Mechanics Escape Room: Escaping the Monotony of Solving Problems

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Abstract: Completion of an escape room activity requires participants to work as a team to find hidden clues and solve challenging puzzles to escape before time expires. The use of escape rooms for active learning may produce a positive classroom environment by improving teamwork skills, encouraging engagement with course materials, fostering intellectual curiosity, and facilitating conceptual understanding beyond the prescribed procedure. An escape room was developed for the Mechanics of Materials course at the United States Military Academy. The escape room was designed based on a hypothetical theme to increase student motivation and curiosity. Students were required to complete five puzzles that involved navigating through underground steam tunnels to locate the boiler in the classroom building where their final examination would take place. This task was intended to force the cancellation of the examination. The five puzzles assessed the students' knowledge of torsional members, statically indeterminate axially loaded members, flexural members, stress transformation, strain transformation, and thin-walled pressure vessels. The escape room was piloted in five sections ranging from 15 to 18 students. Teams of five to six students completed the escape room activity. The escape room increased active participation and made the students aware of the concepts they needed to focus on for the final examination. This case study includes details on the complete design of the escape room, including the problems presented, results of student teams, and student feedback. **DOI: 10.1061/JCEECD.EIENG-2032.**

Introduction: Motivating Students in Engineering Courses

One of the primary challenges for educators is engagement and motivation of students. This is not to say that students are not actively engaged in other activities. A study conducted in 2022 estimated that 66% of Americans play video games at least weekly, and on average, players spend 13 h each week (NPD Group 2022). This time is equivalent to the average time required to complete a four-credit hour college course. A previous study found that the amount of time spent playing games could be closer to a full-time job (40 h/week) (Homer et al. 2012). As a result, it is increasingly more challenging to maintain students' attention, especially in higher education engineering courses. Engineering educators must find creative and innovative ways to inspire their students.

Over the past two decades, research has been focused on "gamification" as a method for creating a stimulating and motivating environment in higher education classrooms (Bodnar et al. 2016). Gamification integrates aspects of gameplay, such as scoring or prizes, to attract and engage students with educational course material (Deterding et al. 2011). While traditional lecture-based classrooms are ideal for targeting the first two levels of Bloom's taxonomy (i.e., remembering and understanding), transmission-based learning has been found to be ineffective in achieving higher levels of knowledge, which require active participation of students (Bloom et al. 1956). However, even active learning activities, such as laboratory exercises, were ineffective in allowing students to apply their knowledge (Abrahams and Millar 2008). These exercises consisted of students following a checklist. Introducing a game environment may provide students with an opportunity to apply their knowledge to solve ill-defined problems. Gamification can improve motivation, concentration, curiosity, and creative exploration.

Garris et al. (2002) identified that the appeal of games comes from voluntary participation of players, making the development of educational games a challenge. Players' or students' choices are needed to directly affect the outcome of the game (Costikyan 2002; Crawford 2003; Salen and Zimmerman 2003). From an educational standpoint, it is critical that the game has a clear set of learning objectives that are achieved as students progress through the game. Sitzmann (2011) and Vogel et al. (2006) showed that one of the greatest outcomes of educational games is improving students' attitudes or perceptions of course topics, which motivates them to seek higher levels of learning.

An educational game-based method that has been growing in popularity is escape room (Clarke et al. 2017; Nicholson 2015, 2018; Wiemker et al. 2015). Escape rooms were developed as a social and team-building activity where participants are required to work together to find clues and solve complex puzzles. The ultimate goal is to complete all challenges to escape the room before time expires. The design of the puzzles must be complex enough to require teamwork, so that one individual cannot dominate the challenge, but not too difficult, making the participants feel overwhelmed or incompetent. One of the challenges for instructors is ensuring that the challenge is properly scoped so as not to introduce additional stress for students due to the complexity of the problems and strict time limit (Manzano-León et al. 2021). When implementing an effectively designed escape room in an educational environment, students need to communicate as members of a multidisciplinary team to formulate and solve problems by

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applying fundamental knowledge. Instructors can assess three of the seven student learning outcomes specified by ABET: (1) solve problems, (2) communicate effectively, and (3) function as a team (ABET 2022).

Previous researchers have implemented escape rooms in several science, technology, engineering, and mathematics (STEM) disciplines, including chemistry, medicine, and engineering (Arnal-Palacián et al. 2019; Borrego et al. 2017; Cain 2019; Eukel et al. 2017; Fuentes-Cabrera et al. 2020; Kinio et al. 2019; de la Flor et al. 2020; López-Pernas et al. 2019; Vita Voros and Sárközi 2017). Escape rooms implemented in engineering courses have observed an increase in student engagement with course material, including their motivation to solve complex problems, the ability to work in a team, and the ability to communicate effectively (Butkus et al. 2022; Newhart et al. 2022; Ross and Bennett 2022; Streiner et al. 2019). Instructors used escape rooms as a design opportunity for students to develop their own challenges (Davis and Lee 2019). Previous research has shown that the creation of an escape room was challenging. To achieve the target level of student engagement, instructors must facilitate student interest in the course topic.

This case study investigated the implementation of an escape room in an engineering mechanics course as an alternative course-end review before the final examination. This paper details the motivation, design, and execution of the escape room. The discussion section briefly addresses student feedback on the escape room and an assessment of the impact of the escape room on student perception and learning outcomes.

Design of the Mechanics Escape Room

The escape room challenge was implemented in an introductory engineering course on the mechanics of materials. The students enrolled in the course included second-year civil and mechanical engineering students and third-year nuclear engineering students. The course was a 3.5 credit hour course with a total of 35 lessons. The course covered fundamental mechanics principles, including internal forces, stresses, and deformations due to axial, bending, and torsional loading; analysis of basic indeterminate structures; principal stresses and strains due to combined loading; and theories of failure. Successful completion of the course learning objectives provided students with the essential prerequisite knowledge required for engineering courses, including structural analysis, machine component design, and capstone design.

During the last final examination review lesson, instructors summarized each topic covered during the semester, answered the students' questions, and solved two to three example problems (time permitting). The instructors typically led this lesson. Students "fished" for specific information on the final examination. This method enabled students to solve problems specific to those reviewed during preparation. The students struggled to solve variations of the problem, which applied the same fundamental principles.

To stimulate an engaging learning environment and increase student confidence in their ability to solve ill-defined problems, an escape room challenge was implemented in lieu of the traditional course review lesson during the spring semester of 2022 and 2023. The escape room activity was implemented in five sections of the Mechanics of Materials course taught by three different instructors, with a maximum of 18 students. The following three primary objectives for the escape room aligned with ABET student outcomes:

1. **Participate** actively in a themed escape room.
2. **Collaborate** as a team to compile clues required to solve puzzles.
3. **Apply** fundamental mechanics knowledge to solve ill-defined problems.

The development of a themed escape room was essential to ensure that the students were entertained and voluntarily participated in the activity (Garris et al. 2002). The escape room design was based on the authors' experience participating in commercial escape rooms. The authors wanted to include aspects, such as combination locks, multistep clues, and distinct puzzles. In terms of organization, there are three typical structures for escape rooms: linear, open, and multilinear (Wiemker et al. 2015). Most previous educational escape rooms were linear, which required less instructor guidance (Veldkamp et al. 2020). The instructor was free to oversee the student progress and provide immediate feedback or hints. However, a linear path reduced the attractiveness of escape rooms to students because their decisions had a limited influence on a single correct procedure (Crawford 2003). The open and multilinear paths were more complicated but provided more opportunities for collaboration and teamwork. For the design of this escape room, a hybrid linear approach was used, where students could make a mistake for certain puzzles but had to answer an alternative mini-puzzle before proceeding back to the main puzzle. These mini-puzzles provided students with immediate feedback to help identify their errors.

The design of the escape room was intended to promote engagement with the course materials, collaboration, and creative thinking. The students applied their teamwork and leadership skills in a time-constrained environment that lacked structure or direction compared to a traditional class. The primary design of the escape room was linear; therefore, deliberate design aspects were needed to facilitate outside-the-box thinking and teamwork. Multilevel clues included in each of the puzzles allowed students to approach solutions from different angles. The puzzles were challenging enough to require collaboration but were achievable within the time constraints (Hays 2005; Manzano-León et al. 2021; Wiemker et al. 2015). The size of each group was selected to determine the amount of participation required by each student (Watermeier and Salzameda 2019). Smaller teams required more individual student participation, whereas larger teams required more collaboration. With section sizes as large as 18, teams consisting of five to six students were created for three escape room teams for each section. These teams were formed by combining two groups of two to three students who worked together during the semester on course projects and laboratory assignments. This gave the team familiarity with each other's skills.

The final objective was to ensure that escape room puzzles were an effective review mechanism for students' fundamental knowledge of the mechanics of materials. The duration of the escape room was 75 min, which corresponded to the duration of one lesson. An initial estimate was made to develop six puzzles, each requiring approximately 10 min to solve. This estimation included the time required to decipher the puzzle, identify clues, and complete the engineering problem. The time required to complete the puzzles was determined similar to examinations, where one author created the escape room theme and puzzles and the second author conducted a test run to ensure that the puzzles were appropriately scoped. The authors assumed that the time required for an instructor to complete the test run equaled that of a team of five to six students. The instructor completed the timed escape room in 70 min. To provide the students with additional time, the instructors converted the sixth puzzle into a bonus puzzle.

The test run helped identify the most difficult aspects of the puzzles and develop appropriate clues and hints to provide the right level of complexity. The topics covered in a traditional review class compared to the escape room are shown in Table 1. The puzzles were designed considering the course learning objectives, as listed in Table 2.

To successfully complete the escape room, the students applied their conceptual knowledge and problem-solving skills to analyze each problem. The problems were abstract and did not appear the same as typical textbook, homework, or examination problems. Solving the problems required the students to identify critical information provided through a series of clues. The goal was to increase the students' confidence in their understanding (or to identify gaps in their knowledge), improve their interest in the topic, and realize the relevance of the course material.

Implementation: The Art of Escape

The design of the escape room for the Mechanics of Materials course started with the selection of six puzzle topics. The Mechanics of Materials course includes eight subtopics, with six selected for the escape room, as shown in Table 1. For the selection of puzzle topics, the authors prioritized topics covered at the beginning of the course, which would be the most difficult for students to recall. The authors also highlighted common errors made on graded assessments. Lastly, each topic supported one or more of the course objectives listed in Table 2. The five topics were statically indeterminate axially loaded members, torsional members, flexural members, stress transformation, and thin-walled pressure vessel. The sixth bonus topic was about the theories of failure. Therefore, only statically indeterminate bending members and combined loading were not included in the escape room.

A common theme tied together the six puzzles within a storyline relevant to the students. The true art of designing an escape room is the formulation of an immersive theme to maintain student interest throughout the duration of the activity. The theme created an environment to encourage engagement, inspire creativity, and connect to the example problems used throughout the course.

At the United States Military Academy, specifically during the freshman and sophomore years, students are required to remain on campus for most of the year to complete military and physical training in addition to their academics. Students entertain themselves through long-standing traditions. It has been rumored that since the 1950s, students have navigated the underground steam tunnel system (Hamel 2016). The author selected navigating steam tunnels as a consistent storyline for the escape room. The theme allowed for creative puzzle designs within a single theme tied directly to the course material.

Before the escape room activity, an introductory slide was presented to set the theme. The escape room activity began by placing the students in their dormitory rooms the night before the final examination on the mechanics of materials. The students were faced with the decision of either studying for the examination or finding a way to have the examination canceled. For the escape room activity, the students were required to navigate the steam tunnels by completing the puzzles. The ultimate goal was to reach the boiler room in the academic building where the examination was held, Mahan Hall. The final puzzle required the students to increase the heat in the building to force the cancellation of the final examination. In reality, the students still took the final examination, but this layer of the storyline provided them with an extra hypothetical incentive to succeed.

Brainstorming challenges that require the application of knowledge of mechanics of materials in the context of navigating steam tunnels was the first step in developing the puzzles. Ideas generated during the brainstorming session included locked doors, flooded pathways, and identification of exact locations in the complex tunnel system. Each challenge was paired with one of the six selected course topics, as shown in Fig. 1.

Before starting the escape room activity, the teams were given a set of rules and assumptions, as shown in Fig. 2. These rules and assumptions included the estimated weight of an individual student on the team, the number of significant figures for numerical values, and the units for each of the problems.

Puzzle 1: Break the Door

The first puzzle for the escape room assessed the students' ability to solve a basic torsional loading problem considering basic failure theories, which corresponded to Course objectives 1 and 3 in Table 2. A basic torsional loading problem is shown in Fig. 3 (Philpot and Thomas 2020). This problem required the students to determine the shear stress on a bolt when applying torque via a wrench. It provided them with a detailed diagram, all necessary geometric, material, and loading information, and explicitly informed them of what they needed to solve. To develop the puzzle

Table 1. Number of students and topics covered in the traditional review class, the escape room activity, and in the final examination

Topics	Traditional class	Escape room	Final examination
Number of students	205	83	288
Topics			
Statically indeterminate axial	×	×	×
Torsional analysis		×	×
Flexural analysis		×	×
Statically indeterminate bending	×		×
Principal stresses		×	×
Thin-walled pressure vessel		×	×
Combined loading	×		×
Failure theories		×	×

Table 2. United States Military Academy Mechanics of Materials course learning objectives

No.	Description
1	Calculate the internal forces, internal stresses, and deformations of axially loaded members, circular members in torsion, thin-walled pressure vessels, prismatic beams in bending, columns, and members subjected to combined loading and/or thermal effects.
2	Apply compatibility of deformations to analyze and design members of a statically indeterminate structure subjected to loading and/or thermal effects.
3	Apply appropriate theories of failure to analyze and design thin-walled pressure vessels and members subjected to loading and/or thermal effects.
4	Given strain data from a strain gauge, determine the applied force, moment, or pressure on a structure.
5	Given a state of stress at a point, determine the principal stresses, maximum in-plane shear stress, angle to the principal plane, and state of stress on any plane.
6	Apply deformation–strain, strain–stress, and stress–force relationships to analyze and design structural members and machine components.
7	Conduct laboratory experiments to verify and apply methods, theories, and scientific laws learned throughout the course, and prepare proper technical reports to clearly communicate the conduct and results of those experiments.

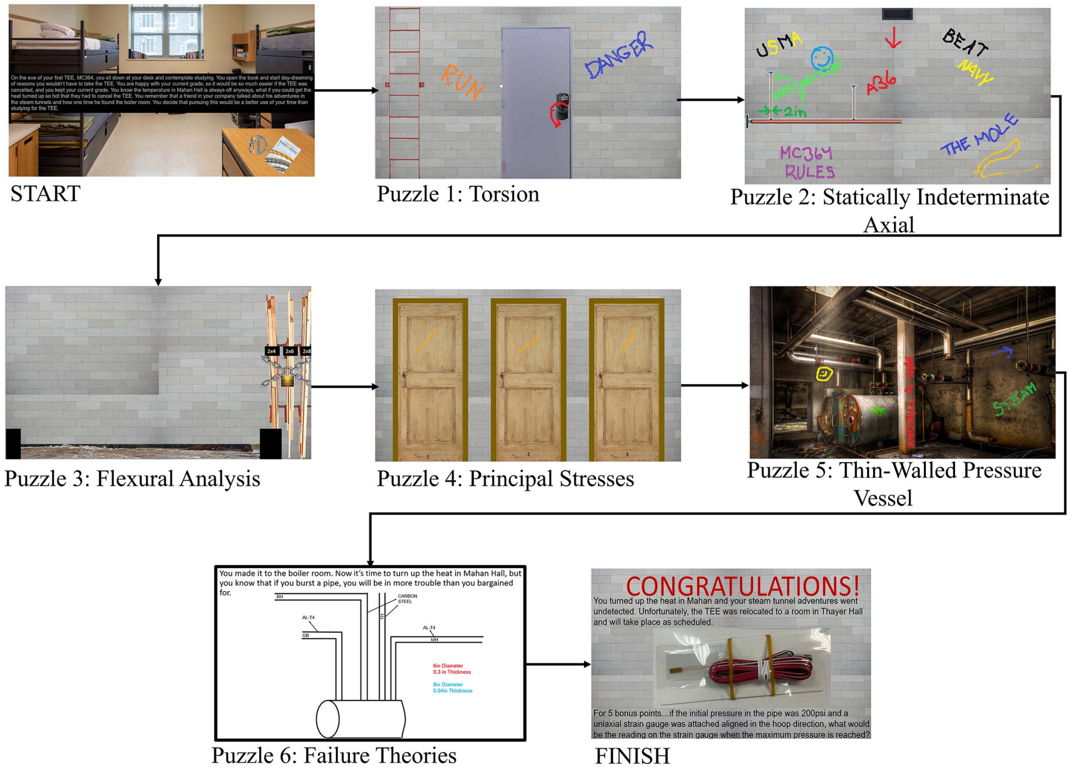

Fig. 1. Flowchart of the escape room.

Fig. 2. Rules and assumptions for the escape room.

P6.6 The nut on a bolt is tightened by applying a force of $P = 16$ lb to the end of a wrench at a distance of $a = 6$ in. from the axis of the bolt, as shown in Figure P6.6. The body of the bolt has an outside diameter of $d = 0.375$ in. What is the maximum torsional shear stress in the body of the bolt?

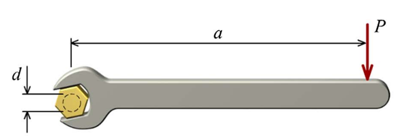

Fig. 3. Basic textbook torsional loading problem. (Reproduced with permission from Philpot and Thomas 2020; Copyright © 2020, 2019, 2017, 2013, 2011, 2008 John Wiley & Sons, Inc. All rights reserved.)

Materials	Specific weight (lb/ft³)	Yield strength (ksi)[a b]	Ultimate strength (ksi)[a]	Modulus of elasticity (1,000 ksi)	Shear modulus (1,000 ksi)	Poisson's ratio	Percent elongation over 2-in. gage length	Coefficient of thermal expansion (10^{-6}/°F)
Aluminum Alloys								
Alloy 2014-T4 (A92014)	175	42	62	10.6	4	0.33	20	12.8
Alloy 2014-T6 (A92014)	175	60	70	10.6	4	0.33	13	12.8
Alloy 6061-T6 (A96061)	170	40	45	10	3.8	0.33	17	13.1
Brass								
Red Brass C23000	550	18	44	16.7	6.4	0.307	45	10.4
Red Brass C83600	550	17	37	12	4.5	0.33	30	10.0
Bronze								
Bronze C86100	490	48	95	15.2	6.5	0.34	20	12.2
Bronze C95400 TQ50	465	45	90	16	6	0.316	8	9.0
Cast Iron								
Gray, ASTM A48 Grade 20	450		20	12.2	5	0.22	<1	5.0
Ductile, ASTM A536 80-55-06	450	55	80	24.4	9.3	0.32	6	6.0
Malleable, ASTM A220 45008	450	45	65	26	10.2	0.27	8	6.7
Steel								
Structural, ASTM-A36	490	36	58	29	11.2	0.3	21	6.5
Structural, ASTM-A992	490	50	65	29	11.2	0.3	21	6.5
AISI 1020, Cold-rolled	490	62	90	30	11.6	0.29	15	6.5
AISI 1040, Hot-rolled	490	60	90	30	11.5	0.3	25	6.3
AISI 1040, Cold-rolled	490	82	97	30	11.5	0.3	16	6.3
AISI 1040, WQT 900	490	90	118	30	11.5	0.3	22	6.3
AISI 4140, OQT 1100	490	131	147	30	11.5	0.3	16	6.2
AISI 5160, OQT 700	490	238	263	30	11.5	0.3	9	6.2
SAE 4340, Heat-treated	490	132	150	31	12	0.29	20	6.0
Stainless (18-8) annealed	490	36	85	28	12.5	0.12	55	9.6
Stainless (18-8) cold-rolled	490	165	190	28	12.5	0.12	8	9.6
Titanium								
Alloy (6% Al, 4%V)	280	120	130	16.5	6.2	0.33	10	5.3
Plastics								
ABS	66	6	5.5	0.3	–	–	36	48.8
Nylon 6/6	69	9	–	0.2	–	–	–	65.6
Polycarbonate	90	16	17	1.1	–	–	–	[illegible]
Polyethylene, Low-density	58	1.4	1.7	0.029	–	–	–	
Polyethylene, High-density	60	3.3	4.3	0.128	–	–	721	
Polypropylene	71	11	12	0.9	–	–	4	
Polystyrene	73	7.5	7.5	0.54	0.2	0.33	39	
Vinyl, rigid PVC	81	6.7	5.5	0.41	0.145	0.42	100	35

Fig. 4. Puzzle 1: (a) partially locked backpack and envelope; (b) scenario; (c) padlock; (d) door-hanger security advertisement; (e) mechanics of materials equation sheet; and (f) table of material properties. [Images (a, c, and d) by authors; (e and f) reproduced with permission from Philpot and Thomas 2020; Copyright © 2020, 2019, 2017, 2013, 2011, 2008 John Wiley & Sons, Inc. All rights reserved.]

for the escape room, the problem was more ill-defined but assessed the same conceptual understanding. To solve this problem, the teams had to identify critical geometric, material, and loading information from several clues.

Fig. 4(a) illustrates the materials provided for Puzzle 1: a partially locked backpack and an envelope with the initial scenario and supplemental resources. The front zipper pocket of the backpack contained additional items, as shown in Fig. 5. However, these items were not pertinent to Puzzle 1 but were required for later puzzles. This encouraged the students to identify relevant information. Additional resources included fundamental equations [Fig. 4(e)] and material properties [Fig. 4(f)] (Philpot and Thomas 2020).

The arrow in Fig. 4(b) indicates that the teams applied torque to the door handle. Fig. 4(d) provides information on the door handle in the form of a door-hanger security advertisement, including material (titanium), geometric properties (diameter of 20 mm), and factor of safety (Increase your home safety factor ×2 today!). The brand "Mises Door Security System" indicates the use of the von Mises failure criteria. The shear yield strength (τ_y) of the material obtained using the von Mises failure criteria was approximately 57.7% of the normal yield strength (σ_y), as shown in Eq. (1):

$$\tau_y = 0.577 \cdot \sigma_y \tag{1}$$

The allowable torsional shear stress (τ_{all}) in the spindle was calculated in terms of the maximum torque ($T_{\max}$) applied, as shown in Eq. (2):

$$\tau_{\text{all}} = \frac{T_{\max} c}{J} \tag{2}$$

where c = radius of the spindle; and J = polar moment of inertia. The students solved the torque required to fail the spindle using the allowable strength design method presented in Eq. (3), where FS = factor of safety:

$$\tau_{\text{all}} = \frac{\tau_y}{\text{FS}} \tag{3}$$

The students input the four-digit numerical value for the maximum torque in the units of kilonewton-meters into the padlock [Fig. 4(c)] on the backpack to unlock Puzzle 2.

M5.7 Rigid bar AD is pinned at A and supported by bars (1) and (2) at B and C, respectively. Bar (1) is aluminum and bar (2) is brass. A concentrated load P=36 kN is applied to the rigid bar at D. Compute the normal stress in each bar and the downward deflection of the rigid bar at D.

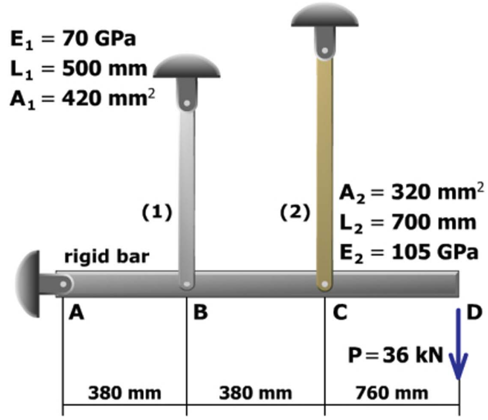

Fig. 5. Basic textbook statically indeterminate axially loaded member problem. (Reproduced with permission from Philpot and Thomas 2020; Copyright © 2020, 2019, 2017, 2013, 2011, 2008 John Wiley & Sons, Inc. All rights reserved.)

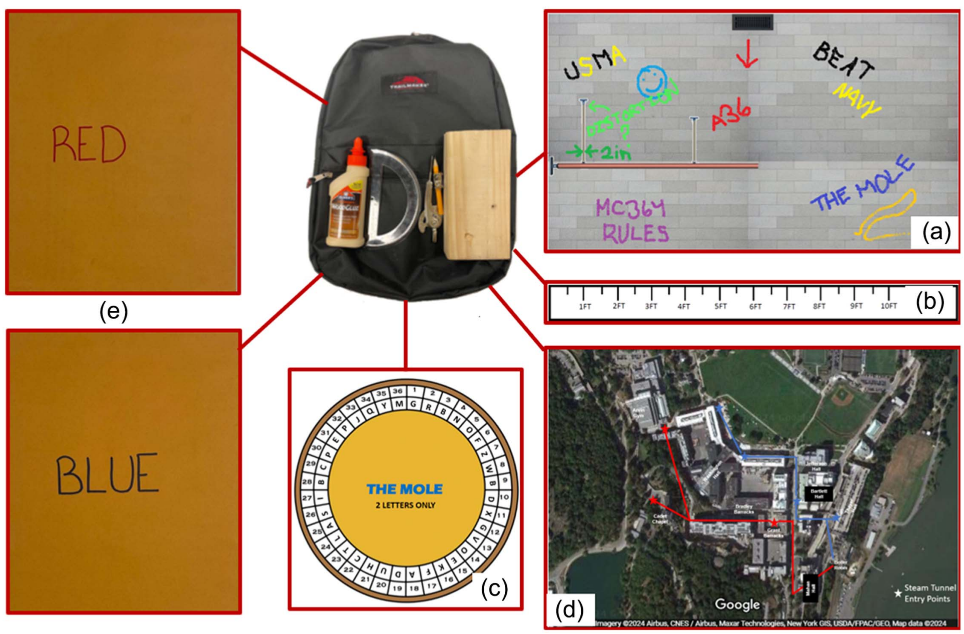

Fig. 6. Puzzle 2: (a) scenario; (b) ruler; (c) alpha numerical decoder ring; (d) West Point campus map (map data © 2024 Google; imagery © 2024 Airbus, CNES/Airbus, Maxar Technologies, New York GIS, USDA/FPAC/GEO); and (e) envelopes marked with the words "red" and "blue."

Puzzle 2: Distortion ≡ Deformation

The second puzzle assessed the students' ability to solve a statically indeterminate axially loaded member problem, which corresponded to Course objective 2 in Table 2. A basic statically indeterminate axially loaded member problem is shown in Fig. 5 (Philpot and Thomas 2020). For this type of problem, the students used the geometry of deformation equations in addition to the equations of equilibrium to solve for all unknown external reactions. The authors previously found that this topic was one of the most difficult mechanics topics for students to conceptually understand (Bruhl et al. 2022).

Fig. 6 shows the items included in the backpack, including the scenario for Puzzle 2 [Fig. 6(a)], a map of the West Point campus [Fig. 6(d)], additional clues, envelopes with padlocks on them (Figs. 11 and 17), and envelopes with color or number indicators [Figs. 6(e) and 11]. Many of these items were used for succeeding puzzles. The Puzzle 2 scenario shown in Fig. 6(a) used an image of a statically indeterminate axial problem similar to those in the textbook to ensure that the teams correctly identified the type of problem.

The teams were required to identify the critical information required to solve the problem based on the graffiti on the wall, as shown in Fig. 6(a). The rod labeled "Distortion?" indicates that the teams solve for the axial deformation. The bar diameter was included. The marking "A36" corresponds to ASTM Grade A36 steel. The team used a ruler [Fig. 6(b)] to measure the length of the bars and rigid member. The students used an assumed weight of 210 lb for the loading at the location of the arrow. The students solved for the axial deformation of the bar using the five-step solution method for statically indeterminate axial structures. The final axial deformation was a two-digit value in units of 10^{-3} inches.

The alpha numerical decoder ring [Fig. 6(c)] converted the two-digit value to two letters, indicating a building on the campus map [Fig. 6(d)]. The teams determined which route, blue or red, led to

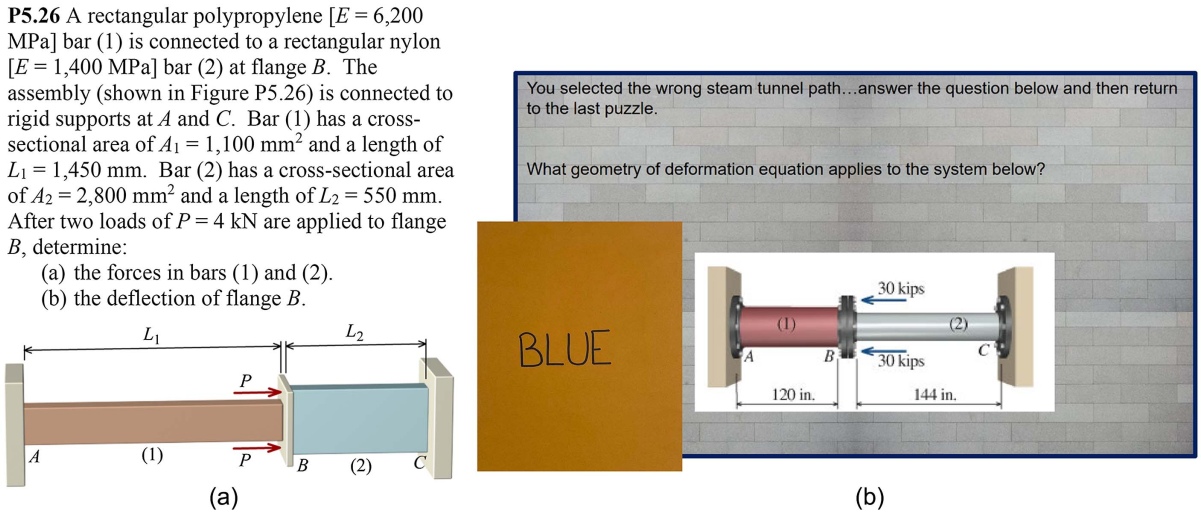

Fig. 7. Penalty Puzzle 2: (a) basic textbook statically indeterminate axially loaded member problem (reproduced with permission from Philpot and Thomas 2020; Copyright © 2020, 2019, 2017, 2013, 2011, 2008 John Wiley & Sons, Inc. All rights reserved); and (b) penalty question.

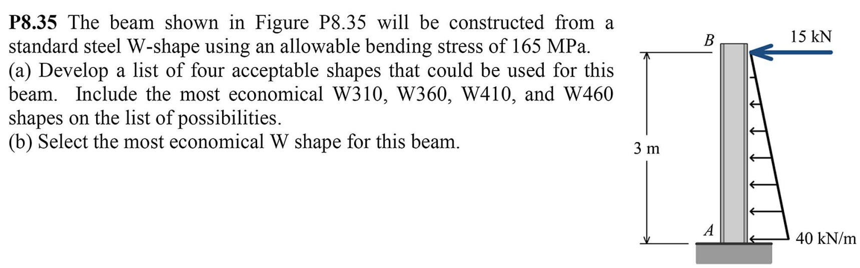

Fig. 8. Basic textbook flexural loading problem. (Reproduced with permission from Philpot and Thomas 2020; Copyright © 2020, 2019, 2017, 2013, 2011, 2008 John Wiley & Sons, Inc. All rights reserved.)

Mahan Hall. Each route color corresponds to one of the envelopes in Fig. 6(e).

The selection of the correct route (red) led to the third puzzle, whereas the selection of the incorrect route (blue) led to a penalty question, as shown in Fig. 7. The selection of the wrong route indicates a lack of mastery of Course objective 2. The penalty puzzle required teams to solve a basic statically indeterminate axially loaded member textbook problem before proceeding to the next puzzle.

Puzzle 3: Balance Beam

The third puzzle assessed the students' knowledge of flexural analysis and design, which corresponds to Course objectives 1 and 3 in Table 2. A basic flexural design question is shown in Fig. 8 (Philpot and Thomas 2020). In these types of problems, the students determined the minimum required geometry, material property, or maximum loading for the system shown.

The folder [Fig. 9(a)] included the scenario for the third puzzle [Fig. 9(b)] and a table with geometric properties for available lumber sizes [Fig. 9(d)] (AWC 2018). In the third scenario, a portion of the steam tunnel was filled with foul-smelling water. A pile of lumber of different sizes was provided. The students identified the size of the lumber with sufficient flexural capacity to allow passage. Based on the estimated weight of one student (P) and the length of the span (L) measured using the ruler shown in Fig. 9(f), the teams calculated the required moment capacity ($M_{\max}$) for a simply supported beam with a point load in the center using Eq. (4):

$$M_{\max} = \frac{P \cdot L}{4} \tag{4}$$

The teams determined the required section modulus (S) based on Eq. (5):

$$S \geq \frac{M_{\max}}{\sigma_b} \tag{5}$$

where the bending strength (σ_b) of the lumber was determined from the materials property table [Fig. 9(d)] and the samples of pine framing lumber [Fig. 9(e)], which were both provided in the first puzzle. The three-digit numerical value for the section modulus unlocked the padlock on the envelope for Puzzle 4.

Puzzle 4: Choose One Mohr Door

The fourth puzzle focused on stress transformation, which corresponds to Course objectives 3 and 5 in Table 2. A basic stress transformation problem required the students to determine the normal and shear stresses along an inclined plane, as shown in Fig. 10 (Philpot and Thomas 2020). The angle or dimensions of the inclined plane relative to the loading direction were clearly stated in the problem.

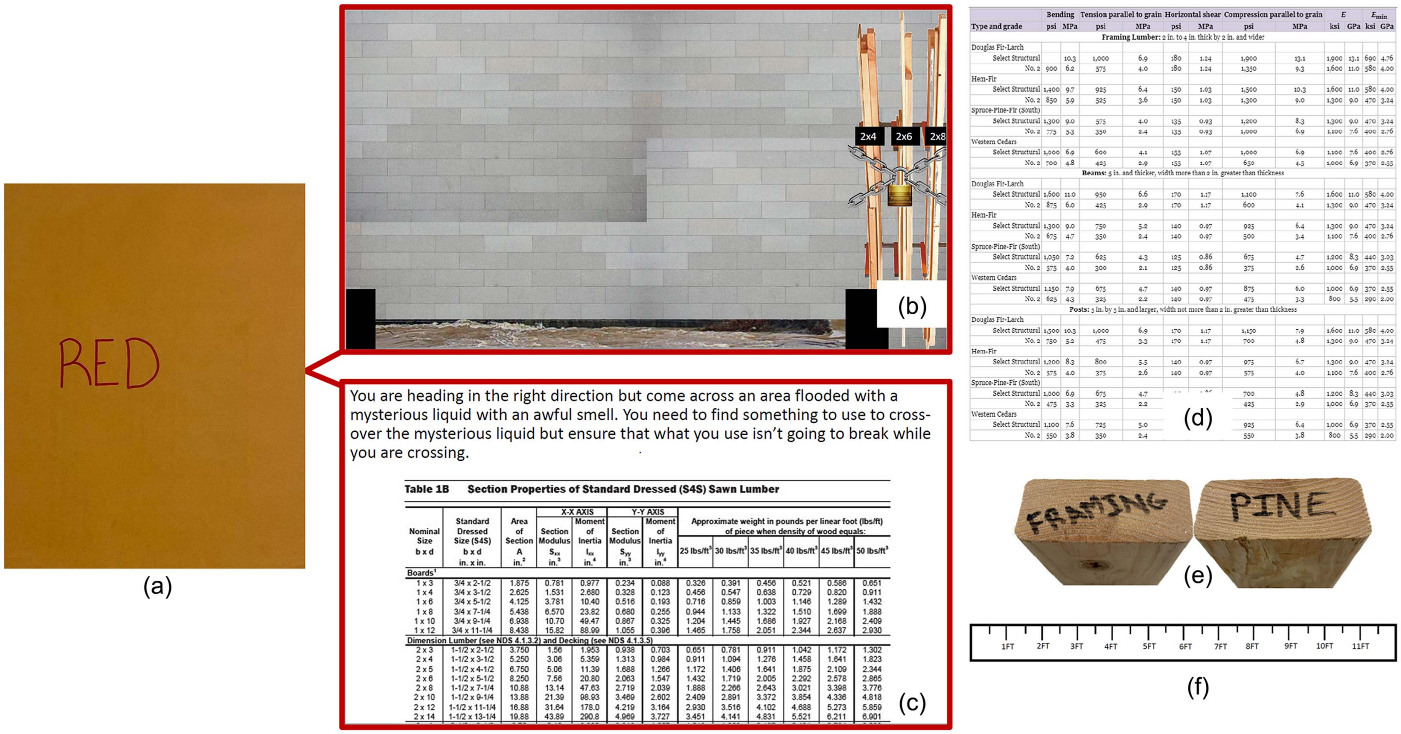

Table 1B Section Properties of Standard Dressed (S4S) Sawn Lumber

Nominal Size b x d	Standard Dressed Size (S4S) b x d in. x in.	Area of Section A in.²	X-X AXIS Section Modulus S_{xx} in.³	X-X AXIS Moment of Inertia I_{xx} in.⁴	Y-Y AXIS Section Modulus S_{yy} in.³	Y-Y AXIS Moment of Inertia I_{yy} in.⁴	25 lbs/ft³	30 lbs/ft³	35 lbs/ft³	40 lbs/ft³	45 lbs/ft³	50 lbs/ft³
Boards[1]												
1 x 3	3/4 x 2-1/2	1.875	0.781	0.977	0.234	0.088	0.326	0.391	0.456	0.521	0.586	0.651
1 x 4	3/4 x 3-1/2	2.625	1.531	2.680	0.328	0.123	0.456	0.547	0.638	0.729	0.820	0.911
1 x 6	3/4 x 5-1/2	4.125	3.781	10.40	0.516	0.193	0.716	0.859	1.003	1.146	1.289	1.432
1 x 8	3/4 x 7-1/4	5.438	6.570	23.82	0.680	0.255	0.944	1.133	1.322	1.510	1.699	1.888
1 x 10	3/4 x 9-1/4	6.938	10.70	49.47	0.867	0.325	1.204	1.445	1.686	1.927	2.168	2.409
1 x 12	3/4 x 11-1/4	8.438	15.82	88.99	1.055	0.396	1.465	1.758	2.051	2.344	2.637	2.930
Dimension Lumber (see NDS 4.1.3.2) and Decking (see NDS 4.1.3.5)												
2 x 3	1-1/2 x 2-1/2	3.750	1.56	1.953	0.938	0.703	0.651	0.781	0.911	1.042	1.172	1.302
2 x 4	1-1/2 x 3-1/2	5.250	3.06	5.359	1.313	0.984	0.911	1.094	1.276	1.458	1.641	1.823
2 x 5	1-1/2 x 4-1/2	6.750	5.06	11.39	1.688	1.266	1.172	1.406	1.641	1.875	2.109	2.344
2 x 6	1-1/2 x 5-1/2	8.250	7.56	20.80	2.063	1.547	1.432	1.719	2.005	2.292	2.578	2.865
2 x 8	1-1/2 x 7-1/4	10.88	13.14	47.63	2.719	2.039	1.888	2.266	2.643	3.021	3.398	3.776
2 x 10	1-1/2 x 9-1/4	13.88	21.39	98.93	3.469	2.602	2.409	2.891	3.372	3.854	4.336	4.818
2 x 12	1-1/2 x 11-1/4	16.88	31.64	178.0	4.219	3.164	2.930	3.516	4.102	4.688	5.273	5.859
2 x 14	1-1/2 x 13-1/4	19.88	43.89	290.8	4.969	3.727	3.451	4.141	4.831	5.521	6.211	6.901

(Approximate weight in pounds per linear foot (lbs/ft) of piece when density of wood equals: 25–50 lbs/ft³)

Fig. 9. Puzzle 3: (a) envelope marked with the word "red"; (b) scenario; (c) table of lumber sizes (courtesy, American Wood Council, Leesburg, VA); (d) material properties (reproduced with permission from Philpot and Thomas 2020; Copyright © 2020, 2019, 2017, 2013, 2011, 2008 John Wiley & Sons, Inc. All rights reserved); (e) samples of lumber; and (f) ruler.

P12.19 Two steel plates of uniform cross section are welded together as shown in Figure P12.19. The plate dimensions are b = 5.5 in. and t = 0.375 in. An axial force of P = 28.0 kips acts in the member. If a = 2.25 in., determine the magnitude of
(a) the normal stress that acts perpendicular to the weld seam.
(b) the shear stress that acts parallel to the weld seam.

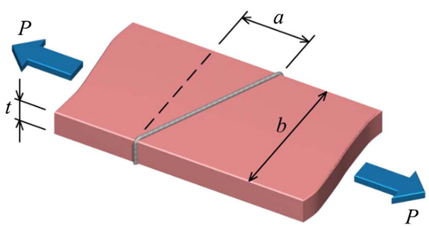

Fig. 10. Basic textbook stress transformation problem. (Reproduced with permission from Philpot and Thomas 2020; Copyright © 2020, 2019, 2017, 2013, 2011, 2008 John Wiley & Sons, Inc. All rights reserved.)

The envelope unlocked from Puzzle 3 [Fig. 11(a)] included the scenario for Puzzle 4 [Fig. 11(b)], a pry bar with dimensions labeled [Fig. 11(c)], and envelopes labeled 1 to 3 [Fig. 11(h)]. The teams decided which of the three doors led to the Mahan Hall boiler room. The teams were also required to use clues provided in the earlier puzzles, including a container of wood glue [Fig. 11(e)] and a protractor [Fig. 11(g)].

The teams first identified the discoloration at different angles on the doors, indicating wood glue repair. Fig. 12 shows the crowbar that was used to apply a compressive force to the door, with the intention of causing it to fail. The teams created a stress element along the glue joint to determine the normal and shear stresses in accordance with Eqs. (6) and (7):

$$\sigma_n = \sigma_x \cos^2\theta + \sigma_y \sin^2\theta + 2\tau_{xy} \sin\theta\cos\theta \tag{6}$$

$$\tau_{nt} = -(\sigma_x - \sigma_y)\sin\theta\cos\theta + \tau_{xy}(\cos^2\theta - \sin^2\theta) \tag{7}$$

where σ_x and σ_y = normal stress in the x and y directions, respectively; τ_{xy} = shear stress in the x–y plane; θ = transformation angle from the x axis to the n axis; σ_n = normal stress in the n direction; and τ_{nt} = shear stress in the n–t plane.

The teams measured the angle of the glue joint on each of the three doors using the protractor. The door with a normal stress or shear stress exceeding the yield strength of the glue identified on the back of the glue container [Fig. 11(f)] failed, allowing the team

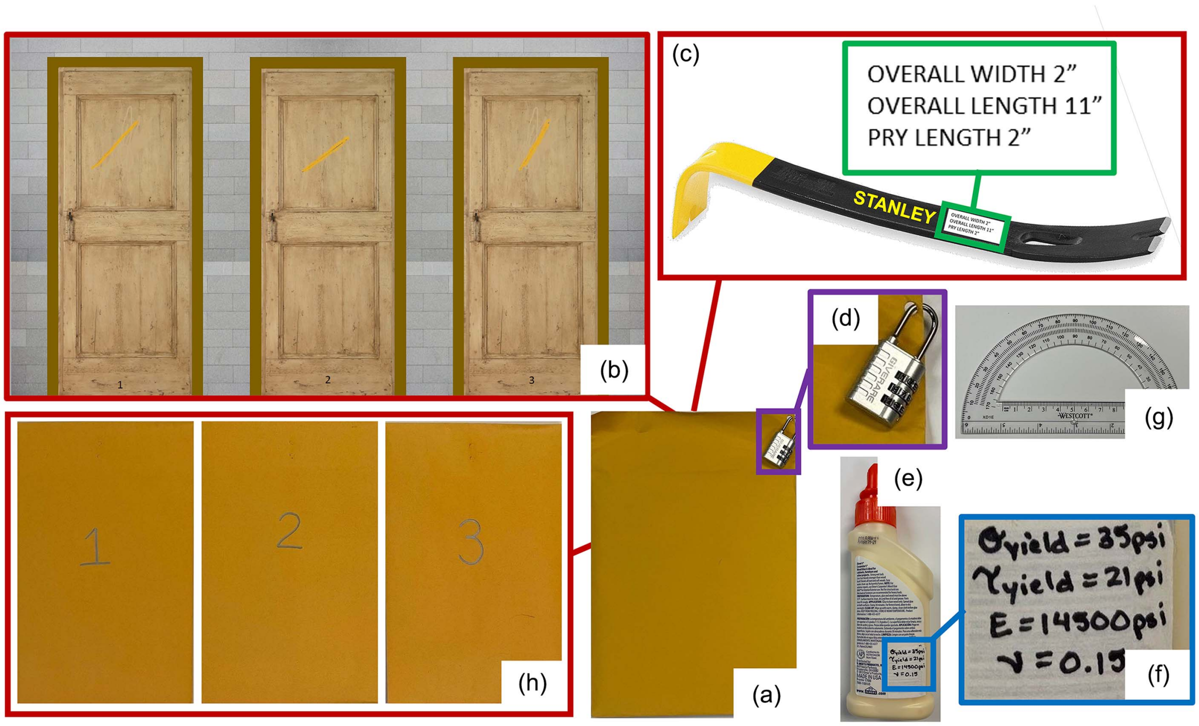

Fig. 11. Puzzle 4: (a) locked envelope; (b) scenario; (c) pry bar with dimensions; (d) padlock; (e) wood glue; (f) material properties of wood glue; (g) protractor; and (h) envelopes representing the three doors.

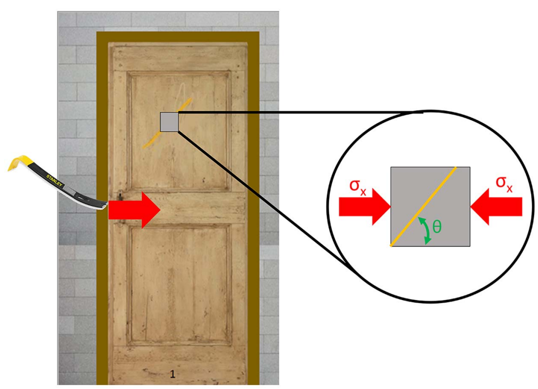

Fig. 12. Solution to Puzzle 4 by applying a compression force to the door using the pry bar and analyzing a stress element along the wood glue joint.

to continue the journey through the steam tunnels. If the teams selected the incorrect door, they solved a penalty question on determining the transformation angle, as shown in Fig. 13.

Some teams used their conceptual understanding of stress transformation and failure theories to solve Puzzle 4. The door with an angle closest to 45° contained the largest shear stress along the inclined plane and therefore failed first.

Puzzle 5: Do Not Fail under Pressure

The fifth puzzle focused on thin-walled pressure vessels and theories of failure, which correspond to Course objectives 1, 3, and 5 in Table 2. A basic thin-walled pressure-vessel problem required students to determine the hoop stress or longitudinal stress, calculate the minimum thickness or maximum pressure required for a given design, or solve for the maximum shear stress. Most of the problems were independent closed systems. The students were not often required to make assumptions or analyze connected systems of thin-walled pressure vessels, such as pipes. An example of a standard thin-walled pressure-vessel problem is shown in Fig. 14 (Philpot and Thomas 2020).

Selecting the correct door in Puzzle 4 [Fig. 15(a)] led to the scenario for Puzzle 5 in the boiler room of Mahan Hall [Fig. 15(b)]. A sketch of the boiler-room pipe system [Fig. 15(c)] includes the diameter, thickness, and material of the pipes. The students identified the maximum normal stress in the hoop direction of the thin-walled pressure vessel under tensile stress. The teams solved for the maximum allowable pressure (p_{all}) by applying the maximum shear stress failure theory shown in Eq. (8):

$$\sigma_{\mathrm{hoop}} = \frac{p_{\mathrm{all}} d}{2t} \leq \sigma_{\mathrm{yield}} \tag{8}$$

where σ_{hoop} = hoop stress; d = inner diameter; t = wall thickness; and σ_{yield} = yield strength determined based on the table of material properties in Fig. 4(f).

The three-digit numerical value for the maximum allowable pressure unlocked the padlock of the final envelope and signified the successful completion of the challenge to turn up the heat in Mahan Hall to force the cancellation of the final examination.

Bonus Puzzle: How Much Strain before It Bursts?

The sixth bonus puzzle assessed an additional course objective. Course objective 4 in Table 2 is focused on using data from strain gauges to analyze the structures. This is directly tied to the Mechanics of Materials topics of strain transformation and generalized Hooke’s law. As shown in Table 1, it was not its own problem on the final examination but was included as a subcomponent of

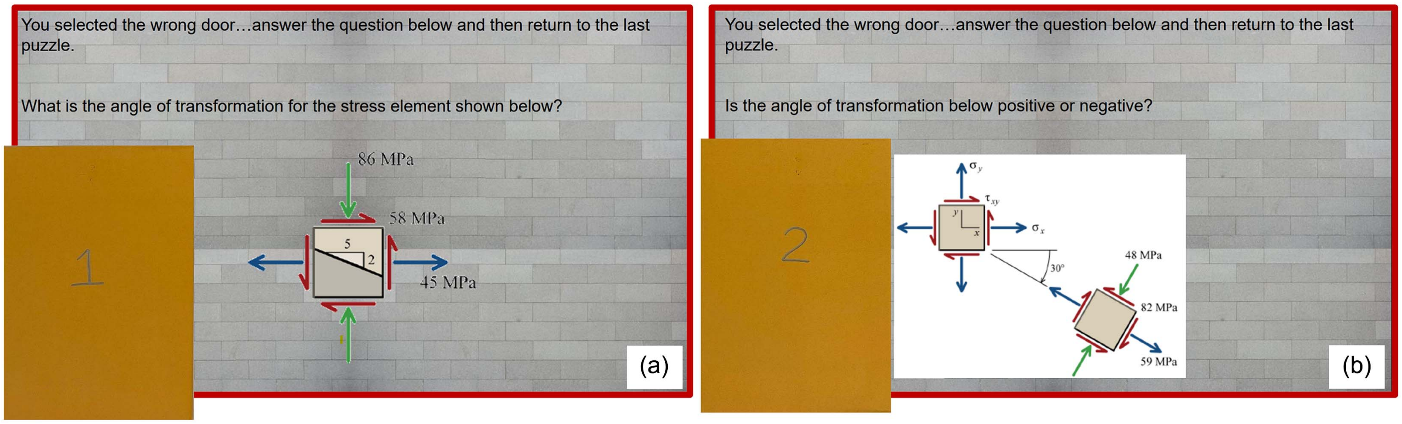

Fig. 13. Stress transformation penalty puzzles for Puzzle 4: (a) Door 1 folder; and (b) Door 2 folder. (Reproduced with permission from Philpot and Thomas 2020; Copyright © 2020, 2019, 2017, 2013, 2011, 2008 John Wiley & Sons, Inc. All rights reserved.)

P14.6 A typical aluminum-alloy scuba diving tank is shown in Figure P14.6. The outside diameter of the tank is 7.20 in. and the wall thickness is 0.55 in. If the air in the tank is pressurized to 3,500 psi, determine:
(a) the longitudinal and hoop stresses in the wall of the tank.
(b) the maximum shear stress in the plane of the cylinder wall.
(c) the absolute maximum shear stress on the outer surface of the cylinder wall.

FIGURE P14.6

Fig. 14. Basic textbook thin-walled pressure-vessel problem. (Reproduced with permission from Philpot and Thomas 2020; Copyright © 2020, 2019, 2017, 2013, 2011, 2008 John Wiley & Sons, Inc. All rights reserved.)

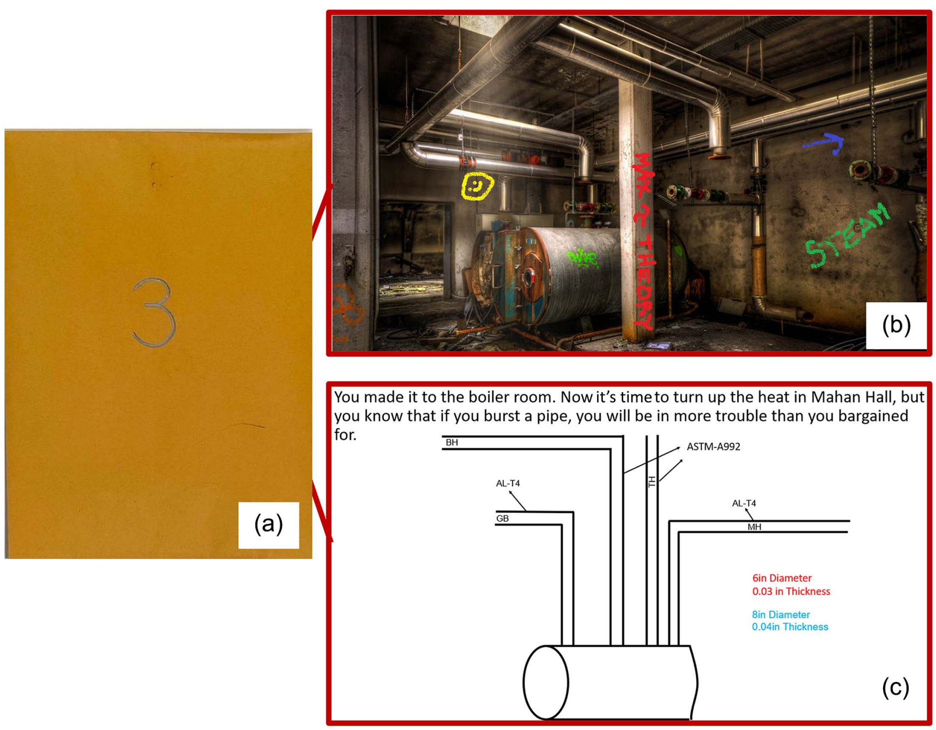

Fig. 15. Puzzle 5: (a) correct envelope from Puzzle 4; (b) scenario; and (c) boiler-room pipe sketch.

the thin-walled pressure-vessel problem. An example of a standard problem in which students used a strain gauge to analyze a thin-walled pressure vessel is shown in Fig. 16 (Philpot and Thomas 2020).

The sixth bonus puzzle is shown in Fig. 17. The teams estimated the reading of a strain gauge oriented in the hoop direction after the pressure was increased. They used the generalized Hooke's law according to Eq. (9) to determine the strain in the hoop direction (ε_{hoop}):

P14.14 A strain gage is mounted to the outer surface of a thin-walled boiler as shown in Figure P14.14. The boiler has an inside diameter of 1,800 mm and a wall thickness of 20 mm, and it is made of stainless steel [$E = 193$ GPa; $\nu = 0.27$]. Determine:
(a) the internal pressure in the boiler when the strain gage reads 190 $\mu\varepsilon$.
(b) the maximum shear strain in the plane of the boiler wall.
(c) the absolute maximum shear strain on the outer surface of the boiler.

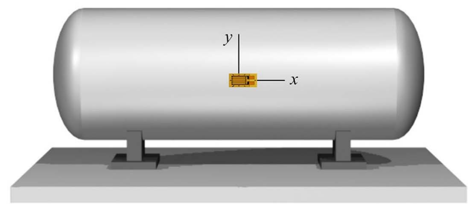

FIGURE P14.14

Fig. 16. Basic textbook thin-walled pressure-vessel problem with uniaxial strain gauge mounted in the longitudinal direction. (Reproduced with permission from Philpot and Thomas 2020; Copyright © 2020, 2019, 2017, 2013, 2011, 2008 John Wiley & Sons, Inc. All rights reserved.)

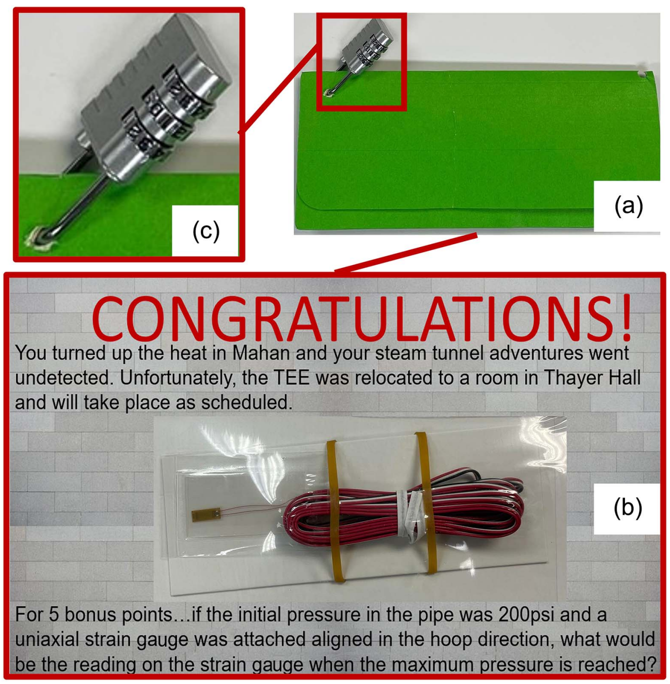

Fig. 17. Bonus puzzle: (a) final locked envelope; (b) scenario; and (c) padlock.

$$\varepsilon_{\text{hoop}} = \frac{1}{E}(\sigma_{\text{hoop}} - \nu\sigma_{\text{long}}) \tag{9}$$

where E and ν = modulus of elasticity and Poisson's ratio, respectively, determined based on the table of material properties in Fig. 4(f); and σ_{hoop} and σ_{long} = normal stress in the hoop and longitudinal direction, respectively. Successful completion of the bonus puzzle granted the students bonus credit toward the final examination.

Discussion

The pilot escape room activity for the Mechanics of Materials course assessed the students' learning and prepared them for the final examination. The activity was implemented during the final lesson of the course in two semesters (spring of 2022 and 2023) to a total of five sections with section sizes of 15, 17, 17, 16, and 18 for 83 students. The sections were divided into three teams of five to six students each. The teams were not aware of the escape room before arriving in the class to increase their intellectual curiosity.

The students entered the classroom to find three sets of desks with a large envelope and a locked backpack on each one. At the start of the lesson, the instructor introduced the escape room and presented the simplified rules and assumptions, as shown in Fig. 2. The simplified rules and assumptions were necessary to standardize the solutions, especially the numerical solutions required for the combination padlocks. The teams were allowed the entire 75-min lesson to complete the escape room activity. They were allowed to request three hints from their instructor. The instructor was flexible with the hints while avoiding provision of overall hints to all three groups in the classroom. The flexible hints encouraged the completion of the entire escape room activity and avoided stagnation (Watermeier and Salzameda 2019; Wiemker et al. 2015). The escape room activity challenged the students ahead of the final examination and encouraged collaboration.

Of the 15 teams that participated, six successfully completed the escape room activity in the 75-min time period. The escape rate of 40% corresponds to a novice escape room (Nicholson 2015).

The escape room activity required a significant amount of instructor time and resources to develop. The instructors created the escape room for approximately 40 h. The development of integrated puzzles took approximately 30 h. The purchase and organization of the clues and materials for the escape room took an additional 8 h. The final modifications of the escape room after completion by the second instructor took 2 h. Compared to a traditional course end review lesson where the instructor prepares and completes three to four problems, the execution of the escape room activity required 10 times more preparation time.

Completion of the escape room did not have a significant impact on student performance in the final examination (Rocha et al. 2023). After completing the escape room activity, the students completed a survey regarding their experiences. Of the 83 students who participated, 48 completed the survey (58%) and 24 completed a commercial escape room challenge before the educational escape room (50%). The feedback showed that the students appreciated the difficulty and interactiveness; 79% responded that the escape room activity was an effective course end review activity, 82% reported that it was more effective than the previous techniques used by instructors, 79% perceived the escape room to be the appropriate difficulty, and only 65% believed it was an appropriate length.

Based on open-ended feedback, the students found it difficult to determine what the puzzle asked of them, which consumed a significant amount of time. As stated in the motivation for this study, the majority of traditional course problems explicitly state the objective. Some students recommended including more conceptually challenging puzzles and fewer tedious calculations. Students also recommended decreasing the size of the teams to three to four participants. Some team members failed to contribute to solving a puzzle, and often, only one or two members completed the calculations. According to the survey, 65% believed that the puzzles required teamwork to be solved, and 77% perceived that they contributed to their team. However, this did not include 42% of the participants who did not complete the survey. One significant impact of decreasing the size of teams would be the requirement of additional escape room sets. Only three sets were created for each section.

The students also provided constructive feedback to the authors, which will be implemented in future iterations of the escape room. The students recommended including additional information or clues in the initial packet, such as the original hints and assumptions printed out, ensuring that envelopes and clues cannot be opened early, and providing students with a formal solution for reference while studying after completion of the escape room activity.

Future Work

The authors plan to continue implementing the escape room activity for the Mechanics of Materials course. They hope to increase the survey response rate to accurately assess the effectiveness of the in-class activity on both student perception and performance in the course. The small sample size was a significant limitation in quantifying the impact of the escape room activity. Future work will focus on improving the delivery of the escape room activity to ensure clear expectations for each puzzle while still providing a challenging ill-defined problem that requires student teams to identify additional key information to solve. The changes will focus on providing more clarity in classifying the problem type while still requiring students to find the critical information hidden within the puzzles. Additionally, smaller team sizes of four to five members will be used to ensure that all members of the team are actively engaged. The authors are currently implementing an escape room activity for the Design of Reinforced Concrete Structures course, which includes a more open design path.

Conclusions

This paper presented the results of a case study on the implementation of an educational escape room activity in the Mechanics of Materials course. The overall student feedback indicates that the escape room activity was valuable for them to review the course material. The students perceived the escape room as a conceptually challenging activity that required them to work in a team and identify key information to succeed. The difficulty of the activity increased some students' motivation to apply course concepts to solve problems in the mechanics of materials. The students also viewed the escape room as a fun activity and enjoyed deciphering the puzzles and physically unlocking additional clues. Participation in the escape room did not have a significant impact on student performance in the final examination.

The development of an escape room requires significant time, resources, and effort. Creation requires approximately 10 times more time than a traditional course end review class. However, once the escape room activity is developed, it could be implemented fairly seamlessly in future semesters. The authors would like to note that successful implementation of the escape room activity requires course instructors to have a strong understanding of the escape room puzzles. Instructors must ensure that student teams remain on track and provide hints to accelerate their completion of the puzzles.

The study showed that the implementation of the escape room activity increased motivation, engagement, and collaboration during the course end review. The activity helped the students review the course concepts and prepare for the final examination. By including complex, ill-defined problems, the students worked in a collaborative team to connect the provided clues to the course material.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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