VISUALIZATION, EXPERIMENTATION AND DISCUSSION: A TEACHING STRATEGY FOR TEACHING-LEARNING OF MECHANICS OF MATERIALS

Jorge Montoya

Universidad de Ibagué (COLOMBIA)

Abstract

An inductive-deductive-inductive pedagogical approach was taken in a mechanics of materials course. The first inductive phase consisted of visualization and experimentation with a simple physical model. The second inductive phase consisted of problem solving and physical model development. The two inductive phases were bridged with a more deductive development of the constitutive equations. The implementation of this approach in a course that previously only used lecture resulted in a significant increase in the student passing rate and decrease in the number of withdrawals. The importance of the three phases is discussed.

1 INTRODUCTION

The development of conceptual understanding of and practical application of phenomena associated with mechanics of materials are fundamental to students’ academic training and their subsequent professional performance in a number of engineering fields, including structures in the civil engineering. Students’ acquisition of the basic knowledge of stress and strain relationships in a Mechanics of Materials course presents a challenge for engineering professors and students due to the highly analytic and theoretical content that often appears to students to be in opposition to their lived experiences with objects (Brown, 2013). It is well documented in the literature that students have misconceptions about these phenomena (e.g., Montfort, Brown, & Pollock, 2009). Students’ struggles to understand and demonstrate proficiency with the content may be a factor in high failure and dropout rates from mechanics of materials courses. Low academic performance in and a high dropout rate from a mechanics of material course were the drivers for this study.

Mechanics of materials must be understood as an integrated collection of its parts. All sub-topics must relate to the global connection of stress and strain. Observations and studies have demonstrated that students have difficulty observing this global connection and even the brightest students have difficulty remembering some concepts shortly after taking a course (Burns & Egelhoff, 2011). Most students have little to no practical experiences with the theoretical-mathematical content. Theoretical and mathematical representations require comparison, as well as physical and visual proof, to guarantee and favor adequate knowledge appropriation (Roylance, Jenkins, & Khanna, 2001).

Mechanics of Materials courses in most engineering programs, including civil engineering, employ the traditional method of classroom lectures. Yet, evidence points to the classroom lecture approach in engineering courses being ineffective - not leading to the development of advanced problem solving skills, not generating creative or critical thought, and not preparing students for the types of problems they will confront during professional life (Johnson, 1999). Further, theory, presented on its own, has led to lower levels of comprehension and motivation and, consequently, higher rates of failure and withdrawal (Mahendran, 1995). In moving towards more active approaches to instruction, a balance must be found between students’ active participation in their knowledge acquisition and the professor’s role in and out of the classroom. In finding this balance, it is necessary that the professor consider that each student has a preferred way of learning, particularly visualization and construction of models (Felder & Silverman, 1988). A balance must be struck in instructional methods between engaging students in real-life situations, theories, and mathematical models, thus permitting students to gain and demonstrate comprehension within and across the different representations. That is, it is recommended there be a balance between concrete and abstract information conveyed in a course (Felder, Woods, Stice, & Rugarcia, 2000).

The intervention used in this study had two parts: the inductive-deductive-inductive active learning pedagogical approach used in the classroom instruction and a team project that continued the inductive pedagogical approach. An inductive approach to teaching and learning starts with students making observations and experimenting; the instructor then guides students to general principles.
Whereas, a deductive teaching and learning approach starts with instructors presenting the general principles and then moving on to applications of those principles. Engineering instruction has a long tradition of being deductive in nature, with the instructor at the center of learning (teacher-centered). Inductive instruction, in contrast, puts students at the center, requiring them to fit new information into their cognitive structures. Inductive instructional methods all involve active learning (e.g., discussion and problem solving) and collaborative or cooperative learning (working in groups) (Prince and Felder, 2006). Such instructional methods are grounded in cognitive constructivism (originating with Piaget, 1972), which says learning is the result of processing one's experiences, and social constructivism (e.g., Vygotsky, 1978), which focuses on language and interactions with others as a means of making sense of one's experiences. Evidence that inductive teaching and learning approaches have positive impacts on students' education are convincing. For example, Freeman et al. (2014), in a meta-analysis of 225 studies of traditional lecturing versus active learning in undergraduate science, technology, engineering, and mathematics (STEM) courses, found that average examination scores significantly increased and failure rates decreased.

In the context of this study, it was evident that a new pedagogical approach was needed in the Mechanics of Materials course to promote deeper learning of the course content. The overarching goals of adopting a new pedagogical approach were to reduce the number of students failing and dropping the course, increase the students' conceptual and analytical capacity, and improve academic performance in advanced courses in the area of structures in civil engineering. In keeping with an inductive approach, it was desired that students take a greater lead in their learning process and the professor more often assume the role of facilitator and guide, without giving up conceptual and mathematical rigor.

1.1 Research Questions

In this study, we sought to quantitatively determine whether an inductive-deductive-inductive learning pedagogical approach used in a Mechanics of Materials course resulted in a change in the percent of students passing and dropping the course and the academic performance of the students completing the course. In this study we also sought to understand how much time the professor and students were active when the inductive-deductive-inductive active learning pedagogical approach was used in the classroom.

2 METHODOLOGY

2.1 Setting and Participants

This study was conducted in a typical mechanics of materials course in a 5-year civil engineering program offered at a small private university in Colombia. Students enrolled in this course were in their fifth semester of the program. The two course sections offered in 2011B and 2012A, where A and B represent first and second semester of the academic year respectively, served as the Control for this study. Treatment 1 (described below) for this study occurred in the three sections offered in 2012B, 2013A, and 2013B. Treatment 2 occurred in the five sections offered in 2014A (two sections), 2014B (one section), and 2015A (two sections). Section size ranged from 29 to 45 students. The total enrolment across the treatment sections was 297 students. There were 82 students in the Control group, 114 in Treatment 1, and 183 in Treatment 2.

This course met 3 times a week for 120 minutes each. There was no formal lab activity for this course. For the Control, the course was taught in a teacher-centered fashion; class time was spent in lecture and in application exercises, mainly done by the instructor with students taking notes and asking for clarification. For the Treatments, the course was student-centered, with the role of the teacher being primarily facilitator. Lectures were given at the beginning of a new topic. For the Control, the final course grade was in three parts: 60% for written exams (one for each third of the semester), 10% for independent problem solving (during the whole semester), and 30% for a final theoretical group project, done mainly in the last 4 weeks of the semester. For the Treatments, the final course grade was divided into three parts: 20% for class participation and team problem solving, 30% for the final team project, and 50% for written exams. There were three written exams, each covering a third of the semester's content. The team project began in the second week and was submitted in the last week of the semester.

Three main topics (stress, strain and axial load; torsion; and flexion stress and strain) linked to seven phenomena or material properties were selected to be taught using the intervention described in detail.
below. Other course topics (e.g. flexural moment, shear force diagrams, and stress transformation) were taught in a traditional fashion, as they were deemed more difficult to physically represent.

2.2 Inductive-Deductive-Inductive Teaching and Learning Intervention

An inductive-deductive-inductive (I-D-I) pedagogical approach was employed to engage students in the construction of knowledge related to select mechanics of materials concepts. The elements of this approach are shown in Figure 1. To support inductive learning, the professor brought simple physical models to the class sessions to demonstrate and allow students to visualize and experiment with a concept being studied. The physical models were used to create a space for discussion of the physical manifestation of the concept. Once the students demonstrated understanding of the concept, the instructor, through a mix of inductive and deductive approaches, led the students through the development of the constitutive equations. The learning strategy then switched to a more deductive, though still active, approach. The instructor led the solving of example problems. Switching back to a more inductive approach, students working in groups solved additional application problems in class. Finally, continuing with an inductive approach, the students, working in groups on the course project, designed and constructed a more complex physical model to deepen their understanding of one concept.

![Figure 1: Inductive-deductive-inductive pedagogical approach elements.](image)

Visualization of and experimentation with each concept (phenomena or property) was made possible through the use of a simple physical model (Figures 2a-b). Each model was made of a visibly deformable material so that the concept presented and discussed was visible to the students’ naked eyes. For example, cylindrical polyisobutylene rubber (Figure 2a) of various diameters between 8 and 16 mm and lengths between 300 and 600 mm was selected to demonstrate what happens when normal forces are applied. For this example, the instructor applied a force to the model in front of the class; then the students, organized in groups of 3 and 4, took the model and subjected it to forces. Similarly, a rigid polyurethane foam cylinder was used to demonstrate the application of torque (Figure 2b). Following visualization and experimentation, student groups reported their findings to the class. The instructor’s role was to encourage individual participation and guide elicitation of a full description of the physical manifestation of the phenomena or property.

![Figure 2: Simple physical models used for visualization and experimentation.](image)
Using the students’ experiences with the simple physical model, the professor guided inductive conceptual development followed by core equation development. That is, the practical use equations were developed with active participation from the students, with the professor constantly reinforcing the relationships among the students’ conclusions from visualization and experimentation, the concept, and the equations.

Upon completing the development of the constitutive equations, the professor solved one or two carefully selected application exercises with student participation. The objective of these exercises was to relate the constitutive equations to the physical models presented and reinforce the physical model’s theoretical and mathematical foundation. The professor formulated loose questions to verify students’ understanding and to guide the solution development. After this, the students, working groups, assumed the challenge of solving more complex application exercises. The professor highlighted the importance of group discussion around the concepts and mathematics, as well as of the results obtained. For outside of class, the professor assigned application exercises for individual work. Exercises assigned for individual work, were real-world applications, and related to the profession, whenever possible.

In the final element of the intervention, student groups constructed their own physical models for the final project. Each group selected one course topic or phenomena (i.e., normal stress, shear stress, Poisson ratio, elasticity modulus, torsion/rotation angle, or torsion/shear strain, or flexion/deflection). For Treatment 1 sections, the objective was solely to have the students construct a model to represent the topic or phenomena. For Treatment 2 sections, the objective was to have the students not only construct a physical model but also construct the model in a way that measurements could be taken using the models. For example, the model for axial tension force assigned as a potential project after period 2014A, had two objectives: (1) to represent the phenomena associated with normal stress and (2) to analyse the behaviour of the materials under axial tension load and, hence, characterize said materials by calculating properties like elasticity modulus and Poisson’s ratio. For these purposes, the students constructed physical models to not only represented bending, torsion, shear, or tension but also enabled measurement of the respective strains for each case.

Project selection occurred in the second week of class and counselling was personalized for each group. Besides the six regular class hours per week, six additional hours per week were devoted by the professor to counselling the groups in a lab facility. Some groups attended this counselling regularly; some others did not seem to need it. Given that some of the project topics had not yet been studied in class at the time of selection, the students had to do independent research and request clarification from the professor. At the end of the semester, students’ projects were evaluated by a group of professors and research assistants. The projects were evaluated on aspects such as phenomena portrayal and the physical characteristics used to measure the phenomena.

2.3 Data Collection and Analysis

To summarize the student groups for this study, the Control group (2011B, 2012A) did not experience the inductive-deductive-inductive active learning pedagogical approach; nor did this group complete a project. Treatment 1 (2012B, 2013A, 2013B) experienced the inductive-deductive-inductive active learning pedagogical approach and completed a physical model only for the project. Treatment 2 (2014A, 2014B, 2015A) also experienced the inductive-deductive active learning pedagogical approach, but the project required not only the physical model but also the mathematical model component.

For each study period, whether or not a student passed (e.g., had a course grade higher than 3.0 out of 5.0) or dropped the course (i.e., officially withdrew or stopped attending after the withdrawal period - the first third of the semester) was recorded. The percentage of students passing the course was computed on the basis of those completing the course. The percentage of students dropping the course was computed on the basis of those initially enrolled in the course. The following null hypotheses were tested using a paired Chi-squared test, with a significance level at $p = 0.01$:

$H_0$: The percent of students passing the course is the same for the control and treatments

$H_0$: The percent of students dropping the course is the same for the control and treatments

In addition, students’ final course grades were recorded. Those students that stopped attending the class were issued a final course grade; those grades were included in the calculation of the academic average. The following null hypothesis was tested using a paired $t$-test, with a significance level at $p = 0.01$:
H₀: The academic average of the students completing the course is the same for the control and treatments.

During each class session of Treatments 1 and 2, a student teaching assistant measured, with a stopwatch, the time spent in class on each inductive-deductive-inductive active learning element disaggregated by the active participation of the professor or the students. That is, the time that the professor was talking and the time that the students were talking was measured. The average duration of a class in which a single topic was introduced was 115 minutes and was divided into 6 elements: attendance check, model observation, group discussion and experimentation, socialization (professor and student discussion of the concept based on the experimentation), equation deduction, and problem solving.

3 RESULTS

As can be seen in Figure 3, the percentage of students passing the course increased from 36% (average of the Control sections) to 61% for the last section (2015A). The passing rate for Treatment 1 (55%) was not significantly different than the Control (39%) ($\chi^2 = 5.0354, p = 0.0248$), though certainly it is a meaningful improvement. The passing rate for Treatment 2 (58%) was also significantly different than the Control ($\chi^2 = 8.1042, p = 0.0044$). The treatment groups were not significantly different from each other.

The academic average of those students completing the course increased from 2.50 to 3.21 on a scale of 0 to 5 (Figure 3). The academic average for Treatment 1 ($M=3.16, SD=0.99$) was significantly different than the Control ($M=2.52, SD=1.81$) ($t = 3.803, p < 0.0001$). The average passing rate for Treatment 2 ($M=3.20, SD=1.19$) was also significantly different than the Control ($t = 4.330, p < 0.0001$). The treatment groups were not significantly different from each other.

The course dropout rate diminished from 34% to 8% during the study (Figure 4). The number of official withdrawals from the course remained relatively steady at 1 to 3 per course offering, while the number of students that stopped attending after the withdrawal period dropped from 13 to zero by the end of the study (Figure 5). The dropout rate for Treatment 1 (15%) was significantly different than the Control (32%) ($\chi^2 = 9.0937, p = 0.0026$). The dropout rate for Treatment 2 (7.9%) was also significantly different than the Control ($\chi^2 = 51.2284, p < 0.0001$). The dropout rate for Treatments 1 and 2 were also significantly different from each other ($\chi^2 =16.5359, p<0.0001$).
There were a total of 56 class sessions taught across Treatments 1 and 2 using the I-D-I pedagogy. The time registration was carried out in 35 of the total 56 I-D-I class sessions across Treatments 1 and 2. Time registration was not carried out in all sessions due to lack of availability of the teaching assistants. Figure 6 shows a sample, and typical, average breakdown of class time for a single topic. Figure 7 presents the averages time spent on each I-D-I element disaggregated by the professor and students. Students played a leading role in solving application exercises independently, after the foundation exercises were introduced (82%). Socialization and discussion were also course elements wherein students were the main players (88% and 80%, respectively). The professor took the lead when developing the constitutive equations (83%). The professor and students shared the leading roles in observing the phenomena (54% and 46%, respectively).
3.1 Discussion

The I-D-I pedagogical approach taken in this study to teach Mechanics of Materials in the area of structures to civil engineering students did result in a significant increase in academic performance and decrease in course dropout rate. These results are likely attributed to the considerable shift in roles of students from passive learners to active learners and professor from “sage on the stage” (King, 1993) to facilitator. The time being spent in a deductive mode in the Treatments was essentially reduced to approximately one-fifth that of the Control. The increasing level of comfort of the professor with this new role may also be evidenced in the reduction of students that stopped attending class.

The first inductive phase of the I-D-I pedagogical approach followed principles of effective instruction (Prince & Felder, 2006). The professor presented each concept through a concrete example (i.e., simple physical model) that was somewhat familiar to students, enabling the students to relate the concept to their current knowledge structures. But through experimentation, the concrete example challenged students to think more deeply about the concept. The second inductive phase (i.e., problem solving and model building) required students to go beyond the material presented. Both inductive phases capitalized on group interactions, enabling social construction of knowledge. The more deductive phase connecting the two inductive phases appropriately used lecture to transmit knowledge (Bligh, 2000), in this case, to ensure the constitutive equations were developed correctly.

It is not possible to tease apart the impact of the changes in the classroom instruction from the addition of the physical model project as they were both implemented together. The literature would suggest that each plays a critical role in student learning as well as in the increase in student passing rates and reduction in dropouts from the course. The extermination and project combination used in this study may be framed as both project-based learning and problem based learning. Problem-based learning, on the one hand, is related to knowledge acquisition, while project-based formation is directed at the application of knowledge, beyond both being founded on principles of collaboration,
multidisciplinary orientation, and self-direction (Perrenet, Bouhuijs, & Smits, 2000). In truth, the I-D-I pedagogical approach developed here did both. Students controlled parts of the content and interacted in groups, while the professor played a role in which he favoured students' active and collaborative participation. The visualization and experimentation that lead to the development of the constitutive equations may be said to be a critical activity, a necessary condition for subsequent learning through the project (Hadgraft & Young, 1998). However, the creation of external representations is important as that act transforms concepts and processes into symbolic and visual forms required to develop ideas, objects, and relations (Nathan, Srisurichan, Walkington, Wolfgram, Williams, & Alibali, 2013). Confirming the findings of Crone (2002), it may be possible to say that the use of experiments with and the design of physical models to demonstrate mechanics concepts are two strategies that can improve undergraduate mechanics courses.

4 CONCLUSIONS

An inductive-deductive-inductive pedagogical approach to teaching mechanics of materials resulted in a significant increase in the student pass rate and overall course performance and decrease in student withdrawals from the course. The approach taken in this study coupled visualization and experimentation with mechanics of materials concepts (inductive learning) with problem solving and physical model construction (inductive learning) via professor-led, but student co-generation, of the constitutive equations (deductive learning). The considerable impact of the approach may be attributed to the high level of student active learning in the course which included both the changes in the classroom instructional practice and the addition of a physical model development project. Adding mathematical modelling to the project did not significant change the student pass rate, overall course performance, or withdrawal rate, though this addition may have had other impacts not accessed in this study.

REFERENCES


