The role of representations in an inductive deductive inductive approach in engineering: perspective from Mechanics of Materials

Jorge Olmedo MONTOYA VALLECILLA
Civil Engineering Department, Universidad de Ibagué
Ibagué, Colombia

ABSTRACT

An inductive-deductive-inductive (I-D-I pedagogical approach, strengthened with physical model representation (PMR) 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 and the physical representation is discussed.

Keywords: mechanics of materials, active learning, inductive, deductive, physical model, team work, representation

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 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 [1]. It is well documented in the literature that students have misconceptions about these phenomena (e.g., [2]). 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 [3]. 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 [4].

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 [5]. Further theory, presented on its own, has led to lower levels of comprehension and motivation and, consequently, higher rates of failure and withdrawal [6]. 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 considers that each student has a preferred way of learning, particularly visualization and construction of models [7]. 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 [8].

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) [9], [10].

Such instructional methods are grounded in cognitive constructivism (originating with Piaget, 1972) [11], which says learning is the result of processing ones experiences, and social constructivism (e.g., [12]), 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, [13], 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. To do so, physical representations of stress and strain were constructed and used as a key element in the inductive phase.

1.1 Research Questions

In this study, we sought to quantitatively compare students' academic achievement in a mechanics of materials course when two different teaching learning approaches were employed - a traditional lecture approach and an inductive-deductive-inductive learning pedagogical approach. The research questions were: Does the use of an inductive-deductive-inductive learning pedagogical approach improve the academic performance of the students completing the course? Does the use of an inductive-deductive-inductive learning pedagogical approach result in a change in the percent of students passing and dropping the course?

2. METHODS

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 a ten-semester program. The two course sections offered in 2011B and 2012A, where A and B represent the first (February to May) and second (August to November) 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).

This course, mechanics of materials, 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 (lecture approach); 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. Class time was spent with students working with concepts and problems in teams. The instructor was the same for the Control and Treatments 1 and 2.

Table 1 shows a comparison of the assessments used to determine students' final course grade. 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 design project, (team work) done mainly in the last 4 weeks of the semester. For the Treatments, the final course grade was divided into three parts as well: 60% for written exams, 10% for class participation and team problem solving carried out actively in class, and 30% for the final model building team project, carried out by groups of four students.

For all groups, there were three written exams, each covering a third of the semester's content. The nature of the questions on the exams was similar across the Control and Treatment offerings of the course. There were two kinds of written exams: multiple choice for concept acquisition verification and mathematical problem solving, such as computing stress and strain for rigid bodies

Also for all groups, ten percent of the grade was allocated for problem solving. However, in the Control, this percentage was used for independent (of the instructor) problem solving (either individually or in groups), while in the Treatments, this percentage was used to assess class participation as well as team problem solving. Finally, for all Treatment groups, the team project began in the second week and was submitted in the last week of the semester. Thirty percent of the course grade was allocated for project work in both the Control and Treatments. For the Control, the design project was mainly theoretical in nature, while in the Treatments, the project entailed constructing a physical model.

Table 1: Assessments for the Mechanics of Materials Control and Treatments

Assessment Type	**Percent of Final Grade**	
	Control	**Treatment 1 and 2**
Written Exams	60	60
Independent Problem Solving	10	---
Class Participation and Team Problem Solving	---	10
Final Design Project (team work)	30	---
Final Model Building Project (team work)	---	30

Three main topics (stress, strain and axial load; torsion; and flection 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 lecture approach as they were deemed more difficult to physically represent, however, these topics were not included in assessments for written exams.

An inductive-deductive-inductive pedagogical approach was employed to engage students in the construction of knowledge related to select mechanics of materials concepts. 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.

Figure 1: Different types of models used for class

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 shows different types of physical representations used in the class.

Visualization of and experimentation with each concept (phenomena or property) was made possible through the use of a simple physical model. 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 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.

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.

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.

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, Poison ratio, elasticity modulus, torsion/rotation angle, or torsion/shear strain, or flection/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 analyze the behavior 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 counseling was personalized for each group. Besides the six regular class hours per week, six additional hours per week were devoted by the professor to counseling the groups in a lab facility. Some groups attended this counseling 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.

2.1 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 model building project. Instead, they designed a project (theoretical). 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 (model construction and strain measurement).

For each study period, whether or not a student passed (e.g., had a course grade of 3.0 or higher, 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: Ho: The percent of students passing the course is the same for the control and treatments

Ho: 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:

Ho: The academic average of the students completing the course is the same for the control and treatments

To characterize the I-D-I class sessions 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. FINDINGS

There were a total of 56 class sessions taught across Treatments 1 and 2 using the I-D-I pedagogy. The time registration (to monitor teacher and students participation) 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 2 shows a sample, and typical, average breakdown of class time for a single topic. Figure 3 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).

Figure 2: Typical average break down of class time

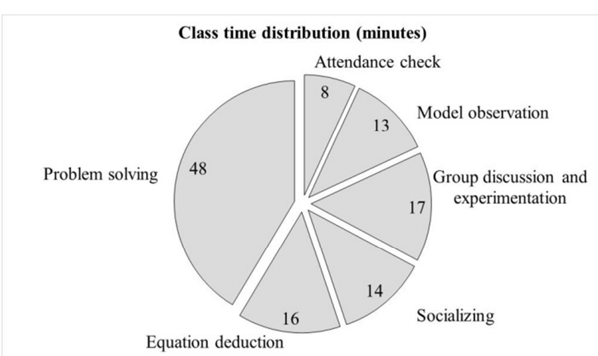
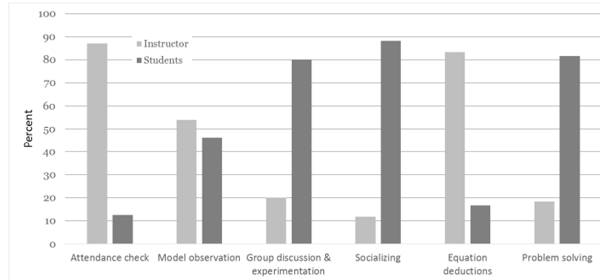


Figure 3: Average time spent in each I-D-I element

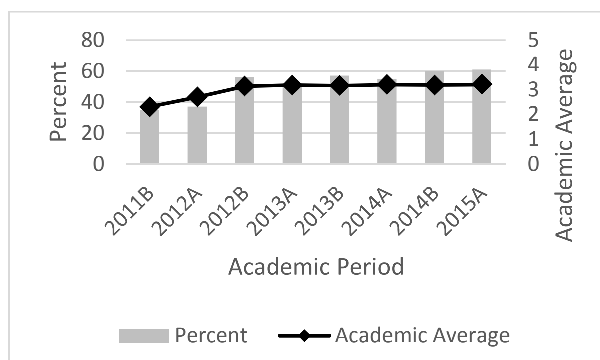


The percentage of students passing the course increased from 36% (average of the Control sections) to 61% for the last section (2015A). The passing rate for Treatment 1 (55%) was not significantly different than the Control (39%) (X^2 = 5.0354, p = 0.0248), though certainly it is a meaningful improvement. The passing rate for Treatment 2 (58%) was significantly different than the Control (X^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 5). The academic average for Treatment 1 (M=3.16, SD=0.90) was significantly different than the Control (M=2.52, SD=0.77) (t = 3.803, p < 0.0001). The academic average for Treatment 2 (M=3.21, SD=1.02) 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 7).

Figure 4: Academic average and percent of students passing



The dropout rate for Treatment 1 (15%) was significantly different than the Control (32%) (X^2 = 9.0937, p = 0.0026). The dropout rate for Treatment 2 (7.9%) was also significantly different than the Control (X^2 = 51.2284, p < 0.0001). The dropout rate for Treatments 1 and 2 were also significantly different from each other (X^2 =16.5359, p<0.0001). This information can be seen in figures 5 and 6

Figure 5: Dropout rate for the different periods

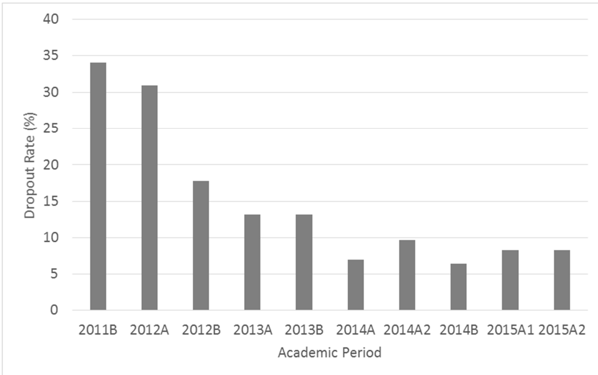


Figure 6: Students withdrawing and stopping attending

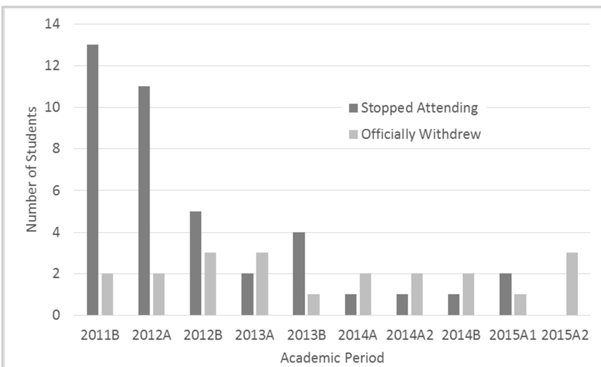


Table 2 shows the breakdown of the course grade for the Control and Treatment groups by assignment type. There were significant increases in the means between Control and both Treatments for the written exams and problem solving components of the course. Between Treatments, differences were only found significant for the problem solving component. So, each assignment type contributed to the increase in the academic average of the Treatment groups. Due to the weighting of the exams in the final course grade, the largest impact on the final grades was the increase in the exam scores from Control to Treatment. This alone accounts for a 0.56 increase in average course grade.

Table 2 Mean and standard deviation (SD) for different types of assessment

Assessment Type	Score out of 5: Mean/SD		
	Control (n= 82)	Treatment 1 (n=114)	Treatment 2 (n=183)
Written Exams	2.22/0.75	3.16/0.89*	3.15/1.02*
Independent Problem Solving	2.75/0.38		
Class Participation and Team Problem Solving		3.12/0.90*	3.42/1.00*†
Final Design Project (team work)	3.05/0.41		
Final Model Building Project (team work)		3.16/0.90	3.25/1.04

* paired t-test between Treatment 1 or 2 and Control, $p<0.001$

† paired t-test between Treatment 1 and Treatment 2, $p < 0.001$

As the A and B semester occur at different times of the year, one might expect different student performances due how far along the students are in the program, but this is not the case because either for A or B period, the students have covered the same amount of credits in the program. However, for comparison, student performance in the A (February to May) and B (August to November (A) period offerings was parsed as shown in Tables 3 and 4, respectively. No statistically significant differences were found between

Control A and B, Treatment 1 A and B, or Treatment 2 A and B. Similar to the combined results, there is significant difference in the passing rates and course academic average for the Control and Treatments for the A and B periods when examined separately. From Tables 4 and 5 it is possible to notice that the main difference between the Control and Treatments occurs in in the 0-0.9 grade range, where the percentage of students who earned grades in this range dropped from 30% to 0-3% for the A period and 32% to 0-7% for the B period.

Table 3: Assessments for the Mechanics of Materials Control and Treatments

	A period: February to May	Course academic average	Percentage of students with grades 0-0.9	Percentage of students with grades 1.0-1.9	Percentage of students with grades 2.0-2.9	Percentage of students with grades 3.0-3.9	Percentage of students with grades 4.0-5.0	Percentage passing
Control	2012A	2.70	30%	14%	19%	27%	10%	37%
Treatment 1	2013A	3.18	0%	9%	40%	37%	14%	51%
Treatment 2	2014A1	3.20	0%	22%	22%	36%	20%	56%
	2014A2	3.20	0%	14%	31%	34%	21%	55%
	2015A1	3.21	0%	14%	29%	25%	32%	57%
	2015A2	3.21	3%	9%	27%	43%	18%	61%

Table 4: Assessments for the Mechanics of Materials Control and Treatments

	B period: August to November	Course academic average	Percentage of students with grades 0-0.9	Percentage of students with grades 1.0-1.9	Percentage of students with grades 2.0-2.9	Percentage of students with grades 3.0-3.9	Percentage of students with grades 4.0-5.0	Percentage passing
Control	2011B	2.30	32%	12%	21%	21%	14%	35%
Treatment 1	2012B	3.14	7%	12%	24%	43%	14%	57%
	2013B	3.16	0%	16%	27%	33%	24%	57%
Treatment 2	2014B	3.16	2%	20%	18%	33%	27%	60%

4. DISCUSSION

The I-D-I pedagogical approach strengthened by the used of physical representation of phenomena (PMR) taken in this study to teach mechanics of materials did result in a significant increase in academic performance and decrease in the course dropout rate. Further, there was a considerable drop in the number of students receiving course grades in the range of 0 to 0.9 out of 5. 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” [14] 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 [9]. 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 [15]**,** in this case, to ensure the constitutive equations were developed correctly.

Alternative explanations for the increase in the academic performance were explored. Changes in the nature of the assessment types might contribute to changes in the grades. Certainly some bias may have been part of the problem-solving component, but increases in students' performance on that part of the course do not account for the amount of increase. The increase seems to mostly come from the exams scores which are less subjective. Student's maturity did not play a major role in the results since they are all in the same age range for Control and Treatments, the same occurs with the case of the instructor, who was the same for the three periods.

On the other hand, focusing in written exams which seems to be the big difference for the positive correlation, it is important to point to the fact that not all topics evaluated in written exams in Control were assessed in Treatments, since there were some topics (flexural moment, shear force diagrams, and stress transformation) whose physical representation was more difficult, so they were taught in the traditional lecture approach, although they were included in Team Problem Solving assessment. If possible to represent physically, it would be interesting to see for further studies, how the inclusion of these topics in written exams would affect the results.

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 [16]. In truth, the I-D-I pedagogical approach developed here did both.

PMR was a key element that highly contributed to students' engagement in class and it is evident after taking a glance to participation results. Students controlled parts of the content and interacted in groups, while the professor played a role in which he favored 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. [17]. 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 [18]. Confirming the findings of [19], 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.

5. 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 attributes 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 as representation of phenomena in class. (PMR).

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