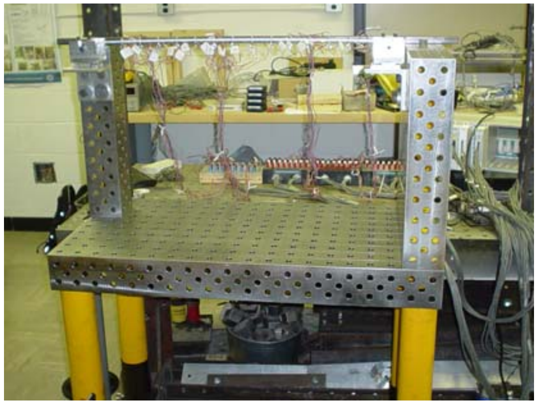
BEAM DEMONSTRATION USER GUIDE



CEE 498 Experimental Methods

Derek Jacobs
Julia Johnson
Matt Eatherton

University of Illinois at Urbana-Champaign
Spring 2007

Table of Contents

Acknowledgements

Special thanks go to the civil engineering machine shop which assisted in the construction of the beam demonstration. Thanks also go to Dr. Kuchma for his ideas and guidance, as well as the University of Illinois engineering education budget for providing the necessary funds.

1. Introduction

1.1. Statement of Objectives

The purpose of this project is to create a working beam demonstration for an undergraduate level structural engineering course. Specific goals for the demonstration include:

- Measure extreme fiber strains in an example beam.
- Calculate and display deflection, slope, moment, shear, and loading in real time.
- Ability to change support conditions from roller type support to fixed rotation supports.
- Record moment, deflection, slope, moment, and shear values to allow comparison with theoretical values.
- Allow different types of loading including point loads, distributed load, and linearly varying load.
- Allow expansion for possible future configurations and programming.

1.2. General Description

A beam demonstration was created based on the previously stated objectives. A modular rolling table manufactured by Bluco was already owned by the University and provided the base for the demonstration. An additional modular post and supplies were obtained from various venders as described in Appendix C.

The beam is made of high strength aluminum that is 3.175mm x 25 mm cross-sectional dimensions. The beam span is 800 mm for the pinned-pinned configuration and 750mm for the fixed-fixed configuration. Multiple loading configurations such as point loads, uniformly distributed loads, and linearly varying loads are possible as well as different support conditions such as roller support and fixed rotation.

The beam is instrumented with 29 strain gages on the beam underside. Data collection and processing is performed using National Instruments hardware and LabVIEW software. The measured strains are used to calculate the distribution of moment, shear, slope, and deflection, and all graphs are displayed in near real time.

1.3. Organization of this Manual

This report is organized as a user's manual for the beam demonstration. As such, the main sections include detailed description of the setup, operation of the beam demonstration, and examples. Additional information on the LabVIEW program, challenges encountered in this project, materials, and ideas for future expansion are included in appendices.

2. Beam Demonstration Setup

2.1. Overview

The beam demonstration as shown in Figure 1 consists of the following main components:

1. Modular table with modular back wall and modular post
2. Two aluminum support angles with ample bolts for attaching to the modular wall and post
3. Support devices that consist of a linear bearing, aluminum channel, aluminum drum with lid, and a though bolt that sits in the cradle of the aluminum channel.
4. Instrumented aluminum beam that spans between supports.
5. A multitude of weights including two different types – slotted weights on hangers that can be adjusted between 50g and 250g and solid weights ranging between 10g and 1kg.

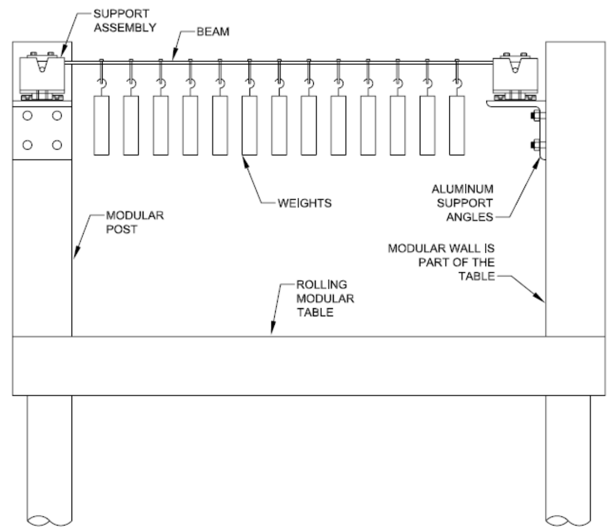


Figure 1. Side View of Test Setup

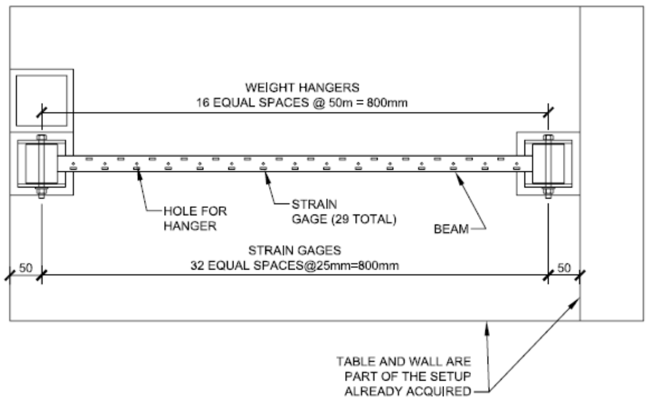


Figure 2. Plan View of Test Setup

2.2. Detailed Description

The beam consists of 7075-T6 aluminum material that was purchased from OnlineMetals.com and cut to 25mm x 3.175mm x 800mm. Twenty-nine general purpose strain gages, purchased from Vishay Micro Measurements, are applied at 25mm spacing along the beam length. All strain gages are oriented longitudinally on the underside of the beam on alternating sides of the centerline as shown in Figure 2. Fifteen eye hooks are bolted at 50mm spacing along the centerline of the beam to accept loads. The gages are protected by tape and wires are also taped to the beam to reduce the amount of strain applied to the wire-to-gage connection.

The beam is set into a machined slot on the drum and held in place by a 10mm thick aluminum cap plate. When the support is not fixed, it rotates about the axis of the shoulder bolt. The span for the simply supported (pinned-pinned) configuration is 800mm from bolt to bolt. In the fixed configuration, the span is 750mm from face of support to face of support.

As shown in Figures 3 and 4, the support drum has a shoulder bolt going through its center. The shoulder bolt rests on the aluminum channel that acts as a cradle. The support is designed to allow easy transformation between roller and fixed boundary conditions. The shoulder bolt labeled as number 14 in Figure 4 can be tightened so that rotation is restricted. When the bolt is loose, the support drum, labeled as number 11, is allowed to rotate freely. Both supports are free to slide longitudinally on linear bearing tracks.

Weights ranging from 10g to 1 kg may be hung from each of 15 load hooks.

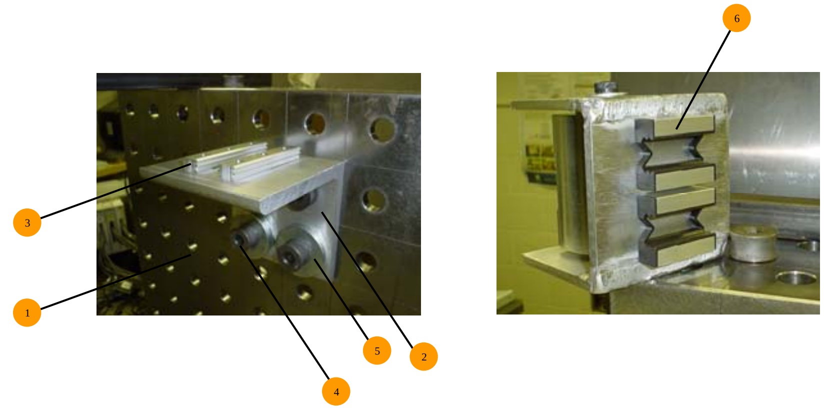


Figure 3. Support Details

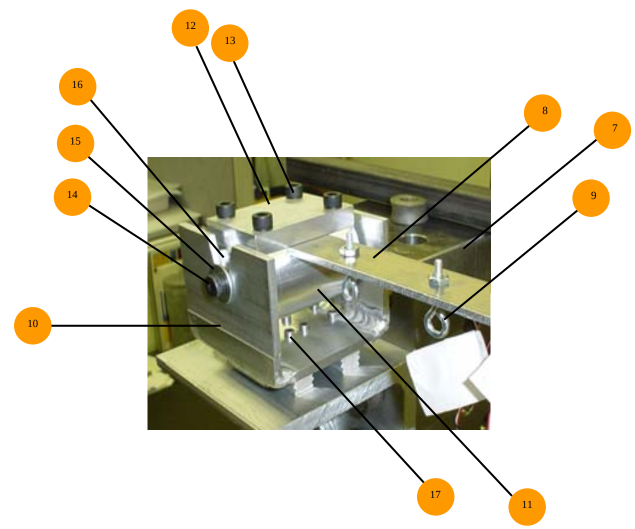


Figure 4. Support Details

Table 1. Description of Beam Demonstration Components

Parts Description	Quantity
1. Existing strong table modular fixture	1
2. 6061-T6 aluminum angle, 3/8” x 4” x 4”	2
3. Linear bearing track	4
4. Bluco Corporation bolts	10
5. 5/8” Grade 5 steel washers	12
6. 108# capacity square linear bearings	4
7. Bluco Corporation post	1
8. 7075-T6 aluminum beam, 25mm x 3.175mm x 800mm	1
9. 1/8” x ¾” eye hooks with nuts	15
10. 75mm x 75mm x 5mm thick aluminum channel	2
11. 6061-T6 aluminum drum, 2” diameter x 2-3/8” long	2
12. Aluminum plate, 10mm x 60mm x 41.4mm	2
13. Socket bolts, 15mm long	8
14. Shoulder bolt, ¼-20 x 3-1/2” long with nut	2
15. ¼” Grade 5 steel washer	6
16. ¼” aluminum washer	4
17. Socket bolts, 4-40	16

3. Operation

3.1. Calculation of theoretical predictions

The operation of the beam demonstration might start with a prediction of the shear, moment, slope, and deflection. Even though the exact dimensions, modulus of elasticity, span, and gage locations can vary from the assumed values, the calibration that is described in later sections is based on specific values for these quantities. The following values can be used in calculating the beam response to particular loading:

- Beam dimensions = 3.175mm x 25mm (1/8” x 1”)
- Modulus of Elasticity of Aluminum = 68,950 N/mm^2 (10,000 ksi)
- Span = 800mm (31.5”) for pinned-pinned configuration and 750mm (29.5”) for fixed-fixed configuration

3.2. Cabling and Data Acquisition

A data acquisition system is required to run this beam demonstration. Currently the strain gages are connected to four – 8 channel terminal boxes that were made at the University of Illinois. The terminal boxes are semi-permanently connected to National Instruments NI SCXI 1314 Terminal Strips. The NI SCXI 1314 modules are connected to NI SCXI-1520 cards that are inserted in an NI SCXI-1001 Chassis. The chassis is then connected to a NI DAQCard 6036E PC Card in the experimental methods class laptop.

To begin a demonstration, ensure that all parts of the data acquisition are connected, and the chassis is turned on. Turn the laptop on and open the file called Beam Demo.VI that is located at

C:/CEE498/Beam Demo/Beam Demo.VI

There are a number of sub programs that need to be in the same directory.

3.3. Fixing and Unfixing the Supports

The boundary conditions of the beam may be easily converted from roller to fixed rotation by means of a 7/16” box wrench and a hex key wrench. To create a roller support, the drum must be permitted to rotate about the center shoulder bolt, held in place loosely with a ¼-20 nut. A fixed support is then created by simply tightening the center shoulder bolt with the before mentioned tools so the drum does not rotate.

3.4. Starting Program, Zeroing, and Calibration

First choose the tab corresponding to the support conditions that will be used for the demonstration. Currently there are two tabs available: pinned-pinned and fixed-fixed.

These descriptions, however, are somewhat misleading. When the support bolts are loosened, the support more closely represents a roller since it is allowed to move in the longitudinal direction. Similarly, the fixed support condition is also allowed to move in the longitudinal direction. The longitudinal movement does not affect the typical beam flexure calculations and removes the possibility of developing axial forces in the beam for which the instrumentation is not designed to handle.

The Beam Demo.VI program can be run by clicking on the button at the top left of the screen that shows an arrow . The program starts by taking an initial strain reading from each strain gage, which will be subtracted from all subsequent readings. This zeroing process is only carried out when the program is started, so it is recommended to restart the program before each loading configuration.

Since the beam dimensions, gage locations, strain gage factors, and modulus of elasticity are not exactly the same as those used in the calculations, it is necessary to calibrate the strain readings. The theoretical strains at each gage location based on a 1 kg load at midspan have been incorporated into the LabVIEW program. Place a 1 kg weight at midspan and click “Calibrate”. When the “Calibrate” button is clicked the strain readings are each individually factored to replicate the ideal strain readings. The resulting shear, moment, slope and deflection graphs will now agree exactly with theory. The 1 kg load can then be removed and the chosen loading can be applied.

3.5. Applying Load

Many different load configurations are possible with this test setup. The specific load configuration desired will be determined by the user, however, a number of example loading schemes are presented in Section 4. Ideally the loads are already selected and ready prior to starting the program so that they can be placed immediately after calibration. Place weights onto the load hooks of the beam according to the intended load configuration. The solid weights have a bar on the bottom to allow the user to hang multiple weights from one load location. The slotted weights can be adjusted to allow a range from 50g to 300g in increments of 5g. It is handy to have a metric yardstick sitting just above the beam to hang the loads at specific locations along the beam.

It is not recommended to apply more load than that which produces stresses half of the yield stress. The reported yield stress of 7075-T6 aluminum is 434.4 N/mm^2 (63 ksi). This corresponds to a moment of 18,000 N-mm. It is recommended therefore that the moment be kept under 9,000 N-mm. This corresponds to a center span point load of no more than 4.5 kg, or a 500g per-load-hook uniform load.

3.6. Comparing to theoretical prediction

The experimental results can be compared to the theoretical predictions by checking key values on the programs display or by recording the data and graphing the results in a different program like excel. When the "Record Data" button is clicked, a dialog box appears to allow the user to select the location and name for the data file. If a filename ending in the extension .xls is specified, the file can be opened directly by Microsoft Excel.

4. Example Loading Configurations

4.1. Simply Supported – Point Load at Mid-Span

A mass of 1 kg was placed at the center of the beam. The following data was taken right after calibration to ensure that the calibration procedure was working correctly. As shown in Figures 5 through 8 the response is almost exactly as expected.

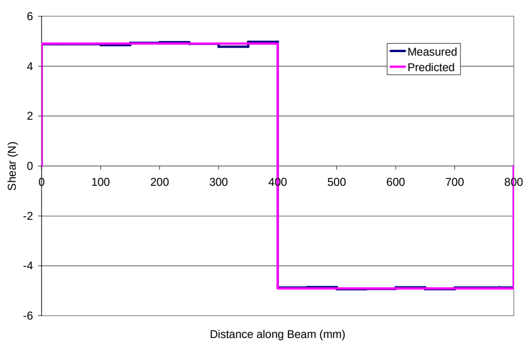


Figure 5. Measured vs. Predicted Shear Diagram

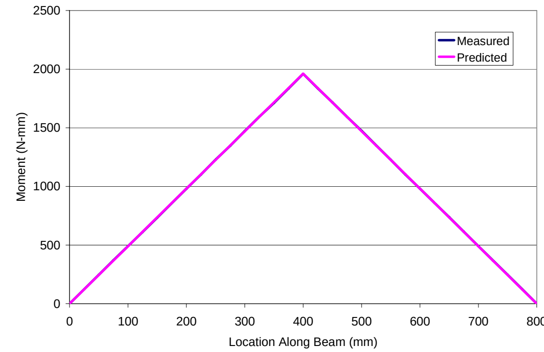


Figure 6. Measured vs. Predicted Moment Diagram

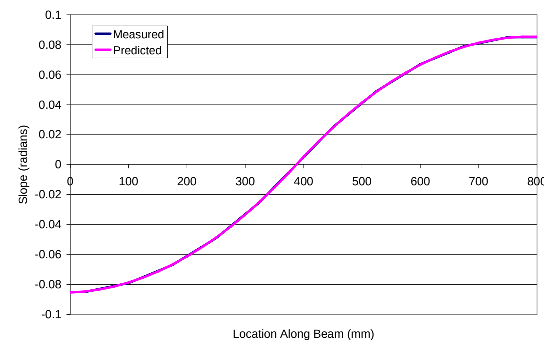


Figure 7. Measured vs. Predicted Slope Diagram

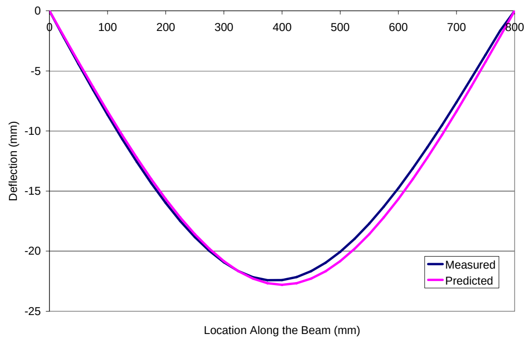


Figure 8. Measured vs. Predicted Deflection Diagram

4.2. Simply Supported - Two Equal Concentrated Loads Symmetrically Placed

Two 1 kg weights were placed at the quarter points (at 200mm and 600mm location). Figures 9 through 12 show the predicted and measured response.

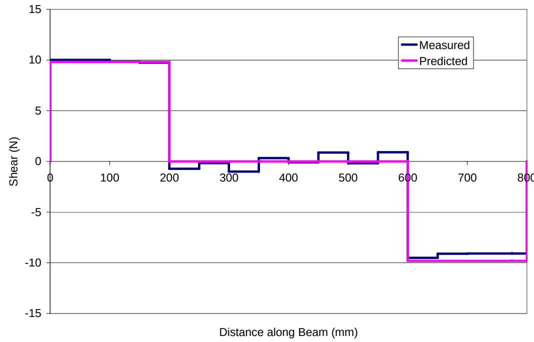


Figure 9. Measured vs. Predicted Shear Diagram

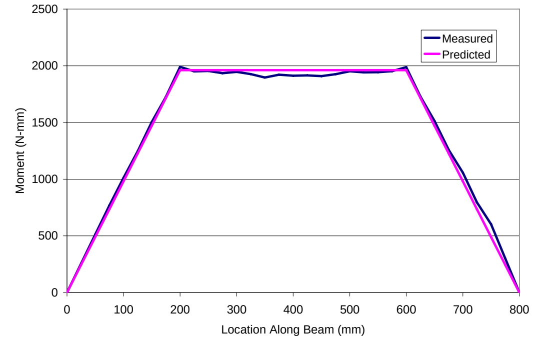


Figure 10. Measured vs. Predicted Moment Diagram

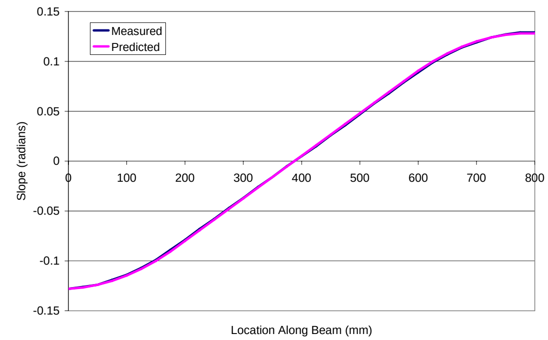


Figure 11. Measured vs. Predicted Slope Diagram

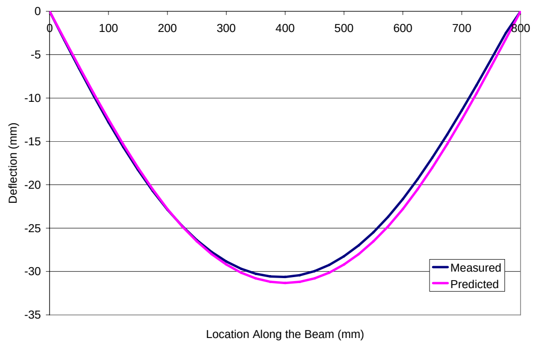


Figure 12. Measured vs. Predicted Deflection Diagram

4.3. Simply Supported – Uniformly Distributed Load

Fifteen 200 gram weights were placed at every load hook (50mm spacing). Figures 13 through 16 show the predicted and measured response.

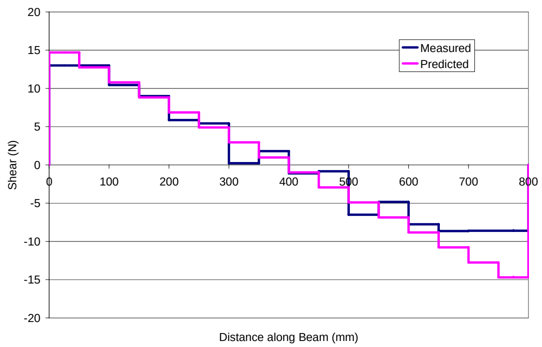


Figure 13. Measured vs. Predicted Shear Diagram

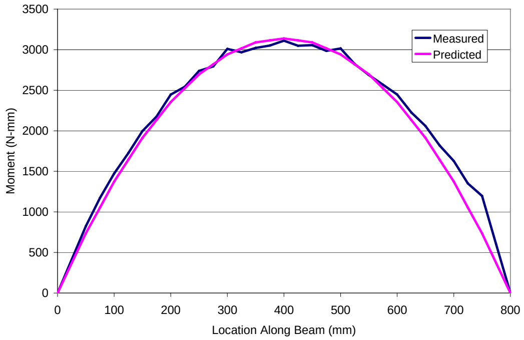


Figure 14. Measured vs. Predicted Moment Diagram

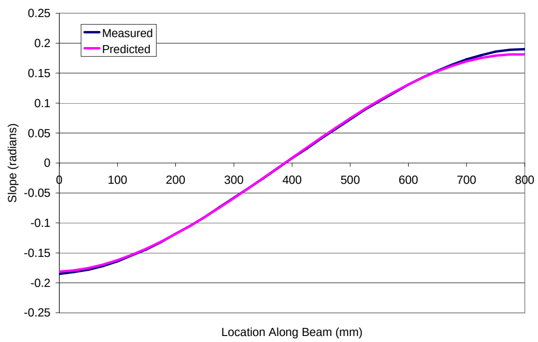


Figure 15. Measured vs. Predicted Slope Diagram

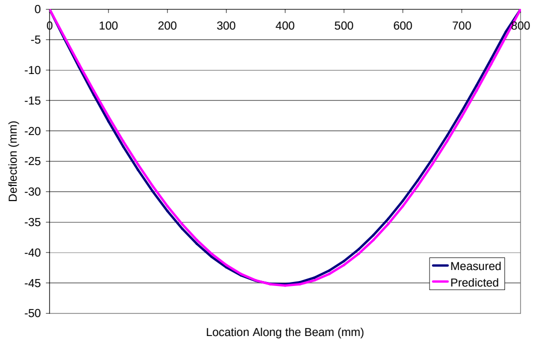


Figure 16. Measured vs. Predicted Deflection Diagram

4.4. Simply Supported – Linearly Varying Load

Loads were placed at every load hook (15 total locations) varying from 50g to 330 grams in 20 gram increments. Figures 17 through 20 show the predicted and measured response.

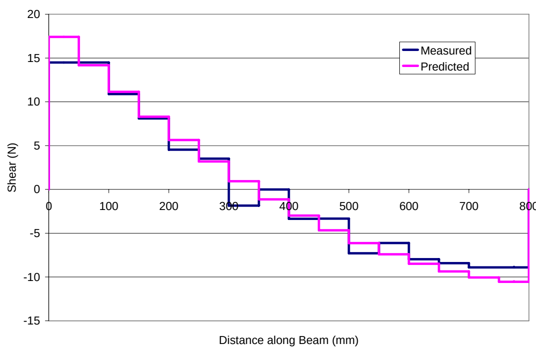


Figure 17. Measured vs. Predicted Shear Diagram

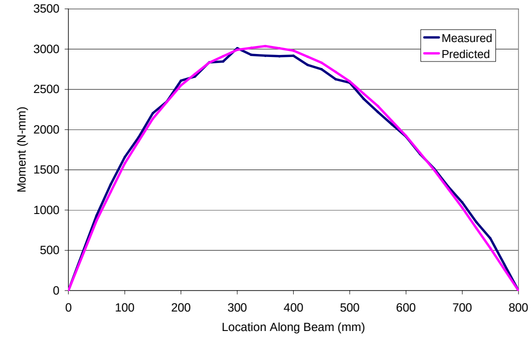


Figure 18. Measured vs. Predicted Moment Diagram

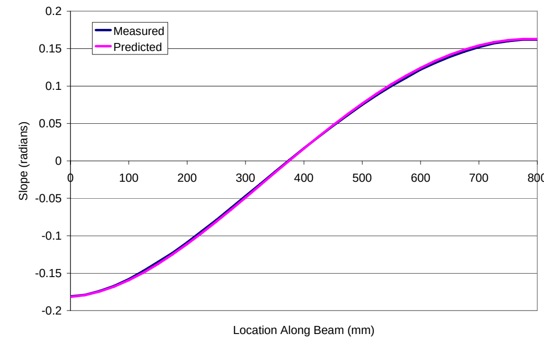


Figure 19. Measured vs. Predicted Slope Diagram

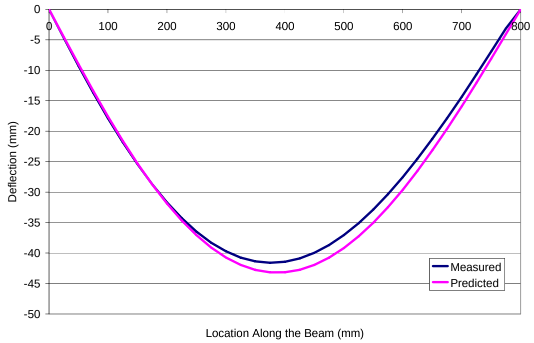


Figure 20. Measured vs. Predicted Deflection Diagram

4.5. Fixed Supports – Point Load at Mid-Span

The supports were fixed, and a 1 kg point load was placed at midspan. Figures 21 through 24 show the predicted and measured response.

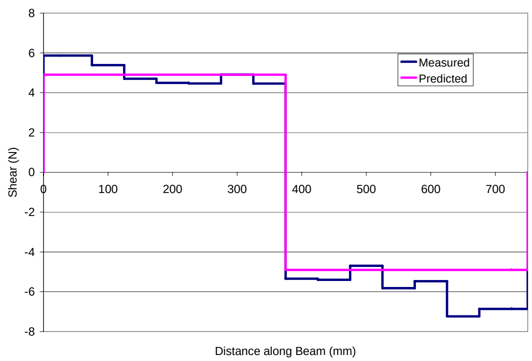


Figure 21. Measured vs. Predicted Shear Diagram

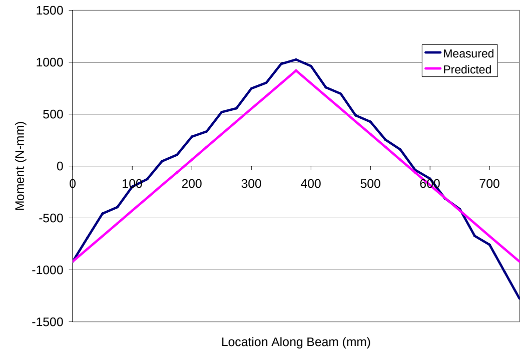


Figure 22. Measured vs. Predicted Moment Diagram

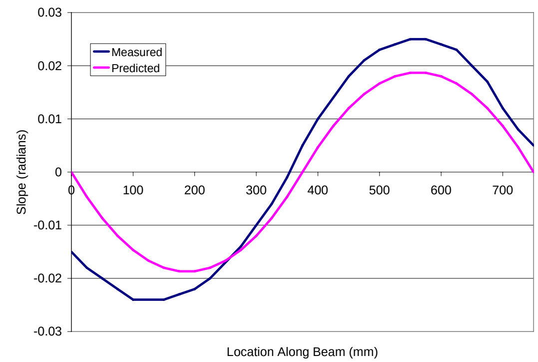


Figure 23. Measured vs. Predicted Slope Diagram

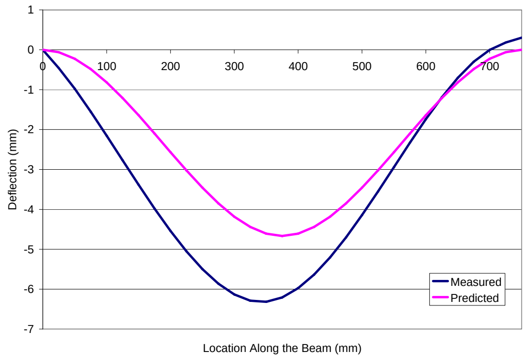


Figure 24. Measured vs. Predicted Deflection Diagram

4.6. Fixed Supports – Quarter Point Loading

The supports were fixed and 1 kg point loads were placed at the quarter points (at 175mm and 575mm locations). Figures 25 through 28 show the predicted and measured response.

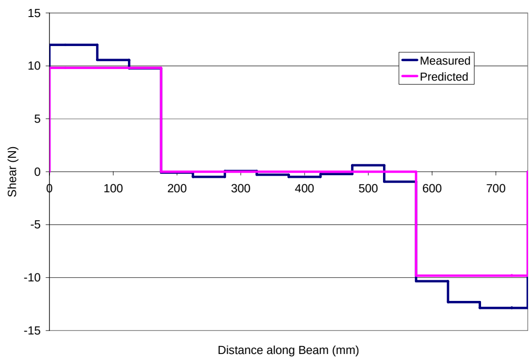


Figure 25. Measured vs. Predicted Shear Diagram

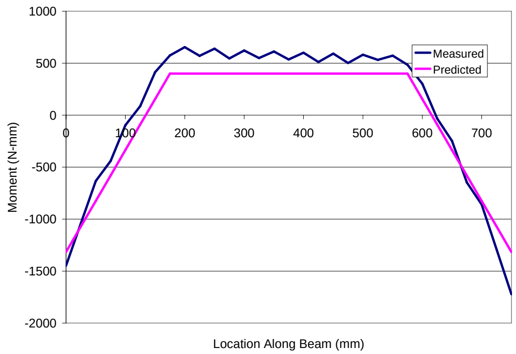


Figure 26. Measured vs. Predicted Moment Diagram

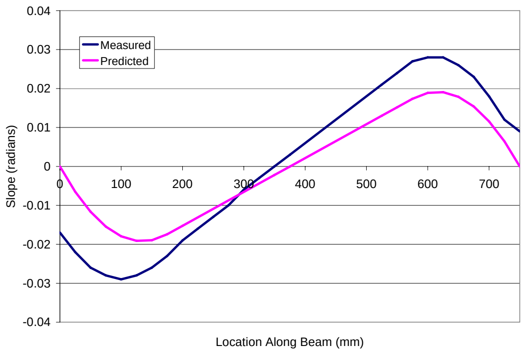


Figure 27. Measured vs. Predicted Slope Diagram

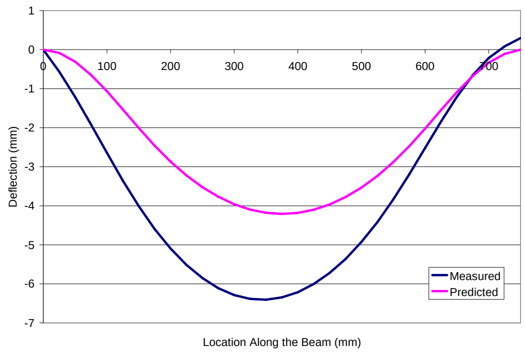


Figure 28. Measured vs. Predicted Deflection Diagram

4.7. Fixed Supports – Uniformly Distributed Load

The supports were fixed and fifteen 200 gram weights were placed at every load hook (50mm spacing). Figures 29 through 32 show the predicted and measured response.

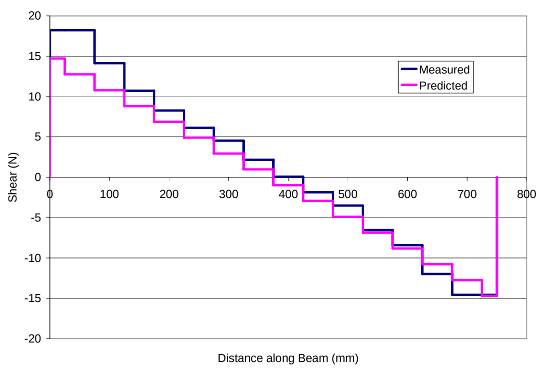


Figure 29. Measured vs. Predicted Shear Diagram

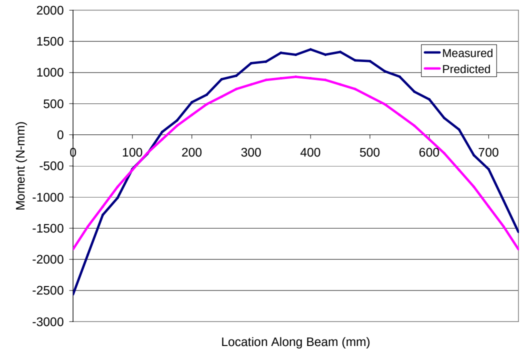


Figure 30. Measured vs. Predicted Moment Diagram

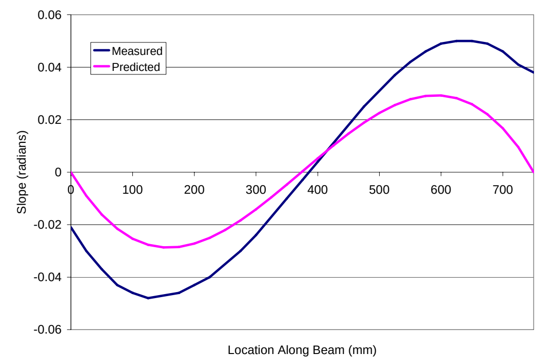


Figure 31. Measured vs. Predicted Slope Diagram

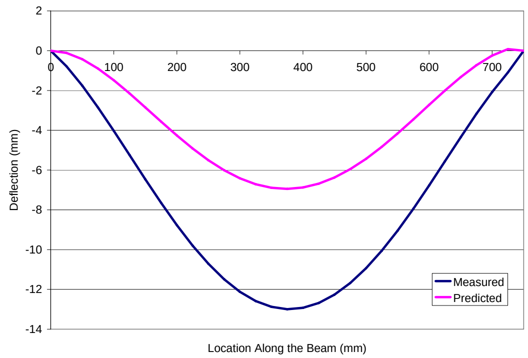


Figure 32. Measured vs. Predicted Deflection Diagram

Appendix A - LabVIEW Program

a. General Structure of the Program

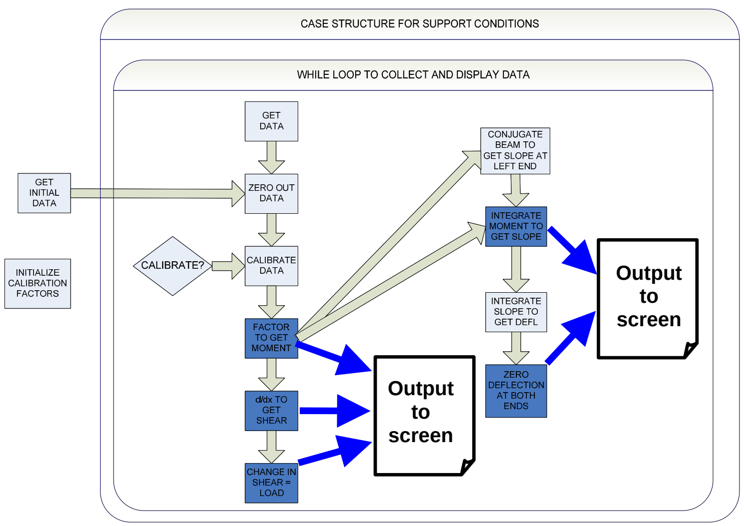


Figure 33. Schematic Representation of LabVIEW Program

b. Theory Behind Calculations

The following is a list of assumptions that the LabVIEW program is based on:

a. The strain distribution is linear and anti-symmetric about the beam mid-depth.
b. As a corollary to the first point, it is assumed that there is no axial load in the beam.
c. The beam is assumed to be of constant cross-section along its entire length.
d. Shear deformations are negligible.
e. Plane sections remain plane.
f. Any other assumptions included in Bernoulli-Euler Beam Theory.

The following is some additional description of the steps involved in the LabVIEW program:

a. The readings of strain along the bottom of the beam were multiplied by a factor to get moment. The relationship between extreme fiber strain and moment was found to be:

$$M = \varepsilon\left(E\frac{t^2}{6}b\right) = \varepsilon * 2{,}895{,}995 \text{ (N-mm)}$$

Where E=modulus of elasticity = 68,948 N/mm^2 (10,000 ksi)
T=3.175mm (1/8")
B=25mm (1")

b. The moment is differentiated to get shear. Since the slope of the moment diagram has a discrete value between each strain gage, the shear diagram is a series of flat lines at each slope value. Theoretically there should be no changes in shear at the strain gage that is between load points, so the two shear values between load points are averaged together. See the section below on challenges for a discussion of beam torsion.
c. The difference in shear at a load point is the measured load. Differentiating has the effect of amplifying noise or inconsistencies in the measured response such that the shear and load diagrams are generally the least accurate of the values displayed.
d. Going in the other direction, the moment is integrated to get the slope diagram. To obtain the slope value at the left end of the beam, conjugate beam analogy is used. The reaction at the left end of the conjugate beam loaded with the M/EI diagram of the physical beam yields the initial slope value.
e. The slope is integrated another time to get the deflection.

c. Additional Programming Notes

The following are some additional notes about the LabVIEW Program:

a. The value of deflection at the left end is subtracted from all of the deflection values to get a zero deflection at the left end. The error in the deflection calculation at the right end is distributed over the length of the beam by subtracting the error, multiplied by the ratio of the current length to the overall length, from the deflection value at each point.

b. For the pinned-pinned program, there are no strain gages at locations 0mm 25mm, 775mm, and 800mm. The moment is assumed to be zero at 0mm and 800mm, and the moment is interpolated between zero and the first moment reading for locations 25mm and 775mm.

c. For the fixed-fixed program, there are no strain gages at locations corresponding to 0mm and 750mm. The moment diagram is extrapolated to find the moment at these locations.

d. Challenges

There were several challenges in developing the beam demonstration. Perhaps the most significant challenge involves torsion in the beam. Either the beam is slightly warped, or the supports are not in the exact same plane, because when the beam is loaded, some amount of torsion is induced in the beam. This is most readily seen in the sawtooth shape of the moment diagram. Since the strain gages are located on alternating sides of the beam centerline, the torsion causes an increase in one reading while reducing the readings of the adjacent gages. Tests were also conducted where the beam was removed from the clamped supports and set on small supports. The reduction in torsion effects was notable.

The linear bearings have considerably more slop than what was hoped. It is clear from the figures shown in sections 4.5, 4.6, and 4.7 that the supports are not fully fixed against rotation. Not only are they allowing rotation, they also contribute to the torsion problem by allowing the support to twist on the bearings.

Appendix B – Ideas for Future Expansion

One of the initial objectives of this project was to allow for the expansion of this beam demonstration to handle other loading methods, measurement methods, and other demonstrations of engineering principles. Some of the ideas for improving the beam demonstration or adding functionality include:

a. The eye hooks could be removed from the beam and a rolling load could be fabricated which demonstrates influence line diagrams.

b. A secondary measurement of displacement could be used to verify the method currently used to calculate deflection. The secondary displacement measurement could consist of a laser based deflection measurement, LVDT, string pot, or even a ruler attached behind the beam.

c. The beam could be loaded with dynamic or impulse loads and the resulting natural frequencies and mode shapes could be examined.

d. The modular support post could be repositioned to create a cantilever span.

e. If the linear bearings were improved, a demonstration of the moment distribution method would be possible – locking and unlocking rotation fixity and observing the moment distribution.

f. If the fixed support configurations are to be used in earnest, it is suggested that the linear bearings be replaced with more precise linear bearings. The amount of slop in the bearings seems to pollute the results.

g. To avoid the affect of torsion, strain gages could be added on the other side of the beam centerline and the two readings could be averaged. It is expected that this would greatly improve the accuracy of the shear and load diagrams and negate the effect of torsion. If the data acquisition requirements associated with 43 gages is considered too burdensome, the gages at the load points only could be used to keep the channel requirements below 30.

h. A more mobile data acquisition system could be created. Dedicated terminal boxes could be attached to the side of the modular table. A smaller more portable NI data acquisition system could be used rather than the full SCXI chassis and modules.

i. There were a couple improvements to the modular table that were not completed due to time restrictions. A cable tray was planned to keep the beam from having to support the weight of the wires. Also, a shelf beneath the table surface was planned. Neither of these items were accomplished.

j. A low budget way to track beam deflection would be adding a poster board with a grid behind the beam. Not only could deflection be more readily observed, the location along the length of the beam could be marked.

k. The program could be modified to allow a snapshot of the graphs for a particular loading to be saved while the loading is changed. This would allow the graphs for two loading configurations to be readily compared.

l. The program currently is set up to handle pinned-pinned, and fixed-fixed support conditions. The program could be modified to handle fixed-pinned support conditions.

Appendix C – Materials, Costs, and Drawings

The following pages include material lists, costs, and drawings generated during the completion of this project.