Final Report

Evaluation of the Altimeter for Measuring Bridge Deflections

FDOT Contract No. BDK83 TWO #988-05
FSU Project ID 028434

Submitted to:

Florida Department of Transportation
Research Center
605 Suwannee Street, MS 30
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November 10, 2011

Disclaimer

Prepared in cooperation with the State of Florida Department of Transportation.

SI* (Modern Metric) Conversion Factors

*Approximate conversions **to** SI units*

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	squareinches	645.2	square millimeters	mm^2
ft^2	squarefeet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	Megagrams (or metric ton)	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square	6.89	kilopascals	kPa

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

SI* (Modern Metric) Conversion Factors

Approximate conversions ***from*** *SI units*

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Evaluation of the Altimeter for Measuring Bridge Deflections	5. Report Date November 10, 2011
	6. Performing Organization Code
7. Author(s) S. Jung, M. D. Roddenberry, and A. Stilson	8. Performing Organization Report No. FSU Project ID 028434
9. Performing Organization Name and Address FAMU-FSU College of Engineering Department of Civil and Environmental Engineering 2525 Pottsdamer St. Rm. 129 Tallahassee, FL 32310-6046	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. BDK83 TWO #988-05
12. Sponsoring Agency Name and Address Florida Department of Transportation Research Center 605 Suwannee Street, MS 30 Tallahassee, FL 32399-0450	13. Type of Report and Period Covered Final Report May 2010 – August 2011
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The Florida Department of Transportation frequently measures the displacements of bridges to monitor their condition or perform load ratings. Due to the limitations and cost associated with conventional sensors, a low-cost, rugged altimeter was evaluated as an alternative displacement sensor. The tested altimeter is the ZipLevel Pro 2000 high-precision model manufactured by Technidea Corporation.

A brief guide on using the device and extensive testing results are presented in this report. The testing results include verification of the accuracy of the device, and the effects of sloped conditions, temperature, wind, vibration, and localized pressure applied on the sensor cable.

The device is expected to measure the displacement with a ±0.02” (0.508mm) accuracy provided that the sensor cable remains relatively straight and lies on a flat surface, and that care is taken to minimize the effects of the pressure, temperature and wind. Error due to the rotation of the measurement module was 4.5% for a rotation of 44.3°. The error was much higher when the base module was rotated. The error for the base module was 10.6% after a rotation of 44.3°. Distributed loading of 80 lb/ft applied on the sensor cable decreased the displacement reading up to 0.33” (8.38mm). If the device was calibrated at a certain temperature but is used at a different temperature, the measurement will have errors. The error will be 0.03” (0.762mm) or less if the temperature difference is 10°F or less. This error exponentially increases if the temperature difference is greater. For example, a 20°F difference will cause close to a 1/4" (6.35mm) error. When the sensor cable is subjected to a 20 mph wind, the measurements may have up to 20% error for the displacement up to 0.5”, and 10% error for the displacement greater than 0.5”.

17. Key Word Bridge deflection, altimeter, sensor	18. Distribution Statement No restrictions.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 44	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Acknowledgements

The authors would like to thank the Florida Department of Transportation (FDOT) for providing the funding for this research. The authors are grateful to the FDOT Structures Research Laboratory crew for their help and for performing the tests that were the basis for this study.

Executive Summary

The Florida Department of Transportation frequently measures the displacements of bridges to monitor their condition or perform load ratings. Due to the limitations and the cost associated with conventional sensors, a low-cost, rugged altimeter was evaluated as an alternative displacement sensor. The tested altimeter is the ZipLevel Pro 2000 high-precision model manufactured by Technidea Corporation.

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The device is expected to measure the displacement with a ±0.02” (0.508mm) accuracy provided that the sensor cable remains relatively straight and lies on a flat surface, and that care is taken to minimize the effects of the pressure, the temperature and wind. Error due to the rotation of the measurement module was 4.5% for a rotation of 44.3°. The error was much higher when the base module was rotated. The error for the base module was 10.6% after a rotation of 44.3°. Distributed loading of 80 lb/ft applied on the sensor cable decreased the displacement reading up to 0.33” (8.38mm). If the device was calibrated at a certain temperature but is used at a different temperature, the measurement will have errors. The error will be 0.03” (0.762mm) or less if the temperature difference is 10°F or less. This error exponentially increases if the temperature difference is greater. For example, a 20°F difference will cause close to a 1/4" (6.35mm) error. When the sensor cable is subjected to a 20 mph wind, the measurements may have up to 20% error for the displacement up to 0.5”, and 10% error for the displacement greater than 0.5”.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Background

The Florida Department of Transportation (FDOT) frequently measures the displacements of bridges to monitor their condition or perform load ratings. Conventional sensors such as LVDTs require a fixed reference point that is often difficult to access. Other technologies such as laser scanners exist, but they may not be practical to implement due to their high cost.

As an alternative, the FDOT Structures Research Center identified a low-cost, rugged altimeter that could potentially be used as a displacement sensor. That altimeter is the ZipLevel Pro 2000 high-precision model manufactured by Technidea Corporation. The device was originally designed for surveying applications with much lower precision. The company later created a high-precision model to address the demand of the customers who needed higher precision. Its advertised specification is 0.005" (0.127mm) precision up to a distance of 200' (60m) and a maximum relief of 4' (1.2m) between base station and measurement module.

Figure 1. ZipLevel Pro 2000 High-Precision Model

1.2. Objectives

The overall goal of the project is to test the ZipLevel Pro High-Precision Model in various conditions that reflect experiments that the FDOT conducts. Specific objectives are: first, to test the performance of the altimeter rigorously by collecting and analyzing the data in various conditions, including the effect of challenging environmental conditions such as wind, vibration, or the temperature; and second, to develop a guide including calibration, data collection, and downloading of the data to a computer.

2. Guide on Using the Device

2.1. To Obtain the Vertical Displacement

2.1.1. Zeroing

Whenever the device is used in a new site, it requires "zeroing" which sets the current location of the measurement module as zero-elevation. All subsequent measurements will report the difference in elevation, which may be used to measure the displacement.

The steps for the zeroing are shown below.

1) Place the device on a flat surface.
2) Press and hold the button located in the middle of the device with one hand and pull up on the lower door with the other hand, to access the measurement module.

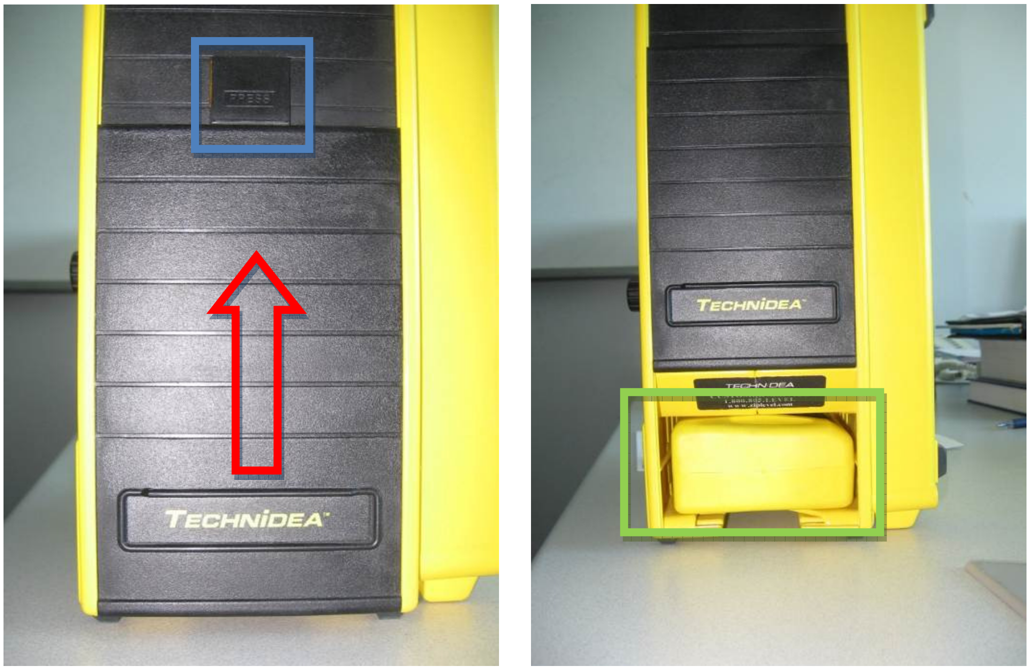


Figure 2. To access the measurement module

3) Carefully take out the measurement module and lay face up exposing the screen. Then, momentarily press the ON/OFF key to turn the device on.
4) Press and hold ZERO for 2 seconds to set the current location as the reference. Wait until the unit makes one beeping sound.

Figure 3. The measurement module of the ZipLevel Pro 2000

2.1.2. To read the displacement

In order to read displacements, simply move the measurement module to a different elevation. It will display the difference in elevation from the reference point to the new point, which can be used to measure the displacement. Note that for the high precision model, the number shown in the display should be divided by 10 to obtain the true reading.

Although the manufacturer's advertised precision is 0.005" (0.127mm), we found that the device is very sensitive to the arrangement of the cable. When we artificially introduced bending of the cable, the error was as high as 0.05" (1.27mm). When the cable arrangement was straight and flat, an error of ±0.01" (0.254mm) was typical. Therefore, in ideal conditions, the expected accuracy is approximately ±0.01" (0.254mm). Results from further experiments will be explained in later sections.

2.2. Calibration Due to the Temperature Change

In many cases zeroing is the only necessary initialization before using the device. However, additional calibration must be done when there has been significant change in the temperature. According to the manual, the device needs to be calibrated again "when there has been a temperature change of 36°F (20°C) or greater since its last calibration". However, our recommendation is to re-calibrate the device when there has been 10°F or greater change (see section 4.2).

The steps for the calibration due to the temperature change are shown below.

1) Carefully place the device on a level surface on its back.

Figure 4. Orientation of the ZipLevel Pro when calibrating for the temperature change

2) Obtain the Calibration bolt located in the storage area behind the base unit door and screw into the bottom of the measurement module until snug.

Figure 5. Setting up the measurement module for the temperature calibration

3) Place the measurement module on the flat surface as shown below. Turn on the device, and then press and hold the CAL key for two seconds and then release.

Figure 6. Initial orientation of the measurement module when calibrating for the temperature change

4) When the display flashes [0], press the CAL key momentarily. The display will then flash [48] at which time the measurement module should be raised 4.8 inches. (The unit must not be raised until [48] flashes.) Balance the measurement module on the Calibration Bolt and hold it steady against a flat surface so that the measurement module is completely level.

Figure 7. Temperature calibration: to raise the module against a flat surface

5) After raising the module 4.8 inches, press the CAL button once more. When the display stops flashing and shows 4.8 inches, Calibration is complete. Note that the displayed number should be divided by 10 in order to obtain the true reading for the high precision model.

Figure 8. Completion of the temperature calibration

2.3. To Record and Download the Data

2.3.1. Record

To record the measured data, the unit first should enter the recording mode. Press and hold the REC & MARK keys for 2 seconds. The word “REC” will appear on the left side of the display. Press the HOLD key momentarily to store the measurement of the current location. Wait until a series of beeps stop, and then move the measurement module to the next location.

To exit the recording mode, press and hold the REC & MARK keys for 2 seconds.

2.3.2. Inspect

The user may inspect the recorded data before downloading it to a computer. Press and hold CAL & REC keys simultaneously for 2 seconds to enter/exit the inspect mode. Use MARK/REC keys to cycle through data one by one. Use CAL/HOLD keys to sequence up or down in 10 point increments.

2.3.3. Dump

Dump function allows the user to download the data to a computer. The steps are shown below.

1) Slide the bottom door up completely to expose the button behind.

Figure 9. To access the serial-link cable from the top compartment of the device

2) Push the button and pull both doors downward to expose the top compartment where the serial-link cable is located.
3) Remove the cable and attach it from the measurement module to a computing device.
4) Execute the “Link” software provided by the manufacturer. Momentarily press CAL & REC keys simultaneously to dump the data to the computer. The functions of the software are limited and straightforward (such as saving data to a file, displaying graphs, etc.) so instructions are not provided here.

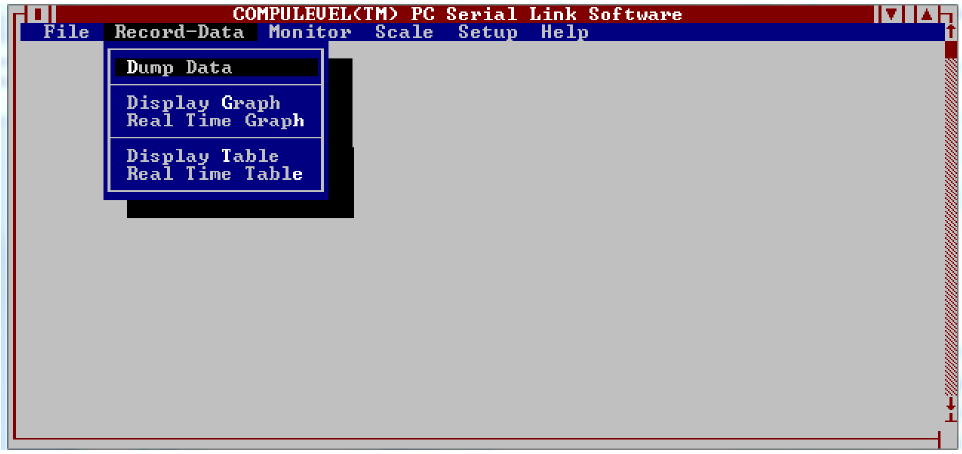


Figure 10. Link software provided by the manufacturer

2.3.4. Real-time monitoring and recording

The software has an option to record the data to a file in real time. Since the recording is done in fixed sampling frequency, this option can potentially be used to synchronize the data obtained from the device and the data from other sensors. However, the synchronization needs to be done after completing the experiment, because the data from the device is stored to an external file.

In order to use this function, press ON/OFF & CAL for two seconds. From the software, select “Monitor” from the menu. Check “Log Monitor Data To File” option to store the monitored data with the frequency specified in “Log Interval”.

3. Verification of the Accuracy in Indoor Conditions

3.1. Overview of Experiments

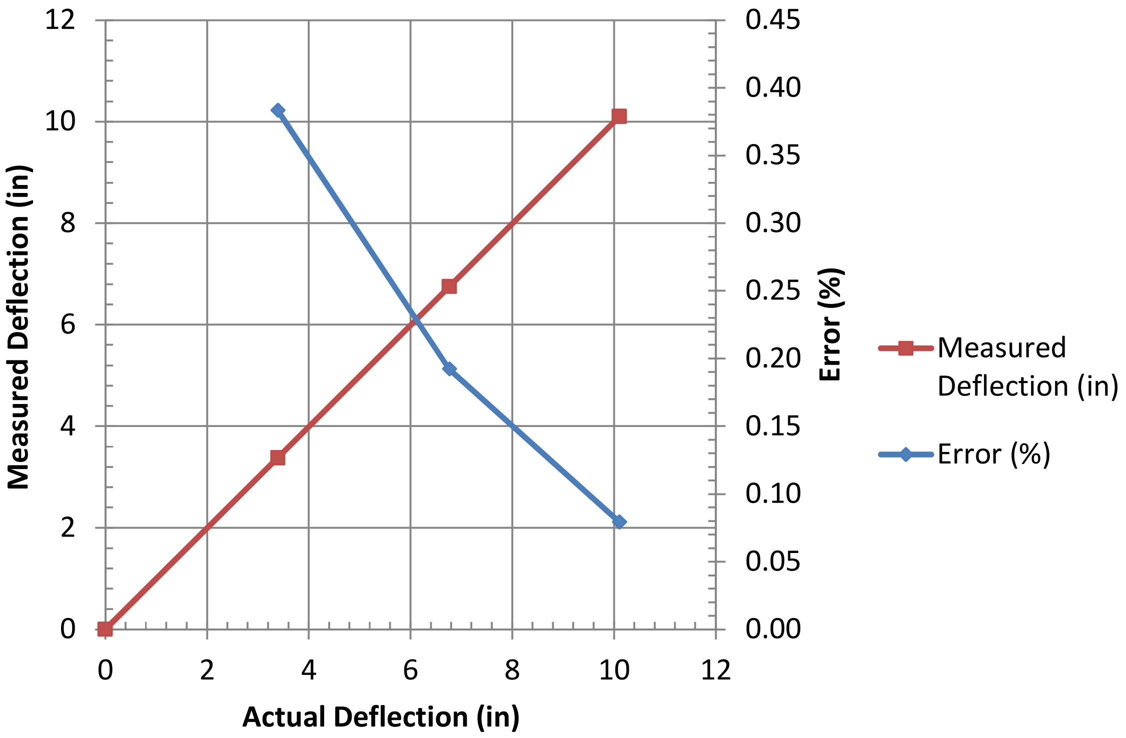
The purpose of each experiment in this section is to verify the accuracy of the device operating in ideal indoor conditions. This category includes the testing of the altimeter in response to angled conditions, and comparison to other sensors in two different lab experiments.

3.2. Test A: Flat Surface

The pictures below depict the flat surface testing for both large displacement (left) and small displacement (right) scenarios. Three 3 inch thick wood blocks were used to test large displacements while twelve 1/8 inch thick steel plates were used to test small displacements. For the exact increment of the thickness, refer to the first columns of Table 1 and Table 2 in the Appendix. The entire measurement module rests on a 30.5 inch 4”x4” wood cross member and is lifted in fixed increments.

Figure 11. Set up for Test A: flat surface

The results are summarized in the figures below. All raw data is presented in the Appendix. The error for the large displacement test was less than 0.4%. For the small displacement test, the error was less than 2.5% except for 1/8” displacement, in which the error was 7.4%.



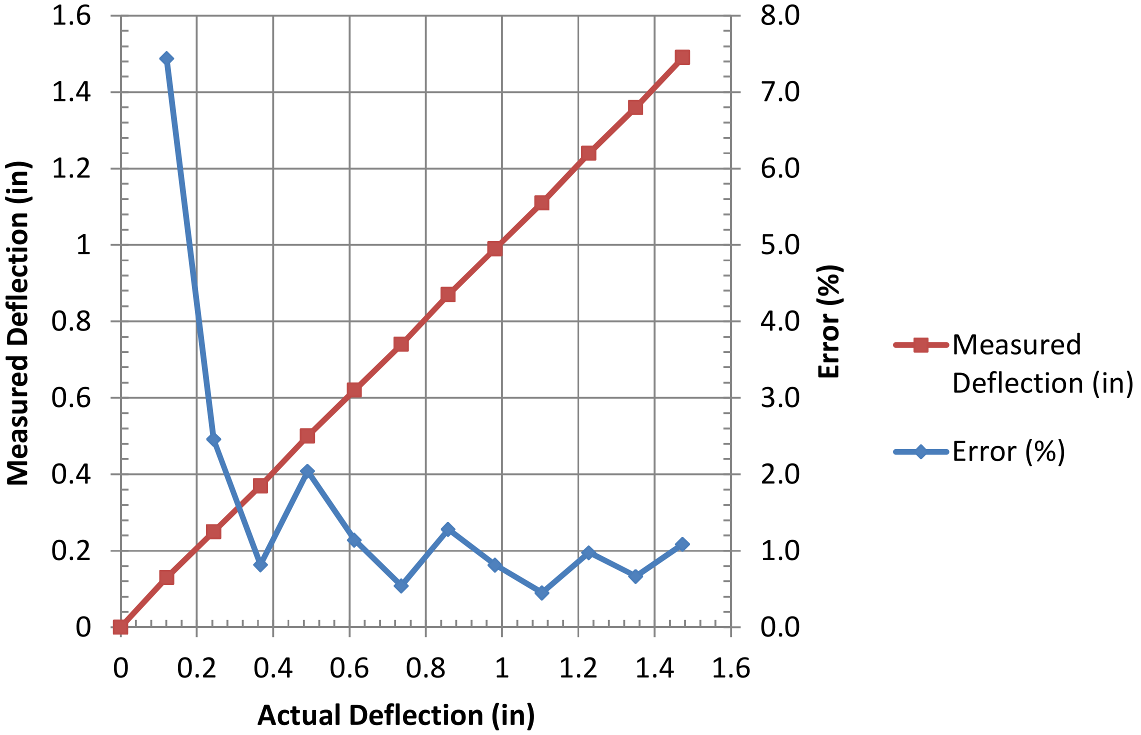


Figure 12. Test A: flat surface results. Top: large displacement, Bottom: small displacement

3.3. Test Set B: Angled Surface

Test Set B contains Tests B1, B2, and B3. In Test B1 (Figure 13, left picture), the measurement module is raised at a fixed angle while the base module remains level. In Test B2 (Figure 13, right picture), the base module is raised at a fixed angle while the measurement module remains level. In Test B3 (not pictured), both the measurement module and the base module are raised at a fixed angle.

Figure 13. Test B1 (left): the measurement module is raised at a fixed angle, Test B2 (right): the base module is raised at a fixed angle.

Experiments for each case were conducted for 5°, 10°, and 15° angles. Results are presented for the worst performing case for each test. Error in large displacement testing was not significant. Error in small displacement testing was typically less than 5%. However, the error could become much higher when the displacement was less than 1/4" — 26.8% for Test B1, 21.2% for Test B2, and 5.7% Test B3. The error appeared to be the result of fluctuations in the readings as explained in section 2.1.2. However, it was unclear if the small fluctuations were increased due to the skewed angle.

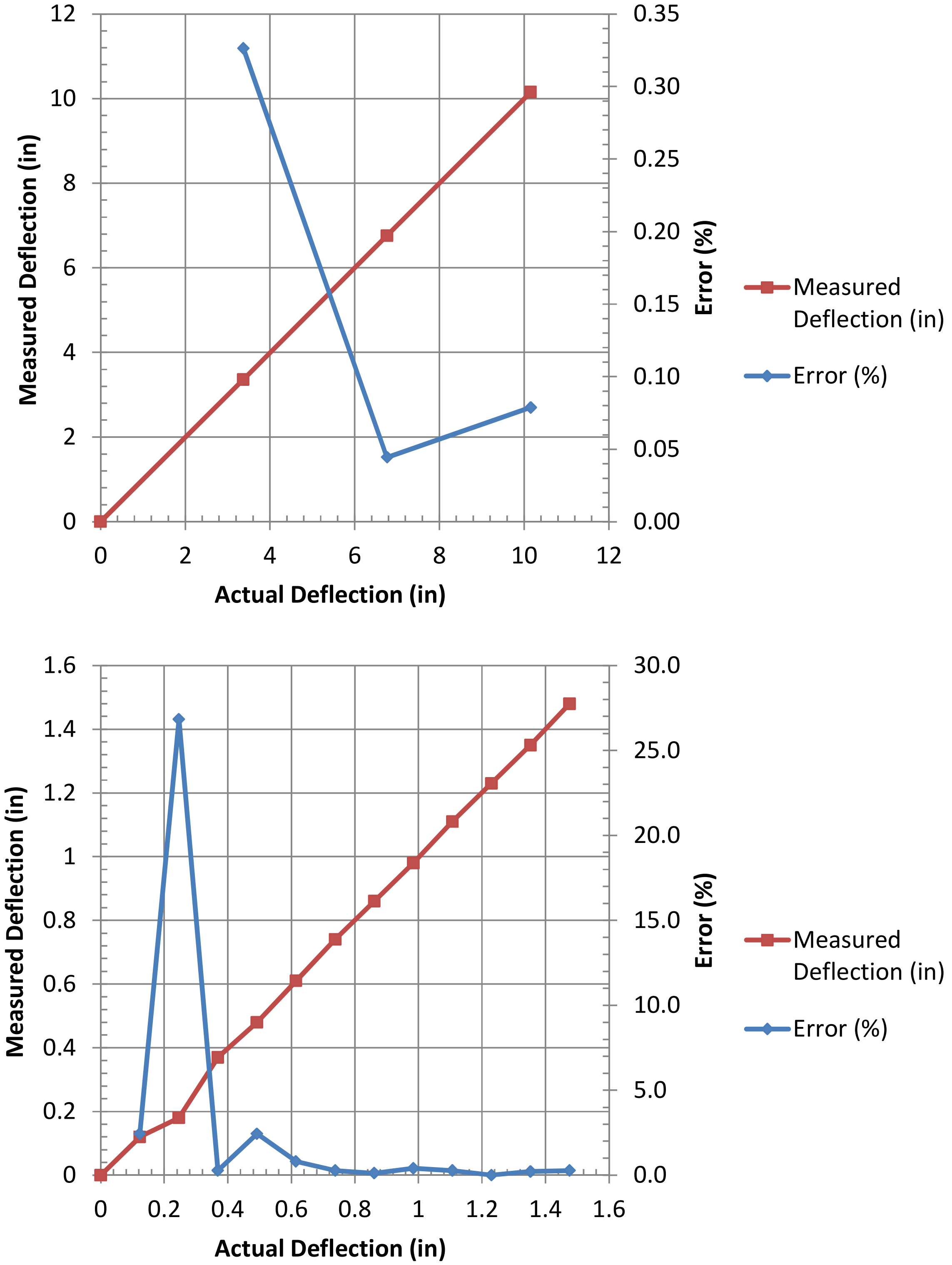
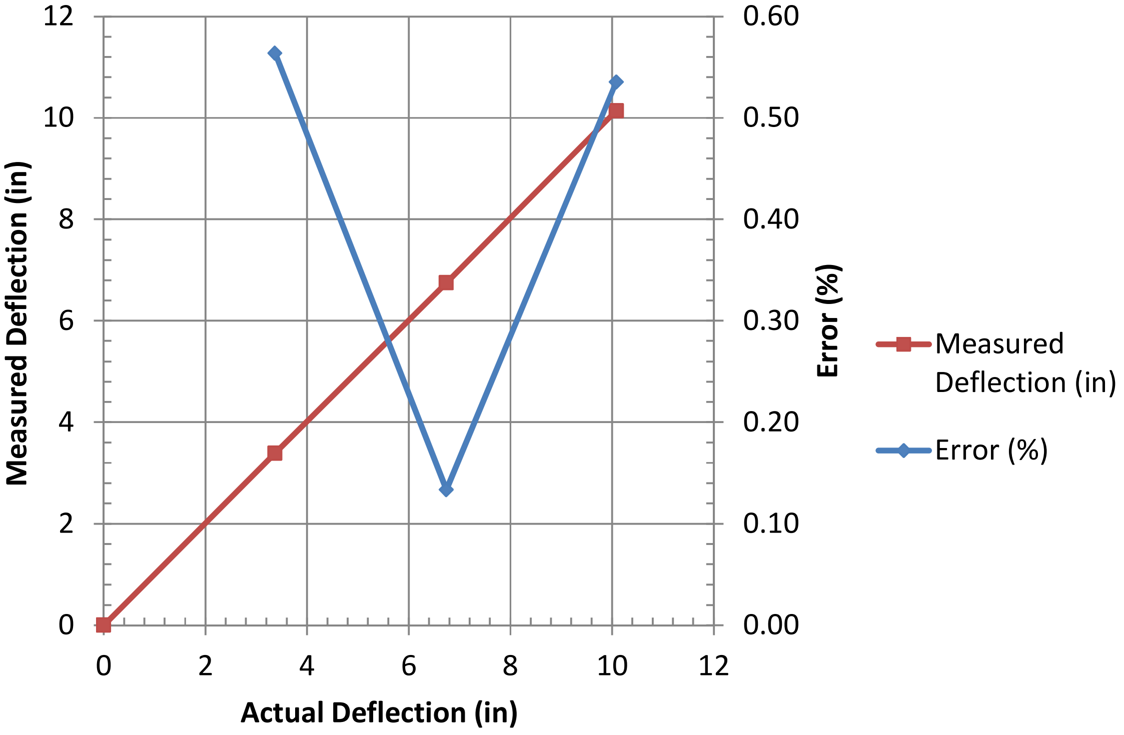


Figure 14. Test B1 results. Top: large displacement (measurement module at 5°), Bottom: small displacement (measurement module at 5°).



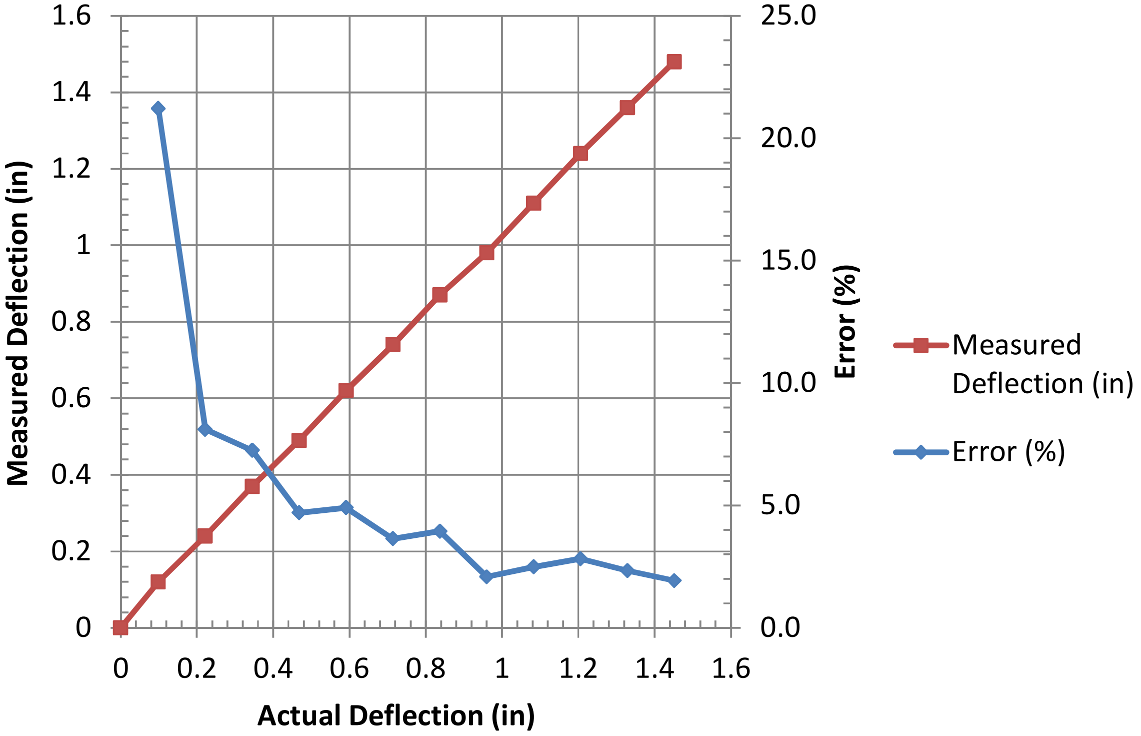
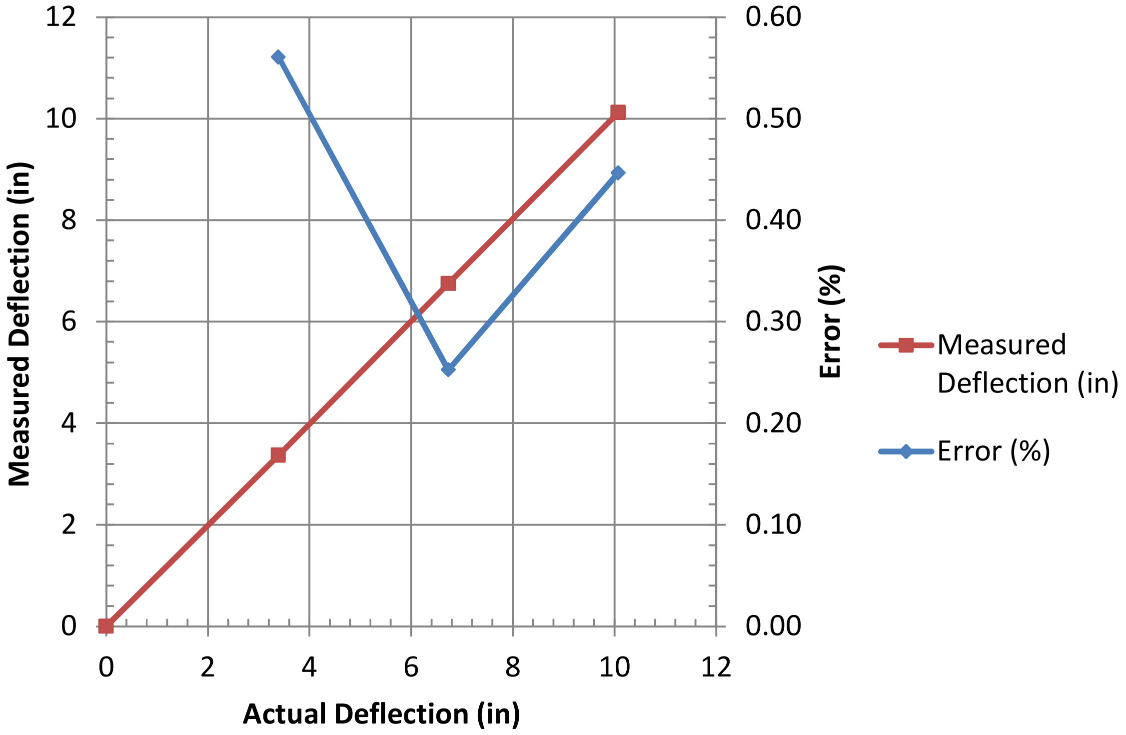


Figure 15. Test B2 results. Top: large displacement (base module at 5°), Bottom: small displacement (base module at 5°).



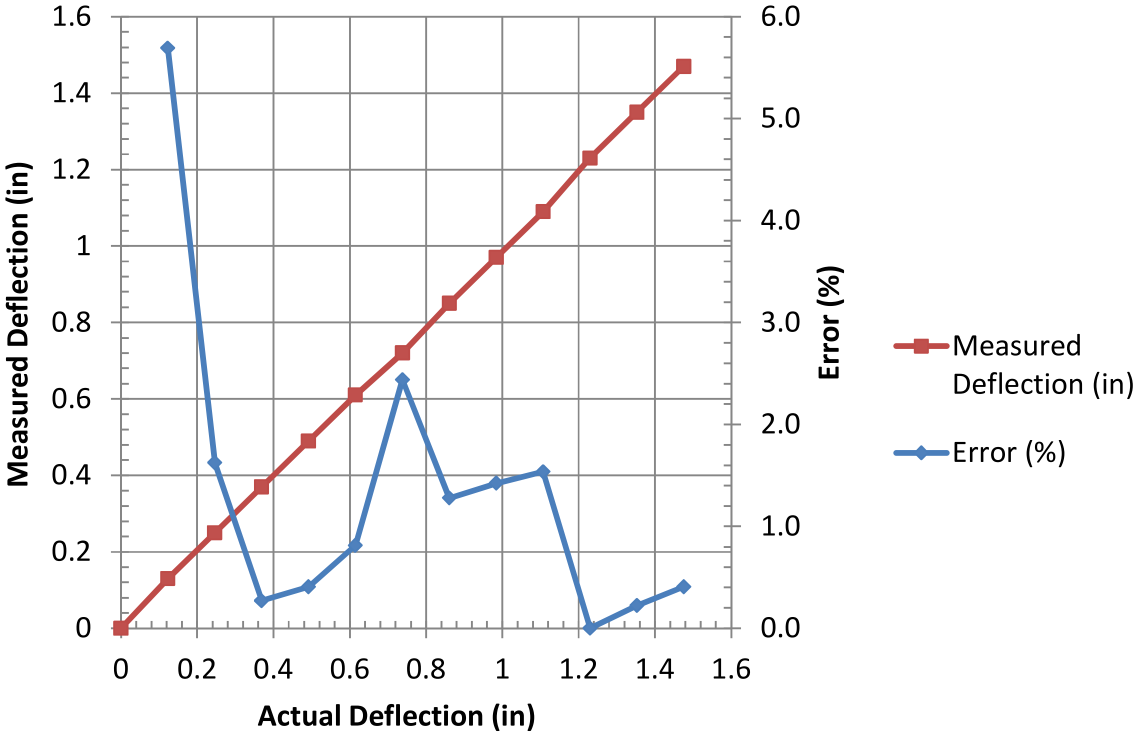


Figure 16. Test B3 results. Top: large displacement (10° for both the base and the measurement module), Bottom: small displacement (10° for both the base and the measurement module)

3.4. Test C: Rotational Testing

In Test C rotations of the measurement module and the base module were simulated by using three blocks as shown below. One block (triangular block only) causes 17.0° rotations. Two blocks cause 29.7° rotations. Three blocks cause 44.3° rotations. When the measurement module was being rotated and elevated, the base module remained at a fixed location. The same was true when the base module was being rotated and elevated — the measurement module remained at a fixed location.

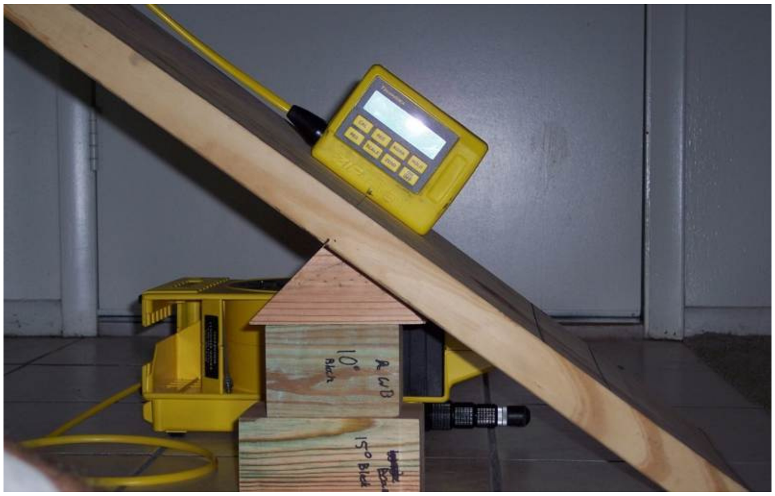
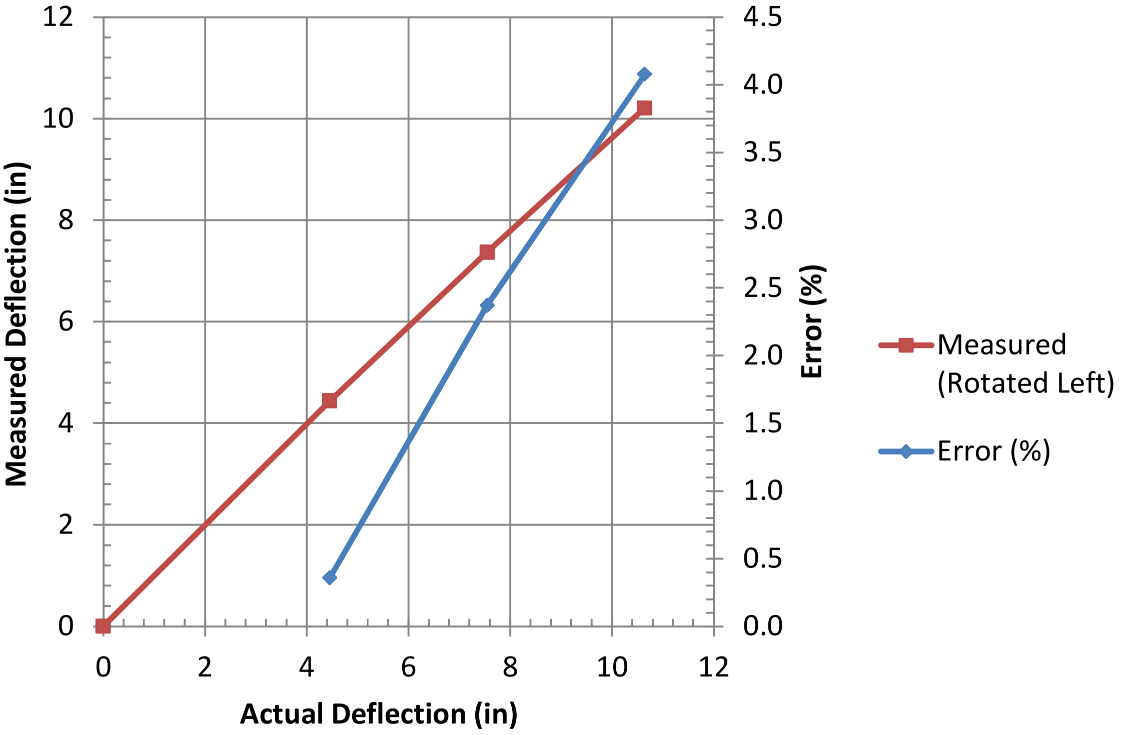


Figure 17. Test C: rotational testing set-up (rotated right). The base module was rotated similarly.

Error due to the rotation of the measurement module was 4.5% for a rotation of 44.3°. The error was much higher when the base module was rotated. The error for the base module was 10.6% after a rotation of 44.3°. For the rotations of 30° or less of the base module, the error was within 5%.



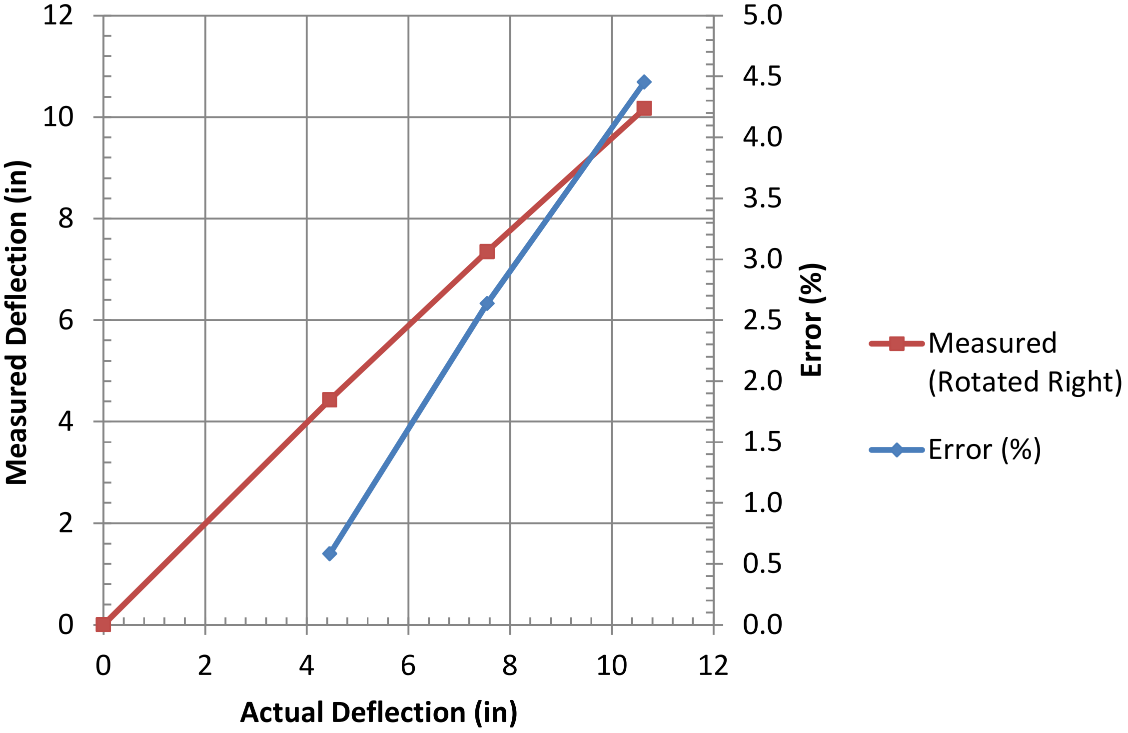


Figure 18. Test C: rotation of the measurement module, Top: rotated left, Bottom: rotated right.

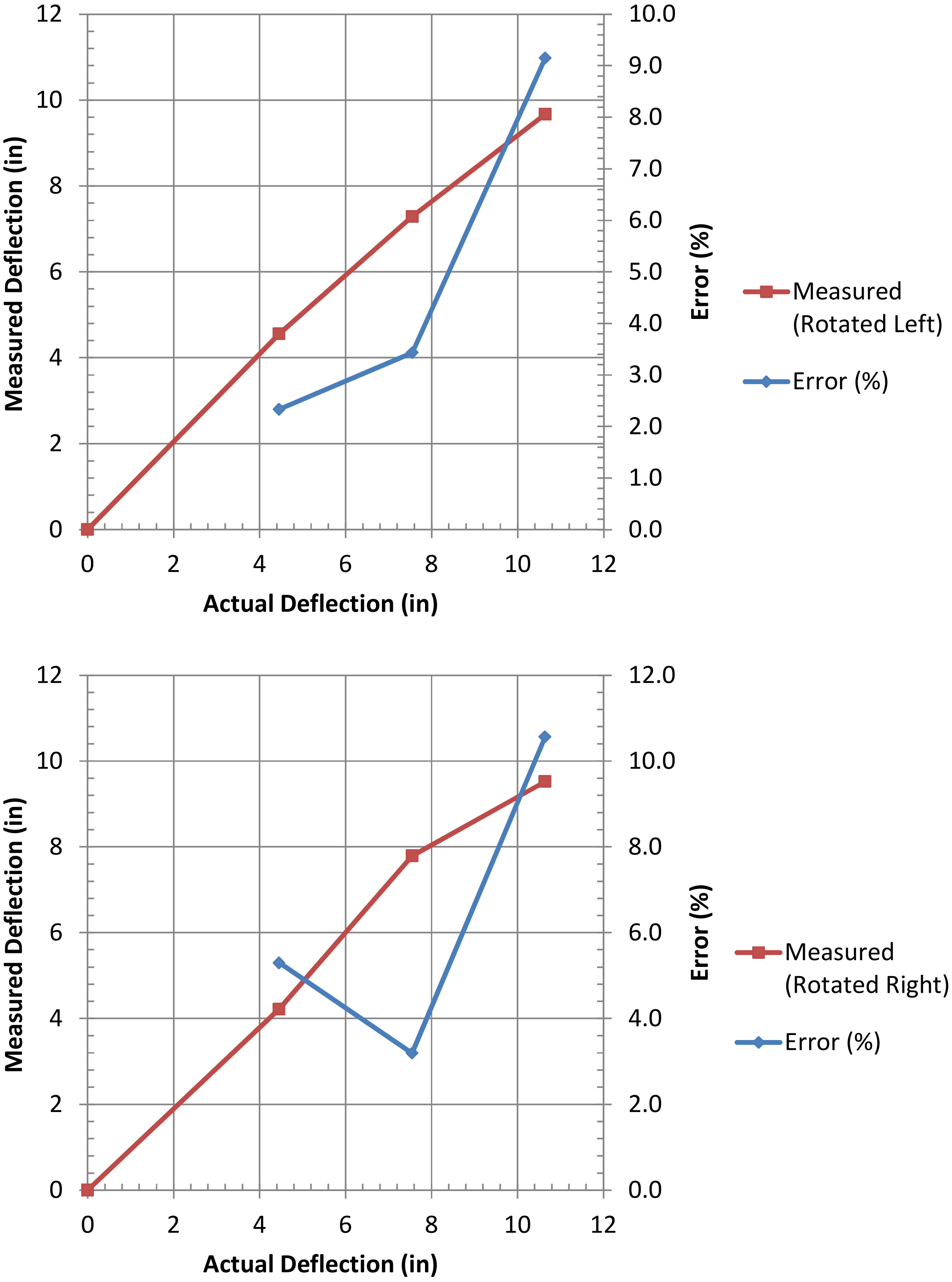


Figure 19. Test C: rotation of the base module, Top: rotated left, Bottom: rotated right.

3.5. Test D: Cantilever Testing

Large displacement of a cantilever beam was measured in another project by the principal investigator. The cantilever beam was connected to the vertical member using aluminum connections. The beam was lifted by an actuator as shown in Figure 20. Since the aluminum connection was ductile, it allowed large displacement.

The measurement using the ZipLevel Pro was compared to the measurement by another cable-based displacement transducer manufactured by Firstmark Controls. "Actual Deflection" of Figure 21was obtained using this transducer. The transducer, model #: 161-2145-C7SS, measures up to 26.75 in (679 mm) with an independent linearity error of ±0.35%. For the displacement up to 6", the error will be up to ±0.021". The error is the independent linearity error, meaning that the magnitude of the error will decrease linearly if the displacement decreases. On the other hand, the ZipLevel Pro has an absolute error of ±0.02" when the cable goes up or down (see section 5), which was the case of this experiment as shown in Figure 20. Therefore, the transducer will be at least as accurate as the ZipLevel Pro at 6" displacement, but gradually more accurate for the smaller displacements.

Overall, the measurements from the ZipLevel Pro were comparable to the displacement transducer and showed a 5% or less error with the exception of one point that showed an 8% error (see Figure 21). The test involved both the large deflection and the rotation. The ZipLevel Pro had very small error for the large deflection (see Figure 12). Therefore, the error should come primarily from the large rotation. The length of the cantilever beam was 30 inches, and the displacement was continued up to 6 inches, so the maximum rotation of the test was 11.3°. As shown in section 3.4 and Figure 18 (the first point in the graph), the error was 0.58% for a rotation of 17.0° of the measurement module, which is substantially smaller than typical 5% error observed in these tests.

Two possible explanations of the typical 5% errors of these tests are the local failure of the cantilever beam and the error from the sensor cable. During the experiment, a local failure was observed around the actuator. The cantilever beam was primarily composed of aluminum plates, and the local failure created a non-uniform surface condition that affected the measurement module. The second explanation is the error from the sensor cable. Typical error due to the condition of the cable was ±0.02" when the cable went up or down between the base module and the measurement module. This error corresponds to a 2% error for 1" displacement. The error from the sensor cable explains the observation that two out of three tests showed greater error for the smaller displacement, yet it is unclear why two tests had decreasing errors whereas one test had increasing errors. It appears that the local failure affected the measurement module somewhat randomly. Overall, the results should be interpreted considering these additional errors. However, even with these additional errors, the ZipLevel Pro was comparable to the other transducer with up to 5% error, with the exception of one point that had an 8% error.

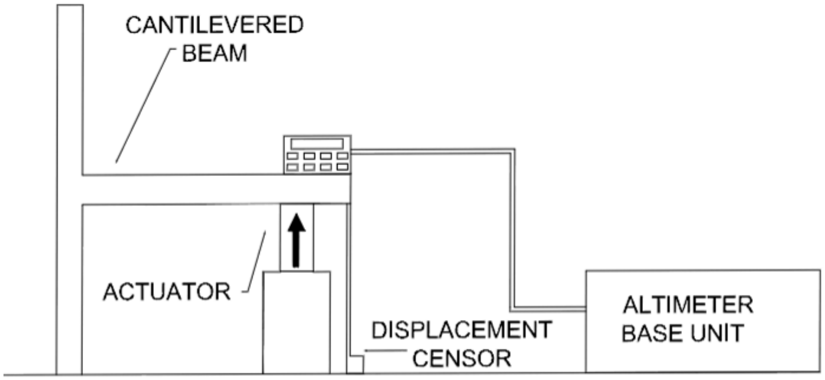
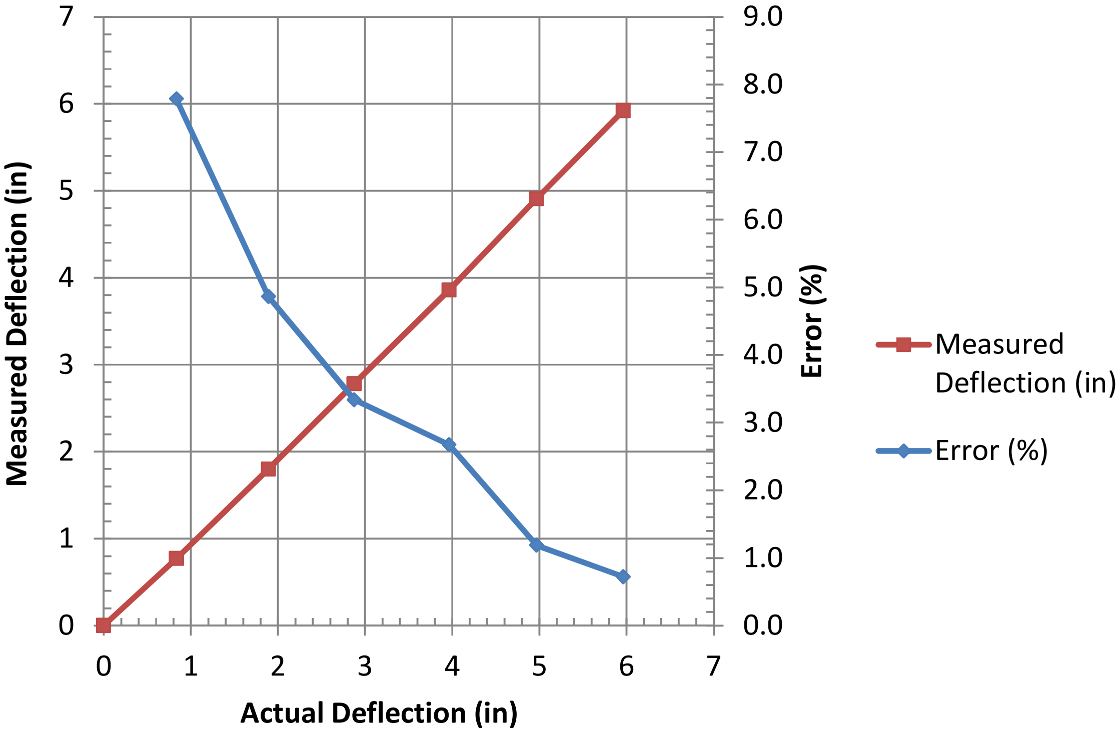
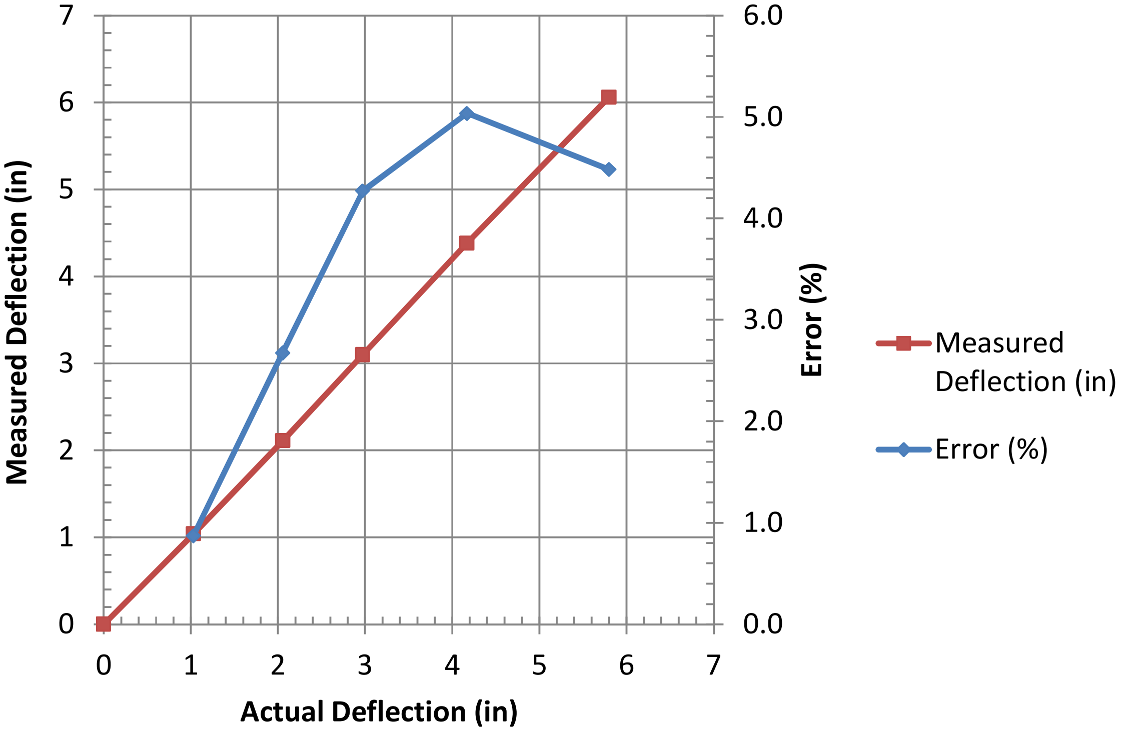


Figure 20. Schematic illustration of the cantilever testing





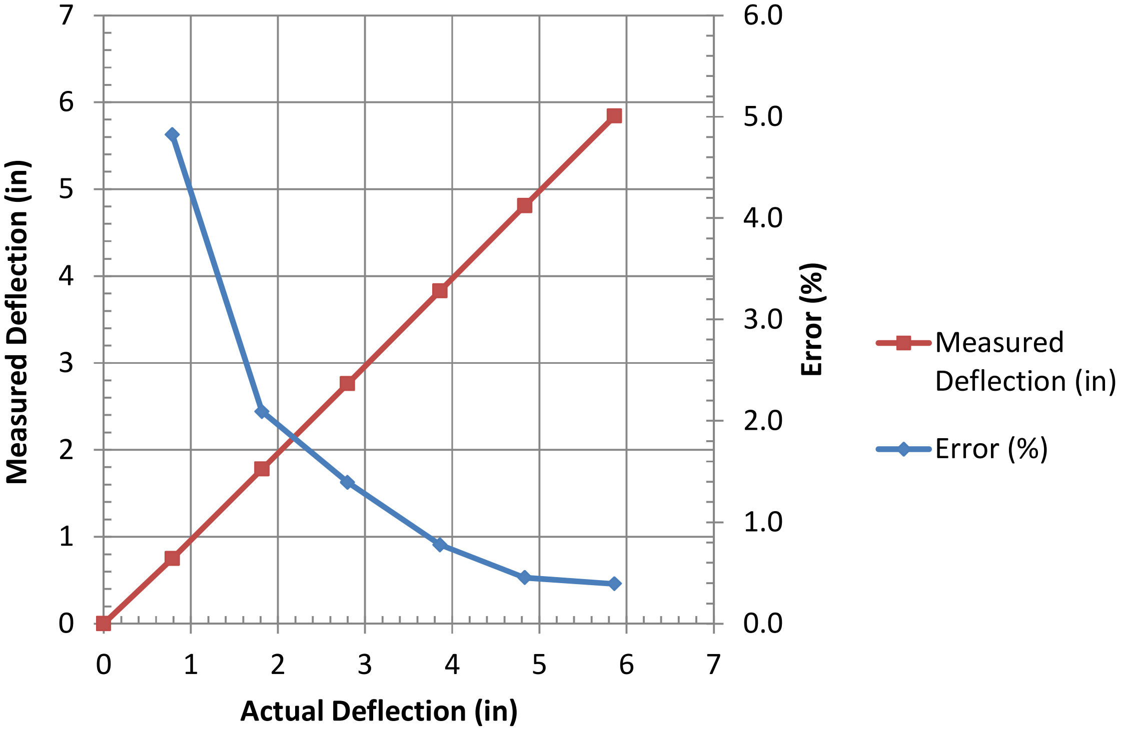


Figure 21. Test D: cantilever testing results from three specimens

3.6. Test E: Beam Slab Testing in the Laboratory

Destructive testing of a concrete slab performed at the FDOT Structures Lab was utilized in the testing of this device. The base module was placed toward the end of a concrete bridge slab (above one of the supports on the top surface) while the measurement module was placed close to the middle of the concrete section directly adjacent to a displacement transducer. When the load was applied, deflection from both instruments was recorded every ten to twenty seconds with paper and pencil until critical failure of the beam was imminent.

The results from the testing are presented here just for reference information. It should not be used to judge the accuracy of the device because significant errors occurred due to the lack of synchronization. However, the error was less than 10% for all deflections greater than 0.5”. Comparison of the results from Test E and the results from Test C is informative. In Test C, the maximum error due to the rotation of the measurement module was 4.5%, and the maximum error due to the rotation of the base module was less than 10.6%. Test E involved the rotation of both the measurement module and the base module, and the maximum error from Test E (14.7%) is comparable to the maximum error predicted by Test C (4.5% + 10.6% = 15.1%).

Figure 22. Placement of the measurement module (left) and the base module (right) in the experiment

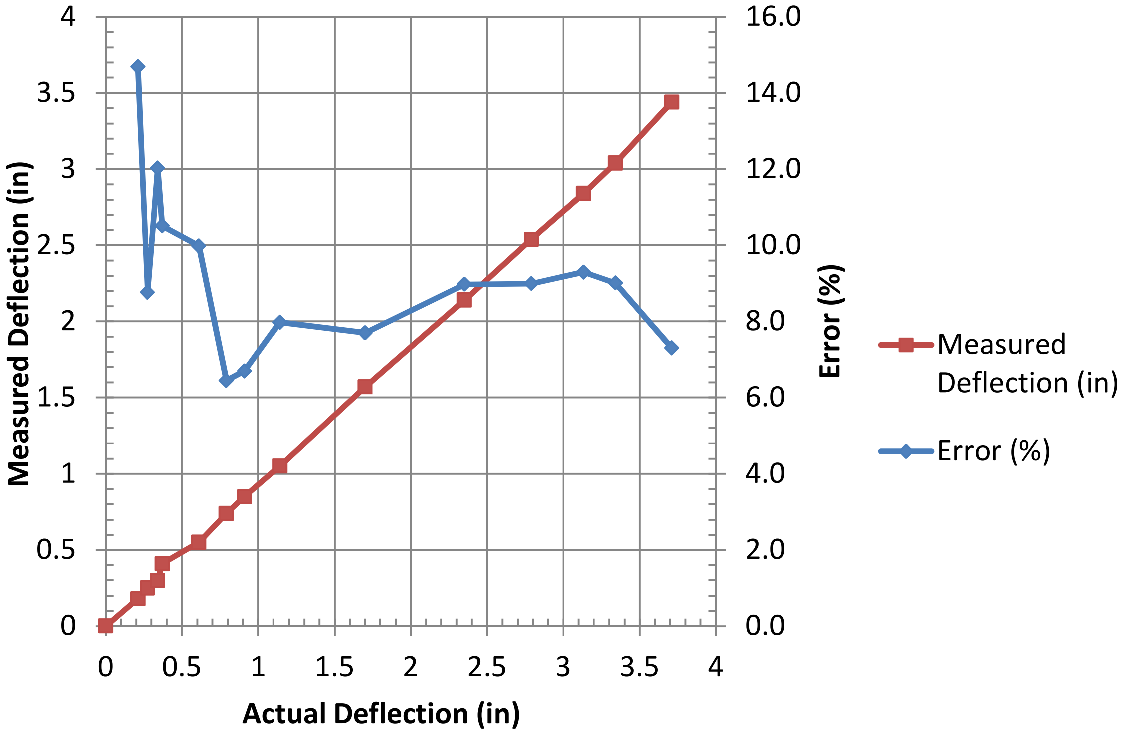


Figure 23. Test E: results from the concrete slab testing

4. Effects of Environmental and Field Conditions

4.1. Overview of Experiments

Experiments in this section introduce variables that reflect the potential use of the instrument in the field. These tests include temperature, wind, vibration, and induced pressure on the cable.

4.2. Test F: Temperature

The effect of temperature change was studied by calibrating the device at 95°F, and using it in a room with a constant temperature of 75°F. The figure below compares the actual displacement, altimeter displacement without re-calibration, and altimeter displacement after re-calibration at 75°F.

The graphs so far were presented by subtracting the measurement at zero-block (zero-plate) from the raw data, so that the graphs begin from the origin. On the other hand, the graphs below used the raw data to explain the error when the device was not properly calibrated against the temperature change.

As shown in Figure 24, a 20°F reduction in the ambient temperature decreased the uncalibrated reading by 1.3” to 1.5” (average decrease: 1.41” for large displacement and 1.31” for small displacement). When the device was properly re-calibrated, the accuracy was consistent with what was presented earlier.

The measured temperature is the ambient temperature and not the temperature of the device. The testing was repeated again using the device temperature. The temperature of the device can be obtained from the measurement module. This time, the device was calibrated at 75°F, and then used without re-calibration at 85°F, 95°F, 105°F, and 115°F.

As shown in Figure 25, the displacement increased significantly due to the increase in the temperature. For 10°F, 20°F, 30°F, and 40°F increase, the displacement on average increased 0.026”, 0.240”, 0.376”, and 0.434”. Note that even the 20°F change in the device temperature caused close to 1/4" (6.35mm) error, which is not acceptable in high-precision applications. Up to 10°F change in the device temperature caused 0.03” (0.762mm) error, so the relationship between the temperature and the error is definitely nonlinear.

Although the user’s manual recommends re-calibration when there is 36°F or greater change (see section 2.2), we recommend re-calibration whenever the temperature change is 10°F or greater if up to 0.03” error is acceptable. If higher precision is required, the user should measure a known height to check the need of re-calibration even for a small change in temperature. According to the results shown in Figure 25, the standard deviation of the shift for 10°F, 20°F, 30°F, and 40°F difference are 0.005”, 0.005”, 0.018”, and 0.01”, which are comparable to the device accuracy of ±0.01” (0.254mm). Therefore, only a single measurement of a known height will be needed for re-calibration for most purposes. If very high precision is necessary, then re-calibration with multiple points is recommended.

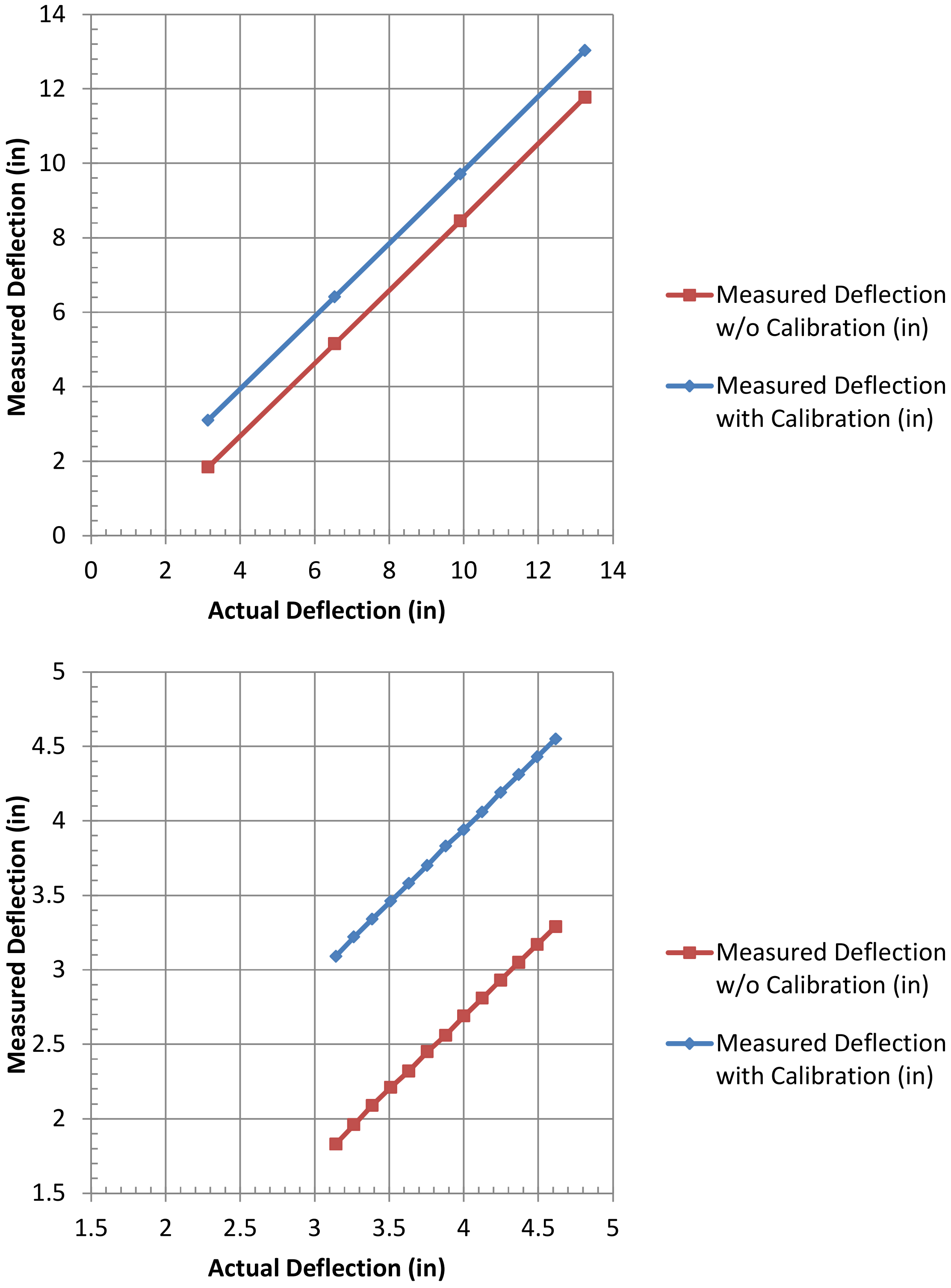


Figure 24. Test F: the effect of not re-calibrating after 20°F reduction in the air temperature. Top: large displacement, Bottom: small displacement

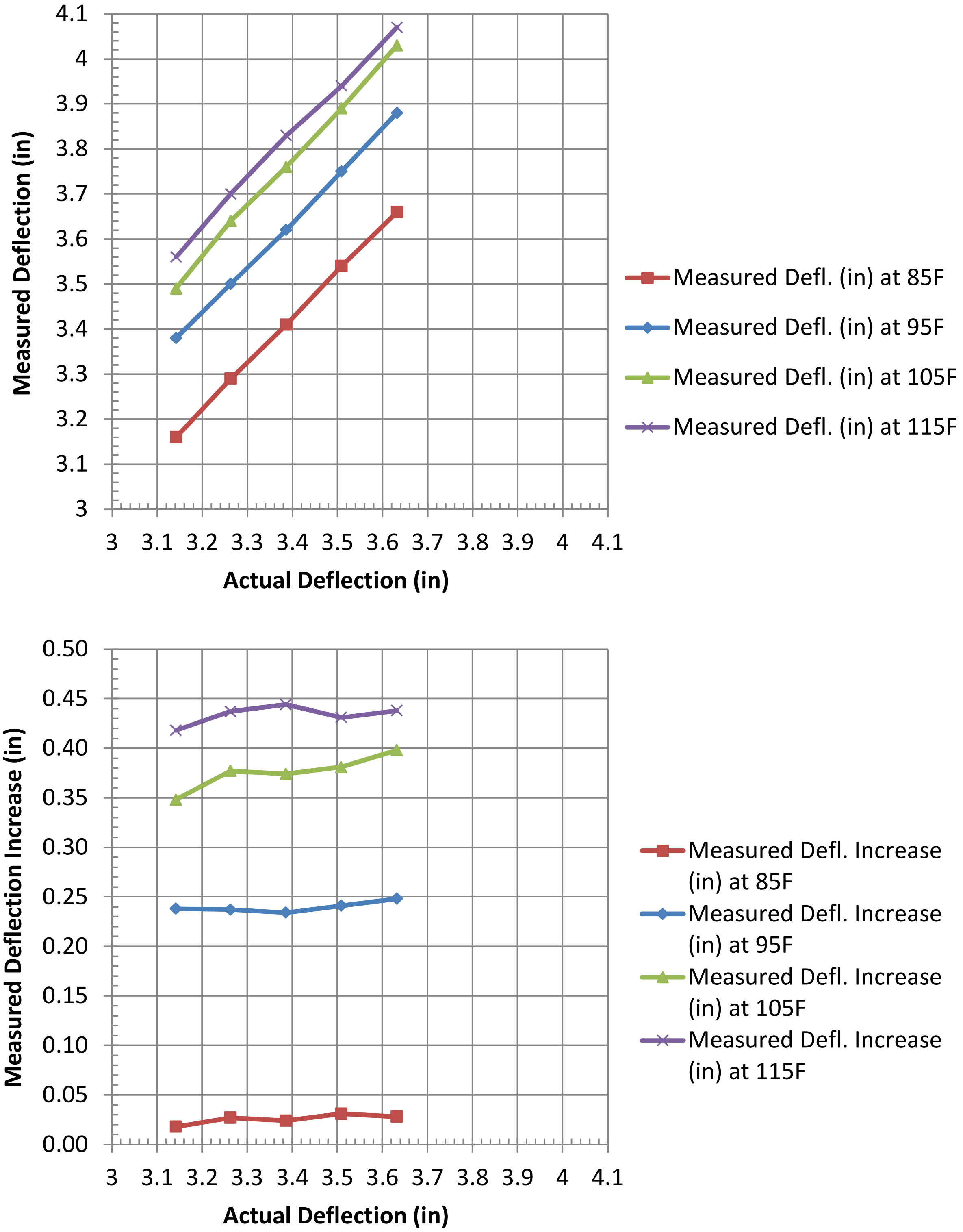


Figure 25. Test F: the effect of not re-calibrating after various increases in the device temperature

The effect on the temperature is one of the most significant factors in using the device in the field condition. If the FDOT collects all data points when the temperature change is less than 10°F, the effect should not be a problem. On the other hand, if the FDOT calibrates the device when the temperature is cool, and collects the data when it is much warmer (or the other way around), the error can be significant as shown by the above graphs.

The testing above was done by locally heating the device and the cable simultaneously, under the constant ambient temperature. The magnitude of the temperature explained above should be used as a guideline, not as a definitive number. The reason is because of the difficulty of correlating the temperature inside the cable, the device temperature reported by the measurement module, and the air temperature. A 10°F change in the air temperature (or the device temperature) may cause higher or lower change in the temperature inside the cable, which affects the measurement.

4.3. Test G: Wind

To study the effect of wind on the device, a fan was placed one foot away from the measurement module. The wind speed was approximately 20 mph. Tests were conducted at 0, 30, 60, and 90 degree orientations. Both the measurement module and the cable were subjected to the wind produced from the fan.

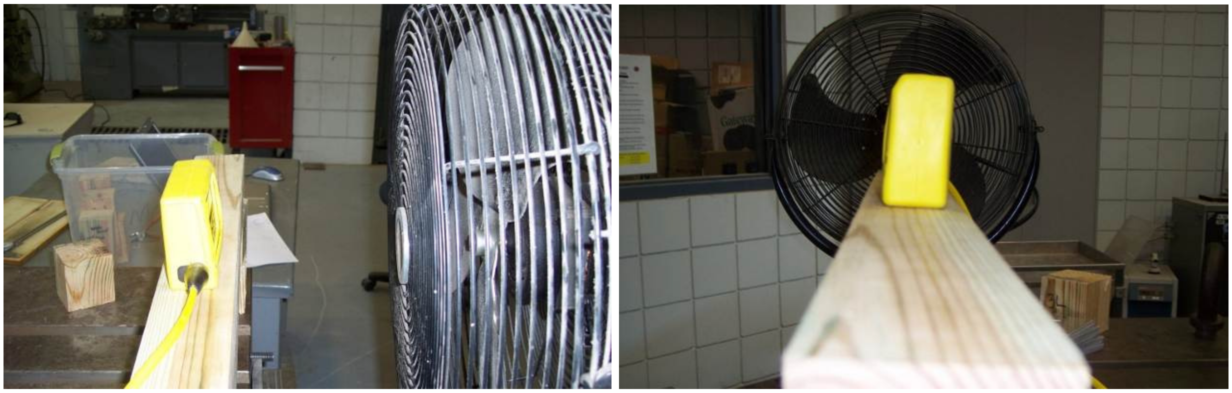
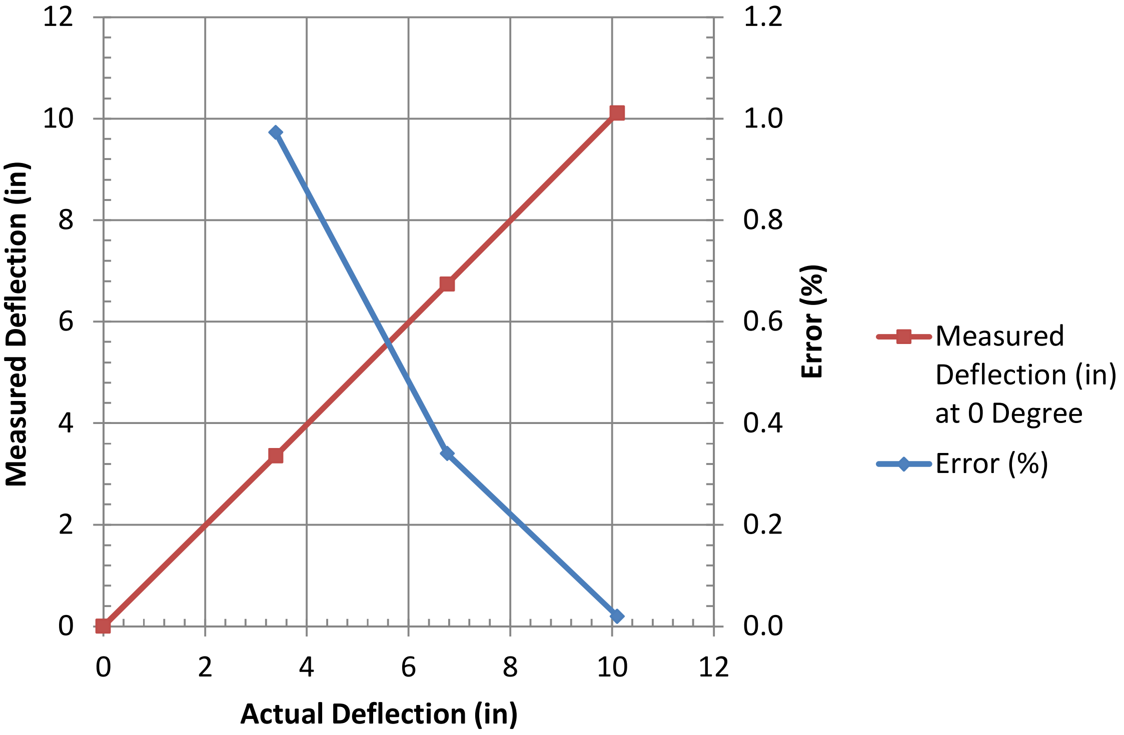
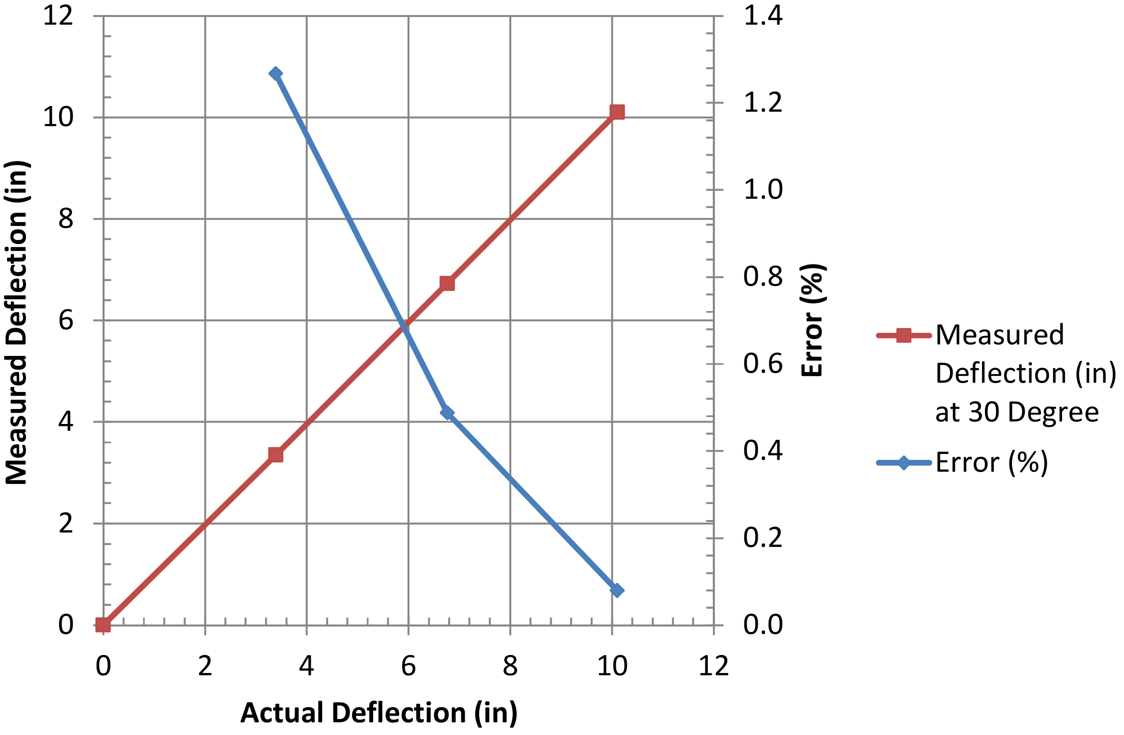


Figure 26. The fan at 0 degree and 90 degree orientations


12
10
8
6
4
2
0
Measured Deflection (in)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Error (%)
0
2
4
6
8
10
12
Actual Deflection (in)
Measured Deflection (in) at 0 Degree
Error (%)


12
10
8
6
4
2
0
Measured Deflection (in)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Error (%)
0
2
4
6
8
10
12
Actual Deflection (in)
Measured Deflection (in) at 30 Degree
Error (%)

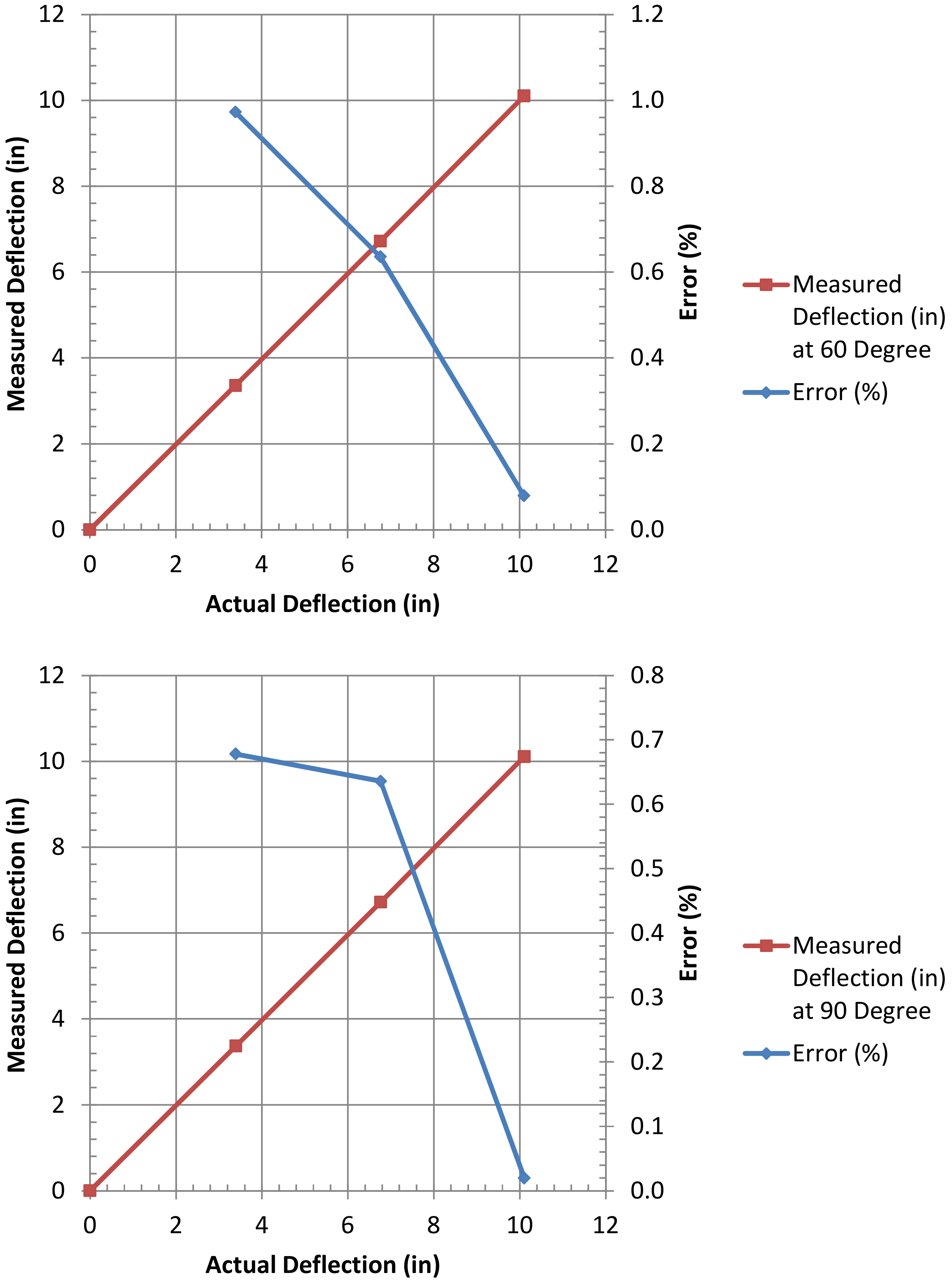
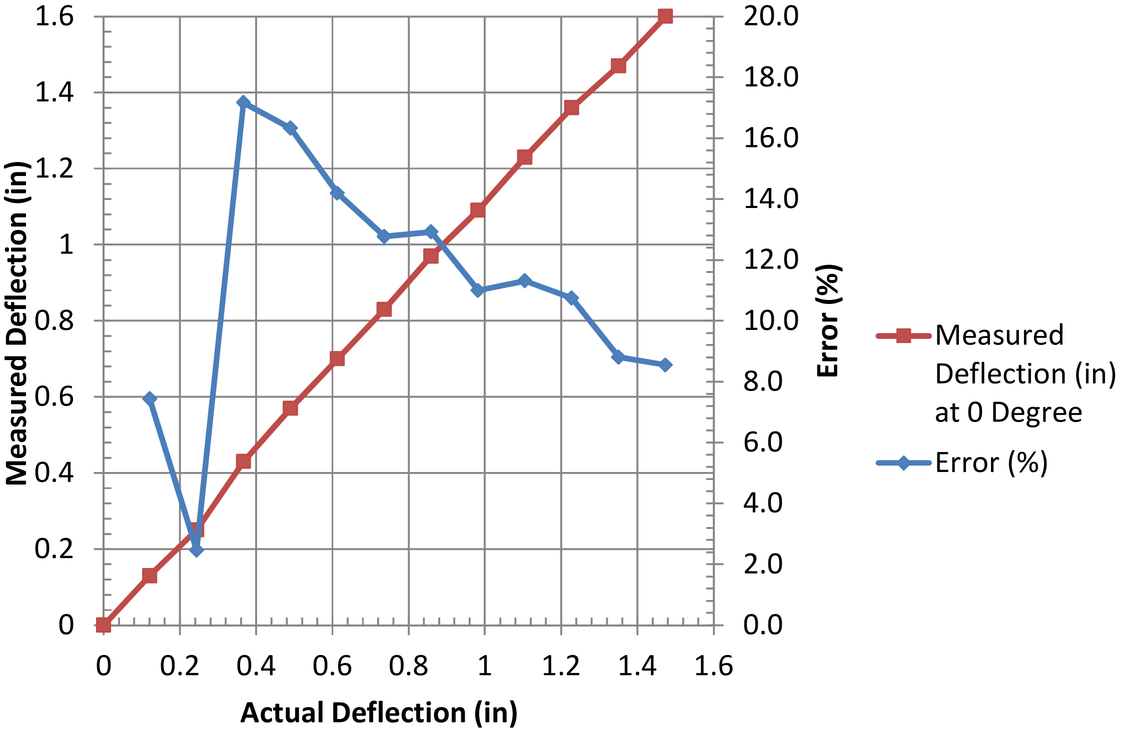
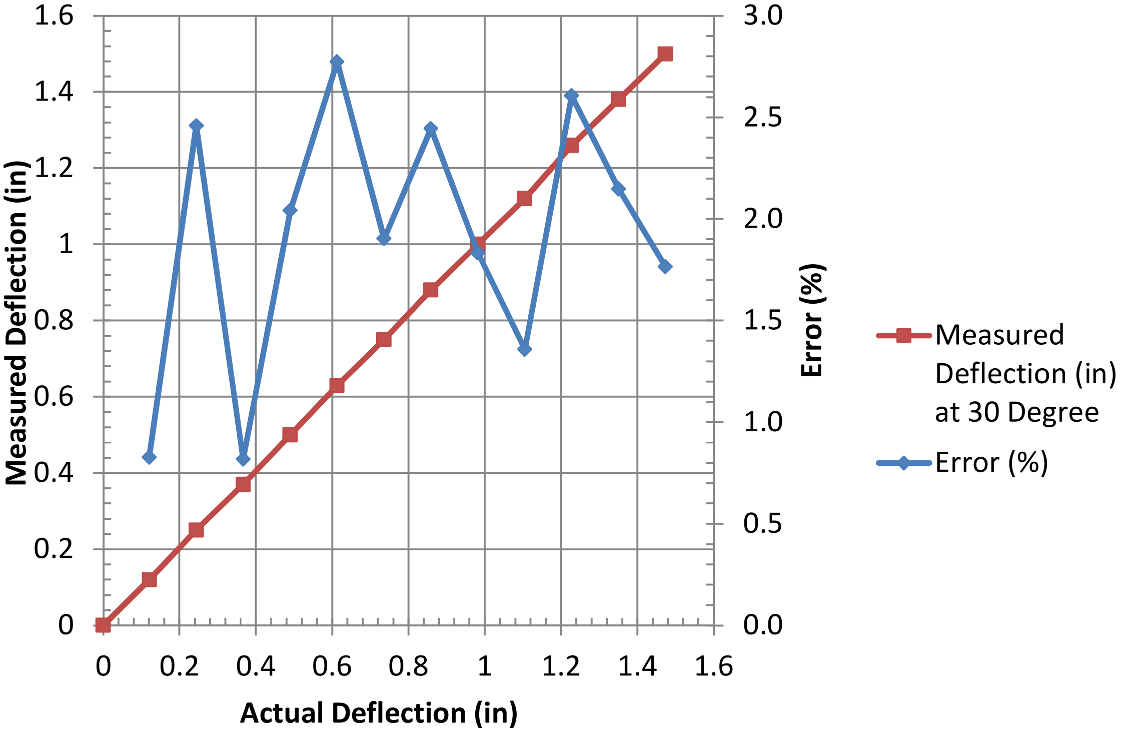
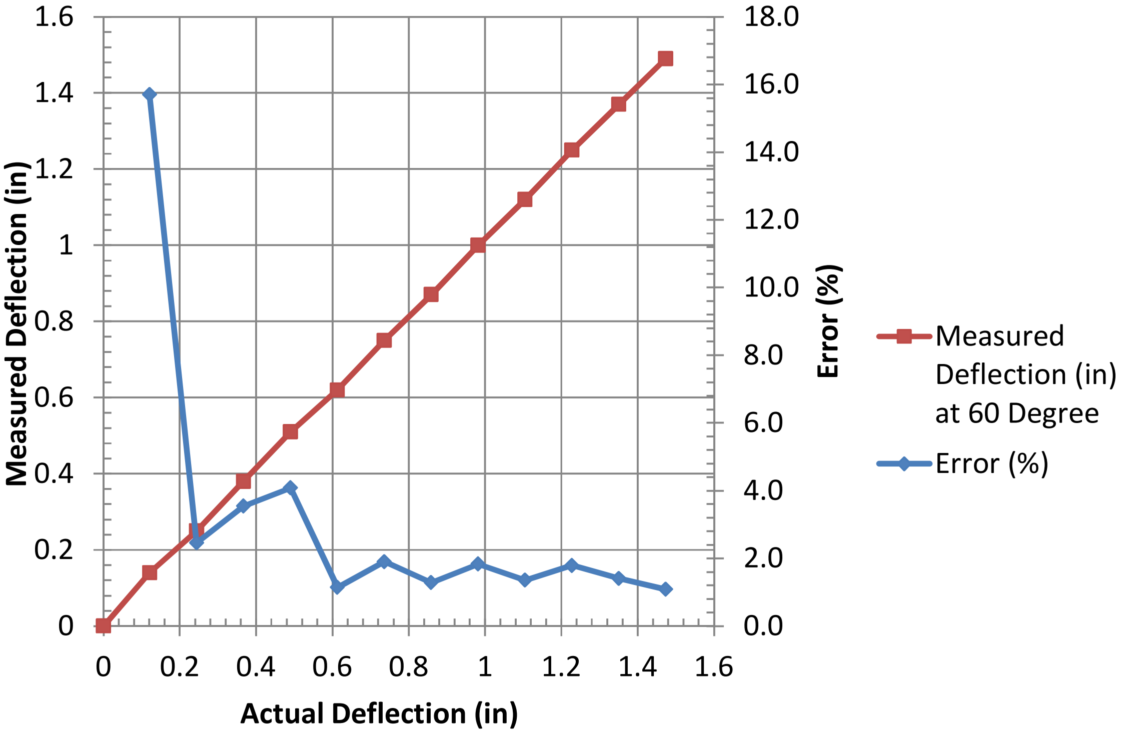


Figure 27. Test G: the effect of the 20 mph wind, large displacement. From top to bottom, 0, 30, 60, and 90 degrees.


Measured Deflection (in)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Actual Deflection (in)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Error (%)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
Measured Deflection (in) at 0 Degree
Error (%)


Measured Deflection (in)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Actual Deflection (in)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Error (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Measured Deflection (in) at 30 Degree
Error (%)



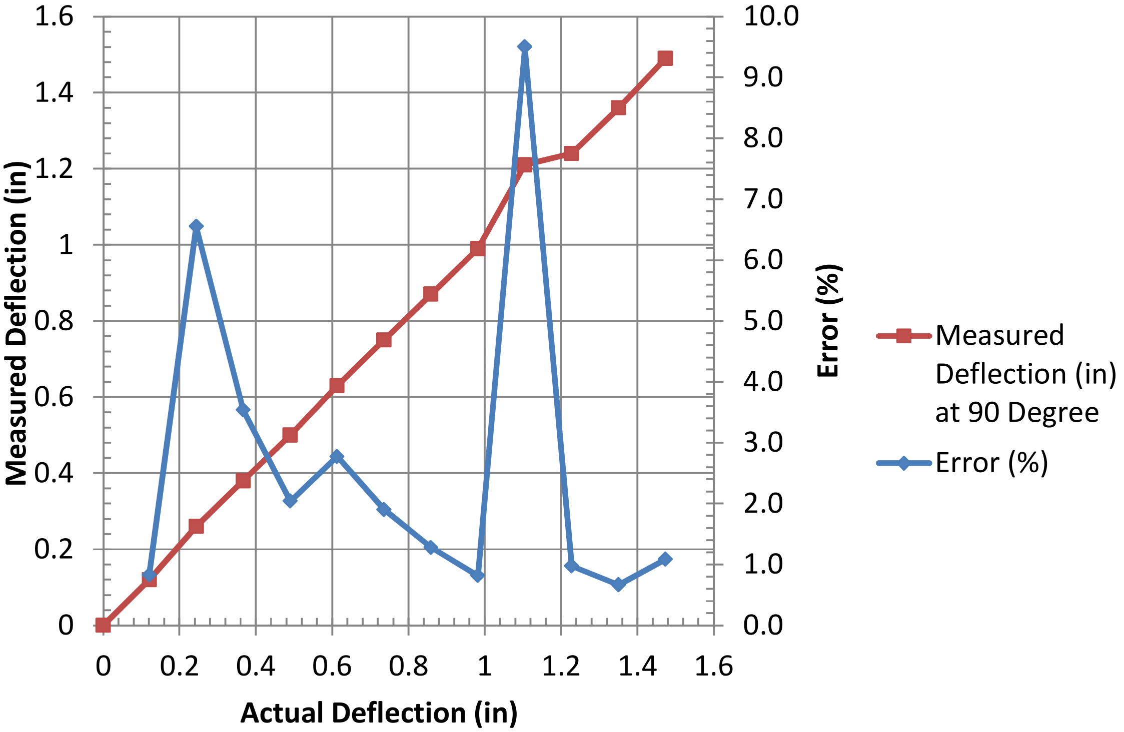


Figure 28. Test G: the effect of the 20 mph wind, small displacement. From top to bottom, 0, 30, 60, and 90 degrees.

As shown in the graphs, the error for large displacement testing was less than 1% for all cases with the exception of one case that had a 1.3% error. For the small displacement testing the error was much higher. When the displacement was less than 0.5” the error was as high as 20%. When the displacement was greater than 0.5” the error was as high as 15%. The largest error occurred at the 0 degree condition, or when the measurement unit was facing the wind directly. In other orientations, the error was less than 5%.

4.4. Test H: Vibration

To simulate the effect of environmental vibrations on the device, a vibration table set was used. The cord was laid over the vibration table as shown in Figure 29 and displacement was measured. Results showed that vibration was not a significant factor affecting the accuracy of large displacements. Small displacement testing showed more error, but the error was 2% or less for all measurements.

Figure 29. Vibrations applied to the cable

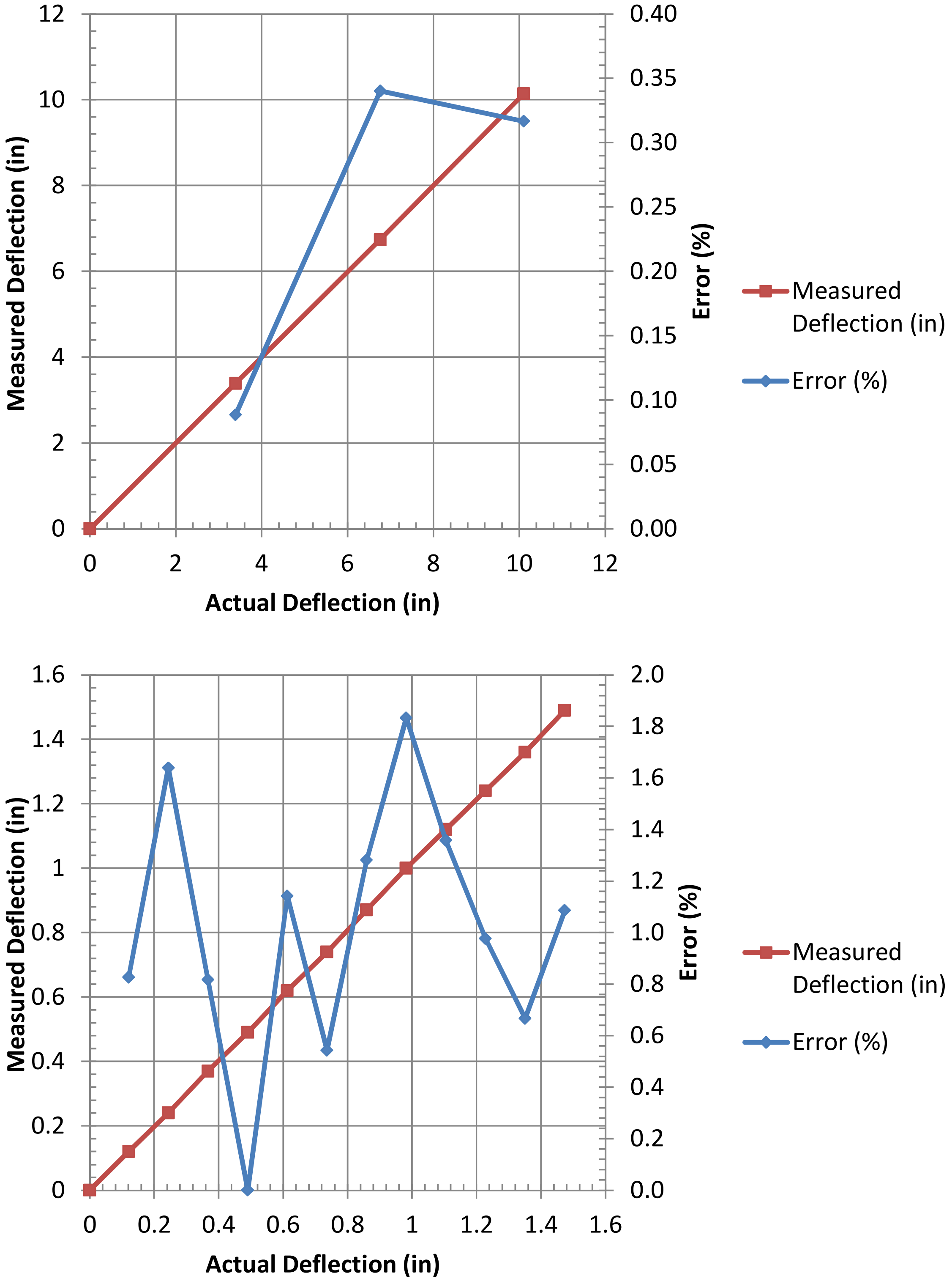


Figure 30. Test H: the effect of the cable vibration. Top: large displacement, Bottom: small displacement

4.5. Test I: Induced Pressure on the Cord

In this testing, the effect of stepping on the sensor cable while in operation was simulated. Due to the difficulty of applying a consistent pressure, a 1 foot steel I-beam (W18x40) was used to apply the pressure. The sensor cable was placed under the center of the beam, perpendicular to the web, so the contact distance was the width of the flange or 6", as illustrated in Figure 31. Therefore, the approximate distributed loading was 80 lb/ft.

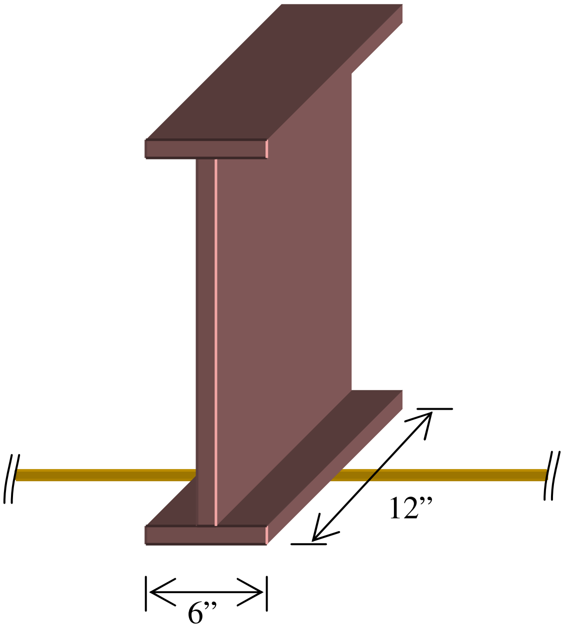


Figure 31. Placement of the sensor cable in Test I

Similar to the temperature testing, the near-constant pressure had the effect of shifting the entire graph. Therefore, the raw data is presented here like the temperature testing (the measurement at the zero-block/plate was not subtracted), in order to show the effect of the shifting more precisely.

Large displacement testing was affected more by the near-constant pressure. The difference in the displacement was between 0.15" and 0.32". The small displacement testing was affected less. The difference in the displacement was between 0.12" and 0.14".

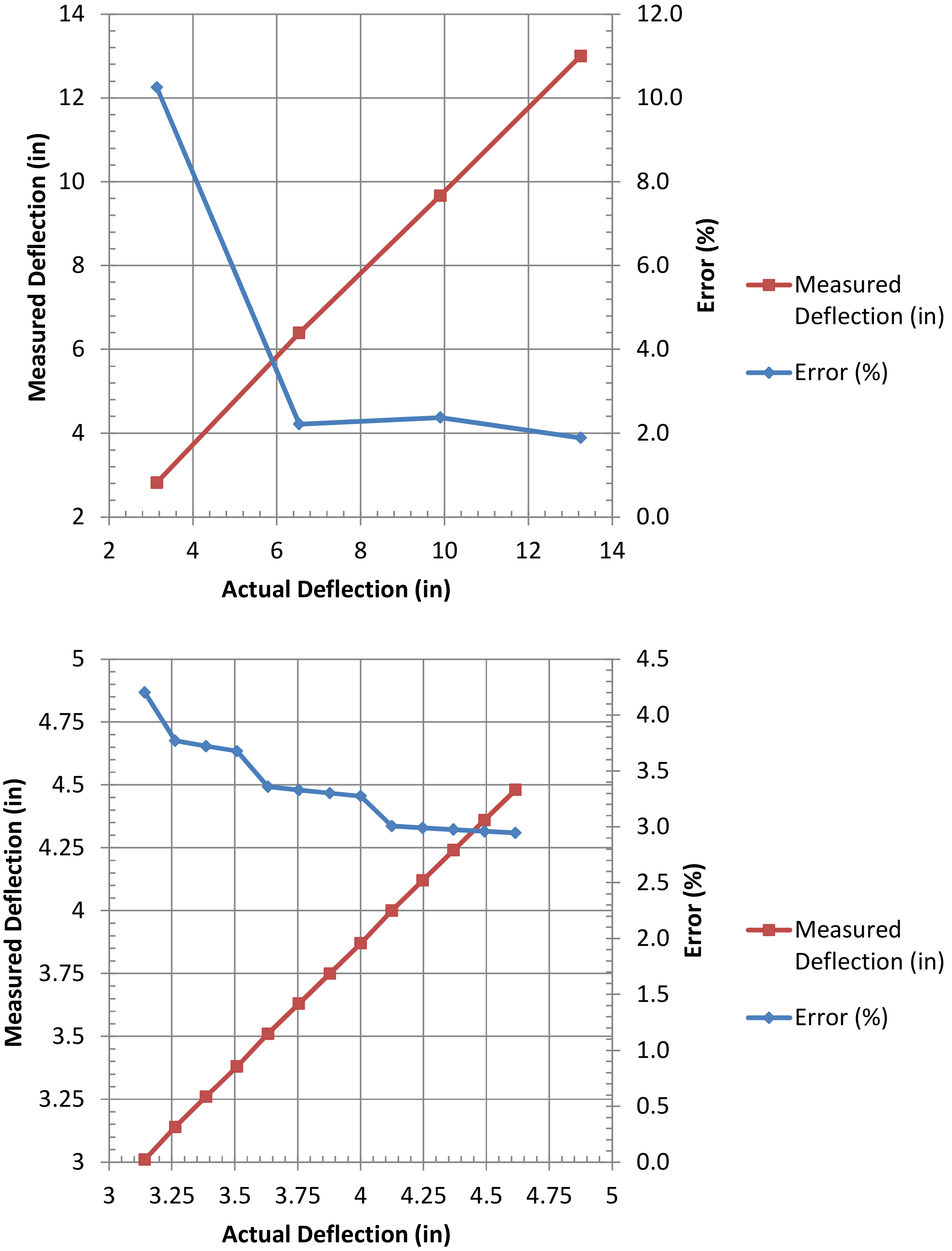


Figure 32. Test I: the effect of near-constant pressure applied on the cable

5. Conclusions

Overall, the ZipLevel Pro high-precision model showed excellent performance achieving ±0.01" (0.254mm) accuracy, or conservatively ±0.02" (0.508mm) accuracy provided that the device was used under ideal conditions. However, the following conditions could introduce much larger error. We recommend that the user of the device is aware of the following conditions, even though the device is relatively rugged and robust.

<u>Cable condition</u>

- The device is sensitive to the cable arrangement. Even when the cable is relatively straight and lies on a flat surface, ±0.01" (0.254mm) fluctuations in the reading can be introduced. The fluctuations were slightly higher than the manufacture's specification of ±0.005" (0.127mm) precision.
- If there are several bends in the cable run and/or the cable goes up and down due to the surface condition, the error could be as high as ±0.05" (1.27mm) although it would be rare to observe such high error. The error due to the cable condition was typically within ±0.02" (0.508 mm) range.
- Distributed loading of 80 lb/ft applied on the sensor cable reduced the reported displacement up to 0.33" (8.38mm). For accurate measurement, avoid applying any pressure on the cable.

<u>Rotation of the measurement module and the base module</u>

- Error due to the rotation of the measurement module was 4.5% for a rotation of 44.3°.
- The error was much higher when the base module was rotated. The error for the base module was 10.6% after a rotation of 44.3°.
- The measurement module reports the displacement around its center, so place the center of the device where the displacement is to be measured.

<u>Temperature</u>

- If the device is calibrated at a high temperature and used at a lower temperature without re-calibration, the device will report the displacement smaller than what it should be. If the device is calibrated at a low temperature and used at a higher temperature without re-calibration, the device will report the displacement larger than what it should be.
- The error is 0.03" (0.762mm) or less if the temperature difference is 10°F or less.
- The error exponentially increases if the temperature difference is greater than 10°F. For example, 20°F difference will cause close to 1/4" (6.35mm) error.

<u>Wind</u>

- When the device is subjected to a 20 mph wind, the measurements may have up to 20% error for a displacement up to 0.5" (up to 15% error for the displacement between 0.5" and 2"), so avoid using the device under windy conditions. However, when the deflection was greater than 4" the error was less than 1.5%.

Appendix: Raw Data from the Tests

The tables below list the raw data from the tests. A corresponding figure in the main text can be found by following the test index and the description.

Table 1. Test A: flat surface, large displacement

Displacement (in)		Error (%)
Actual	Measured	
0	0	
3.393	3.38	0.383
6.763	6.75	0.192
10.108	10.1	0.079

Table 2. Test A: flat surface, small displacement

Displacement (in)		Error (%)
Actual	Measured	
0	0	
0.121	0.13	7.438
0.244	0.25	2.459
0.367	0.37	0.817
0.49	0.5	2.041
0.613	0.62	1.142
0.736	0.74	0.543
0.859	0.87	1.281
0.982	0.99	0.815
1.105	1.11	0.452
1.228	1.24	0.977
1.351	1.36	0.666
1.474	1.49	1.085

Table 3. Test B1, large displacement (measurement module at 5°)

Displacement (in)		Error (%)
Actual	Measured	
0	0	
3.371	3.36	0.326
6.763	6.76	0.044
10.158	10.15	0.079

Table 4. Test B1, small displacement (measurement module at 5°)

Displacement (in)		Error (%)
Actual	Measured	
0	0	
0.123	0.12	2.439
0.246	0.18	26.829
0.369	0.37	0.271
0.492	0.48	2.439
0.615	0.61	0.813
0.738	0.74	0.271
0.861	0.86	0.116
0.984	0.98	0.407
1.107	1.11	0.271
1.23	1.23	0.000
1.353	1.35	0.222
1.476	1.48	0.271

Table 5. Test B2, large displacement (base module at 5°)

Displacement (in)		Error (%)
Actual	Measured	
0	0	
3.371	3.39	0.564
6.741	6.75	0.134
10.086	10.14	0.535

Table 6. Test B2, small displacement (base module at 5°)

Displacement (in)		Error (%)
Actual	Measured	
0	0	
0.099	0.12	21.212
0.222	0.24	8.108
0.345	0.37	7.246
0.468	0.49	4.701
0.591	0.62	4.907
0.714	0.74	3.641
0.837	0.87	3.943
0.96	0.98	2.083
1.083	1.11	2.493
1.206	1.24	2.819
1.329	1.36	2.333
1.452	1.48	1.928

Table 7. Test B3, large displacement (10° for both the base and the measurement module)

Displacement (in)		Error (%)
Actual	Measured	
0	0	
3.389	3.37	0.561
6.733	6.75	0.252
10.075	10.12	0.447

Table 8. Test B3, small displacement (10° for both the base and the measurement module)

Displacement (in)		Error (%)
Actual	Measured	
0	0	
0.123	0.13	5.691
0.246	0.25	1.626
0.369	0.37	0.271
0.492	0.49	0.407
0.615	0.61	0.813
0.738	0.72	2.439
0.861	0.85	1.278
0.984	0.97	1.423
1.107	1.09	1.536
1.23	1.23	0.000
1.353	1.35	0.222
1.476	1.47	0.407

Table 9. Test C, rotation of the measurement module

Rotation angle	Actual disp.	Measured disp. (rotated left)	Error (%)	Measured disp. (rotated right)	Error (%)
17.0°	4.456	4.44	0.359	4.43	0.583
29.7°	7.549	7.37	2.371	7.35	2.636
44.3°	10.644	10.21	4.077	10.17	4.453

Table 10. Test C, rotation of the base module

Rotation angle	Actual disp.	Measured disp. (rotated left)	Error (%)	Measured disp. (rotated right)	Error (%)
17.0°	4.456	4.56	2.334	4.22	5.296
29.7°	7.549	7.29	3.431	7.79	3.192
44.3°	10.644	9.67	9.151	9.52	10.560

Table 11. Test D: cantilever testing of three specimens

Displacement (in)		Error (%)
Actual	Measured	
0	0	0.000
0.835	0.77	7.784
1.892	1.8	4.863
2.876	2.78	3.338
3.966	3.86	2.673
4.969	4.91	1.187
5.963	5.92	0.721

Displacement (in)		Error (%)
Actual	Measured	
0	0	0.000
1.031	1.04	0.873
2.055	2.11	2.676
2.973	3.1	4.272
4.17	4.38	5.036
5.8	6.06	4.483

Displacement (in)		Error (%)
Actual	Measured	
0	0	0.000
0.788	0.75	4.822
1.818	1.78	2.090
2.799	2.76	1.393
3.86	3.83	0.777
4.832	4.81	0.455
5.863	5.84	0.392

Table 12. Test E: beam slab testing

Displacement (in)		Error (%)
Actual	Measured	
0	0	0.00
0.211	0.18	14.69
0.274	0.25	8.76
0.341	0.3	12.02
0.371	0.41	10.51
0.611	0.55	9.98
0.791	0.74	6.45
0.911	0.85	6.70
1.141	1.05	7.98
1.701	1.57	7.70
2.351	2.14	8.97
2.791	2.54	8.99
3.131	2.84	9.29
3.341	3.04	9.01
3.711	3.44	7.30

Table 13. Test F: temperature effect (20°F reduction in the air temperature), large displacement

Displacement (in)		
Actual	Measured w/o calibration	Measured
3.142	1.84	3.1
6.535	5.15	6.41
9.905	8.45	9.71
13.25	11.77	13.03

Table 14. Test F: temperature effect (20°F reduction in the air temperature), small displacement

Displacement (in)		
Actual	Measured w/o calibration	Measured
3.142	1.83	3.09
3.263	1.96	3.22
3.386	2.09	3.34
3.509	2.21	3.46
3.632	2.32	3.58
3.755	2.45	3.7
3.878	2.56	3.83
4.001	2.69	3.94
4.124	2.81	4.06
4.247	2.93	4.19
4.37	3.05	4.31
4.493	3.17	4.43
4.616	3.29	4.55

Table 15. Test F: temperature effect (various increases of the device temperature), small displacement

Actual disp. (in)	Measured disp. (in) under various testing temperatures. Device was calibrated at 75°F.			
	85°F	95°F	105°F	115°F
3.142	3.16	3.38	3.49	3.56
3.263	3.29	3.5	3.64	3.7
3.386	3.41	3.62	3.76	3.83
3.509	3.54	3.75	3.89	3.94
3.632	3.66	3.88	4.03	4.07

Table 16. Test G: wind effect, large displacement

Actual disp. (in)	0 degree		30 degree		60 degree		90 degree	
	Measured (in)	Error (%)	Measured (in)	Error (%)	Measured (in)	Error (%)	Measured (in)	Error (%)
0	0		0		0		0	
3.393	3.36	0.973	3.35	1.267	3.36	0.973	3.37	0.678
6.763	6.74	0.340	6.73	0.488	6.72	0.636	6.72	0.636
10.108	10.11	0.0198	10.1	0.0791	10.1	0.0791	10.11	0.0198

Table 17. Test G: wind effect, small displacement

Actual disp. (in)	0 degree		30 degree		60 degree		90 degree	
	Measured (in)	Error (%)	Measured (in)	Error (%)	Measured (in)	Error (%)	Measured (in)	Error (%)
0	0		0		0		0	
0.121	0.13	7.438	0.12	0.826	0.14	15.702	0.12	0.826
0.244	0.25	2.459	0.25	2.459	0.25	2.459	0.26	6.557
0.367	0.43	17.166	0.37	0.817	0.38	3.542	0.38	3.542
0.49	0.57	16.327	0.5	2.041	0.51	4.082	0.5	2.041
0.613	0.7	14.192	0.63	2.773	0.62	1.142	0.63	2.773
0.736	0.83	12.772	0.75	1.902	0.75	1.902	0.75	1.902
0.859	0.97	12.922	0.88	2.445	0.87	1.281	0.87	1.281
0.982	1.09	10.998	1	1.833	1	1.833	0.99	0.815
1.105	1.23	11.312	1.12	1.357	1.12	1.357	1.21	9.502
1.228	1.36	10.749	1.26	2.606	1.25	1.792	1.24	0.977
1.351	1.47	8.808	1.38	2.147	1.37	1.406	1.36	0.666
1.474	1.6	8.548	1.5	1.764	1.49	1.085	1.49	1.085

Table 18. Test H: cable vibration effect, large displacement

Displacement (in)		Error (%)
Actual	Measured	
0	0	
3.393	3.39	0.088
6.763	6.74	0.340
10.108	10.14	0.317

Table 19. Test H: cable vibration effect, small displacement

Displacement (in)		Error (%)
Actual	Measured	
0	0	
0.121	0.12	0.826
0.244	0.24	1.639
0.367	0.37	0.817
0.49	0.49	0.000
0.613	0.62	1.142
0.736	0.74	0.543
0.859	0.87	1.281
0.982	1	1.833
1.105	1.12	1.357
1.228	1.24	0.977
1.351	1.36	0.666
1.474	1.49	1.085

Table 20. Test I: pressure effect, large displacement

Displacement (in)		
Actual	Measured	Error (%)
3.142	2.82	10.248
6.535	6.39	2.219
9.905	9.67	2.373
13.25	13	1.887

Table 21. Test I: pressure effect, small displacement

Displacement (in)		
Actual	Measured	Error (%)
3.142	3.01	4.201
3.263	3.14	3.770
3.386	3.26	3.721
3.509	3.38	3.676
3.632	3.51	3.359
3.755	3.63	3.329
3.878	3.75	3.301
4.001	3.87	3.274
4.124	4	3.007
4.247	4.12	2.990
4.37	4.24	2.975
4.493	4.36	2.960
4.616	4.48	2.946