Paper ID #23645

Exploration of Expert and Novice Reasoning in Mechanics of Solids

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Exploration of expert and novice reasoning in mechanics of solids- A work in progress

Introduction

Engineering degree programs such as civil engineering, mechanical engineering, materials engineering, and industrial engineering generally require an advanced course in engineering mechanics, typically in the second or third year. The course is most commonly known as “Strength of Materials”, “Mechanics of Materials”, or “Mechanics of Solids”. For the duration of this paper this course will referred to as Mechanics of Solids (MOS) [1].

Mechanics of Solids (MOS) has become the bridge and bond between elementary and specialized knowledge for engineering students. Although categorized as a basic course, engineering mechanics, and MOS specifically, differ from truly fundamental subjects. Mechanics is closer to engineering applications, unlike subjects such as mathematics, physics, chemistry, biology, astronomy and geography. It is distinct from the purely technological areas because of its strict system of logic. Due to this, and partly because of the large number of concepts and formulas that the students need to learn, MOS has been regarded as one of the most difficult undergraduate courses at Rutgers University. This can be validated by a two-tail t-test with an $\alpha=.05$ comparing the average D,W,F percentage spanning ten semesters for MOS at 30.1% which was determined to be statistically significantly higher than any other course offerings from the department with the next closest average D,W,F percentage for ten semesters of Elements of Structures at 10.6% ($p = .000531$).

A central concern for engineering educators is how to get students to master so many equations and definitions while also understanding the physical mechanisms in such a limited time [2]. Recent research initiatives have demonstrated that engineering faculty do not possess a good solution. They found that contrary to high passing rates, students are failing to comprehensively understand the concepts that they need to master in mechanics of solids courses [3]. This failure has prompted many researchers to investigate potential causes of this discrepancy with the intention of identifying teaching and learning approaches that can help students develop a foundation of technical knowledge that is later expanded upon on with applications specific to their major. This paper describes an exploratory case study using qualitative methods which is an attempt to add to the already established body of knowledge. The purpose of this study is to identify patterns in the way expert and novice engineers approach problems to better inform future research in the field of engineering mechanics. The research questions of the study are as follows:

1) How do experts approach demanding engineering problems?
2) How do students approach demanding engineering problems?

The study will use qualitative methods of data collection and analysis, since the research questions ask the question of “how”. While numbers can be used to *summarize* qualitative data, fully answering these questions generally requires rich, contextual descriptions of the data, what is often called “thick” description.

The main benefit of qualitative research is that it "allows participants to define factors and highlight influences that they find meaningful and essential to describe their life experiences. Additionally, qualitative investigations are often carried out in natural settings and specific *attention is paid to the process* rather than outcomes or products" [4]. Qualitative research also differs from quantitative methods in that the former seeks to use thick description to generalize a specific context, allowing the reader to make connections between the study and his or her own situation. Summarily, qualitative research places the burden of identifying appropriate context for transferability on the reader [5].

Several authors have pointed out the error in assuming that qualitative research is easier and less rigorous than quantitative research [6], [7]. Another common misconception is that qualitative research is synonymous with anecdotal information. Tonso specifically contrasts qualitative research with anecdotal information [8]. She explains that "anecdotal information is collected haphazardly as it becomes available, while qualitative research involves the careful planning of a research design that encompasses all aspects of the study, from research questions to sampling to data collection and analysis" [8]. As the previously mentioned authors point out, qualitative research, when done properly, can be just as rigorous as quantitative investigations, as it involves its own set of data collection and analysis methods that ensure the trustworthiness of the findings.

The main qualitative method that guides this study is called the case study. More specifically, an embedded single case study design has been chosen. This design is the most applicable since there will be one case (MOS) being studied but will have multiple units of analysis (experts and novices). It is important to note that case study as a research strategy differs from case studies used as teaching devices. For teaching purposes, a case study does not need to contain a complete or accurate rendition of actual events. Its purpose is to establish a framework for discussion and debate among students [9].

A more detailed description of this research method can be found in Yin's book [9]. A summary of Yin's technical definition of a case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, relies on multiple sources of evidence, and benefits from the prior development of theoretical propositions to guide data collection and analysis [9]. Yin's description and procedures for case study research was found to be more applicable in this study over Merriam [10] or Stake [11]. Yin gives a more general definition of a case study and argues that it is a valid research strategy for all three phases of research; exploratory, descriptive, and explanatory. Since a case study benefits from the use of previously established theoretical frameworks, it is important for the reader to have a general understanding of the frameworks addressed in this study.

Background

Expert-novice literature

Expert/novice is one of the most commonly used frameworks in education research. An expert is defined as a person who has more knowledge in a domain that is structured and organized, relative to a non-expert or novice [12]. Other behavioral indicators of expertise have also been researched at great length. One behavioral indicator is that experts are more successful at choosing the appropriate strategies to use than novices [13]. For example, in solving physics problems, the instructors tend to work forward, starting from the given state to the goal state, whereas students of physics tend to work backwards, from the unknown to the givens [14]. Experts are also good at detecting features that novices cannot. For example, in a study by Chi, Feltovich, and Glaser [15], subjects were asked to sort a collection of problems based on similarities in how they would solve them. Experts classified the problems according to the major physics principles governing the solution of each problem. In contrast, the novices focused on the "surface structure" of the problems, such as a spring, or a block on an inclined plane. Lastly, experts in science and mathematics often make use of qualitative reasoning to approach a problem that will require a quantitative solution. Experts tend to spend a great deal of time analyzing a problem qualitatively by developing a problem representation that include many domain specific and general constraints of the given problem. In contrast, novices rush into quantitative manipulations and plug-in formulas [13].

In an engineering education study by Papadopoulos [16], the author was able to observe this "plug and chug" activity. He noted that students circumvent the application of procedure and attempt to identify a single equation to solve a problem. They are so proficient in this method that when presented with a design problem, they are limited in their ability to simplify the problem and apply or transfer their knowledge beyond the idealized confines of basic textbook problem. Ignoring the procedural aspects of problem solving leaves students to strictly focus on classifying the given problem as a familiar one where they use a specific equation. Researchers studying novices and experts in design engineering found that novice subjects would spend a large portion of their time defining the problem and did not produce quality designs due to becoming stuck in the problem definition stage. They also found that other novice groups gathered a large amount of information, but for them "gathering data was sometimes just a substitute activity for actually doing any design work" [17]. Experts were found to move rapidly to early solution estimations and use these conjectures as a way of exploring and defining problem and solution together. Expert designers are solution focused, not problem focused and they are able to move quickly from identifying a problem frame to proposing a solution [18]. This initial qualitative phase of problem-solving is key in the investigation of expert performance.

As can be seen in the above paragraphs, the expert/novice framework is intimately linked to research on problem solving. For the purposes of this study, Hayes' [19] definition of problem solving is being used:

> "Whenever there is a gap between where you are now and where you want to be, and you do not know how to find a way to cross that gap, you have a problem and the problem solving is what you do, when you do not know what to do."

Litzinger et al.[20] describe the problem-solving process of students in a mechanics course as such:

> "The problem-solving process typically begins with a fairly well-defined problem consisting of a short problem statement, often with an accompanying figure. As students read the problem and study the figure, they begin to form a mental model of the problem. They are generally instructed to create a free-body diagram that contains the elements of the problem that are critical to the solution. From the

> free-body diagram, they must construct the set of equations required to solve the problem. As they proceed from the problem statement to the solution, students engage a problem-solving process, either one of their own or one specified by the instructor. In order to solve the problem, students must draw on pertinent prior knowledge, e.g., the nature of reactions that may be present at a specific contact between the body and its surroundings. They must also must work across multiple representations of the problem as their solution unfolds, i.e., the problem statement, the engineering diagram, and the set of equations" [20]

This process sounds straightforward and simple, yet students continue to struggle. Heyworth [21] suggests that these unsuccessful students find it difficult to make connections between what they have learned, and the information provided in the questions (transfer of knowledge), especially when students are unfamiliar with the type of the questions. Therefore, they tend to use more means-ends analysis methods and take an algorithmic approach, looking for equations that serve their purpose rather than trying to understand the questions conceptually or examining the underlying principle in the question [21]. This is much like the method previously discussed in the above expert/novice section. Successful students think ahead, devise strategies, and modify those strategies as needed in a working-forward method (similar to experts) [22]. Moreover, they seem to have a wider and deeper knowledge base, can make more relevant connections to the real world, and usually have better justifications for their answers [23]. In order to observe and collect data on the methods used by experts and novices when they solve problems, a commonly used method called the think aloud protocol will be used.

Methods used to study experts and novices

Studies of cognitive processes that experts and novices employ while solving problems are generally done by giving experts and novices an identical problem to solve. Researchers then observe the cognitive processes used for the experts and novices and comparing/contrast the results. A common method used to reveal the cognitive processes that experts and novices apply is called the think aloud protocol.

The think aloud protocol has its roots in psychological research. It was developed from the older introspection method, which had many theoretical problems. These theoretical problems concern the model of introspection as perception of the contents of consciousness. For example, the model of introspection makes a separation between the processes in consciousness and the introspective process itself, thereby suggesting that the latter is not accessible in consciousness. The think aloud method's solution to some of these theoretical problems is to "assume a simpler process (verbalization instead of observation and interpretation) and to assume that only the contents of working memory are verbalized instead of the entire cognitive process" [24]. In other words, the think aloud method treats the verbal reports as data, instead of the processes in consciousness.

The think aloud protocol involves participants "thinking aloud" as they are performing a set of specified tasks. "Thinking aloud" means that participants are asked to say whatever comes into their mind as they complete the given task. This might include what they are looking at, thinking, doing, and feeling. This gives observers insight into the participant's cognitive processes, rather than only their final product. Participants are asked to make thought processes as explicit as possible during task performance.

Think aloud protocol is often used when doing expert novice and problem-solving studies. By studying participants with varying levels of expertise within a certain domain of knowledge one can better describe what information the participants concentrated on and how information is structured during a problem-solving task. From the data, inferences can be made about the process(es) participants used while making decisions and reasoning during the problem solution phase [25]. Using direct observation and the think aloud protocol is proven to be a valid method of data collection, however the reliability of the data collected can be enhanced by the use of interviews

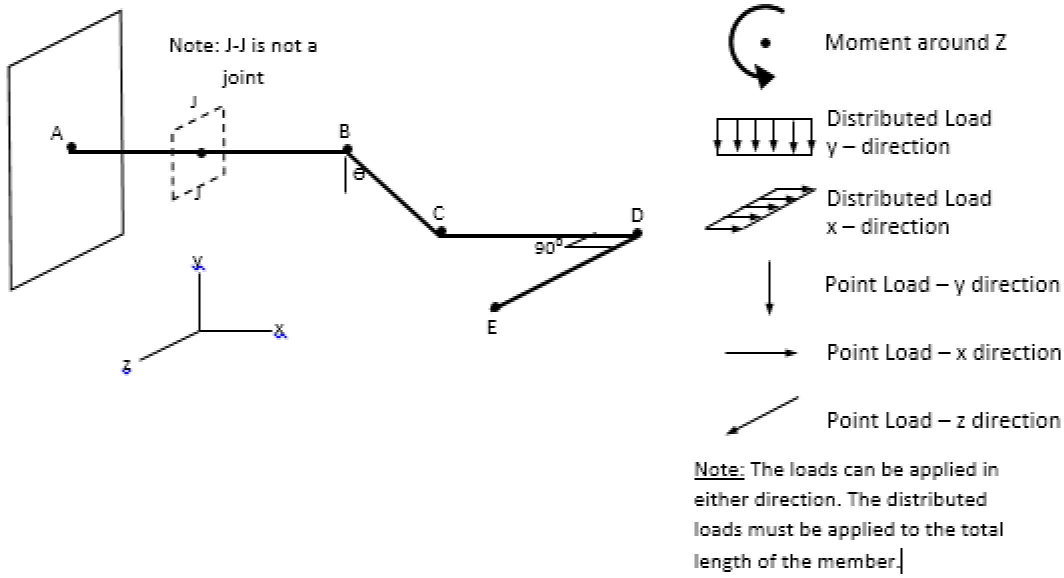
Interviewing is an important way for a researcher to check the accuracy of the impressions he or she gained through direct observation. This study will utilize a focused interview style, where the interview will remain open-ended but will follow a certain set of pre-determined questions. Patton suggested employing strategies to ensure that the interviewees respond in their own words to express their personal perspectives [26]. Moreover, the researcher should never supply nor predetermine the sentences, terms or categories to be used by the interviewees during the interview.

Methodology

The Procedure

Participants will first be asked to participate in a problem solving session. In this session they will try to solve a complex and unique engineering problem. The two main qualities of such a problem are: 1) to include basic engineering concepts found in a mechanics of solids course and; 2) must be presented in a way in which an expert's intuition alone cannot be used to formulate a solution. Quality '2' is vital because according to cognitive science, as a problem decreases in familiarity, an expert's performance will proportionately decrease and begin to approximate that of a novice [27].

The problem created for this research includes an initially unloaded cantilever structure and a list of potential loads that can be applied. Participants will be asked to load the structure with at least 4 of the 6 given loads in order to determine which combination gives a maximum value for each stress condition at plane J-J (Fig. 1).



Place 4 of the 6 loading situations on the above structure to result conceptually in the maximum value at plane J-J for each of the following stresses. Loads can only be added to joints and can be either in the positive or negative direction.

NOTE: All joints are rigid

1) $\sigma_{\text{bending stress}}$

2) $\sigma_{\text{axial stress}}$ (tension or compression)

3) $\tau_{\text{shear stress due to bending}}$

4) $\tau_{\text{axial shear stress}}$

5) $\tau_{\text{torsional stress}}$

Figure 1- Problem given to participants

As can be seen in (fig. 1), the problem does not include values for the loads nor dimensions for the structure. There is no “correct” answer to this problem since participants may make any number of assumptions about the structure. This was done intentionally in order to present experts with a challenging problem that still relied on elementary engineering concepts and equations. After the problem solving session, participates will take part in a short individual interview.

Participants

This research is categorized as an embedded single case study, and thus has multiple units of analysis, the expert and the novice. The expert participants will be subdivided into two categories, academia (professors) and industry (practicing engineers). Criterion for both categories of experts include familiarity with concepts and curricula taught in a mechanics of solids course. Professors were recruited from the Rutgers School of Engineering. Practicing engineers were recruited from local civil engineering firms in the tri-state area and had at least three years of working experience.

The novice participants consist of the students from the Rutgers School of Engineering who are enrolled in a civil engineering specific mechanics of solids course as well as students who have recently completed the course. Participation will be optional and will have no negative effect on the students' grade in the course, although extra credit may be given as compensation pending approval from the instructor. Since the inclusion criterion significantly narrows the sample size, convenient sampling will be used for data collection and content analysis.

Participants were selected from civil engineering due to the authors' personal experience with the civil engineering version of this course. At Rutgers University, there are two versions of MOS courses, one for civil students and one for mechanical. Each course is taught by a professor from the respective department and each respective syllabus has been specifically designed for the type of engineering student enrolled.

Problem solving session

As previously mentioned, the participants will take part in a problem solving session followed by a short individual interview. The two tools used to collect data are the think aloud protocol and interview protocol. During the problem-solving session, subjects will work in a quiet comfortable setting that facilitates thinking aloud. Subjects are then instructed to think aloud as they work on the problem seen in Figure 1. The entire session is audio and video taped in order to aid in transcription. This study will use pairs of subjects because as Rogers et al. [28] points out, when subjects work alone they find it hard to verbalize their though process when the task becomes difficult. Van Someren et al. strongly suggests that "all interaction between subjects and the investigator must be kept to a minimum as to not skew data collection. This can be especially hard when the investigator is familiar with the task domain and is inclined to correct or help the subjects when they are stuck" [24].

The rigor and trustworthiness of qualitative methods relies on the researcher's ability to identify and address any threats to the validity and reliability of their specific data collection tools. Two threats to the validity of the data collected by using the think aloud method are; (a) incompleteness due to synchronization problems and (b) invalidity due to problems with working memory. Thinking aloud takes place concurrently with the cognitive process, hence a cognitive process takes longer when think aloud method is used. For example, subjects frequently report that sometimes verbalization does not keep up with the cognitive process and that their thought processes may look incomplete or contains "holes" of which it is necessary to assume that an intermediate thought occurred here. The second reason states that "if the task is non-verbal and complicated, then verbalization will not only cost time but also space in the working memory which then becomes a cognitive process of itself" [24]. This will cause the reporting of the original process to be incomplete and can sometimes even disrupt this process. Ericsson and Simon [29] maintain that the verbalization of one's thoughts will not interfere with ongoing cognitive processes, nor will it affect the speed of task performance, unless verbalizations are queued by the investigator probing. Reliability will be obtained by augmenting think aloud data with retrospective data obtained through a follow-up interview conducted after the think aloud session, and thus obtaining a more complete description about the subjects' reasoning strategies.

Interviews

Subjects will be individually interviewed directly after their problem solving session. Interviews will be video and audio recorded in order to aid in transcription. The interviews will ask the subjects questions based on their recent problem solving experience. As previously mentioned, this study will use a focused interview strategy with a semi-structured format. The semi-structured format will allow the selected participants to add whatever they feel might be relevant to the discussion but was not explicitly asked.

During the interview process, some aspects of a focused interview might compromise the validity and reliability of the data collected. For example:

- Lack of flexibility and flow during the interview process (can render some participants uncomfortable or more prone to forget the ideas they intended to share).
- Wording of the questions might be a difficulty to some participants (choice of words, interpretations could be made, leading question, etc.)

After the interview process, the aspects which could compromise the validity and/or reliability of the data collected are mostly related to:

- The process of data transcription (researcher will type the interview which will be audio-recorded).
- The interference between the researcher and the data collected (researcher might try to interpret or directly code the data as they transcribe; or might involuntarily attribute some sense/value/emotion so a part of the data (breach of bracketing).

Patton [26], advises an alternative approach to validity and reliability. He believes the terms ‘reliability’ and ‘validity ’are too strict and restricted in the context of interviews. In replacement, he names four characteristics: Credibility, Confirmability, Transferability and Dependability. He goes on to suggest that, ‘it can be helpful to minimize issues of legitimacy and credibility by carefully collecting the same information from everyone who is interviewed’ [26]. After the raw data from the interviews and problem-solving session has been collected, audio and video recordings will first be broadly explored and integrally (i.e. not modified from the original recorded version) transcribed.

Data Analysis

Thematic analysis

Transcriptions of the videos from the problem solving session and interviews will be coded and analyzed by combining the procedures from both thematic analysis and the think aloud method. Thematic analysis is a method for identifying, analyzing, and reporting patterns (also called themes) within data. It minimally organizes and describes your data set in rich detail [30]. It is a form of pattern recognition within the data, where emerging themes become the categories for analysis [31]. A theme captures something important about the data in relation to the research question and represents some level of patterned response or meaning within the data set. It should be noted that a theme is different from a code as illustrated in [32, Fig. 2].

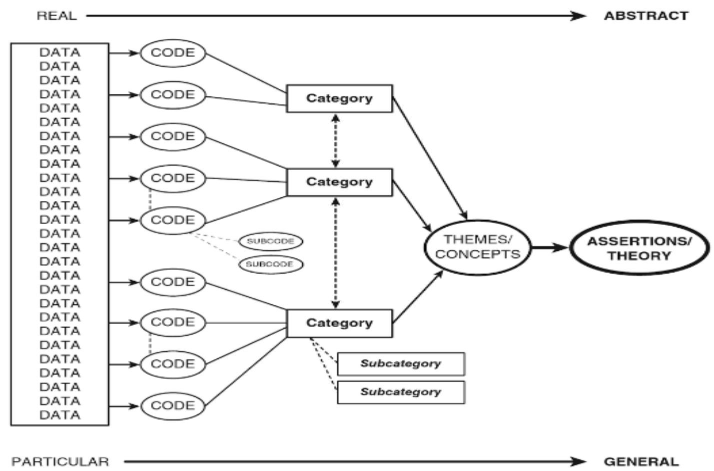


Figure 2-A streamlined codes-to-theory model for qualitative data.

It is often recommended that researchers "code for themes". This can be misleading because the theme is more general than a single code. The code is the label that is given to particular pieces of the data that contribute to a theme [32]. In other words, several codes can be grouped into a category, and several categories can be grouped into a theme. The phases of thematic analysis can be best described by Braun and Clarke as seen in [30, Tab. 1].

Phase	Description of the process
1. Familiarising yourself with your data:	Transcribing data (if necessary), reading and re-reading the data, noting down initial ideas.
2. Generating initial codes:	Coding interesting features of the data in a systematic fashion across the entire data set, collating data relevant to each code.
3. Searching for themes:	Collating codes into potential themes, gathering all data relevant to each potential theme.
4. Reviewing themes:	Checking in the themes work in relation to the coded extracts (Level 1) and the entire data set (Level 2), generating a thematic 'map' of the analysis.
5. Defining and naming themes:	Ongoing analysis to refine the specifics of each theme, and the overall story the analysis tells; generating clear definitions and names for each theme.
6. Producing the report:	The final opportunity for analysis. Selection of vivid, compelling extract examples, final analysis of selected extracts, relating back of the analysis to the research question and literature, producing a scholarly report of the analysis.

Table 1 - Phases of thematic analysis.

Inductive coding will be used for data analysis and segmentation will be based on sematic features. Due to this, the units chosen for analysis will vary in grain size between short expressions and/or sentences. The grain size of a unit will vary from a single word (smallest grain size of a unit) to a short grouping of sentences (largest grain size of a unit). The same segment of an artifact might be attributed to multiple codes. As a starting point, a small sample from the transcripts will be used to create a basic coding scheme based on the frameworks previously discussed. The next phase will follow the inductive approach where the coding scheme will be extended and refined as more data is coded and analyzed. A coding manual will be used for later verification as well as for establishing intercoder reliability. As recommended by Creswell [33]; the coding manual will include a definition of the codes, themes and levels, positive and negative examples of codes/themes occurrences encountered during the ‘sample coding/intercoder reliability’ determination, as well as short notes describing how the codes and themes occurrences where determined.

Think aloud protocol

The think aloud protocol has its own procedure for data analysis, which will be used in combination with the thematic analysis procedure. This alternative way to analyze data is to pre-develop a coding scheme based on a procedural psychological model (i.e. problem-solving procedure). Since the model describes which cognitive processes will occur and in which order they will occur, it will be possible to create a coding scheme that specifies how elements of the model can be identified in the data. Every process described in the model will need to be identified and defined as to how it is expected to appear in the raw data. Van Someren [24] suggests that it is usually very helpful to give some examples of prototypical statements for each category.

Validity and reliability

As is necessary with data collection, validity and reliability shall also be checked for the content analysis coding process and the analysis of the results. During the coding process, validity and reliability will be ensured in various ways, including:

- Using separate/different subsets of artifact segments to calculate the intercoder reliability
- Comparing standard value indicators such as Cohen’s Kappa
- Having each coder code the same transcript segment at two different times (one month apart) to see if there is an observable difference with a single coder over time.
- Having at least two coders working collaboratively to develop the coding scheme
- Having both coders working on a same segment to code for disparities identification. If coding disparities occur, the two coders will discuss and come to an agreement.

The validity and reliability of the results obtained from data analysis will be ensured following these guidelines as well:

- Acknowledging that no matter which results are obtained, co-occurrence does not imply causation
- Acknowledging that no matter which results are obtained, proportions, frequency distributions and other statistics will not necessarily reflect the nature of the whole data set.
- Avoiding the omission of contradictory evidence
- Checking the analytical interpretations using multiple external reviewers.
- Discussing all inconsistencies in patterns/co-occurrences/trends with peers/colleagues as they emerge and discuss whether these inconsistencies invalidate the overall anticipated patterns.
- Using research team member checking and peer debriefing as regular techniques to validate methodology, data analysis, as well as conclusions drawn from data analysis.

Lastly, once all the data has been analyzed and determined to be valid and reliable, it will be used to then go back and answer the initial questions posed by this study in a significant and meaningful way. These answers can then be used for both further research and to aid in the betterment of engineering educator's approach to teaching MOS courses.

Current State of Research

Data is currently being collected as per the above methodology. Preliminary data analysis will be available in time for the 2018 ASEE Annual Conference.

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