Designed Beam Deflections Lab Project

Dr. Wei Vian, Purdue University at West Lafayette

Wei Vian is a continuing lecturer in the program of Mechanical Engineering Technology at Purdue University Statewide Kokomo campus. She got her Ph.D from Purdue Polytechnic, Purdue University, West Lafayette. She got her bachelor and master degree both from Eastern Michigan University. Her recent research interests include grain refinement of aluminum alloys, metal casting design, and innovation in engineering technology education.

Prof. Nancy L. Denton PE, CVA3, Purdue Polytechnic Institute

Nancy L. Denton is a professor in Purdue University's School of Engineering Technology, where she serves as associate head. She served on the Vibration Institute's Board of Directors for nine years, and is an active member of the VI Academic and Certification Scheme Committees. She is a Fellow of ASEE and a member of ASME.

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Abstract

Structural mechanics courses generally are challenging for engineering technology students. The comprehensive learning process requires retaining knowledge from prior mechanics, materials, and mathematic courses and connecting theoretical concepts to practical applications. The various methods for determining deflection of the beams, especially statically indeterminate beams, are always hard for students to understand and require substantial effort in and out of class. To improve learning efficacy, enhance content understanding, and increase structural learning interest, a laboratory group project focusing on beam deflections has been designed for strength of materials students.

The project spans design, analysis, construction, and validation testing of a metal bridge. Students design, construct, and test their bridges and do corresponding beam deflection calculations to verify the beam deflection type. Each group provides a technical experimental project report presenting their design idea, sketches, data analysis, and results discussion. Pre-project and post-project surveys focused on learning efficacy, topic understanding, laboratory, and team working were completed by the students. This paper presents the results of both student surveys and the analysis of the related learning outcomes from examinations. Learning outcome achievement was compared to those of previous students who completed a highly structured beam deflection laboratory exercise rather than the beam deflection project.

Keywords: Beam deflection, project-based learning, engineering technology

Background

For mechanical engineering technology (MET) students, and most mechanics students, strength of materials is a conceptually and technically demanding course. Students are required to understand and analyze the deformation of structures of various geometries and materials. Among the topics included in this fundamental structural course, beam stress and deflection are relatively complicated and difficult to grasp. Beam analysis not only requires students to apply their previous strength of materials knowledge, but also apply the fruits of their study of statics, materials and processes, and mathematics. Students generally learn their beam mechanics from lectures, textbook and homework assignments. MET students at Purdue University, in addition, conduct two fully defined beam experiments; a four-point bending experiment for beam stress and a three-point bending experiment for beam deflection. In both cases, the beam is simply-supported and statically determinate. The loadings correspond to ASTM standards for various material property tests but do not accurately represent many real structures [1, 2].

To increase students' learning interest, enhance the understanding of knowledge, and improve their learning outcomes in beam deflection while highlighting the effects of real processes, a group laboratory project has been designed and implemented at the Purdue University Kokomo campus. Students here are primarily commuters, with up to 15 students in a typical engineering technology class, and most classes taught in a studio format. The campus culture tends to emphasize efficient completion of all educational tasks performed by students. As a side benefit of the designed beam deflection laboratory project, students gain experience with a guided open-ended project, beginning preparation for their senior capstone project.

Introduction

The road bridge is a structure familiar to all students, characterized as a beam, and normally made from a combination of steel and concrete. The bridge should be very strong and durable, sustaining variable loads, impacts, vibrations, and surviving its local environmental conditions for many years with routine maintenance. Design engineers address critical construction aspects such as bridge safety, building cost, structure sustainability, durability, material properties (e.g., tensile strength, Young's modulus, yield strength, fatigue, creep, thermal expansion), construction processes such as welding, and geometry. The road bridge can be either statically determinate or indeterminate structure based on its support conditions and processing. In particular, welded joint quality affects the determinacy of the bridge, and cannot consistently be identified [3]. In this designed lab, the bridge loading applied quasi-statically and in a facility with standard ambient conditions.

The explicit goal of the designed beam deflection project is to help students understand and correctly categorize their beam type through the analysis of the beam deflection by cases from beam deflection tables [8]. Students extend theoretical knowledge to personal hands-on built-model and analysis. On the theoretical side, the students explore how to appropriately do beam design, apply the most accurate method to calculate beam deflection toward their designed model, and compare their analytical results to their beam's experimental data. Implicit instructional goals of the project start with the intention of shifting student learning from the lower levels of Bloom's cognitive taxonomy (remembering, understanding, applying), expectations of the existing beam stress and deflection laboratory experiments, to the higher levels (analyzing, evaluating, and to some extent, creating) [4]. Getting students to recognize that theoretical models represent idealistic rather than fully realistic cases is a second implicit project goal. In particular, recognition of the effects of processing on the applicability of the theoretical model was desired.[5] To connect theory and application, students designed and welded the model bridges they tested. Basic welding knowledge and techniques were introduced and practiced in the freshman-level materials and processes course. Affording students the opportunity to draw on relatively disparate learning from previous courses was the third implicit instructional goal for the designed beam deflection project. As the students progress toward their senior capstone integrative experience, this small-scale multi-disciplinary project contributes to establishing the learning scaffolding needed to prepare them for the capstone's broad-based integration of knowledge.[5, 6] This is a great opportunity to connect the previous course learning and hands-on experience to recent study in an applied method.

For the designed beam deflection project, two loading types were used. A concentrated load and a distributed load were separately applied to each bridge. Students were expected to calculate the maximum allowable loading and establish a reasonable initial load based on their beam design analysis. Each loading method was repeated multiple times to get average experimental deformation data values, which would subsequently be compared to calculated theoretical results. Application of analytical methods, comparative analysis, and design factor discussion plus sketches of slope and deflection beam diagrams were the foci of the lab report. Furthermore, recommendations and suggestions for improving future offerings of this designed lab project were required.

Methodology

The nine students in this strength of materials course were assigned to three groups of three students. All students were sophomores and had learned statics and welding previously. The topic of beam deflection starts around three months into the course, nearly the last course topic. Its proximity to the end of the semester limited the project completion to one month. Students were required to design their bridge using CAD software based on the metal beams offered in the lab. All the three teams took two 2-hour lab sessions to process the materials and build their bridges. One lab session was devoted to conducting the lab and collecting the data. Most of the remaining tasks were completed outside of class meetings. The next steps were data analysis, theoretical calculations, and results discussion, culminating in written lab report completion and presentation. Project graded elements and requirements included a pre-project survey, the final report and digital data spreadsheets from each group, an individually submitted peer evaluation form, and a post-project survey submitted with the report.

Project Limitations

The first limitation is about welding. Welding techniques can significantly affect the bridge's quality. Each group welded its own bridge, making inconsistent welds across bridges highly likely. As inexperienced welders, students welded their bridge relatively roughly, with some over-welding. Accounting for the over welding was neglected in the analytical calculations. A second limitation is the expected presence of metal fatigue and residual stress, both of which may affect the deflection testing results. Students discussed these limitations in their lab project reports and presented ideas regarding how to account for them.

Process / Requirements

The materials prepared in the lab for this project are 36 in long AISI 1010 carbon steel square tubes (0.50 in by 0.50 in; nominally 12.5 mm by 12.5 mm) and solid steel plates (3-in width by 4-in length; nominally 76 mm by 112 mm). From the ASTM A513 specification, the material AISI 1010 has an ultimate strength of 45 ksi (312 MPa) corresponding to yield strength of 32 ksi (221MPa) [9]. According to the requirement on project handout, the bridge surface should be a one layer of 18-in (457 mm, length) by 3-in (76.2 mm, width) that included gaps between the material layers. Each end of the bridge is welded to the solid steel plate. Figure 1 presents an orthographic side view and top view from one group's design.

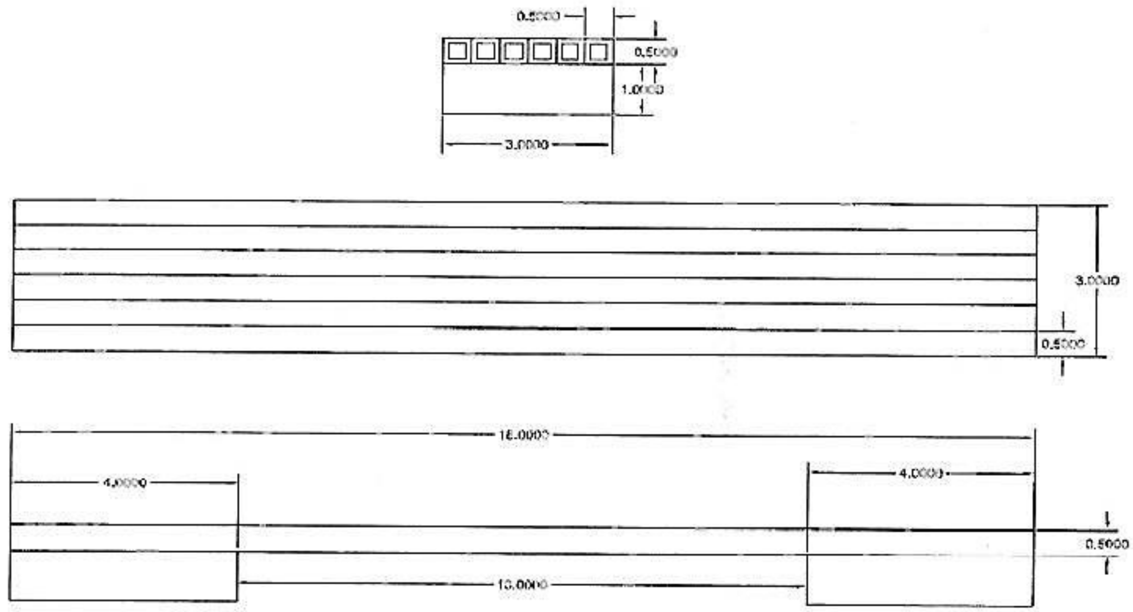

Figure 1: Orthotropic views of one group's bridge design

After sawing the steel tubing, the beams were welded together to form a bridge according to students' design. Figure 2 shows the pictures of the one end side view which also can see the welding spots. Figures 3 and 4 are the welding pictures of bridge suface and side.

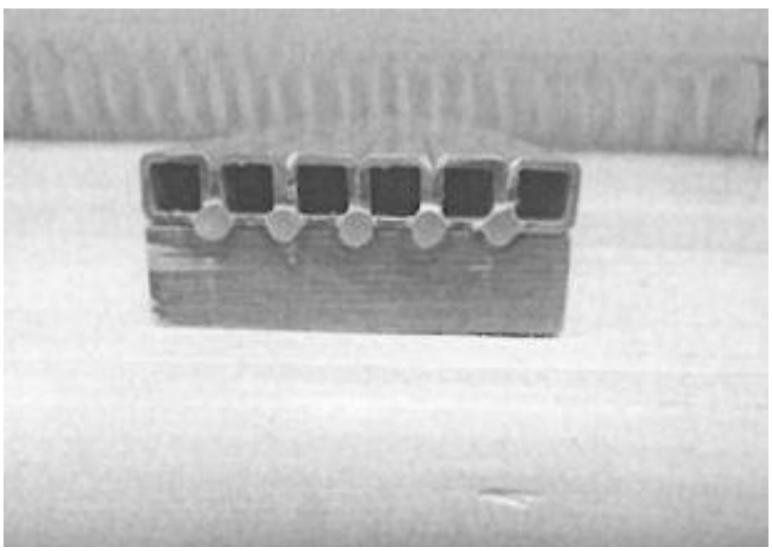

Figure 2: Side view of a beam end that displays the welding locations

Figure 3: Welding of a bridge surface

Figure 4: Welding of a bridge deck

Testing procedure for the designed beam deflection project incorporates two loading cases; a concentrated load at mid-span and a distributed load applied along the full length of the beam. As shown in figure 5, a universal testing machine (UTM) was equipped with custom fixturing to support the students' bridge beams. A 5000 pound load cell (with P-3500 strain indicator for output display) sensed the loading as the UTM's crosshead was lowered. The UTM's position display provided an estimate of beam deflection under load, while a dial indicator gave the beams' direct deflection measurements. At the start of each test cycle, a bridge was placed onto the fixture and the test system was calibrated carefully prior to adding the load. To determine the test loads, the students calculated the maximum allowable loading based on yield strength in flexure. Beginning with

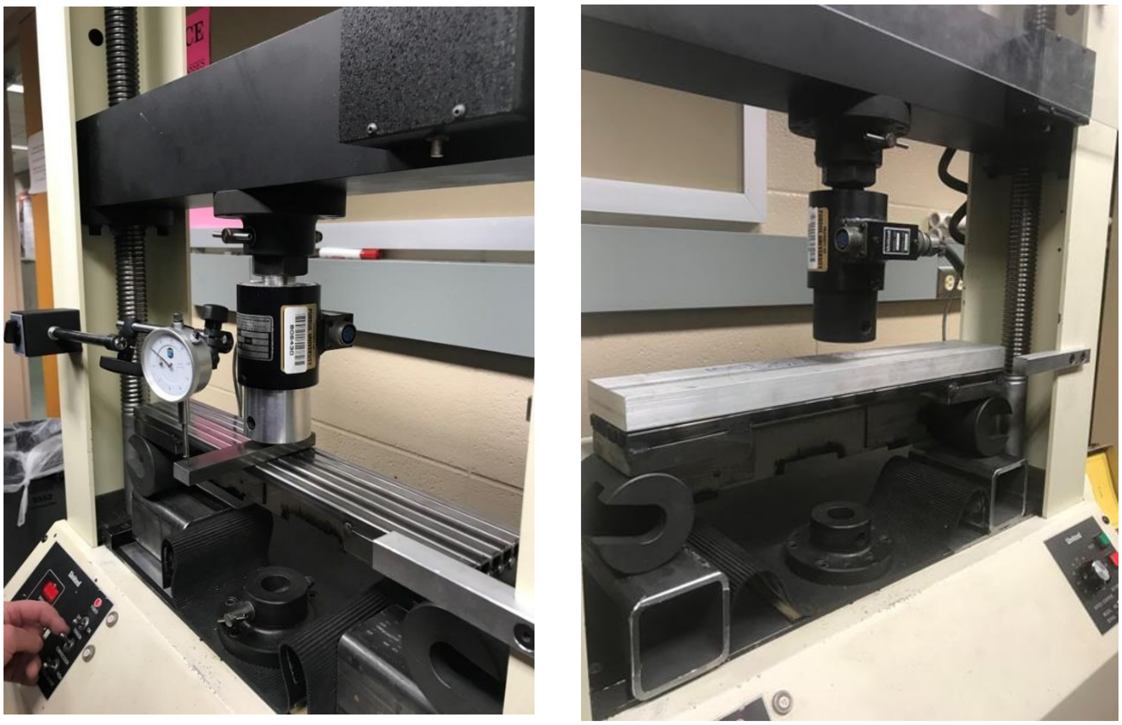

Figure 5: UTM with simply-supported beam under concentrated force loading (left, Case 1) and distributed loading (right. Case 2).

The next step was to calculate the maximum bridge deflection for Case 1 (concentrated load only) and Case 2 (distributed load and concentrated load) by using two sets of equations from the textbook.[14, 15] The equations are for simply supported beam and statically indeterminate beam deflection, using superposition to address combined loading where applicable. Welding effects were neglected in the theoretical deflection calculation, though they may not be negligible.

$$y_{max} = \frac{-PL^3}{48EI}$$ Eqn 1 (concentrated load, statically determinate)

$$y_{max} = \frac{-PL^3}{48EI} + -\frac{5wl^3}{384EI}$$ Eqn 2 (concent+distributed loads, stat. determinate)

$$y_{max} = \frac{-PL^3}{192EI}$$ Eqn 3 (concentrated load, stat indeterminate)

$$y_{max} = \frac{-PL^3}{192EI} + -\frac{5wl^3}{384EI}$$ Eqn 4 (concentrated+dist. load, stat indeterminate)

The theoretical beam deflections for Cases 1 and 2 based on average experimental loading were compared to the experimental value, giving due consideration to percent error effects on the deflection values. From beam deflection tables [8] students then identified which beam loading(s) seemed appropriate for their application and compared the deflection of their bridge to each identified type of beam deflection. To complete the analysis of their beams, students generated traditional slope and deflection diagrams for their beams, corresponding to the maximum experimental loads. Full project documentation took the format of a technical report, including theoretical development, test procedure, analysis, experimental results, and appropriate figures.

Results and Discussion

Based on the students' calculations, two groups thought their bridges were statically determinate structures. There was around 14% difference between the theoretical and experimental deflection values for the beams under concentrated force loading and 7.5% difference when the distributed load was added.

Post-project survey responses indicate most students think they completed this designed project successfully and believe that this project has given them a full understanding of how beam deflections are applied in real world. Beyond human error and calculation approximations, they also understood the geometry, material, and types of loading can affect the beam deflection result significantly through doing this project. The students commented that this lab helped them apply the theoretical knowledge of beam deflection to a real case. Moreover, they enhanced their understanding of welding during the construction process, a valuable project contribution. In the future, the students would choose to remove the inconsistency in the building design and manufacturing process to ensure the repeatable function of the structure. They also would like to develop a better model in CAD software to simulate their testing results.

Table 1 shows the results of the objective design facts portion of the survey, while Table 2 shows the results of the individual opinions toward learning knowledge portion. As indicated by the data in Table 1, more than half of the class thought their design should be an indeterminate beam before they started the project. After they completed the lab, more than half students found their design was a determinate structure. Almost all the students agreed that the force load did not deform the beam permanently before and after the design. The force applied in the laboratory was half of the allowable shear for each designed bridge calculated by the lab. There is also a very tiny difference in answering the rotation tendency question. Since the rotation at the supports has a direct relation to the beam's type, there is instructor doubt that all the students really understand this element. Finally, students all agreed the manufacturing processes can affect the material properties and performance. There is almost no significant change in the pre and post survey results reported in Table 2. Students believe both hands-on lab and team work help to improve their learning.

Table 1: Pre- and post-project survey results (Part a)

Likert-scale Questions in survey	A. Strongly agree		B. Agree		C. Somewhat Agree		D. Disagree	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
The designed bridge is a statically indeterminate beam.	10%	10%	50%	30%	10%	0	30%	60%
The force places on the beam in the lab is in the elastic region	50%	50%	40%	50%	10%	0	0	0
The designed bridge will not have any tendency to rotate during the test.	20%	20%	40%	50%	30%	30%	10%	0
The manufacturing process may affect the tensile strength and stiffness of the material.	60%	20%	40%	80%	0	0	0	0

There are also two multi-item questions in the survey instrument (questions 11 and 12) that address project-specific content impact. The first question asked students to list the major design factor(s) that affect the final beam deflection values. The second question follows up with ratings of the same factors in building process. Table 3 shows the survey results regarding these factors.

Ultimately, the success of an instructional change must account for student learning improvement. Judged solely on that basis, the designed beam deflection project caused an incremental increase in student achievement of their course learning objective with respect to deflection in statically determinate structures, as shown in Table 4. If this was the only benefit to the designed beam deflection project, the motivation to continue with its implementation is low. When implicit benefits are also considered, the project brings value to the MET curriculum. Students gain an understanding of the interactions between theory and practice, design and production, and we believe this type of project sets up the learning scaffolding students will need to thrive when doing their senior capstone projects.

Table 2: Pre- and post-project survey results (Part b)

Likert-scale Questions in survey	A. Strongly agree		B. Agree		C. Somewhat Agree		D. Disagree	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
The joining method may affect the performance and quality of the product.	80%	50%	20%	30%	0	20%	0	0
Hands-on lab projects increase my learning interest.	40%	30%	60%	70%	0	0	0	0
Hands-on lab projects improve my critical thinking skills.	40%	80%	40%	20%	20%	0	0	0
Hands-on lab projects help me to learn and understand course knowledge	30%	50%	60%	30%	10%	20%	0	0
Working with other students on a team improves my experimental project experience	10%	60%	60%	40%	20%	0	10%	0
Experimental research intrigues me.	30%	30%	60%	40%	10%	30%	0	0

Table 3: Design and Process Factor Effects on Beam Deflection

Major Design Factor in Pre-Survey	*Number*
Spaces between the beams	1
Other structure design concern	7
Welding quality	1
Support design	1
Major Design Factor in Post-Survey	*Number*
Welding quality and techniques	9
Major Processing Factor in Pre-Survey	*Number*
Spaces between the beams	3
Structure manufacturing quality	2
Welding quality	4
Material selection	3
Weld locations	2
Calculation accuracy	1
Major Processing Factor in Post-Survey	*Number*
Spaces between the beams	1
Welding methods and quality	7
Beam supports	1
Material processing	1
Welding location and spots	1
Structure improvement (truss design)	3

Table 4: Learning Objective Assessments for beam deflection

Assessment – Calculate deflection in statically determinate structures	2018	2019
Final exam	78%	81%
Three-Point bending Lab	92%	93%
Flexural strain (Four-point bending) Lab	88%	90%

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Appendix

A. ASTM standard 513 - Standard Specification for Electric-Resistance-Welded Carbon and Alloy Steel Mechanical Tubing1

	Yield Strength, ksi [MPa], min	Ultimate Strength, ksi [MPa], min	Elongation in 2 in. [50 mm], %, min	RB min	RB max
		As-Welded Tubing			
1008	30 [205]	42 [290]	15	50	
1009	30 [205]	42 [290]	15	50	
1010	32 [220]	45 [310]	15	55	
1015	35 [240]	48 [330]	15	58	
1020	38 [260]	52 [360]	12	62	
1021	40 [275]	54 [370]	12	62	

B. Group Project Questionnaire
(Q1-10, Likert scale, 5 choices from strongly agrees to strongly disagree).

1. The designed bridge is a statically indeterminate beam.
2. The force placed on the beam in the lab is in the elastic region.
3. The designed bridge will not have any tendency to rotate during the test.
4. The manufacturing process may affect the tensile strength and stiffness of the material.
5. The joining method may affect the performance and quality of the product.
6. Hands-on lab projects increase my learning interest.
7. Hands-on lab projects improve my critical thinking skills.
8. Hands-on lab projects help me to learn and understand course knowledge.
9. Working with other students on a team improves my experimental project experience (when compared to doing an individual research project).
10. Experimental research intrigues me.
11. Which factor(s) in your design may affect your final result?
12. Which factor(s) in your building process may affect your final result?