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Comparison of Conceptual Knowledge of Shear Stress in Beams Between Civil Engineering Undergraduates and Practitioners

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Introduction

Aligning engineering education with engineering practice is essential to prepare students for the professional field. Graduate engineers continue to be challenged when connecting their engineering courses to "real" engineering, which has led to concerns about whether engineering undergraduates are adequately prepared [1]. Investigations examining the disconnect between academic engineering preparation and professional practice in engineering education research are ongoing [2], [3]. In some cases, this education to practice gap has been connected to misaligned preparation between undergraduate engineering education that focuses on fundamental conceptual knowledge to structured problems and engineering practice where design challenges are more ambiguous [4]. To further examine this issue, studies have focused on assessing student's conceptual knowledge of engineering concepts.

Concept inventories in many topics have been developed and implemented to engineering undergraduates as an assessment tool to measure conceptual understanding of engineering concepts. The Foundation Coalition was established to facilitate the development of concept inventories for engineering education [5]. Concept inventories have since been developed for core engineering topics such as Statics [6], Thermodynamics [7], Heat and Energy [8] and Materials [9]. Concept inventories have been used broadly in engineering education for many reasons, including assessing the efficacy of an educational intervention, identifying misconceptions, and providing information about the strengths and weaknesses of individuals' conceptual understanding of the material. Concept inventory questions have one correct answer and two-four incorrect answers. The incorrect answers represent misconceptions or a form of incorrect prior knowledge or preconceptions and previous experience that may impede learning [5], [10]–[12]. Richardson and Morgan [13] developed a concept inventory measuring the understanding of the strength of materials concepts such as normal and shear stress and strain, axial buckling, shear, bending, and stress transformation. Shear stress, a concept found in all strength of materials courses, is an important concept commonly used in civil and mechanical engineering and structural engineering design. Studies researching conceptual understanding of shear strength have shown that it is a challenging concept for undergraduates to grasp [11], [14]. While concept inventories have been used to assess engineering undergraduates' conceptual knowledge, very few have been implemented to assess practicing engineers. The purpose of this study is to compare engineering undergraduates and practicing engineers (structural and non-structural) on three shear stress questions from the Strength of Materials Concept Inventory (SOMCI).

Having engineering practitioners take a concept inventory can provide information on how conceptual knowledge compares in an academic setting to industry. Since shear stress is an important foundational concept and a standard part of civil and structural engineering practice, it would be expected that practicing engineers would perform better on conceptual shear stress questions in the strength of materials concept inventory (SOMCI). Implementing a concept inventory to assess engineering practitioners' and undergraduate engineers' conceptual knowledge can provide engineering educators and researchers with the opportunity to investigate conceptual understanding and misconception patterns.

Shear stress

Strength (or mechanics) of materials is a fundamental course for civil and mechanical engineers and is typically taught during the undergraduate engineering program's sophomore year. The content covered includes topics such as normal and shear stress and strain, axial buckling, shear, bending, and stress transformation. It is essential to understand how applied loads affect material deformation and failure of a member. Generally speaking, the designer will determine which loading conditions control (result in the worst combination of internal stresses or deformations) and which stress(es) are considered to determine the controlling design criteria. One of these design considerations is shear stress. The magnitude of shear stress varies depending on the loading conditions and the material's geometry. In structural design, the shear stress magnitude is important when designing beams because they can fail while bending. A beam is a structural member primarily designed to support loads perpendicular to the member's length. Bending basically results in the beam going from a straight line when unloaded to a curve when loaded (Figure 1) and can produce both normal stress and shear stress. The shearing stress in a beam is defined as the stress that occurs from the beam's internal shearing due to shear force [15]. Shear stress is distributed on the beam's cross-section, represented by a parabolic curve where the maximum shear occurs at the geometric centroid (or neutral axis) of the beam (Figure 2). Shear stress is an essential concept in material science, and it would be expected that practicing engineers who utilize this concept in their daily work would have a better conceptual understanding of shear stress than engineering students. In addition, performance in the SOMCI reveals shear stress misconceptions that participants may have.

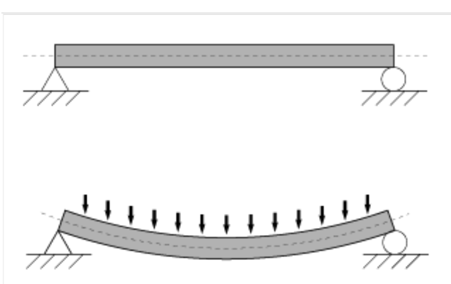


Figure 1. Bending stress in beams.

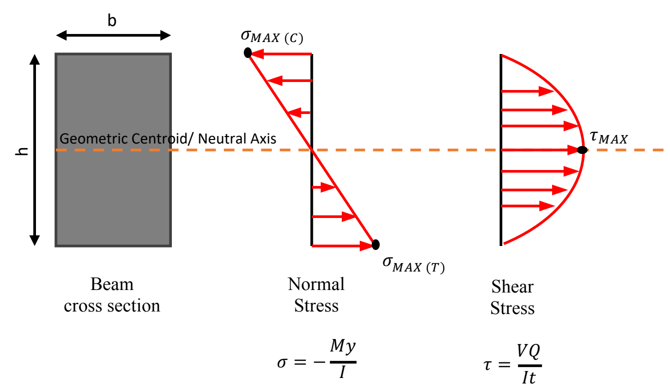


Figure 2. Normal and Shear Stress Distribution in a rectangular beam.

Misconceptions

Concept inventories have been used as an assessment tool to evaluate a students' understanding of a particular core concept [9], [13], [16]. Applications of concept inventories fall into three main categories: a diagnostic tool, evaluation of instruction, and placement exam [16]. A concept inventory can be used to identify individual questions' strengths and weaknesses and of participants' knowledge. Identifying students' strengths, weaknesses, and conceptual misunderstandings provide the opportunity to intervene and clarify misconceptions and areas where a course needs to be modified [17], [18]. In the case of this research, implementing the CI to practicing engineers and undergraduates allows us to compare performance and misconceptions on a small set of questions and begin to understand how engineers understand shear stress.

Research on conceptual understanding of the strength of materials has focused on the development of a concept inventory [5], [7] and on investigating the level of students' conceptual understanding [11] through interviews. Findings have shown that students have difficulty understanding relationships relating to loading and stress distribution and other fundamental concepts [11], [19]. The strength of materials concept inventory is used in this study to investigate differences in understanding of students and engineers on three questions about shear stress in beams.

Conceptual understanding has been used to differentiate between students' abilities to perform calculations and understand the content. Having a conceptual understanding of the material implies knowing more than isolated facts and methods, such as transferring their knowledge into a new situation and applying it to a new context. Learning can be impeded by shortcomings in conceptual understanding, also described as misconceptions. Krause [10] defines misconceptions as students' mental models not aligning with the scientific community's consensus and suggests that misconceptions are formed from personal experience or incorrect knowledge development from previous courses. Krause [10] further states that misconceptions can create two types of impediments to future learning, null impediment, which refers to missing information, and substantive impediment, which refers to faulty concept models. Misconceptions have also been described as alternative views of a student that develops aside from scientifically accepted facts or obstacles that prevent students from learning and applying concepts properly and maintaining the learning process's efficiency [5], [17].

While there is an abundance of literature [5], [7], [8], [10], [20] devoted to conceptual understanding and efforts on how to address misconceptions, very few investigate the presence of misconceptions and how patterns may differ between students and engineering practitioners. Concept inventories can be administered to practicing engineers and undergraduates to further this research agenda. This would also highlight if and how misconceptions differ between practicing engineers and engineering students. One of the viewpoints in the book, How People Learn: Brain, Mind, Experience, and School [12], highlights how novice learners (undergraduate engineers) are unlike expert learners (practicing engineers) in that experts have developed the learning skills to build a deep content understanding and organization of their subject that facilitates their retrieval and transfer to new and different applications. This would imply that if a concept inventory were to be provided to both of these groups, practicing engineers would perform better than students and have minimal misconceptions about the strength of materials concepts.

Methods

Instrument

The strength of materials concept inventory consists of 23 multiple choice questions covering concepts centered around normal and shear stress and strain, buckling, bending, torsion, and deflection. Each question was designed to include one correct answer and several incorrect answers, which are identified as "distractors" and which are based on common student misconceptions [13]. An essential quality of a concept inventory is its reliability. The SOMCI has been through two iterations, with the most recent one in 2003. After the first implementation of the SOMCI, the developers applied a psychometric analysis of the instrument, in which they found that the inventory had no internal consistency [13]. Although the instrument's reliability is not validated, it is still a valuable tool to inform possible misconceptions participants may have on a question-by-question basis. The SOMCI needs to be validated to function as an overall instrument analyzing particular concepts, however in its current state, we can look at individual question performance.

Sample

Undergraduate engineering students and practicing engineers were recruited, via email, from across the nation to take the concept inventory (CI) through surveymonkey.com voluntarily. Participants who agreed to participate were provided a link to the SOMCI and were asked to help recruit other engineers from their companies and affiliated engineering societies. A link was emailed to faculty to recruit undergraduate participants. No class time was used for the CI, and students were not penalized if they elected not to take the concept inventory. All participants were provided with information and terms regarding the research study.

A total of 119 practicing engineers volunteered to take the SOMCI, which included 108 completed responses. Participants were asked to provide demographic information, including gender, years of engineering experience, the highest level of education, and engineering area(s) of expertise shown in Table 1. Practicing engineers' years of industry experience varied from 1 year to 39 years, and the sample consisted of 26% female, 72% male, and 2% identified as other. As an incentive to take the concept inventory, the engineers were invited to participate in a $250 raffle. A total of 153 engineering undergraduates elected to take the concept inventory, with 129 complete responses. The students who took the concept inventory came from 8 institutions ranging from community colleges to four-year institutions. The undergraduates had already taken an introductory strength of material course prior to taking the SOMCI, but the academic level at the time they took the survey was not gathered. The gender make-up of the engineering undergraduate sample was 14% female, 84% male, and 2% identified as other. In examining time completion in entries, it did not seem plausible to complete this concept inventory in less than 5 minutes; therefore, all results that had a completion time of 5 minutes or less were eliminated. Incomplete entries were removed from student and engineering practitioner's data. This process resulted in the final count of participants being 129 undergraduates and 108 engineering practitioners.

Table 1. Demographics of the engineering practitioners

		Gender		Highest education	
Civil engineering specialization	Total	Female	Male	Bachelor	Master
Civil engineering	36	8	27	30	6
Structural engineering	28	8	20	13	15
Civil engineering + other [a]	24	7	16	19[c]	5[d]
Structural engineering + other [b]	17	5	12	7	10[d]
Other	14	3	11	6	8

[a]Civil engineers who indicated more than one engineering expertise, including geotechnical, environmental, water resources, transportation, construction management, and others.
[b]Structural engineers who indicated more than one engineering expertise, including civil, geotechnical, environmental, water resources, mechanical, and others.
[c]One engineer reports high school education
[d]One engineer reports PhD.

Data Analysis

The SOMCI was used to examine the differences in conceptual understanding between the three groups, practicing structural engineers, practicing non-structural engineers, and engineering undergraduates. A one-way ANOVA was performed to determine if an overall difference in performance exists between the structural engineers, the non-structural engineers, and the students. An independent samples t-test was conducted on the overall results to determine if the difference in performance is significant and the effect size between pair groups, structural vs. undergraduate, structural vs. non-structural, and non-structural vs. undergraduate. A Chi-Square test of independence was performed on each of the 23 questions to determine if there are any differences or patterns of understanding or relationships between these three groups. The confidence intervals for effect sizes are included because they are a measure of the precision of the analysis [21]. A parametric and non-parametric test was conducted for the t-test and the one-way ANOVA; no discernable difference in p-values was found, indicating that the data is robust to any normality violations [22].

Results and Discussion

Results from a one-way ANOVA on the overall SOMCI show that there is a statistically significant difference between the three groups ($F(2,234)=35.062$, $p<0.001$). In pairwise comparisons, an independent samples t-test revealed that structural engineers ($M=15.62$ $N= 43$, $SD= 2.86$) performed better than non-structural engineers ($M=12.00$ $N= 65$, $SD= 3.52$) and better than engineering undergraduates ($M=10.26$ $N= 129$, $SD= 3.45$) in the SOMCI with a significant level of difference in performance, $t(106)=49.50$, $p<0.001$ and $t(170)=8.46$, $p<0.001$ respectively. An independent samples t-test indicates a significant level of difference in performance $t(192)=3.30$, $p<0.001$ between non-structural engineers and engineering undergraduates.

The pairwise comparisons of the three individual questions shown in Table 2 indicate a significant difference between structural vs. undergraduates and structural vs. non-structural in Q11 and Q13. Results show no significant difference in performance between non-structural and undergraduates in all three questions and no difference in performance between any of the three groups in Q12. Questions in which there is a statistically significant difference for each group pair comparison is bolded and asterisks are used to indicate the level of significance, small(*), medium(**), and large(***) with the corresponding effect sizes (0.1-0.29), (0.3-0.49), and (0.5+) respectively.

In order to better understand this difference in performance among participants, the discussion will focus on three beam-related questions from the SOMCI. A description of the correct answers are provided so that someone unfamiliar with the content can follow the results. In addition, a discussion of one or more misconceptions will be reviewed. Table 2 summarizes statistical analysis results from beam-related questions; however, the focus will be on questions Q11, Q12, and Q13. Each question in the SOMCI consists of multiple-choice responses. Table 3 includes the percent of respondents who selected multiple-choice options from A-G, in which ABCDEFG are options of answers to SOMCI questions.

Table 2. Statistical Analysis Results for Structural, Non-structural, and Undergraduate Engineers SOMCI performance

	Total Correct Score (%)			Chi-Square			Independent t-test (Pairwise comparison)					
							S vs UG		S vs NS		NS vs UG	
Question	SE	NSE	UG	X2 (df)	*p*	Effect Size (V)	*p*	Performance	*p*	Performance	*p*	Performance
Q11	40%	15%	20%	9.488 (2)	0.009	0.200	**0.011***	S>UG	**0.005****	S>NS	0.420	-
Q12	19%	14%	19%	0.936 (2)	0.626	0.063	0.911	-	0.506	-	0.339	-
Q13	37%	12%	22%	9.379 (2)	0.009	0.199	**0.044***	S>UG	**0.002****	S>NS	0.112	-

Note: In pairwise comparisons, questions that are statistically significant ($p<0.05$) are bolded and noted with their corresponding (*) small (0.1-0.29), (**) medium (0.3-0.49), or (***) large (0.5+) effect size.

Table 3. Compare Structural, Non-Structural, and Undergraduate Engineer Responses

		A	B*	C	D	E	F	G
Question 11	Structural	16%	40%	26%	0%	5%	2%	12%
	Non-Structural	14%	15%	28%	8%	11%	8%	17%
	Undergraduate	11%	20%	7%	6%	25%	10%	21%
Question 12	Structural	0%	19%	19%	5%	19%	7%	33%
	Non-Structural	14%	6%	6%	3%	17%	9%	37%
	Undergraduate	5%	4%	4%	5%	23%	8%	36%
Question 13	Structural	14%	33%	33%	2%	5%	9%	-
	Non-Structural	15%	25%	25%	8%	20%	20%	-
	Undergraduate	6%	10%	10%	9%	28%	25%	-

Structural engineers' participants (N=43). Non-Structural engineers' participants (N=65). Undergraduate participants (N=129). Values represent the percent of respondents who selected multiple-choice options from A-G. ABCDEFG are options of answers to multiple-choice questions. Symbol (*) denotes correct answer.

The three selected beam questions all ask participants to identify the maximum shear stress on a specified plane. Essentially, the maximum shear stress location is the same in all three questions. In order to facilitate the discussion on the selected misconception response in each question, it would be helpful to first walk through the correct response. The shear force distribution along the beam's length begins at a maximum value, decreases linearly along the length of the beam passing through zero at the geometric center, and ends at the maximum shear value, as shown in Figure 3. The shear force is higher at the plane where A, B, and C are located and is zero at the plane where D, E, and F are located. The distribution of shear stress at the beam cross-section is parabolic, with zero values at the top and bottom of the cross-section and maximum at the vertical geometric center as shown in Figure 4. Therefore, with the given loading conditions, the maximum shear stress is at location B.

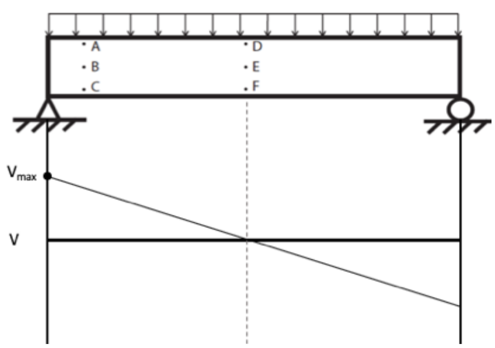


Figure 3. Shear diagram for beam with distributive load.

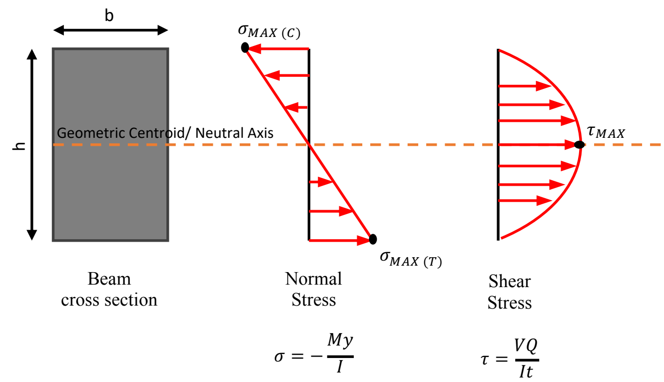
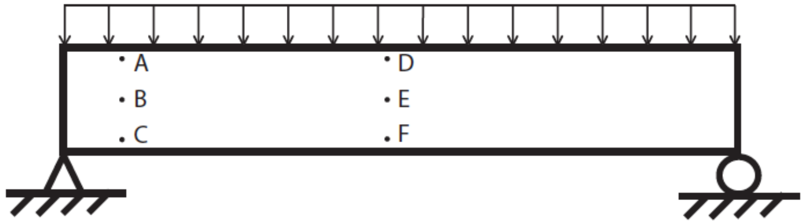


Figure 4. Shear stress distribution in rectangular beam cross section.

The problem statement and results of question 11 are shown in Figure 5. In question 11, 40% of the structural engineers, 15% of non-structural engineers, and 20% of undergraduates selected the correct answer. The most chosen incorrect answer by undergraduates (25%) in question 11 is choice E, in which participants believe that the maximum shear stress is located at the center of the beam. This selection indicates that undergraduates may have recognized that the maximum shear stress is located at the geometric center of the beam but didn't consider that the shear force is zero at the center of the beam. The first most common selection for non-structural engineers (28%) and the second most common selection for structural engineers (26%) is choice C. Although location C has a larger shear force than the plane where D, E, and F are located, the shear stress is lower than at location B. We can speculate that the engineers recognized that the location of the maximum shear force is at the end of the beam but didn't recall the shear stress distribution in the cross-section.

11. At which location in the beam below is the shear stress on a vertical plane maximum ?



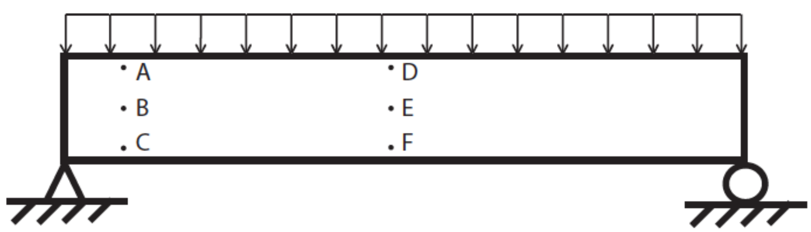
a) Location A
b) Location B
c) Location C
d) Location D
e) Location E
f) Location F
g) the stress is the same at all locations

Question 11	A	B*	C	D	E	F	G
Structural Eng (N = 43)	16%	40%	26%	0%	5%	2%	12%
Non-Structural Eng (N=65)	14%	15%	28%	8%	11%	8%	17%
Student (N = 129)	11%	20%	7%	6%	25%	10%	21%

Symbol (*) denotes correct answer.

Figure 5. SOMCI Question 11 problem statement and results.

12. At which location in the beam below is the shear stress on a horizontal plane maximum ?



a) Location A
b) Location B
c) Location C
d) Location D
e) Location E
f) Location F
g) the stress is the same at all locations

Question 12	A	B*	C	D	E	F	G
Structural Eng (N = 43)	0%	19%	19%	5%	19%	7%	33%
Non-Structural Eng (N=65)	14%	14%	6%	3%	17%	9%	37%
Student (N = 129)	5%	19%	4%	5%	23%	8%	36%

Symbol (*) denotes correct answer.

Figure 6. SOMCI Question 12 problem statement and results.

The results for question 12 shown in Figure 6, seem to be similar for all participants. Correct score percentages are as follows, 19% for structural engineers, 14% for non-structural engineers, and 19% for undergraduates who selected the correct answer. Many participants believe G is the correct answer, with 33% of structural engineers, 37% of non-structural engineers, and 36% of undergraduates selecting G as the correct answer. Selecting G implies that respondents believe that the stress is the same at all locations. The shear force is a single value across any particular cross-section of a beam. Respondents may believe the question is asking about shear force. Even in this case, the shear force is different at the cross-section where A, B, and C are located compared to the cross-section where D, E, and F are located. Participants may also believe that the shear stress is zero at all locations, because they may be thinking about a shear stress element, in which all four shear stresses have equal magnitudes, are pointed toward or away from each other at opposite edges of the element, and therefore canceling out (Figure 7).

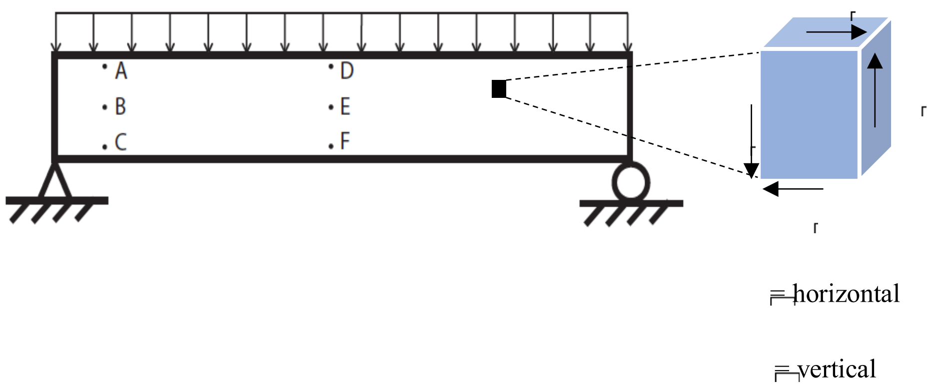
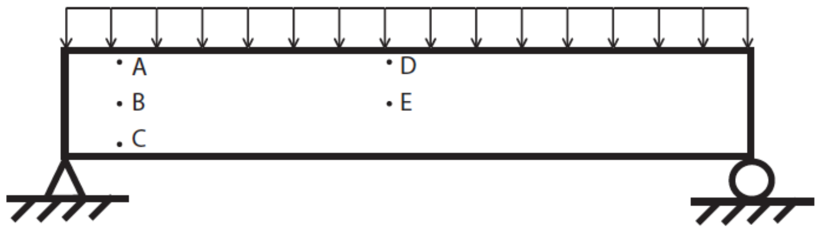


Figure 7. Shear stress element.

The problem statement and results of question 13 are shown in Figure 8. Structural engineers have a higher correct score percentage than non-structural and undergraduates in Q13, with 37% of the structural engineers, 12% of non-structural engineers, and 22% of undergraduates selecting the correct answer. The first most common selection for non-structural engineers (25%) and second most common selection for structural engineers (33%) is choice C. Similar to Q11, participants believe that the maximum shear stress is located at the bottom left of the beam. It seems that just like in Q11, the same misconception is present in Q13, in which practicing engineers recognize that the location of maximum shear force is at the end of a beam, but didn't consider the shear stress distribution at the beam cross-section. It is possible that practicing engineers are thinking about shear failure in beams. Shear failure occurs when the shear stress is maximum at a 45° cross-section, causing a diagonal crack at the end of the beam (Figure 9). This may explain why practicing engineers selected C. The most selected incorrect answer in Q13 by undergraduates (28%) is choice E, in which they believe that the maximum shear stress is located at the center of the beam. Since the wording of the question has changed, we can speculate that undergraduates may be thinking about the location of the maximum bending stress. The maximum stress can be found using the flexure formula (Figure 10) that requires the maximum moment located at the center.

13. At which location in the beam below is the shear stress on any plane maximum ?



a) Location A
b) Location B
c) Location C
d) Location D
e) Location E
f) the stress is the same at all locaations

Question 13	**A**	**B***	**C**	**D**	**E**	**F**	**G**
Structural Eng (N = 43)	14%	37%	33%	2%	5%	9%	-
Non-Structural Eng (N=65)	15%	12%	25%	8%	20%	20%	-
Student (N = 129)	6%	22%	10%	9%	28%	25%	-

Symbol (*) denotes correct answer.

Figure 8. SOMCI Question 13 problem statement and results.

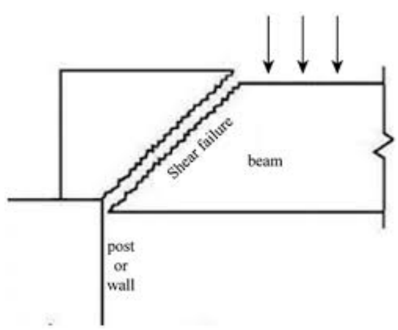


Figure 9. Image of beam shear failure.

$$\sigma_{\max} = \frac{cM_z}{I_z}$$

$$\sigma_x = -\frac{yM_z}{I_z}$$

Figure 10. Flexure formula.

Overall, results show that practicing engineers performed better than non-structural engineers and undergraduates, which may be because structural engineers use these concepts more than non-structural engineers and undergraduates. However, the results revealed that shear stress continues to be a challenging concept for all participants. Concept inventory questions are designed to be answered without calculations, using basic conceptual knowledge and revealing common misconceptions. In some cases, on the strength of materials, it is possible to visualize the relation between loads and stresses. For example, the distributive load exerted on the beam will deflect into a "smile" shape, resulting in the bottom of the beam getting longer and the top getting shorter. This change in length directly results from the bending stresses. The maximum compressive normal stress from bending would occur at the top of the beam and the maximum tensile normal stress from bending would occur at the bottom of the beam. The "smile" shape corresponds with these stresses. However, when analyzing shear stress in planes, it may not be that intuitive because it can be challenging to imagine shear stress relationships. The deflected beam shape in the previous example does not give any apparent hints about the distribution of shear force and stress across the beam. Determining shear stress then arguably occurs in the abstract with no visual cues to assist the learner, affecting the concept inventory shear stress-related questions.

Conclusion

The results from this exploratory study may be beneficial to strength of materials educators since it reveals shear strength misconceptions from students and practicing engineers. Statistical analysis results indicate that practicing structural engineers performed better than non-structural engineers and engineering undergraduates, as predicted. However, the low performance on the discussed beam problems demonstrates misconceptions of shear stress. It may be that shear stress design is not used in the field as much as we anticipate, or these concepts are implemented in codes and standards such that it is more procedural and requires less conceptual understanding for use on a day-to-day basis. Perhaps, the conceptual representation of shear stress in the problem statement is different than what practicing engineers see in their daily activities, which may also explain their poor performance. In addition, a large portion of respondents selected the same incorrect answer, revealing shear stress misconceptions. For example, practicing engineers are thinking about beam shear failure, or undergraduates are thinking about bending stresses, in which the maximum stress is found using the flexure formula that requires the use of the maximum moment, or they could be considering an individual shear stress element, in which the shear stress will be the same in the vertical and horizontal plane.

Research has shown that concept inventories are assessment instruments to help identify student misconceptions, understand misconceptions, help enhance learning instruction and advance the engineering education field. There is minimal literature analyzing practicing engineers' conceptual understanding of engineering concepts. A unique aspect of this research study is that the strength of material concept inventory was implemented with different groups, undergraduates, and practicing engineers to understand the difference in performance in three questions related to shear strength conceptual understanding. As with the Force Concept Inventory, used in physics to comprehend student's misconceptions of physics concepts, the SOMCI may be one tool in investigating change in engineering misconceptions that may help improve students' conceptual understanding of engineering concepts. Future work could involve a qualitative approach such as interviewing undergraduates and practicing engineers to help enhance problem statements and track their reasoning as they work through SOMCI items. Further research is needed to comprehend how conceptual understanding of engineering concepts transfers from an academic context to the professional engineering field. Investigating how practicing engineers interact with and make sense of various concept inventory items can provide a better understanding of engineering work and offer tools to align educational practices. This may help students develop a strong conceptual understanding of engineering concepts and adequately prepare them for the engineering workforce.

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