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An Investigation of Students’ Conceptual Understanding in Related Sophomore to Graduate-Level Engineering and Mechanics Courses

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Abstract

Interviews were conducted with students from a sophomore-level mechanics of materials class, a sophomore/junior-level structures class, a senior-level steel design class and a graduate-level advanced steel design class to investigate students' conceptual understanding of bending and normal stress. The graduate students generally demonstrated higher computational skill and confidence but they were not significantly different from the sophomores in terms of conceptual understanding. Interestingly, the seniors showed markedly lower confidence in their ability to solve the problems posed in the interviews. Common difficulties include a conceptual definition of stress and reasoning involving the normal stresses developed under bending.

Keywords: civil engineering, conceptual understanding, qualitative research methods

I. Introduction

Engineering educators are increasingly concerned with their students' understanding of engineering and the underlying physical sciences. Recent research indicates that despite high passing rates in most universities, most students do not understand their course content very deeply (Gray et al., 2005; Hake, 1998; Halloun and Hestenes, 1985; Lawson and McDermott, 1986; Steif, 2003; Steif, Dollar, and Dantzler, 2005; Streveler et al., 2004, 2006). While this concern is relatively new to engineering faculty, research in the teaching and learning of science and mathematics, particularly in the field of physics education, has been progressing for more than 20 years. Problems and questions particular to engineering have only begun to be addressed. There are three main foci of research on how to increase student conceptual understanding. The first considers creating curricular materials and proving their effectiveness; the second determines how and why students develop conceptual understanding; and the third develops and validates broadly-applicable assessments in order to investigate more general trends in student conceptual understanding.

In order to discuss the phenomenon of deeper understanding, many researchers use the construct "conceptual understanding." This phrase often loosely differentiates students' abilities to perform calculations and their understanding of the significance of the calculations. In this study, conceptual understanding of a particular topic is defined as the beliefs and framework used to acquire new knowledge or perform new applications of old knowledge in that topic. It can be thought of as an understanding of the phenomena underlying a calculation, including the context, purpose, necessary assumptions, and range of reasonable values expected.

While students' computational abilities have been shown to develop with quantitative, problem-based homework, lecture, and exams, conceptual understanding is more difficult to develop and assess (Chi and Roscoe, 2002; Hake, 1998; Halloun and Hestenes, 1985; Margolis, 1999; Streveler et al., 2004). Computational skill is predictable and epitomized by familiarity with a standard process, but conceptual understanding is often applied in the form of intuitive leaps or unexpected solutions. A body of research—again, largely in the physics education field—has grown around measuring students' conceptual understanding and developing curricular materials to improve it in specific topics. Most of the studies done in physics education research are performed within one course or focus on one concept. The theoretical frameworks of these approaches describe learners' development of concepts in standard progressive stages.

The purpose of this study is to begin describing how conceptual understanding of related concepts develops through multiple courses.

A. About Conceptual Understanding

Because the purpose and importance of this research depend on the meaning of the phrase "conceptual understanding," it will be described here for clarity. There is no universal definition of conceptual understanding. The book *Concepts: Core Readings* by Margolis and Laurence (1999) presents a summary of some of the key psychological and philosophical issues involved in defining cognition. Conceptual understanding is often associated with intuition instead of knowledge because is it so much more internal; you don't *remember* something you understand conceptually, it is just true. Conceptual understanding is not the abstract and theoretical perspective taken by world-renowned experts, but rather the phrase encompasses all the perspectives taken by all people. For example, anyone who has noticed that the moon seems to follow the car when driving at night has some personal explanation of why it does so, whether or not they are familiar with the application of gravity to astronomy. It may take years before one's knowledge and experience make it possible to conceive of the distances involved in astrophysics, and more years before that knowledge is applied to the moon during a car ride.

This example also demonstrates some of the difficulties of researching conceptual understanding. A parent may tell a child, "the moon looks like it's following us because it is so far away and is so big that our movement is insignificant," and that child may even be able to repeat that to a friend. This repetition, though, is only evidence of memory. Instructors often encounter this distinction when students who are successful at performing complex calculations in their homework cannot answer ostensibly simple questions about the nature of what is being studied. For example, a student might be able to calculate the longitudinal normal stresses developed due to bending, but may reason that no longitudinal stresses exist when asked to generally describe the stresses present. The child in the example would not truly understand what is meant by "so far away" until they have some experience to relate it to, perhaps noticing that cars on the highway appear to be going much slower when they are far away. This knowledge will only be useful to the child (by being applicable to new situations or helping them learn related concepts) once it has been internalized and personalized in this way. Conceptual understanding of something could therefore be called "useful knowledge" about that thing. Note that in this example, the "usefulness" of knowledge refers to how able a person is to apply it outside of the context in which it was learned. This is often referred to as the *transferability* of knowledge. Conceptual understanding (people's personal explanations of how and why the world works) is knowledge in context, and is therefore more transferable than computational ability.

II. Literature Review

A. Underlying Theories of Learning and Cognition

Contemporary theoretical frameworks adopted for examining student cognition are based on Jean Piaget's (1963) seminal work in cognitive development (Trowbridge and McDermott, 1980). Piaget described learning as a developmental process in which people progress through standard stages of increasing understanding to internalize knowledge. Piaget identified six stages of cognitive development that he believed to be universal when learning. Although new information is gained throughout the stages, each stage is defined by a particular perspective and method of obtaining and organizing information. At each stage a person gains a broader, more thorough, and more flexible understanding.

He theorized that a person's knowledge is organized into categories. These catageories, called *schema*, could be thought of as a kind of automatic sorting system. When people encounter new information they must either fit it into an existing schema or change the organization and definitions of their schema to fit the new knowledge. Piaget found that people were more likely to change new information to fit existing categories than to change or add categories. A classic example involves a child's first encounter with a cow. In the example, the child refers to the cow as a large dog, probably because it has the same basic body type. Eventually, the child will construct new schema based on "cowness," but in order to do that the child must become aware of what differentiates dogs from cows. This process requires much more work than simply using the existing schema for dog. Piaget's approach was unique in its time because it implies that students' responses are usually valid in the context of their existing knowledge.

Some cognitive psychologists (for examples see Limón and Mason, 2002) described the process of changing or adding Piagetian schema as conceptual change. Chi and Roscoe (2002) hypothesize that this process is difficult because certain deeply-held beliefs about a subject interfere with conceptual change in that subject. These beliefs are defined as misconceptions. An example of a misconception from Chi and Roscoe's research is that some students believe that heat and cold behave like two separate fluids, flowing out of and filling up objects (Chi and Roscoe, 2002). Even though this misconception is contradicted many times in a typical thermodynamics lecture, it is a part of the framework students use to make sense of the lectures, so they must either adjust what they hear to fit their beliefs, change their beliefs, or ignore the contradiction. Chi finds that students rarely change their existing beliefs because of lectures.

Constructivism differs functionally from Piaget's theory in that it emphasizes interrelated knowledge and does not assume standard stages of learning. Bruner (1960), a cognitive psychologist, described learning as a complex process in which learners are constantly readjusting their existing knowledge and, more importantly, the relationships between the things that they know. Constructivists believe that individuals interpret their experiences to create their own understanding of the world. Instead of Piaget's schema, constructivists often work in terms of mental models. The concept of schema implies complex, but discrete cognitive building blocks that are at least universal enough to be useful to educational researchers. However, mental models involve a more holistic, interrelated and widely diversified view of how people think. The internal justifications we all have for why the moon appears to follow the car at night are an example of mental models in action. Both the concepts that are utilized and how they are related are of interest. At one level, a constructivist may be interested to see if the concept of gravity is included in the explanation, or they may also be interested in how a person relates their knowledge of gravity to the moon's apparent motion.

The constructivist concept of education depends on facilitating student experiences so that they can construct complex, useful understandings of science, technology, engineering, and mathematics (STEM) fields. To do this Bruner focuses on what he calls the structure of a field. He explains, "grasping the structure of a subject is understanding it in a way that permits many other things to be related to it meaningfully. To learn structure, in short, is to learn how things are related" (Bruner, 1960). Structure is not limited to knowledge of how facts and equations are related, but also includes an epistemological perspective on how knowledge is created and organized within a subject. He writes, "Mastery of the fundamental ideas of a field involves not only the grasping of general principles, but also the development of an attitude toward learning and inquiry, toward guessing and hunches, toward the possibility of solving problems on one's own" (Bruner, 1960). It is important to notice that the second half of Bruner's quote is not limited to the context of the field being mastered. When the structure of a field is understood it allows the knowledge of that field to be transferable to other fields

The concept of structure presents new challenges to educators, mainly in putting a name to the large cognitive and perceptual differences between instructors and students. In investigations of what has come to be known as expert-novice theory, researchers have found that experts in a field usually have completely different mental models than novices in the field, and that these differences affect how they learn and even how they perceive phenomena (Bransford, Brown, and Cocking, 2000; Chase and Simon, 1973).

B. Previous Work

Concept inventories (Evans et al., 2003; Hake, 1998; Halloun and Hestenes, 1985) suggest that most students do not truly understand the concepts covered in their STEM courses. Concept inventories are tests that have been rigorously developed to measure students' conceptual understanding. The first of these was developed by Halloun and Hestenes (1985) to investigate freshmen knowledge of the most fundamental physics concepts and was called the Force Concept Inventory (FCI). Halloun and Hestenes were surprised by students' extremely low scores on this test because the questions were intended to elicit the most basic applications of the most basic physics principles. They expected most students to score nearly perfectly because most students could perform calculations based on the Newtonian concepts tested in the FCI. However, they found that students consistently chose non-Newtonian explanations for common physical phenomena, and that a "student's initial qualitative, common sense beliefs about motion and causes have a large effect on performance in physics, but conventional instruction induces only a small change in those beliefs."

In the field of engineering education, the FCI methodology and findings inspired the Foundation Coalition (2008) to develop concept inventories in 13 different areas, including strength of materials (Richardson, Morgan, and Evans, 2001). Preliminary results from the engineering-specific fields of statics (Steif, Dollar, and Dantzler, 2005) and thermodynamics (Olds, Streveler, and Nelson, 2004) imply that student conceptual understanding of engineering topics is as low as observed in other STEM areas. Results from the strength of materials concept inventory have not been published, although it is reasonable to assume that student conceptual understanding is low. In order to mature these assumptions, one goal of the research described here was to investigate the general level of student conceptual understanding in mechanics of materials.

A group of engineering education researchers involved in the development of engineering-specific concept inventories have used them as a springboard to study students' conceptual understanding in more detail. Notable investigations include Krause's (Krause, Tasooji, and Griffin, 2004) and Streveler's (Streveler et al., 2006) separate investigations into the causes of misconceptions; various studies identifying content-specific misconceptions in materials science (Krause et al., 2003) and thermodynamics (Miller et al., 2005); methodological approaches to investigating conceptual understanding (Miller et al., 2005; Newcomer and Steif, 2007; Streveler et al., 2004; Streveler et al., 2003); and how to develop conceptual understanding in the classroom (Mays et al., 2007; Reed-Rhoads et al., 2007; Steif and Dollar, 2003; Steif and Hansen, 2006). The bulk of this research deals with the content areas of thermodynamics and statics.

Much of the work on conceptual understanding of engineering concepts is based on the University of Washington Physics Education Group (UW Physics Group)'s methodology following Piaget's developmental model of learning. The UW Physics Group measures conceptual understanding using "as an indicator of degree of understanding the extent to which a student's understanding corresponds to that of a physicist" (Trowbridge and McDermott, 1980). This definition respects the validity of each student's representation and aims to measure a student's progress along Piaget's cognitive development by comparison to an expert. This methodology was used to develop curricular materials for each topic in introductory physics (McDermott, 1996). Misconceptions were identified in each topic—e.g., one-dimensional velocity (Trowbridge and McDermott, 1980), work-energy and impulse-momentum relations (Lawson and McDermott, 1986), or Archimedes' principle (Kautz et al., 2005, 2005)—and addressed separately. The curricular materials' effects are measured by pre- and post-tests using the FCI or similar concept-based assessments, with typical results increasing student performance on these assessments by 20 to 40 percent. The curricular materials were combined (McDermott, 1996) but not interrelated. Materials developed to improve understanding of one topic were not assessed for their impact on related topics. For example, angular momentum was addressed using objects rolling down inclined planes and inherently involved the concepts of gravity, acceleration, and friction, but these topics were not addressed in the angular momentum materials. This separation fits the Piagetian theoretical framework, where a student's progress in understanding a topic follows a linear pattern and curricular materials need to be designed to support that pattern.

Because, according to Bruner (1960), true learning involves relating existing knowledge to what is being learned, researchers will need to move beyond examining single concepts or examining students at a single point during their education. Students are constructing their understandings of phenomena throughout their academic careers. The UW Physics Group has demonstrated success in addressing student difficulties in individual concepts (for examples, see Trowbridge and McDermott, 1980; Lawson and McDermott, 1986; Loverude and McDermott, 2003), but it is still unknown how these incremental increases in conceptual understanding improve students' overall understanding of physics or if demonstrated improvement in basic concepts will help students learn more complex ones.

Engineering faculty generally agree that concepts taught in the sophomore year are required to learn concepts in the senior year. This may be true from the expert's perspective, but it is also possible that students need the concepts from their senior year to construct an understanding of the sophomore concepts. Engineering faculty's division of concepts—for example, defining the concept of buckling as a part of the concept of failure—probably does not match students' divisions of the same information, especially when they are learning and undergoing conceptual change (Chi and Roscoe, 2002).

The persistence of low conceptual understanding through college cannot be attributed to concepts not being taught or being taught improperly (Chi and Roscoe, 2002; Halloun and Hestenes, 1985; Lising and Elby, 2005; Prince and Felder, 2006; Tobias, 1990, 1992). There is a complex cognitive phenomenon related to students' beliefs that interferes with the learning of certain subjects.

Current theories explaining this phenomenon agree that people learn by constructing their own context for understanding (Bruner, 1960) and that previous knowledge has a large effect on learning (Chi and Roscoe, 2002). Previous methods of addressing student conceptual understanding guide students through predetermined stages of understanding and do not reflect the complexity of how individual students will construct their understanding of the concepts' interrelations through their collegiate career. The existing research in student conceptual understanding is sparse in engineering-specific content areas. The research that does exist addresses individual concepts in the context of single courses.

III. Purpose of Study

The purpose of this study is to begin to investigate how students construct their conceptual understanding throughout the engineering curriculum by comparing "snapshots" of student reasoning in different years. The word "snapshot," or "cross-sectional," is used to differentiate this research from a longitudinal study: this is not an investigation of how individual students develop their conceptual understanding but a look at how the general trends of conceptual understanding differ between school-years. This study is the beginning of a line of inquiry that will eventually accomplish the following broader goal: to understand how students' conceptual understandings develop through their academic careers in engineering, in part by determining what misconceptions students develop at what points and using this information to modify engineering curriculum to most efficiently help students develop a robust conceptual understanding of mechanics of materials.

A. Research Questions

This study will answer the following questions:

1. How does student conceptual understanding of bending differ among sophomores, juniors, seniors, and graduate-level civil and environmental engineering students?
2. How is student conceptual understanding similar among these groups?
3. Which underlying beliefs might account for the similarities in conceptual understanding?

IV. Methods

To achieve these goals and answer these questions, qualitative interview and analysis methodologies were implemented. It is important to note that qualitative researchers use different methods to describe the quality of research (for a more complete description of qualitative research methods in use in engineering education see Leydens, Moskal, and Pavelich, 2004; Robson, 1993). The two primary dimensions of measurement are credibility and dependability. Credibility is parallel to validity and refers to the "relative truth value of qualitative findings and interpretations" (Leydens, Moskal, and Pavelich, 2004). A study's credibility is built on the strength of the methods and the expertise of the researcher (Patton, 2002). Dependability is similar to reliability and relates to how similar the results of a qualitative study would be if performed again or by different people. A primary source of both dependability and credibility in research methods is through the use of triangulation—forming conclusions only when multiple data sources agree (Patton, 2002).

Interviews were conducted with approximately five students from the Spring 2007 semesters of each of the following courses, for a total of 21 students: MoM_2 – Mechanics of Materials; $Struct_3$ – Introduction to Structures; $Steel_4$ – Structural Steel Design and; $Adv\text{-}Steel_5$ – Advanced Structural Steel Design. These interviews provide a snapshot in time of the student participants. The interviews were structured around a set of four concepts that are traditionally believed to be related to and build upon each other: labeled stress, bending, buckling, and local buckling of the flange of a beam. Experts believe that the last concept is mostly constructed from the previous three concepts. A brief discussion of the four concepts is found in the Results and Discussion section. The interviews were analyzed using the constant comparative (Patton, 2002) method for student conceptual understanding and then analyzed to compare between classes and between concepts for individual students.

A. Courses and Concepts

The concept of bending was chosen as the focus of the research. The phenomenon of local buckling of the flange was chosen as a complex, real-world application of the concept of bending, which necessitated the inclusion of the concept of buckling as a transition between bending and local buckling of the flange. The specific courses were chosen because all four share the same basic concepts of stress, buckling, and bending, but in each course the application becomes more complex. Also, because the first two courses are required for all civil engineers and the structural engineering emphasis classes are sufficiently large, this allows for truly purposeful sampling. Similar to quantitative studies' use of random sampling to avoid biases in their analyses, qualitative studies use purposeful sampling to ensure that the data they collect will be meaningful (Patton, 2002).

Through interviews with a structural engineering faculty member who has taught all of these courses, bending was chosen as a focus because it presented persistent difficulty for students (Brown, Montfort, and Findley, 2007a, 2007b). Including local buckling provided more data for triangulating the assessment of students' understanding of buckling and bending. Approximately half of the students interviewed had not discussed local buckling in their classes, and their related responses provided a baseline for analyzing their responses on other concepts.

MoM_2 is a sophomore class and is typically one of the first engineering content classes taken by civil and mechanical engineers at Washington State University. It introduces students to the concepts of stress, strain, and basic design of structural members. $Struct_3$ is also required for all civil engineers and is the last structural engineering course that non-structures students will take. Starting with the analysis techniques learned in MoM_2, $Struct_3$ covers the design and analysis of basic structural elements, including columns, beams, and frames. $Steel_4$ is a design elective course taken almost exclusively by senior civil engineers who have chosen to emphasize structures in their undergraduate coursework. It covers the intricacies of designing steel elements, including columns, beams, and local buckling. $Adv\text{-}Steel_5$ is a graduate-level course taken mostly by first-year graduate students on the structural engineering track. It covers more complicated analysis and design topics for types of steel structures, including combined loading, plastic collapse analysis, and local buckling analyses. Table 1 summarizes the course descriptions.

Course	Abbreviation	Student Grade	Buckling	Bending	Local Buckling
Mechanics of Materials	MoM_2	Sophomore	X*	X	
Introduction to Structures	$Struct_3$	Junior	X	X	
Structural Steel Design	$Steel_4$	Senior	X	X	X*
Advanced Structural Steel Design	$Adv\text{-}Steel_5$	Graduate	X	X	X

* These concepts are covered briefly in the indicated courses.

Table 1. Concepts covered in each course and correlated student year in the engineering program. The subscript numbers in the abbreviations indicate student year: 2 for sophomores, 3 for juniors, etc.

In the Spring 2007 semester, MoM_2 was taught by a professor whose research emphasis is in environmental engineering and had been teaching for approximately one year. $Struct_3$ was taught by a structures professor who had been teaching for approximately 19 years and had been teaching in his current position for about 13 years. Both $Steel_4$ and $Adv\text{-}Steel_5$ were taught by a structures professor who had been teaching for approximately 10 years and, as a co-author of this paper, was involved in developing the interview materials for this study.

Although the professors for these classes are diverse in ways that could be expected to affect their effectiveness in teaching these courses, (e.g., familiarity with the structural field and overall experience) this should not affect the credibility of this study. As Halloun and Hestenes (1985) and others have shown (Hestenes, Wells, and Swackhamer, 1992; Hake, 1998; Lising and Elby, 2005; Prince and Felder, 2006; Trowbridge and McDermott, 1980), lecture-based instruction does not affect students' conceptual understanding as much as their previous beliefs. While all three professors used a variety of pedagogical techniques, lecture was their primary method of instruction. Additionally, the differences in instructor quality would affect the analysis of student responses within the same classes, as well as across them. For example, some students in the graduate-level course have come from other universities and some of the students in the senior-level course may have had different instructors for MoM_2. The instructor was an intervening variable in this study, but the sample was chosen such that the effects of instructor quality would be non-directional: the random variations would not bias the analysis even if there was a strong correlation between instructor and conceptual understanding, because the analysis is between classes while the variation is both between and within the classes (Patton, 2002).

B. Sample Selection

Critical case sampling was used to achieve the research goals. Critical case sampling is a form of purposeful sampling that allows directional inferences about broader populations (Patton, 2002). "Critical case" refers to an individual or group that, when studied, can shed light on the status of the context or system they are in. It is important to note that critical cases are not meant to be representative of the population they are taken from. Instead, they are groups or individuals positioned in such a way that a description of them also describes some aspect of the larger population. In this study, the professors were asked to select from among the "4–8 best students in your class." The professors asked the students if they would be willing to participate, and set up contact with the interviewer for those who were. Of the 27 who were initially contacted, 21 participated in interviews. Table 2 presents general information about these students, summarized by course. The grade point averages (GPA) and grades in the course were self-reported during the interviews and are recorded here on a four-point scale.

Course	*Number of Participants*	*Mean GPA*	*Expected Grade in Course*
MoM_2	4	3.3	3.5
$Struct_3$	7	3.6	3.8
$Steel_4$	6	3.5	3.8
$Adv\text{-}Steel_5$	4	3.9	3.9

Table 2. Summary of participants and participants' grades.

The non-specific term "best" was used intentionally and is central to this selection being considered a critical case. In separate discussions with each of the professors involved, the key criteria involved in choosing the students appeared to be primarily (1) interaction with the professor and peers, (2) exam and homework quality and scores, and (3) overall academic performance, based either on knowledge of the student's GPA or anecdotal evidence from class. Although true correlations between year in program and conceptual understanding are not the goal of this research, the differences between students in each year of the program are of interest. Therefore, these students, who are most engaged and successful in the program form a critical case. If the degree program does not appear to have an effect on these students' conceptual understanding, it is reasonable to assume that success in the degree program is not closely related to conceptual understanding.

C. Development of Interview Materials

Following McDermott, the interviews were based on Piaget's clinical interviewing method (Trowbridge and McDermott, 1980). Ginsburg (1997) describes exploration and hypothesis testing as key elements in an interview designed to describe the participant's perspective with limited effects from the interviewer's bias.

Exploration is key because the interviewer cannot guess what the participant knows or how that knowledge is organized. For example, a mechanics of materials instructor may view the course as examining three main concepts and ask a question like, "What do you think are the main concepts of this course?" The student may view the course as a series of loosely linked procedures and though this belief would be important to the instructor, it could not be discovered without more exploration. The order and timing of verbal questions in the interviews were organized to facilitate this exploration. For each ranking task, the instructions (see Figures 1 and 2) were carefully worded to elicit the participant's responses to the phenomena of interest without limiting those responses to a certain framework. The participant's response to the instructions guided the next part of the interview. If they began ranking the figures immediately, they were asked to explain their ranking. However, if they asked questions, wrote equations, or began explaining their response the interviewer listened or asked clarifying questions. The dependence of this interviewing structure on the participant's first responses allowed the interviewer to explore the participant's perspective without calling undue attention to any statements.

Hypothesis testing is a form of triangulating data. When the interviewer forms a hypothesis about the participant's perspective, it should be tested with follow-up questions. Again, this was incorporated into the questions themselves: each concept of interest is repeated in at least two questions. Additionally, students were asked to repeat their reasoning for each ranking decision in multiple ways. For example, if a student explained that *a* is greater than *b* because *a* has more area, they would later be asked to explain why they ranked *c* as greater than *d*.

Using the guidelines presented in Ginsburg's *Entering the Child's Mind* (1997) and the example of Piaget's motion tasks (1970), the interviews were structured by the interviewer and coauthor (an experienced clinical interviewer) around a set of problems (these problems will be described in detail in the paragraphs to follow). Further questions were used to encourage students to think aloud, clarify student statements, and test the strength of student statements. This structured format limited the amount of improvisation required of the interviewer and facilitated the exploration and hypothesis testing that is valuable in the analysis stage.

Ranking tasks were used to observe the students constructing understanding. A ranking task is a quick way to assess or improve a student's understanding (O'Kuma, Maloney, and Hieggelke, 2003). Ranking tasks require students to compare features of physical situations without being given equations or the context of a specific topic. For example, a ranking task used in this study shows six identical beams under different loadings and requires students to rank the normal stress due to bending at a specific point from highest to least. This example was designed to assess student understanding of normal stress due to bending. Individuals construct the structure of a subject when applying it to new but related topics (Bruner, 1960; Bransford, Brown, and Cocking, 2000; Vygotsky, 1962). Because the students were not familiar with ranking tasks, and probably had not been asked to use their knowledge to compare similar situations before, they were constructing understanding during the interviews. For example, knowing the bending stress equation is sufficient to be successful in most MoM_2 and $Struct_3$ homework problems on the topic, but not every student who referred to this equation possessed the understanding required to apply the equation to the relatively new context of the ranking tasks.

Seven ranking tasks were developed, and an additional page of written short-answer questions about stress gave the students eight pages of questions, which they completed in 50–80 minutes. The topic of each question is summarized in Table 3, and materials presented to the students for each question are shown in Figures 1 and 2. Note that the figures and text have been revised graphically to facilitate presentation in this paper. The first ranking task and a page of open-ended questions were designed to elicit the students' conceptual understanding of stress. The second and third ranking tasks were designed to discuss buckling. The fourth, fifth, and sixth dealt with bending. The final ranking task concerned local buckling in the flange. The interview packet was revised after the first two interviews, so those two students responded to an additional question about stress and did not respond to question 4. The revised interview packets were checked for consistency and face validity through interviews with the instructors from MoM_2, $Struct_3$, $Steel_4$ and $Adv\text{-}Steel_5$.

The ranking tasks all provided numbered spaces for students to enter their rankings, and the following two questions with space for handwritten answers: "1) Please describe your reasoning?" and "2) What key equations or properties did you use to make your ranking?"

Question 2 was not a ranking-task, and was included to serve a number of purposes. The first was to generally investigate student conceptions of stress in simple loading cases. Secondarily, both Question 1 and Question 2 were intended to encourage students to ask questions, and to make them more comfortable answering the more specifically focused ranking tasks.

D. Interview Methodology

In general, the interviews' pacing and content was guided by the interview materials. In order to identify and address (if possible) any student difficulties in interpreting the figures, each set of figures was described verbally by the interviewer immediately after the student had read the instructions. Clarification questions were encouraged throughout the interview, with the interviewer often asking questions like, "Is it clear what this is showing?" While there was some variation in clarification questions by the students about the figures, there were no questions about the figures that remained unanswered.

After being introduced to the project and the concept of ranking tasks the students were presented with Question 1 and asked to read the instructions. Most of the interviewer's questions directly addressed student comments by asking for clarification or a deeper explanation. To test hypotheses about the students' understanding, the interviewer occasionally asked broader questions not directly related to the interview materials. For example, during their responses to Question 2 (see Figure 1), students were asked how they would explain to a non-engineer why stresses were present in the middle of the member if all the forces were on the outside. This question was used to test the hypothesis that students lacked an understanding of the internal phenomena of stress. This hypothesis was generated when students' definitions of stress depended mostly on describing external loading conditions.

Although the interview materials were designed for hour-long interviews, not all of the interviews proceeded at the same pace. If the students felt rushed their responses would likely not be representative of their conceptual understanding, so the interviewer consistently encouraged them not to limit their responses based on time. For example, if a participant indicated that they could use an analytical procedure or calculation to help them complete their

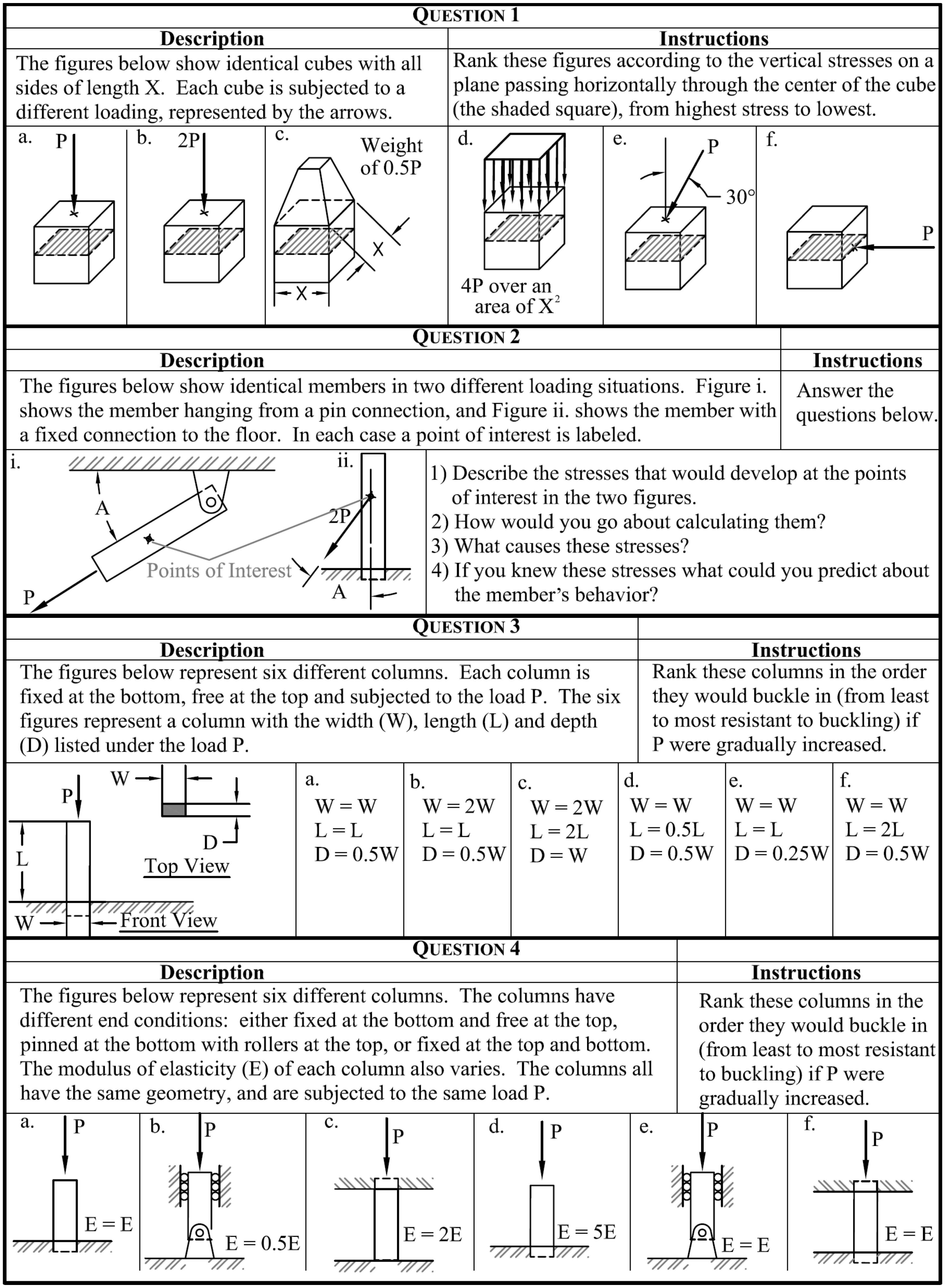
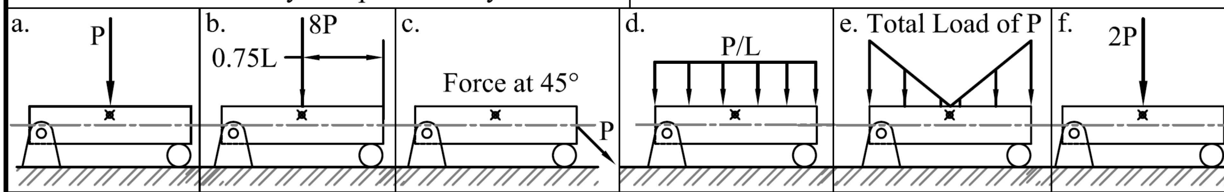


Figure 1. Figures, directions, and ranking tasks for interview questions 1 to 4.

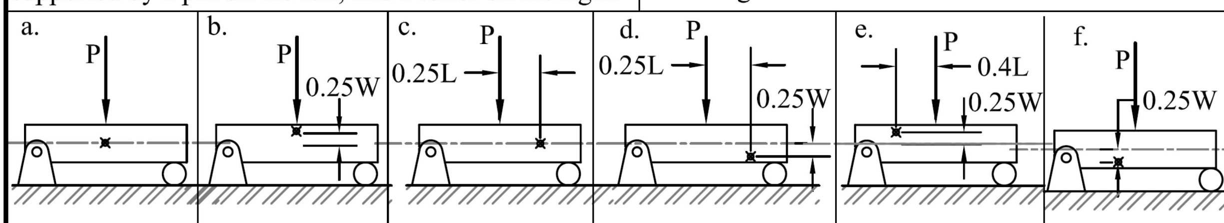
QUESTION 5

Description	Instructions
The figures below show identical members of length L and width W, with identical sections. Each is supported by a pin on the left, and a roller on the right. Each is loaded differently as represented by the arrows.	Rank these figures according to the normal stresses developed due to bending at the point indicated (midway between the upper edge of the beam and the centerline), from highest stress to lowest.



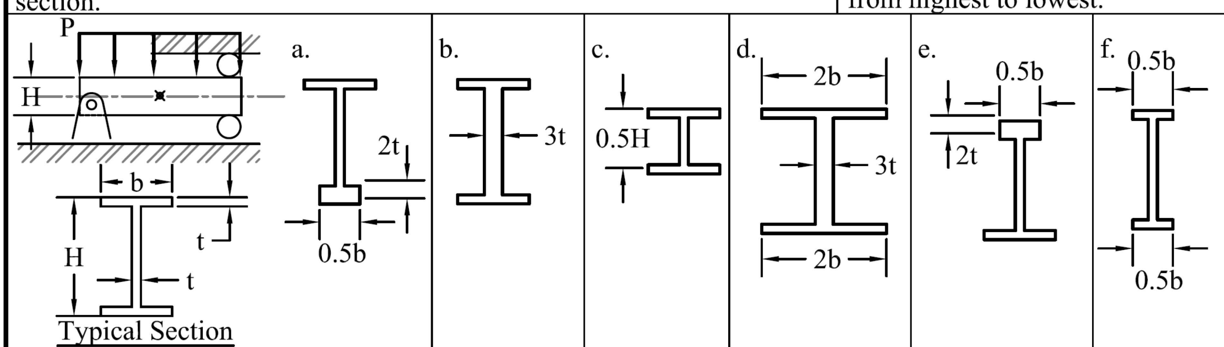
QUESTION 6

Description	Instructions
The figures below show identical members of length L, with identical sections, under identical loads. Each is supported by a pin on the left, and a roller on the right.	Rank these figures according to the normal stresses developed due to bending at the point indicated, from highest stress to lowest.



QUESTION 7

Description	Instructions
The figures below show a member of length L, under a point load P at mid-span. Six different possible sections are shown. The dimensions that are labeled in the six figures represent differences the typical section.	Rank these figures according to the normal stress developed due to bending at the point indicated, from highest to lowest.



QUESTION 8

Description	Instructions
The figures below show a member of length L, under a distributed load of magnitude P along its entire length. It is supported by a pin on the left, and two rollers on the right. Six different possible sections are shown. The dimensions that are labeled represent differences from section a.	Rank these figures according to their susceptibility to local buckling in the flange, from highest to lowest. It may not be possible to distinguish between all of the figures, so some figures may have the same ranking.

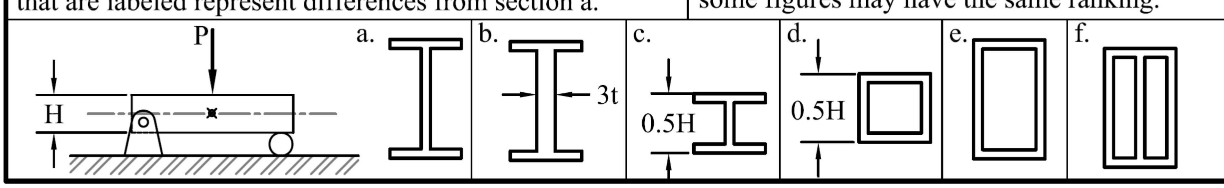


Figure 2. Figures, directions, and ranking tasks for interview questions 5 to 8.

Abbreviation	Type	Central Concept
Q1	Ranking Task	Stress
Q2	Open-ended Questions	Stress
Q3	Ranking Task	Buckling
Q4	Ranking Task	Buckling
Q5	Ranking Task	Bending
Q6	Ranking Task	Bending
Q7	Ranking Task	Bending
Q8	Ranking Task	Local Buckling in the Flange

Table 3. Summary of interview question types and concepts covered.

ranking, but did not feel that they had enough time to pursue it, they were encouraged to complete an example. They were then asked to explain or justify their approach, and, if time permitted, asked to repeat their process with a different figure. In these cases the analysis focused on their proposed procedure and example analysis. Each student responded to each question during the hour-long interviews, but not all students were equally satisfied with the completeness of their answers.

Because the interviewer had previous interactions with some students, either as a teaching assistant or as a classmate, the social effects of the interviewer may have resulted in bias. The interviewer attempted to mitigate this bias by taking a few minutes for introductions and discussion before interviews with students whom he had not met and by explicitly addressing the issue with students he had met while going over the informed consent form. The discomfort of being interviewed, video-, and audio-taped by a peer in a perceived position of power was addressed directly in each interview. The interviewer took time between most questions to check in with the participant and to attempt to encourage or relax them. Known and unknown students displayed a consistent level of moderate discomfort. Finally, because the interviewer had previous contact with two or three students in each course, the analysis between classes will remain credible and dependable.

The student interviews were audio- and video-recorded, and interview packets were collected to record student notes and sketches. After each interview, notes were taken describing the interviewer's general impression of the student's comfort in the interview, level of effort, and overall understanding of the topics covered. General notes to guide analysis were recorded periodically through the interviewing process. The course instructors were also interviewed and audio-recorded.

Each interview was transcribed from the audio-recording in the order in which it was conducted. All but two interviews were transcribed by the interviewer. Review of the transcripts with the video recordings and the students' notes was used to clarify non-specific statements (e.g., "I think this one is bigger than this one") and misstatements (e.g., a student says "c is more than e" when he or she actually means the reverse).

E. Data Analysis

The transcripts were analyzed using the constant comparative method. This method of analysis involves comparing new pieces of data with all existing data trends (Maykut and Morehouse, 1994). If the new data do not fit into existing trends, a new trend is hypothesized and all existing data are reanalyzed to look for occurrences of the new trend. In this study, the smallest unit of data is a student statement. A statement is defined as a group of words intended by the speaker to convey an idea. For example, the word "yes" would constitute a statement if the student was responding to a closed question. Because the purpose of the analysis was to describe student reasoning, the trends being developed were explanations of bending or buckling phenomena.

Coding proceeded in two phases using a qualitative analysis software program. The first phase was a mostly unstructured categorization of student statements. This categorization was unstructured in that it was not intended to achieve the particular goals of this study, but instead to identify what types of statements students made frequently.

The next phase of coding was more analytical. This phase—sometimes called "pattern coding" (Miles and Huberman, 1994)—consisted of identifying and coding patterns in student statements. The patterns had been identified during the previous phase of analysis, and this second phase verified and recorded (or discarded) those patterns. In this phase, the general notes made during the interviews were also addressed by comparison to the actual data. The second phase was specifically oriented to identifying and evaluating examples of student reasoning. For example, in the normal stress due to the bending example described (see Question 6 in Figure 2), seven codes were used to describe student reasoning. These codes are included as an example in Table 4. In Table 4, the number of quotes is included to provide an example of the number of instances used for each code, but this value should not be given too much attention. For example, if a student made a strong statement that revealed confusion about the cause of bending stress and then referred back to it throughout the rest of the interview that would probably only be coded once (or counted as one quote) as "[0.6] Causes of Bending." However, if another student frequently checked their reasoning or made strong, specific statements about what they knew and did not know about the causes of bending stress, each of those statements would be coded. The coding facilitates, but does not complete the analysis.

Judgment of which statements indicate mature understanding can appear arbitrary, but depends on the theoretical framework guiding the research. Constructivist learning theory and the interpretive perspective utilized in this research deny the positivist assertion that there is a singular reality that people can be more or less aware of. In this framework, it is misleading to categorize some beliefs as right and others as wrong. Practically, however, some beliefs about bending will obviously be more useful in analysis and reasoning. The beliefs that are most useful are those which are internally consistent, consistent with observable phenomena, and can be used in communications with others in the discipline. Because experts in structural engineering (represented in this study by engineering faculty at Washington State University) share internally and externally consistent beliefs, those beliefs are the most useful and relevant for examining student beliefs. For convenience, student beliefs are described as beneficial when they agree with the experts' and divergent when they correspond to an alternative perspective.

Code Name	Definition	Quotes	Students Quoted
[0.6] Causes of Bending	Confusion about what causes bending stress or conceptual meaning of MC over I.	11	7
[0.6] Further from Load	When students use distance from the load in their reasoning without reference to the moment diagram.	16	8
[0.6] Normal Stress	When confusion about what normal stresses are interferes with reasoning.	29	12
[0.6] Memorized Process	When students proceed through analysis using a memorized process or rely on equation without conceptual checks.	6	4
[1.6] Moment Distribution	When students use moment diagram in reasoning out of horizontal distribution of normal stresses	11	10
[1.6] Conceptual	When students use conceptual reasoning or verification in their ranking.	11	6
[1.6] Vertical Distribution	When students identify and use vertical distribution of normal stresses in a bending beam.	16	10

Table 4. Codes used in analyzing Question 6.

Similarly, the theoretical framework adopted makes it difficult to discuss degrees of conceptual understanding. The purpose of this data analysis is to describe the nature of students' deviations from an expert's understanding of bending and buckling. It is impossible to rank these deviations in terms of higher or lower conceptual understanding without assuming that some concepts are more important than others. It is significant to note that while the Piagetian description of linear cognitive development provides a framework for choosing which concepts are most important, the constructivist learning theory adopted in this study holds that different concepts will be important for different students.

Because it is easy to observe, but difficult to interpret in terms of the underlying conceptual understanding, particular attention was paid to the coding of students' use of equations. When used appropriately, equations are vital tools in expressing and applying conceptual understanding. Questions 7 and 8 of the interview packet, for example, would be very difficult to rank without the use of equations. Correctly recalling and applying an equation to a physical phenomenon is an indication of some mature conceptual understanding and would be coded as evidence of beneficial beliefs. One of the basic assumptions of research in students' conceptual understanding, however, is that proficiency with equations often masks divergent conceptual understanding (for examples see Hake, 1998; and Tsui, 2002). Therefore, recall and use of appropriate equations was not considered in itself to be evidence of beneficial beliefs about the concepts represented. Analysis of student use of equations depended largely on students' responses to questions about the terms in the equations, and whether or not their calculations "made sense" to them.

When all the transcriptions were coded in both these phases, there were approximately 90 codes and 1,400 quotations. In order to summarize and begin to analyze this data, we created a very loose point system for the understanding of each question. Each question was worth three points, and each point was assigned to a specific component concept. For example, in Question 6 the component concepts were (1) meaningful application of the relevant equation, (2) understanding the vertical distribution of normal stresses during bending, and (3) understanding the horizontal distribution of normal stresses during bending. These component concepts were not intended to capture the complete complexity of the problem, but only to represent the concepts that would be necessary for the local buckling question at the end. The points were developed in part from our own knowledge of the questions, but also came from the analysis of the expert's response to the question. Each student's responses were then scored and compared.

After a period of exploration using the loosely defined student scores, the research questions were specifically addressed. This process involved using the score data to generate a hypothesis and then using the coded transcripts to verify or disprove it. As shown in Table 4, many of the codes used are based on a subjective analysis of a particular statement. In some cases opposing codes can be found in the same interview, and the number of codes a student receives is dependent on their talkativeness as much as their level of understanding. These shortcomings are integral in the analysis. This analysis is dependent on trends and patterns, and therefore should not attach much significance to any single code or statement. The credibility in this analysis is maintained by only making statements or conclusions that can be strongly supported by the data in multiple ways. For example, a student could not be described as lacking in understanding of buckling unless they could be quoted exhibiting serious confusion in Questions 3, 4, and 8 concerning the basic concept of buckling.

V. Results and Discussion

The results will be organized according to each research question. To facilitate the discussion of student understanding of bending, Figure 3 shows the stresses and internal moment diagrams present in a simple beam in bending. The key features of this loading situation—often used to introduce bending phenomena to students—are that the internal moment in the beam increases linearly from zero

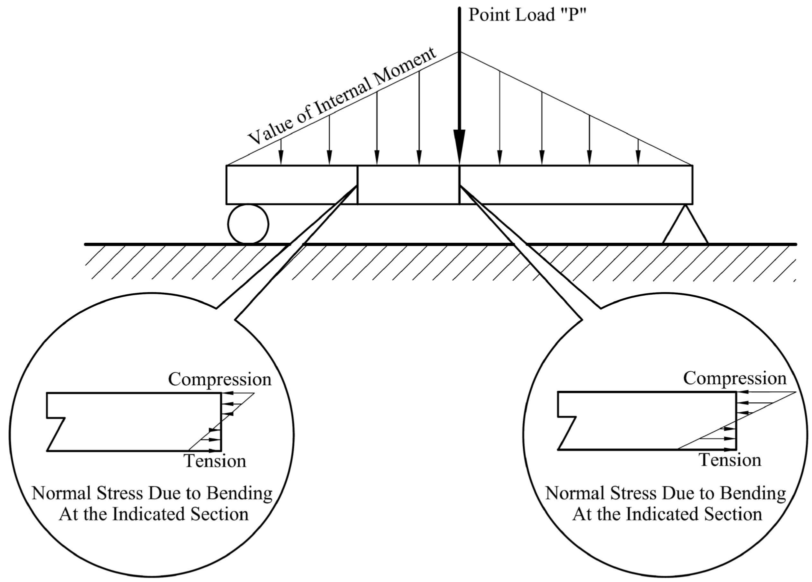


Figure 3. Distribution of stresses in a simple bending beam.

at the right and left ends to a maximum value in the center and that the normal stresses caused by that moment vary vertically through the cross-section. The vertical distribution of stresses is also linear and symmetrical about the neutral axis (in this case the neutral axis is at the geometric center of the cross-section). In bending, one side of the beam experiences compressive normal stresses and the opposite side experiences tensile stresses of an equal magnitude. Questions 5, 6, and 7 in the interviews dealt exclusively with this situation, and Questions 2, 5, and 8 included some of the same concepts. Note that all student names in this paper are pseudonyms intended to protect student confidentiality.

A. How does student conceptual understanding of bending differ between sophomores, juniors, seniors, and graduate-level students?

Students in higher-level courses were more able to solve problems, but, within our framework, did not demonstrate significantly more conceptual understanding than students in the earlier courses. Students from each course-level generally used the same analysis procedure to decide on their rankings. The most significant difference between course-levels lay in the students' relative abilities to complete the procedures they proposed. The graduate students used the same basic approach as the undergraduates, but were more often able to reason through how the equations they remembered would affect the interview questions. For example, in response to Question 3 (Figure 1), which required students to determine which properties were more important in buckling, most students (about three-quarters) made statements identifying the weak axis as contributing to buckling. More than half of the undergraduate students also based their ranking primarily on cross-sectional area, indicating that they did not understand the concept of the weak axis in the context of buckling. These students discussed area in terms of "more material," or "more resistance" to the load. Some graduate students also mentioned area, but did so firmly within the context of the buckling formula. All of the *Adv-Steel*$_5$ students who mentioned area directly did so in the context of the columns' radii of gyration: the radius of gyration is a geometrical property of a cross-section that directly affects a column's resistance to buckling and is inversely related to the area.

All but one of the *Steel*$_4$ students who identified the weak axis also used cross-sectional area in their reasoning. For example, Lena reasoned that Figure *f* (as shown in Question 3 in Figure 1) would be the most susceptible to buckling because of its length and small cross-section:

> *Lena:* Uh, it's the longest, and…has the smallest width. And, a small depth, also…well…kinda small. [Pause.] And then. [Very long pause.] Probably this one? [Referring to figure *e*, shown in Figure 1]
>
> *Interviewer:* Okay. Why's that?
>
> *Lena:* [Pause.] Uhm. [Long pause.] Actually, I'm not…it has small depth, and, you know, I think that'll make it more susceptible to buckling. Kinda doesn't have as big of a cross-section.

In general, the *Steel*$_4$ students had more difficulty reconciling their beliefs than students from other courses. For all of the ranking questions except for two, more *Steel*$_4$ students were unable to choose a ranking than students from any of the other classes. This does not mean that the *Steel*$_4$ students showed less knowledge: for example, in Question 3 a higher proportion of *Steel*$_4$ students identified the weak axis and length as the key contributors to buckling and used an appropriate buckling equation than in any of the other undergraduate classes. However, most of those students were unable to reconcile that knowledge with their intuition that cross-sectional area is important in failure. For example, Lena later said, "Uhm, these are both…this would be susceptible, I think, to buckling because of the length.… But I don't know how much, 'cause I don't know. 'Cause it, the 'W,' has been doubled. But I still think [it would be susceptible], because of the length." Hank, another *Steel*$_4$ student was also unable to reconcile his two beliefs that both length and cross-sectional area of the column mattered to buckling, saying:

Hank: Uh, because the area is the greatest? Oh, crap, nevermind. You caught me in my own logic swing. No, that wouldn't be right. Because the length gets higher, and like I just said if the length is higher, or if the length is greater, then it's more likely to buckle… [Sigh.] So you have twice the length, but twice the area. [Pause.] So there has to be something…that determines which is more important. [Laughs.]

Eventually, Hank added, "I don't think I'm gonna have any other epiphanies or deductions about it in the time allotted. But, well, let's face it, even if there was more time I probably wouldn't. [Laughs.]" Hank's difficulty is particularly enlightening because he was one of the *Steel*$_4$ students who remembered the key equations that related length and area.

The students from *Adv-Steel*$_5$ appeared more confident and methodical. They used equations more freely and engaged in self-checks more frequently than the other students, but still rarely. The undergraduates would often refer to their lack of knowledge when first presented with a question, saying "I dunno," or "These are hard," but the graduate students more often explained their hesitation in terms of communication, saying, "How could I explain this?," or asking questions about what answer was expected. For example, Rita, a graduate student, used the following reasoning to decide whether length or geometry were more important in Question 3.

Rita: Pi-squared E I over K L over R-squared. I think is the quick critical buckling stress? Uhm. And in the Euler… buckling…stress is what I think it is. Uhm. And the k-factor is, uh, an effective length factor depending on what the fixity is. They all have the same fixity, so they're all gonna have the same k-factor, so basically, uh…since…the, the mathematical explanation, I mean I know that the longer column's buckle first with the same cross-section. But as far as the mathematical explanation, L's in the denominator; the bigger L gets, the smaller the buckling stress gets, which means it'll buckle at a smaller load. So…you know, that's the…formula. The explanation for the longer, the bigger, L the easier it'll buckle.

Interviewer: Outside of the formula you know that length makes it more susceptible to buckle from life-experience, or just remembering homework that you've done, or…

Rita: It makes sense, and…you see it all the time.

It is important to note that Rita did not display any more conceptual understanding of this topic than Hank or Lena, but she was much more confident in her ability to answer the questions. Where Hank and Lena were silent or laughed when asked to describe the reasons for their beliefs, Rita displayed very high confidence in ignoring the framework of the specific question and stating, "you see it all the time."

Although the *Adv-Steel*$_5$ students were usually more able to recall and apply pertinent equations, this use of equations usually masked underlying confusion that was more obvious in other students' comments. For example, all of the graduate students recalled Euler's buckling formula for Question 3. Luke, an *Adv-Steel*$_5$ student, took ten minutes to calculate equivalent strength values for each of the figures, and was completely confident (a self-reported 10 out of 10 for confidence) that this approach gave him the correct answer. However, because he did not address the assumptions he was making by using particular equations, his rankings were confused. A revealing line of reasoning occurs when Luke is asked to explain one of his calculated values: he said that *b* (shown in Figure 1) would be "one-fourth" as strong as *e*.

Interviewer: Why do you know it's less than a fourth?

Luke: Uhm. Because it's the one-fourth. Cubed? Does that make sense? So one-fourth cubed is less than a fourth.

Interviewer: Less than a fourth.

Luke: Yeah. That's because the H is cubed [the width, labeled W in Question 2 in Figure 1, is cubed in the equation Luke has written to describe buckling], so if that, if that makes sense [checking that the interviewer follows]. So the other one, the weakest one after that was that. So it's gonna be weaker than this guy [indicating *f*]. Which… makes sense if you just think about, even without numbers 'cause it's….the only difference, well [realizing a new idea] the length is, is also there. Sooo, I guess that might make sense, but yeah, it should be less than a fourth. Would be my bet.

Like most of the sophomores, juniors, and seniors interviewed, Luke is unable to conceptually understand how the geometry of a column relates to buckling, but this lack of understanding is hidden beneath math skills and familiarity with the equations. Luke's intuition seems to contradict his calculations ("I guess that might make sense"), but is immediately overridden by his confidence in the numbers ("It should be less than a fourth"). Indeed, Luke's mental math skills and confidence were the two most remarkable aspects of his interview.

B. How is student conceptual understanding similar among these groups?

The students interviewed demonstrated consistent abilities to: recall the appropriate equation to describe the stresses under examination for Questions 1 to 6; draw the vertical distribution of normal stresses resulting from the loadings shown in Questions 5, 6, and 7, often without direct reference to the equation; and identify shear-and-moment diagrams as a useful analysis technique in response to Questions 5 and 6. All students knew that the length of a column inversely affected its resistance to buckling, and students from all levels indicated that some properties of the cross-section were also important. They often knew that fixity affects resistance to buckling. Awareness, but not understanding, of the moment of inertia was spread evenly among the courses, and an approximately equal proportion of students from all course-levels knew that flange buckling would only be an issue in the compression flange.

As implied in the previous section, the similarities among students' conceptual understanding consisted primarily of their approach to the ranking tasks and the consistently low level of understanding. Along with this computational focus, the most salient common features of student understanding were difficulty comparing properties they believe to be important, combining incomplete visualizations with incomplete computational knowledge, and difficulty relating loading to stresses.

In general, students attempted to compare interview questions to previously completed homework problems. The centrality of procedure and equations in most students' approaches was at odds with the expert's approach when interviewed. Where students used equations as the foundational truth of a concept, the expert used equations and analysis procedures as tools to support his intuitive understanding of the phenomena.

To best present the common areas of low understanding, the rest of this section will discuss student responses to the interview questions in a different order than they were presented to students. The questions about buckling (Q3 and Q4) will be discussed first, because they most clearly exemplify the common types of student difficulty. The questions concerning normal stress (Q1 and Q2) and normal stress due to bending (Q5) will be discussed next. Student responses to interview questions Q6 to Q8 will be discussed in the following section, because of their close relationship to key student beliefs.

Table 5 lists the interview questions in the order that they are discussed, as well as the underlying key component concepts they required students to apply. The concepts listed in Table 5 are not intended to be a complete listing of all the conceptual components of the questions. Table 5 lists the core concepts in each problem situation that were emphasized by this investigation during the design, implementation and analysis of the interviews.

As shown in Figure 1, Q3 asked students to compare six columns with varying cross-sections and lengths. There were, effectively, only three variables to be considered: the column length, depth, and width. Almost all students correctly identified the three variables and their effects on resistance to buckling. Interestingly, however, none of the students were able to determine the relative importance of the different variables, even when they recalled a pertinent equation. Ben, a MoM_2 student, reasoned:

> *Ben:* The change in length is the first and foremost. The longer it is, I figure, the, the easier it is to break.
>
> *Interviewer:* Okay. Would you write that? Just for [breaks off]
>
> *Ben:* [Laughs indicating he doesn't know what to write.]
>
> *Ben:* Well it, it really, it…like, if you got a thinner board and it's really long or if it's like this long [holds thumb and forefinger approximately 2 inches apart] or if it's this long, [indicates approximately 6 feet by stretching arms out] or even longer…it's gonna be easier to break than the thicker board, whether it's [longer or shorter]. So actually, I might retract my statement. Yeah. I'd say the change in the width and the depth are more important.

This statement and retraction are particularly strong evidence of conceptual difficulties (as opposed to simply gaps in knowledge or human error), because Ben used the same experiential knowledge to justify both the claim that length is more important and the claim that width is more important. This suggests that Ben is reorganizing his memories and knowledge as he talks and that he does not have the strongly interconnected knowledge that defines conceptual understanding.

Student responses to Question 4 revealed similar difficulties. As shown in Figure 1, students were asked to compare the buckling strengths of columns with different end-conditions and moduli of

Question	Central Concept	Key Component Concepts
Q3	Buckling	Necessary simplifying assumptions to apply Euler's Buckling equation, the effects and relative importance of cross-section dimensions and member length in buckling
Q4	Buckling	Necessary simplifying assumptions to apply Euler's Buckling equation, the effects and relative importance of modulus of elasticity and end condition fixity in buckling
Q1	Stress	The difference between normal and shear stress, stress distributions in a material due to point and distributed loads
Q2	Stress	How loadings create stresses, stress concentrations and distributions, definition of stress
Q5	Bending	Relationship between loading and normal stress due to bending
Q6	Bending	Relationship between location on member and normal stress due to bending
Q7	Bending	Relationship between cross-section geometry and normal stresses due to bending
Q8	Local Buckling due to Bending	Combination of all buckling and bending concepts from Q1 to Q7

Table 5. Overall and component concepts investigated in student responses to each question.

elasticity. Some students from all course-levels recalled the equation governing the phenomena, but, again, none were able to decide which characteristic was most important. Again, the way the students dealt with this difficulty suggested an underlying conceptual cause. Many students, like the $Steel_4$ student Geoff, struggled to combine their computational knowledge with a visualization of what would happen.

> *Geoff:* Um, intuitively I would think this… these fix-fix connections. But when I was going through the k thing.…I was like…I think they like the higher k. No, a small k… 'cause if you look at this [indicates a figure on sheet] it's going to come like this [indicates buckling in plane with the paper with hand] and buckle out. So your effective length is smaller. So that's going to be the best one. So c…although to 2E to 5E [indicating the different moduli of elasticity in the figures]…I'd have to figure out that difference.
>
> *Interviewer:* How might you do that?
>
> *Geoff:* Well, I don't know…So if I had this factor…this k-factor and this k-factor. I think it's like 0.5 actually. For k. Your effective length. So, that means you only need to look at half the column length. And here, you're looking at seven-tenths of it. But you have 5E, and that's only 2E…So this will be five halves greater than that one…right?
>
> *Interviewer:* You're just doing the math…and multiply…
>
> *Geoff:* Yeah, two and a half…So this one is going to be two and a half times stiffer than this one. But you have these factors… And so I would say… oh, that's not two and a half times. So I maybe I would say this one is more stiffer actually.

Although Geoff's statements about *k* (a factor used to calculate the end-conditions' effect on resistance to buckling) are in close proximity to his statements about how the column will move or react, they are not at all integrated with each other.

Determining the relative importance of these characteristics would be very difficult to do without using the buckling equation to calculate representative values. Even though Geoff was one of the students who wrote out the full buckling equation, he could not combine that knowledge with his visualizations in a useful way. Many students who expressed computational knowledge but did not use it described inconsistent or vague visualizations. For example, John recalled the buckling equation, but believed that "the rollers, whatever helps it keep from buckling, in a sense, in the x-direction, those rollers help it…yeah, would help it channel, uhm...channel the force downward?" The microscopic reactions and stresses that occur at the ends of the columns are very complex, and are most often considered negligible in coursework. However, students often tried to visualize these stresses and reactions, indicating a belief that understanding this interaction was key to determining the overall relationship between strength, end-condition, and resistance to buckling. This concern with the microscopic exceptions to the general rule will be discussed again as an important feature of student difficulties understanding bending.

Students at all levels had difficulty relating loading to stress distributions. This difficulty took several forms during the interviews. Question 1, shown earlier in Figure 1, presented the most surprising challenge considering its simplicity. In their responses to Question 1 many students were confused about how a point load and a distributed load would cause different stresses. Some students believed that distributed loads cause more stress than point loads. For example, a $Steel_4$ student reasoned "I would definitely do [meaning rank in terms of normal stress developed]…4P first. Because number one, it's 4P and it's a distributed load?… Uhm…Then I'd probably do [meaning rank in terms of normal stress developed] this one, because it's still a distributed load, even though it's 0.5P?" A different $Steel_4$ student believed the opposite, stating "I don't know how [the distributed load] compares to the single P's [referring to point loads], but…I would think it's [referring to the distributed load] still gonna be less than all of them [referring to the point loads]." Several students relied entirely on a mathematical expression of stress and were unable to use the definition in their reasoning. For example, one MoM_2 student reasoned, "Because if it's, uhm, if the area of this was, say like a tenth of a meter or something, and this is uh, the force was, like kilonewtons per meter, it would be less than the actual force."

Question 2 (Figure 1) was not a ranking task, but asked students to "describe the stresses that would develop at the points of interest in the two figures." Further questions asked students to describe how they would calculate those stresses, what caused the stresses, and "If you knew these stresses, what could you predict about the members' behavior?" Determining and calculating stresses to analyze member behavior is a central purpose of mechanics of materials. These skills should be taught in every mechanics of materials course and used frequently throughout the curriculum of other structures courses. However, 13 of the 21 students (including 2 of the 4 graduate students) did not display understanding of this concept when interviewed. For example Pete, a $Steel_4$ student, described the stresses present in Figure ii of Question 2 in the following way:

> *Pete:* Uhm. Tensile and compression.
>
> *Interviewer:* Tensile and compression?
>
> *Pete:* Yeah, and uh…well…it's causing, it's gonna cause a moment too. So that'd be a, some 'tor,' is that torsion? [Laughs.] I don't know.
>
> *Interviewer:* …yeah. What makes you, what makes you say torsion?
>
> *Pete:* Well, it uh, there's a…you got a fixed connection here. Is that? Yeah, fixed. It's uh…that force there is gonna wanna. Well, torsion's twisting so…What am…I'm trying to…
>
> *Interviewer:* In terms of stresses what would you say?
>
> *Pete:* Compression. Uhm. And shear. I don't know!

Andy, an $Adv\text{-}Steel_5$ student knew that it was common to break a force like the one shown in Figure ii of Question 2 into components, but he seemed to believe that this was based on the physical properties of stress rather than computation convenience. He reasoned,

> *Andy:* Obviously you have a cross-section [that]…at…each point will be the same. But. The force is what's gonna be

different. Uhm. Oh, shoot. So on this one you're gonna have…you're gonna have a component of the force… like over one area, so like…the part that's pulling down would act over like…an area and then…the force pulling out would act over a different area?

Andy, like most of the students interviewed, displayed a familiarity with the equation that was limited to a particular context. When he tried to justify his procedure by explaining why it was useful to divide a force into components, he experienced some confusion.

In response to Question 2 (Figure 1), approximately half the students were unable to identify all of the stresses that would develop as a result of the simple loadings shown. The confusion seemed primarily caused by uncertainty about bending. Question 5 (Figure 2) required students to compare normal stresses due to bending in identical beams under different loadings. Although most students—even those who were unable to describe the bending in Question 2—correctly stated that normal stresses in bending are due to moment, they were still unable to determine how distributed loads would affect normal stresses. Many students from all the courses condensed the distributed loads into an equivalent point load, which indicates that their understanding of how moment causes normal stresses does not include how the normal stresses are distributed through the beam. For a point load, as shown in Figure 3, the value of the internal moment varies linearly, because only the distance from the load and reactions is changing. When a distributed load is applied to a beam, the value of the internal moment changes parabolically along the beam, because both the distance and the value of the load are changing, and the internal moment at any point is equal to the distance from the load times the value of the load.

Students seemed at least superficially aware of this difficulty. Most students either drew or mentioned the vertical distribution of normal stresses in response to Question 5 even though all the points they were considering where in the same vertical location (shown as a small "X" on the beams in Figure 2). The vertical distribution did not help any students with their analysis, but it was frequently cited in responses showing difficulty in relating load to stress. For example, when asked what causes the normal stresses in Question 5, Pete, a *Steel*$_4$ student, timidly guessed "The position of the load?" This answer could be correct if it was supported with an understanding of how load position affects the bending moment and how the bending moment affects the normal stresses. Pete's supportive reasoning, however, is interestingly unrelated. He said,

Pete: Uhm, let's see, so if...it was at the center of the beam here…I would say that it would be zero. Uhm. Since it's [referring to the point of interest] closer to the top it'd be, uh, compression. Uhm. Since it's [referring to the loading] going down, and at the bottom, [there would] be uh, tensile, uhm. In the member. I mean is that, is that what you're wanting?

Pete is unable to determine what causes the normal stresses in bending, but he relates this lack of knowledge to his lack of understanding of how those stresses are distributed through the beam. Rod, a *Struct*$_3$ student, also makes a series of statements that reveal he knows what he should understand, but still cannot make sense of it. When asked, "If you just saw this set-up in a homework problem, and you hadn't read the description yet, what would you expect the problem to be about? What does that mean to you, that picture?," Rod responds first with what he knows. He says,

Rod: Uh, I would say…[Pause.] Hm. Probably they're gonna ask you to…well, okay. It's gonna bend, like this [indicating sagging down under the load]? Obviously, and then, uhm, so then the top part will be in compression. So, this part is…, like halfway in the top part, so. I mean, this little member is gonna be in compression, but, it's also gonna be in compression this way because the force is directly above it?

At this point, even though the interviewer says "Okay," Rod realizes he has not answered the question and says "So, I don't know, they're probably asking you to find [pause] like what the… I don't know, I guess what the stress is, on that one…member, in both directions or something? Yeah, sorry, I don't know." Again, Rod demonstrates a firm grasp of some concepts (the vertical distribution of normal stresses, in this case) and an inability to apply them in this context.

C. Which underlying beliefs might account for the similarities in conceptual understanding?

It appears that students had trouble relating loading to stress because of how they visualized point loads affecting the members. Many students, and all of the students who had consistent difficulty relating loading to stress, used reasoning that assumed stress was largest closest to the load. This belief can be considered a misconception because it interferes with a correct understanding of many topics and because it persists even when students possess directly contradictory knowledge (Chi and Roscoe, 2002). Its persistence may result from its proximity to a beneficial understanding. Localized stresses do behave in this way, radiating out from the point of loading. This phenomena, however, occurs at a much smaller scale than the stresses the students were asked about, and localized stresses require a separate analysis with different goals than the general descriptions of beam behavior requested in these interviews.

Rod's prediction of what types of questions would typically be asked about the situation presented in Question 5 (see Figure 2) is an excellent example of this. In the same statement Rod demonstrates that he is aware of the vertical distribution of stresses in a beam (he says, "the top part will be in compression") and that he believes the parts of the beam underneath the load will experience stress in the direction of the load ("it's also gonna be in compression this way because the force is directly above it").

This misconception is most apparent in student responses to Questions 6, 7, and 8. In response to Question 6 (shown in Figure 2), approximately half of the students interviewed (11 of 21) reasoned like Andy, an *Adv-Steel*$_5$ student who said, "Since that's [referring to the point of interest] farther away [from the load], there's actually gonna be less stresses, 'cause you know, as you get farther away from the load, the stress would be less. So I'm gonna say that most stresses would occur closer to P." Even though Andy's analysis of the previous question disproved this statement at several points, he remained confident that it was generally true, saying "It's just like, it gets taught in every class, and it, I mean you...don't even have to apply it. It just makes more sense."

Andy and most other students were able to correctly identify moment as the cause of normal stresses in bending and to apply this concept to Question 5, at least partially. When asked in Question 6 to compare different points on a similarly loaded bending beam, however, students' reasoning was impaired by the misconception that stress is at its maximum under a point load.

In response to Questions 7 and 8 (shown in Figure 2), this misconception led many students to ignore their previous statements about bending and instead focus on the idea of the web supporting the vertical bending load. For example, Brian, a $Struct_3$ student, compared two figures by stating, "These two [indicating *e* and *f* in Question 8] are quite similar except this one's got another part, so that extra part can hold more force, can just help distribute the force more." Brian was one of the many students to accurately draw the vertical distribution of normal stresses in response to Question 5. The knowledge that he displayed when trying to rank the figures in Question 4 contradicts the belief that the web "supports" the bending load, but Brian's belief persists due to his misconception of stress flow. Barb, a $Steel_4$ student, stated, "These are gonna buckle first, but then this [referring to the load] is gonna be transmitted through this web? Which could make that one…less susceptible to buckle. So, I'll say that. Because there's gonna be more transmitted, like, through the thicker web."

When asked to rank the normal stress developed in different cross-sections in Question 7 (see Figure 2), many students displayed a similar belief that stress is less further from a load. Lena was very reluctant to speak about this question. When asked why Figure *e* is more susceptible to bending than Figure *f*, she said "Mm-hm. Uhm. [Long pause.] It's not supported…[Interviewer says 'Okay.']…in the middle." Similarly Heidi, a MoM_2 student was asked, "What do you think is important about the section?," and responded "Uhm. Well I think that maybe, this one probably has the least [referring to stress], because it seems to be, more supported." Using the idea of a "supportive" cross-section is indicative of this misconception, because (1) it is divergent because experts use a section's moment of inertia about the neutral axis to determine the normal stress developed from bending; (2) it is indicative of a deep misunderstanding of the concepts of bending and moment because the magnitudes of both vary horizontally; and (3) it coexists and interferes with correct beliefs. In their responses to Question 5, Heidi and Lena displayed that they knew that moment would be used to calculate normal stresses (see Figure 2), but were unable to reconcile this fact with their belief that the stresses flowed out from the load.

C. Discussion of Counter-Explanations

The following issues will be addressed in this sub-section: (1) the possible disconnect between content emphasized in class and content evaluated in this study; (2) the possibility of misrepresenting the student population due to a small sample size; (3) the possibility that students' discomfort during the interviews interfered with the expression of their true level of understanding; and 4) the possible misrepresentation of student understanding caused by difficulties interpreting the figures used in the ranking tasks.

The structural steel design courses at WSU now emphasize the concept of "capacity" instead of stress. This shift is part of a larger change in structural engineering practice to a new design paradigm: Load and Resistance Factor Design (LRFD). In the older Allowable Stress Design (ASD) method, design calculations were based on the magnitude of stress a member could withstand. This is a material-centered perspective, but most structural engineering problems are more concerned with loads, e.g., what combination of wind and snow loads should a roof system be able to safely support. When analyzing bending, the shear forces and moments are calculated and then compared to standardized, factored shear and moment capacities. LRFD analysis determines the loads a member can withstand, and ASD analysis determines the stresses a material can withstand. For example, an engineer using ASD would have to calculate how the loads cause stress in a particular steel beam to make sure it doesn't exceed the maximum allowable stress for steel. An engineer using LRFD only needs to make sure the loads in his design do not exceed the loads allowed for steel beams of that size and shape.

This means that students do not gain sustained experience with the concept of stress after MoM_2. It is arguable then that seniors and graduate-students' understandings of stress should not differ considerably from those of sophomores', and could even be less due to the increased time span since having learned the material. While not weakening the conclusions stated in this study, this fact would decrease their significance.

However, it is debatable that capacity and stress are truly distinct concepts. Because stress causes failure and capacity is a concept that is dependent on the concept of failure, stress is an integral part of the concept of capacity. The relationship between concepts is one of the main features of constructivist learning (Bruner, 1960) and the definition of conceptual understanding adopted by this study. We would argue that conceptual understanding of capacity should include the concept of stress.

It is possible that the results reported above do not reveal much about the engineering student population because they are based on data from too small a sample to be representative. This particular concern is addressed above in the Sample Selection sub-section of the Methods. It is worth noting again, however, that the significance of the results does not depend on the students being representative. These students were, in fact, chosen because they would be expected to perform better than the average student. It is a significant finding in itself that five academically successful senior civil engineering students emphasizing structures have difficulty with the concept of stress.

The most potentially damaging counter-explanations are that the interviews did not accurately reveal the students' understanding—either because of the unfamiliarity of the situation and their resulting discomfort, or confusion resulting from the way the problems were presented. The first is a definite concern when conducting any interviews and was addressed in this study by encouraging an atmosphere of curiosity and sharing during the interviews. Each participant expressed some discomfort in describing their reasoning at first, but quickly became more talkative as they were encouraged. For example, Heidi was so concerned with saying something wrong that at first she refused to talk even about the concepts she understood well. She was told repeatedly, "anything you say is helpful," and was asked to explain things in a way that someone who had not taken the course would understand. By encouraging her to assume an explanatory role and by being explicit about the non-judgmental purpose of the interviews, the interviewer eventually helped Heidi become comfortable enough to share a response she described as a "total guess."

One of the primary goals of making the students comfortable was to encourage them to ask questions. Only two of 21 students interviewed did not ask any clarification questions, and of those two one displayed highly beneficial beliefs relative to his class and the other displayed more divergent beliefs than his classmates. Clarification questions were most often specific, for example, "so all the points are different?" or "is this directly on the centerline?" Additionally, because student comfort level and motivation to ask questions was unknown, the interviewer verbally explained each new figure and asked if the figures were clear. In no case did a student say the figures were unclear, or appear to be confused about the problem set-up at the end of formulating their ranking. Even in the case of MoM_2 students interpreting the local buckling figures, students were able to refer to specifics of the problem situation in their reasoning.

VI. Conclusion

The results of this study indicate that student misconceptions of normal stress in bending are not significantly different among students at different points in their engineering academic career, even while students' computational skills and familiarity with the topic increase. It appears that these misconceptions may interfere with reasoning—or at least confidence—in the senior year design course.

The students interviewed, with very few exceptions, seemed to use the same approach to problem-solving. At the beginning of the interview each student was told that the purpose of the research was to study how students understand mechanics of materials conceptually. However, each student seemed to approach the problem as if problem-solving were a simple if-then logical statement: "if it is a problem of type A, then we use equation B." Most of the students interviewed were confident in their classifications of the types of problems, but ability to link those categories to equations seemed to correlate to academic year. The uniformity of approach in this academically successful sample suggests that this approach may be linked with academic success.

These inferences obviously require more direct research to be supported, but they may suggest an underlying cause of the persistence of low conceptual understanding among STEM students. Whether students who prefer the problem-categorization approach are naturally more successful or whether success relates to how well students learn that approach does not matter as much as how an academic program encourages it. It is a highly methodical approach that requires students to develop skills and knowledge, but this learning appears unrelated to the development of conceptual understanding, and may not match the work they will be asked to do as professional engineers.

Students' difficulty with the concept of stress, and in particular their tendency to assume it decreases further away from the load, may match trends other researchers have identified in thermodynamics, physics, and electrical engineering (Chi, 2005; Reiner et al., 2000; Streveler et al., 2006). Stress is similar to force, voltage, diffusion, and heat because they all cause robust misconceptions. Chi (2005) theorizes that this is because these concepts are a new type of category for students—which she calls an "emergent process"—and developing conceptual understanding of these concepts requires not just new knowledge, but new ontological skills (Slotta and Chi, 2006). It is interesting to note that these misconceptions may actually facilitate early learning about the phenomena: imagining stress flowing away from point loads is an important step in understanding the internal effects of forces on objects.

The conceptual discomfort displayed by the students in the $Steel_4$ course suggests a number of interesting possibilities. Although it seems counter-intuitive that students would be more confused after more coursework on a concept, it could be predicted from theory. The process of addressing misconceptions is called conceptual change and requires students to reevaluate many of their beliefs about the subject, which often results in a seeming decrease in confidence or knowledge about the topic as students question the foundational truths on which they had previously based their knowledge (Chi and Roscoe, 2002; Mayer, 2002; Limón and Mason, 2002). It stands to reason that students would become more aware of inconsistencies in their mental model of phenomena when they are attempting to apply their knowledge to the new context of design. If future research observes the phenomena of design-course-inspired conceptual change, the next step will be to identify specific aspects of these design courses that cause conceptual change. Of particular interest would be how changes in students' attitudes toward engineering and the engineering discipline relate to conceptual change. Similarly, it would be of interest to further investigate the increased confidence displayed by graduate students in this study, in particular to determine if students who choose to enter graduate school are generally more confident, or if there is an aspect of graduate study that increases student confidence in their content knowledge (but not their conceptual understanding).

Further research will need to be performed to confirm the generalizability of the characterization of student understanding made in this study. Specifically, future research could focus on the following questions: do students who are academically less successful possess different misconceptions than academically successful students? Do similar patterns in student conceptual understanding exist in concepts that are categorized as "easy" by professors? Would students exhibit richer conceptual understanding if interviews were phrased in terms more similar to the day-to-day content of their current classes, i.e., in terms of capacity instead of stress? Do students at similar universities exhibit similar conceptual understandings, and what characteristics of a university affect student conceptual understanding of these topics?

Future research may also investigate the importance of students' reliance on the concept of area to describe buckling. This study suggested that this belief interferes with a correct understanding of buckling, but it did not fully describe students' understandings of buckling. Similarly, future research may examine students' difficulty comparing properties they know to be important. The commonality of this difficulty across different levels of computational ability and conceptual understanding suggests that there may be something inherent in this level of abstraction that interferes with student learning. For instance, students may not believe that the relationships between concepts are important.

In the context of engineering education research it is not surprising that academically successful students do not possess robust conceptual understanding of fundamental concepts in their field. This finding is not an indictment of those students, their instructors, or the collegiate education system; the purpose is not to reveal someone's failure, but to describe a problem facing stakeholders in engineering education. The primary purpose of investigating and describing students' misconceptions in mechanics of materials is to serve as a basis for future research to address those misconceptions.

Because addressing students' low conceptual understanding requires systemic changes, people at all levels of engineering education must first be convinced that it is a problem. Further work with the specific student difficulties identified in this study could include the development of a survey to assess student conceptual understanding of normal stresses due to bending. A broadly implemented survey would produce quantitative, easily interpreted data that could be efficiently shared with many educators and utilized to initiate change in engineering education.

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