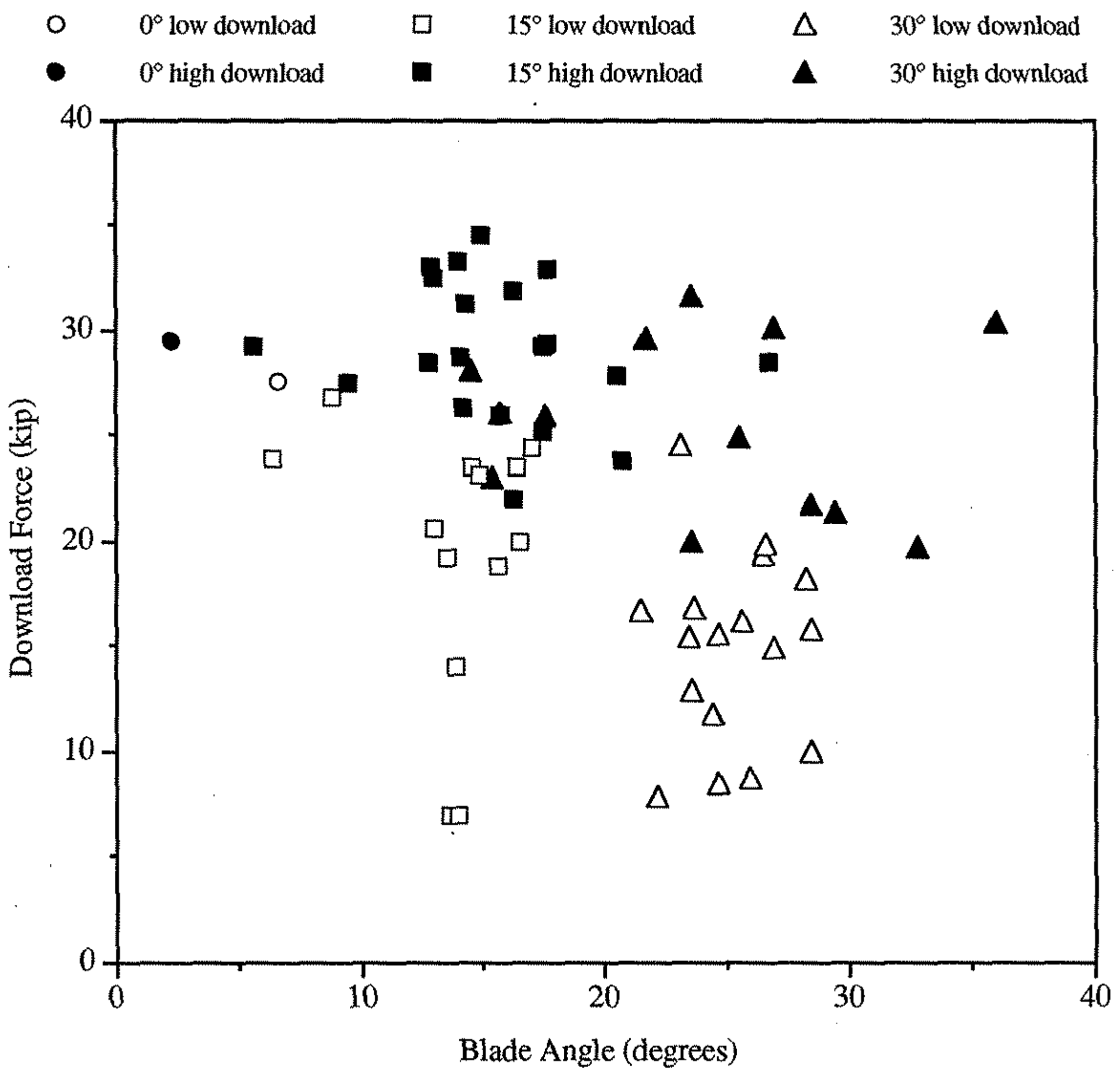


Figure 48. Comparison of testing conditions for all tests.

B. Comparison of Efficiency Results for Different Blades. As shown in figure 18 the value of the force ratio (ratio of vertical to horizontal force), remained nearly the same for all tests for blade 1. For both the low and high download conditions over the range of blade angle the force ratio did not change by any significant amount. In order to determine how significant any variations between testing conditions might be, t-tests were performed between the results for each testing condition. The results of the t-tests for blade 1 are shown in Table 1, in which the p values for each pair of test conditions are given. Values of 0.01 or less indicate that differences exist between the results for the two test conditions at the 99% level of probability. This means that it is very likely (a 99% chance) that the two conditions cause differing behavior and thus that the parameter changed between the conditions does have an effect on scraping load. Values less than 0.05 indicate significance at the 95% level. This suggests that the parameter changed between the two conditions may have an effect on the scraping load. Any values greater than 0.05 indicate that the changed parameter between the two tests does not have any significant effect on scraping load.

Table 1. Blade 1 t-test p value for force ratio.

test conditions	0° low	0° high	15° low	15° high	30° low	30° high
0° low	x	0.000	0.420	0.360	0.340	0.046
0° high	0.000	x	0.002	0.770	0.038	0.110
15° low	0.420	0.002	x	0.140	0.310	0.005
15° high	0.360	0.770	0.140	x	0.091	0.150
30° low	0.340	0.038	0.310	0.091	x	0.004
30° high	0.046	0.110	0.005	0.150	0.004	x

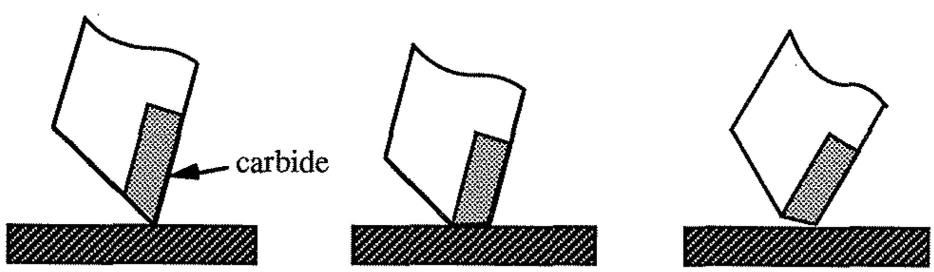
Having said this, some care must be used with the t-test results in this case, because the number of tests conducted for each condition was small. Nonetheless, from table 1 it is clear that the download (low or high) has a clear effect on scraping load for blade 1, while the angle of the blade (0°, 15° or 30°) has little effect.

The results for blade 2 had a wide range of variability as indicated in figure 19 by the large error bars. Blade 2 results suggest that the blade has a dependency on the blade angle with the smaller blade angle being the more desirable condition for more efficient ice removal. Again as noted in blade 1 there is a slight increase in force ratio with the increasing download. However this does not appear to be significant (see table 2). In contrast, the t-test values indicate that blade angle has an effect for blade 2, with both low and high download conditions showing significance between 15° and 30°.

Table 2. Blade 2 t-test p value for force ratio.

test conditions	15° low	15° high	30° low	30° high
15° low	x	0.054	0.006	0.002
15° high	0.054	x	0.073	0.030
30° low	0.006	0.073	x	0.770
30° high	0.002	0.030	0.770	x

Results for blade 3 have been separated into two parts due to a large amount of wear the blade received in removing snow and ice from the test area deposited as result of bad weather that occurred between January 10-13. After the storm the blade experienced a great deal of use in clearing the access road to the test site and the testing area. As a result the blade flat width was increased from nearly 0" to about 3/8" when the blade was in the 15° position. The effect of this wear is apparent in figure 20. At the 15° position there was a significant increase in the force ratio between the no wear and worn blade tests. The t-test results shown in Table 3 support this conclusion. Tests before the wear took place are indicated by the (b) and tests after the wear took place by the (a). The change in force ratio is not as apparent for the 30° blade angle. This could be partly due to the fact that at 30° the blade flat width was much smaller than at 15° as shown in figure 49. Figure 49 (a) shows blade 3 at 15° before it received any wear. Figure 49 (b) shows the blade after the wear and figure 49 (c) shows the worn blade at 30°. Even with the wear at 30° the blade has a pointed surface to work with and not a flattened portion as in the 15° position as shown in figure 49 (b). This new unworn point could still provide good ice removal at 30°, as indicated by the low force ratio results obtained for this condition with blade 3.



(a) Before Wear 15° (b) Worn blade 15° (c) Worn blade 30°

Figure 49. Wear characteristics of blade 3.

As previously observed the higher downloads resulted in higher force ratios. It was observed during testing that before the wear on the blade at a low download blade 3 removed approximately 1/8 inch of ice across the entire blade width of 8 feet. For high download tests approximately all of the ice was removed across the entire blade width. Blade 1 and 2 did not at anytime in the test series exhibit any results that approached those of blade 3 before the wear took place. Even after the wear of blade 3 it removed more ice at 30° than blade 1 or 2 did at any angle.

Table 3. Blade 3 t-test p value for force ratio.

test conditions	15° low (b)	15° high (b)	30° low (b)	30° high (b)	15° high (a)	30° low (a)	30° high (a)
15° low (b)	x	0.480	0.920	0.077	0.006	0.680	0.170
15° high (b)	0.480	x	0.700	0.000	0.056	0.900	0.440
30° low (b)	0.920	0.700	x	0.230	0.008	0.780	0.200
30° high (b)	0.077	0.000	0.230	x	0.110	0.320	0.640
15° high (a)	0.006	0.056	0.008	0.110	x	0.005	0.250
30° low (a)	0.680	0.900	0.780	0.320	0.005	x	0.190
30° high (a)	0.170	0.440	0.200	0.640	0.250	0.190	x

When all the test configurations of blade, blade angle, and download are compared with the average test force ratio for each configuration it becomes evident that blade 3 provided the most efficient scraping of ice. The results (see in figure 21) show that there was not much difference in test average force ratio separating the configurations. This is most likely due to the lack of control in the variables of the study. However, it indicates that blade 3 had overall the best performance slightly ahead of blade 1.

1. Air temperature effects on efficiency. Figure 22 indicates the effects air temperature has on the force ratio for blade 1. It seems that there is no direct relation between the air temperature and the results of the tests. Similar trends (figures 23 - 25) indicate air temperature does not affect force ratio for blades 2 and 3. However, it was observed during testing that more ice was removed from the pavement on warmer days. This underscores the difference between good efficiency and good ice removal. A low ratio of vertical to horizontal force indicates that ice is being removed efficiently (i.e. with a relatively low download). However, this gives no indication of how much ice was removed. Thus it is possible to remove ice very efficiently (low ratio), but not very effectively (not much removed). The horizontal force gives an approximate measure of effectiveness, but it does not correlate across blades. That is, a horizontal force of 10,000 pounds on blade 1 may not result in the same amount of ice being removed as a horizontal force of 10,000 pounds on blade 2. Further work is needed in this area.

Temperature values were taken by laying a thermometer on the surface of the pavement prior to testing and reading the temperature after setup of the truck was completed. A more appropriate means of obtaining the temperature would be to place thermistors at various depths of the pavement and record the temperature continuously during the testing period. The equipment for this purpose is available, but security of the equipment cannot be guaranteed at the test site.

2. Effects of wear on efficiency. Another factor to consider was the wear of the blade as the test series proceeded. This was examined by plotting the test average force ratio against the test number for the blade. Figure 26 shows the results obtained for blade 1 and indicates the different test configurations. There does not appear to be any direct correlation between the wear and the force ratio for this blade.

Figure 27 shows the results for blade 2. As can be seen the results are scattered in a random manner which also suggests no correlation. Results from blade 3, shown in figure 28 show at first a rising trend as the test were performed and then a scattering after the point in time when the blade experienced a large amount of wear as indicated by the dashed line. After the blade received the wear the results are very similar to blade 2 which has the flat portion on the leading edge as can be seen in figure 7. Blade 3 also had a flat width similar to blade 2 due to the wear from removing the snow and ice.

C. Comparison of Effectiveness Results for Different Blades. As shown in figure 29 the horizontal force decreased with increasing blade angle for both the low and high download conditions for blade 1. T-tests of the results are given in table 4 which indicate a significant difference between 0° and 30°. Results with 15° compared to other angles is mixed which could be attributed to the small sample size. No significant difference in results are evident between the effectiveness of low and high download tests. Further tests with blade 1 are necessary to better establish the effectiveness of the blade. (Note that effectiveness is defined in Section III.B).

Table 4. Blade 1 t-test p value for horizontal force.

test conditions	0° low	0° high	15° low	15° high	30° low	30° high
0° low	x	0.000	0.061	0.570	0.006	0.000
0° high	0.000	x	0.046	0.550	0.005	0.000
15° low	0.061	0.046	x	0.760	0.001	0.610
15° high	0.570	0.550	0.760	x	0.060	0.900
30° low	0.006	0.005	0.001	0.060	x	0.012
30° high	0.000	0.000	0.610	0.900	0.012	x

The results for blade 2 are shown in figure 30 and the t-tests presented in table 5. Results show that for like downloads the horizontal force was reduced significantly with the increasing blade angle. Also the high download tests resulted in higher horizontal loads. At 15° blade angle the difference between low and high download is not significant at the 95 % confidence level due to the large scatter of test results. However, there is significance in the effectiveness at 30° blade angle.

Table 5. Blade 2 t-test p value for horizontal force.

test conditions	15° low	15° high	30° low	30° high
15° low	x	0.240	0.003	0.140
15° high	0.240	x	0.001	0.025
30° low	0.003	0.001	x	0.030
30° high	0.140	0.025	0.030	x

Figure 31 shows the results of effectiveness for blade 3. T-test results are presented in table 6. The most significant results are for the tests that occurred before the wear of the blade. For both low and high download tests the blade proved to be most effective at the smaller blade angles and at the higher downloads. After the wear took place the effectiveness for all conditions was nearly the same with a fair amount of scatter.

Table 6. Blade 3 t-test p value for horizontal force.

test conditions	15° low (b)	15° high (b)	30° low (b)	30° high (b)	15° high (a)	30° low (a)	30° high (a)
15° low (b)	x	0.022	0.009	0.850	0.086	0.091	0.170
15° high (b)	0.022	x	0.000	0.000	0.004	0.006	0.023
30° low (b)	0.009	0.000	x	0.007	0.370	0.300	0.300
30° high (b)	0.850	0.000	0.007	x	0.150	0.130	0.210
15° high (a)	0.086	0.004	0.370	0.150	x	0.950	0.870
30° low (a)	0.091	0.006	0.300	0.130	0.950	x	0.980
30° high (a)	0.170	0.023	0.300	0.210	0.870	0.980	x

The results of the vertical force versus the horizontal force, or effectiveness, for all blades and all testing configurations is shown in figure 50. From this figure it becomes apparent what the overall trends were between the testing conditions. For nearly all cases the horizontal force was larger at higher downloads. This was not the case for blade 3 at 15° blade angle for the before and after wear conditions, but was true for the other conditions of blade 3. The only other exception was blade 1 at 15° blade angle. However for this condition the low and high download were nearly the same. This was also true for blade 1 at 0°. These tests were performed at the beginning of the research project and the testing procedures, as well as familiarity of the equipment, had not yet been refined. So comparison between these conditions does not provide any valuable information. Another point that is evident from figure 50 is that for all of the tests the effectiveness was better at smaller blade angles. The only exception being for the wear effect of blade 3 at 15° blade angle, high download.

By comparing the horizontal force for all blades and all configurations of blade angle and download (see figure 32), it is seen that blade 3 had the highest effectiveness at 15° blade angle and high download. However, figure 32 does not make apparent the visually observed differences between blade 1 and blade 3 (see section D below).

1. Air temperature effects on effectiveness. Figures 33 through 37 indicate how the effectiveness of the test changes with air temperature. As before with the force ratio versus air temperature, there does not appear to be any relation between the measured effectiveness and the air temperature for any of the blades. However, this could be due to the method of gathering the air temperature data and not the pavement temperature.

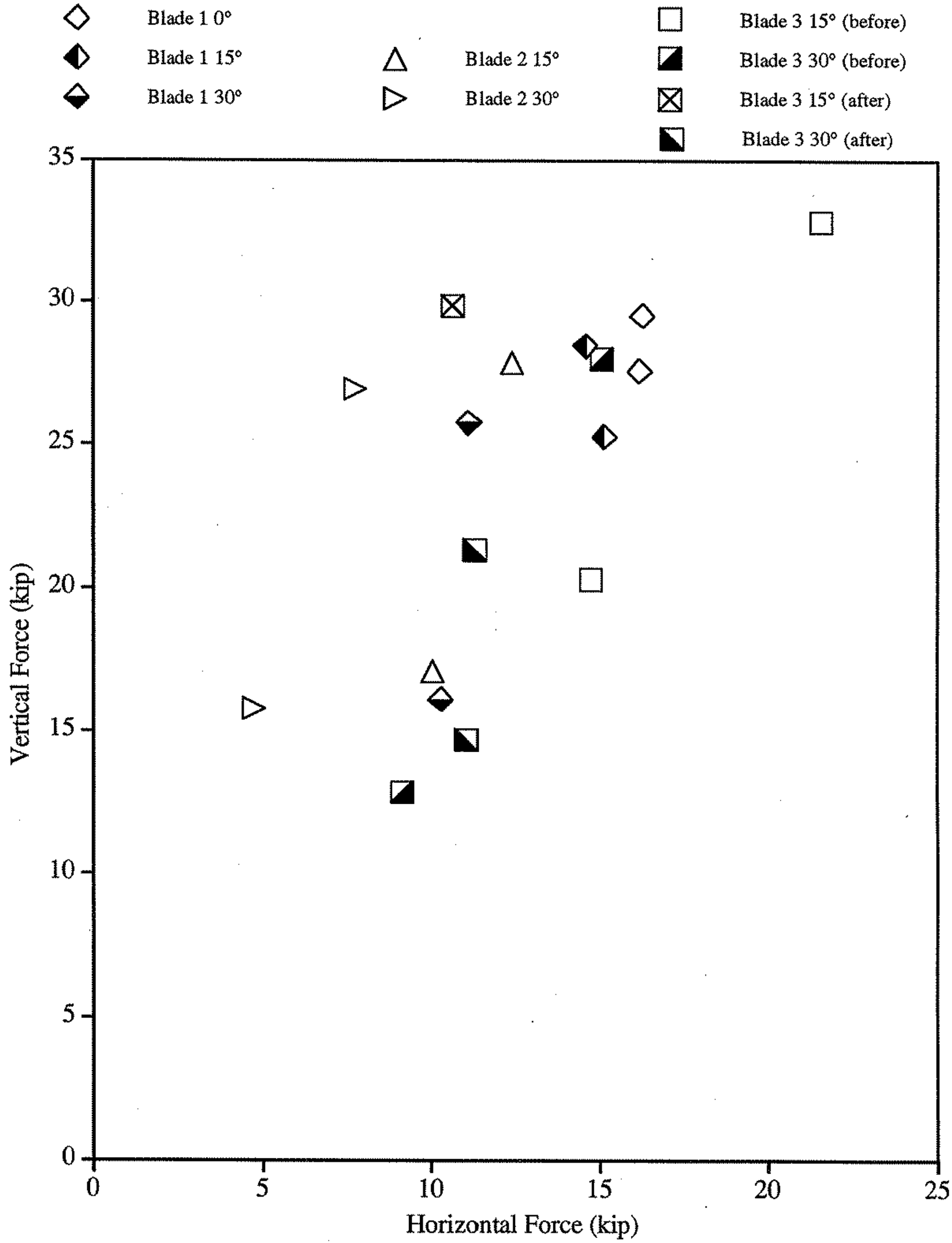


Figure 50. Effectiveness of all blades and testing conditions.

2. Effects of wear on effectiveness. Figures 38 through 40 show the test chronologies for blade 1, 2, and 3 respectively. From these figures the effect of wear to the blade surface does not seem to have any apparent effect on the effectiveness of the blade to remove ice.

D. Visual Results. From figures 41 - 42 the results of scraping the ice with blade 1 can be seen for the 15° low download case. The test shows that the blade will removed some of the ice, but never removed ice across the entire width of the blade. At times ice was removed clear down to the pavement and at other times only half the thickness of the ice was removed. It is not understood why the blade behaves in this manner, but all the tests performed on blade 1 displayed this behavior. It was also observed that during tests with blade 1 that although ice was not removed across the entire width of the blade, sparks were seen coming from the blade during the tests indicating that the blade was in contact with the pavement.

Figures 43 - 44 show the results of scraping with blade 2 at 15° low download. For this test the blade was not mounted straight with the pavement surface. This was due to the distortion of the blade mount caused by the use it had received in its lifetime, and for further testing repairs will have to be made to the mounting to remove this possible source of error. From this test it can be seen that the blade removed between half and all of the ice on the outer edge of the test strip. When the blade was adjusted to fit to the surface of the pavement better, however, similar results to blade 1 were obtained. Generally all tests at 30° with blade 2 and 3 showed this sort of behavior with ice only being removed from the outer edges of the testing run. This was due to the distortion of the blade mount and could not be corrected.

The results for blade 3 are shown in figures 45 - 46. It can be seen that the blade removed nearly half of the ice thickness across the entire width of the blade for a 15° low download test. Figure 47 shows a close up of the edge of a test performed at 15° high download. The figure indicates that nearly the total thickness of the ice was removed. Upon further examination it was also apparent that in spots the blade had removed some of the pavement surface as well. Also for this test the truck did not have sufficient power to maintain the speed during the test and was brought to a stop from 15 mph. However, as the speed decreased nearly all of the ice was removed throughout the test. This test is number 26 in appendix B.

E. Tentative Model of the Ice Scraping Process. From observations made during the tests and from the photos and videotape of the tests described herein, it is possible to develop a tentative model for the failure of ice under the blade. The tests show that the ice is fractured into very small particles (having the consistency of powder) during scraping. It appears that the ice is crushed by compressive forces generated ahead of and beneath the blade. Figure 51 shows the truck scraping ice with blade 1. This particular test was a preliminary test to ensure that the data acquisition system was functioning properly (therefore it does not appear with the results in appendix B) and was performed on November 7, 1991. This picture shows that ice fragments are ejected both before and behind the blade, which suggests that there are two zones of failure as indicated in figure 52.

Figure 51. The truck scraping ice with blade 1.

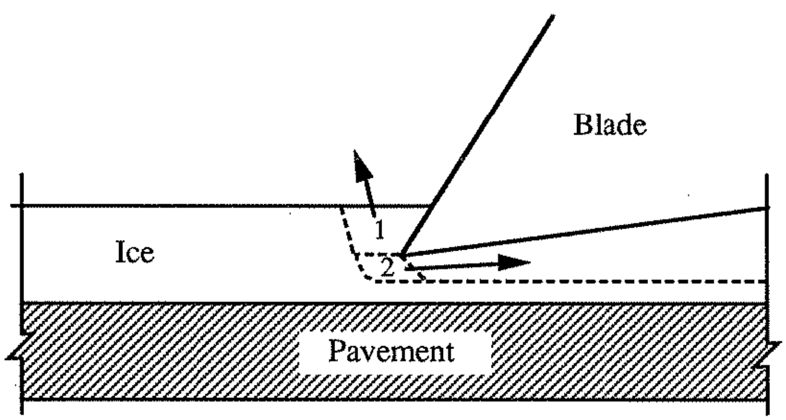


Figure 52. Tentative model of ice failure under the blade.

Ice in zone 1 is ejected upwards, before the blade. Because the ice is so finely fractured, there is relatively little friction between the blade and ice and thus cast angle has a minimal effect on the force. The ice in zone 2 is also fractured, but in order to clear, it must pass underneath the blade. Upon fracturing, the ice takes up more volume than in its unfractured state, and thus requires some clearance in order to pass beneath the blade. If this clearance is not available the broken ice fragments must be recompressed by the blade, resulting in a high downforce. This is a preliminary model and requires further examination, both by way of testing and also by some finite element modeling.

V. CONCLUSIONS

From the work performed in this study, the following conclusions can be drawn.

1. A test technique was developed which can measure and record forces on a cutting edge while scraping ice in near field conditions. The testing apparatus is available to use with other blades and can be a useful tool in the development of new cutting edges.

2. Two parameters (efficiency and effectiveness) were defined which provide a measure of how well a cutting edge removes ice from pavement. The efficiency is the ratio of vertical to horizontal force. The lower this is, the more ice is being removed for a given download. A low download being desirable for better vehicle control. Effectiveness is related to the horizontal load, though exactly how is unclear. It appears that the higher the horizontal load is, the greater the depth of ice being removed. Laboratory experiments are underway to determine this relationship more closely, and further field testing may be worth while. Also it is apparent that the effectiveness of a particular blade shape cannot be directly compared to that of another blade as a determination of which blade will remove the most ice.

3. Three blades were tested and compared in this study. Test results of the standard blade currently used for ice removal (blade 1), show that the blade has the best effectiveness at a blade angle of 0° with a high download. Blade 2 also performed the best at the smaller blade angle (15°) and high download, but displayed a large amount of variability in the results. Blade 3 displayed the best effectiveness and efficiency of the three blades by removing the largest amount of ice with the smallest vertical to horizontal force ratio. However, blade 3 performance can be reduced due to wear.

4. All three blades performed best (removed the most amount of ice) at angles close to 0° with high downloads.

5. The blade flat width size can have detrimental effects on the blades effectiveness. This was the case for blade 3 at 15° after it received a high amount of wear caused by constant use at that angle. The development of such flats could be changed by altering the blade angle at regular intervals during its life. Each alteration of blade angle would return the tip of the blade to a sharp point, which appears to be the most effective geometry for ice scraping.

6. Advances in computers and feedback control systems could make it possible to develop an automatic control system to adjust the blade (angle and download) for the best scraping performance. Such a system would prevent a flat width from forming and could prevent damage to the blade mount from wearing the entire blade away. Concomitant with development of such a system is the need to survey practitioners who operate plows with underbody blades, to assist in the development of the expert system required to exercise computer control over the cutting edge during testing. In addition to optimizing ice removal, an automated computer controlled system of this sort would have significant safety benefits.

7. A number of further tests could be made using the system which has been developed in this study. The system is now operational, and its use is limited only by the scope of testing required and of value. Possible future tests which could be conducted include the following:
    - Tests to measure the forces developed with a front mounted (rather than underbody) plow blade.
    - Tests of other, more exotic cutting edges, such as scalloped blades.
    - Tests of automated systems as described in point 6 above.
    - Tests of the relationship between horizontal forces and the depth of ice removed.
    - Tests of the effectiveness of chemical pre-treatment on ice scraping forces.

8. The final series of tests which are an obvious development of such a system are a full scale field trial. While this limited field study has indicated that the new (SHRP developed) cutting edge appears more effective than a regular cutting edge, only field

use will determine if this is really the case. Accordingly, a study could be envisaged in which two trucks in a given district are equipped with appropriate measuring devices, one with the new blade mounted and one with a more standard blade. They would be deployed in appropriate weather (with suitably trained personnel) and real comparisons between the two cutting edges could be made. Now that forces have been measured successfully on one truck, the application of similar measuring devices to other trucks is much simpler, and more easily accomplished.

REFERENCES

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APPENDIX A

Test #	Date/ Test conditions	Displacement (ft)		Vertical Force (kip)	Horizontal Force (kip)	Blade Angle (degrees)	Ratio	speed (ft/s)
1	12/1/91	147.9	max	26.46	12.96	28.10	2.99	?
	30° low		min	3.31	3.03	20.55	0.33	?
	Blade 1		mean	15.55	9.02	24.68	1.74	?
	Temp. 14°F		stdev	3.00	1.39	1.37	0.28	?
2	12/1/91	142.5	max	43.03	29.67	11.01	2.45	?
	0° low		min	9.65	10.42	1.65	0.64	?
	Blade 1		mean	27.60	16.19	6.63	1.73	?
	Temp. 14°F		stdev	4.10	3.25	1.49	0.22	?
3	12/4/91	147.9	max	20.00	16.21	25.42	2.02	?
	30° low		min	11.36	8.09	17.50	1.00	?
	Blade 1		mean	16.67	11.52	21.49	1.46	?
	Temp. 12°F		stdev	1.49	1.57	1.87	0.18	?
4	12/4/91	102.8	max	32.07	21.27	17.67	2.29	?
	15° low		min	19.05	12.35	4.79	1.27	?
	Blade 1		mean	26.79	15.62	8.85	1.74	?
	Temp. 12°F		stdev	2.53	1.86	2.85	0.26	?
5	12/4/91	92.5	max	32.83	23.44	11.01	2.48	?
	15° low		min	16.50	7.78	3.24	1.23	?
	Blade 1		mean	23.81	14.70	6.44	1.65	?
	Temp. 12°F		stdev	3.38	3.03	1.45	0.22	?
6	1/18/92	154.9	max	23.89	12.44	26.41	6.05	?
	30° high		min	16.00	2.98	18.54	1.82	?
	Blade 1		mean	19.97	7.24	23.60	2.91	?
	Temp. 17°F		stdev	1.44	1.82	1.80	0.66	?
7	1/18/92	136.8	max	31.39	16.76	24.58	4.14	?
	15° high		min	22.58	5.87	15.19	1.62	?
	Blade 1		mean	27.84	11.61	20.53	2.46	?
	Temp. 17°F		stdev	1.43	1.99	2.09	0.40	?
8	1/18/92	133.2	max	40.89	40.44	6.42	2.97	?
	0° high		min	19.85	9.38	-1.76	0.90	?
	Blade 1		mean	29.50	16.30	2.36	1.97	?
	Temp. 17°F		stdev	3.48	6.54	1.80	0.44	?
9	1/19/92	120.2	max	36.04	27.35	29.27	4.99	?
	30° high		min	25.27	5.88	14.61	1.16	?
	Blade 1		mean	31.57	14.94	23.53	2.23	?
	Temp. 25°F		stdev	1.94	3.81	3.87	0.49	?
10	1/19/92	168.7	max	36.79	33.55	10.31	2.67	?
	15° high		min	17.76	8.40	2.28	0.87	?
	Blade 1		mean	29.14	17.58	5.71	1.69	?
	Temp. 25°F		stdev	2.69	3.42	1.78	0.23	?

Test #	Date/ Test conditions	Displacement (ft)		Vertical Force (kip)	Horizontal Force (kip)	Blade Angle (degrees)	Ratio	speed (ft/s)
11	1/26/92	110.4	max	31.66	23.56	16.47	1.75	21.69
	15° low		min	3.53	8.89	9.46	0.17	15.69
	Blade 2		mean	19.21	15.18	13.57	1.28	18.09
	Temp. 23°F		stdev	4.59	2.70	1.39	0.25	1.18
12	1/26/92	77.8	max	33.29	20.21	15.12	2.48	22.54
	15° high		min	23.84	11.39	8.27	1.43	12.40
	Blade 2		mean	28.41	15.11	12.78	1.90	16.27
	Temp. 23°F		stdev	1.94	1.76	1.10	0.19	2.42
13	1/26/92	139.0	max	25.22	10.84	32.61	10.19	26.20
	30° low		min	9.72	1.86	18.83	2.11	13.53
	Blade 2		mean	19.80	5.43	26.66	3.93	19.04
	Temp. 23°F		stdev	2.23	1.53	3.48	1.17	1.82
14	1/26/92	121.3	max	28.45	17.17	31.96	6.51	21.08
	30° high		min	19.78	3.61	8.27	1.57	11.82
	Blade 2		mean	24.93	8.20	25.55	3.29	16.80
	Temp. 23°F		stdev	1.45	2.48	5.94	0.87	1.76
15	1/28/92	172.6	max	21.05	13.71	19.03	2.30	26.76
	15° low		min	3.33	3.00	8.71	0.60	14.95
	Blade 2		mean	6.90	6.06	14.03	1.15	21.52
	Temp. 23°F		stdev	2.10	1.60	2.53	0.26	2.37
16	1/28/92	149.0	max	16.83	9.06	34.99	8.21	24.33
	30° low		min	4.86	0.81	16.60	1.40	16.61
	Blade 2		mean	8.72	3.38	25.93	2.78	19.97
	Temp. 23°F		stdev	2.07	1.22	4.31	0.84	1.68
17	2/8/92	136.8	max	17.59	13.36	17.17	2.07	22.65
	15° low		min	2.66	6.50	10.86	0.29	11.08
	Blade 2		mean	6.86	8.61	13.69	0.79	19.16
	Temp. 18°F		stdev	3.10	0.93	1.47	0.34	1.47
18	2/8/92	136.9	max	22.68	9.09	31.41	8.43	23.18
	30° low		min	4.51	0.57	19.33	0.89	15.47
	Blade 2		mean	11.70	4.93	24.48	2.46	19.44
	Temp. 18°F		stdev	3.30	1.40	3.10	0.68	1.54
19	2/8/92	60.5	max	27.82	11.99	26.20	10.18	15.21
	15° high		min	13.62	1.53	16.15	2.20	6.66
	Blade 2		mean	23.79	7.35	20.77	3.47	11.51
	Temp. 18°F		stdev	1.84	2.00	2.72	0.98	1.52
20	2/8/92	130.7	max	29.31	9.43	33.78	12.52	23.54
	30° high		min	13.18	1.51	24.15	2.34	9.96
	Blade 2		mean	21.78	5.55	28.42	4.23	18.94
	Temp. 18°F		stdev	2.90	1.41	1.60	1.48	1.85

Test #	Date/ Test conditions	Displacement (ft)		Vertical Force (kip)	Horizontal Force (kip)	Blade Angle (degrees)	Ratio	speed (ft/s)
21	3/11/92	34.9	max	31.55	30.19	17.61	1.99	19.18
	15° low		min	11.65	10.17	11.15	0.89	10.48
	Blade 3		mean	23.07	17.39	14.82	1.36	15.44
	Temp. 25°F		stdev	3.21	3.38	1.56	0.23	1.51
22	3/11/92	151.5	max	17.13	18.57	26.79	11.18	27.48
	30° low		min	2.49	0.92	16.24	0.30	13.89
	Blade 3		mean	7.79	8.10	22.19	0.97	18.30
	Temp. 25°F		stdev	3.95	2.72	2.85	0.63	2.61
23	3/11/92	92.1	max	32.30	22.63	18.85	2.16	20.28
	15° low		min	3.28	7.30	8.93	0.27	12.59
	Blade 3		mean	14.01	12.85	13.85	1.05	15.72
	Temp. 25°F		stdev	6.91	3.41	2.72	0.35	1.44
24	3/11/92	124.0	max	15.49	17.27	30.23	1.97	33.89
	30° low		min	4.84	2.87	20.09	0.56	12.04
	Blade 3		mean	8.39	7.45	24.69	1.18	18.51
	Temp. 25°F		stdev	1.88	2.36	2.43	0.27	3.44
25	3/13/92	60.4	max	30.02	30.07	24.24	2.84	24.48
	15° low		min	12.53	9.19	9.89	0.88	13.76
	Blade 3		mean	23.50	16.29	14.56	1.52	18.63
	Temp. 21°F		stdev	2.80	4.07	4.39	0.37	2.75
26	3/13/92	44.6	max	38.75	34.87	21.45	2.77	18.74
	15° high		min	25.20	11.14	13.06	0.88	0.76
	Blade 3		mean	32.82	21.53	17.70	1.56	10.41
	Temp. 21°F		stdev	1.91	3.44	2.46	0.25	5.05
27	3/13/92	60.7	max	24.77	19.60	30.52	2.91	20.06
	30° low		min	9.48	4.07	20.09	0.74	10.16
	Blade 3		mean	16.09	10.41	25.61	1.65	13.68
	Temp. 21°F		stdev	2.97	3.37	2.62	0.39	1.86
28	1/9/93	131.5	max	27.14	17.82	30.78	3.55	20.80
	30° low		min	12.57	5.75	21.43	0.97	16.57
	Blade 3		mean	19.34	10.43	26.48	1.91	17.96
	Temp. 23°F		stdev	3.29	2.26	1.68	0.37	1.04
29	1/9/93	149.7	max	26.62	17.22	16.48	2.57	22.36
	15° low		min	11.73	8.81	10.44	1.03	19.59
	Blade 3		mean	20.62	12.35	12.96	1.68	21.51
	Temp. 23°F		stdev	2.74	1.42	1.08	0.20	0.57
30	1/9/93	108.7	max	38.00	20.98	17.33	2.52	20.61
	30° high		min	18.80	9.50	9.36	1.24	16.41
	Blade 3		mean	28.03	15.09	14.47	1.88	18.74
	Temp. 23°F		stdev	2.71	2.06	1.75	0.20	0.98

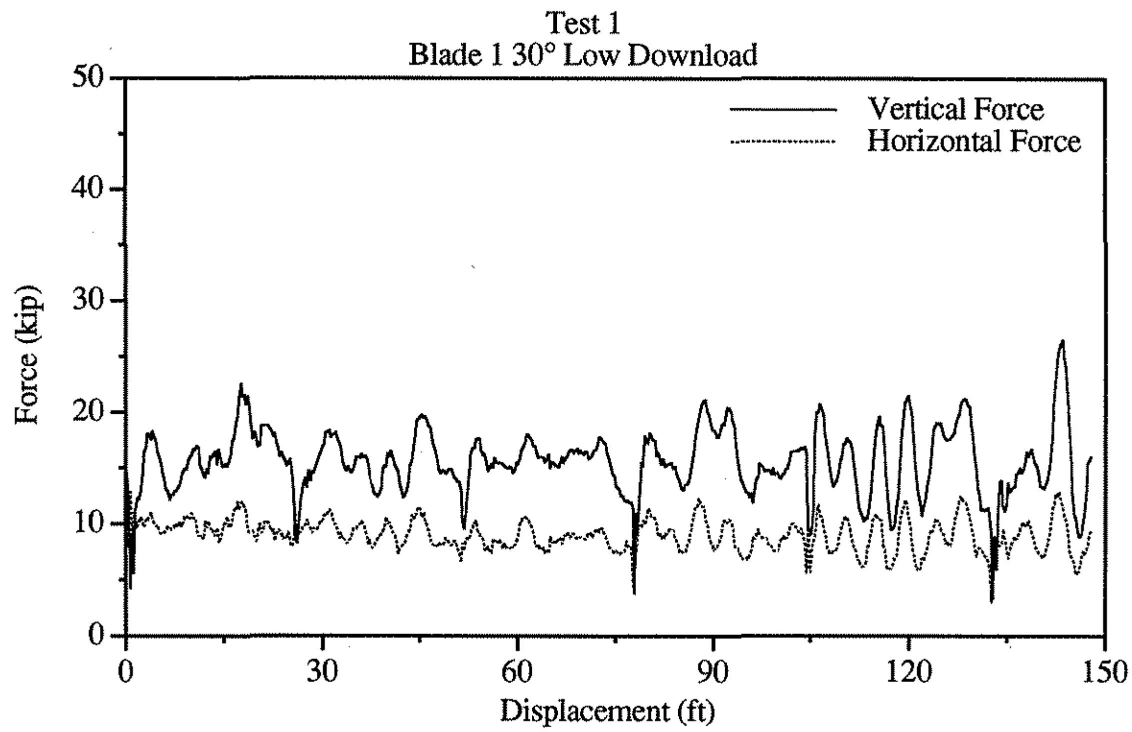
Test #	Date/ Test conditions	Displacement (ft)		Vertical Force (kip)	Horizontal Force (kip)	Blade Angle (degrees)	Ratio	speed (ft/s)
31	1/15/93	127.3	max	37.47	11.47	17.14	7.11	22.25
	15° high		min	23.22	4.83	10.16	2.15	19.43
	Blade 3		mean	28.75	8.13	14.08	3.62	21.22
	Temp. 19°F		stdev	2.22	1.14	1.41	0.70	0.53
32	1/15/93	86.7	max	16.91	16.89	25.97	4.45	19.06
	30° low		min	7.33	3.03	20.73	0.74	15.34
	Blade 3		mean	12.90	7.67	23.56	1.93	17.78
	Temp. 19°F		stdev	1.71	3.16	1.25	0.72	0.68
33	1/15/93	81.8	max	26.23	20.86	39.99	3.43	19.69
	30° high		min	16.03	6.13	19.58	1.00	0.20
	Blade 3		mean	21.35	12.59	29.45	1.80	9.74
	Temp. 19°F		stdev	1.90	3.16	4.17	0.44	4.93
34	1/15/93	148.7	max	37.20	23.37	26.15	5.51	20.42
	15° high		min	10.97	4.81	11.53	1.06	14.29
	Blade 3		mean	25.14	11.48	17.49	2.38	16.71
	Temp. 19°F		stdev	6.09	4.41	3.04	0.76	1.17
35	1/18/93	123.9	max	22.33	16.32	34.40	3.00	20.50
	30° low		min	4.07	3.88	23.35	0.47	14.37
	Blade 3		mean	9.89	9.65	28.48	1.04	16.34
	Temp. 25°F		stdev	4.16	1.95	2.69	0.42	1.48
36	1/18/93	135.8	max	40.13	20.72	21.84	14.08	22.47
	15° high		min	29.51	2.59	7.41	1.78	14.95
	Blade 3		mean	34.56	8.52	14.94	4.42	21.02
	Temp. 25°F		stdev	1.93	2.91	3.18	1.29	1.25
37	1/18/93	110.6	max	37.47	34.72	24.63	4.13	20.23
	15° high		min	9.83	7.65	8.07	0.65	4.45
	Blade 3		mean	26.23	17.82	15.19	1.71	14.82
	Temp. 25°F		stdev	6.16	6.73	4.40	0.81	4.21
38	1/18/93	134.1	max	26.94	19.68	21.36	7.49	22.77
	30° high		min	17.23	3.14	9.13	1.10	19.55
	Blade 3		mean	22.99	7.63	15.35	3.66	21.15
	Temp. 25°F		stdev	1.74	3.55	2.46	1.56	0.71
39	1/18/93	90.0	max	34.19	26.66	36.99	3.87	20.46
	30° low		min	11.18	4.61	13.48	0.58	7.11
	Blade 3		mean	18.15	12.86	28.26	1.64	11.09
	Temp. 16°F		stdev	4.42	5.06	4.39	0.71	3.68
40	1/19/93	108.8	max	38.89	13.06	18.52	7.55	22.64
	15° high		min	25.93	4.35	10.52	2.46	20.50
	Blade 3		mean	31.22	8.11	14.33	4.07	21.58
	Temp. 16°F		stdev	2.18	1.91	2.12	1.02	0.51

Test #	Date/ Test conditions	Displacement (ft)		Vertical Force (kip)	Horizontal Force (kip)	Blade Angle (degrees)	Ratio	speed (ft/s)
41	1/19/93	151.8	max	45.67	21.00	22.69	7.72	22.73
	15° high		min	25.06	4.55	8.29	1.51	19.66
	Blade 3		mean	33.27	9.74	13.94	3.55	21.50
	Temp. 16°F		stdev	3.73	1.91	2.25	0.82	0.64
42	1/19/93	57.0	max	30.93	23.30	36.89	2.35	20.23
	30° low		min	7.95	8.19	11.29	0.44	5.30
	Blade 3		mean	15.79	15.34	28.43	1.04	11.31
	Temp. 16°F		stdev	5.34	3.58	5.93	0.26	4.42
43	1/19/93	62.2	max	26.62	19.65	39.92	4.03	21.21
	30° high		min	12.08	3.75	12.28	1.02	3.13
	Blade 3		mean	19.65	13.60	32.83	1.53	12.81
	Temp. 16°F		stdev	2.68	3.09	8.74	0.44	5.77
44	1/19/93	132.2	max	21.43	20.58	30.76	5.08	20.53
	30° low		min	11.40	3.41	13.61	0.74	12.95
	Blade 3		mean	16.74	9.42	23.71	1.92	15.78
	Temp. 16°F		stdev	1.50	2.72	4.13	0.58	1.80
45	1/19/93	136.9	max	45.25	18.71	17.81	4.23	23.29
	15° high		min	19.03	7.55	8.95	1.28	19.15
	Blade 3		mean	32.97	12.29	12.88	2.72	20.49
	Temp. 16°F		stdev	3.88	1.66	1.79	0.43	0.69
46	2/17/93	123.2	max	31.09	18.23	23.10	7.11	?
	30° high		min	20.04	3.15	8.18	1.49	?
	Blade 2		mean	26.09	10.28	15.74	2.69	?
	Temp. 5°F		stdev	1.99	2.48	3.14	0.72	?
47	2/17/93	127.1	max	33.71	28.07	18.17	2.71	?
	15° high		min	20.80	8.66	0.90	1.09	?
	Blade 2		mean	27.37	18.14	9.49	1.57	?
	Temp. 5°F		stdev	2.36	4.19	3.70	0.29	?
48	2/17/93	111.6	max	35.70	21.26	20.38	5.84	?
	15° low		min	13.75	5.55	3.16	1.06	?
	Blade 2		mean	23.46	10.87	16.37	2.23	?
	Temp. 5°F		stdev	3.45	2.46	1.98	0.47	?
49	2/17/93	143.3	max	27.96	16.47	22.46	2.85	?
	15° low		min	15.21	8.85	10.64	1.06	?
	Blade 2		mean	24.36	12.17	17.05	2.02	?
	Temp. 5°F		stdev	1.68	1.37	1.97	0.23	?
50	2/17/93	103.1	max	32.27	15.80	20.96	4.06	?
	15° low		min	10.26	4.39	12.15	0.90	?
	Blade 2		mean	19.93	8.47	16.43	2.42	?
	Temp. 5°F		stdev	3.33	1.95	1.73	0.47	?

Test #	Date/ Test conditions	Displacement (ft)		Vertical Force (kip)	Horizontal Force (kip)	Blade Angle (degrees)	Ratio	speed (ft/s)
51	2/17/93	130.9	max	20.29	8.71	32.85	15.42	?
	30° low		min	9.50	1.00	15.43	1.71	?
	Blade 2		mean	15.36	4.35	23.46	3.94	?
	Temp. 5°F		stdev	2.00	1.40	4.80	1.61	?
52	2/17/93	135.5	max	33.22	14.89	36.66	8.80	?
	30° low		min	17.35	2.38	10.86	1.71	?
	Blade 2		mean	24.46	7.64	23.09	3.63	?
	Temp. 5°F		stdev	2.06	2.67	7.04	1.34	?
53	2/17/93	118.3	max	19.66	5.85	42.21	45.61	?
	30° low		min	9.69	0.34	17.10	1.91	?
	Blade 2		mean	14.91	2.63	26.90	6.92	?
	Temp. 5°F		stdev	1.80	1.01	4.87	4.49	?
54	2/17/93	119.7	max	34.50	18.62	35.54	19.34	?
	30° high		min	23.66	1.74	12.36	1.65	?
	Blade 2		mean	29.54	10.92	21.69	3.09	?
	Temp. 5°F		stdev	1.96	3.25	5.50	1.63	?
55	2/17/93	139.4	max	34.38	18.53	38.47	12.10	?
	30° high		min	20.25	2.05	18.48	1.73	?
	Blade 2		mean	30.11	8.92	26.99	3.80	?
	Temp. 5°F		stdev	1.99	2.88	5.14	1.51	?
56	2/17/93	110.2	max	38.67	23.92	22.09	2.86	?
	15° high		min	24.71	11.54	8.42	1.26	?
	Blade 2		mean	32.52	19.31	13.02	1.72	?
	Temp. 5°F		stdev	1.96	2.65	2.77	0.29	?
57	2/17/93	106.7	max	36.93	19.80	23.16	3.15	?
	15° high		min	2.58	7.34	8.80	0.18	?
	Blade 2		mean	21.94	12.33	16.28	1.76	?
	Temp. 5°F		stdev	8.15	2.95	3.18	0.40	?
58	2/17/93	169.3	max	36.54	21.58	23.11	3.73	?
	15° high		min	2.74	7.70	9.04	0.17	?
	Blade 2		mean	25.91	15.29	15.67	1.75	?
	Temp. 5°F		stdev	5.61	2.50	3.16	0.54	?
59	2/17/93	190.8	max	36.64	21.32	23.35	5.87	?
	15° high		min	15.58	5.34	8.89	0.80	?
	Blade 2		mean	29.23	10.74	17.47	2.84	?
	Temp. 5°F		stdev	2.17	2.08	2.31	0.73	?
60	2/18/93	136.5	max	35.99	15.51	22.28	11.92	22.58
	15° high		min	20.37	2.32	12.50	1.94	11.75
	Blade 2		mean	29.30	8.60	17.73	3.71	16.73
	Temp. 5°F		stdev	2.60	2.42	2.12	1.26	2.95

Test #	Date/ Test conditions	Displacement (ft)		Vertical Force (kip)	Horizontal Force (kip)	Blade Angle (degrees)	Ratio	speed (ft/s)
61	2/18/93	144.7	max	37.38	11.18	46.01	26.78	22.87
	30° high		min	21.79	1.15	27.44	2.92	13.19
	Blade 2		mean	30.32	4.82	35.96	7.39	20.20
	Temp. 5°F		stdev	2.25	1.86	4.80	3.41	2.22
62	2/18/93	160.2	max	24.67	13.41	20.17	3.98	22.32
	15° low		min	11.20	5.45	9.54	1.15	19.77
	Blade 2		mean	18.81	8.72	15.58	2.21	21.03
	Temp. 5°F		stdev	2.26	1.21	2.29	0.47	0.56
63	2/18/93	165.9	max	36.97	19.80	22.12	10.01	22.57
	15° high		min	23.17	3.12	10.76	1.79	11.81
	Blade 2		mean	31.86	9.85	16.30	3.50	17.32
	Temp. 5°F		stdev	2.20	2.80	2.44	1.11	2.93
64	2/18/93	138.3	max	30.69	10.17	22.82	10.35	?
	30° high		min	16.99	2.51	10.04	2.06	?
	Blade 2		mean	25.90	5.46	17.62	5.00	?
	Temp. 5°F		stdev	2.05	1.30	2.11	1.20	?
65	2/18/93	113.7	max	33.57	12.94	37.42	9.90	?
	15° high		min	21.43	2.55	20.08	2.37	?
	Blade 2		mean	28.41	6.95	26.77	4.49	?
	Temp. 5°F		stdev	1.62	2.03	4.95	1.50	?

APPENDIX B



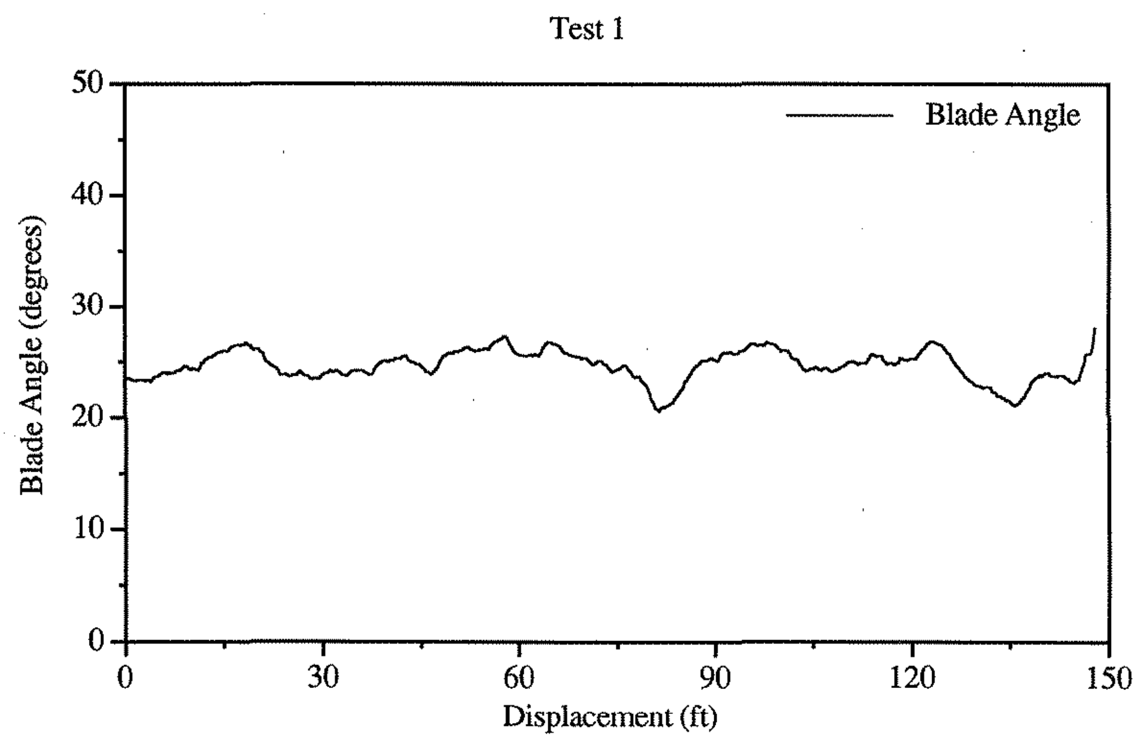
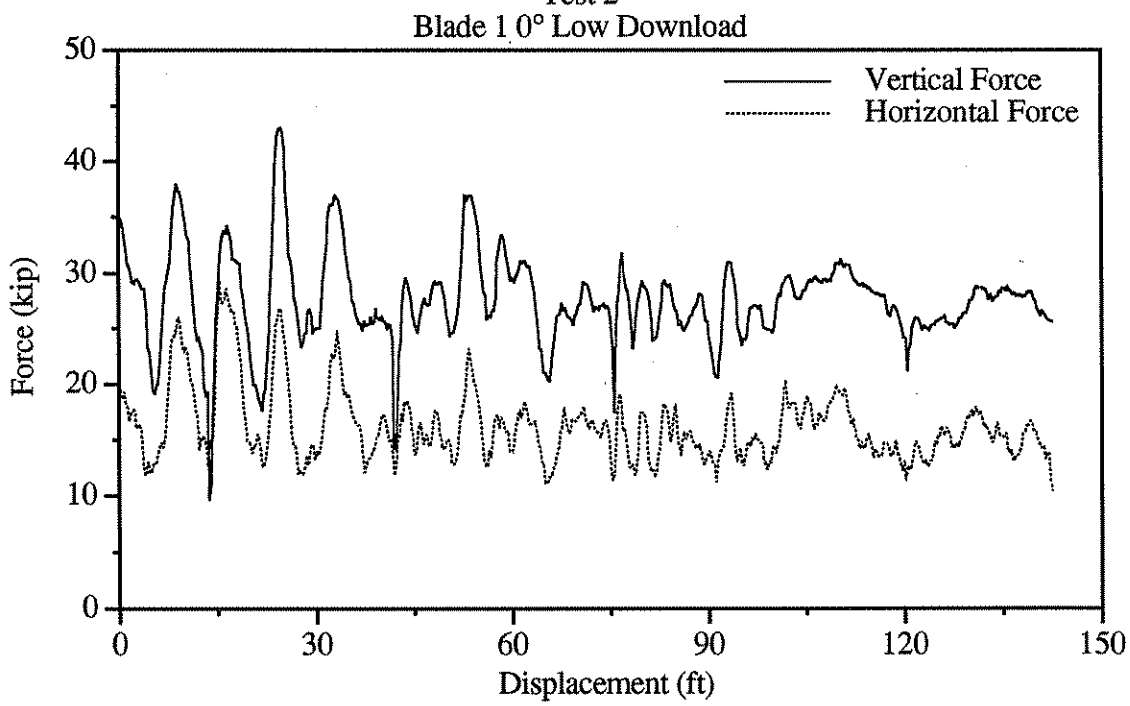


Figure B1. Graphical results of test 1.

Test 2



Test 2

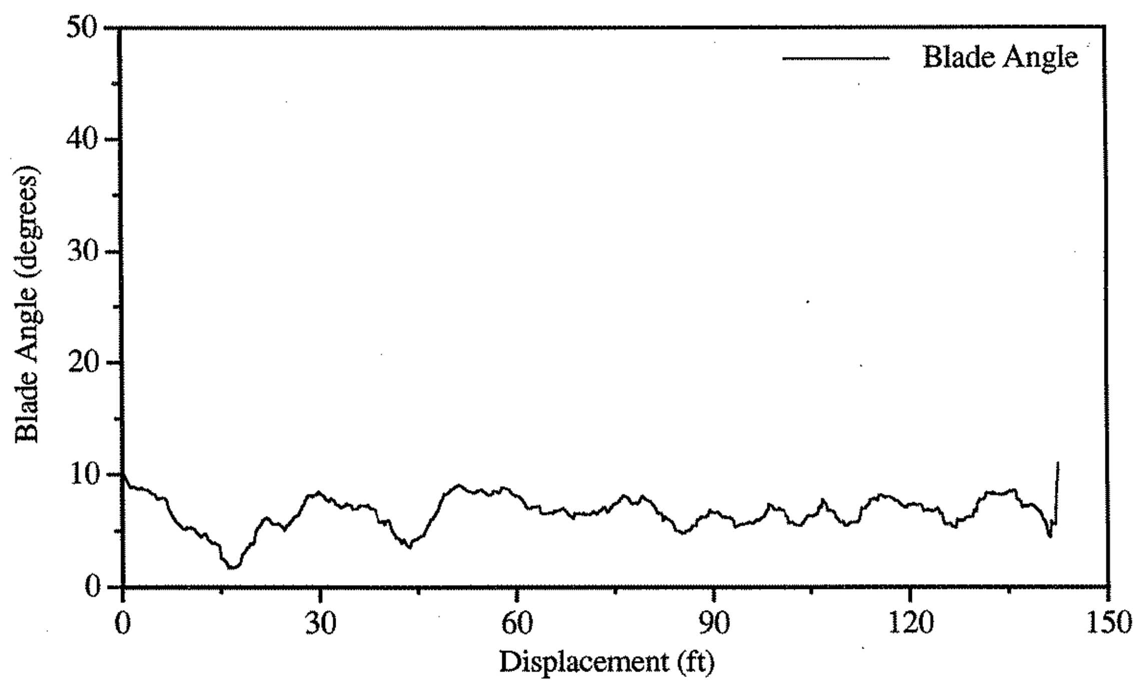
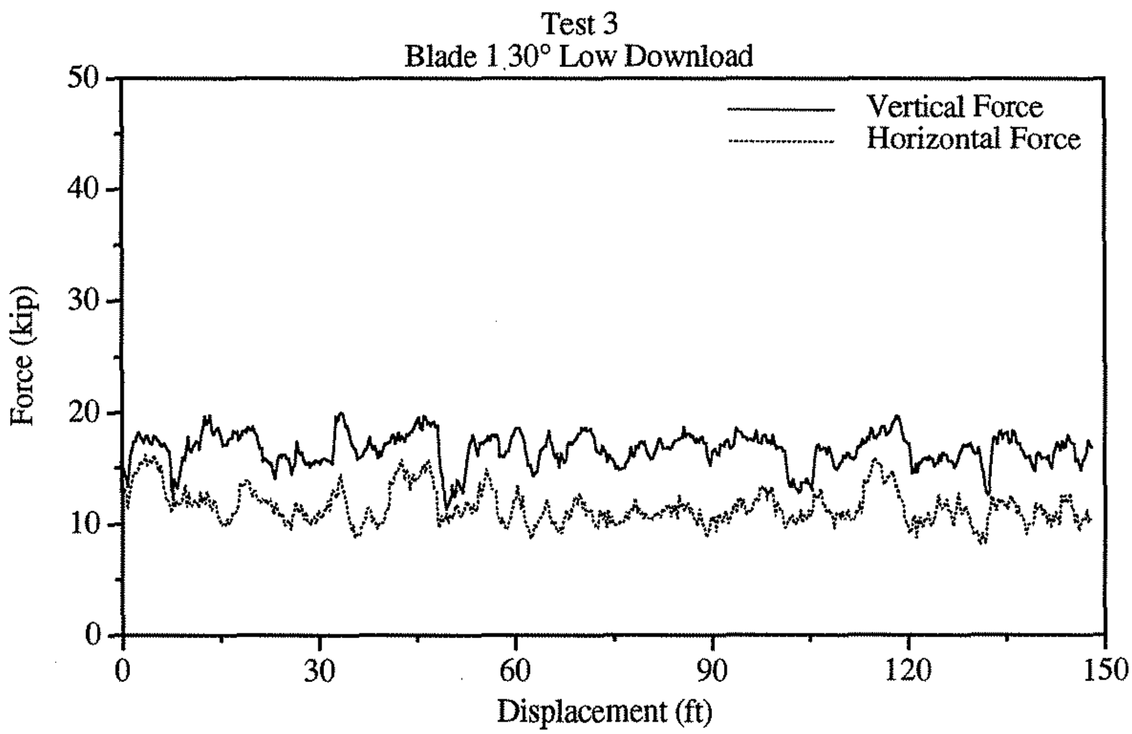


Figure B2. Graphical results of test 2.



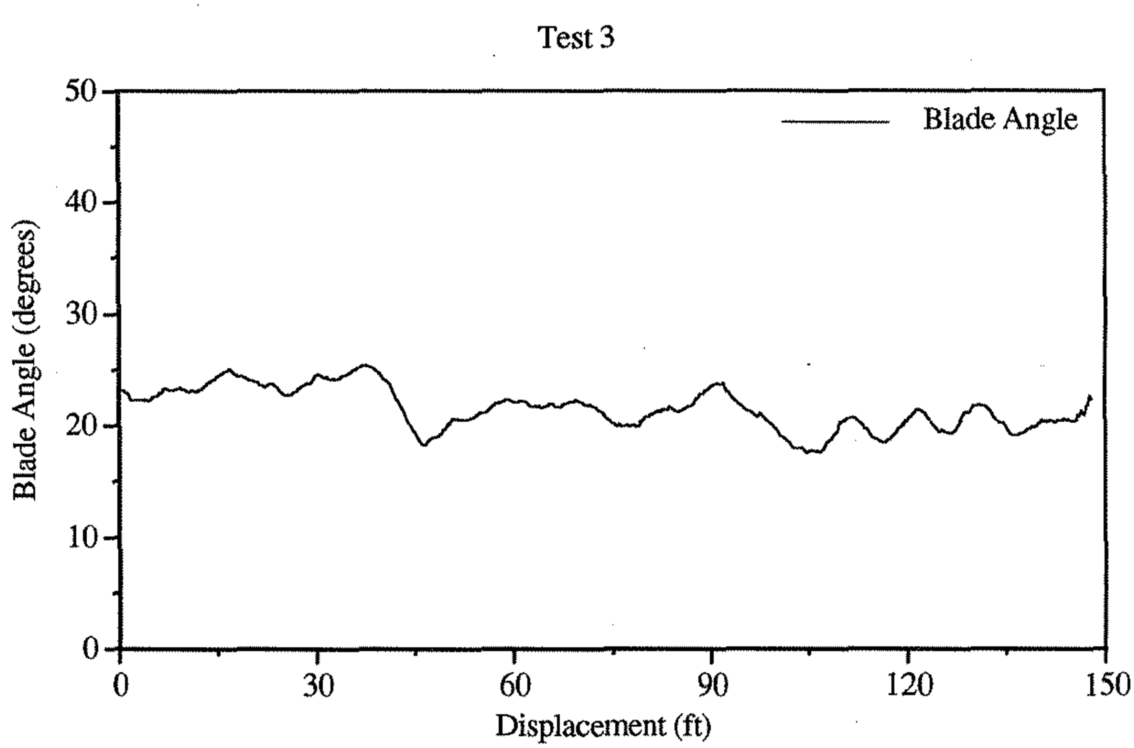
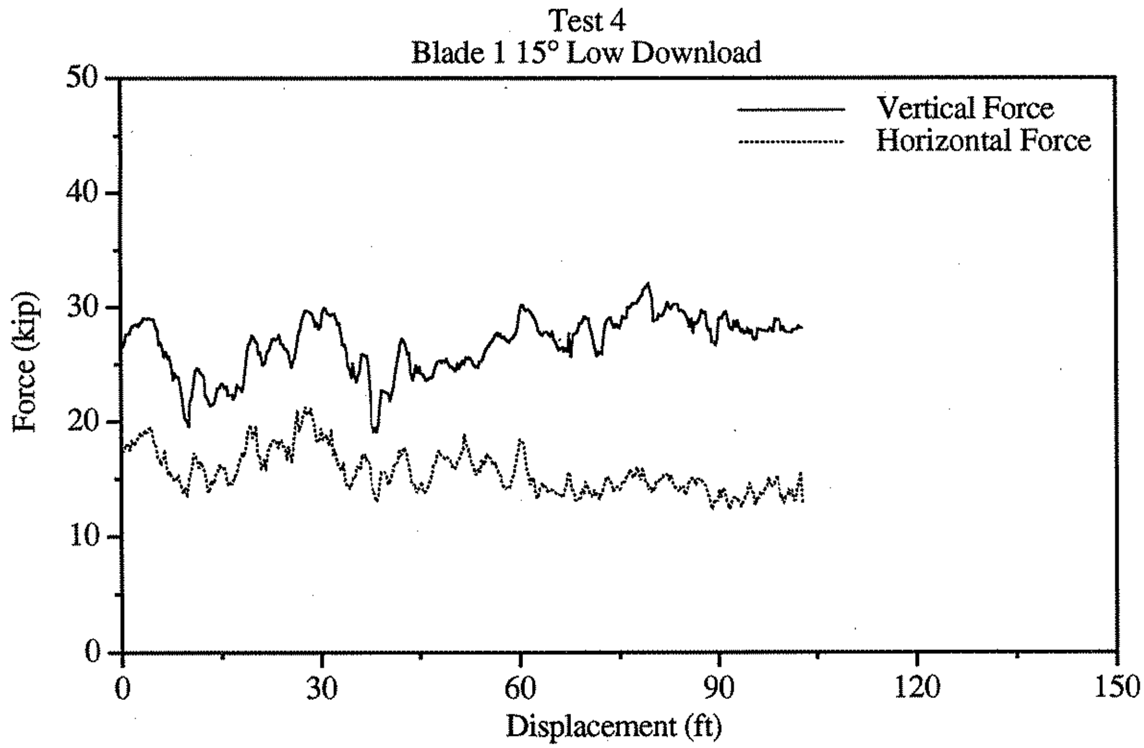


Figure B3. Graphical results of test 3.



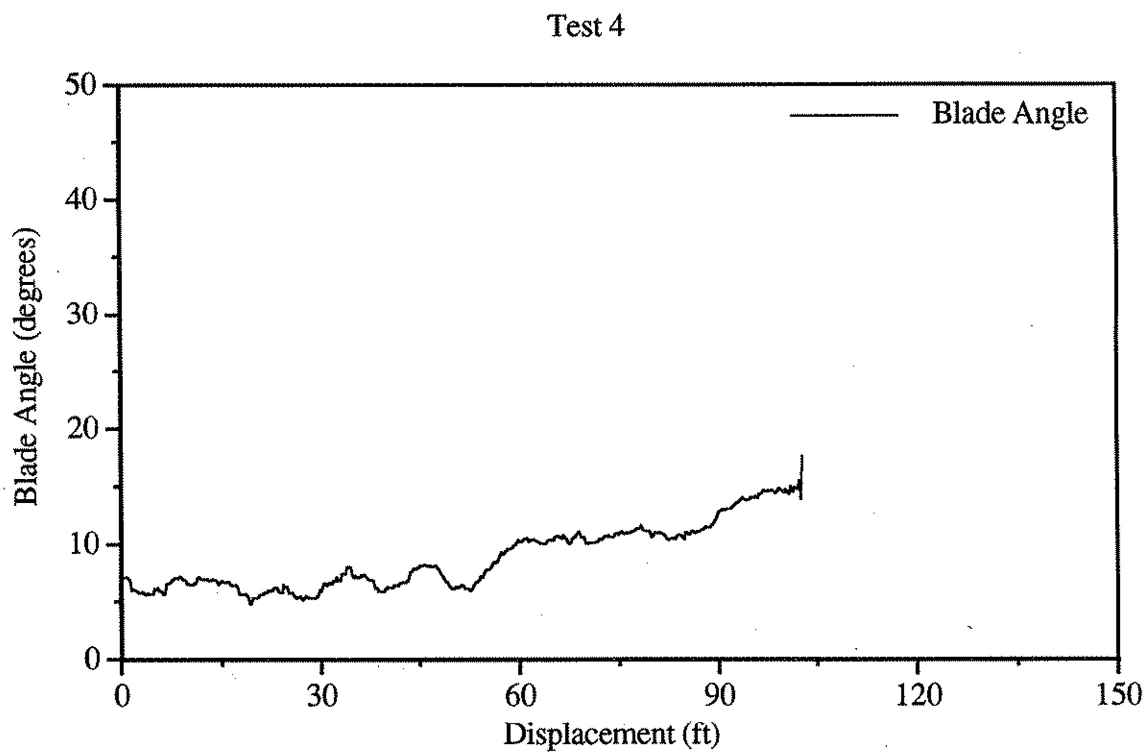
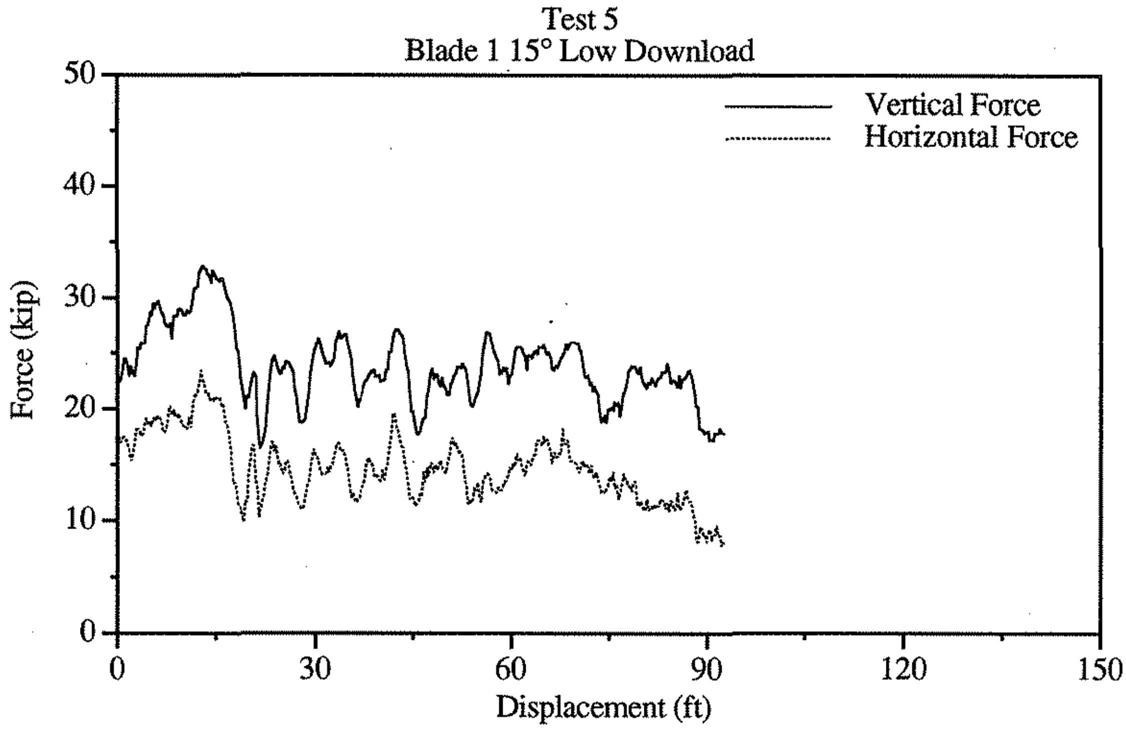


Figure B4. Graphical results of test 4.



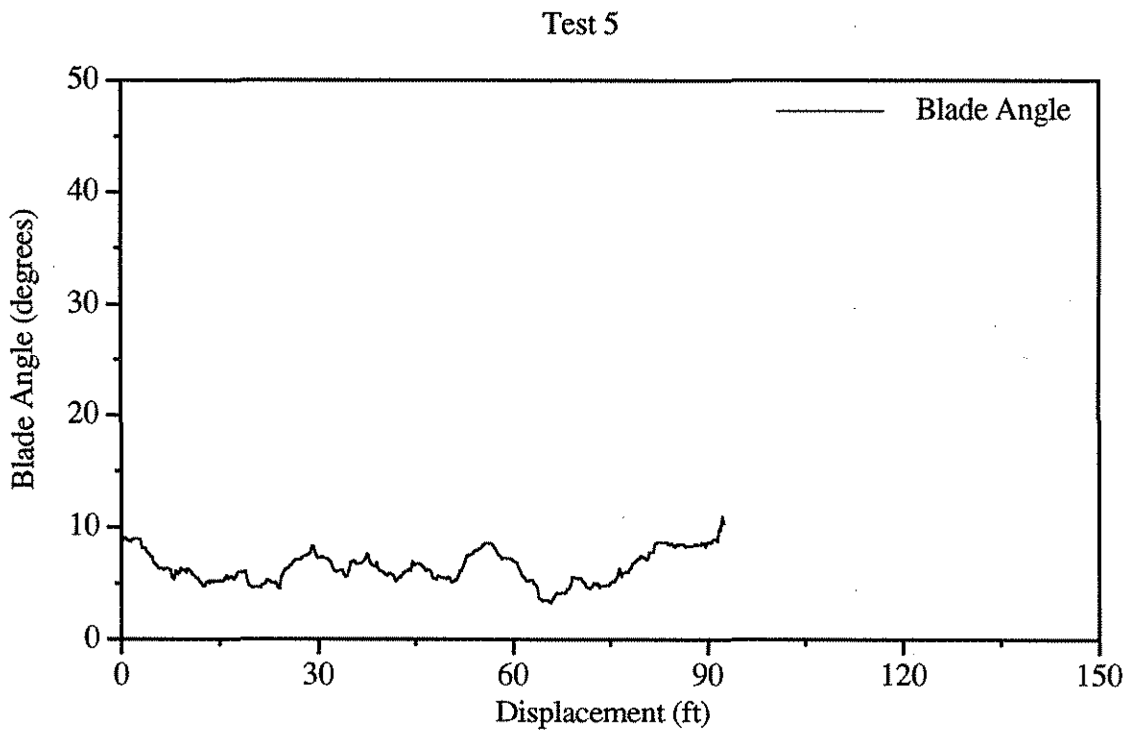
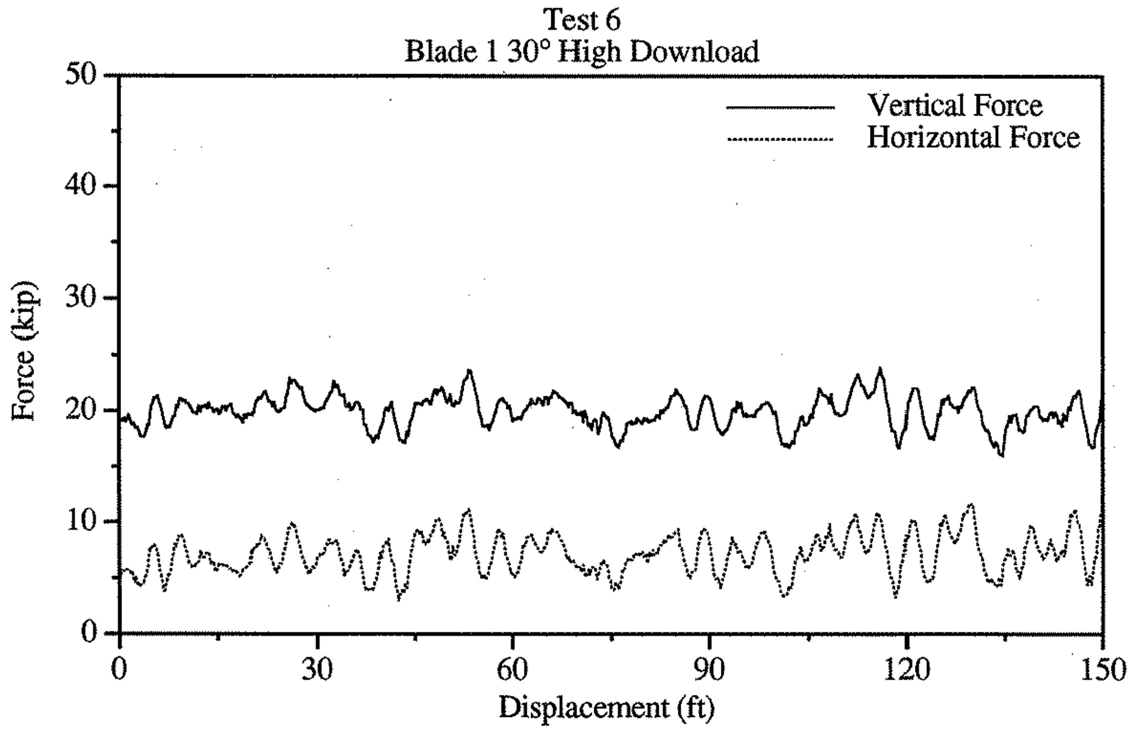


Figure B5. Graphical results of test 5.



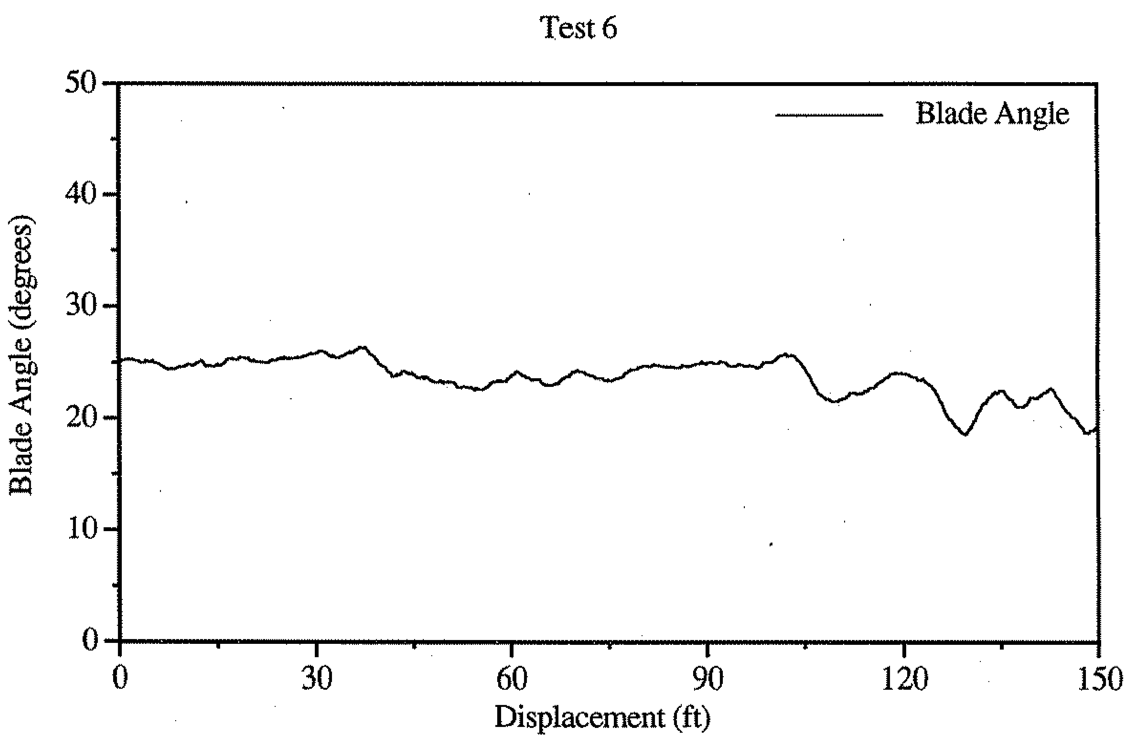
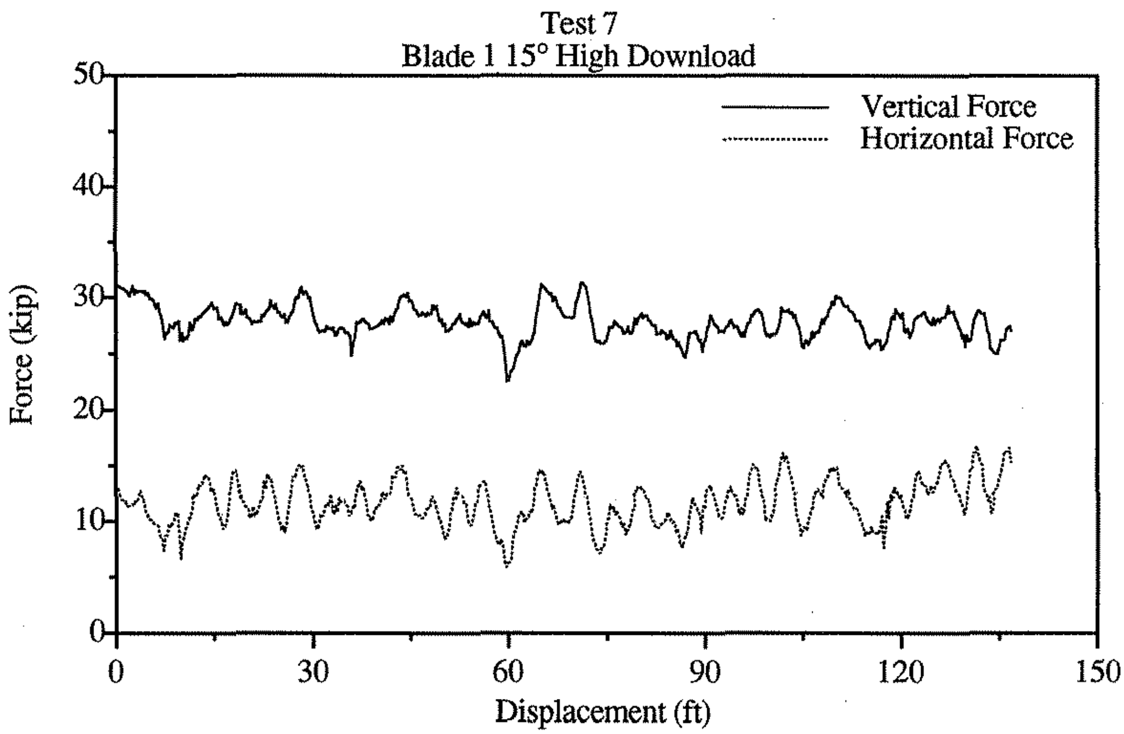


Figure B6. Graphical results of test 6.



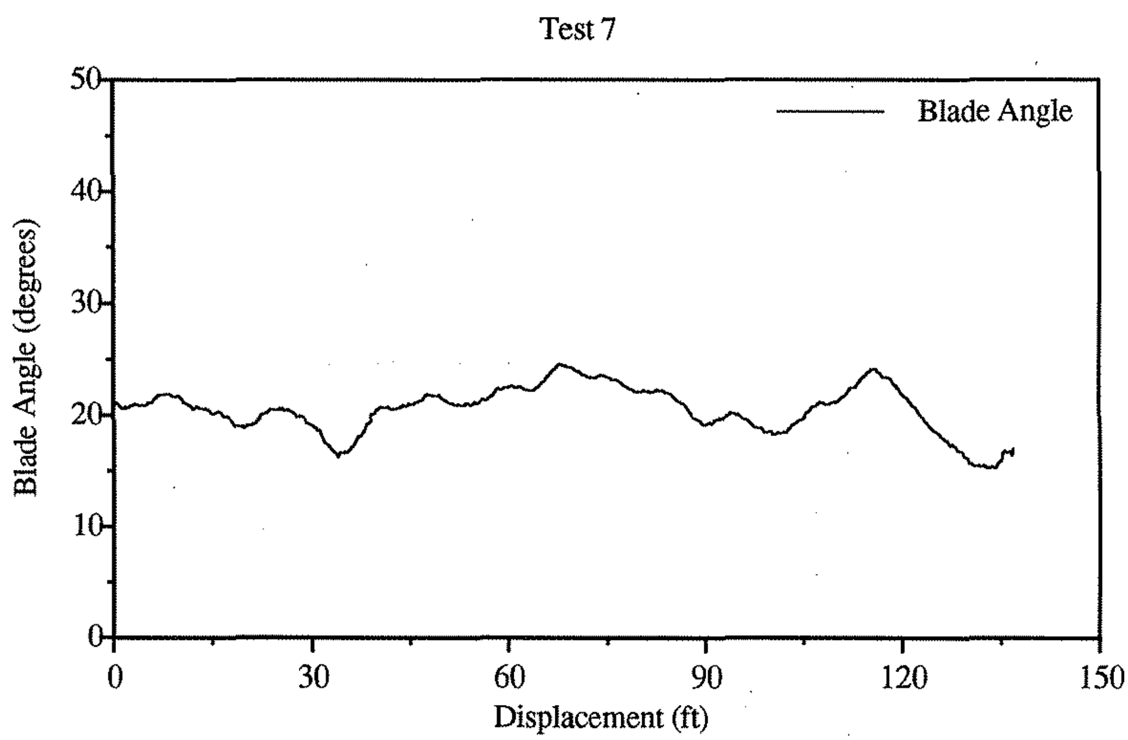
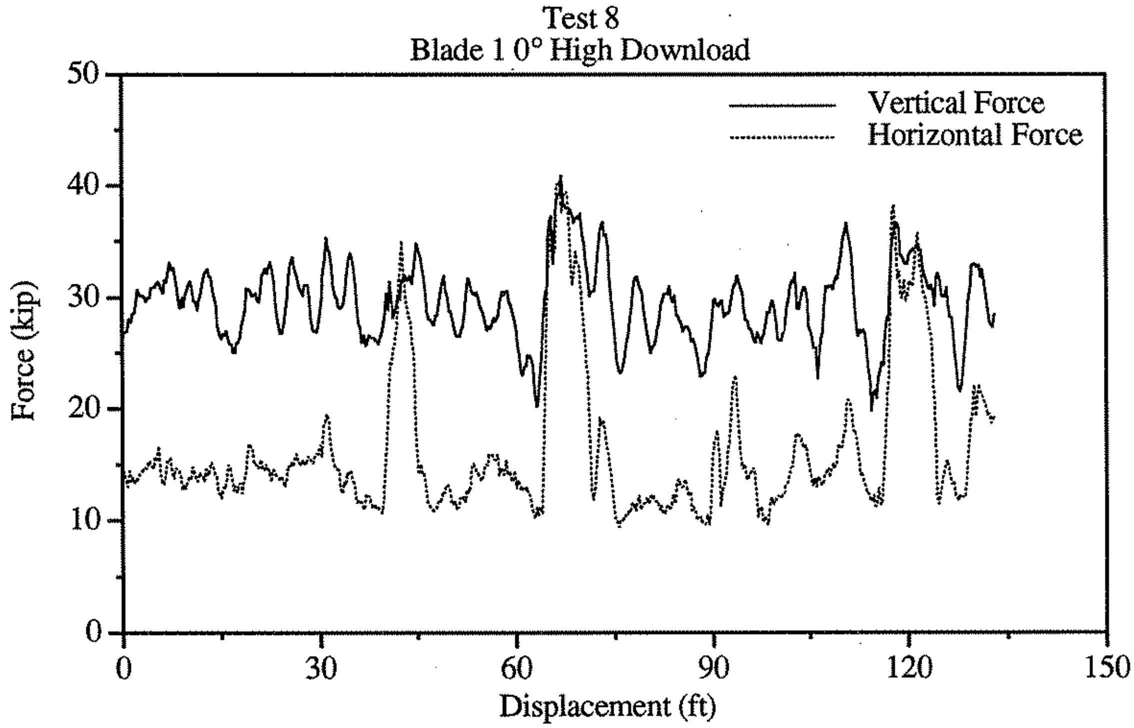


Figure B7. Graphical results of test 7.



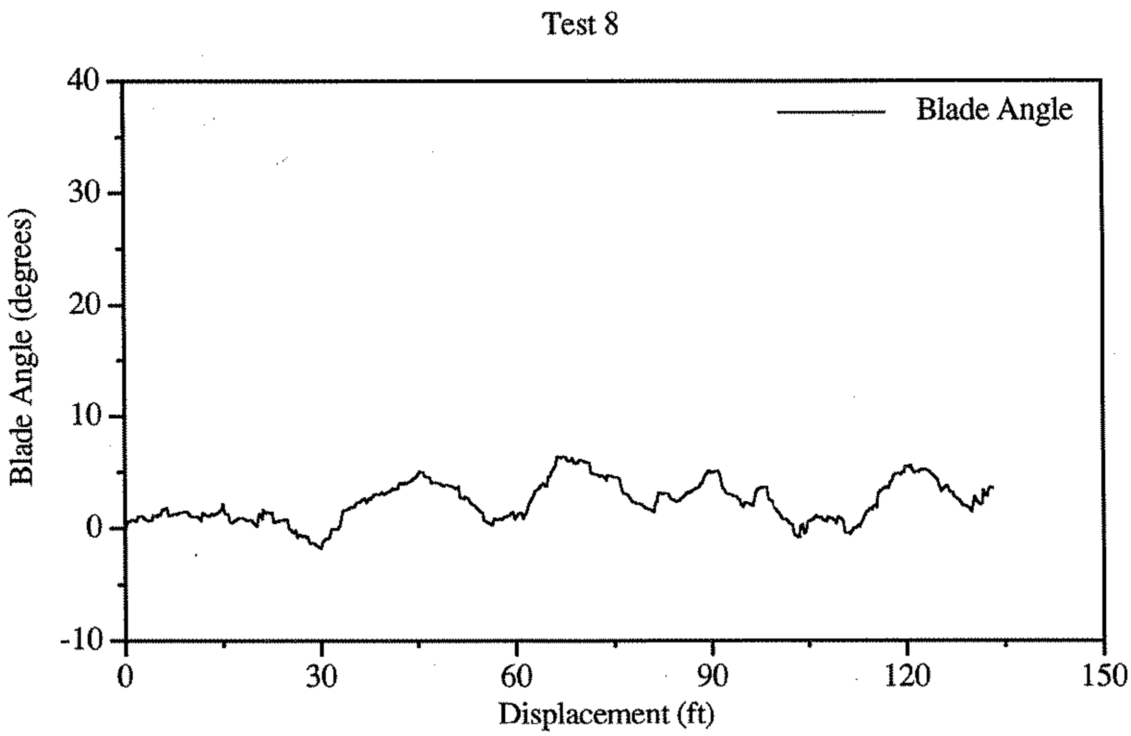
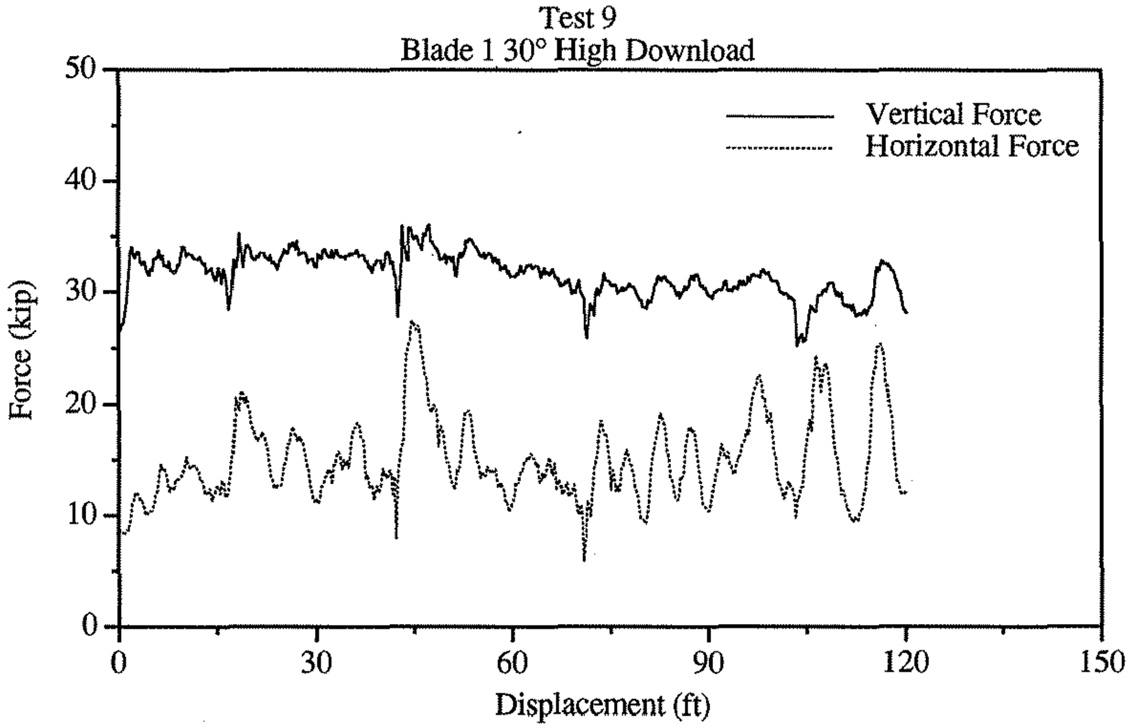


Figure B8. Graphical results of test 8.



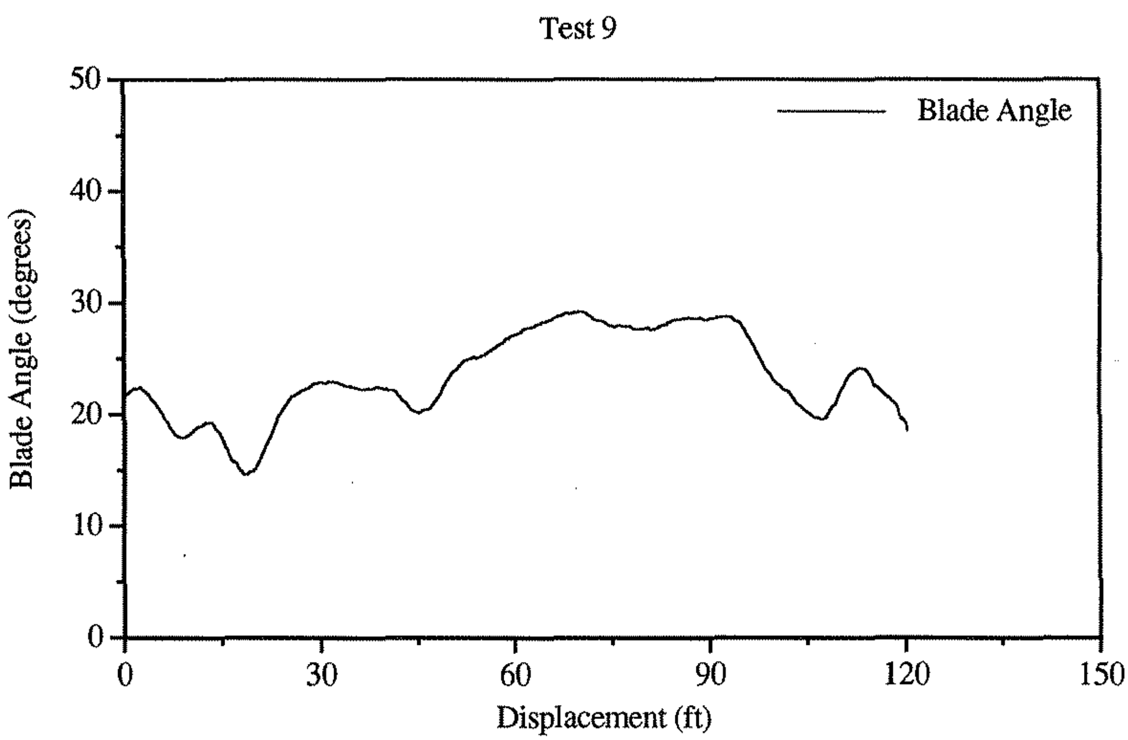
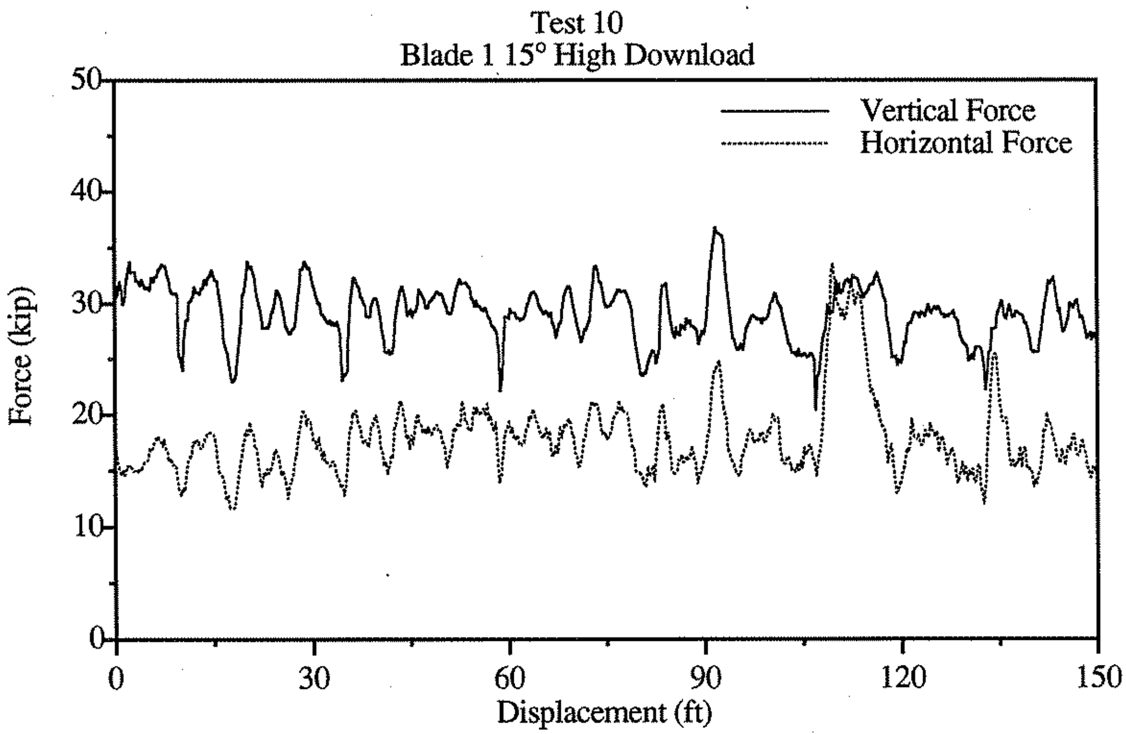


Figure B9. Graphical results of test 9.



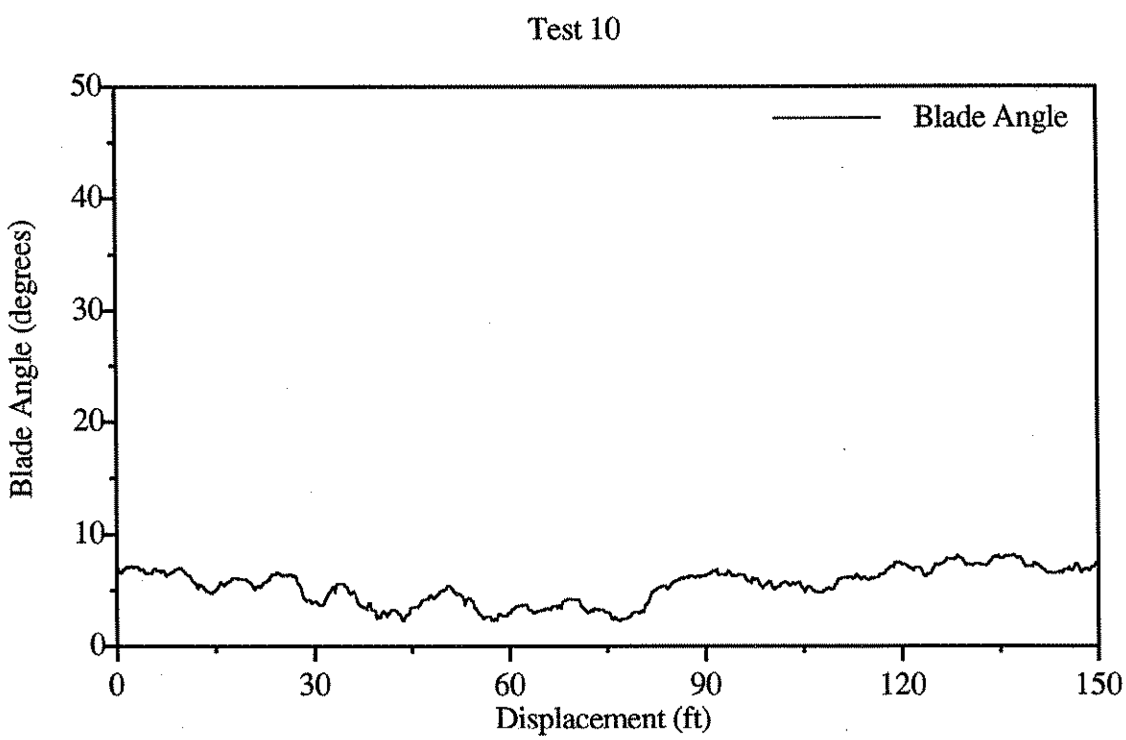
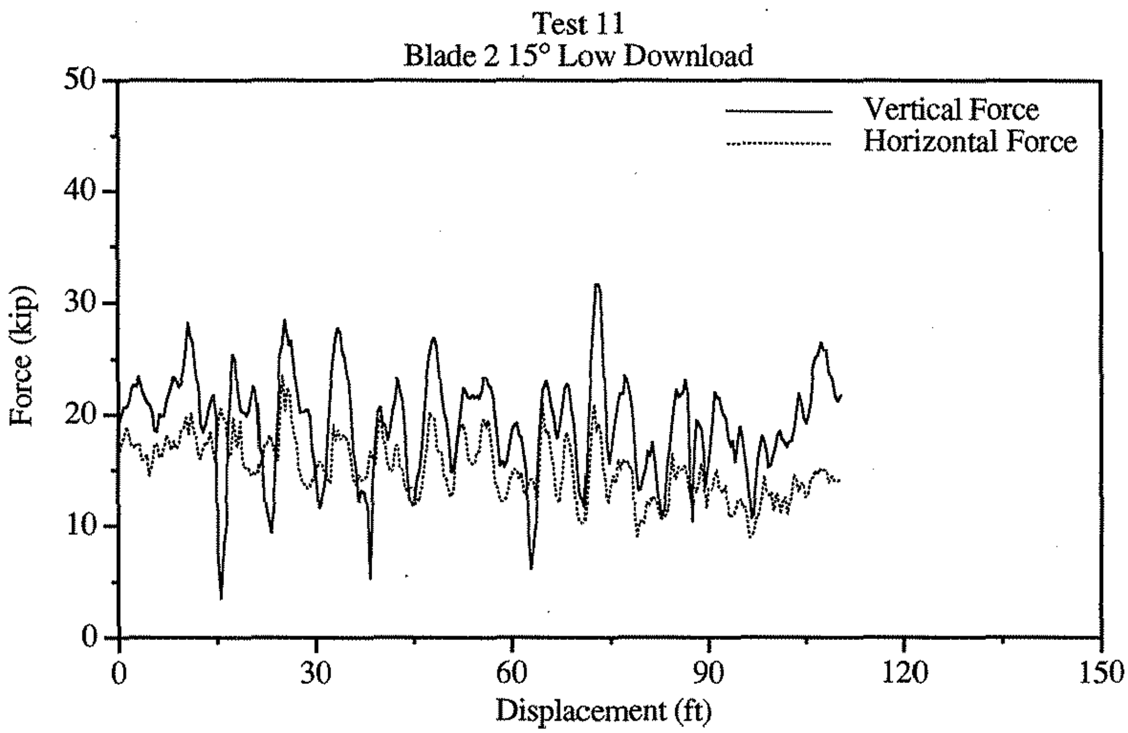


Figure B10. Graphical results of test 10.



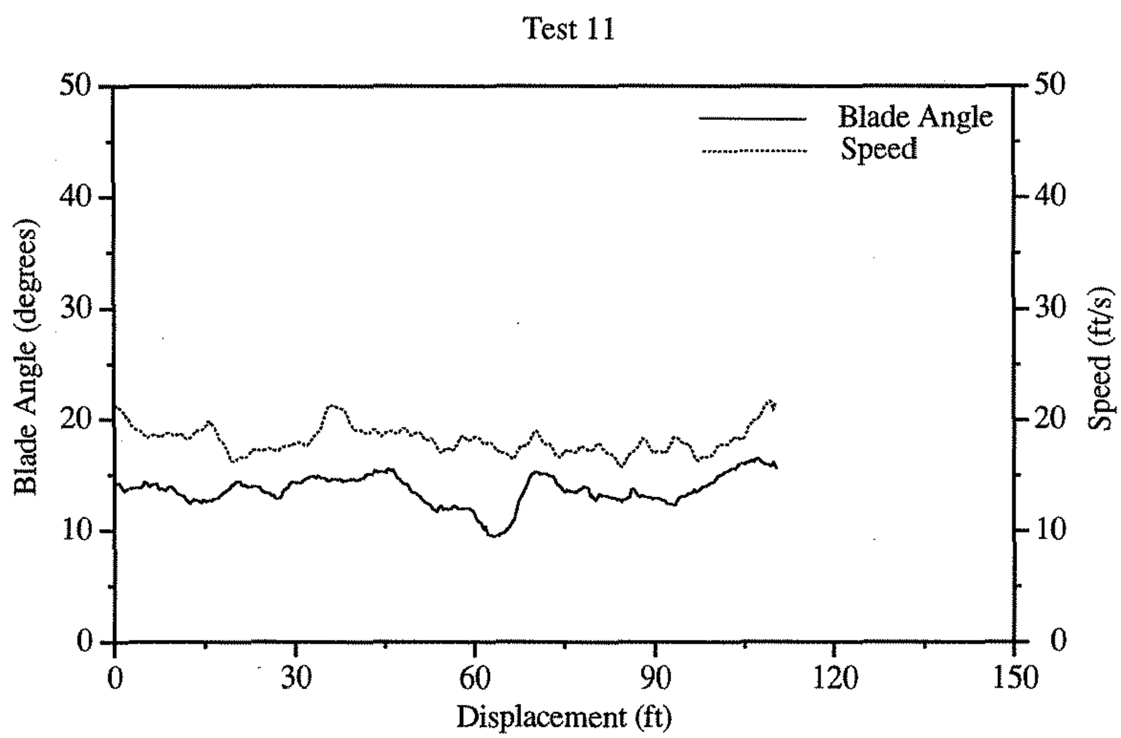
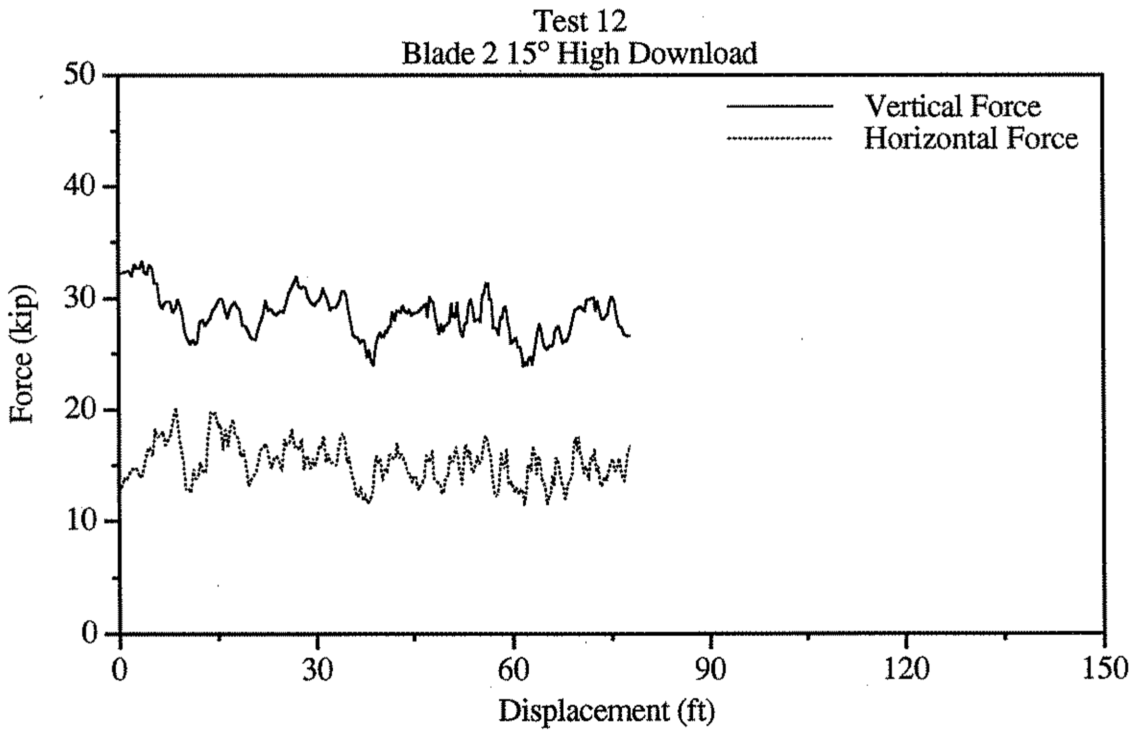


Figure B11. Graphical results of test 11.



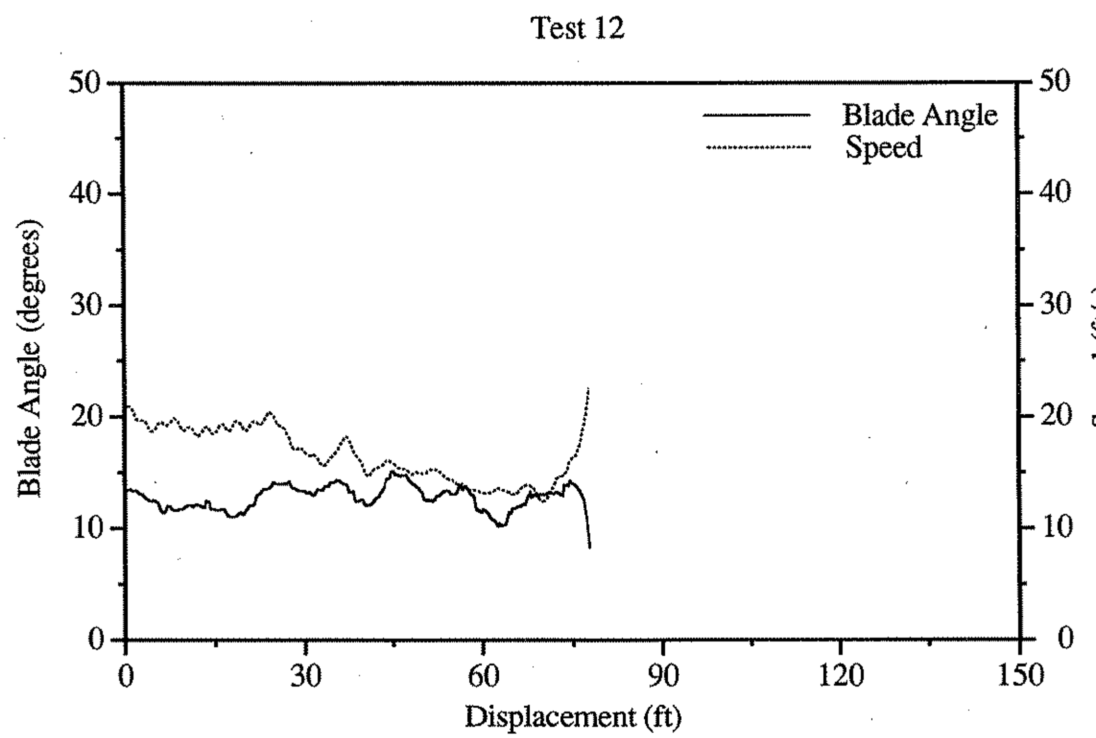
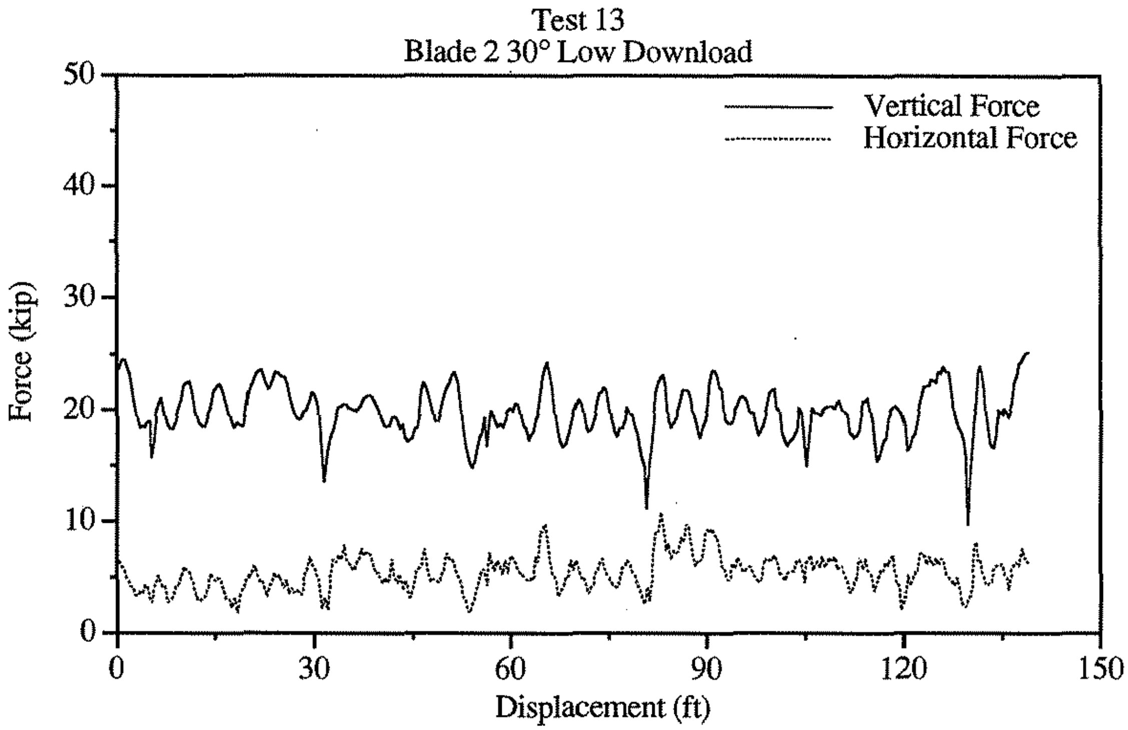


Figure B12. Graphical results of test 12.



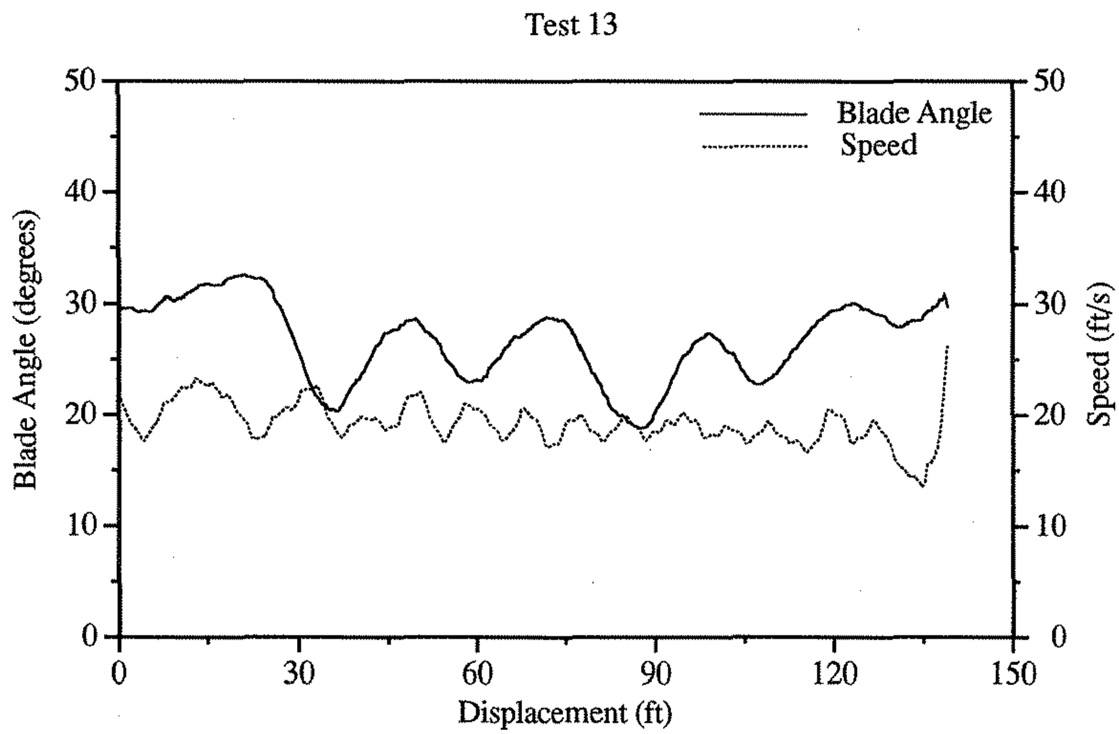
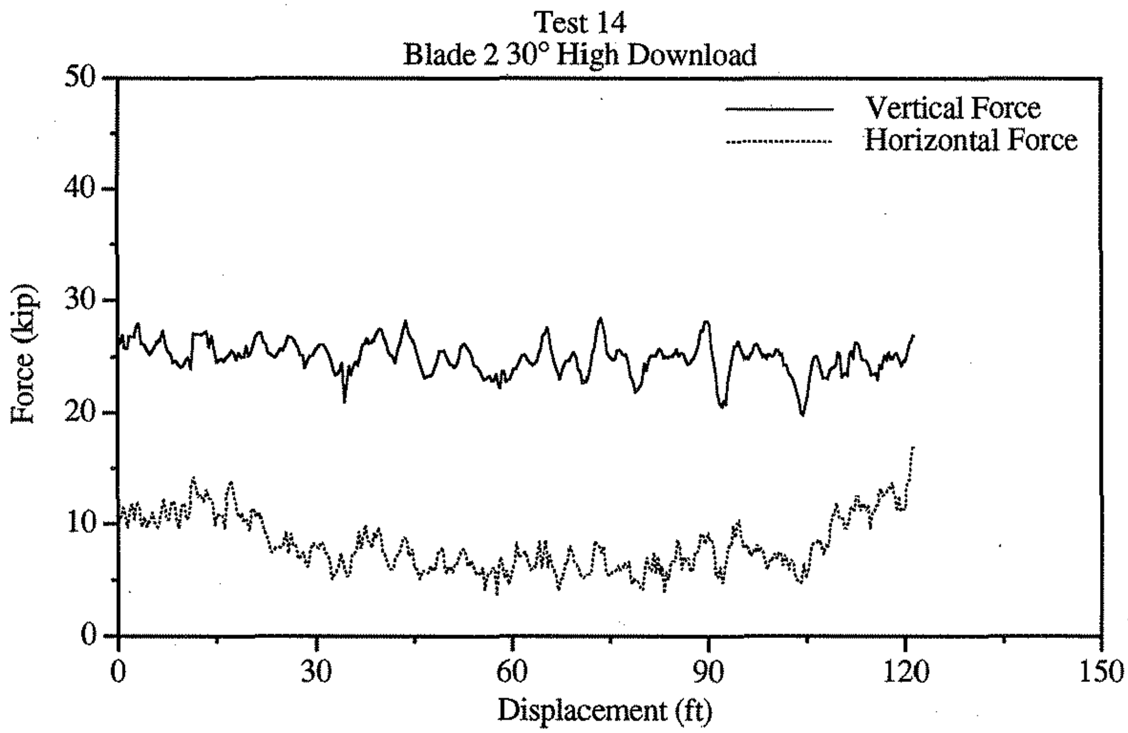


Figure B13. Graphical results of test 13.



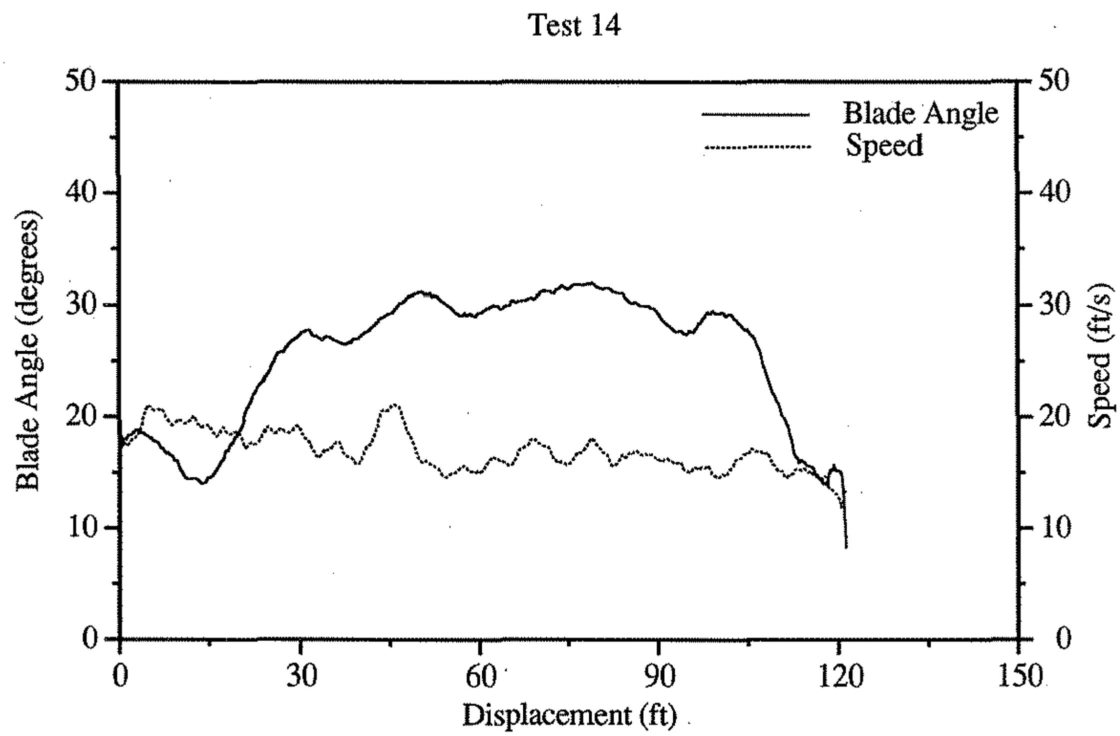
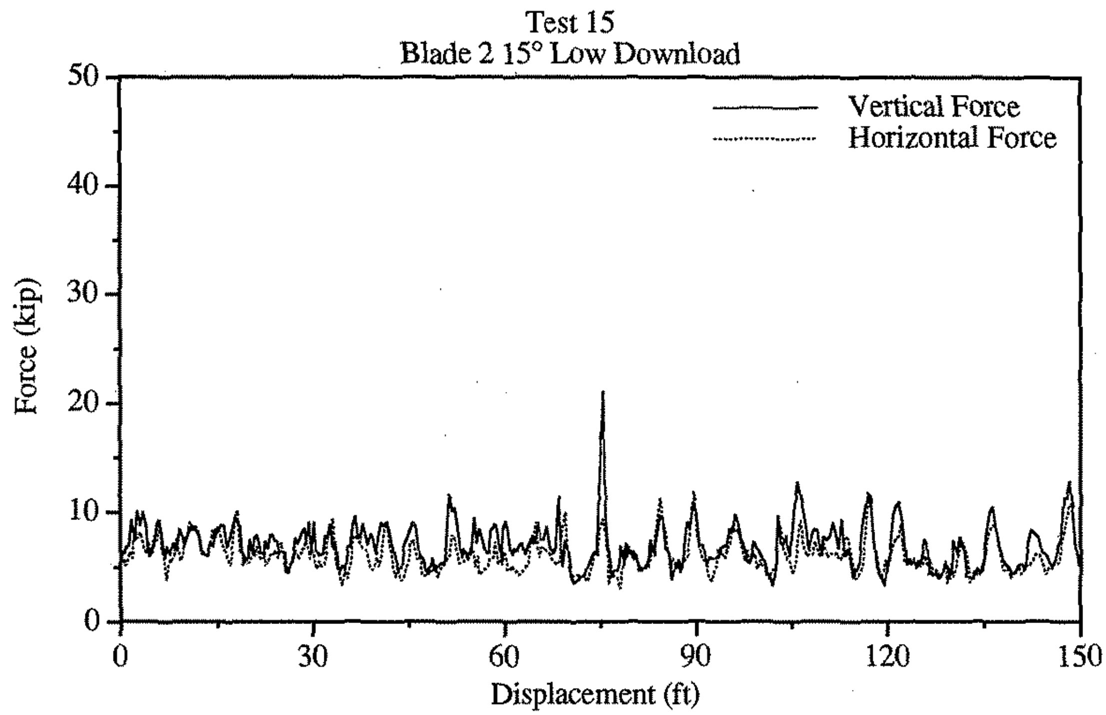


Figure B14. Graphical results of test 14.



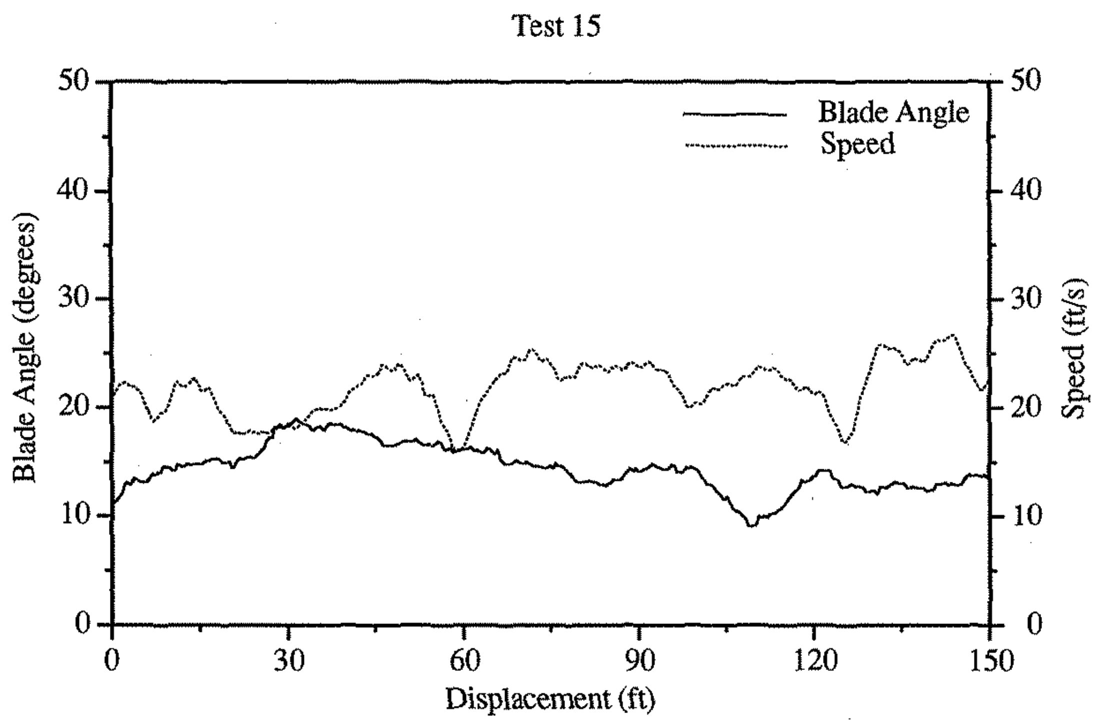
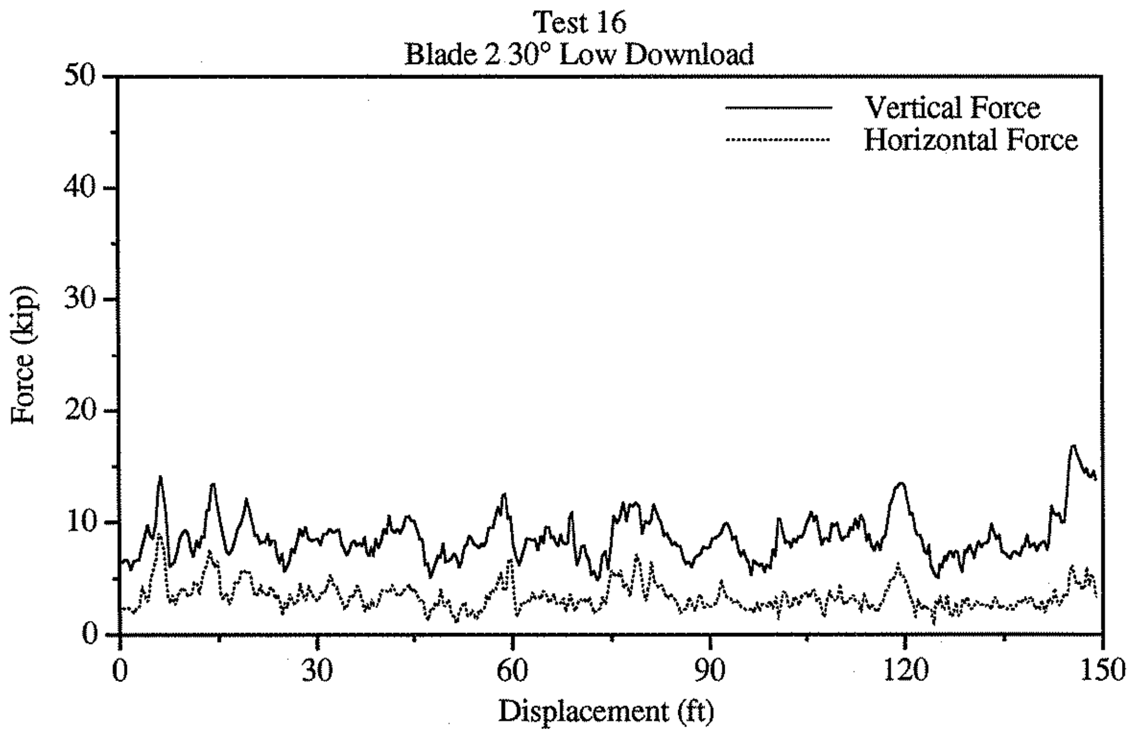


Figure B15. Graphical results of test 15.



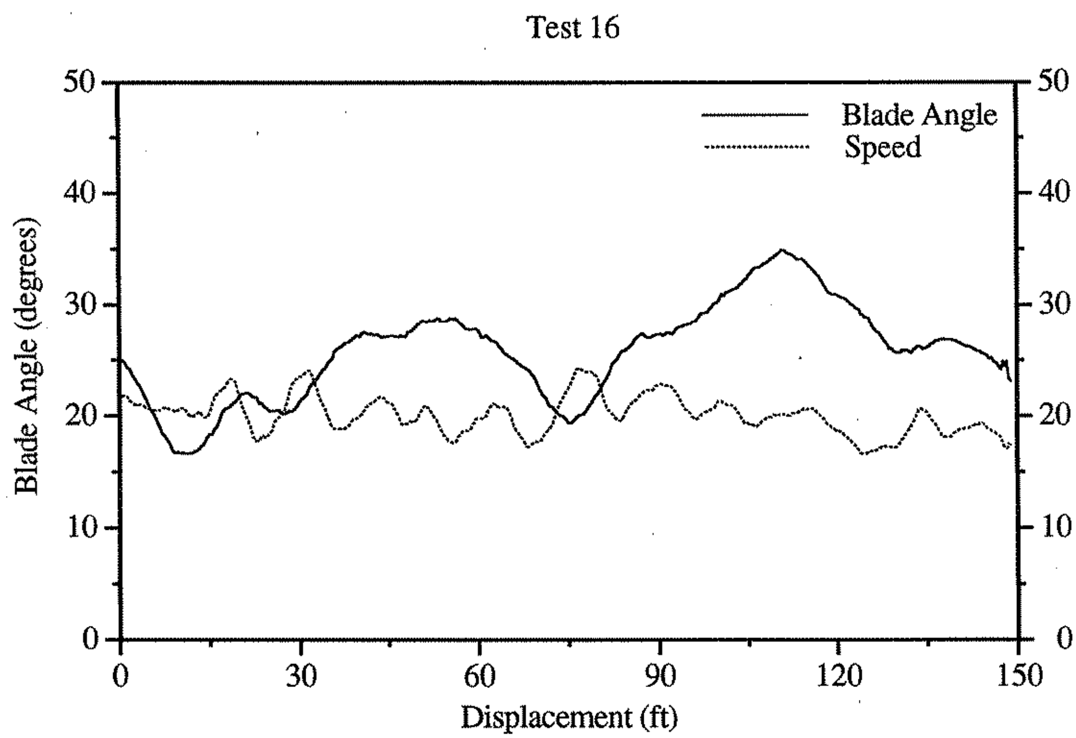
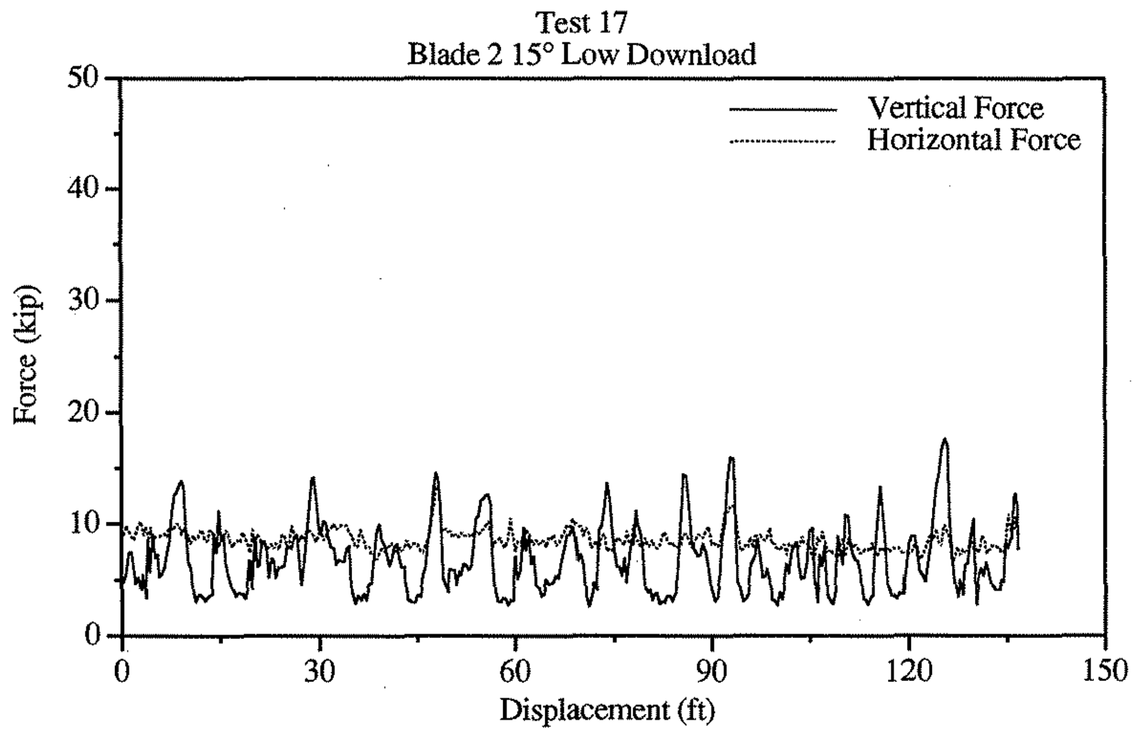


Figure B16. Graphical results of test 16.



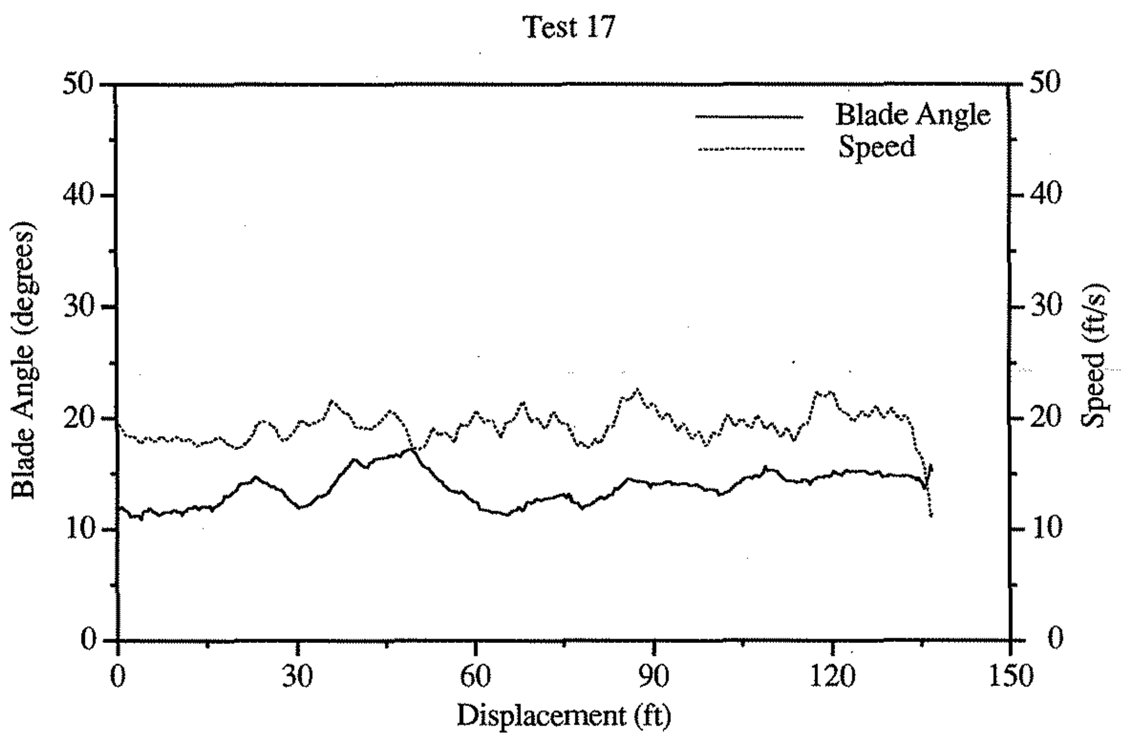
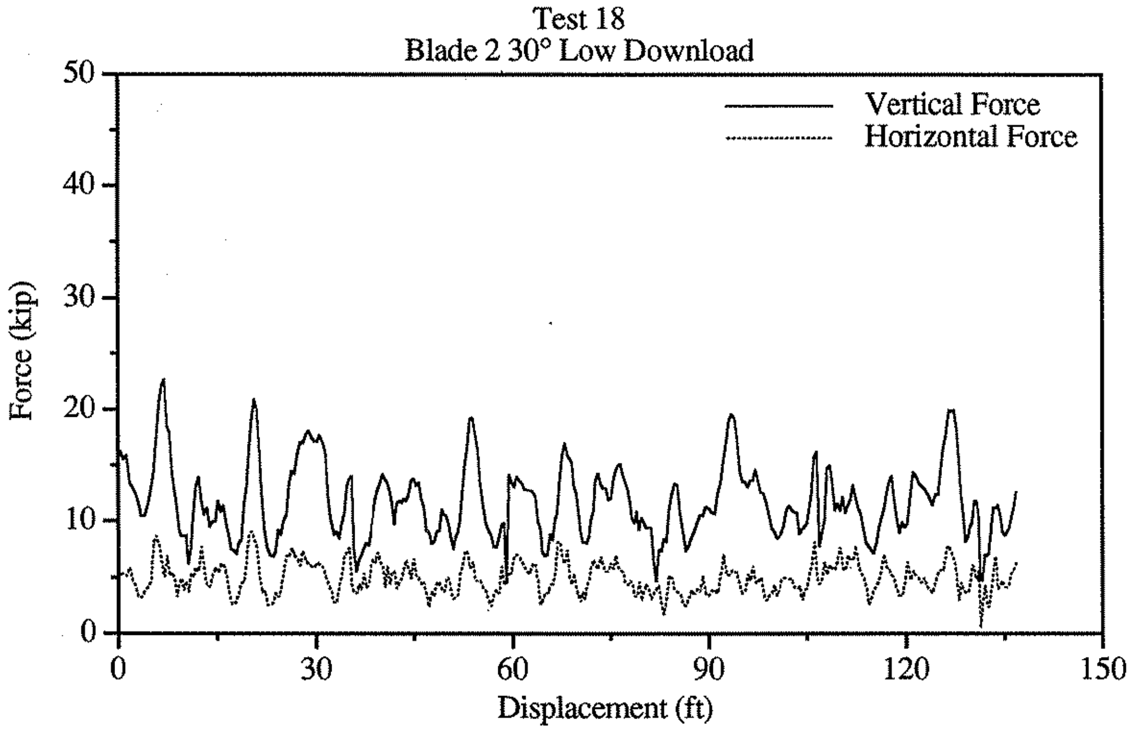


Figure B17. Graphical results of test 17.



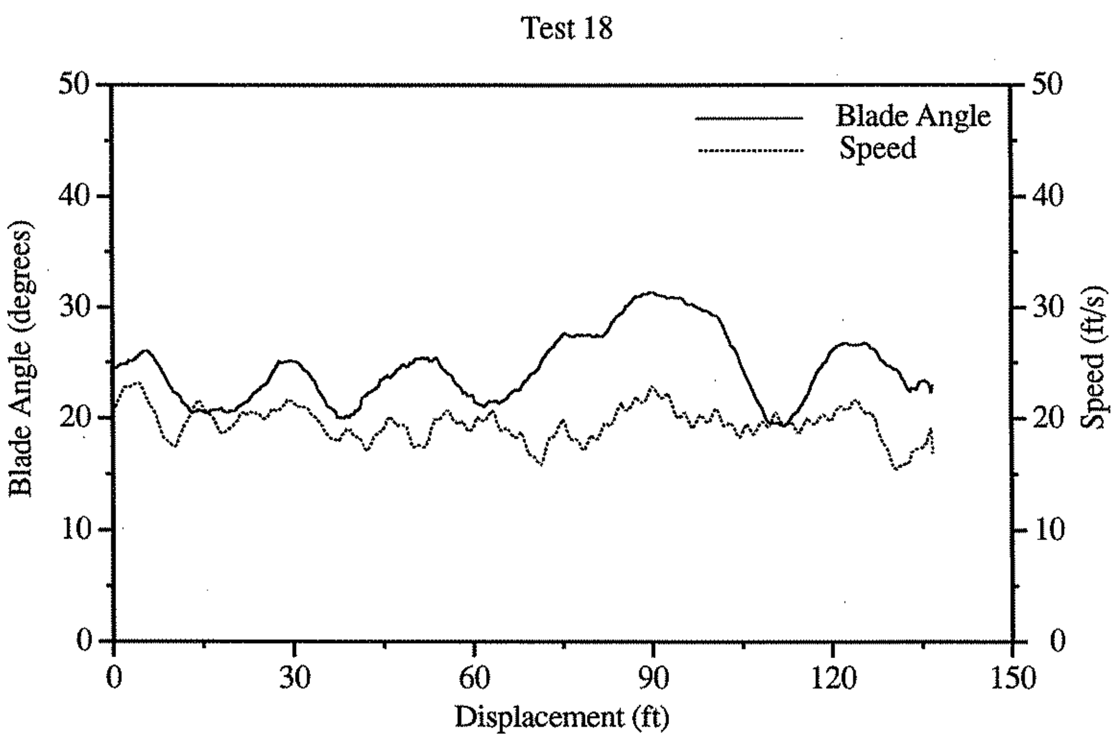
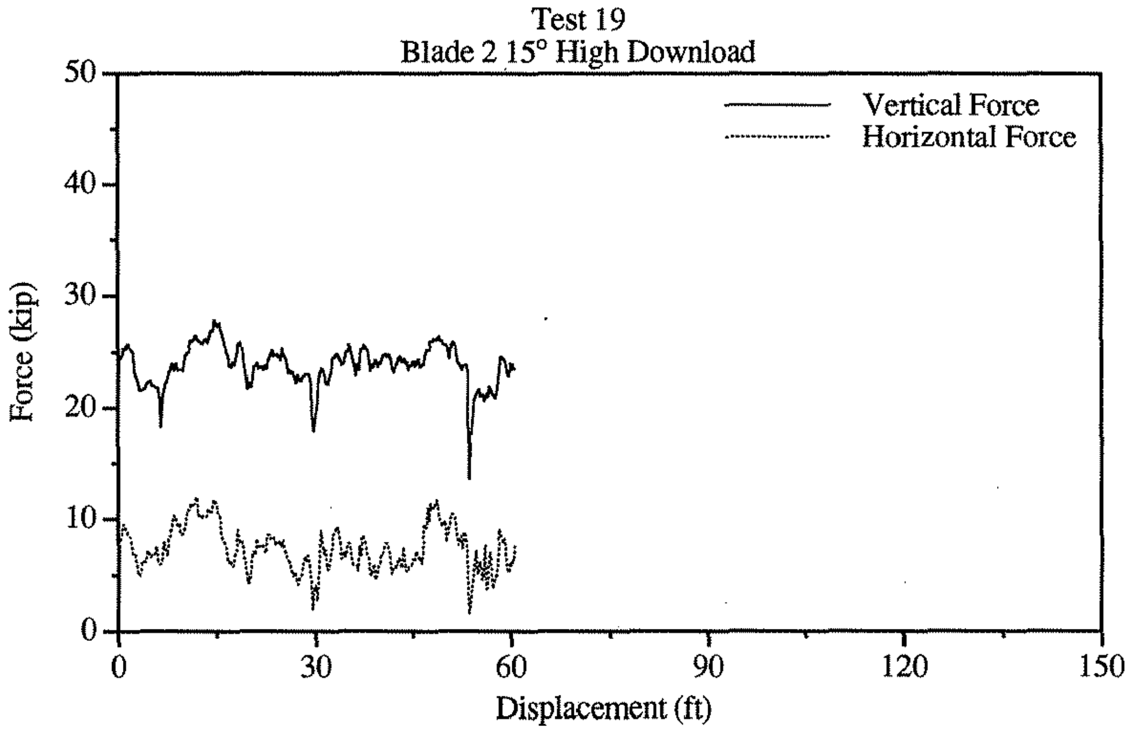


Figure B18. Graphical results of test 18.



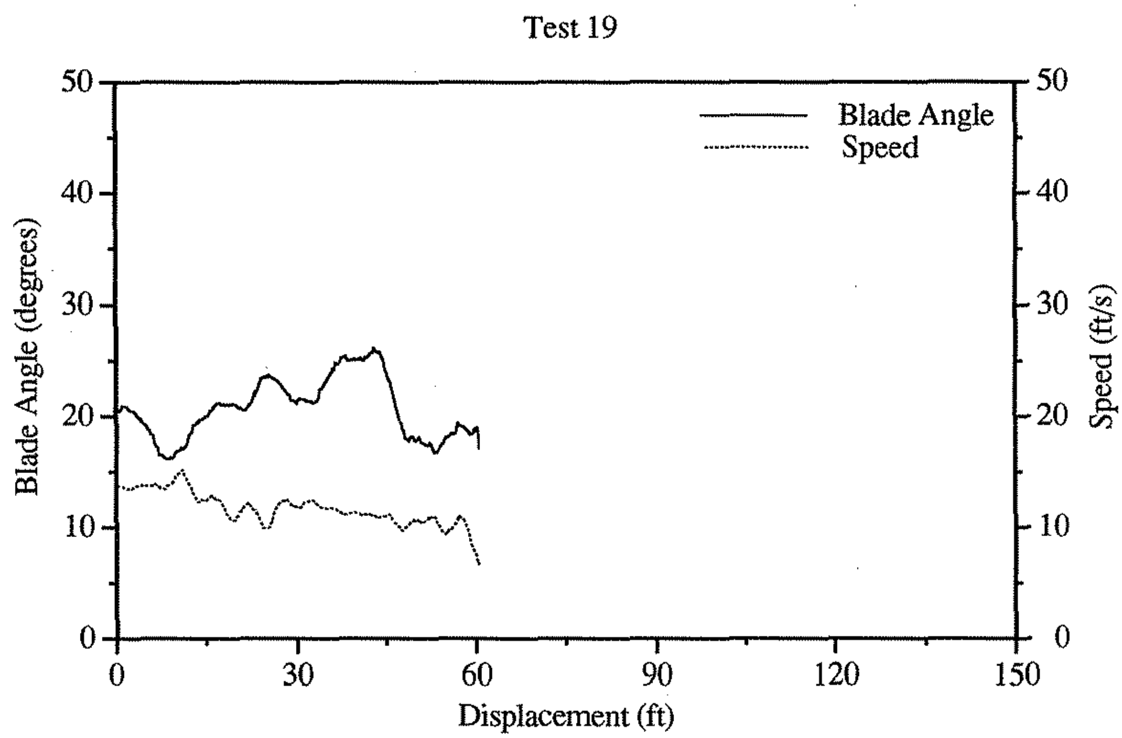
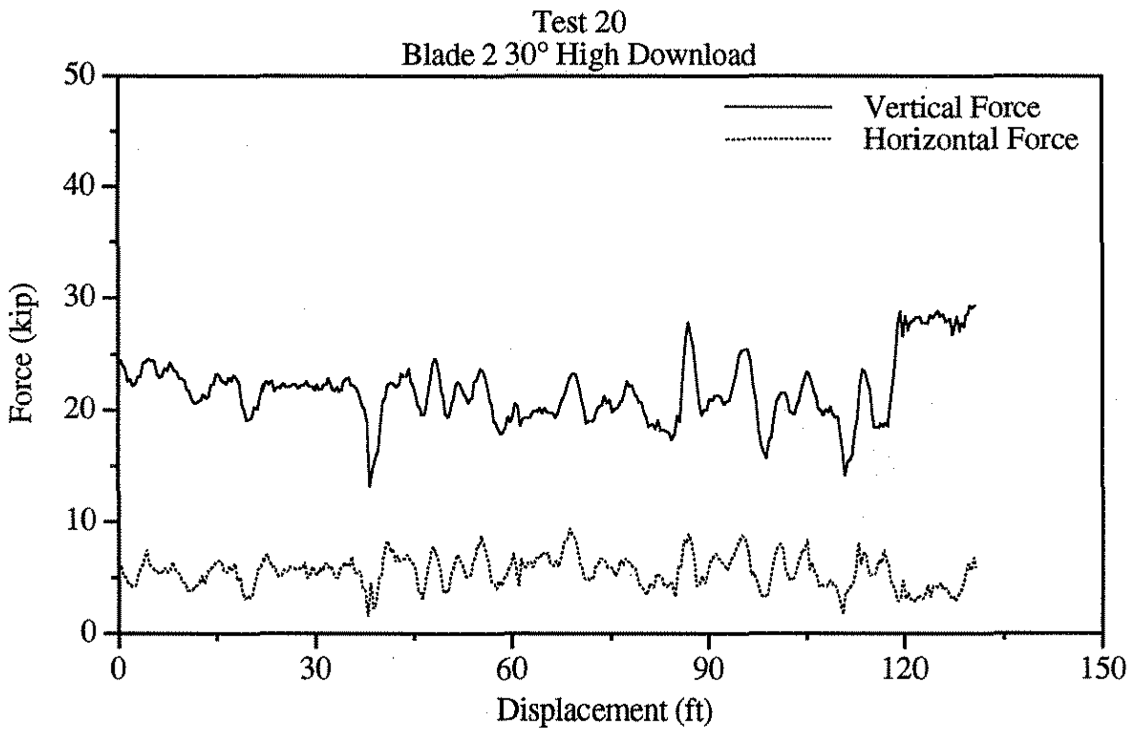


Figure B19. Graphical results of test 19.



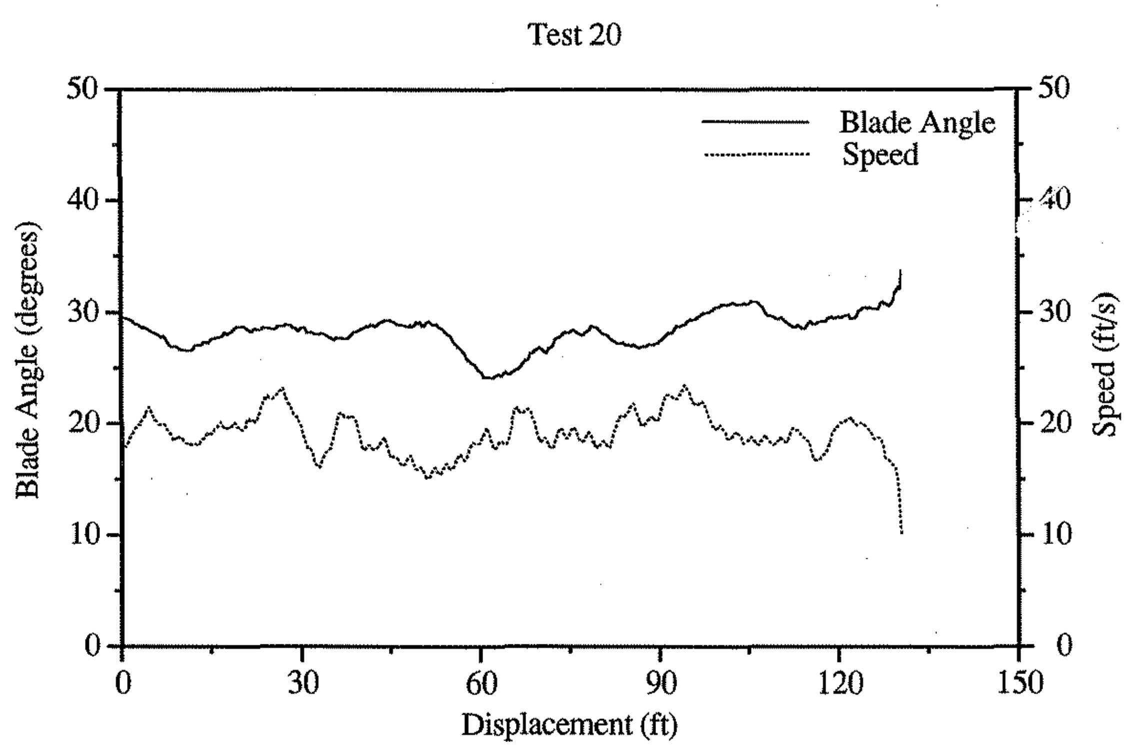
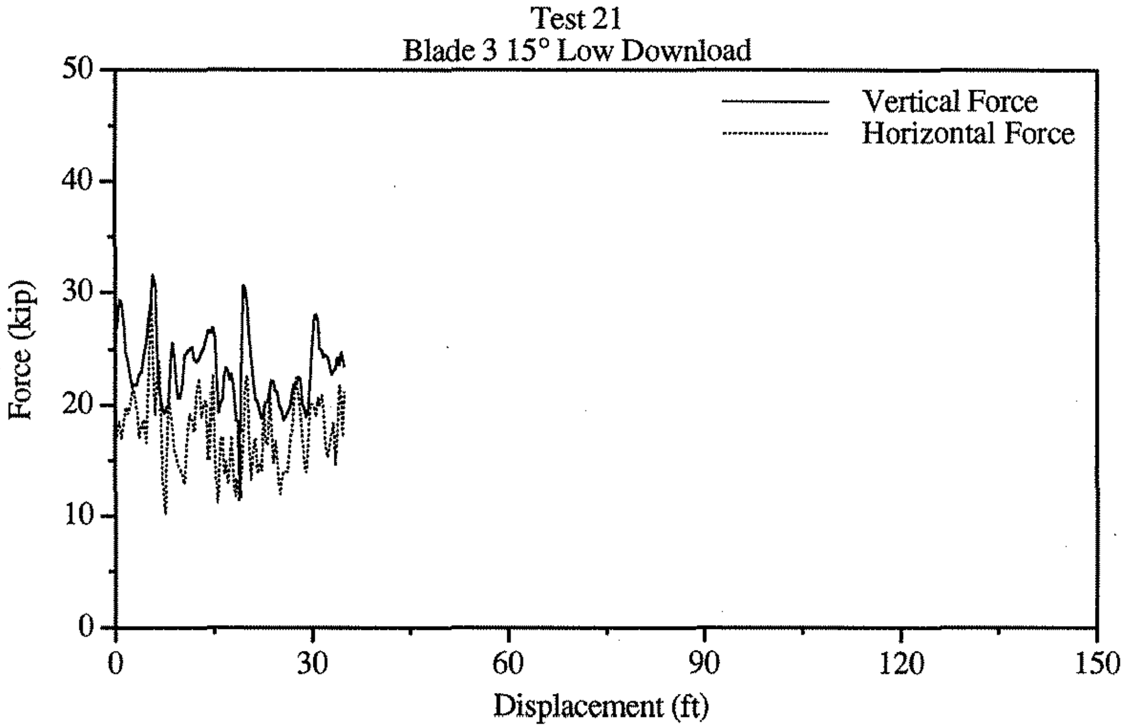


Figure B20. Graphical results of test 20.



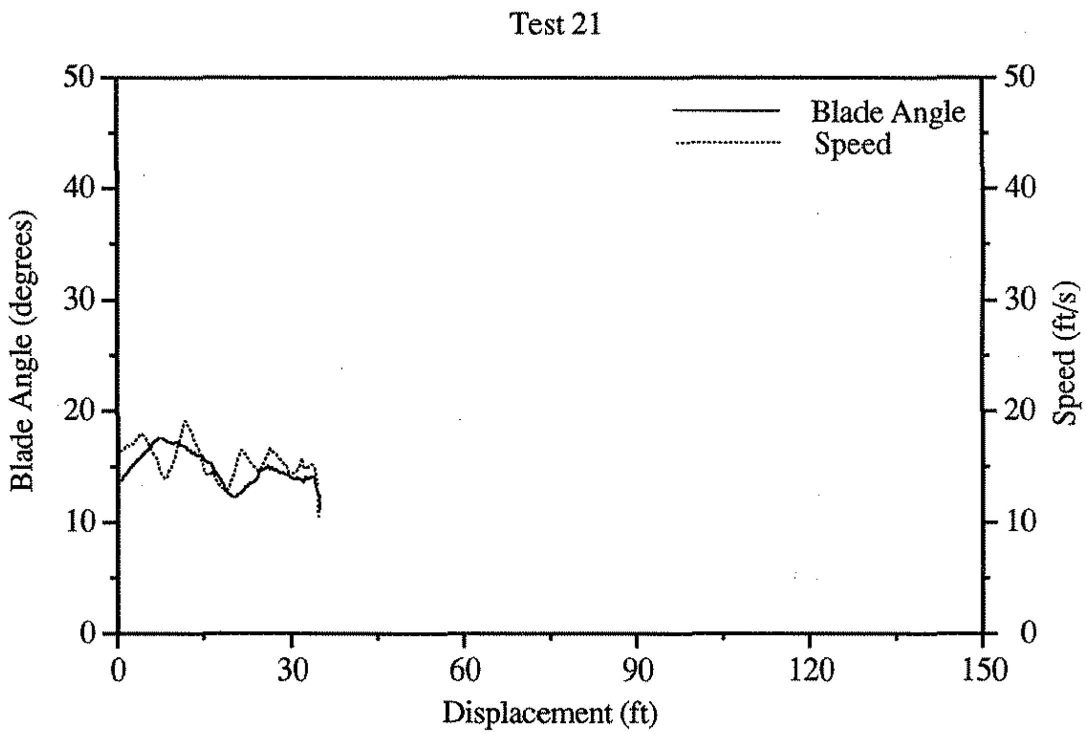
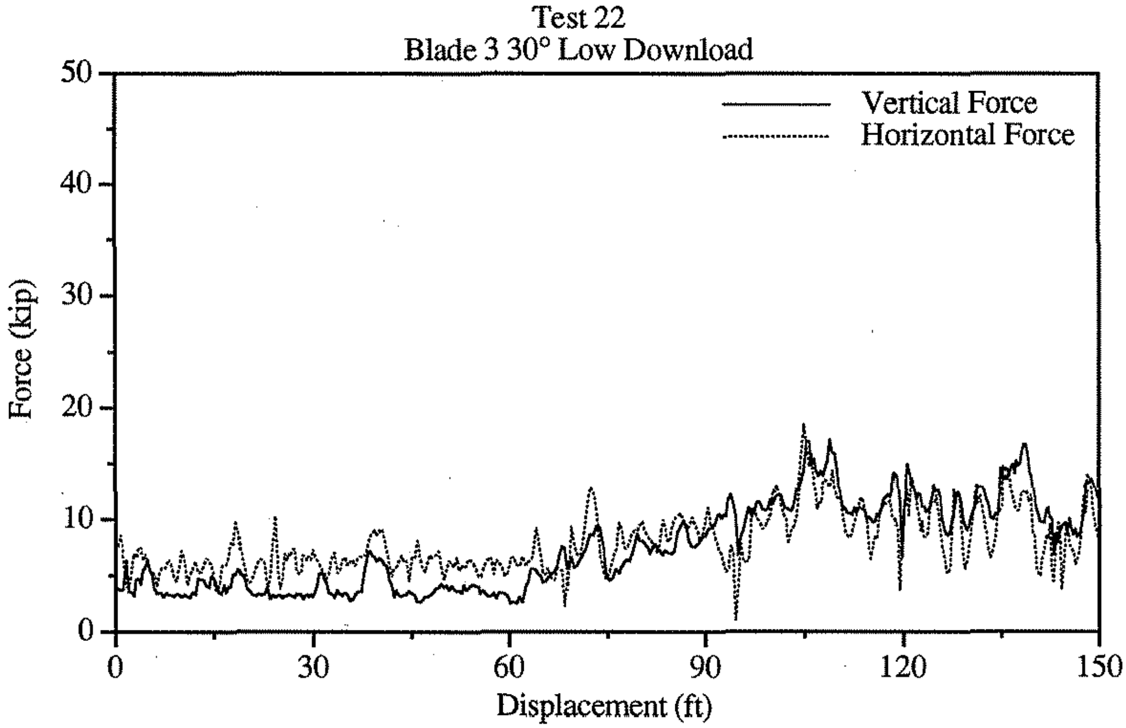


Figure B21. Graphical results of test 21.



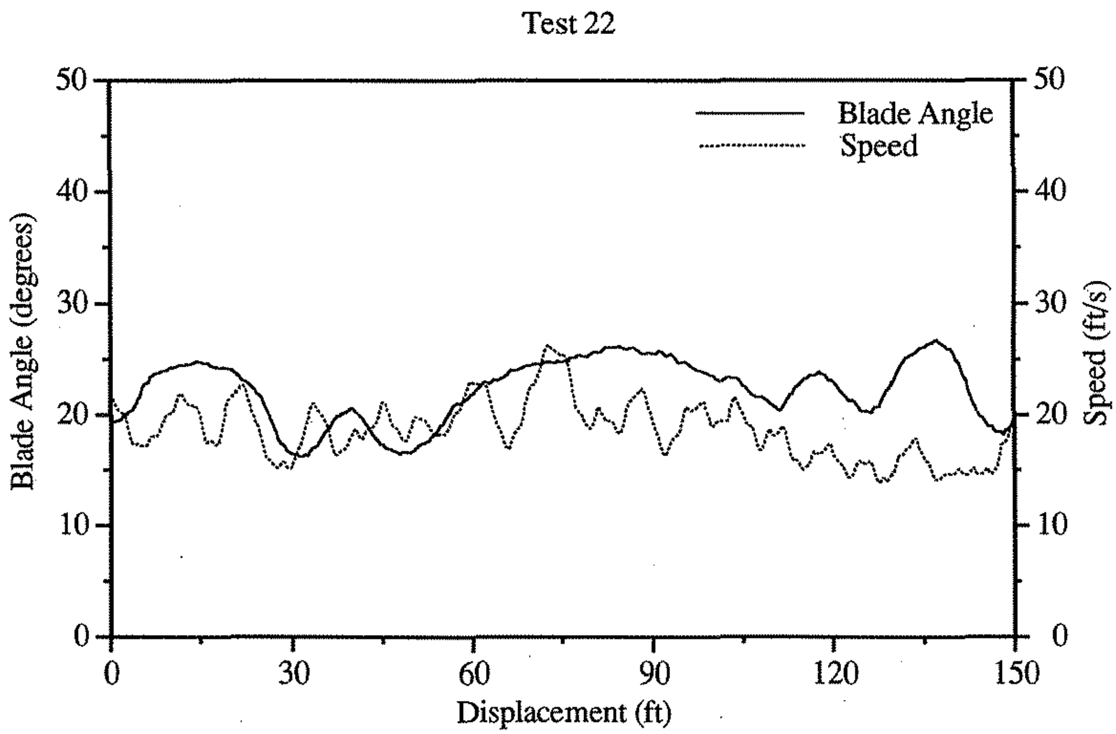
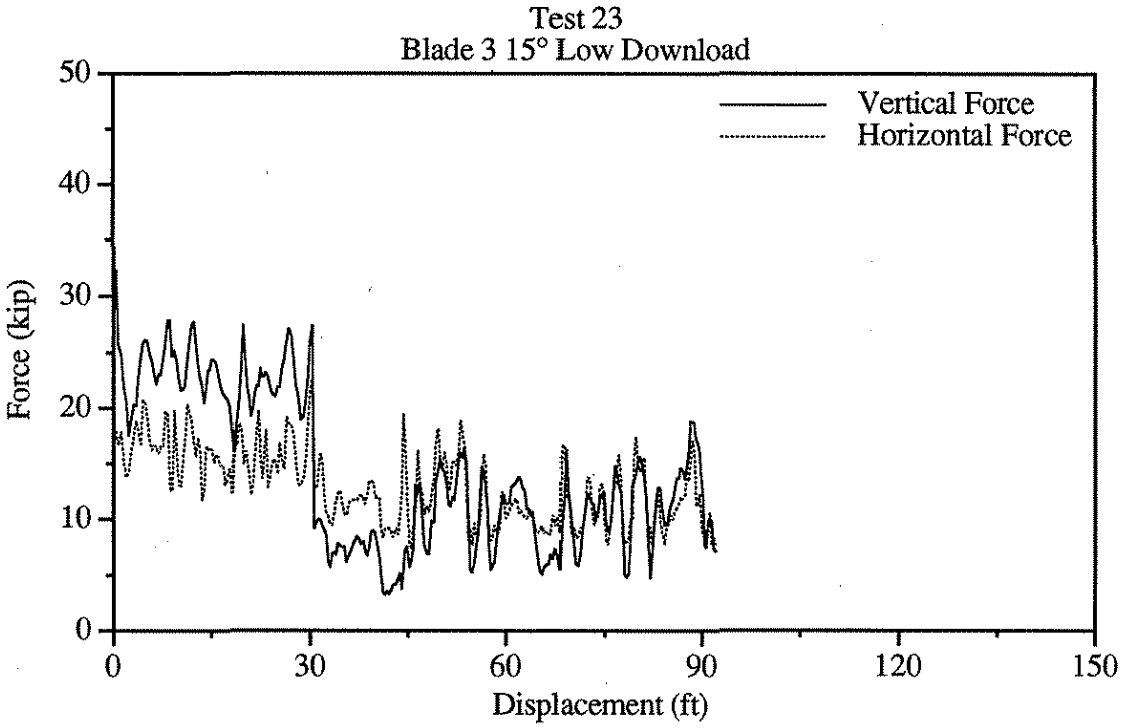


Figure B22. Graphical results of test 22.



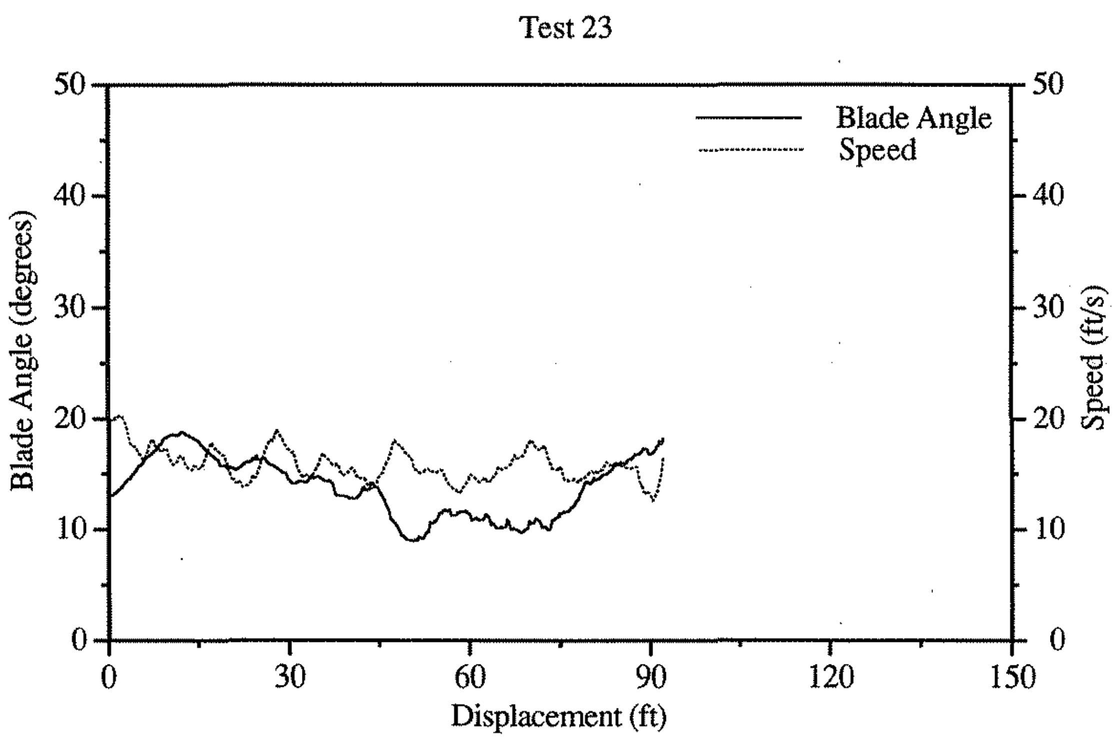
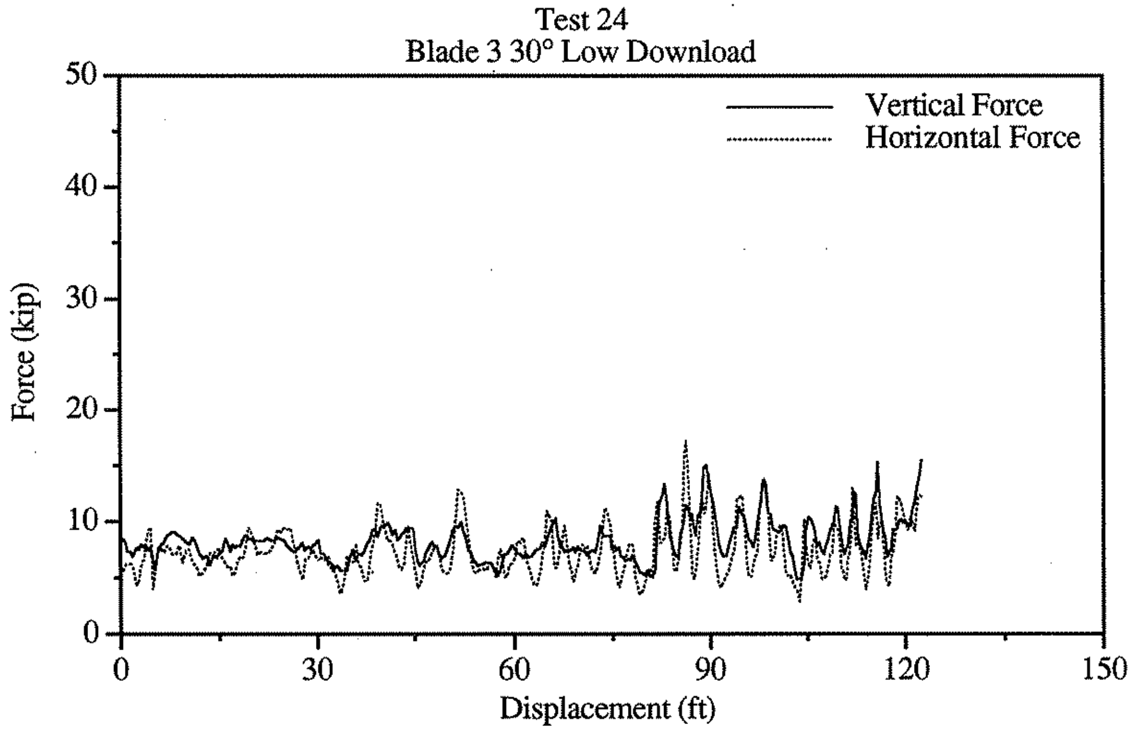


Figure B23. Graphical results of test 23.



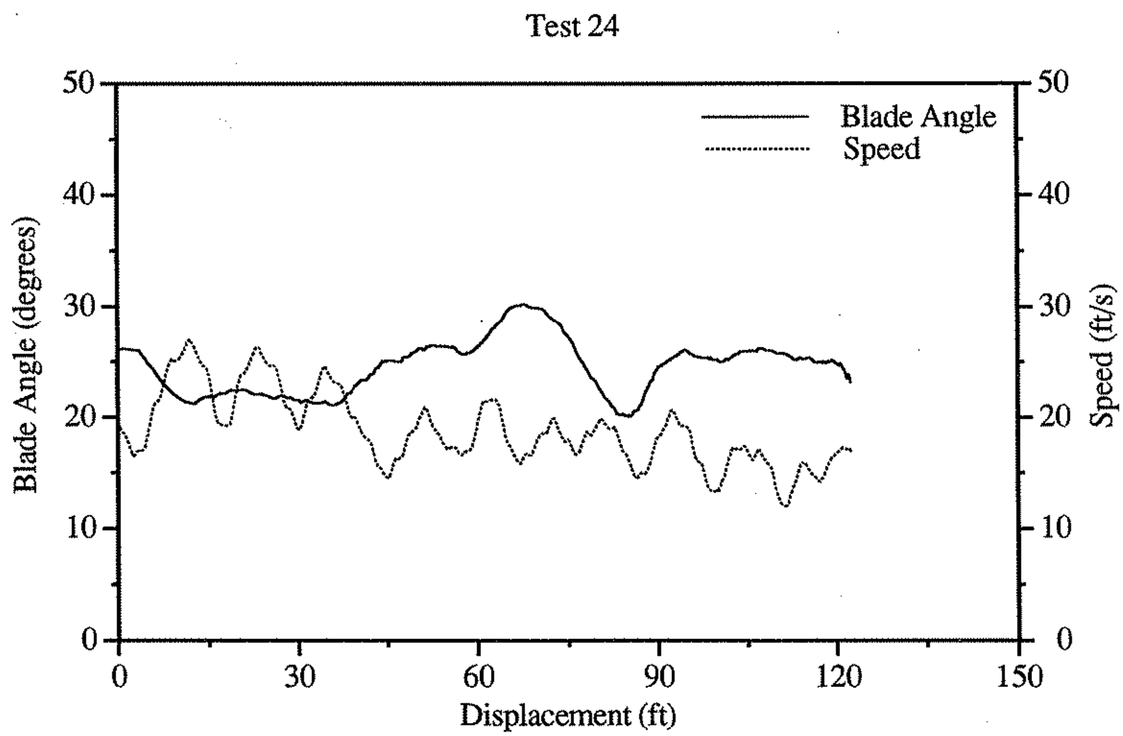
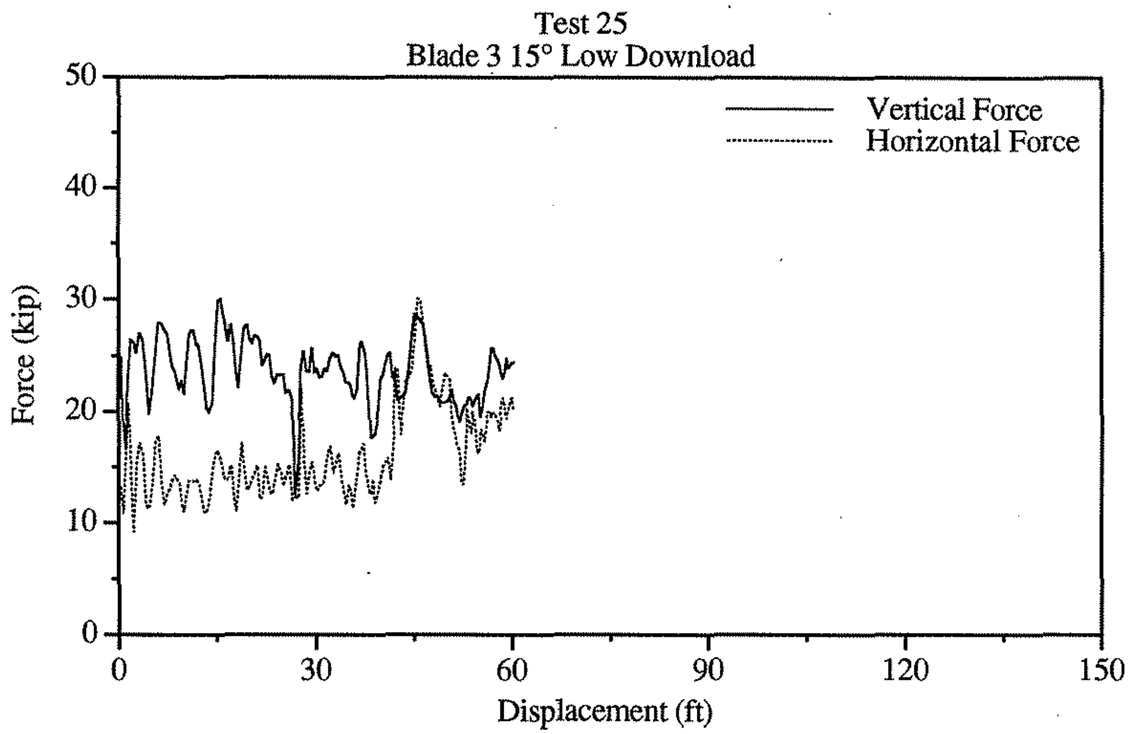


Figure B24. Graphical results of test 24.



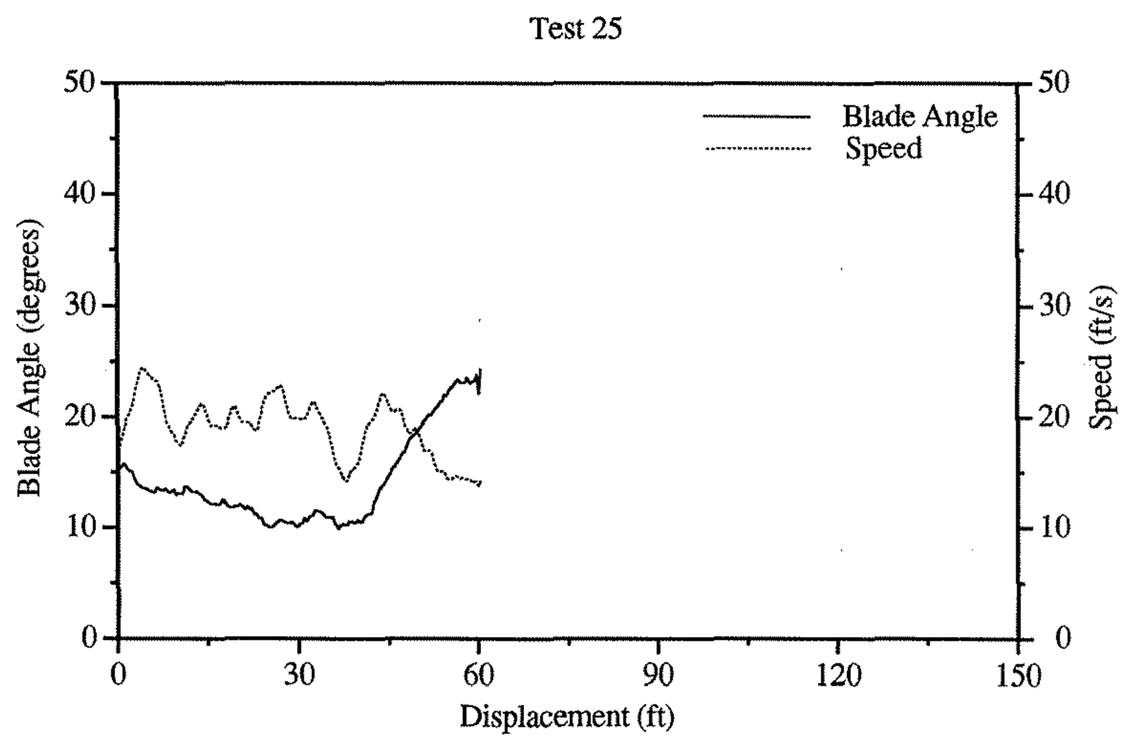
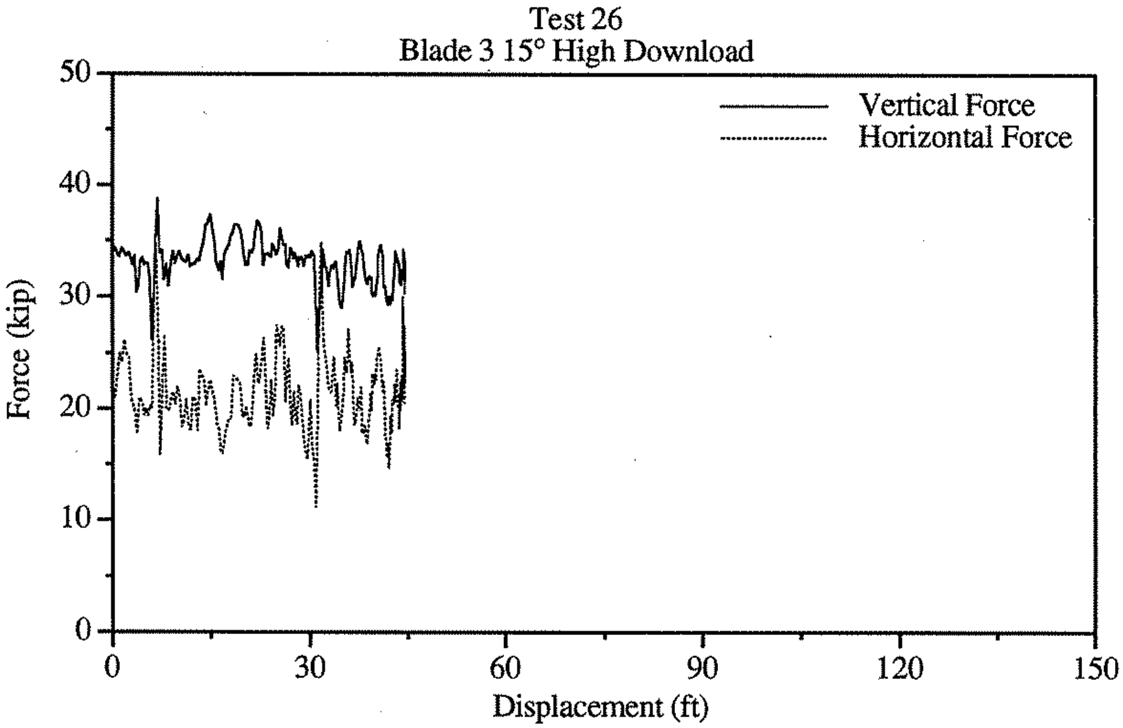


Figure B25. Graphical results of test 25.



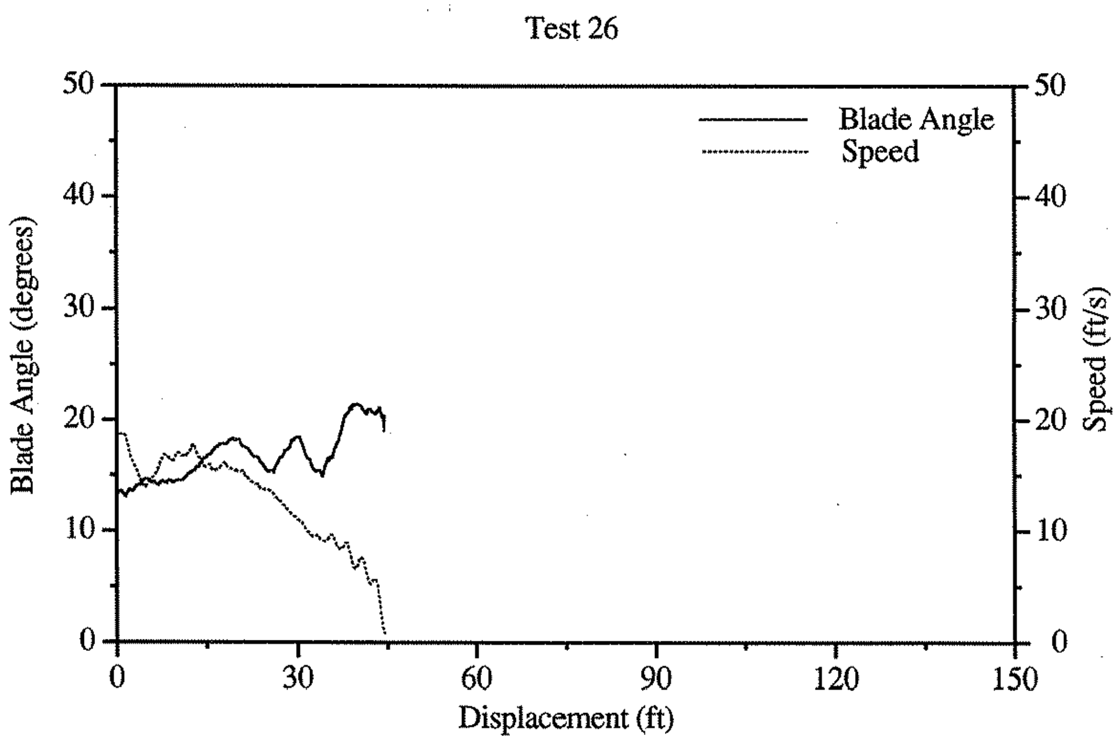


Figure B26. Graphical results of test 26.

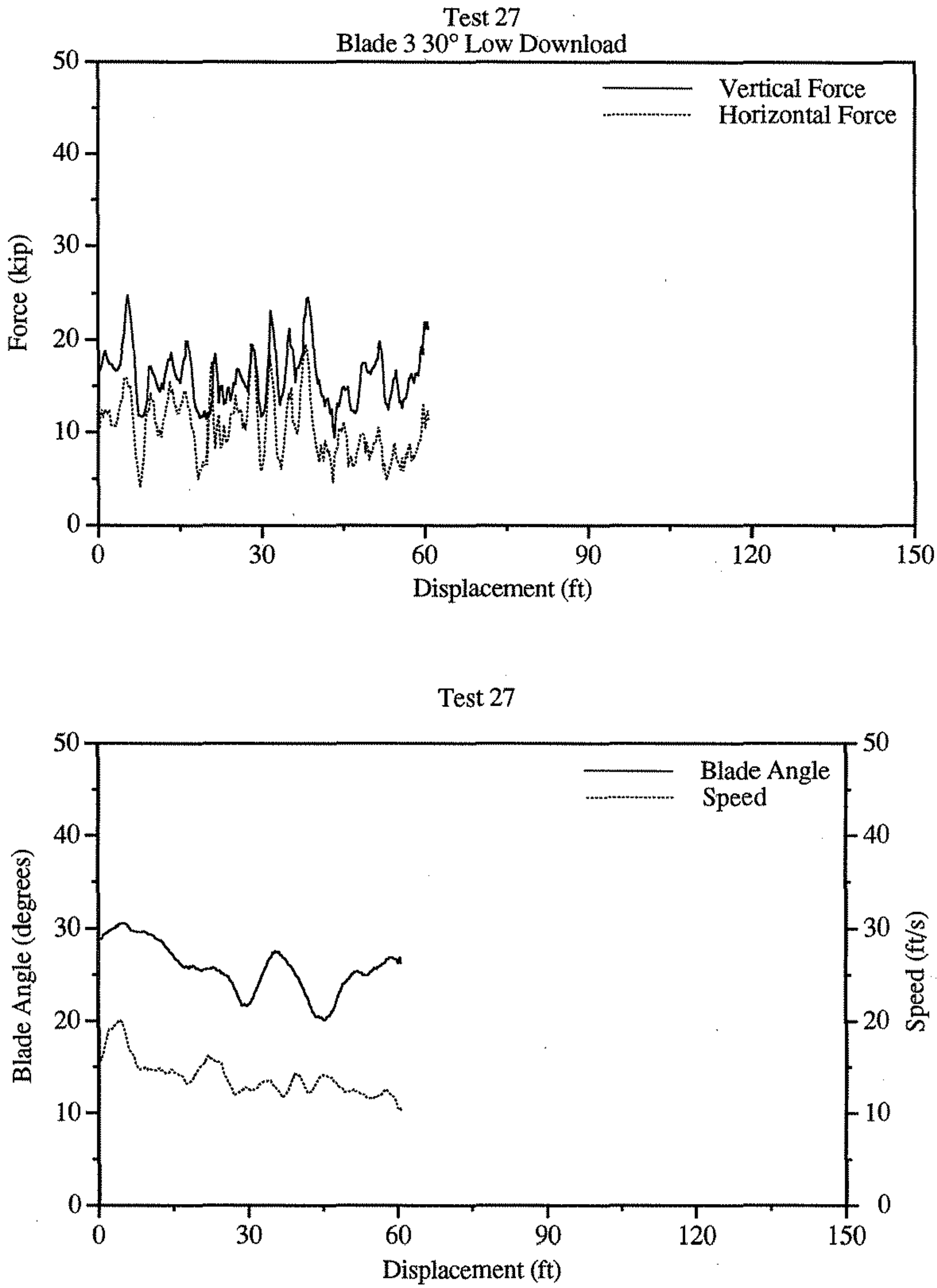
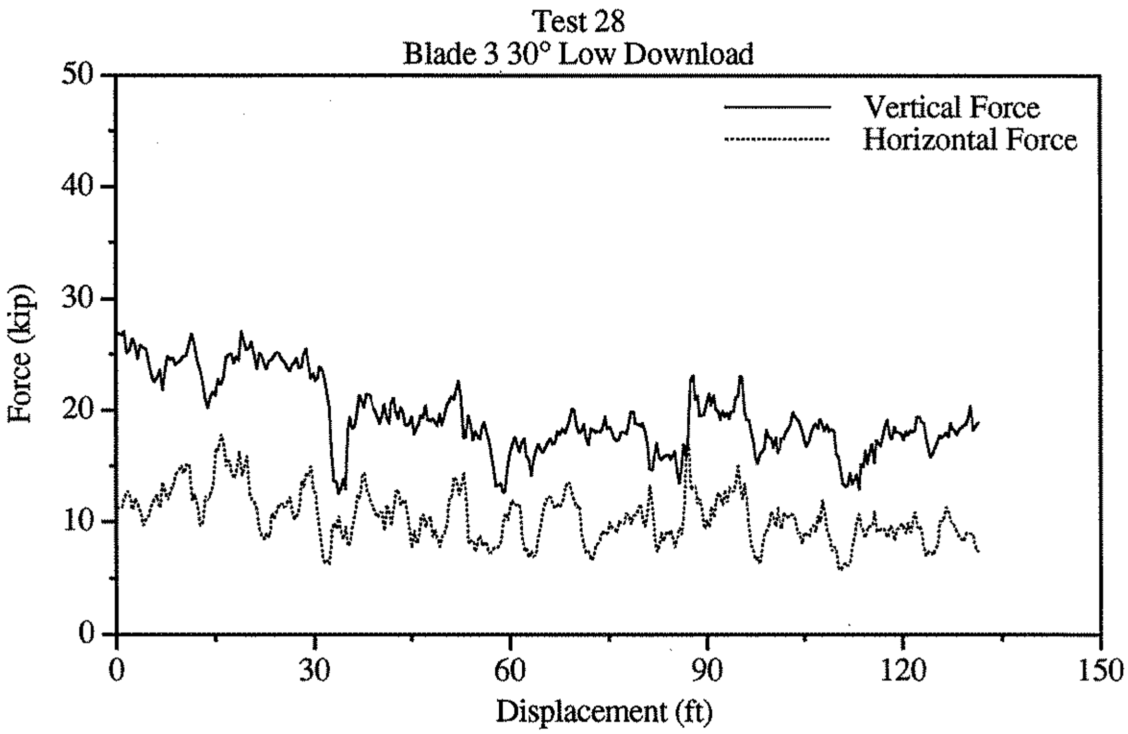


Figure B27. Graphical results of test 27.



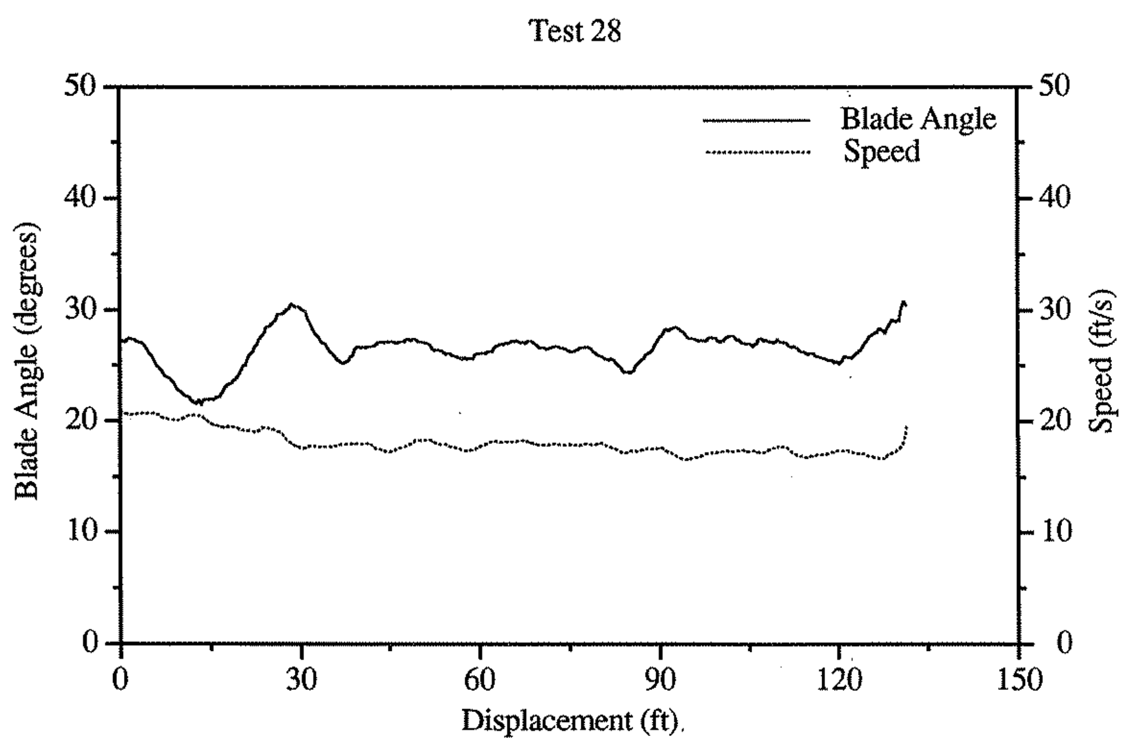
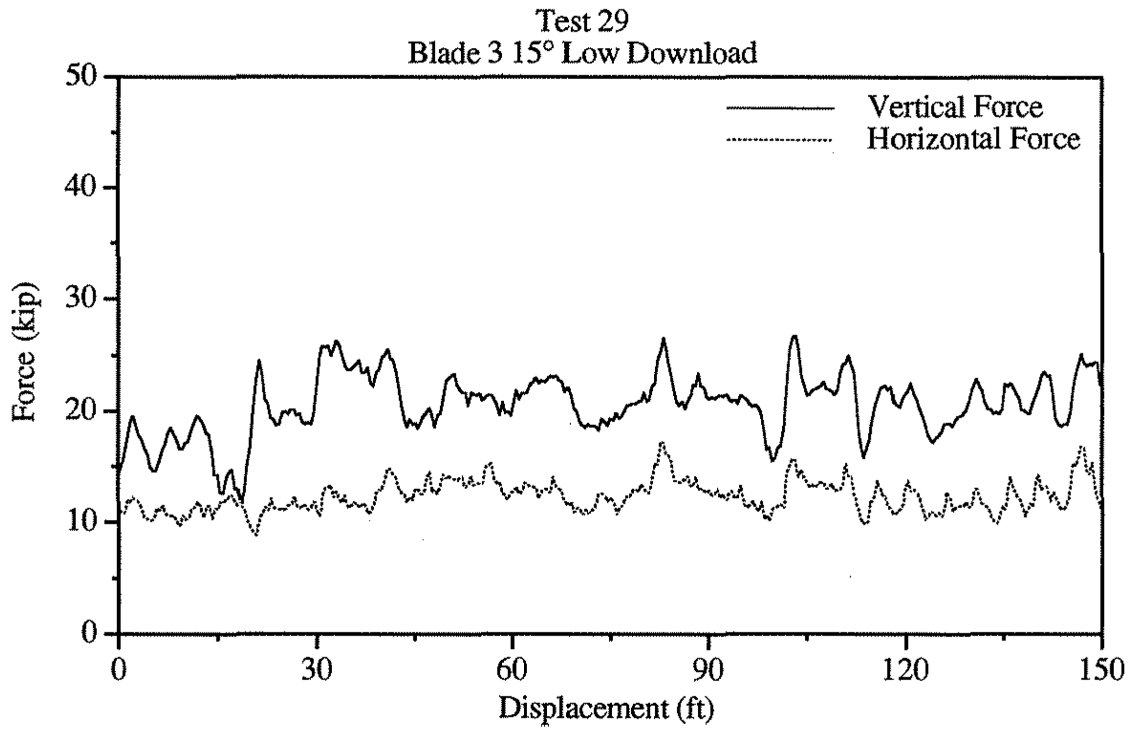


Figure B28. Graphical results of test 28.



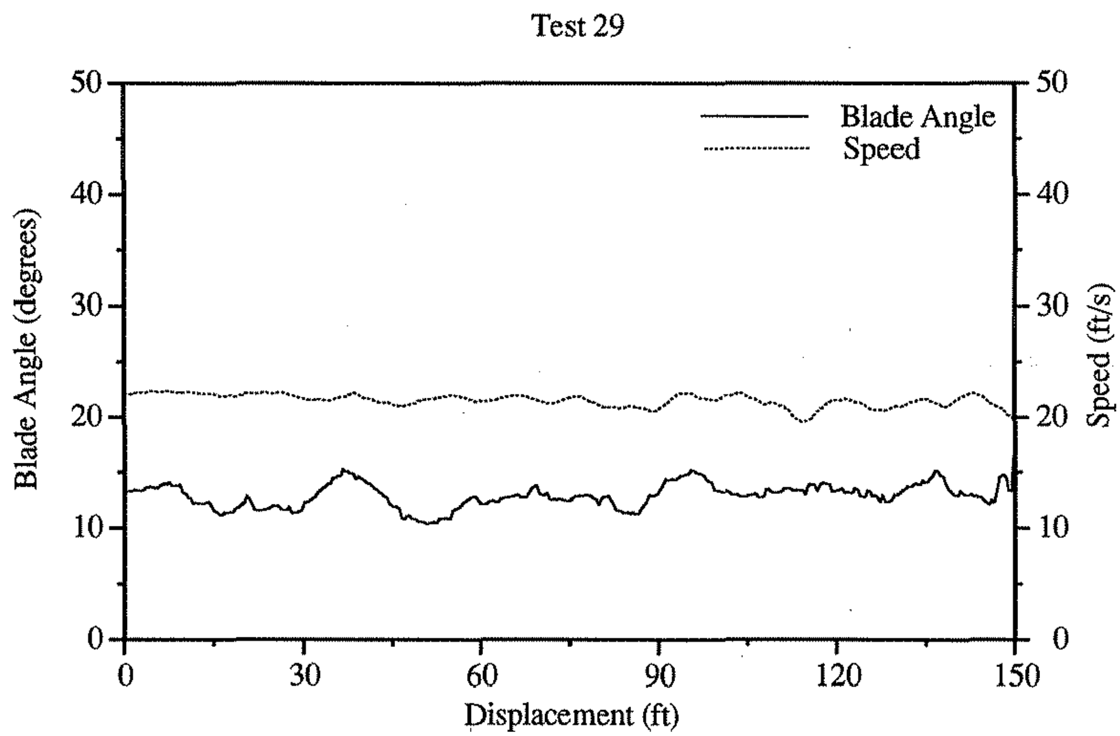
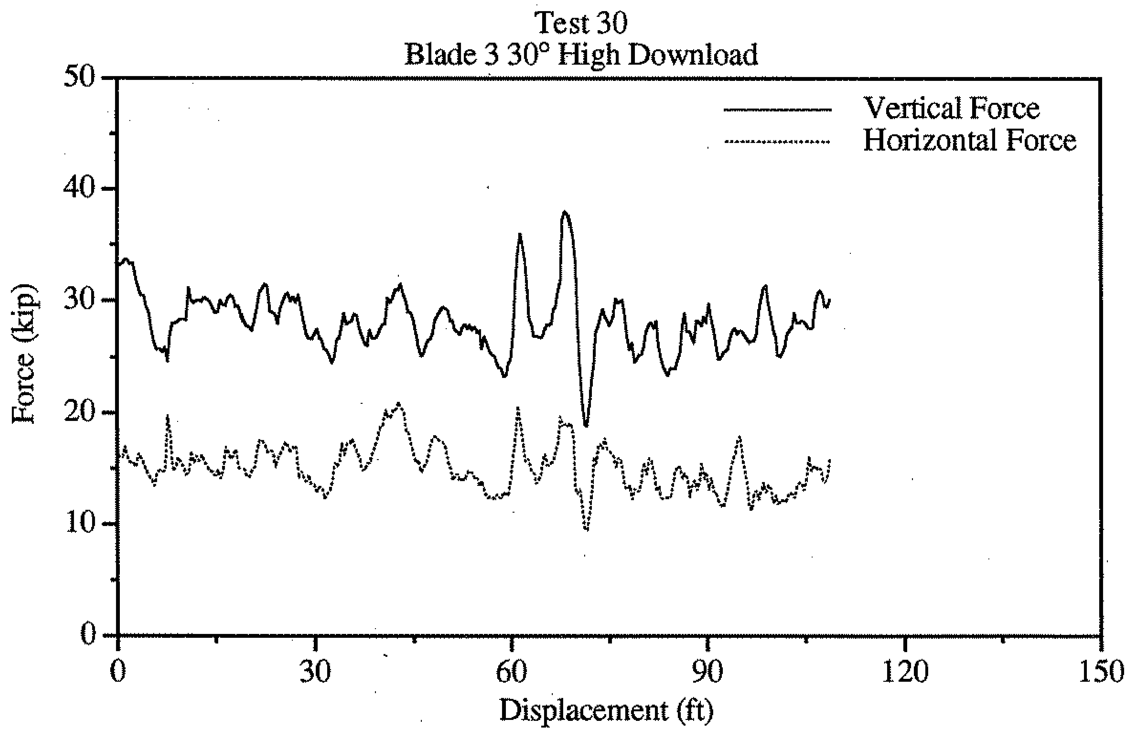


Figure B29. Graphical results of test 29.



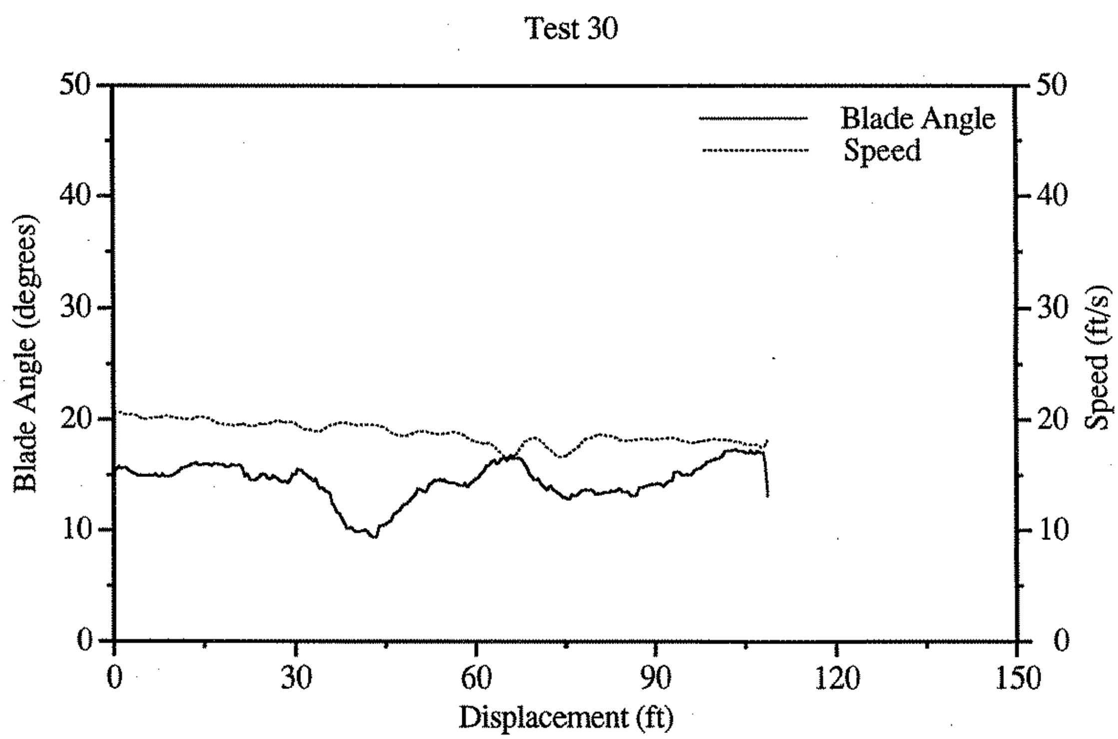
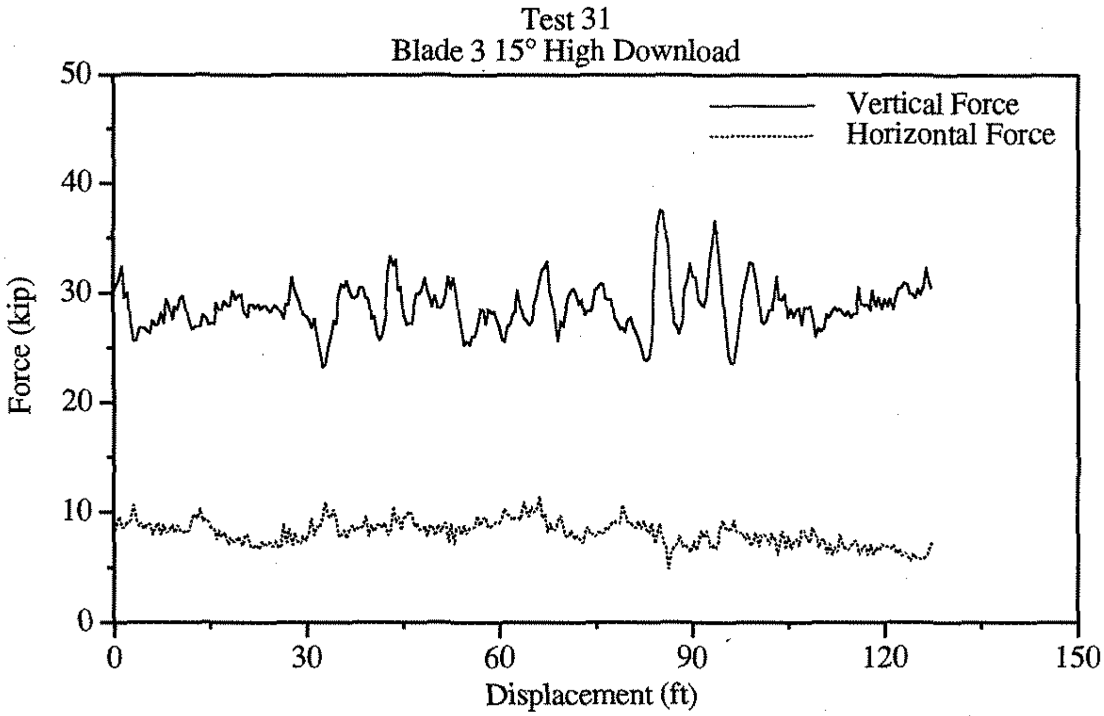


Figure B30. Graphical results of test 30.



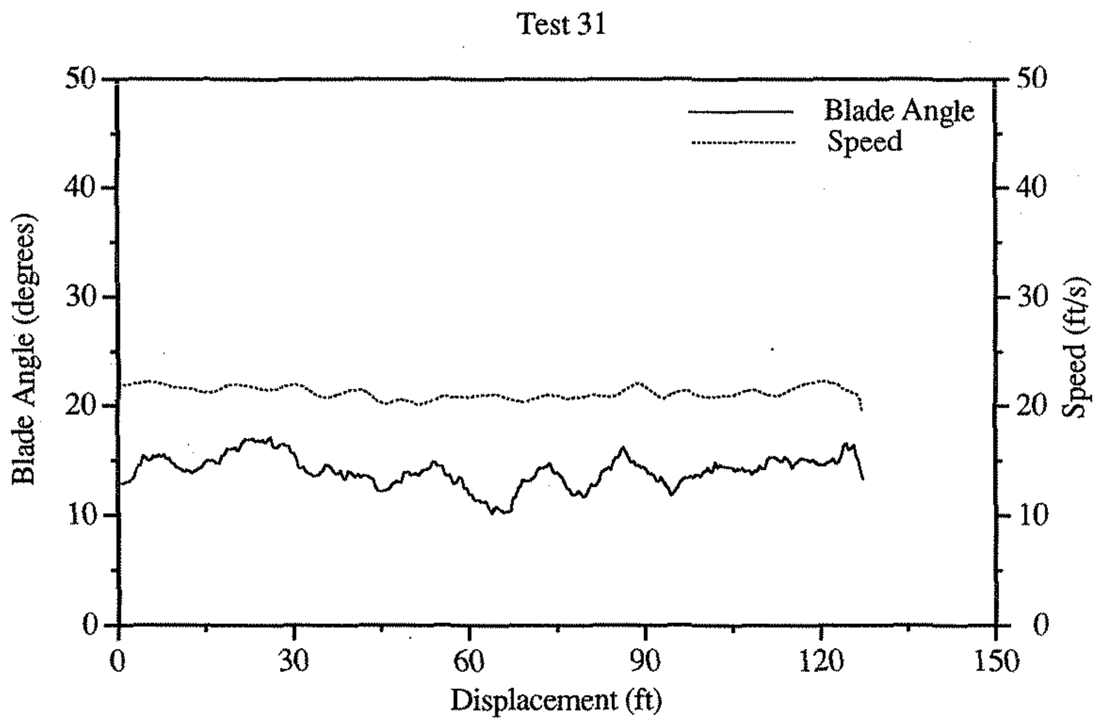
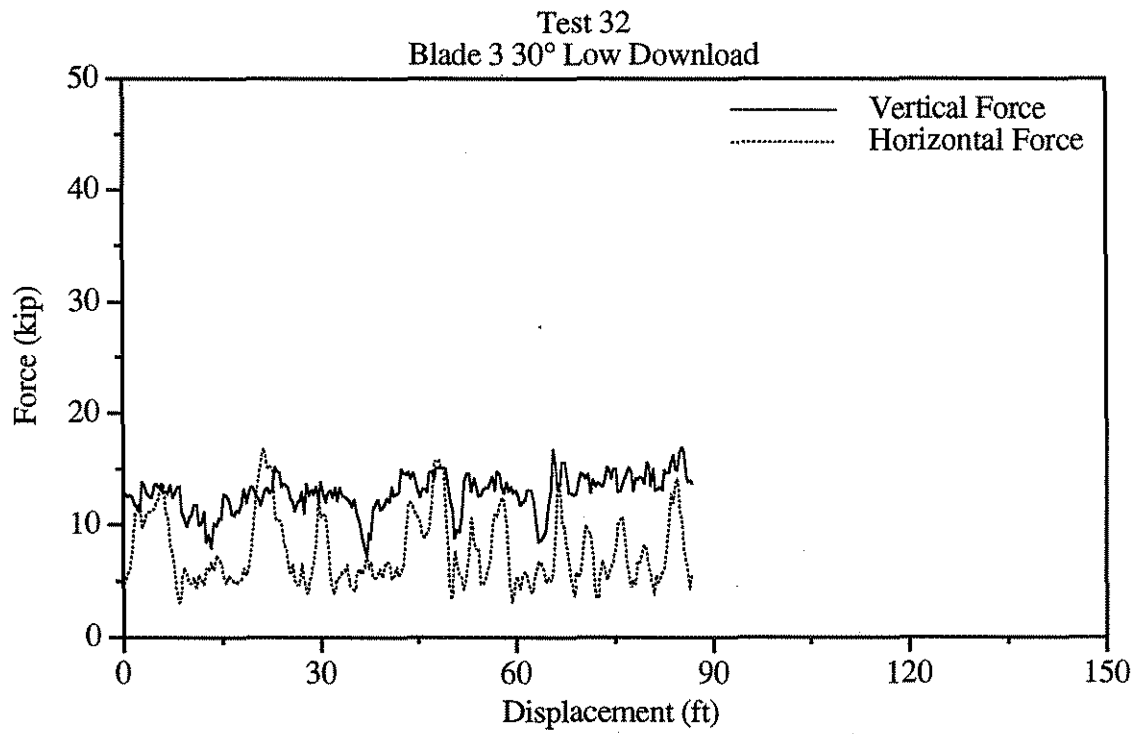
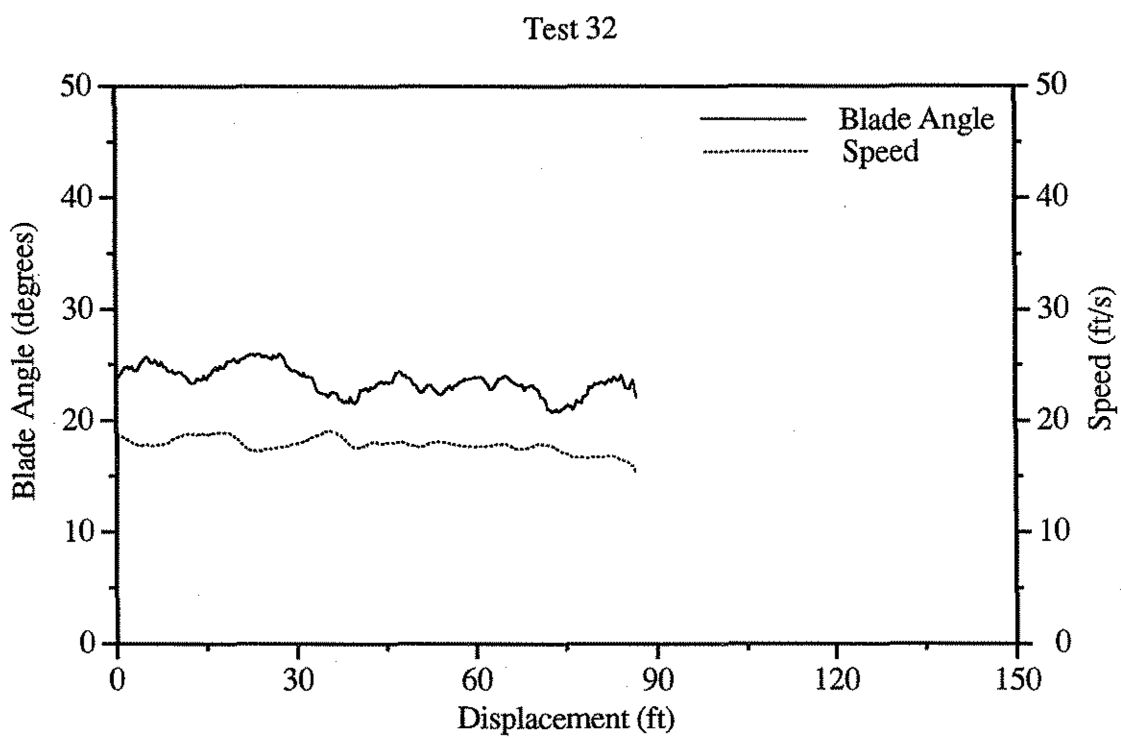


Figure B31. Graphical results of test 31.





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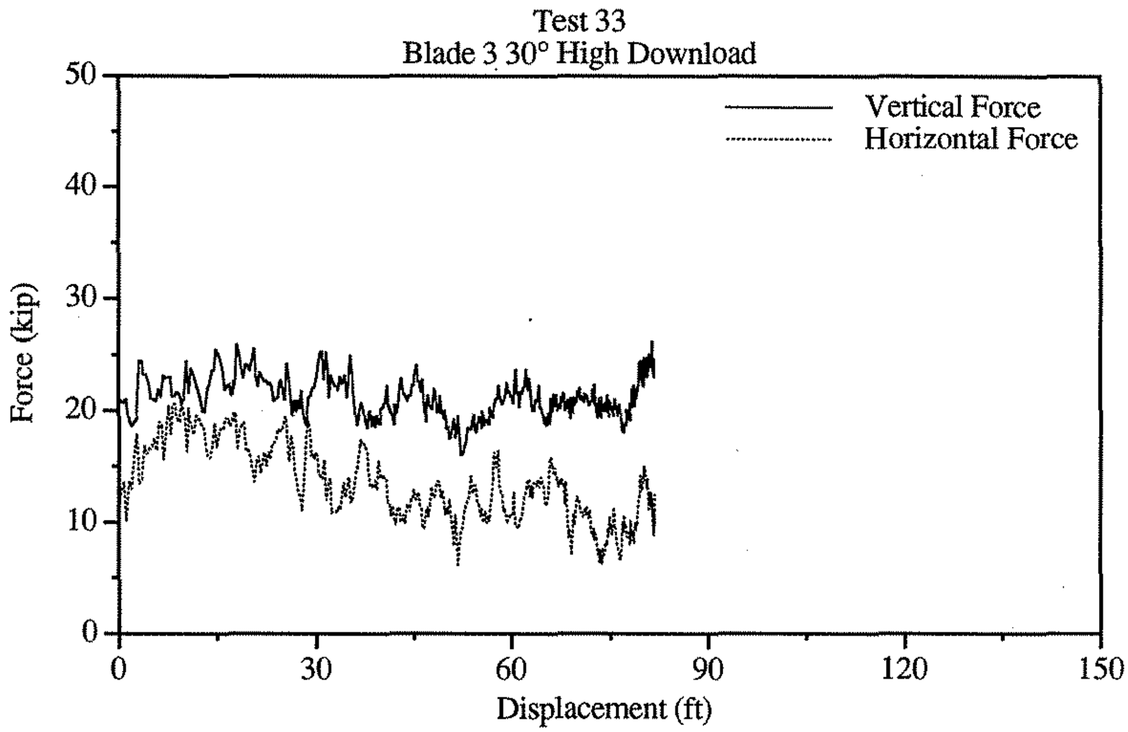


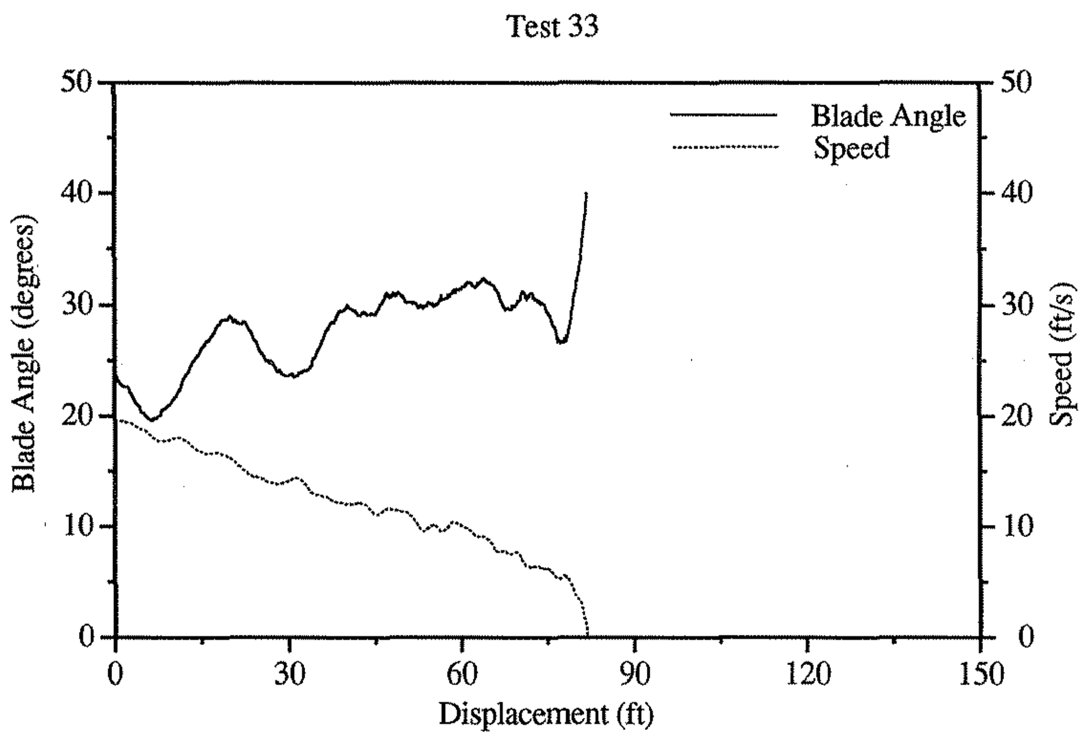
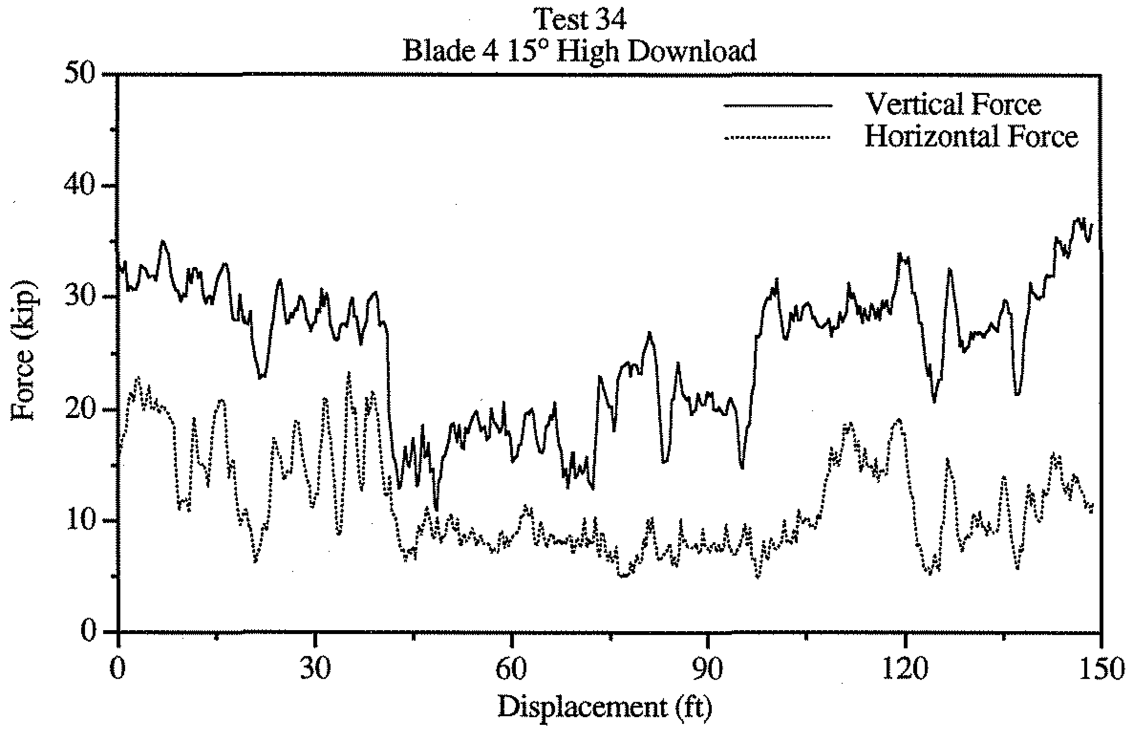


Figure B33. Graphical results of test 33.



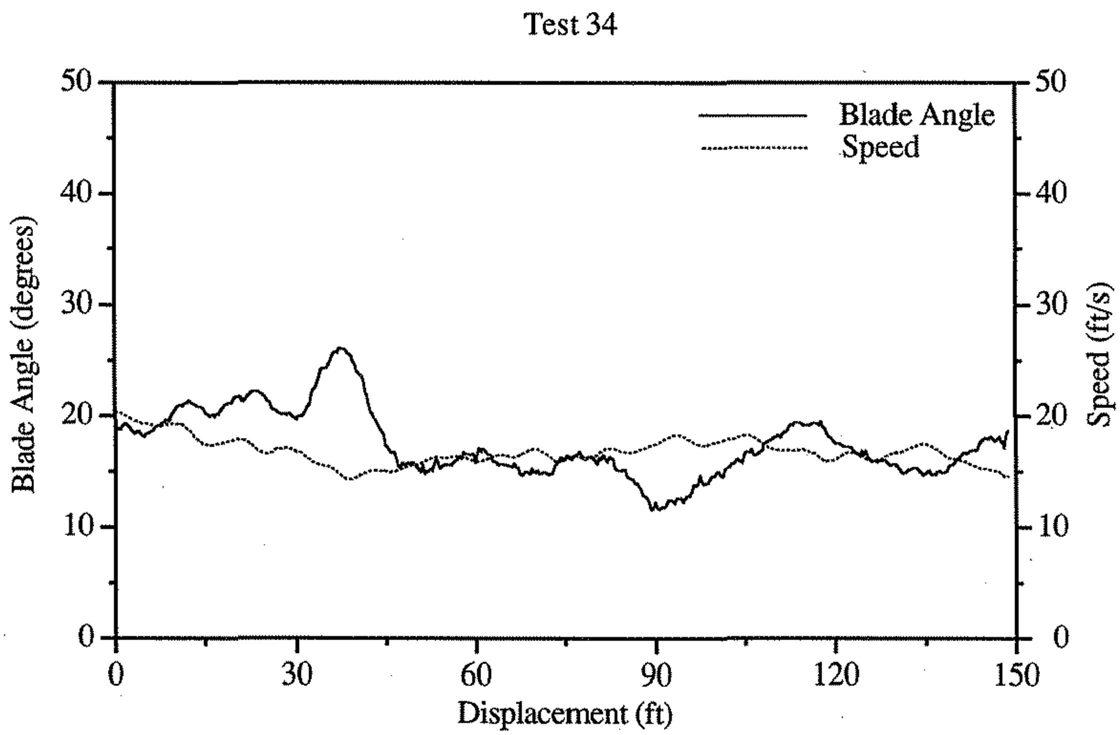
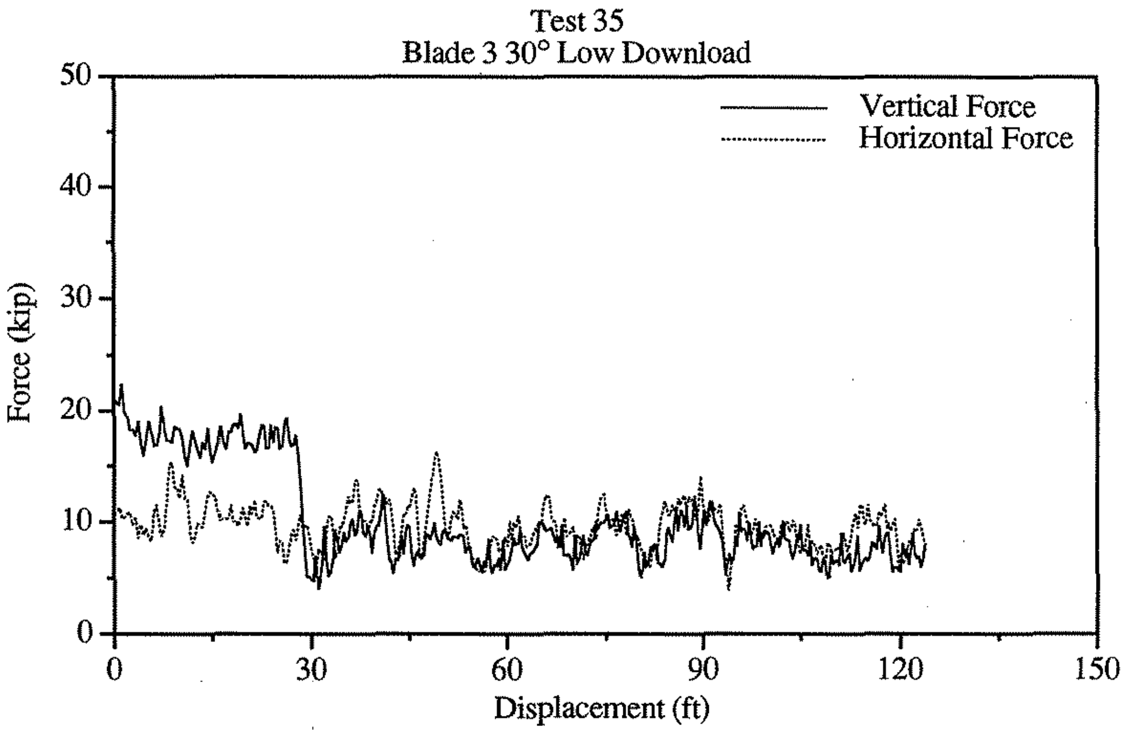
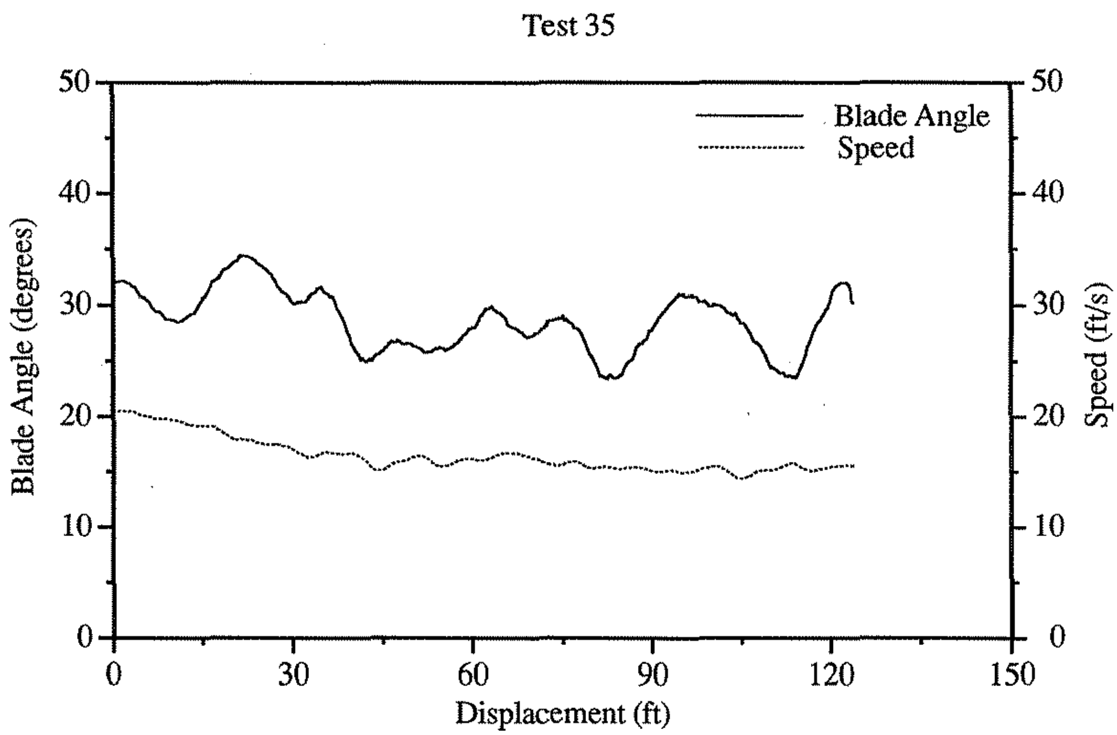


Figure B34. Graphical results of test 34.





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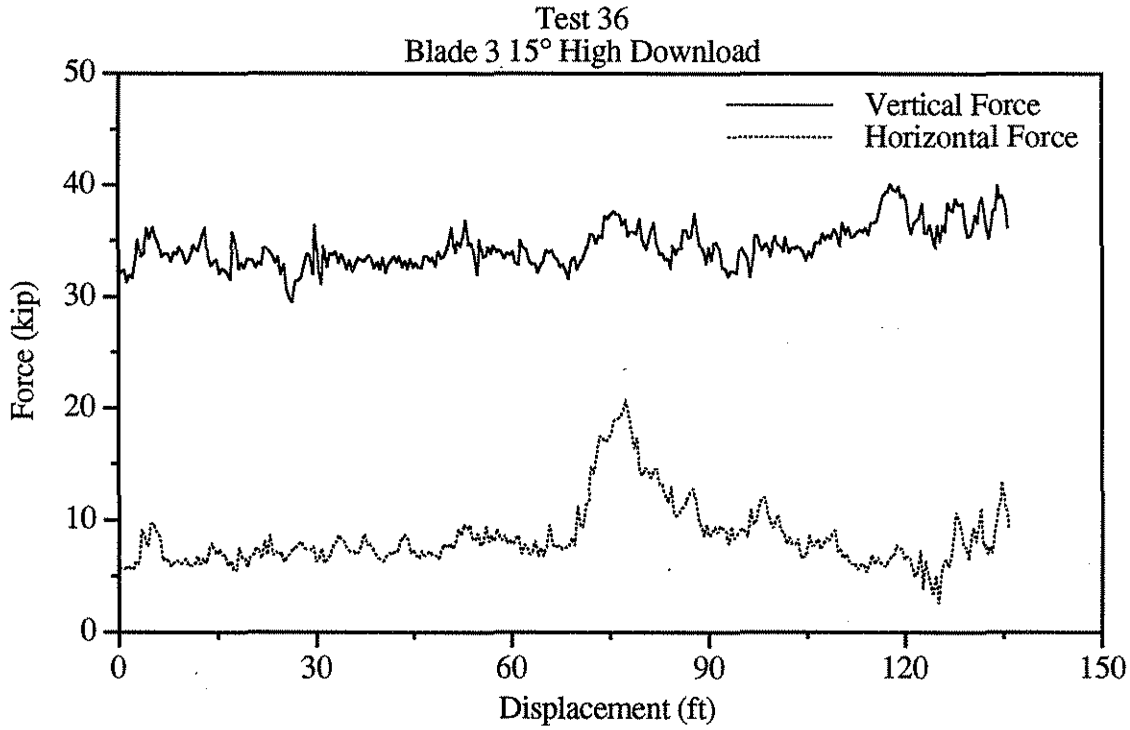


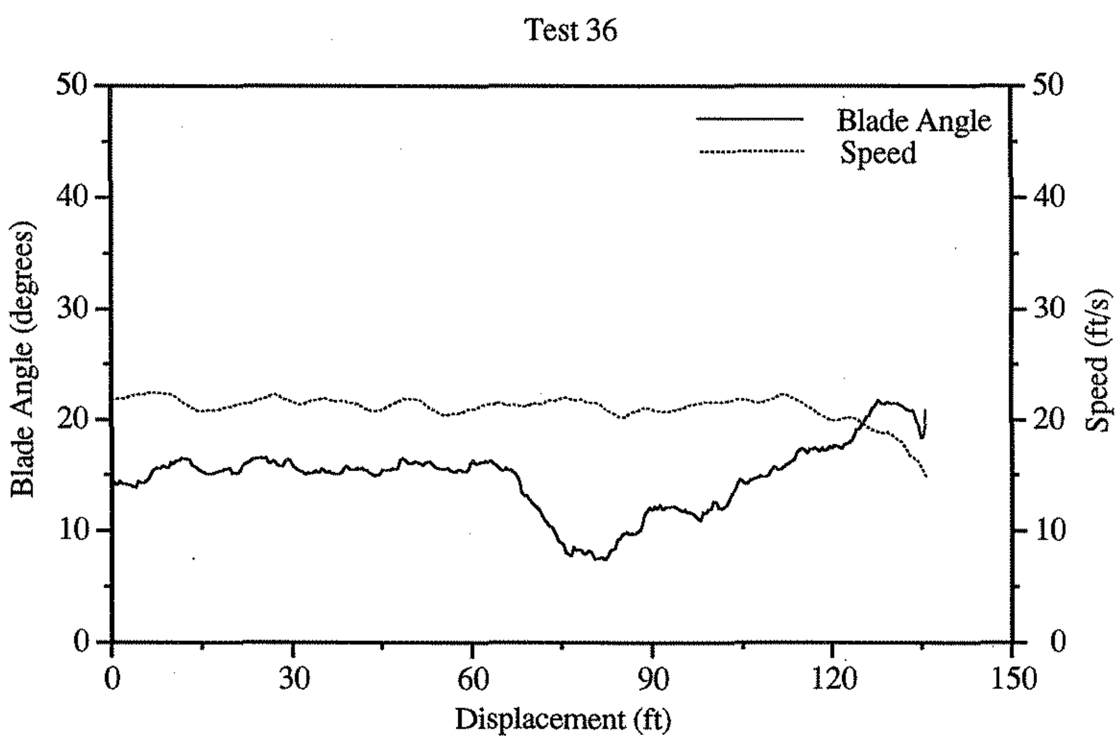
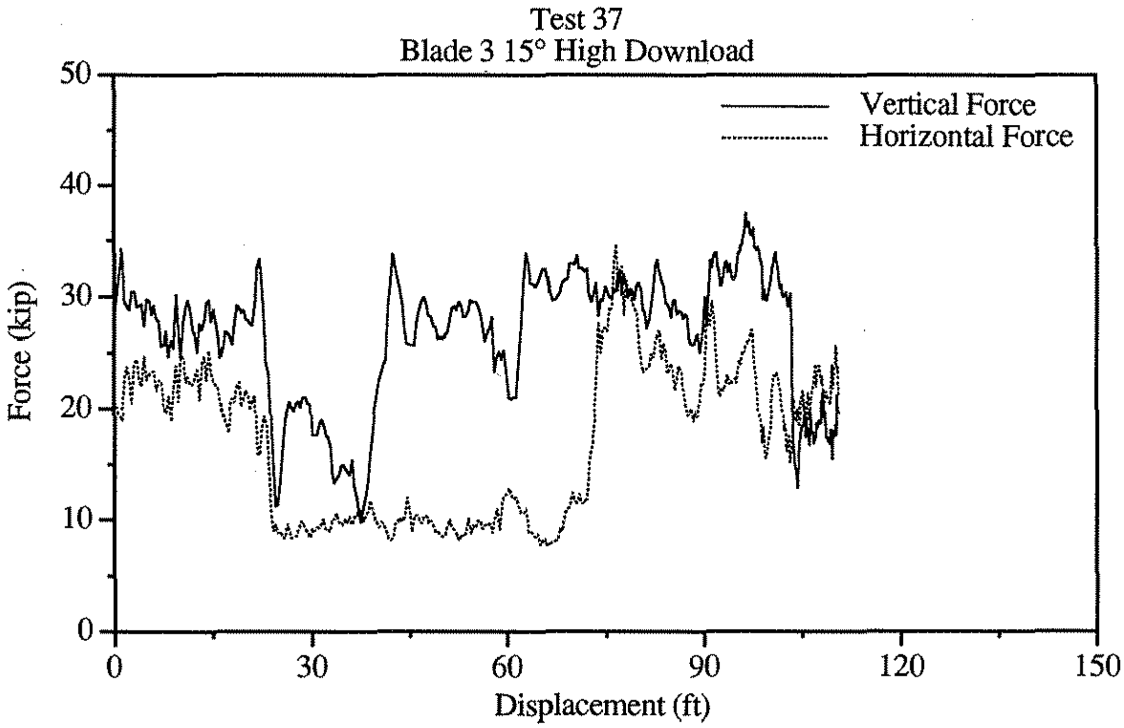


Figure B36. Graphical results of test 36.



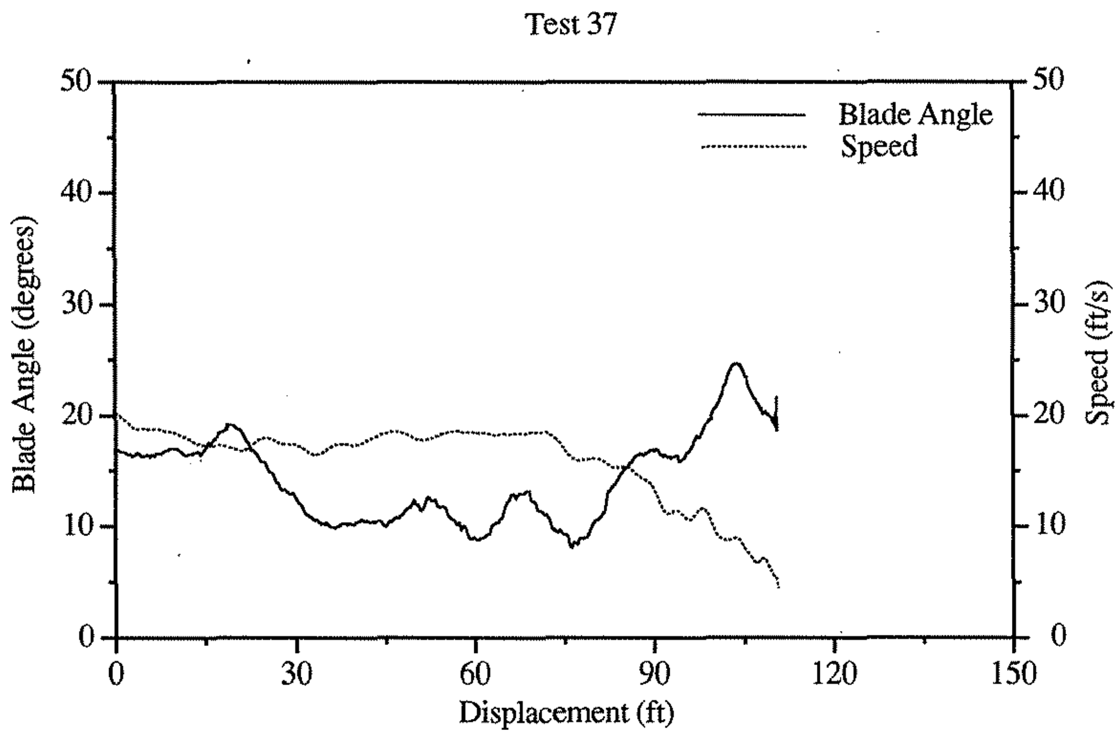
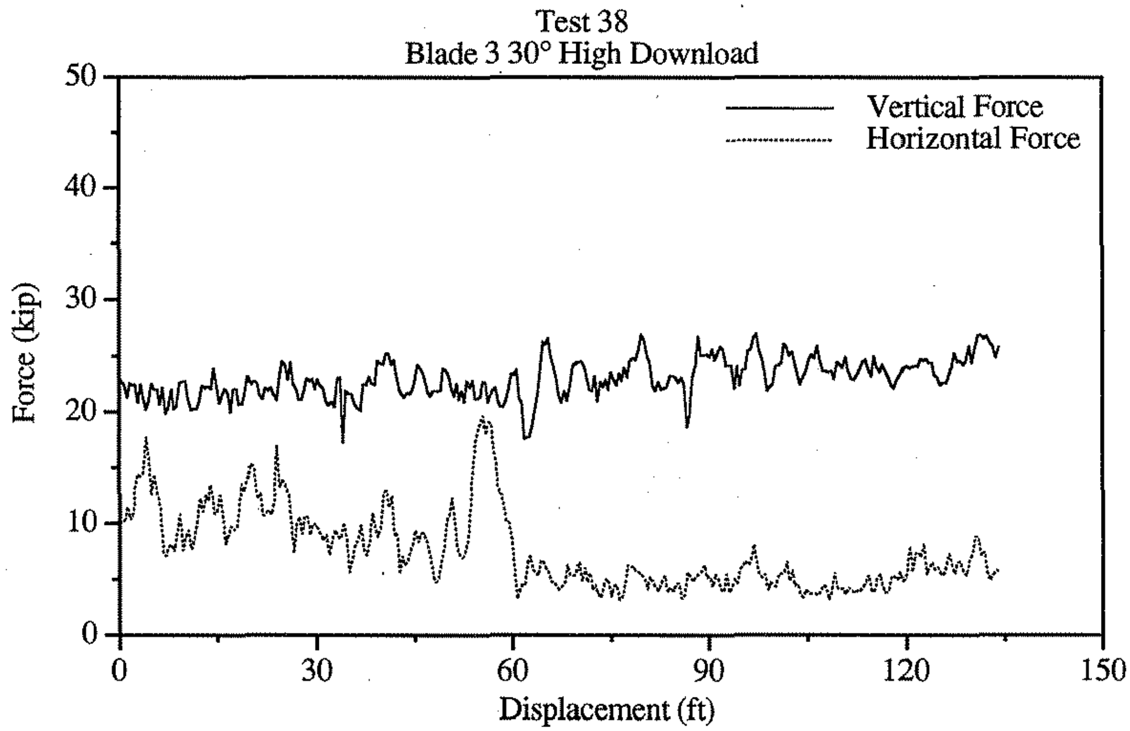


Figure B37. Graphical results of test 37.



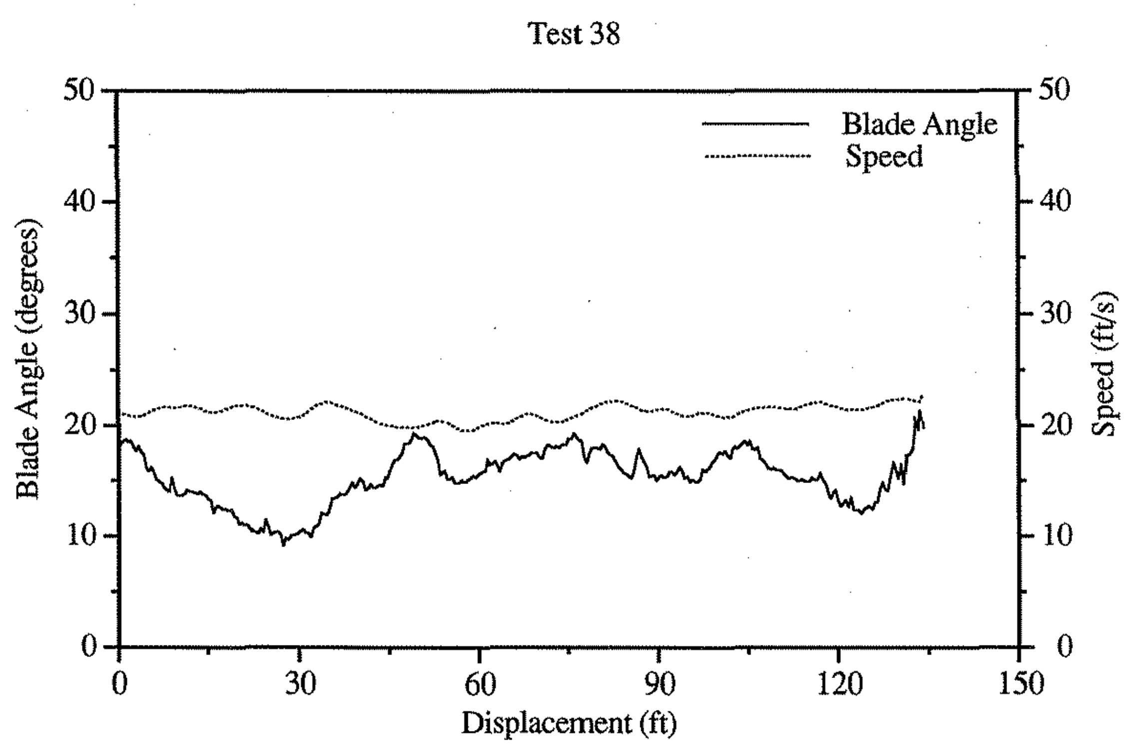
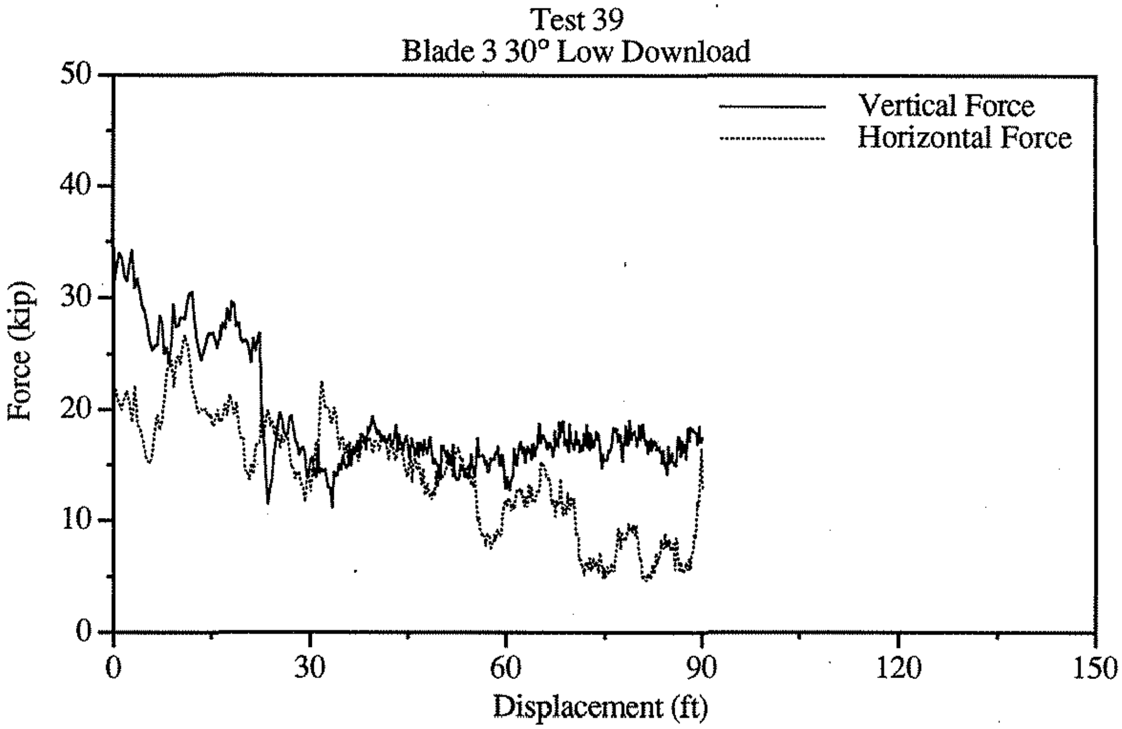


Figure B38. Graphical results of test 38.



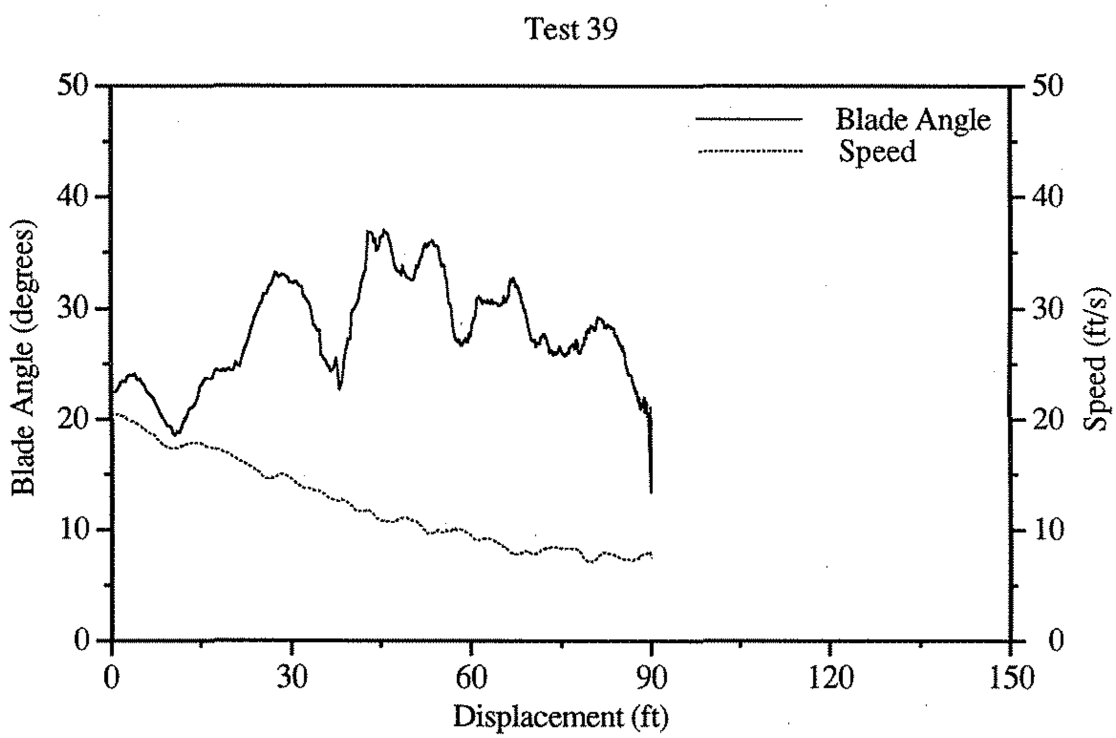
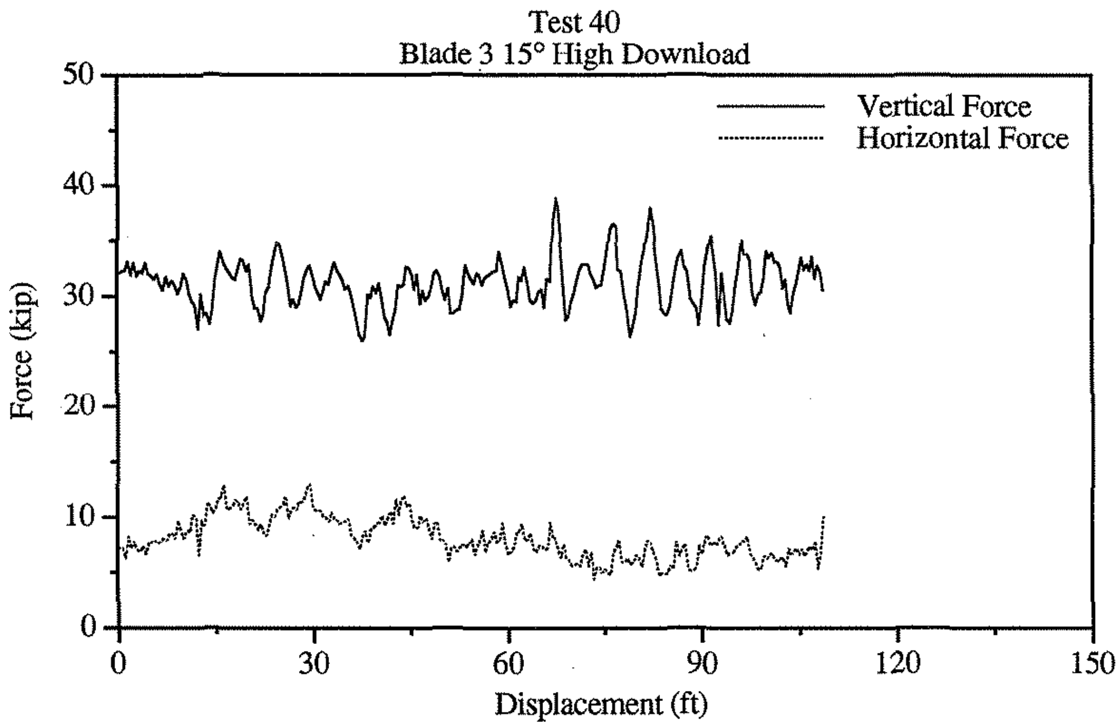


Figure B39. Graphical results of test 39.



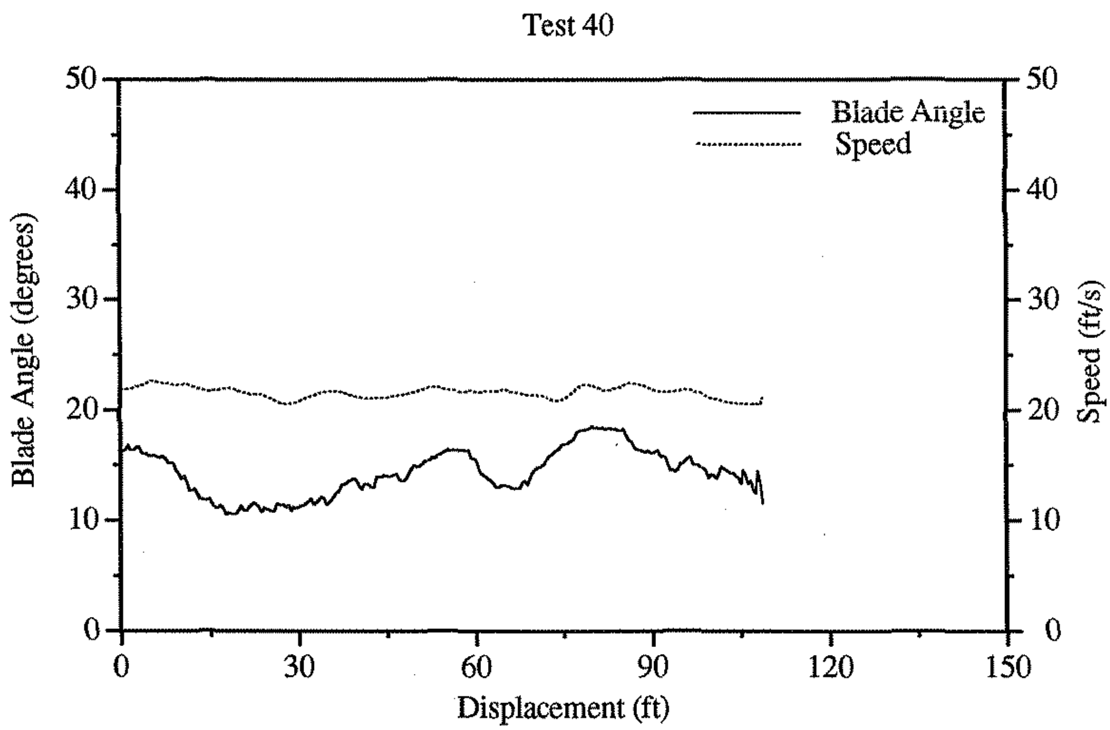
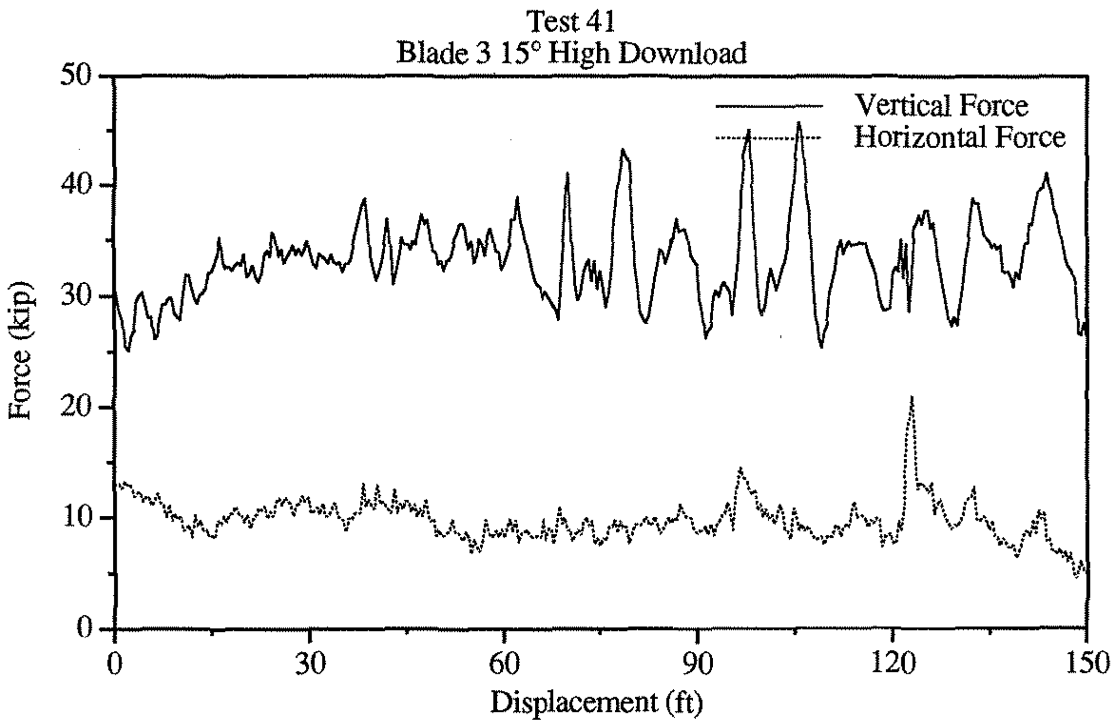


Figure B40. Graphical results of test 40.



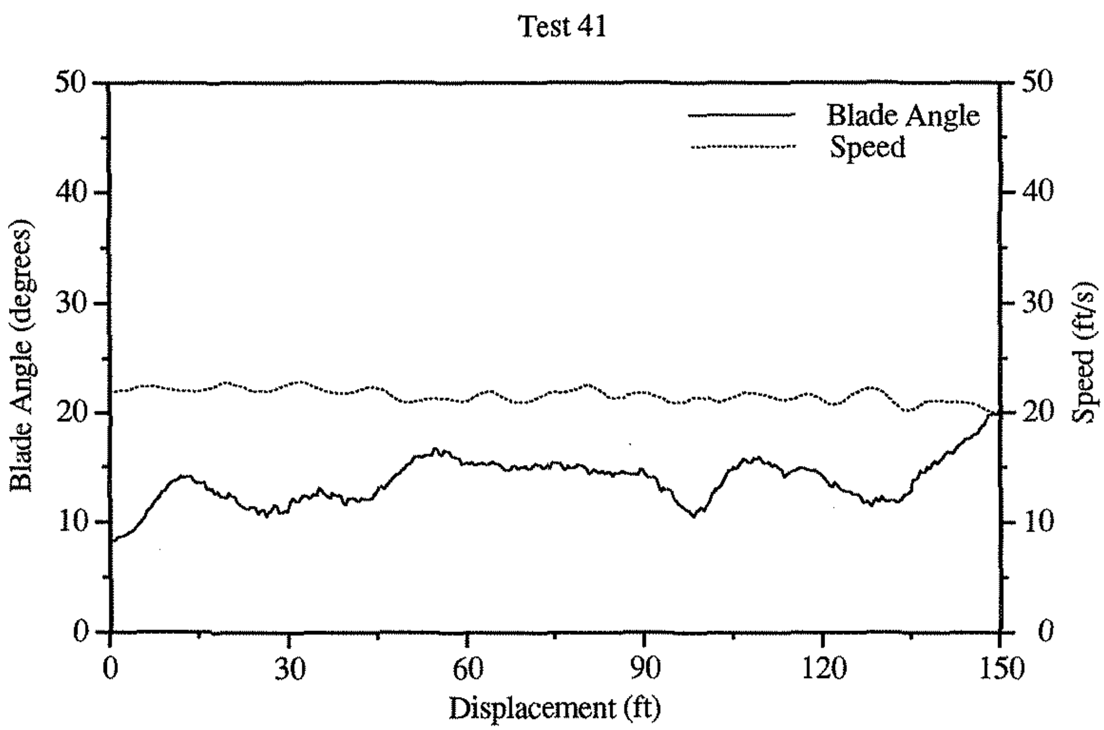
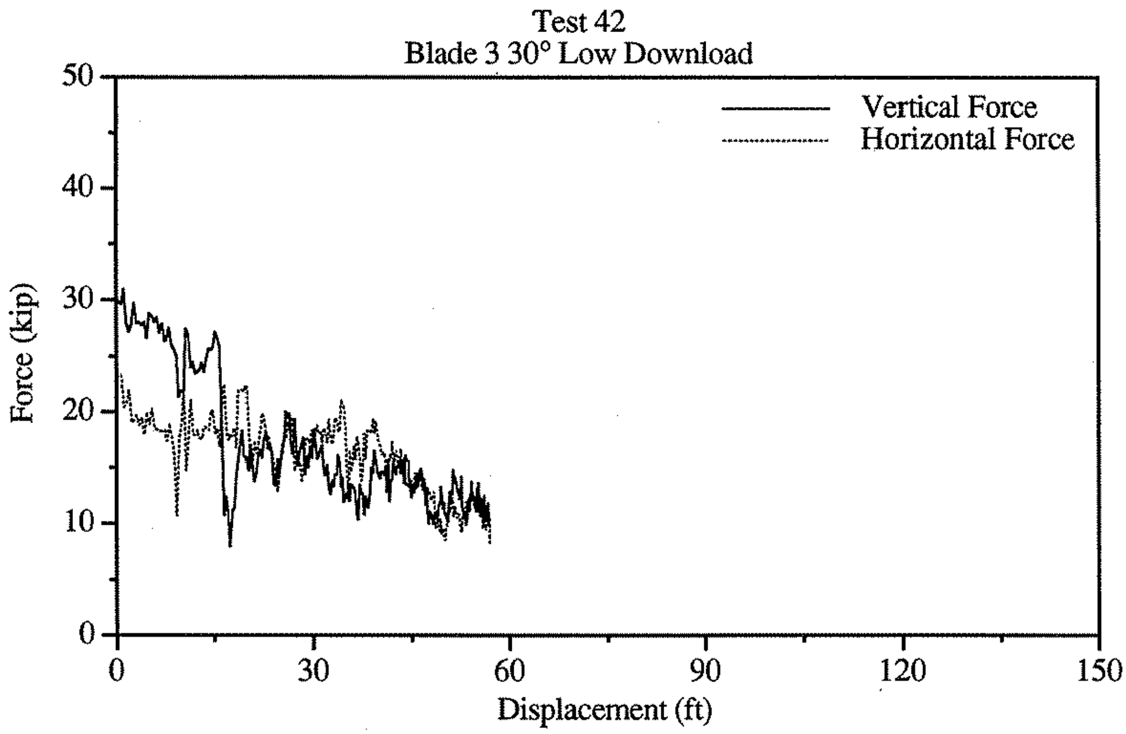
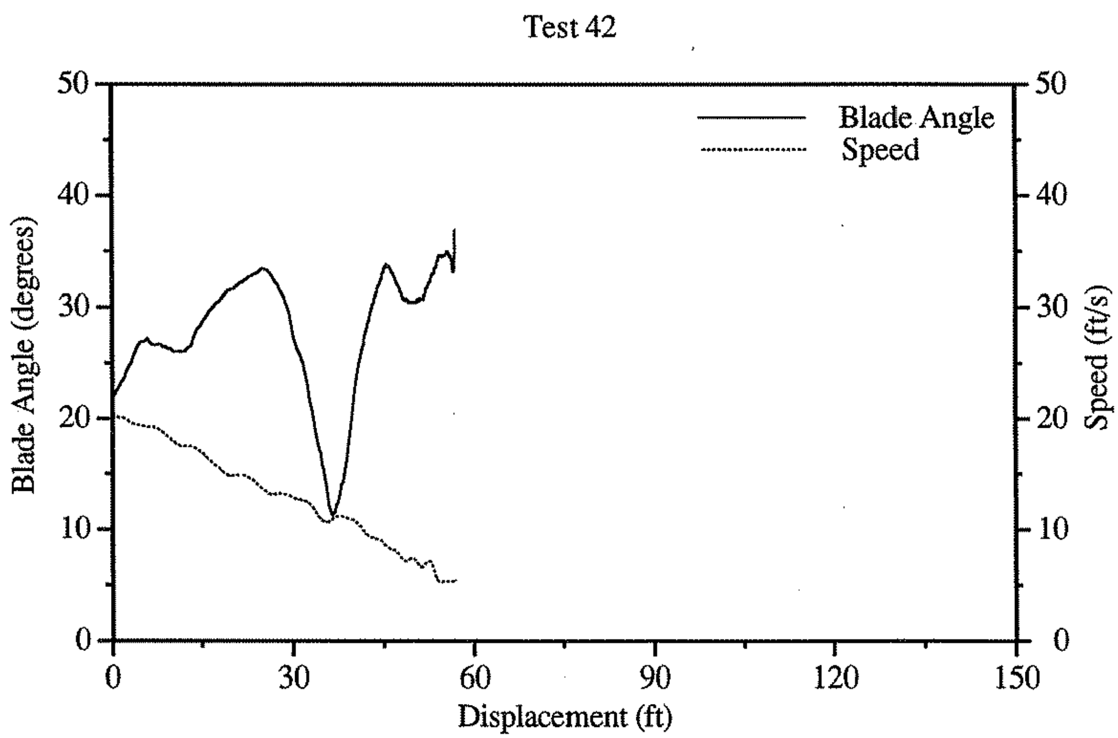


Figure B41. Graphical results of test 41.





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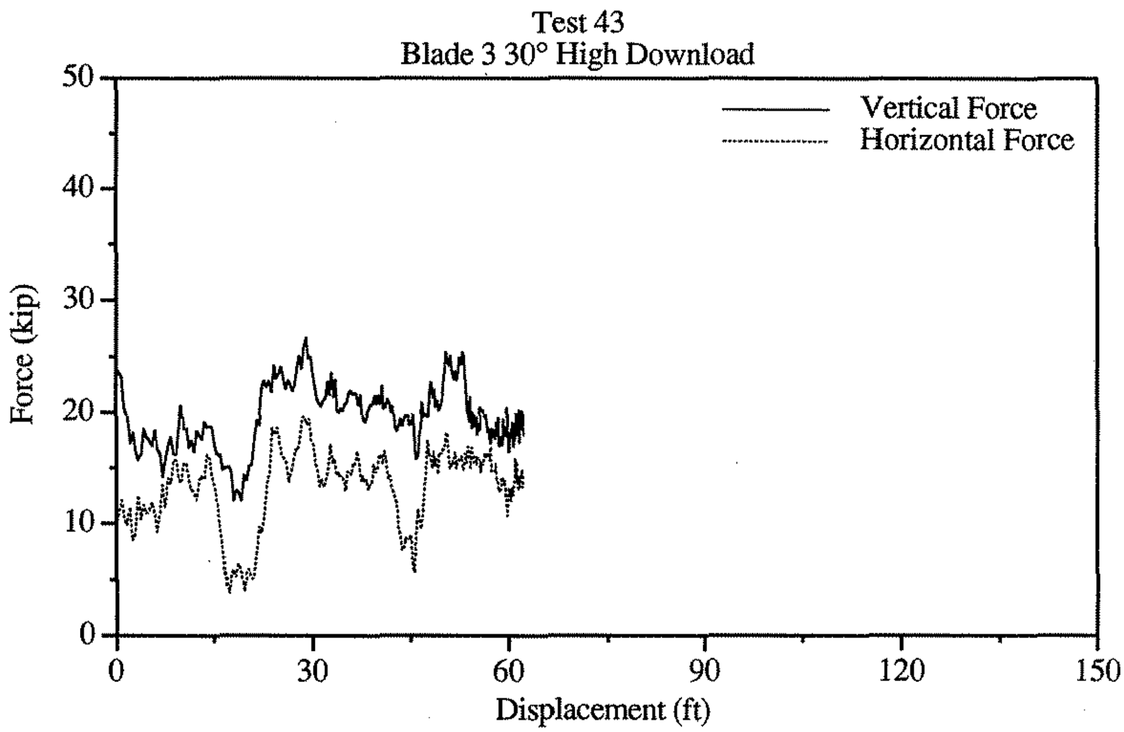

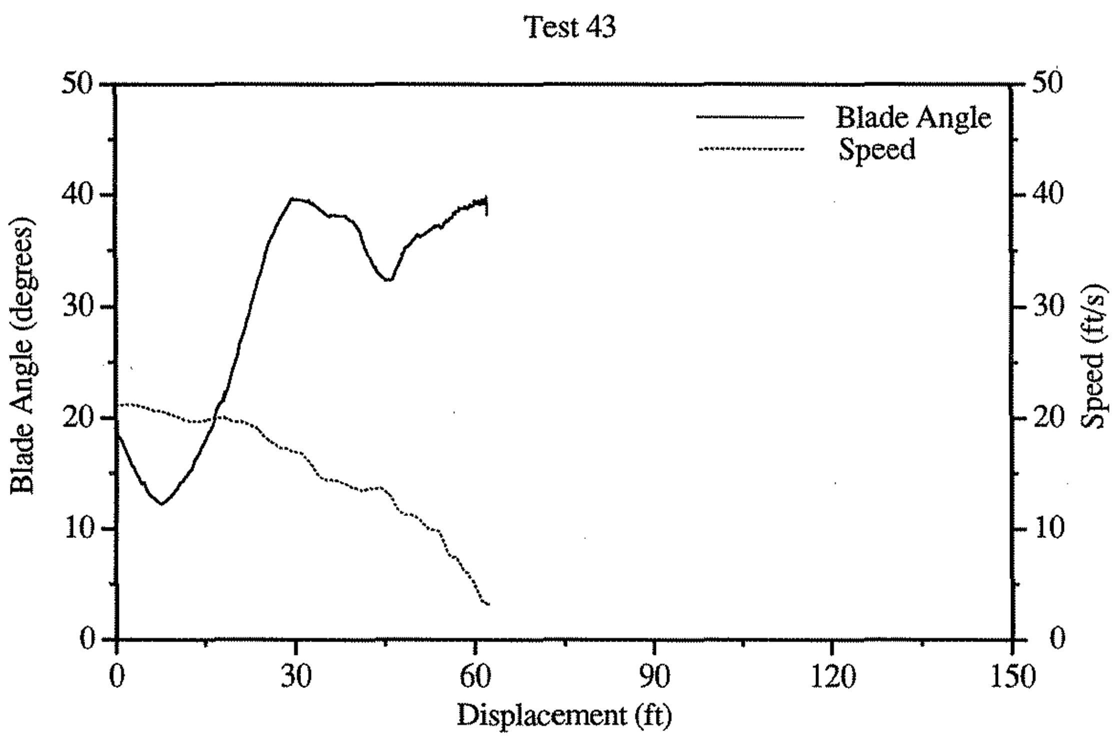

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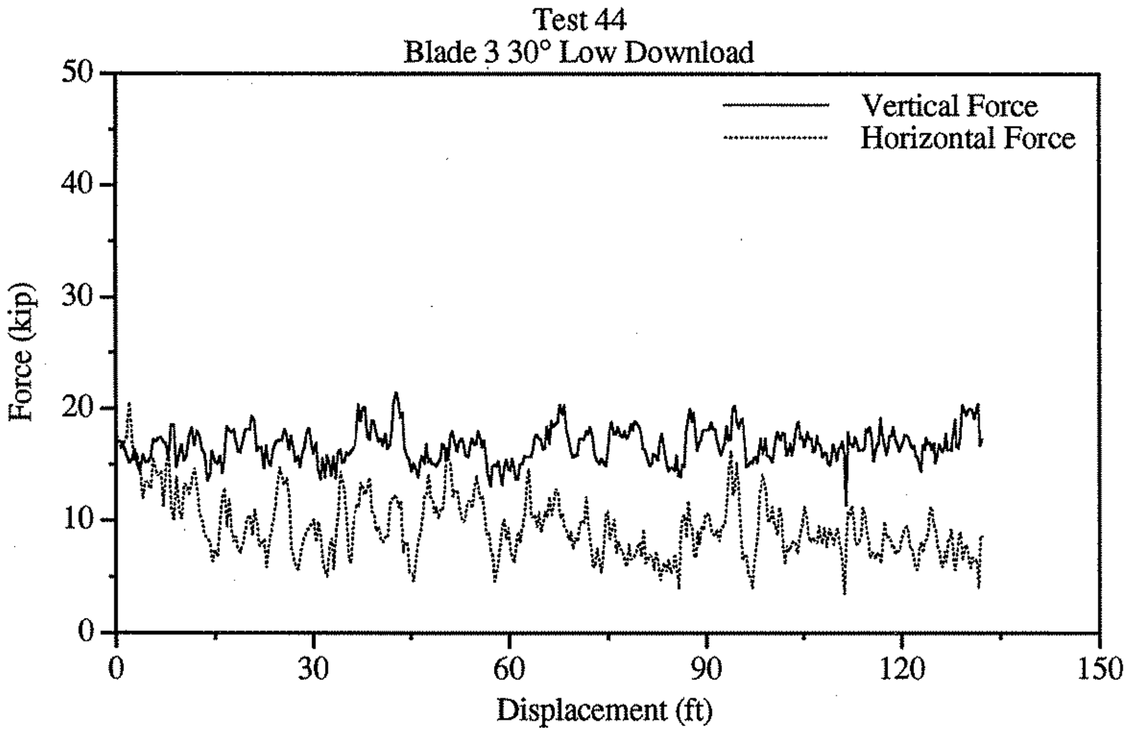

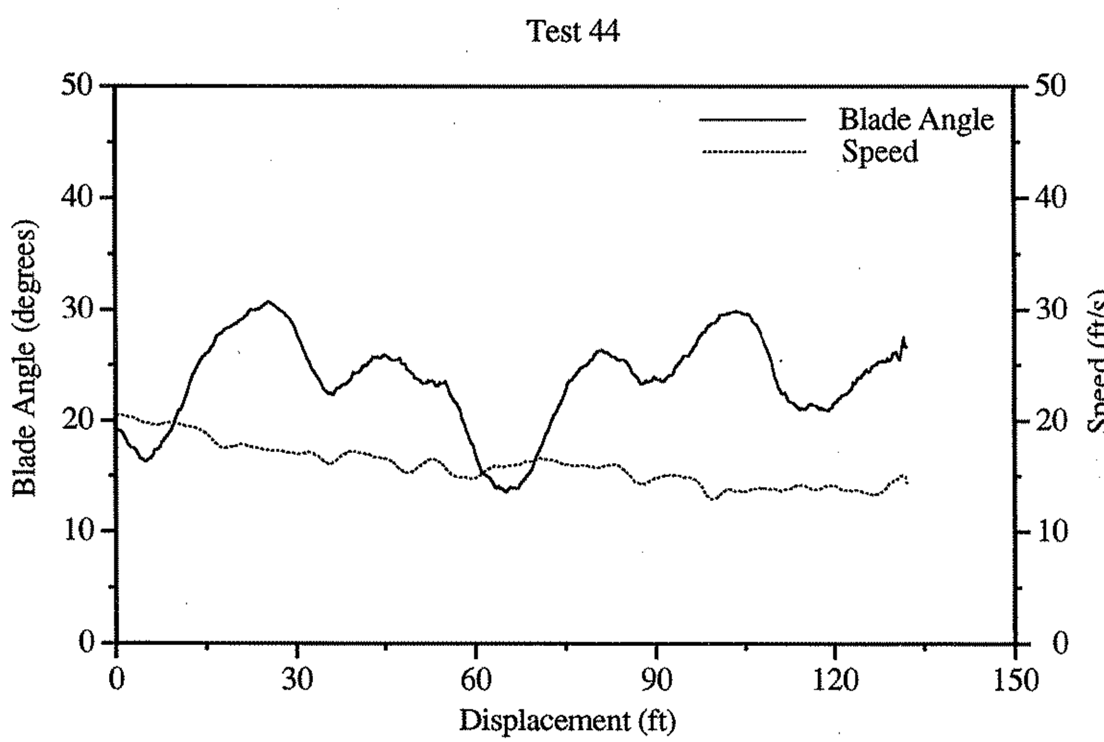

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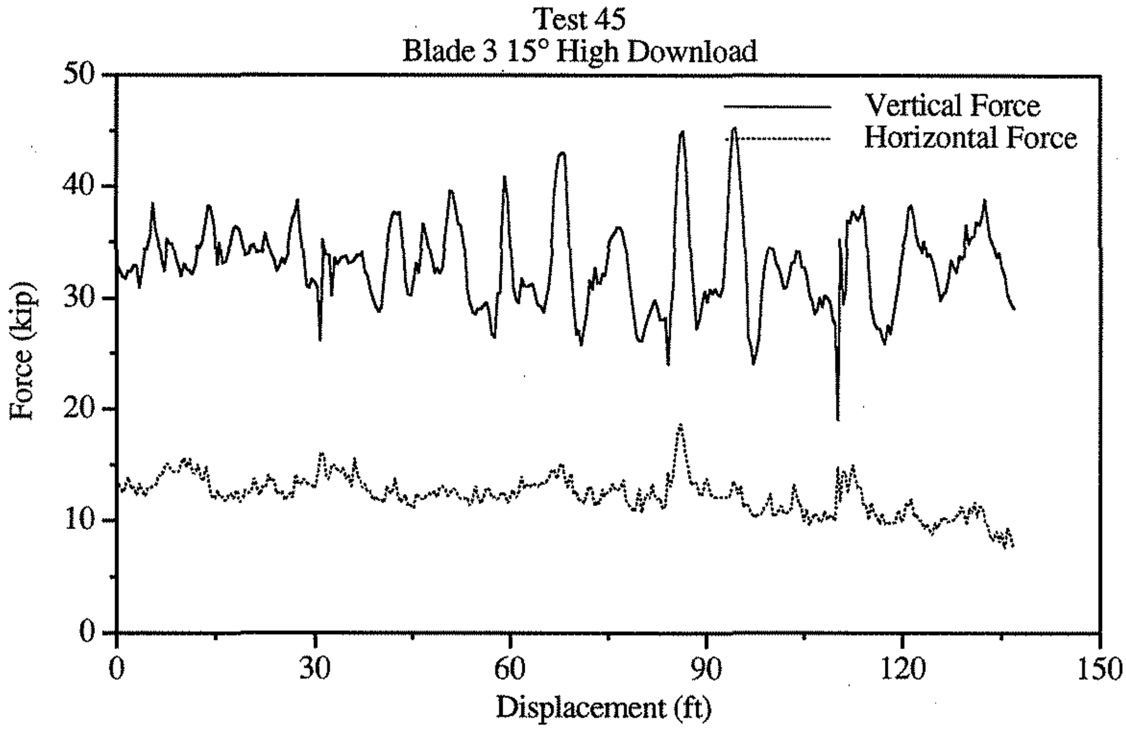

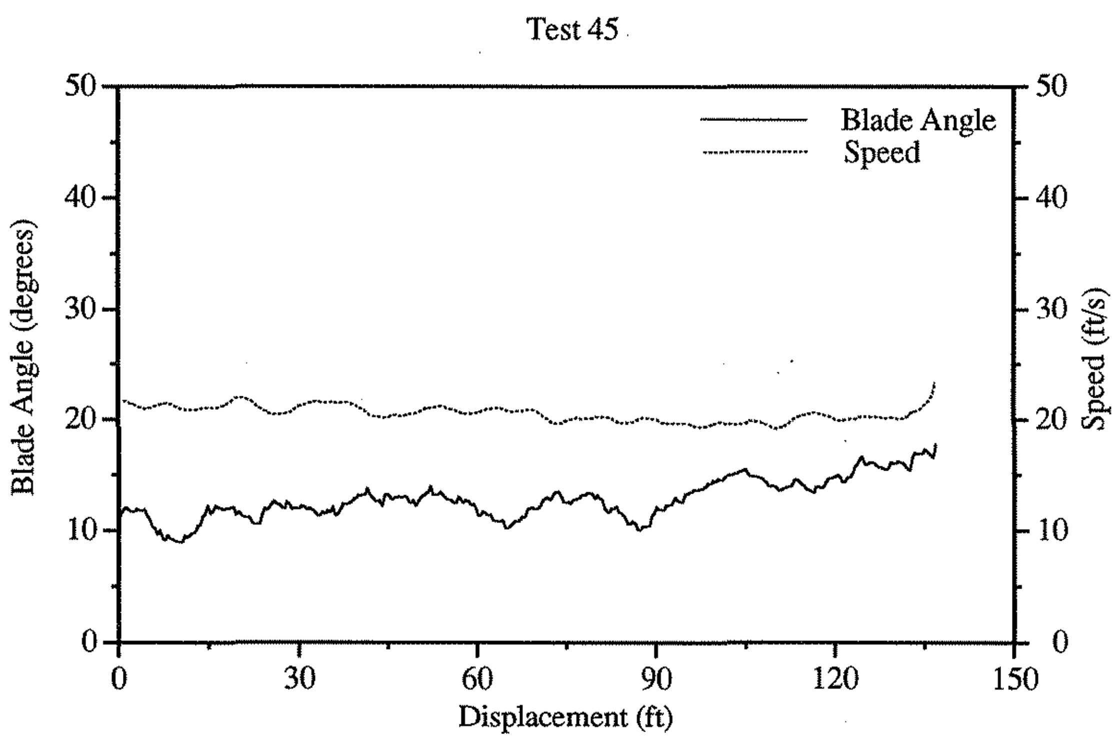

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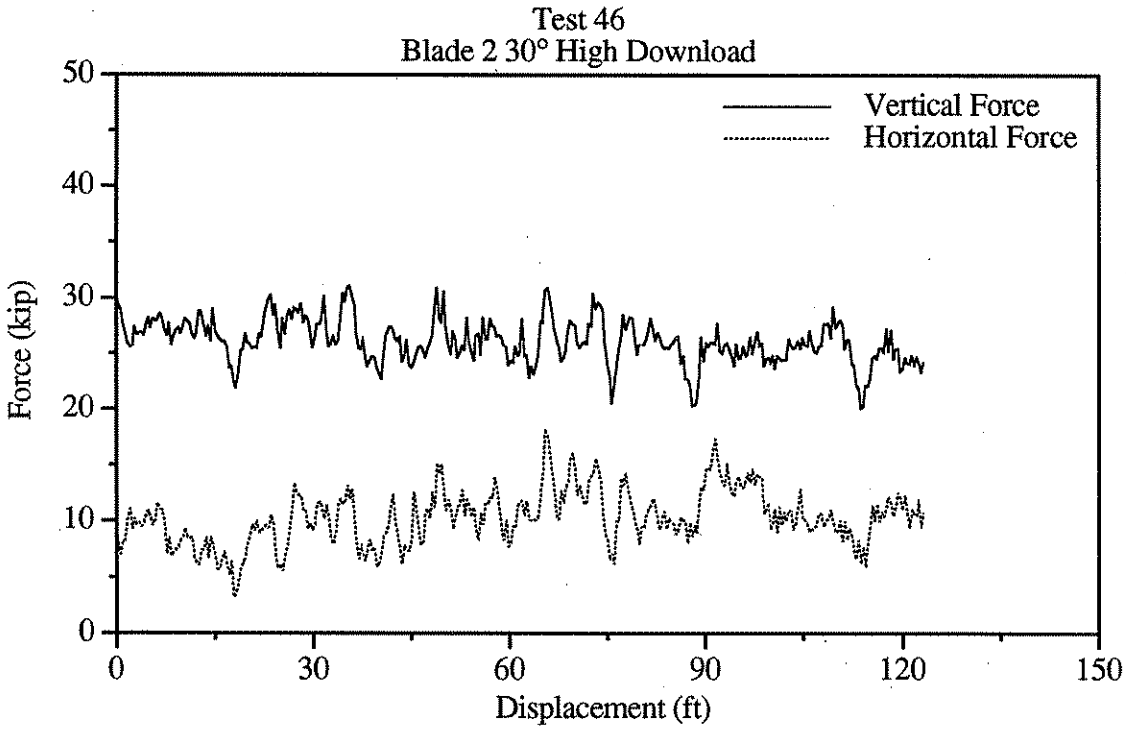

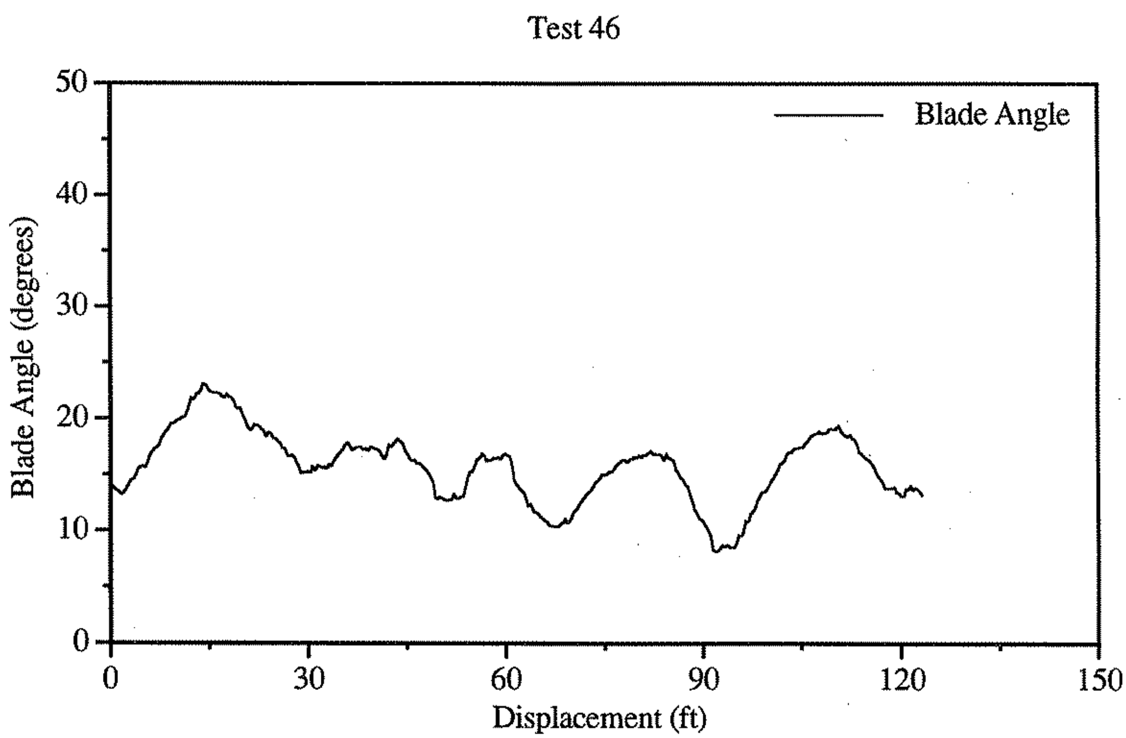

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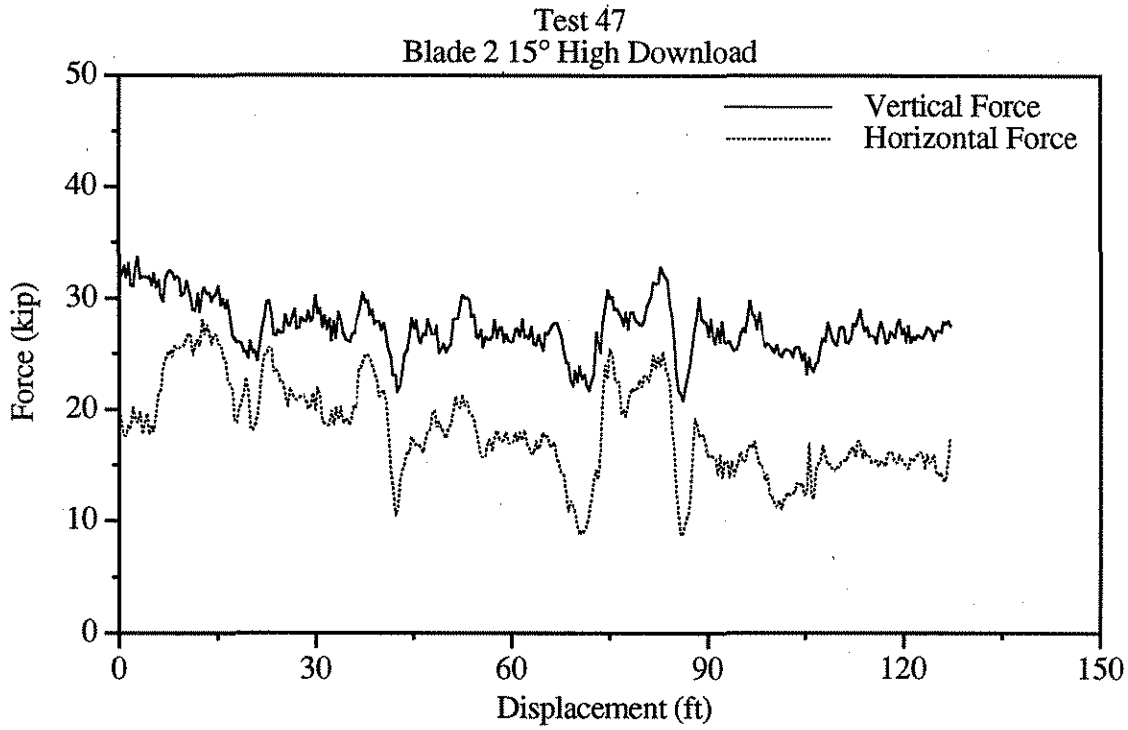

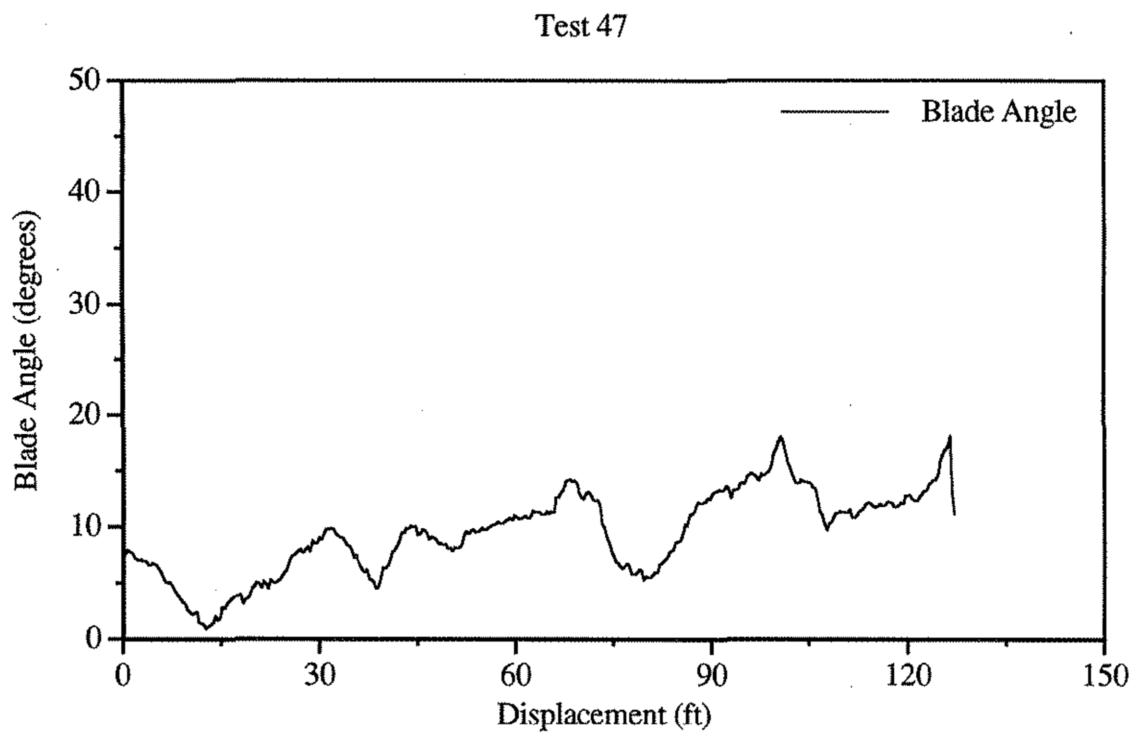

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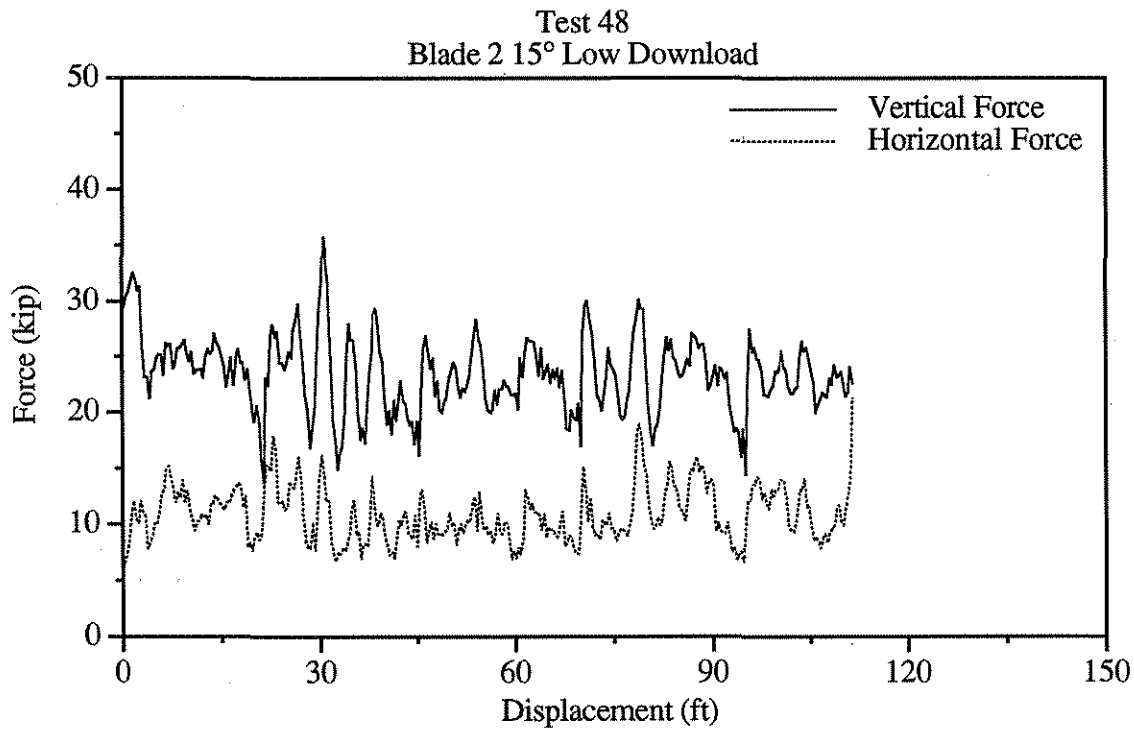

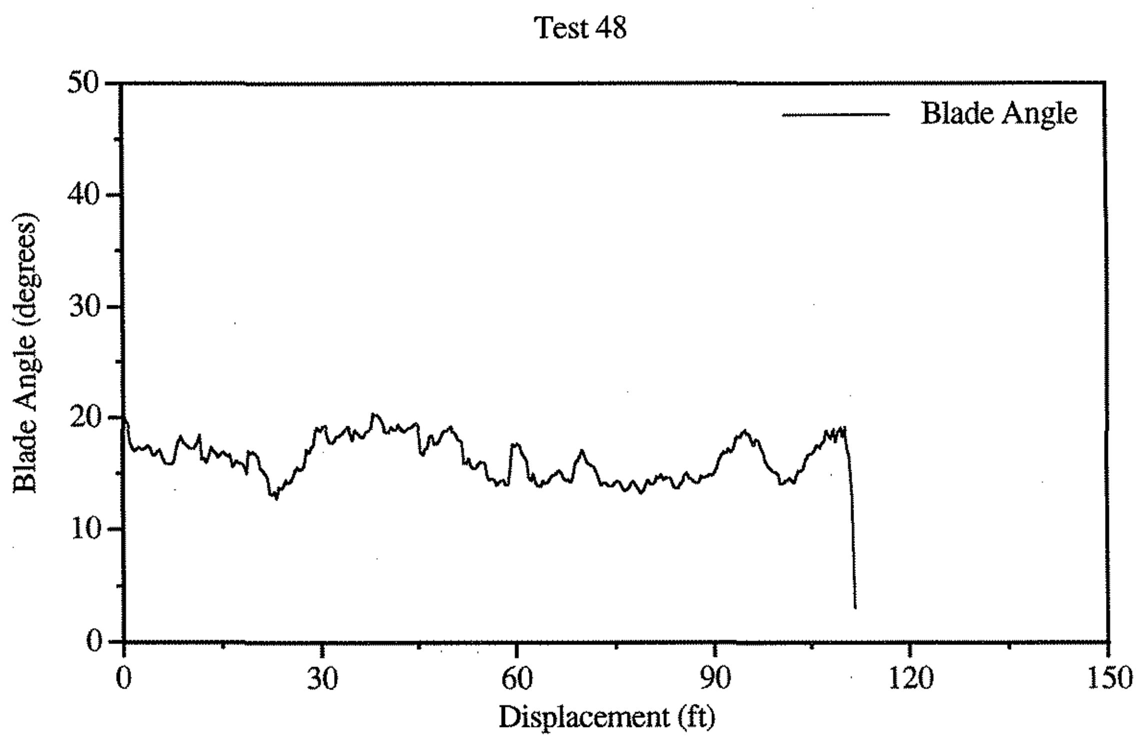

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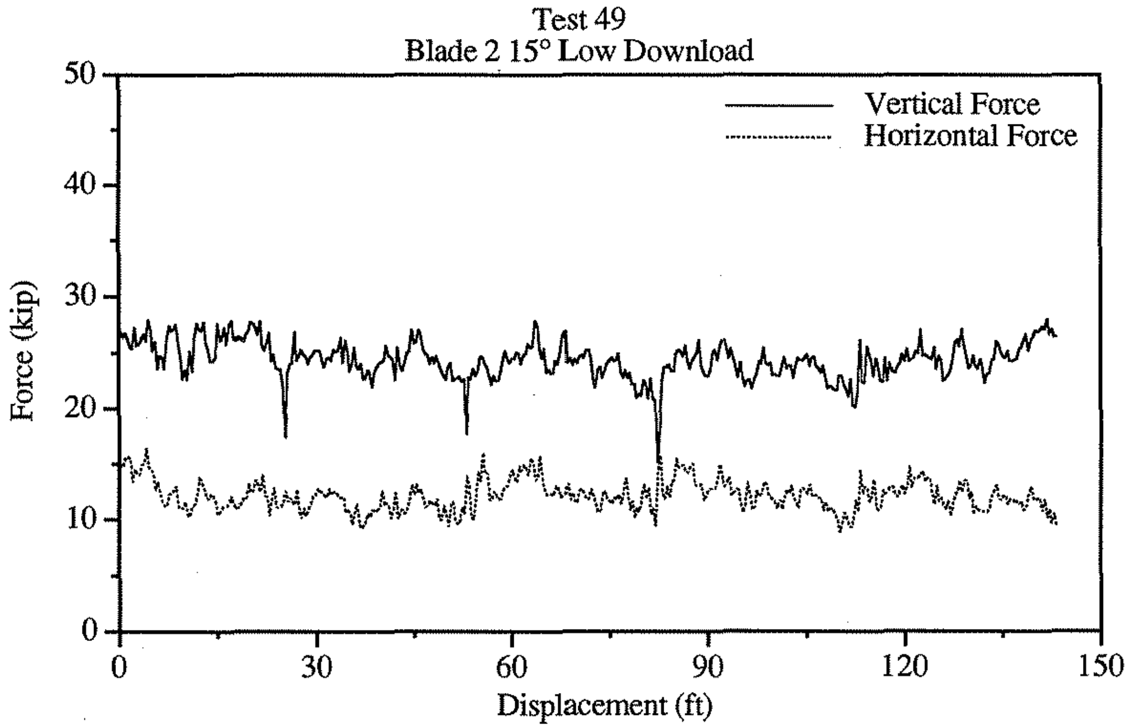

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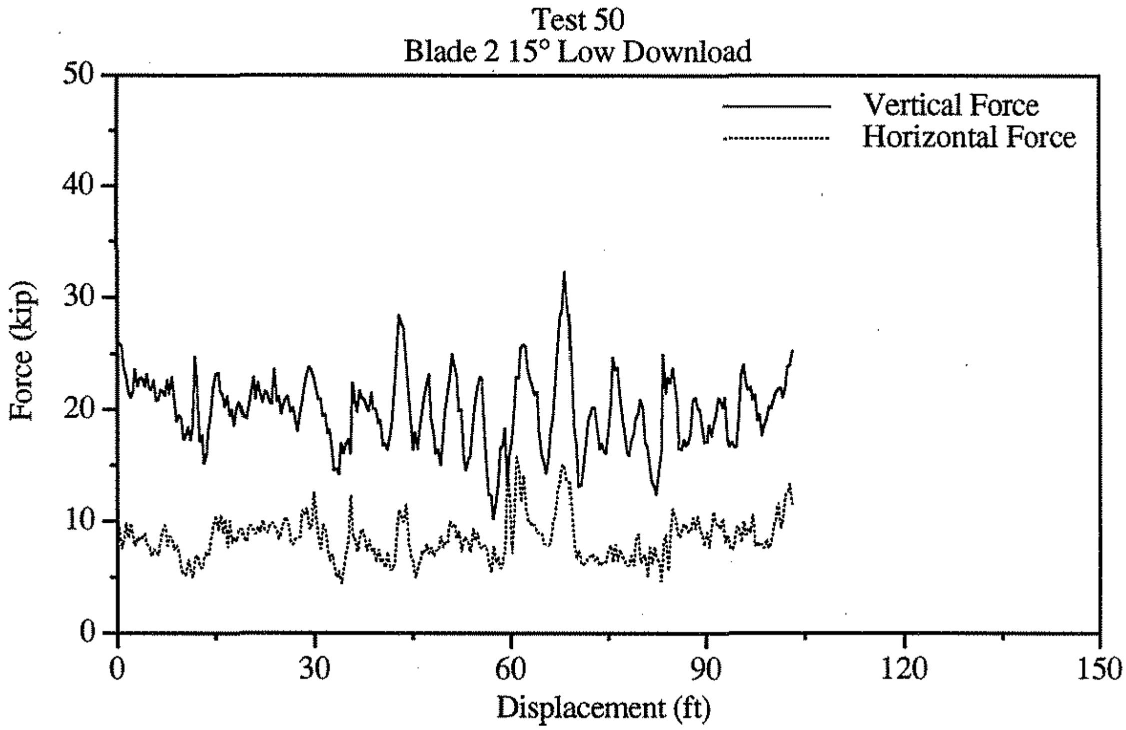

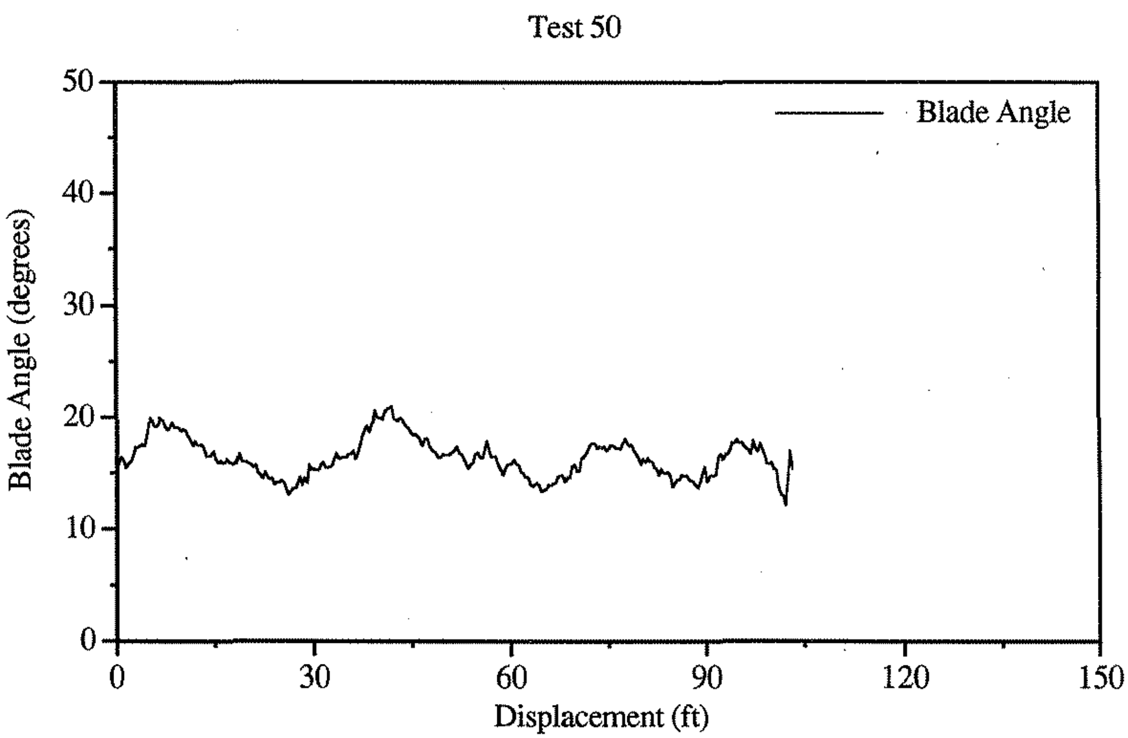

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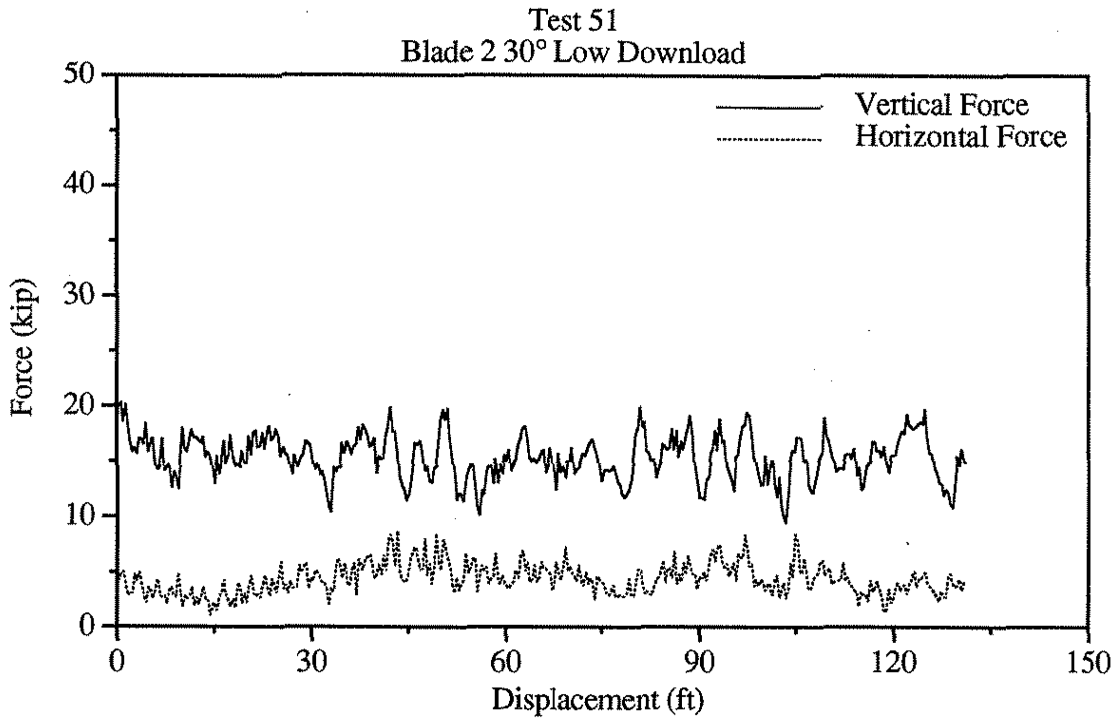


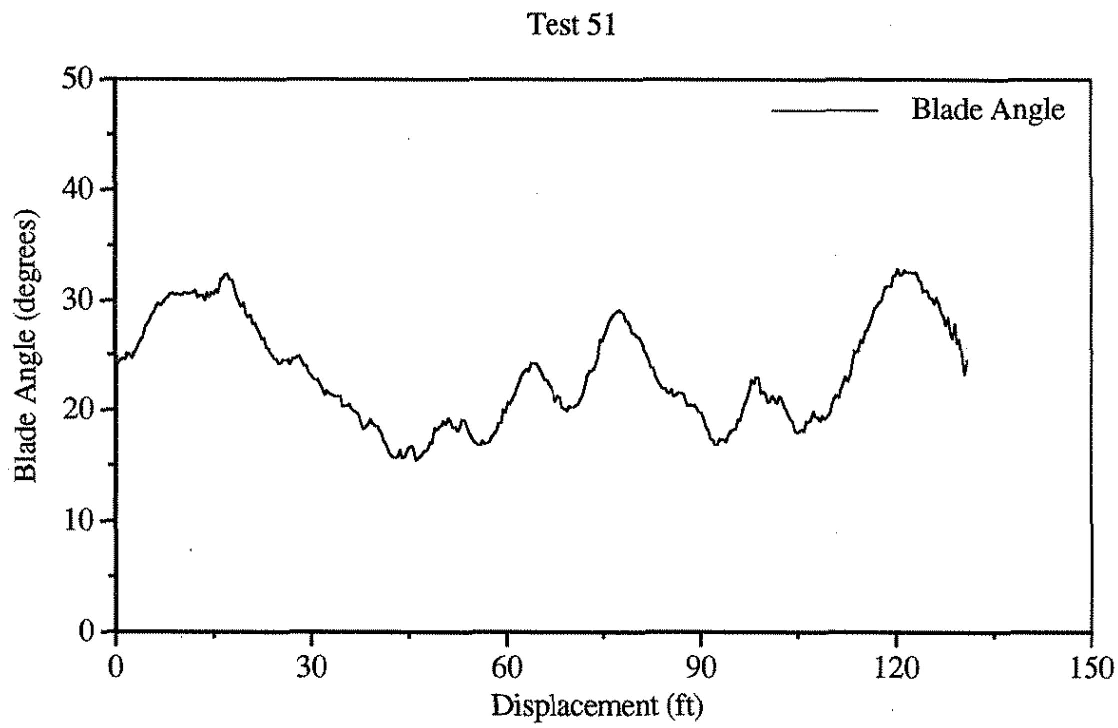
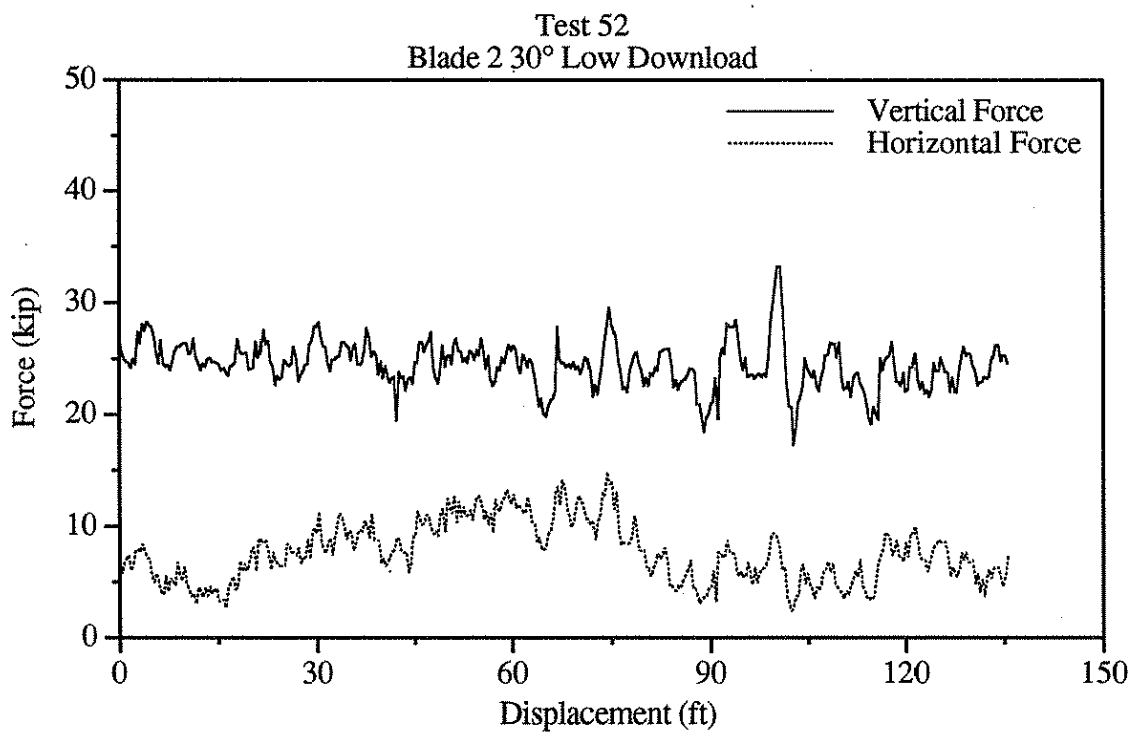
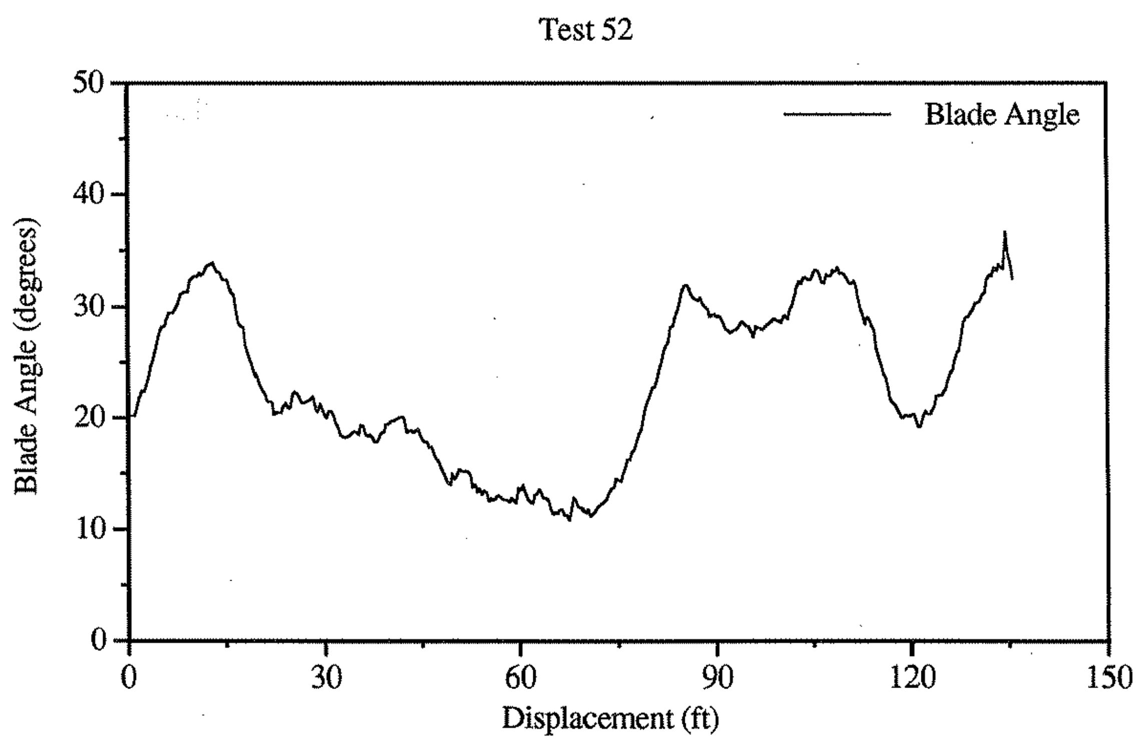


Figure B51. Graphical results of test 51.





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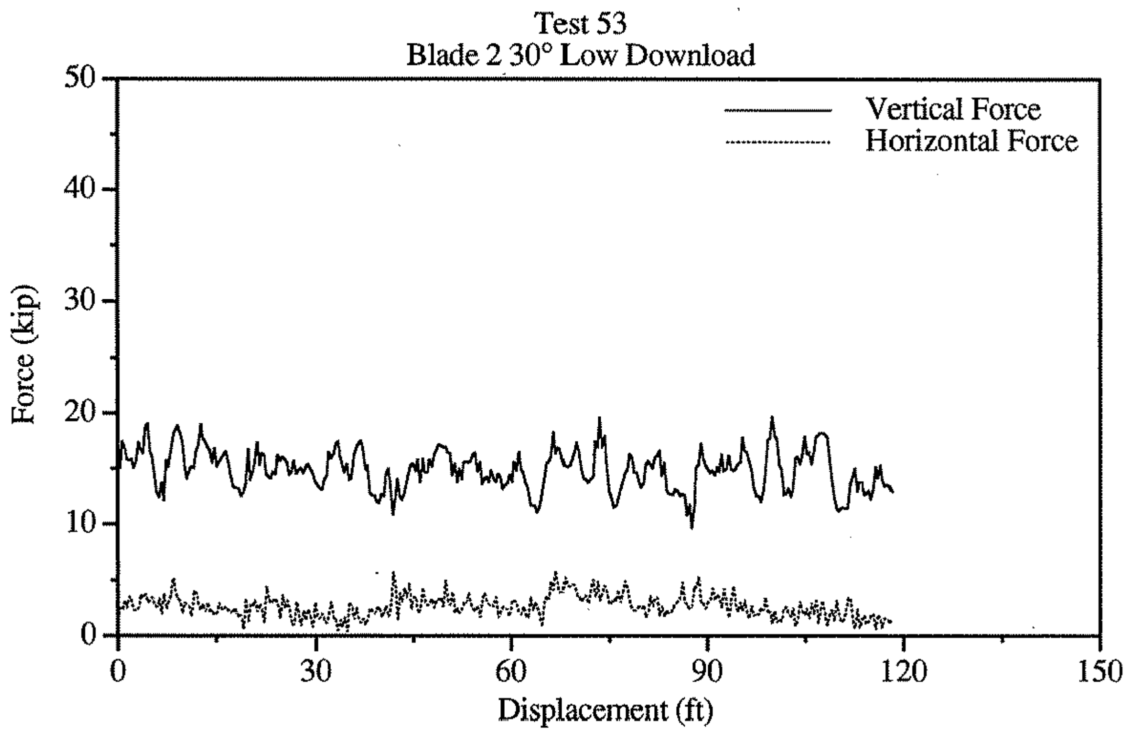

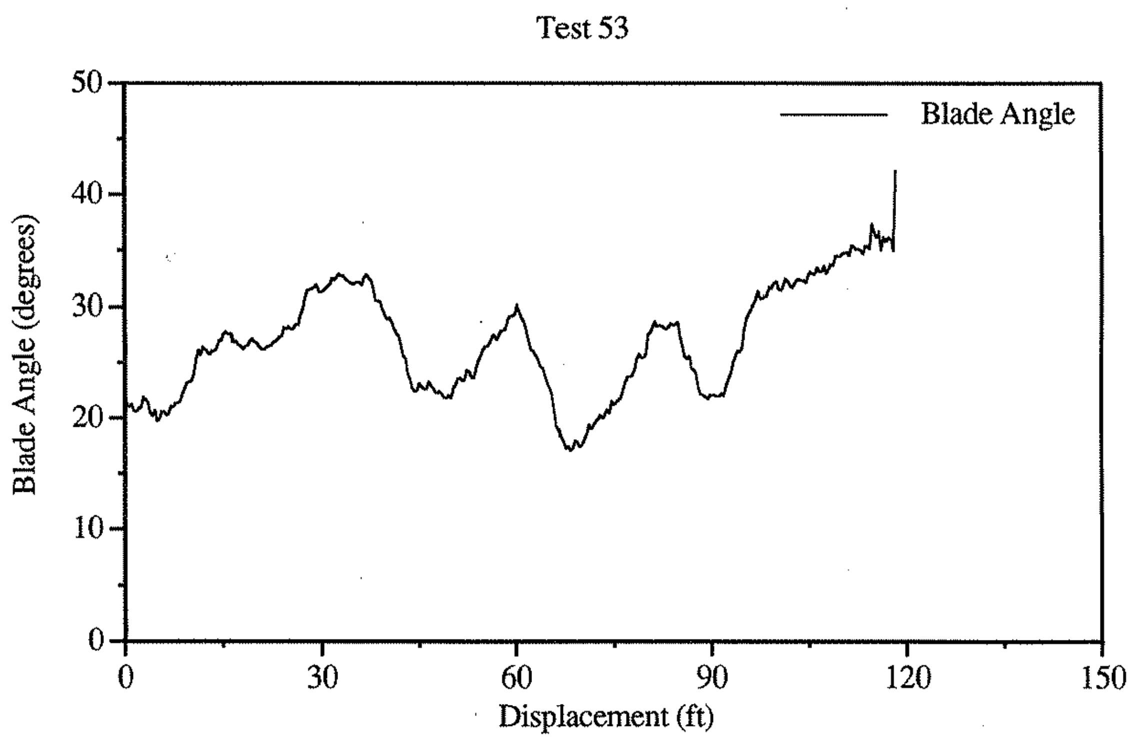

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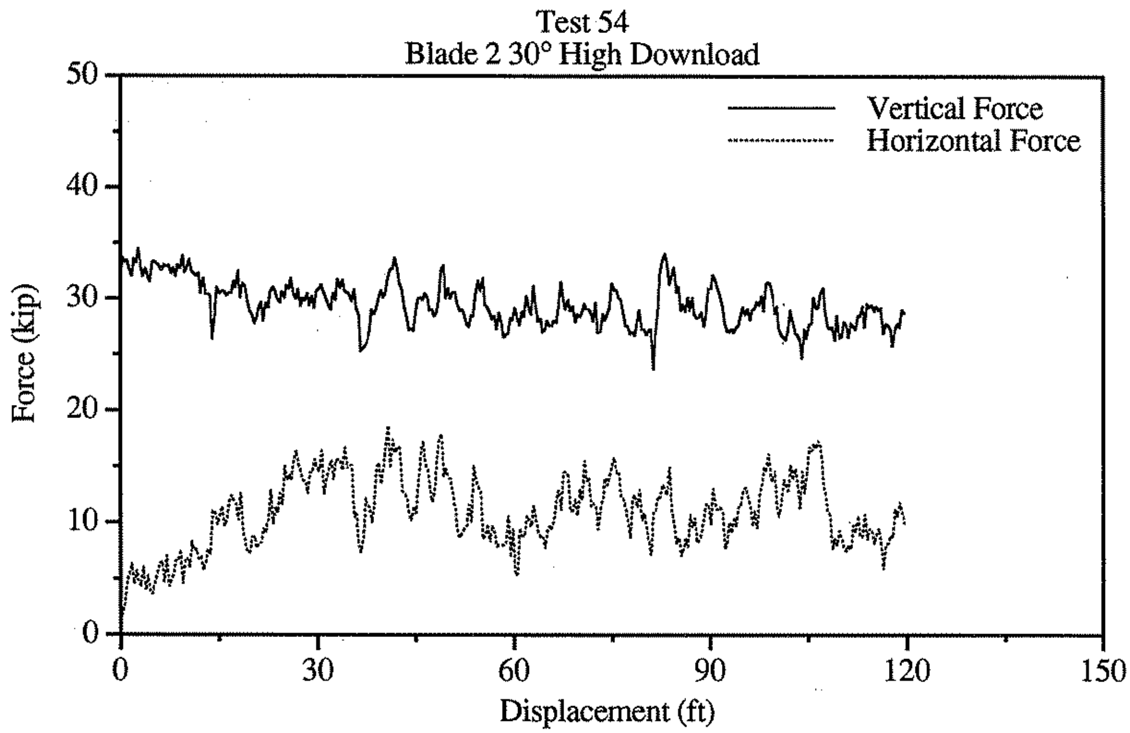

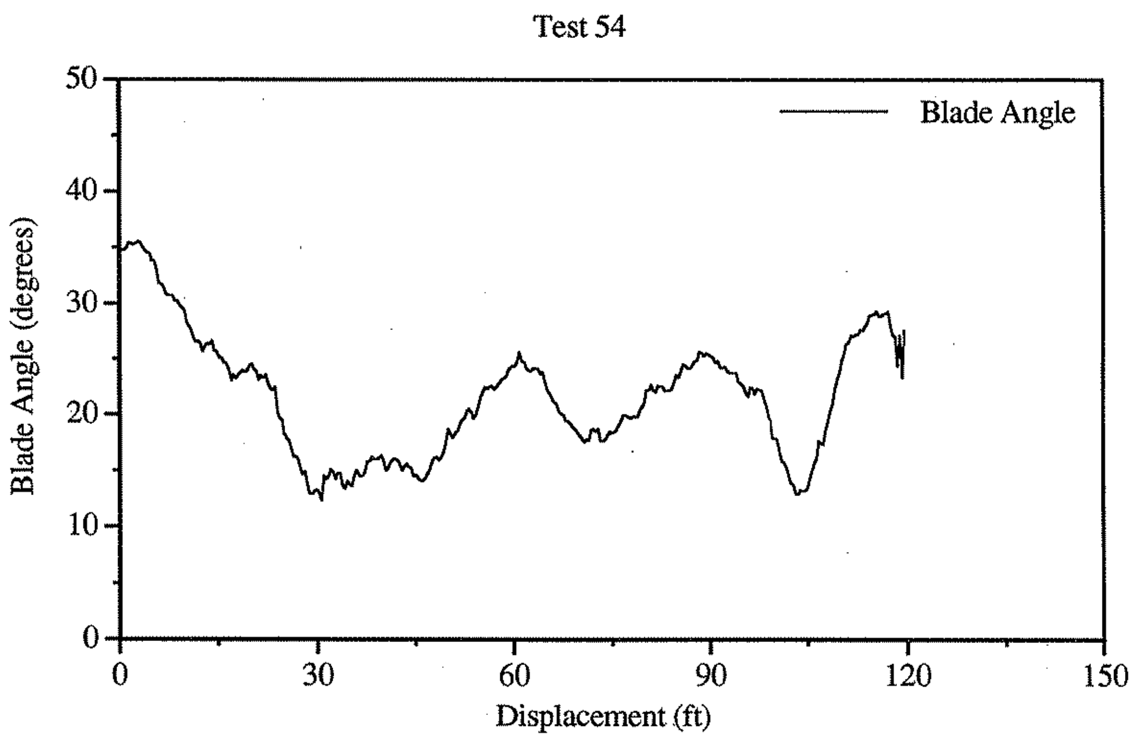

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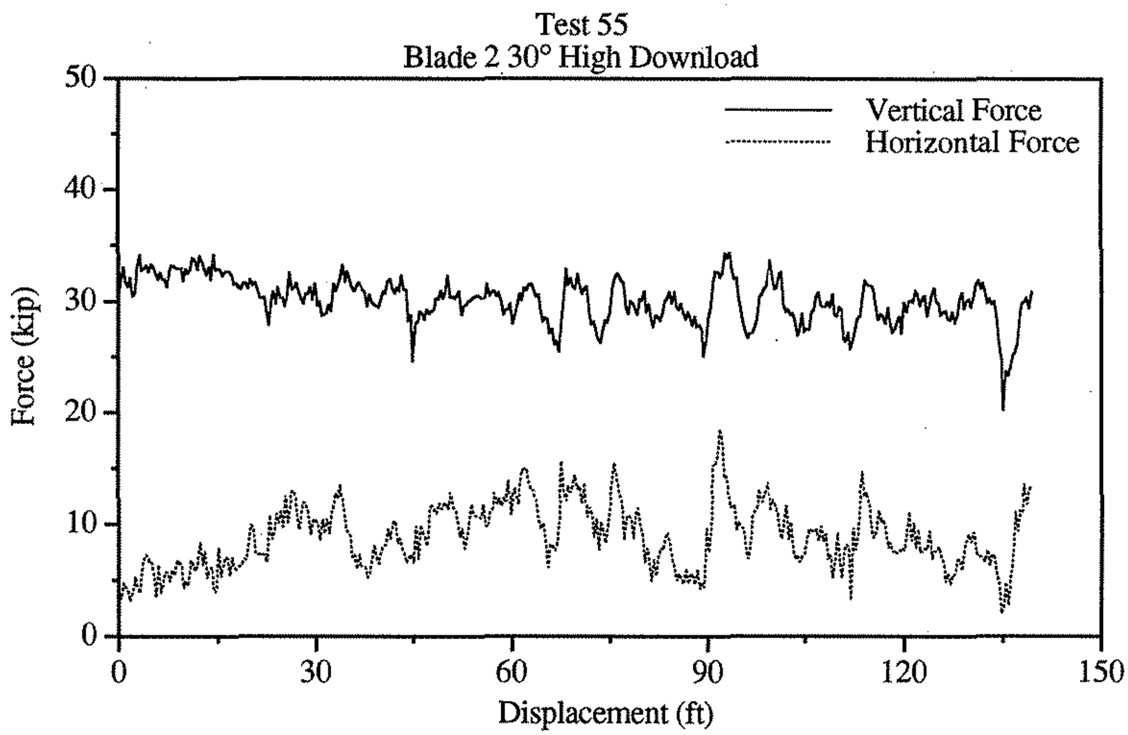

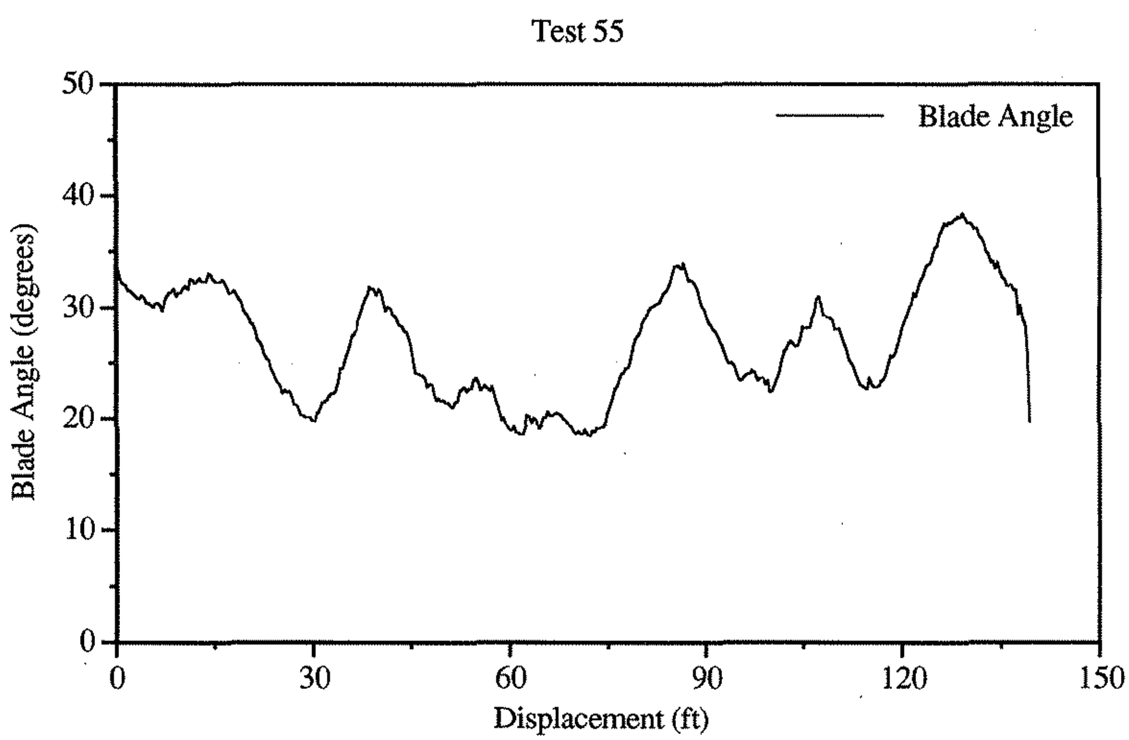

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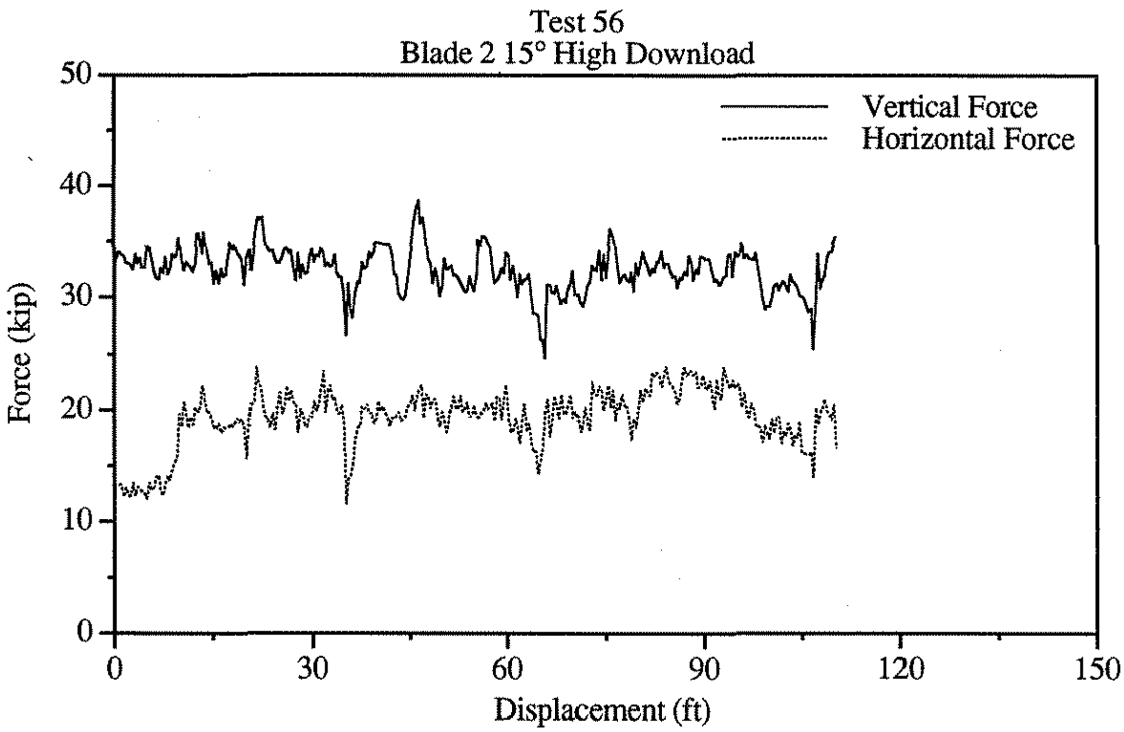

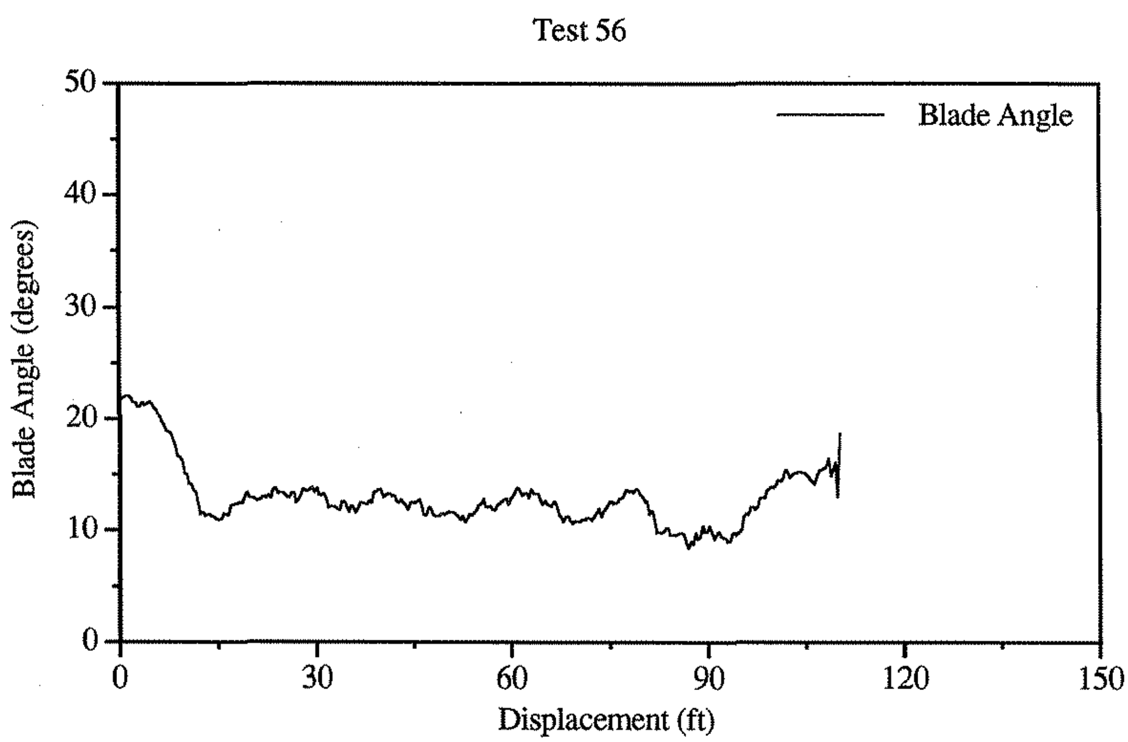

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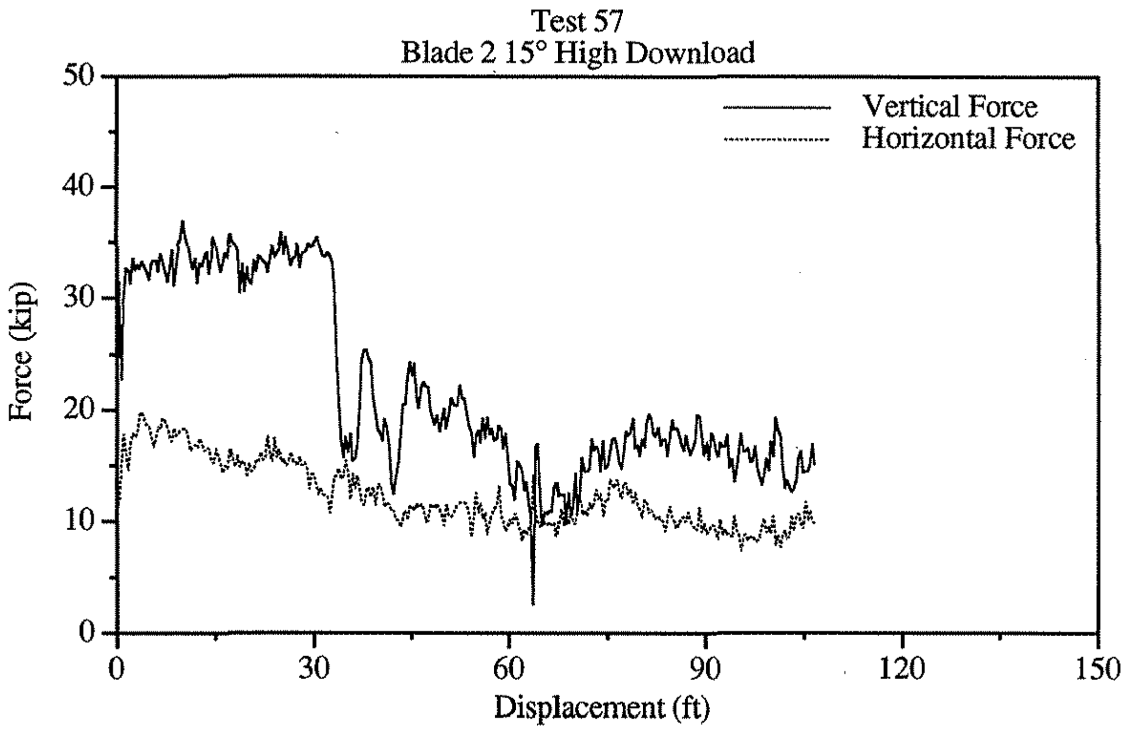

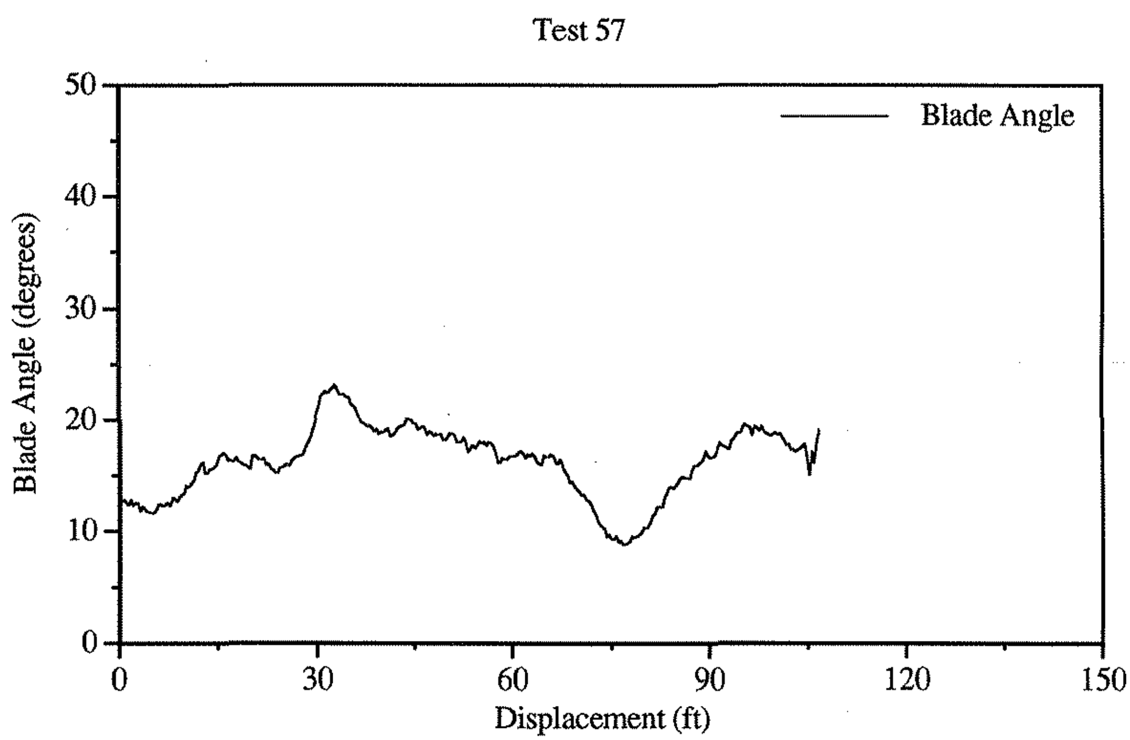

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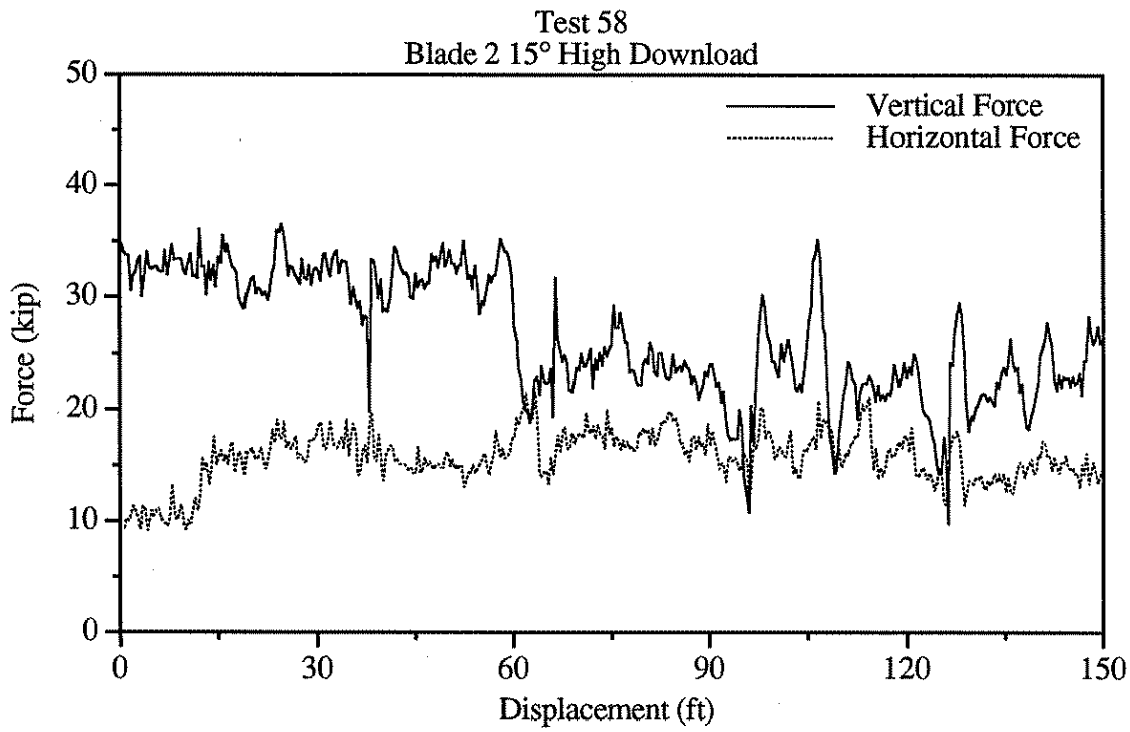

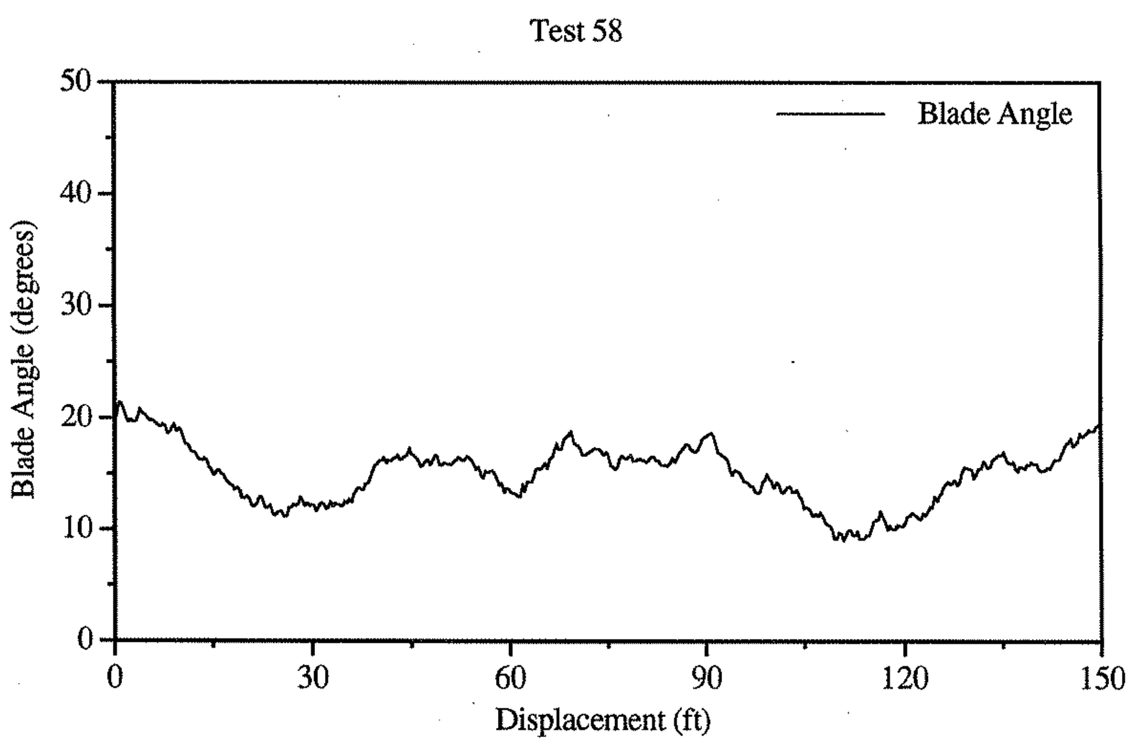

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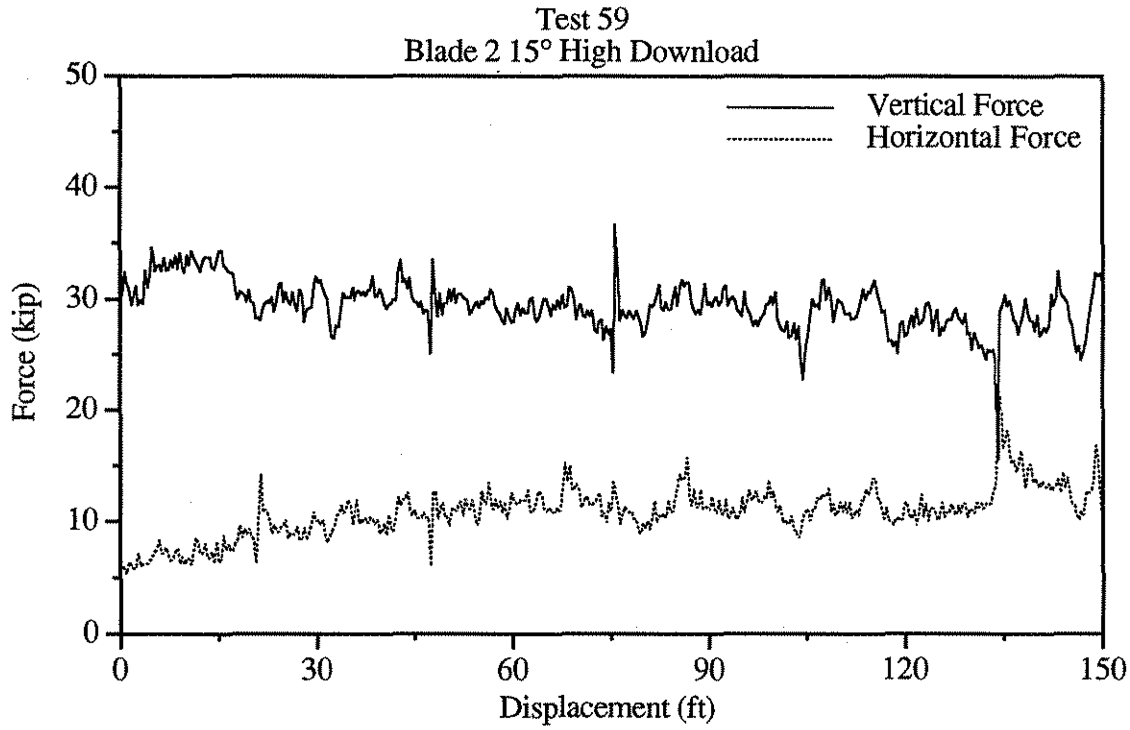

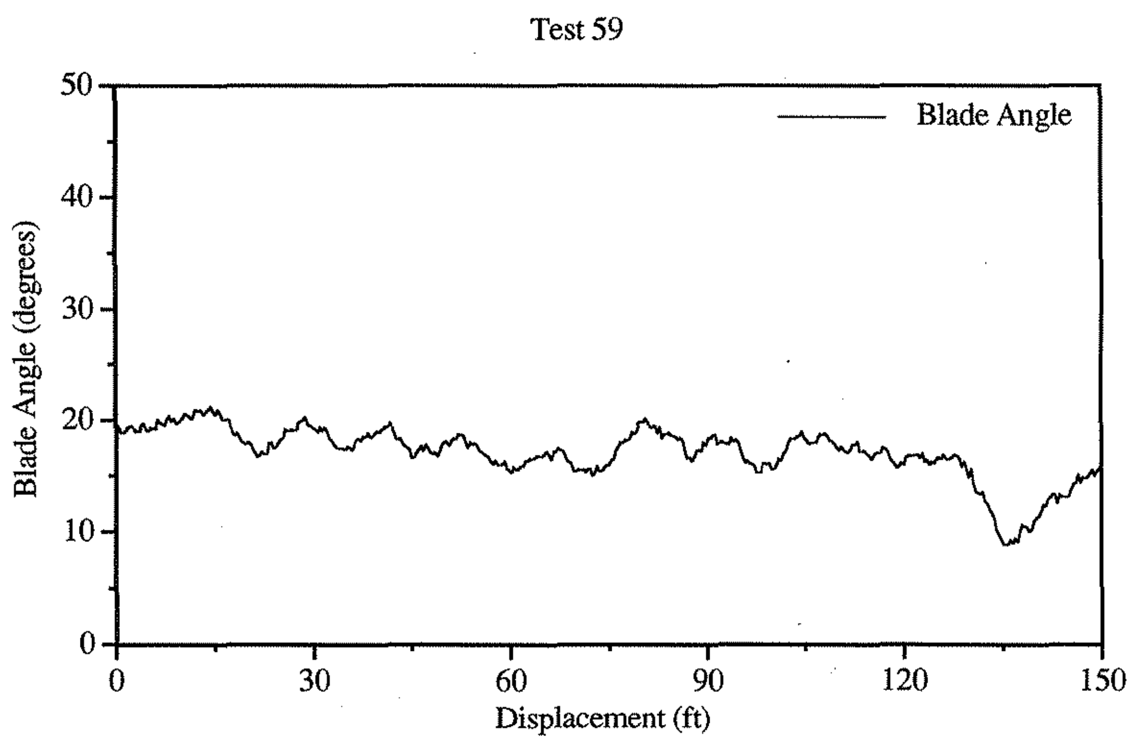

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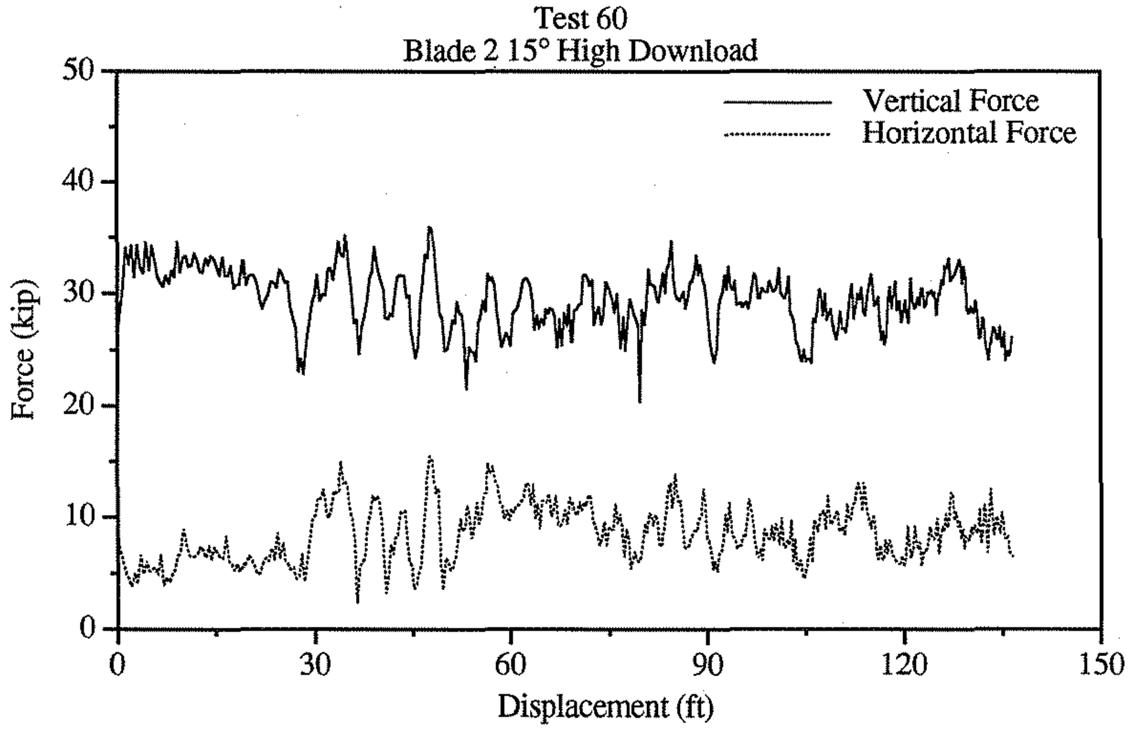

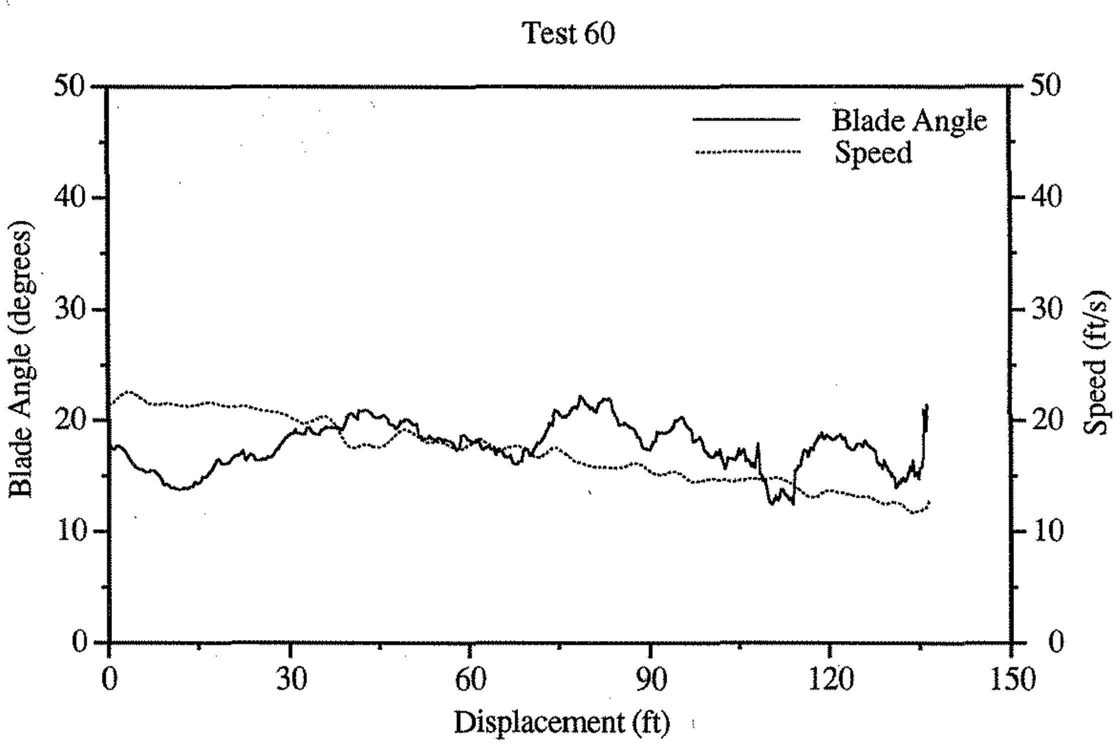

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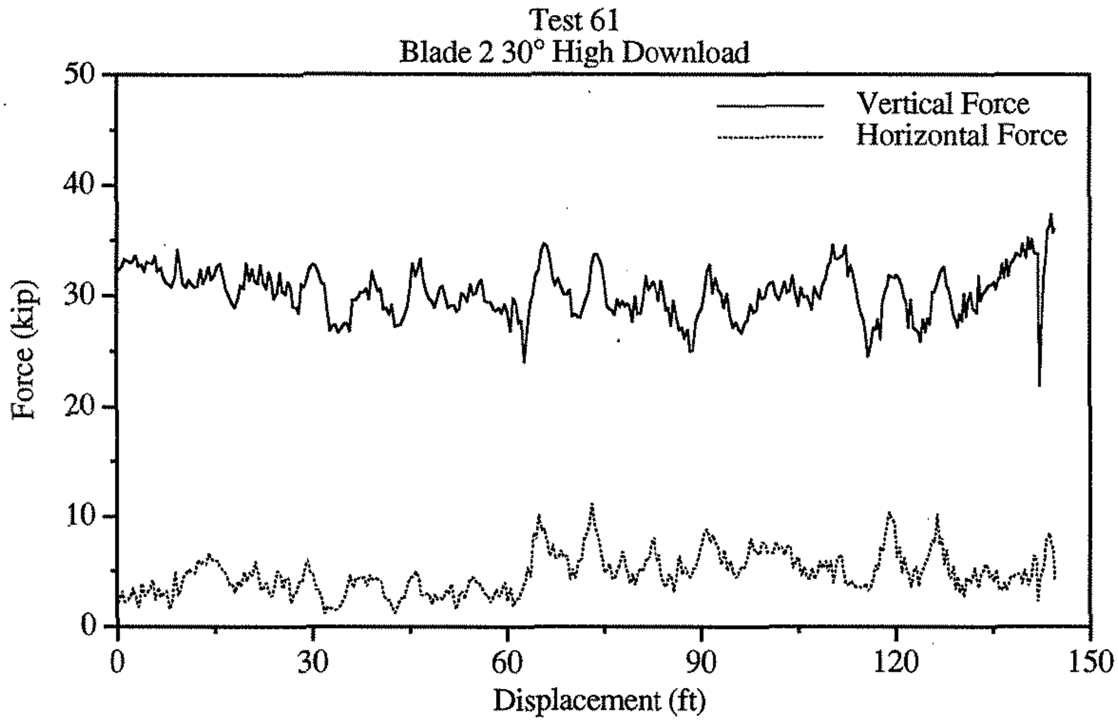

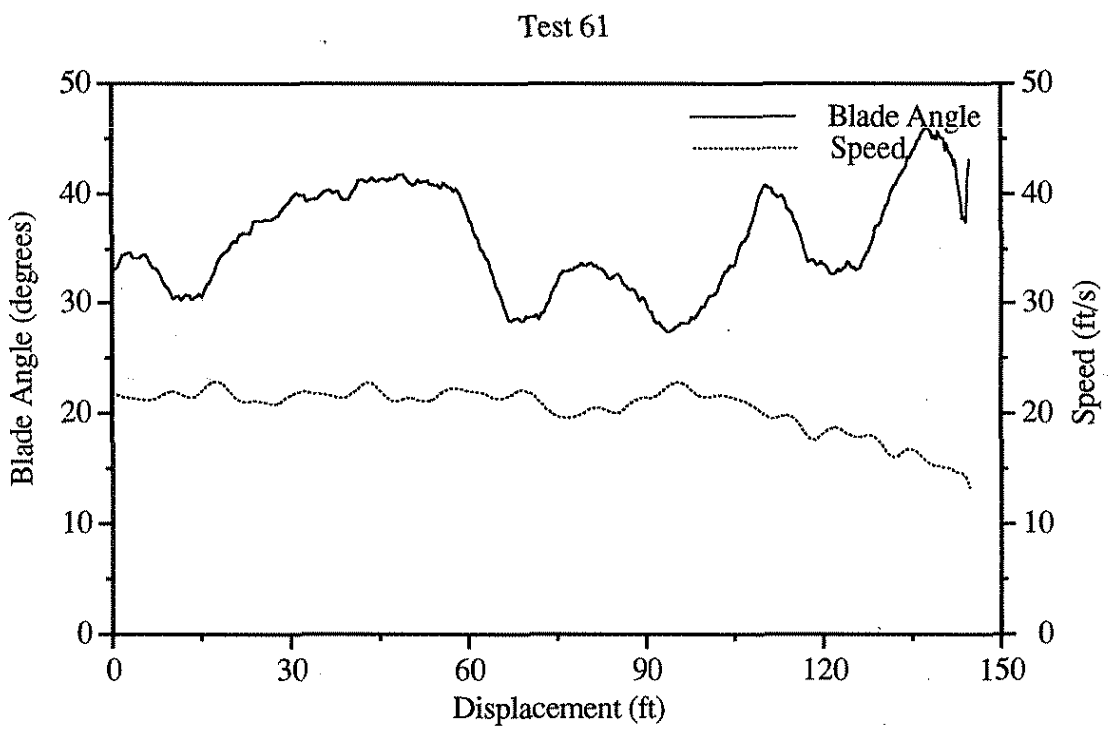

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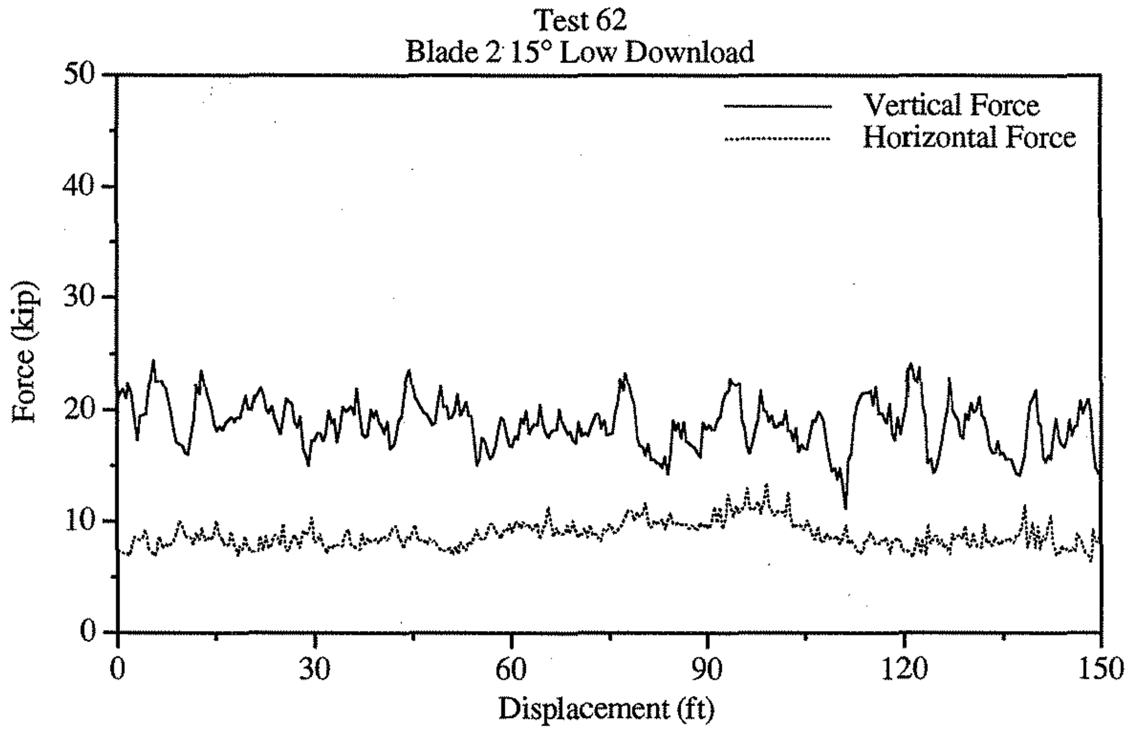

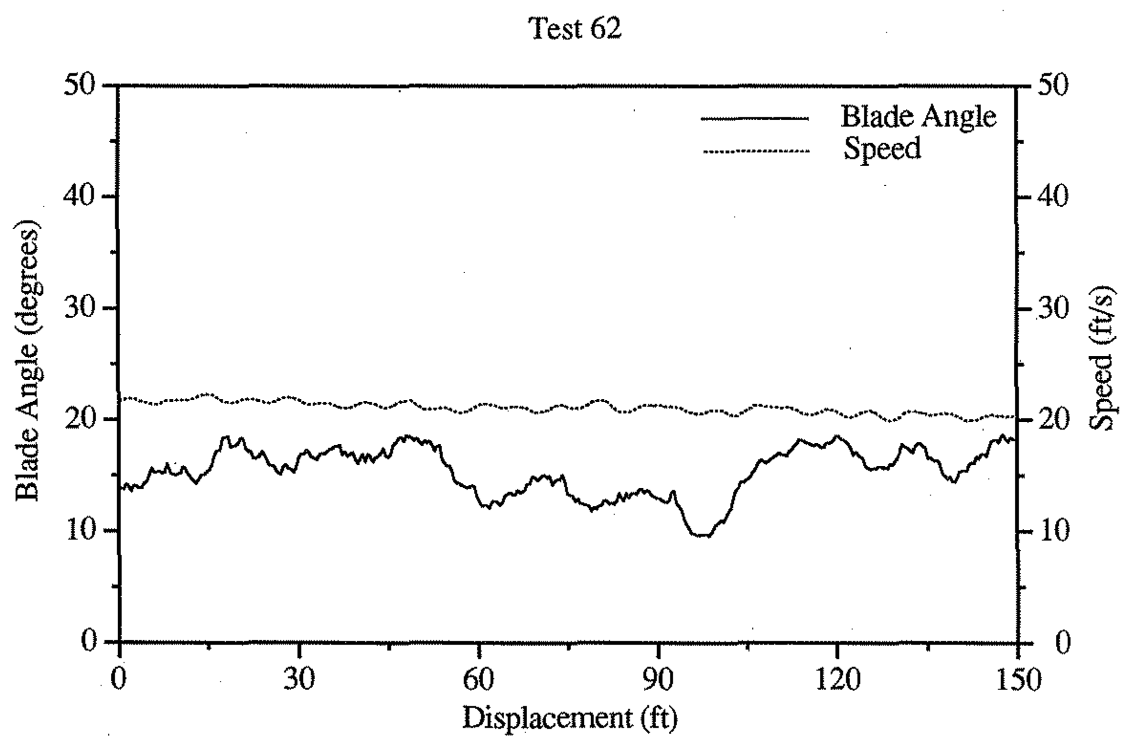

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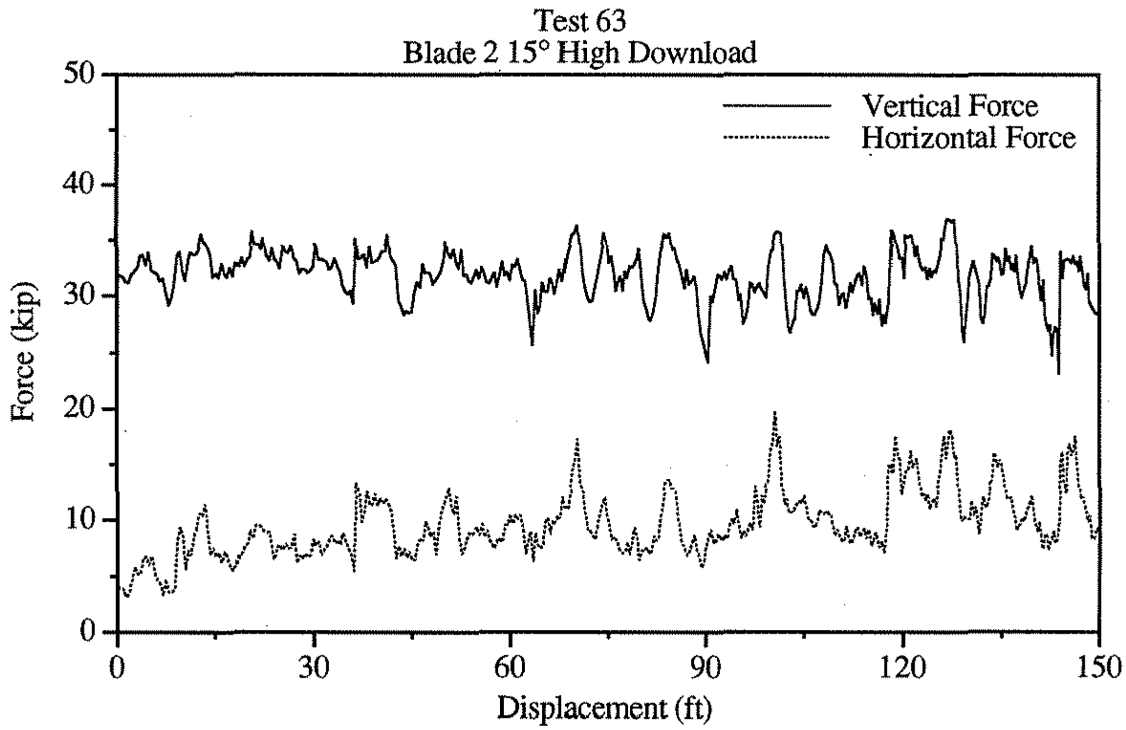


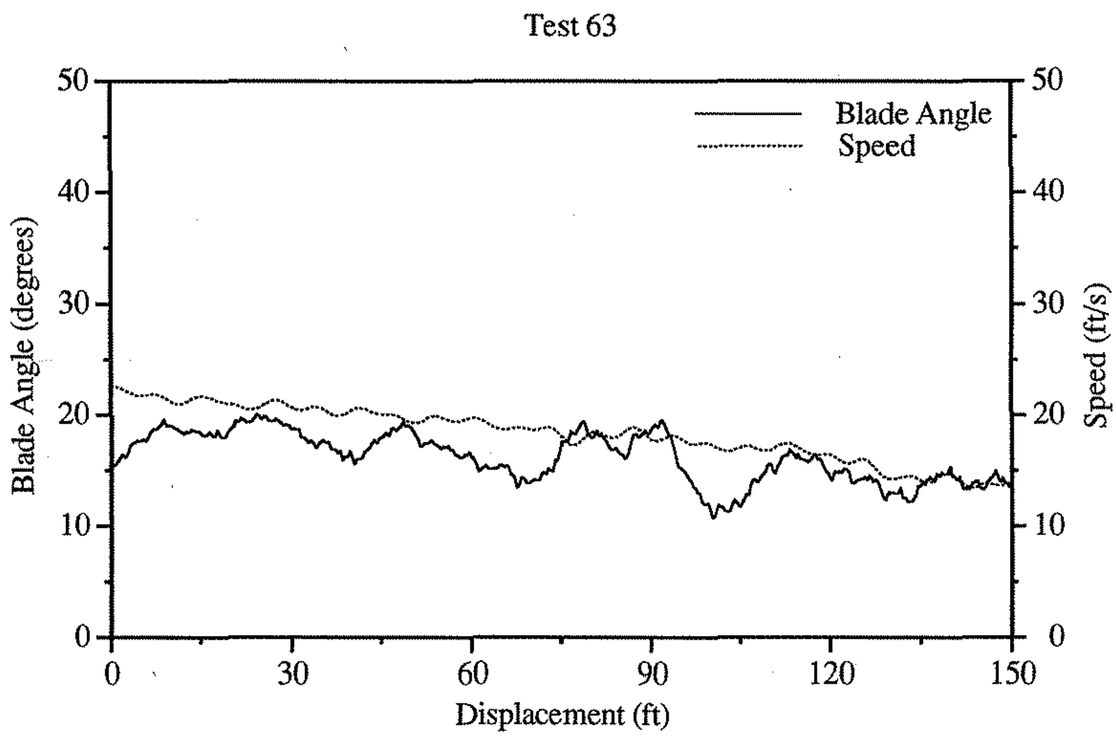
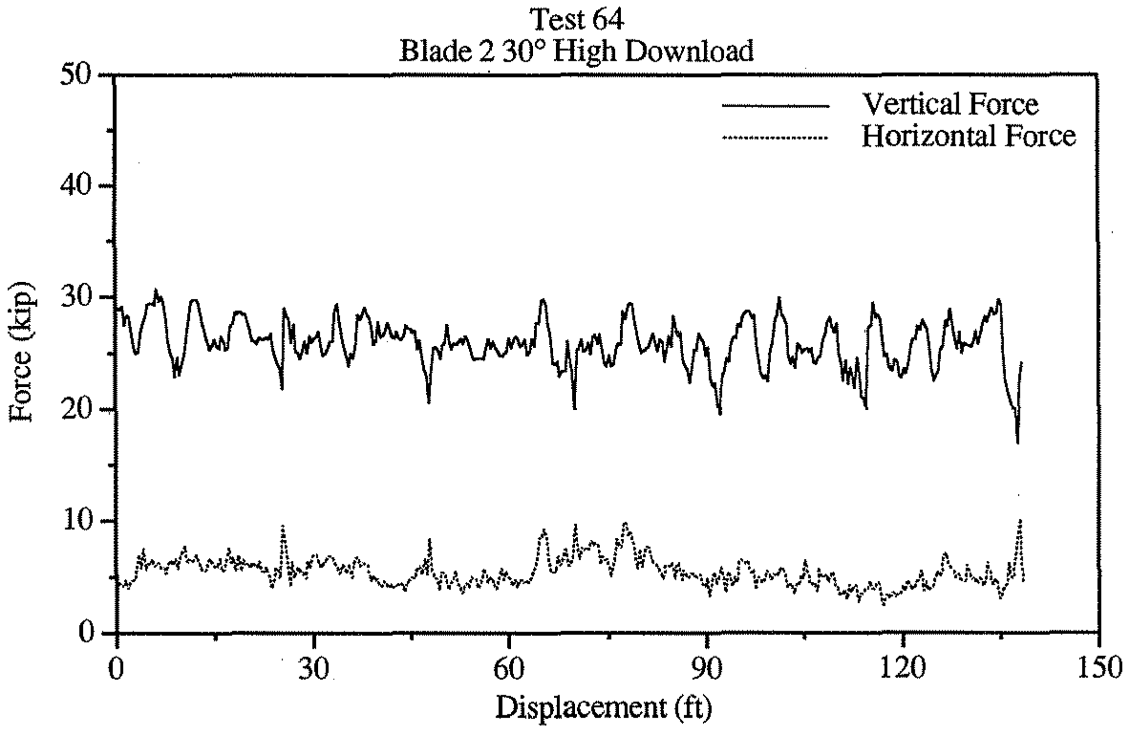


Figure B63. Graphical results of test 63.



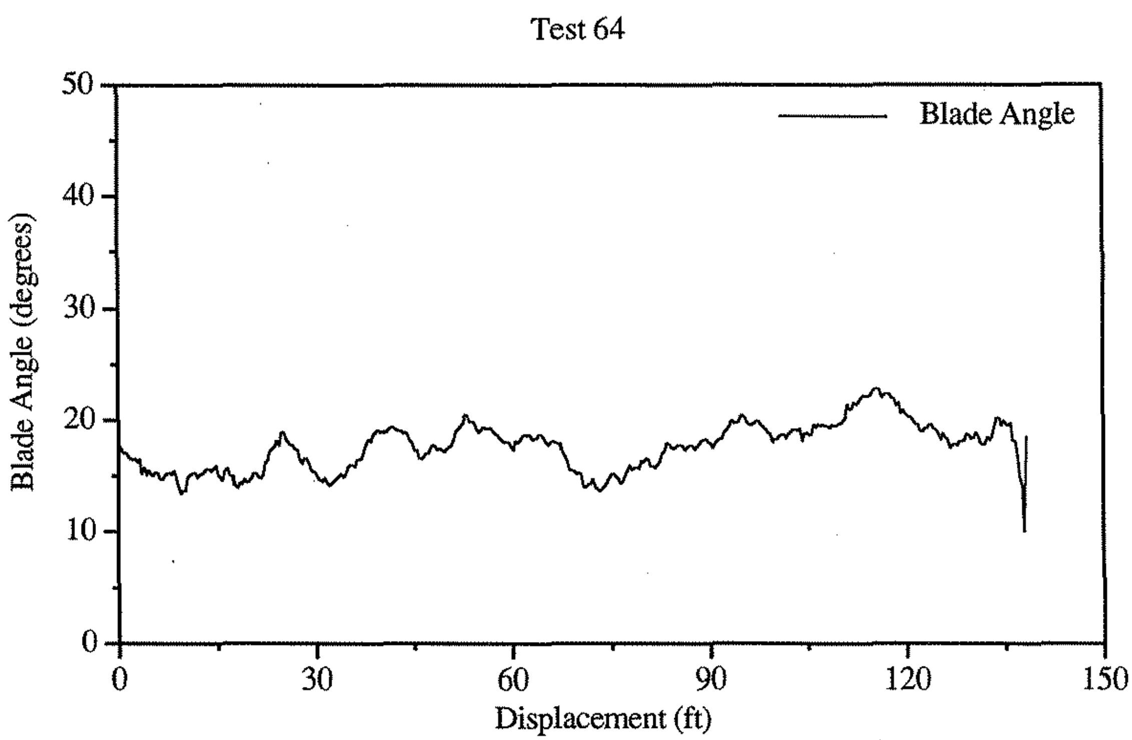
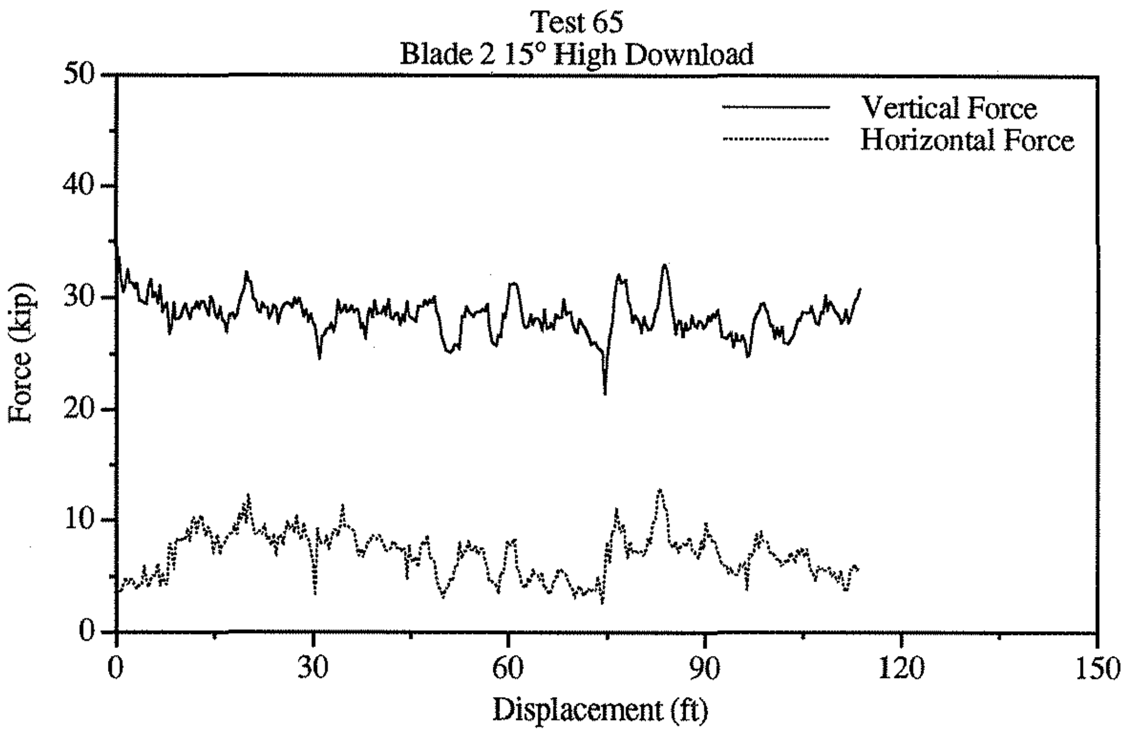


Figure B64. Graphical results of test 64.



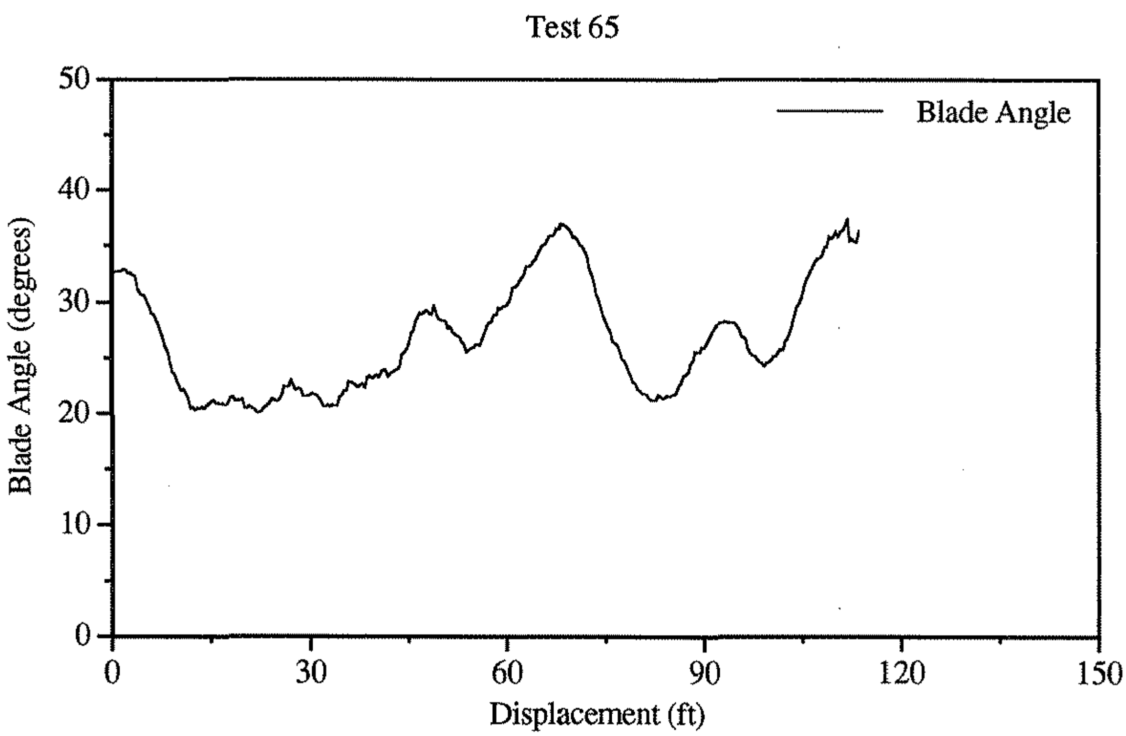


Figure B65. Graphical results of test 65.