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Research article

Enhancing success in fundamental engineering courses: A case study on using team based learning to address high failure rates

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Abstract: This study examines the impact of team-based learning (TBL) on students' performance in mechanics of materials, a fundamental yet challenging course in engineering curricula. Traditional lecture-based instruction has often failed to fully engage students and allow them to enhance their critical thinking skills that can be applied in engineering. This study compares outcomes between traditional lecture-based classrooms and those incorporating TBL at California State University, Fullerton (CSUF). Data from 72 students in traditional settings and 80 students in TBL-integrated classrooms were analyzed over multiple semesters. The results reveal improvement in examination scores and a reduction in failure rates for TBL participants compared with traditional instruction. The survey responses indicate that students in TBL sessions reported increased confidence, improved critical thinking, and enhanced teamwork skills. While the reduction in failure rates did not achieve statistical significance, the positive trends suggested that TBL effectively addresses challenges in high-stakes courses. The study advocates for expanding TBL to other fundamental engineering courses and institutions to further explore its effectiveness and potential to improve student retention, particularly among underrepresented minorities in science, technology, engineering, and mathematics (STEM).

Keywords: team-based learning, engineering education, STEM education, bottleneck courses

1. Introduction

For over two decades, there has been a nationwide push to increase the number of students earning degrees in science, technology, engineering, and mathematics (STEM) fields [1–3]. Despite these efforts, fewer than half of students who start as STEM majors complete their degrees in the field [3,4]. Thus, universities have sought to identify and address bottleneck courses that hinder students' progress. In engineering, one course that pertains to this issue is mechanics of materials. Mechanics of materials focuses on the behavior of solid materials under various conditions to understand their deformation. It equips students with the essential principles for analyzing and designing structural components. However, due to its complexity and the challenges students face in mastering and applying its concepts, it is recognized as one of the major bottleneck courses. A study highlighted this issue, revealing that mechanics of materials has one of the highest failure rates among core engineering courses [4]. Moreover, California State University, Fullerton (CSUF), collected data as shown in Table 1, regarding the failure rate within this course. It tracks the average class size and repeatable grades (C– or lower) over six academic years in the Civil and Environmental Engineering (CEE) department, revealing that approximately 40% of students receive repeatable grades in mechanics of materials. The average class size is 37, and the average failure rate over all semester is 40%. Note that for this course in the engineering curriculum, a C– denotes a repeatable grade, as students are required to receive a score above C– to continue in successive engineering courses to which this is a prerequisite for.

Table 1. Average class size and percent of repeatable grades in mechanics of materials at CSUF from Fall 2018 to Spring 2023.

	Mechanics of Materials									
	Fall 18	Spring 19	Fall 19	Spring 2020	Fall 2020	Spring 2021	Fall 2021	Spring 2022	Fall 2022	Spring 2023
Average Class Size	31	40	60	38	46	36	32	28	39	33
Percent Repeatable Grades (%)	42	37	45	21	50	44	43	45	47	35

There are numerous reasons for the significantly high failure rate in mechanics of materials, but the most important factor is the lack of student engagement. Many STEM classrooms have typically utilized traditional lecture-based teaching methods, which encompasses students passively receiving information without actively engaging in the learning process, or may involve some active learning but not enough structured active learning pedagogies or activities [5,6]. This passive learning environment hinders students from developing a deeper understanding of complex concepts, making it difficult for them to apply theoretical knowledge to real-world problems [6]. Therefore, CSUF's faculty discovered that their traditional lecture-based teaching methods did not effectively connect students with the practical applications of the course material, further widening the gap between what students learn within the classroom and how they apply it in engineering practice or even to simply reach a solution to a given problem within mechanics of materials. This disconnect further highlights the need for pedagogical innovations that would better engage students and improve their understanding, thereby enhancing overall student outcomes.

Team learning methods have proven to be useful in enhancing engineering student outcomes in the form of knowledge acquisition and retention, higher-order learning, and more positive attitudes while learning in general [7,8]. Much literature has been presented that addresses the inclusion of active learning methods to enhance student outcomes. Overall, the four most present areas of active learning found in the literature include: (1) cooperative/collaborative learning [8,9], (2) problem-based learning (PBL) [9–11], (3) enquiry-based learning [11], and (4) team-based learning (TBL) [12–14]. Teamwork, collaboration, and communication skills are all highly sought after by employers in the engineering industry [15]. Due to this strong emphasis on teamwork and collaboration, there has been an increase in the implementation of student learning outcomes centered around creating opportunities for students to work in teams and engage with one another in project design, bringing about more research in various group-based learning strategies.

Out of the four primary active learning methods mentioned, PBL is the most widely applied learning strategy in the context of engineering education. PBL was first introduced in the 1960s at McMaster University in Canada in the context of medical education [16]. General steps of PBL include defining a problem, project/task organization, team development, guidance of the participants by an instructor, and establishing learning outcomes [17]. Researchers have noted potential disadvantages of PBL, which can include a lack of structure [18] and the requirement for several course instructors or tutors in one session [14]. TBL, on the other hand, is a highly structured form of active learning with set guidelines developed by the TBL Collaborative (TBLc) that does not require several instructors or tutors.

Therefore, TBL has developed into a promising method for tackling difficult courses, especially in the field of medical education. TBL is an evidence-based active learning method designed to enhance student engagement, foster collaboration, and improve critical thinking abilities. This method of learning encourages students to work collaboratively in strategically structured teams, where they actively employ problem-solving skills, critical thinking, and peer-to-peer learning. In mechanics of materials, this approach will not only significantly enhance the comprehension of challenging topics, but also improve retention, overall academic performance, and application in the real world. With the implications of TBL in this engineering course, educators create a more interactive and supportive classroom environment while reducing the failure rate and fostering long-term success. TBL has proven to be a highly effective active learning pedagogy in the field of medical education [19–22]; however, little research has been conducted to show its effectiveness in the field of civil engineering. This study aimed to provide a case study with relevant data to show how the implementation of TBL, an active learning pedagogy, affects student outcomes in engineering courses with historically high failure rates across the nation.

2. Theoretical framework of TBL

The traditional role of students as passive note-takers and mere repeaters of information must shift toward an educational approach where students are actively engaged in learning and developing a better understanding of the ideologies presented within a lecture. Active learning methods that incorporate elements of team learning have been proven to drastically reduce failure rates [23]. Therefore, the implication of active learning pedagogies allows for this shift by encompassing students in various forms, including in-class activities and pre-lecture assignments, to reflect an apply ideologies taught within a classroom. Thus, students remain cognitive in their learning by fostering participation, information gathering, and critical thinking. As a result of this teaching method, active learning pedagogies have been shown to increase students’ knowledge acquisition and retention of material, ultimately increasing course grades [24–27]. Active learning pedagogies effectively advance the knowledge transfer between disciplines and promote better information retention. They foster the development of skills required as students in engineering and in the engineering workforce, namely critical thinking and teamwork skills, and the students’ ability to apply the knowledge they are learning in the classroom to real-world scenarios [27].

The selected active learning pedagogy for this case study was TBL, a highly structured evidence-based pedagogy designed by the TBLc. TBL is an evidence-based form of active learning that has been shown to ease the transferability of knowledge, improve critical thinking skills, motivate students to learn, and foster both individual and team performance with higher levels of competency [28–30], where teams allow for a shift from passive knowledge acquisition to active problem-solving. By leveraging both individual and team readiness assessments, students engage in meaningful application exercises, and thus TBL provides a structured framework that not only improves knowledge retention but also encourages deeper comprehension and skill development. Furthermore, incorporating TBL into the teaching strategies for the bottleneck courses can help reduce failure rates and enhance students' performance. By developing a collaborative learning environment where students are encouraged to engage in class activities and tackle complex problems together, TBL motivates students to take an active role in their education, leading to deeper understanding and improved academic outcomes.

Unlike the traditional lecture-based teaching pedagogy, TBL offers a platform by which learners can leverage inter- and intrateam discussions to elevate learning from the acquisition of knowledge to creation and synthesis [31]. This is achieved through TBL's unique 4S design (Significant problem, Same problem, Specific choice, Simultaneous reporting), which utilizes a mix of self-directed completion of readiness material prior to instruction, followed by individual and team readiness assessments at the initiation of instruction (https://www.teambasedlearning.org/). The use of the 4S design allows for immediate feedback via facilitated class discussions and requires class consensus and agreement through debate and dialogue. This added element of facilitated class discussion enhances learners' understanding by logically determining solutions to significant problems, rather than passive retrieval of information. TBL provides the ideal environment for learners to enhance their critical thinking skill sets as well as hone their communication skills while fostering a collegial environment that mimics real-world experiences. As a large element of TBL involves group work with peers, TBL has been proven to increase students' confidence, directly leading to improved overall course outcomes [32].

A typical TBL session consists of four phases. The first phase involves assigning students prework to complete prior to attending class in which the TBL activity will take place. The prework can consist of assigned reading, problem-solving, recorded lectures from the instructor, or any other resources necessary for the students to become familiar with the topic of the TBL activity. The subsequent phases all occur during class time, where the students will be placed in teams of 4–6 individuals. Team members are selected on the basis of grade point average (GPA), ensuring there is an even distribution of performance levels within the teams. These teams are consistent for the entire semester. Phase 2 of the TBL session requires the students to take an individual assessment, called the individual readiness assurance test (iRAT). The iRAT is meant to be designed as a short assessment designed based on the prework that tests each student's preparation for the TBL activity. Phase 3 consists of the team readiness assurance test (tRAT), in which the students, along with their teammates, take the same assessment from the iRAT but now with the opportunity to engage in discussions and critically think about the correct answer. Phase 4, which should be designed to take up the majority of in-class time, requires teams to solve an application question. Between Phase 3 and Phase 4, the instructor may choose to insert a short lecture based on the general atmosphere of the class and how well they did on the tRAT. Throughout all in-class phases, the instructor must facilitate group discussions, go through the assessment solutions, and continuously promote critical thinking through asking probing questions. The InteDashboard (https://www.intedashboard.com/) platform, which is specifically designed for the implementation of TBL, is used for all TBL courses in the case study. InteDashboard works well in both in-person and virtual learning settings.

3. Methodology

3.1. Study context

This case study compared the academic performance of two different student groups enrolled in the mechanics of materials course at CSUF through examination results and final course grades. While both groups of students studied the same foundational concepts in mechanics of materials, what differentiated each group lies in the instructional methods utilized by the professor. The first group, comprising 72 students, received instruction through traditional lecture-based formats. The traditional lecture-based control group was observed over two semesters, with 30 students enrolled in Semester 1 and 42 students enrolled in Semester 2. In contrast, the second group, consisting of 80 students, followed a curriculum that integrated TBL modules. The case study TBL classroom was tracked over three semesters, with 27 students enrolled in Semesters 1 and 2, and 26 students enrolled in Semester 3. Thus, all control and case study classrooms were taught by the same instructor in order to reduce differences in teaching style, which could have been a confounding factor in the final results.

The first group of students enrolled in the mechanics of materials course experienced traditional lecture-based lessons, where information was delivered through a series of lectures. These lectures primarily conveyed information about the key principles, important formulas, and example problems. This approach utilized a one-way communication format; information flowed exclusively from the professor to the students, resulting in a classroom environment that centralized passive learning. Students listened to lectures, took notes, and were expected to retain the material independently. Moreover, as the students focused on transcribing notes, it often diverted their attention from processing information in real time, hindering their ability to grasp and understand complex concepts fully. The lectures focused heavily on content delivery rather than collaboration or active participation from students. Traditional lecture-based learning may fall short in incorporating the critical thinking and problem-solving skills that are essential in mechanics of materials.

The second group of students were taught the same various concepts of mechanics of materials utilizing TBL methods. TBL modules were administered during regularly scheduled class meeting times. To ensure participation of students in TBL modules, the activities counted toward the students' grades. All TBL modules were designed and implemented in accordance with TBLc guidelines, which the principal investigator (PI) of the study is certified and trained in.

Therefore, each TBL module consisted of two activities, with each activity spanning one to two class sessions. Four mechanics of materials modules were developed and implemented in this case study. Other than these TBL modules, all other class sessions consisted of traditional teaching-practices that were primarily lecture-based. The courses included traditional didactic lectures with TBL modules integrated into specific lectures and course periods.

3.2. Research questions

RQ1: Does the implementation of active learning pedagogies in mechanics of materials classrooms affect students' course outcomes in terms of exam grades and the overall course failure rate?
RQ2: Does the implementation of TBL pedagogies in mechanics of materials classrooms enhance students' perceptions of their learning experience?

3.3. TBL modules

Module 1: Resultant forces and moments for equilibrium conditions (two- and three-dimensional)

Module 1 consists of two activities, conditions for equilibrium and resultant force systems. The concepts surrounding resultant forces and moments for equilibrium conditions are taught in the first few weeks of the course; understanding these concepts is vital for success in statics. Prior to the introduction of this module, students will have had traditional lectures during class time that cover and review vector analysis and forces. Implementing a TBL approach in Module 1 will enable students to think critically about equilibrium when multiple forces act on a body. As students work through equilibrium problems, they are encouraged to visualize the concepts. Thus, students gain the ability to better understand the connection between force and moment at specific points on a body – concepts that are often challenging for students to grasp. The learning process of visualizing the connection between forces and moments is directly connected by TBL, as it actively engages students' minds, allowing them to form clearer, more intuitive understandings of these concepts. Moreover, TBL prompts active participation, unlike traditional methods where students are passive recipients of information. When it comes to difficult topics, utilizing TBL methods creates an environment where students can develop a better understanding as TBL provides an extensive methodology for breaking down, reinforcing, and applying theoretical knowledge to various problems Therefore, this hands-on collaboration solidifies the understanding of how forces generate moments, creating a stronger link between theoretical concepts and real-world applications.

Therefore, students first have the opportunity to work through problems independently then collaborate with peers. These peer discussions expose students to different methods of visualizing the concept, either confirming their original understanding or helping them discover new or more accurate ways to approach the problem. This active engagement encourages critical thinking as students analyze and question the approach to solving the problem. Additionally, the professor plays an important role in confirming or correcting individual or group thought processes. Regardless of the outcome, students either reinforce what they completed correctly or uncover the correct solution. Since they are already actively engaged in the process, the professor's feedback becomes more meaningful and solidifies their understanding. As a result, students move beyond simple memorization and develop the ability to critically think through the steps, visualizing the connection between force and moment. This enhanced visualization enables students to transform two-dimensional (2D) problems into three-dimensional (3D) ones, making them capable of solving equivalent systems in more complex scenarios.

However, if students attempt to memorize solutions without truly understanding the connection between force and moment, issues will arise and ultimately negatively affect the student's performance, which will result in poor test scores and final grades. The major issue is surface-level learning. Without grasping the underlying principles, students will focus on memorizing the steps to solve the force method problem. This leads students to be able to replicate a solution but unable to adapt it to different solutions. Thus, those who rely on memorization will struggle to apply their knowledge to new and more complex problems. Furthermore, understanding the concepts of forces, moments, and equilibrium requires the ability to visualize how forces interact at specific points on a body. This understanding helps transform a 2D representation into a 3D application, as these systems operate in the real world. Memorization bypasses this critical step of deep understanding and visualization; therefore, a TBL approach to teach Module 1 is essential, as it significantly reduces the likelihood of this occurring.

Activities 1 and 2 (detailed below) allow students to review the concepts and practice significant problems, then attend class and solve a similar problem that is more advanced so they are able to apply the knowledge from the prework to a new problem.

Module 1's objectives are as follows:

1. Understand how unbalanced forces cause motion/displacement of the structural system
2. Recall and apply vector analysis when dealing with forces
3. Solve for equivalent systems (sum of all forces and moments on a system lead to resultants)

Activity 1: Conditions for equilibrium

The prework covers drawing free body diagrams, establishing primary axes, and solving equilibrium problems. The iRAT and tRAT assessments include questions regarding the effect of unbalanced forces on a system (Objective 1). Following the iRAT and tRAT, a class discussion takes place that is dependent on the students' responses. The application question for this TBL session require teams to analyze and solve a complex equilibrium problem, such as determining the mass of two cylinders, each connected to a spring–rope system (Objective 2).

Activity 2: Resultant force systems

This assigned prework for the TBL session includes concepts regarding the moment of a force, the righthand rule or understanding the sense of rotation, moment arms, the moment of a couple, and the simplification of force and couple systems through the resultant systems. The application activity requires teams to analyze and solve one or more complex problems dealing with the resultant systems, such as replacing multiple loads on a frame with a single resultant force for a 2D problem and replacing several forces acting on a plate for a 3D system (Objective 3).

Module 2: Calculation of internal loading: Shear and moment diagrams

Module 2 consists of two activities, namely internal forces, and shear and moment Diagrams. Shear and moment diagrams are not only of vital importance in statics but in several subsequent courses in civil engineering. To be able to successfully draw a shear and moment diagram for a structural member, students must first be able to calculate the internal loadings and understand the mathematical connection between shear and moment. Students often struggle with applying these mathematical concepts in solving for shear and moment diagrams, as they may lack confidence from their previous mathematics courses. Implementing TBL is a way to help struggling students gain confidence in this area, as they can engage in discussions with their peers and work out problems together through critically thinking about the problem.

Furthermore, utilizing TBL to teach Module 2's topics is essential for students to develop a deeper understanding of these concepts because shear and moment diagrams involve more than just following formulas. These diagrams require critical reasoning and the ability to integrate various pieces of information, such as the loading conditions, support types, and force distributions. Students often struggle with these concepts because they cannot easily see the connection between the mathematical calculations and the visual representation of the forces. Thus, TBL is especially effective in this context because it requires students to repeatedly calculate the internal forces and then draw the corresponding diagrams. By drawing the diagrams, students can visualize this mathematical relationship. Through the peer discussion prompted by TBL, students can collaboratively explore, for example, why the moment diagrams peak where the shear diagram crosses zero, making these concepts more intuitive. Therefore, students are held accountable for both individual and team performance, ensuring that they not only reach the correct solution but also understand the underlying principles, which are then reinforced by the instructor. This structure ensures that all students achieve a solid foundational understanding before tackling more challenging problems, which reduces frustration and boosts confidence. Moreover, by implementing TBL for Module 2, students are encouraged to rely on one another for success, fostering a shared responsibility that creates a supportive learning environment. This collaborative approach from TBL methods ensures that even those who initially struggle with shear and moment diagrams can build confidence through team learning.

Module 2’s objectives are as follows:

1. Differentiate between the internal forces and external reactions in a system;
2. Solve for the internal forces of a structural member at a specific point;
3. Recognize the mathematical relationship between shear and moment; and
4. Construct shear and moment diagrams using graphical and mathematical methods.

Activity 1: Internal forces

Prework for the TBL portion of Session 1 includes material that details the differences in internal forces and external reactions (Objective 1) and covers the method of sections, which can be used to determine the internal loading on a member at a specified location along the member’s length (Objective 2). The application activity requires students to cut a member subject to multiple loading types at different points along the member’s length and determine the internal forces (Objectives 1 and 2).

Activity 2: Shear and moment diagrams

Prework for the TBL portion of Session 2 must provide a review of the concepts from calculus, including the derivative of a function and the integral of a function, and how these concepts translate graphically (Objective 3). Additionally, the prework covers the construction of shear and moment diagrams. The application activity includes calculation of a graphical shear and moment diagram and of a mathematical shear and moment diagram (Objective 4).

Module 3: Material behavior and the relationship between stress and strain

Module 3 consists of two activities, namely types of materials and the stress–strain curve. Both of these concepts are integral components in understanding the material that are utilized throughout the course. These ideas are initially introduced at the beginning of the semester; however, the concepts and ideologies continue to build through future lessons. Therefore, understanding these concepts is not only vital for success in mechanics of materials but also in future engineering courses. This module aids students in visualizing the different types of material behaviors that exist when a load is applied to elements. They begin to understand how force, a concept learned in physics and statics, affects stress, strain, and ultimately the deformation of a system. This concept is often difficult for students to grasp.

TBL provides an effective method for teaching the complex relationship between stress and strain because it integrates structured collaboration, critical thinking, and real-time feedback, linking the theoretical knowledge to the mathematical components. In TBL, students participate in structured activities where they actively engage with peers to explore how different materials respond to various loading conditions. This format allows students to visualize the stress–strain relationship and depict it on a graph. Each section of the stress–strain graph, such as the elastic region, the yield point, plastic deformation, and fracture point, represents a distinct phase of how a material will deform under applied force, with these sections varying in size, depending on the material's properties. For instance, ductile materials exhibit a longer plastic deformation region, allowing them to stretch before breaking, while brittle materials experience minimal to no plastic deformation, leading to sudden fracturing. By analyzing and visualizing these differences on the stress–strain curve, students can gain a clearer understanding of how materials behave. Thus, students can then link this theoretical understanding to the necessary calculations.

Working in structured teams, students tackle problems that simulate real-world engineering scenarios, such as interpreting stress–strain curves to identify a material's limitations and failure points. TBL's collaborative framework encourages students to debate and discuss questions like why ductile materials exhibit a yield plateau or why a brittle material has a sudden failure point. This peer teaching reinforces each student's understanding, as they are held accountable to explain and interpret both the math and physical implications of the material's behavior on the stress–strain curves.

Moreover, TBL's iterative structure – where students first attempt problems individually, then work through them with peers, and finally clarify concepts with instructor guidance – ensures that students internalize key principles through repetition. This progression enables students not only to calculate stress and strain accurately but also to interpret the practical implications of these values. The combination of accountability, teamwork, and immediate feedback fosters a supportive learning environment where students build strong analytical skills that go beyond solving equations to fully understanding material behavior under external forces.

Module 3's objectives are as follows:

1. Recognize the relationship between externally applied forces and internal stress and strain;
2. Recognize the relationship between stress and strain; and
3. Construct the stress–strain curve for ductile materials.

Activity 1: Types of materials

The prework provides a review of ductile and brittle material types. The iRAT and tRAT assessments include questions regarding the the behavior of these materials. Following the iRAT and tRAT, a class discussion takes place that is dependent on the students' responses. The application question for this TBL session requires teams to analyze and solve a complex problem, such as reading a case study and determining material type on the basis of specific characteristics.

Activity 2: Stress–strain curve

This assigned prework for the TBL session includes a review of the definition of both mathematical stress and strain. The application activity requires teams to fully construct and explain how a ductile member experiences different phases of stress and strain while being subjected to external loading.

Module 4: Introduction to structural design

Module 4 introduces students to their first design problems as engineers, something that forms the basis of their future coursework. Module 4 consists of one activity which focuses on applying the concepts of stress and strain along with stress and strain limits to design structural members, such as beams.

Teaching an introduction to structural design through TBL is highly effective because the subject requires students to translate extensive theoretical knowledge into practical applications, especially when designing structural members like beams. Structural design requires a strong foundation in stress, strain, material limits, and how these factors influence the design of structural members like beams. Through TBL, students can tackle these concepts independently to grasp the theory, then refine their understanding through focused team discussions, where they collaboratively analyze how stresses affect beam design under various loading scenarios. These discussions allow students to clarify complex ideas, like determining the appropriate dimensions and materials for a beam on the basis of the allowable stress limits. Working together, students can share insights, challenge misunderstandings, and build a deeper, shared understanding of design principles. This can then be confirmed or corrected by the instructor. Therefore, due to the previous discussion with their peers, active engagement causes the concepts to be embedded within their knowledge. Consequently, as students tackle additional problems, they can clearly identify how the theoretical components apply, allowing them to approach each problem with a genuine understanding rather than blindly following a series of steps. Moreover, this collaborative approach supports them in confidently solving design problems, as they develop a clear, practical understanding of how to apply stress and strain theory to real-world structural design.

Module 4's objectives are as follows:

1. Apply stress and strain limit equations from the provided codes to choose the member's size; and
2. Evaluate and choose the optimal member size for the design problem at hand.

Activity 1: Design problem

The prework provides a review of the stress and strain functions related to different types of applied forces and rotations. The iRAT and tRAT assessments include questions regarding the prework. Following the iRAT and tRAT, a class discussion takes place that is dependent on the students' responses. The application question for this TBL session requires teams to come up with their own design problem, given certain constraints, along with the solution to that design problem. Teams are then tasked with solving other teams' design problems.

3.4. Study instrument

3.4.1. Qualitative data

A survey instrument was employed in this study for the collection of qualitative data that shed light on the participants' motivation and self-efficacy in mechanics of materials. A 5-level Likert scale was provided for responding to Questions 1–7. Question 7 allowed for a freestyle response. The following questions were asked in the survey:

1. Participating in a TBL session strengthened my critical thinking skills.

2. Participating in a TBL session strengthened my teamwork skills.
3. In terms of virtual instruction, I prefer TBL modules rather than traditional classroom lectures.
4. In terms of in-person instruction, I prefer TBL modules rather than traditional classroom lectures.
5. After the TBL module, how confident do you feel about the presented material?
6. I would like to participate in more TBL modules in the future.
7. Additional comments and feedback space.

3.4.2. Quantitative data

Examination grades and the overall percentage of repeatable grades in mechanics of materials were tracked for the control courses (Summer 2020 and Fall 2020 semesters) and the case study TBL courses (Spring 2021, Summer 2021, and Spring 2023). All courses, control and TBL, were taught by the PI of the study to ensure there was no instructor variability in the delivery of course lectures or TBL modules. Traditional courses included primarily lectures for all class sessions with some unstructured group work that counted toward the students' participation grade in the class. TBL was not applied in the course in terms of the guidelines provided by TBLc. Examinations were administered in the same manner for both the control and study courses, which included similar questions that covered the material presented in class. Both courses consisted of two midterm exams and one final exam, which were closed-note and closed-book exams that took place during class time. The exam duration for both courses was 1 hour and 15 minutes. The examinations that were administered for the control and study classrooms were similar but not identical. The examinations in the class were designed to allow students to apply the knowledge they learned in the classroom, whether from traditional lecturing or TBL classrooms, to solving similar problems to what they had seen during class time.

4. Results

Selected free responses (Question 7) are presented in Table 2. General feedback from students in response to Question 7 showcased positive sentiments toward TBL sessions in most cases, with comments that reinforced the students' like for a mix of TBL and in-person instruction. Several students expressed that they needed more time to complete the in-class assignments. Some students stated that they felt unprepared to work with a group and solve a complex problem based on the prework, or that this type of teaching style did not suit their introverted personality. Most students mentioned that the TBL sessions helped prepare them for the examinations.

Table 3 presents a summary of Questions 1–6 from the survey instrument. A sample size of 80 students was used for the case study TBL course. Out of these 80 students, 76 survey responses were collected. From Table 3, it can be seen that the majority of students noted an increase in critical thinking and teamwork skills; however, the majority did not express a preference for TBL in comparison with traditional lecture-based classroom sessions. When referencing the free response feedback from students, this is in line with several students expressing interest in a mix of both TBL and traditional lecture-based sessions. It is worth noting that 73% of students expressed that they felt an increased level of confidence in the subject matter after the TBL session and that 78% expressed interest in participating in more TBL sessions in the future.

Table 2. General student feedback in response to Question 7 of the student survey.

General student feedback from survey questions
"I enjoy working with others when there is a good mix of understanding and when the groups actually communicate."
"Overall, I love the idea of TBL sessions. It's a great way to master what you thought you knew because there is always room to learn more. Thank you!"
"I think that the TBL sessions need more time, so it is better to have at least 15 more minutes, so we can ask more questions."
"It was a good addition to the presented classroom material."
"TBL is a great activity to prepare and be ready for the exams."
"The TBL do not serve introverts or shy students."
"The TBL has its pros and cons in my opinion. It definitely helped me better understand the material, but I don't think it could be used to replace lectures. I think a mix of both would be perfect."
"It forces me to be engaged and present."
"I would like more TBL sessions online or in class; also I prefer that the person that doesn't discuss should lose points."
"Limited time; if it was longer, would've benefited us more, I believe."
"I think the TBL session is very helpful because the whole class collaborates more with each other."

Table 3. Summary of 76 survey responses for Questions 1–6.

% of students who agreed that TBL increased critical thinking skills	74%
% of students who agreed that TBL increased teamwork skills	55%
% of students who stated a preference for TBL over traditional lectures (virtual instruction)	43%
% of students who stated a preference for TBL over traditional lectures (in-person instruction)	38%
% of students who expressed increased confidence in the course material after participating in TBL	73%
% of students who expressed interest in participating in more TBL sessions	78%

Exam grades and course failure rate results are presented in Table 4. The first two rows of the table present the average grades for all course examinations and the course failure rate for the control course where no TBL modules were implemented. Rows 3–5 present the average grades for all course examinations and the course failure rate for the TBL case study courses. In the TBL case study courses, no TBL intervention was presented prior to Exam 1 in order to provide another set of control statistics for the same student group in the same semester. Next, TBL Modules 1 and 2 were presented prior to Exam 2, and TBL Modules 3 and 4 were presented prior to the final examination.

For all TBL case study courses, there was an increase in examination scores between Exam 1, where no TBL module was provided, to Exam 2 and the final exam, where the TBL modules had been provided. Further, grades for the TBL course showed a trend of increasing throughout the entire course, where students' final exam grades were higher than both their Exam 1 and Exam 2 grades. The final exam was cumulative and therefore tested the students' overall understanding of the course material, which implies that students in the TBL course were able to significantly improve their understanding of the material by the final exam. Overall course failure rates for the TBL courses were significantly lower than those of the control courses.

Table 4. Exam scores and course failure rate for students enrolled in the control course with no TBL intervention prior to Exam 1, Exam 2, and the final exam and for students in the TBL course with interventions prior to Exam 1 and the final exam only.

Term	Total number of students enrolled	Intervention type prior to Exam 1	Exam 1 average (%)	Intervention type prior to Exam 2	Exam 2 average (%)	Intervention type prior final exam	Final exam toaverage (%)	Course failure rate (%)
Summer 2020	30	None	70	None	67	None	65	33
Fall 2020	42	None	52	None	54	None	63	55
Spring 2021	27	None	59	TBL Modules 1 and 2	67	TBL Modules 3 and 4	79	26
Summer 2021	27	None	27	TBL Modules 1 and 2	69	TBL Modules 3 and 4	71	30
Spring 2023	26	None	63	TBL Modules 1 and 2	70	TBL Modules 3 and 4	79	23

An unpaired *t*-test was conducted to compare the mean exam scores of the control course with those of the TBL course. The *p*-value was 0.0189, indicating the difference between groups to be statistically significant. A second *t*-test was conducted to compare the failure rate of the control course with that of the TBL course. The *p*-value was 0.1342, indicating no statistical significance between the control course and the TBL course in terms of the overall failure rate.

5. Discussion

The implementation of TBL in mechanics of materials courses at CSUF presents a significant shift from traditional lecture-based teaching methods. This discussion explores the effectiveness of TBL in addressing the challenges faced by engineering students, specifically in reducing failure rates and improving course outcomes.

Addressing the bottleneck

Mechanics of materials has long been identified as a critical bottleneck in engineering education, characterized by its high failure rates and its crucial role in the foundational knowledge required for advanced engineering courses. Historically, the high failure rates associated with this course have led many students to abandon their STEM majors. The traditional lecture-based instruction has been criticized for failing to adequately engage students or connect the material to practical applications. This study sought to address these issues by integrating TBL, a pedagogical approach designed to enhance students' engagement and learning outcomes.

Impact on students' performance

The quantitative data collected from this study reveal promising results regarding the impact of TBL on students' performance. The analysis indicates a significant improvement in examination scores following the implementation of TBL modules. Specifically, the students' performance in exams improved from those taken prior to the introduction of TBL modules to those taken after the TBL interventions. For each semester of the study, scores increased from Exam 1, where no TBL intervention was given, to Exam 2, where the TBL intervention was given. The final exam scores, which encompassed the cumulative understanding of the course material, showed a marked increase, suggesting that TBL effectively enhances students' comprehension and retention of the content.

The reduction in failure rates observed in the TBL courses compared with traditional lecture-based courses further underscores the effectiveness of TBL. Although the statistical significance of the failure rates did not reach conventional thresholds, the trend indicates a positive impact. The lower failure rates in TBL courses align with the study's hypothesis that active learning methods, such as TBL, can mitigate the issues associated with high-stakes courses like mechanics of materials.

The lack of statistical significance in improving course failure rates from the control group to the study group could be to multiple factors that need to be further explored. In the first place, it is possible that the number of TBL sessions was not enough and that more team learning opportunities need to be introduced in the classroom, particularly at the end of the course when the problems become more challenging, and the exams become more cumulative in nature. Furthermore, another observation that needs to be explored is if there are other aspects of knowledge acquisition are occurring that the exams and final course grades are unable to capture. TBL has been proven, in many other fields of study, to enhance learning and the acquisition of knowledge in accordance with Bloom’s taxonomy, so these other factors need to be further explored.

Overall, positive effects were observed in the TBL course, which included the implementation of structured TBL modules. The control group also received group assignments and opportunities to engage in discussions with peers and the instructor; however, these assignments were not structured with the 4S design as outlined by the TBLc. Both courses received the same amount of attention from the instructor, with the primary difference being in the method of instructional delivery. Therefore, it seems likely that specifically the implementation of this structured form of active learning is what led to the improved course outcomes presented in this paper. Ultimately, according to these findings, future studies need to explore whether a hybrid approach to instructional delivery that incorporates TBL and lecture-based discussions could be best for engineering classes or if, potentially, a full TBL course would lead to better outcomes.

Enhancement of critical thinking and teamwork

The survey responses corroborate the quantitative findings, revealing that students perceive TBL to be beneficial in developing critical thinking and teamwork skills. The majority of students reported increased confidence in their understanding of the material following TBL sessions, which is consistent with the observed improvements in examination performance. This enhancement in confidence is crucial, as it likely contributes to students’ persistence in their engineering studies and their overall academic success.

The positive feedback on teamwork skills is particularly noteworthy. TBL’s structured team activities facilitate peer learning and collaborative problem-solving, which are essential skills in engineering practice. The ability to work effectively in teams is highly valued in the engineering profession, and TBL’s focus on collaborative learning helps students develop these skills in a supportive environment.

Students’ preferences and perceptions

While the majority of students appreciated the TBL approach, some expressed a preference for a blend of traditional and TBL methods. This feedback suggests that a hybrid instructional model might offer the most comprehensive benefits. Incorporating traditional lectures with TBL activities could cater to diverse learning styles and provide a more balanced educational experience. The mix of instructional methods could address the varying needs of students, including those who may struggle with the more dynamic aspects of TBL or who benefit from the structured guidance provided by traditional lectures.

The feedback also highlighted that some students felt unprepared for the collaborative nature of TBL or preferred more time to complete assignments. These concerns should be addressed in future implementations to enhance the effectiveness of TBL. For instance, providing additional support and preparation for team-based activities could alleviate some of these challenges.

Effectiveness of TBL over other active learning methods

In the context of engineering, TBL's implementation has not been studied but it has proven to be more effective than active learning in the field of medical education. Many instructors have noted that active learning alone lacks structure and that many commonly studied active learning techniques require too many resources and classroom tutors to be able to implement. TBL bridges these gaps and allows a structured form of active learning outlined by the TBLc, in which instructors can receive rigorous and complete training to learn how to effectively implement. Additionally, the fact that no additional outside resources or tutors are needed makes this method easily implementable in any classroom. This research provides a case study that explored how TBL can be used to address bottleneck courses in the engineering curriculum to improve students' outcomes, such as examination grades and overall course failure rates, as well as increased confidence in the subject.

Connection to existing literature and theoretical implications

The findings from this study align with previous research that highlights the challenges associated with the mechanics of materials course, often identified as a major bottleneck in engineering education. As noted by [4], mechanics of materials has one of the highest failure rates among the core engineering courses, which is also evident in the data collected from CSUF showing a 40% failure rate. This study confirmed that traditional lecture-based methods are insufficient in addressing these challenges, echoing the findings from [17] and [18], who both pointed out that passive learning environments fail to foster deep engagement with complex concepts. Our results indicate that the integration of TBL, a structured form of active learning, significantly improves students' performance (increased exam scores) and reduces failure rates, supporting the work of [19] and [20], who found that active learning methodologies, including TBL, can enhance student outcomes in challenging courses. Furthermore, this study builds on the literature that suggests TBL's structured approach helps bridge the gap between theory and practical application, confirming the potential of TBL to improve students' engagement and retention in engineering disciplines, as discussed by [24]. By highlighting these connections, our findings contribute to the growing body of research advocating for active learning strategies, particularly TBL, in STEM education, and suggest that such approaches could offer viable solutions to address the high failure rates in foundational courses like mechanics of materials.

6. Conclusions and future work

This study aimed to address the persistently high failure rates in fundamental engineering courses, such as mechanics of materials, which are pivotal in civil and mechanical engineering curricula. By integrating TBL, an active learning pedagogy, into the mechanics of materials classrooms at CSUF, we compared two traditional lecture-based courses with three TBL-enhanced courses. The results revealed a statistically significant improvement in examination grades with TBL, though the failure rates did not show significant differences. Nonetheless, the students' feedback was overwhelmingly positive, with many students reporting enhanced critical thinking and teamwork skills due to TBL.

This case study highlights the potential of TBL to enhance students' skills and confidence in the course material. The promising results suggest several directions for future research and practice. Expanding TBL to other fundamental engineering courses and across various institutions could provide insights into the effects of instructor variability and broader applicability. Investigating TBL's impact on student retention, particularly for underrepresented minorities in STEM, is also crucial. Future studies should explore the long-term effects of TBL on students' performance and retention in subsequent courses. Additionally, examining different frequencies and structures of TBL modules may help refine and optimize this pedagogical approach. Incorporating students' feedback to address concerns about preparation, time management, and team dynamics will be essential for enhancing TBL's effectiveness. A broader range of research, including comparative studies with various active learning methods, will offer a deeper understanding of TBL's efficacy and inform strategies for improving STEM education.

The integration of TBL in the mechanics of materials course at CSUF is a promising step forward in overcoming the challenges in engineering education. The positive impact on students' performance and the development of essential skills highlight TBL's potential to enrich the learning experience and enhance educational outcomes. As engineering education evolves, adopting innovative pedagogical approaches like TBL will be key to fostering students' success and advancing STEM disciplines.

While this study provides valuable insights into the effectiveness of TBL in mechanics of materials courses, several limitations should be acknowledged. First, the study's sample size was limited to a single institution, which may impact the generalizability of the findings to other universities or engineering disciplines. Additionally, the relatively short duration of the TBL intervention may not have fully captured the long-term effects on students' learning and retention. The study also relied on examination scores and failure rates as the primary measures of success, which may not fully reflect the broader range of skills and competencies that TBL aims to enhance, such as collaborative problem-solving and critical thinking. Future research could address these limitations by incorporating a larger, more diverse sample and exploring a wider array of assessment methods.

Author contributions

Huda Munjy: conceptualization, data curation, formal analysis, writing – original draft, writing – review and editing; Stephanie Botros: resources, writing – review and editing; Rhona Abouazra: resources, investigation. All authors have read and agreed to the published version of the manuscript.

Use of AI tools declaration

The authors declare they have not used artificial intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare that there are no conflicts of interest in this paper.

Ethics declaration

All ethical standards were upheld while conducting this research.

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