Improved Student Understanding of Materials and Structures through Non-Traditional Laboratory Project

Andrew Assadollahi[1] and Adel Abdelnaby[2]

Abstract - A final project of the mechanics of materials laboratory was assigned to junior level students with the object of having students develop hands-on experimental research skills and an improved understanding of the characteristics of both structures and materials. In this project, students were divided into groups and each group was given a small cantilever steel beam. The beams were tested at the University of Memphis Structures Laboratory testing facility by subjecting them to monotonic and cyclic displacements at the cantilever free end. Students participated in the testing as well as the design and selection of test instrumentation. The flexural stiffness, strength and hysteretic behavior of the beams were evaluated experimentally and the measured response (from the experiment) was compared with the closed form solution predictions. Finally, the ability of the students to work in groups and design and conduct an experiment with minimal guidelines was measured and their skill of analyzing and interpreting the test results was assessed. The enhancement of students understanding of materials and structures characteristics by performing non-traditional laboratory projects is presented.

Keywords: Solid Mechanics, Structural Mechanics, Design Experiment, Hysteretic Behavior, Engineering Judgment

INTRODUCTION

In engineering academia, the incorporation of research projects in undergraduate courses has always been a topic of discussion. Some scholars believe that the undergraduate courses should be dedicated only to teaching the fundamentals of a topic, while others believe that there should be a balance of teaching fundamental topics with students performing independent or group research projects. In the junior-level mechanics of materials laboratory course at the University of Memphis, students were given a group design project to help develop experimental research skills, better understanding of the behavior of both structures and materials, and improve engineering judgment. The objectives of this study are to assess the ability of the students to design and conduct an experiment and determine students' skills of analyzing and interpreting the experimental test results with minimum background information and parameters.

In engineering courses and laboratories, many parameters are given to students in order to solve a problem. In engineering practice, oftentimes ideal parameters are not readily available. Solving most "real life" problems requires the use of engineering judgment. If students are always given ideal parameters to work with, creativity tends to be impeded and the development of engineering judgment is delayed.

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In this project, three groups were given a small cantilever steel beam. The beams were tested at the University of Memphis Structures Laboratory testing facility by subjecting them to monotonic and cyclic displacements at the cantilever free end. Students participated in the testing as well as the design and selection of test instrumentation. The flexural stiffness, strength and hysteretic behavior of the beams were evaluated experimentally and the experimental measured response was compared with predictions made by each group. The ability of the students to work in groups and design and conduct an experiment, with minimum background information and parameters, is measured and their skill of analyzing and interpreting the test results is assessed.

PROGRAM OBJECTIVES

The first objective for the student groups in this project was to determine, understand, and explain the modes of failure that the beam specimen experienced. The second objective was to estimate material properties (modulus of elasticity, yield stress, and ultimate stress). Lastly, the final objective was to criticize the experimental setup and design a new experimental setup indicating the advantages and disadvantages of the new experimental setup.

EXPERIMENTAL APPARATUS

An HSS beam was welded to a small plate using two pieces of angle iron. The small plate was bolted to a larger plate which was bolted to two plates on the flanges of a load frame. The actuator which applied the loads was bolted to a small plate, which was welded to the free end of the beam specimen. Figure 1 shows the experimental setup.

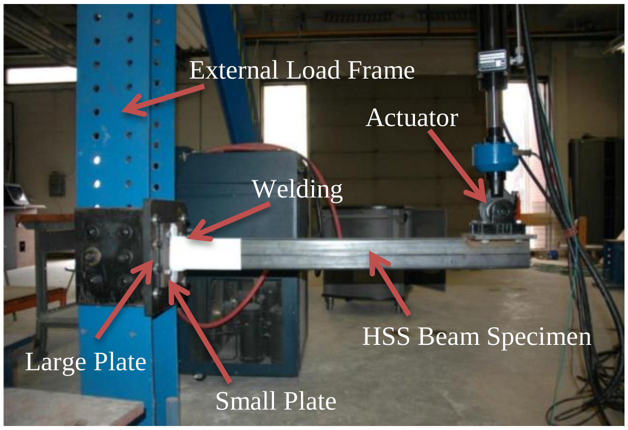


Figure 1. Experimental Apparatus.

TESTING EQUIPMENT

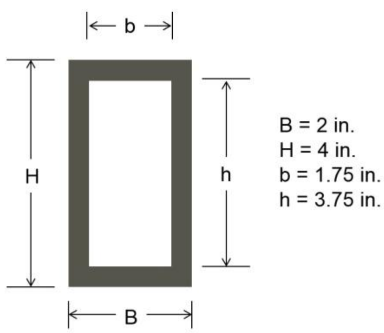
The original test experiment and proposed design experiment both used a hydraulic system to apply the force to cantilever beam. There were three testing components: the control system, hydraulic pump, and hydraulic actuator. The controller software (Figure 2a) includes: single channel component testing, multi-channel component testing, road data replication, civil engineering test suite, and seismic simulation. The source of power for the testing equipment was the hydraulic pump (Figure 2b), which uses pressurized oil to apply force through the actuator in the hydraulic system. The unit used to apply to force from the pump is the hydraulic actuator. The actuator was connected to the top of the rigid load frame. The actuator has a stroke length of ± 10 inches; a force capability of 15/24 kips (tension/compression). Figure 2c shows the actuator that was used in the test connected to the rigid support frame. Additional information on the testing equipment can be found at [Shorewestern, 4]. The beam is an A36 steel HSS section. Figure 3a shows the cross-section dimensions of the beam specimen. Figure 3b shows a profile view of the beam specimen with dimensions.

a. Control System

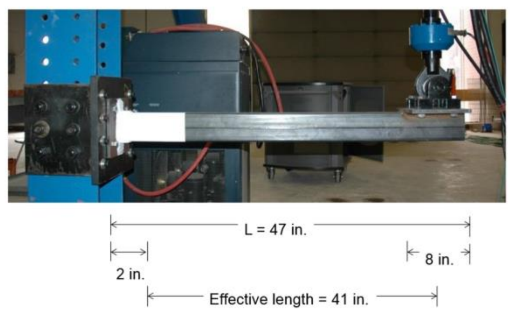
b. Hydraulic Pump.

c. Actuator

Figure 2. Testing Equipment



a. Beam Specimen Cross-Section



b. Beam Specimen with Loading Dimensions

Figure 3. Beam Specimen

EXPERIMENTAL AND ANALYTICAL DATA

The test was conducted using the displacement control approach where the specimen was subjected to specified displacement history while the resultant reaction forces from the specimen were measured. Three sets of cyclic displacements that represent three (design) limit states are applied on the beam free end, namely: (1) elastic beam response (serviceability limit state); (2) first yielding; and (3) local flange and web buckling. The limit states were predicted from a fiber-based finite element analysis of the beam specimen using the commercial open source software, Zeus-NL [Elnashai et al, 3]. This analytical tool is capable of performing the beam analysis incorporating material inelasticity and geometric imperfections. The material inelasticity was depicted using a bilinear steel stress-strain relationship at each fiber of the beam section and along its entire length.

The first, second and third sets consisted of three +/- 0.5, 2.0, 4.0 inches displacement cycles respectively. After these cycles were imposed on the specimen, additional larger displacement excursions were applied till the complete beam collapse. Figure 4 shows a comparison between the analytical predictions and experimental results of the force-displacement hysteresis. It was observed that the analytical predictions (using Zeus-NL [Elnashai et al, 3]) overestimated the stiffness since a fully fixed connection was assumed. In addition, the numerical model did not capture material strain hardening, local buckling, and strength and stiffness degradation as well as steel fracture.

The beam response to the imposed three sets displacement cycles can be summarized as follows: (a) the beam remained in the linear elastic in the first set of cycles of +/- 0.5 inches; (b) during the second set of cycles (+/- 2 inches) the first steel fiber yielding was observed at 1100 lbs force; finally (c) the beam reached its maximum strength (~2500 lbs) at the end of the first excursion, then at the first load reversal the initial local buckling of the bottom flange and web occurred [Dawe et al, 2]. Larger displacement excursions were then applied to better understand the beam behavior up to the complete collapse point. The failure modes of first yield, initial web and flange local buckling, first fracture, and collapse points are marked on the experimental load-displacement plot (Figure 4). It is worth noting that there has been dramatic loss of stiffness and strength in the specimen due to repeated displacement cycles. This damage feature of stiffness and strength degradation was not captured by the numerical model [Abdelnaby, 1].

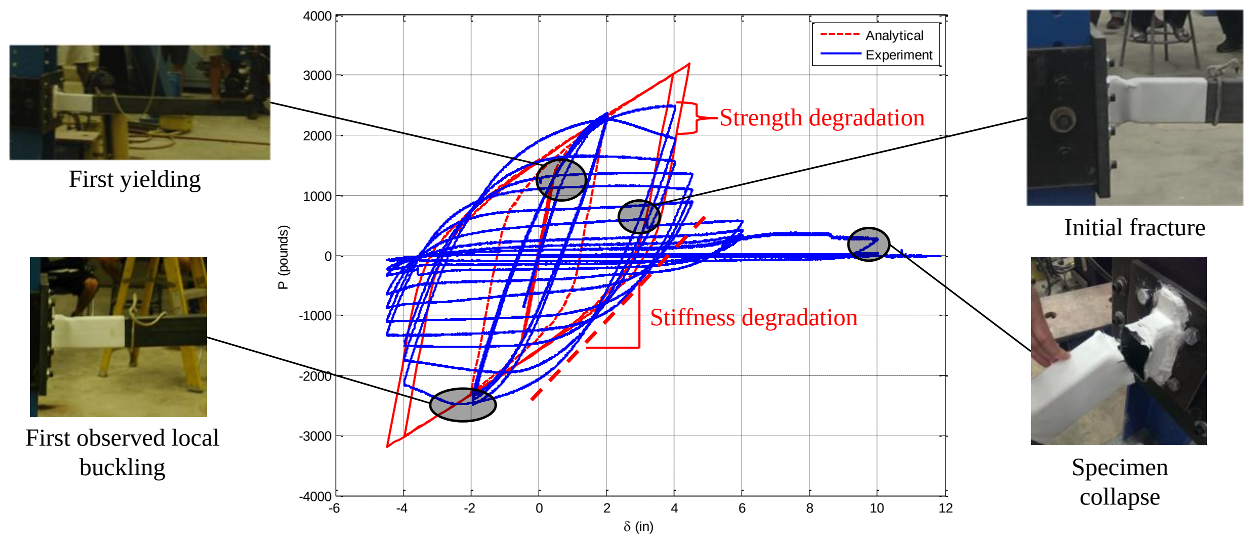


Figure 4. Testing Data and Analytical Predictions

GROUP PERSPECTIVES BEFORE EXPERIMENT

Before the experiment was conducted, the groups were required to predict possible modes of failure that could occur during the experiment. This was done to have a better understanding on students' expectations on the beam failure behavior utilizing the skills they have gained during their previous classes (Mechanics of Materials, Steel Design, and Structural Analysis) and labs (Strength of Materials). Figure 5 shows some sketches and descriptions of the predicted failure modes that were made by the students.

It is seen that some students expected the failure of the beam in the mid-span as well as at the free end location. Other students predicted failure of bolts and welds. In the entire class, no concise description of the expected failure modes was provided by the students before the test was conducted. This indicates that students lacked the fundamentals of understanding the failure behavior of cantilever steel beams when subjected to cyclic loading and also confirms that what students have been taught in class was not reflected in this practical engineering problem.

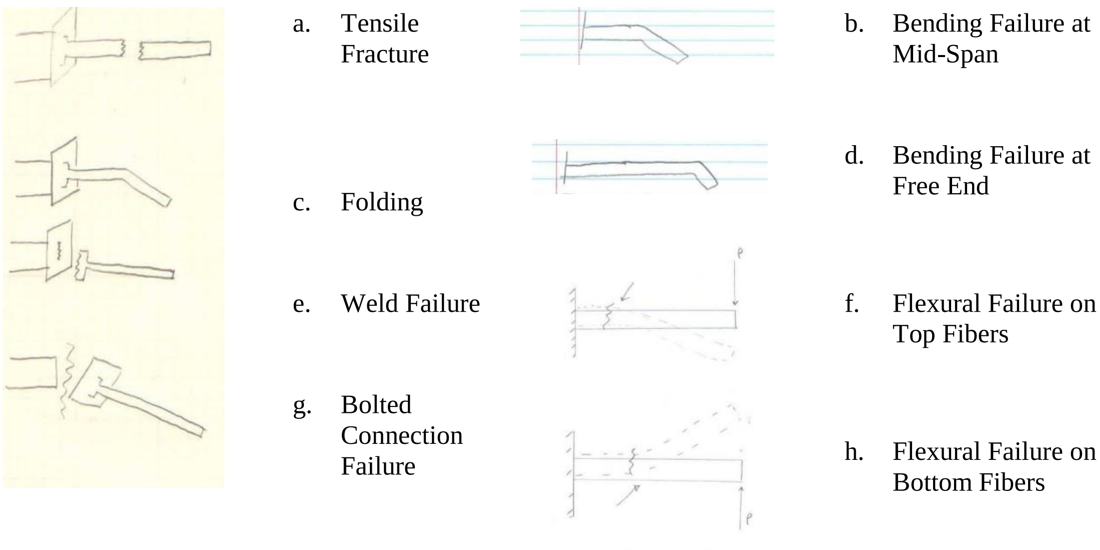


Figure 5. Predicted Failure Modes.

GROUP PERSPECTIVES AFTER EXPERIMENT

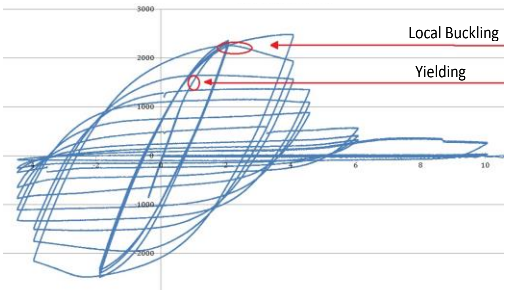
Each of the three groups described the observed modes of failure and calculated section and material properties based on the experimental test results. Finally, each group critiqued the experimental apparatus and provided their own conceptual experimental set-up to accomplish the same task. Based on the descriptions of the actual modes of failure, the calculations of the section and material properties, and the experimental apparatus design, the level of understanding of each group of the experiment can be assessed.

Group 1 Results

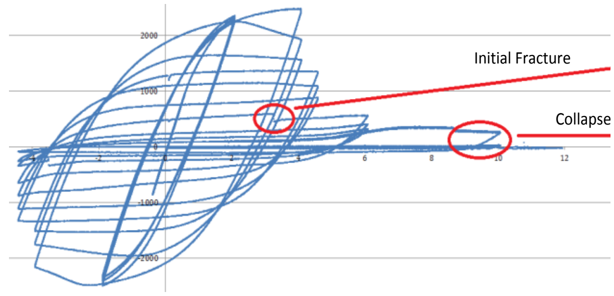
After the experiment was conducted, Group 1 stated that the beam specimen experienced yielding, local buckling, fracturing, and collapse. They provided the load-deflection data to describe each of the modes of failure. Figure 6a shows the points on the load-deflection diagram at which the beam specimen began to yield and buckle, according to Group 1. Figure 6b shows the points on the load-deflection diagram at which the beam specimen first fractured then collapsed.

Group 1 was able to determine the beam properties by taking measurements of the specimen and using the data from the load-deflection diagram. Group 1 calculated the modulus of elasticity based on the linear portion of the load-deflection diagram as 140 GPa. The yield stress was computed as 220 MPa and the ultimate stress was computed as 600 MPa. Since the material was known to be steel (typically with a modulus of elasticity of 200 GPa), there is a 30% error in the value computed by Group 1. Group 1 stated that error could have been introduced from reading values from the load-deflection diagram incorrectly. They also stated "the value for the modulus of elasticity would always be lower in this experiment because the bolts used to connect the specimen to the strong reaction frame have some flexural ability, therefore, reducing the amount of actual deflection in the specimen."

The final part of this project required the groups to criticize the current experimental set-up and develop their own hypothetical set-up, to accomplish the same tasks. Group 1 first considered how to obtain more accurate results for the modulus of elasticity and other required calculations. Group 1 proposed to use a simply-supported beam apparatus instead of a cantilever apparatus. The simply-supported apparatus will be oriented perpendicular to the load frame will be loaded with the actuator placed at the mid-span. Figure 6 shows the experimental apparatus proposed by Group 1.



a. Specimen Yielding and Buckling.



b. Specimen Fracture and Collapse.

Figure 6. Failure Modes for Group 1.

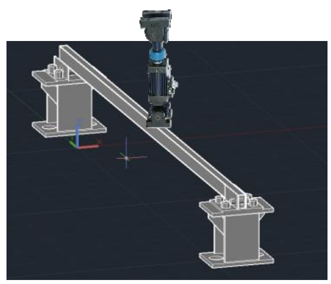


Figure 7. Proposed Apparatus for Group 1.

Group 1 discussed that switching to a simply-supported beam allows for no undesired rotation like that of the cantilever at the fixed end, which yielded low Modulus of Elasticity results because of the rotation allowed by bolts and plates used to connect the beam at the rigid support. Group 1 discussed that the hydraulic actuator may only apply a downward force and then returns to the datum at which it started due to the roller connection. This will result in hysteresis on the load-deflection curve, only in the positive quadrant, on the right side of the graph. This is also beneficial to the experiment in that it makes it somewhat easier to view the data and resolve required calculations. The use of a pin connection will result in some shear force at the actual connection itself. The proposed design is also likely to fail in ductile fracture as seen in the cantilever beam. Another benefit of using the simple supported beam is the cost factor. With a simple supported beam, the number of bolts required is reduced from 24 to 8. Also, the likelihood of a weld not meeting the required strength can be ignored in the simple supported structure because the only weld connection is a plate in the center of beam used to apply the load. Since there will be a constant downward load where the weld is located it is unlikely to see a failure in the weld itself. The proposed design will yield in more accurate results for Modulus of Elasticity and a cheaper design.

Group 2 Results

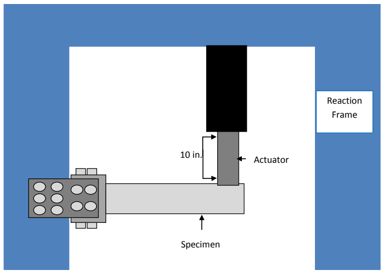
Group 2 stated that the beam specimen failed in shear, due to fatigue and wear. Group 2 stated that the beam specimen first experienced fatigue, leading to plastic deformation, then eventually ductile fracture at the fixed end.

By using the data and hysteresis graph, Group 2 was able to determine the point of first yield in the material. This occurred when the applied load was 1.1 kips. To ensure only the linear-elastic portion of the loading was analyzed in the calculation of the modulus of elasticity, only data up to 90% of the yield load was selected. Group 2 developed the same load-deflection diagram as Group 1. From the data, Group 2 determined the yield moment to be 45.1 kip-in, the yield stress to be 30.3 ksi, the ultimate force to be 2.5 kips, the ultimate moment to be 102.7 kip-in, and the ultimate stress to be 55.5 ksi. The modulus of elasticity was calculated as 14,324 ksi.

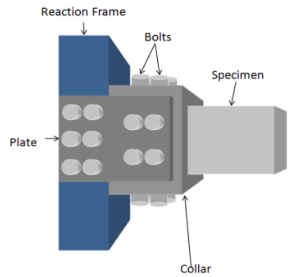
Group 2 discussed that there was a percent error of approximately 51% for the modulus of elasticity calculations. They stated that this could be due to small amounts of rotations at the fixed connections as well as slight asymmetrical loading.

As a criticism to the current experimental set-up Group 2 stated that the actuator's stroke as a measure of deflection was inaccurate due to shifting in the connections allowance of rotation in the welds. The actuator was also only able to pull the beam up 5 inches because of the manner in which it was mounted. Since the actuator's full stroke is 20 inches and the beam had to be pushed beyond 5 inches to get to breaking, this lead to asymmetrical loading.

To address these weaknesses, Group 2 proposed a change in the actuator mounting and a different connection of the beam specimen to the load frame. The difference in the position of the actuator allows it to make full use of its 20 inch stroke by allowing the beam to be pushed and pulled 10 inches. The new connection is a completely bolted connection, without the use of any welding. The new, bolted connection allows for very little rotation and shifting of the beam specimen during loading. Figure 8a shows the overview of the proposed experimental set-up. Figure 8b shows a detail of the beam specimen connection to the load frame. Overall this proposed design is aimed at improving the ease at which the test can be performed and increasing accuracy.



a. Proposed Apparatus for Group 2.



b. Connection Detail.

Figure 8. Design Overview for Group 2.

Group 3 Results

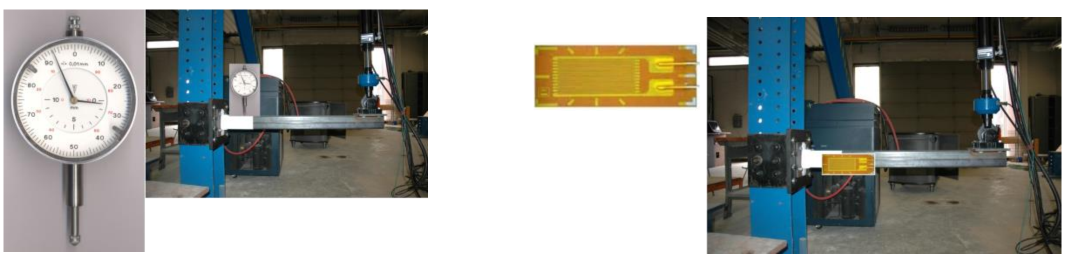
Group 3 stated that when the stresses passed the elastic range, yielding of the specimen occurred and was quickly followed by local buckling. After buckling, the specimen experienced material softening and strength degradation, which was followed by fracturing of the specimen. Group 3 had the same load-deflection figure as Group 1 and Group 2.

Group 3 was able to determine the beam specimen properties by taking measurements of the beam specimen and using the data from the load-deflection diagram. Group 3 calculated the modulus of elasticity based on the linear portion of the load-deflection diagram as 14,300 ksi. The yield stress was computed as 16,000 ksi and the ultimate stress was computed as 55,000 ksi. Since the material was known to be steel, there is a significant error in the value for the yield stress.

Group 3 noted three problems with the experiment. First, the deflections were not uniform. This is a flaw in the experimental setup. The actuator has a 20 in. range; that is, 10 in. of deflection in either direction. The way the experiment was originally set up, the actuator could pull the specimen up 4 in. and push it down 16 in, causing the hysteresis to be skewed to one side and the stresses to be uneven at the top and bottom extreme fiber of the beam. The simple correction would be to move the weld plates holding the specimen further down the load frame, but they were already on the lowest setting. There are two ways to fix this problem: either the horizontal member of the strong reaction frame could have been moved up, or the location of the specimen and the actuator could have been rotated 90 degrees. Figure 9 shows the beam specimen rotated 90 degrees, provided by Group 3.

Figure 9. First Proposed Experimental Apparatus.

Switching the location of the specimen and actuator is the recommended solution to this problem. The second flaw in the original experiment that Group 3 noted is that the steel plates, welds, and load frame still undergo some deformation under loading. The original experimental setup does not account for these deformations, so the data implies a lower modulus of elasticity than the specimen actually has. To correct this, a device for measuring small deflections can be attached to the beam just outside the welded angle irons, with a time-based data recorder fed into the computer system running the actuator. The actual deflections of the beam would be the deflections measured by the actuator minus the deflections indicated by the proposed device. The third flaw with the original experiment that Group 3 stated was that the test yields data in terms of load and deflection, as opposed to stress and strain. They proposed that a strain gage be attached to the specimen near the welds to acquire data in terms of stress and strain. Figure 10 shows another proposed experimental apparatus from Group 3, which includes a dial gage (Figure 10a) and strain gage (Figure 10b).



a. Use of Dial Gage.

b. Use of Strain Gage.

Figure 10. Second and Third Proposed Experimental Apparatus.

Conclusions

In this study, a final project was assigned to junior level students to enhance their understanding of structures behavior in the elastic and inelastic ranges till the complete collapse. In this project, a cantilever beam was tested under cyclic displacement using a hydraulic actuator. The class was divided into three groups and each group was required to (1) predict the failure behavior of the beam before the test; (2) perform the test and interpret the data to determine the beam properties; (3) criticize the existing experimental setup; and (4) design their own setup that provides less cost and complexity. The groups' predictions before the test indicated that the students lacked the fundamental knowledge of the behavior of structures under large load excursions (post the elastic range of the material). It also confirmed that the students' skills gained from previous classes in solving design and assessment problems of structural systems (without fully understanding their response behavior) were not reflected in their predictions.

In the final reports and after the test was conducted, all three groups demonstrated a basic understanding of the design experiment. Group 1 appeared to have the most firm grasp on the overall objectives of the project. They demonstrated the ability to locate and understand the key points of the data. They also concisely described the actual modes of failure. The hypothetical design apparatus was presented clearly and concisely and showed a deep level of thinking. Group 2 lacked much detail in the final report. They failed to locate the key points of the data on the load-deflection plot. They did not clearly define and describe the beam behavior during the test and they did not state the modes of failure in sufficient detail. Lastly, Group 2 did not provide sufficient detail for their proposed experimental apparatus. Group 3 demonstrated a strong grasp of the project objectives. Although, their modes of failure and sequence of specimen damage was not well presented. Their experimental apparatus also lacked detail. In addition, none of the groups were able capture the degrading response of the beam due to repeated load cycles that was highlighted in Figure 4.

This study provides a method of improving students understanding of materials and structures behavior by using hands-on experience techniques.

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