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Situated cognition theory emphasizes the role that social and material contexts have on learning and knowledge application. Several studies of engineering workplace environments have noted differences between the social and material contexts of the workplace and those of undergraduate engineering education. No existing research has studied the social and material contexts of both workplace and academic environments, specifically focusing on how these contexts influence conceptual representations within a single engineering discipline. Conceptual representations are the social and material contexts that mediate how concepts are represented, such as language, text, symbols, diagrams, equations, and other tools. Differences in the social and material contexts mediating conceptual representations across workplace and academic environments may be partially responsible for the engineering education-practice gap and is an underexplored topic. The purpose of this research is to explore a structural engineering workplace environment and undergraduate structural engineering courses to document conceptual representations and the social and material contexts that mediate them within both these workplace and academic environments. Ethnographic methods were used to access and explore these environments in-depth through participating in and observation of their respective social and material contexts. Findings from this exploration noted that

conceptual representations in the academic environments exhibited a lesser degree of tangibility to real-world conditions, project/stakeholder constraints, and engineering tools than conceptual representations in the workplace. Furthermore, engineering tools such as codes and standards were applied in more evaluative ways in the workplace environment compared to more prescriptive applications of these tools in the academic environments. Lastly, engineering heuristics in the workplace environments were more likely to be practice-based than the heuristics used in the academic environment, which were more profession-based. These findings offer unique frameworks for characterizing conceptual representations such as: degrees of tangibility, prescriptive versus evaluative code use, and practice-based versus profession-based heuristics, which may be applicable for describing the sociomaterial nature of conceptual representations across other engineering workplace and academic environments.

Conceptual Representations within the Social and Material Contexts of an Engineering Workplace and Academic Environments

by
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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Matthew S. Barner, Author

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CONTRIBUTION OF AUTHORS

Dr. Shane Brown assisted with the design of this research, interpretation of the data and editing of all manuscripts presented herein. Dr. Floraliza Bornasal assisted with data collection, interpretation of data, and the writing and editing of Chapter 2. Allyson Barlow assisted with editing Chapter 3. David Linton assisted with the writing and editing of Chapters 2 and 4. Sean Gestson assisted with the writing and editing of Chapters 4 and 5.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

DEDICATION

This dissertation is dedicated to my mother. You have always been my biggest supporter in all my pursuits. I can still remember you teaching me how to use Microsoft Word when I was in third grade and wanted to write my own stories. I would not be the writer I am today without your endless love and support and the countless hours we spent reading together when I was a child.

Chapter 1 – Introduction

1.1 Overview

The intent of this research is to explore how structural engineering concepts are represented in engineering practice and education. This dissertation presents a series of manuscripts examining how structural engineering concepts are represented within the social and material contexts that are commonplace in the engineering design activities of a professional practice setting and common undergraduate structural engineering courses. The work presented in this dissertation provides insight into how practicing engineers represent concepts within the social and materials contexts of their engineering design activities, and compared this with how similar concepts are represented in undergraduate engineering courses.

This first chapter introduces the existing research on the role of concepts and their representations in learning, and subsequently in engineering education and practice. The first chapter also summarizes the organization of the dissertation presented herein by providing a description of the research, research settings, overview of the research questions, and methodology for answering these questions. Each of the next four chapters are manuscripts that have been submitted to peer-reviewed publications. The first manuscript has been submitted to the *Journal of Engineering Education* and the next two manuscripts have been submitted to the *Journal of Professional Issues in Engineering Education and Practice*. The fourth and final manuscript was accepted in the refereed conference proceedings of the American Society of Engineering Education’s (ASEE) Annual Conference and Exposition. The common theme across all four manuscripts is representation of concepts in professional practice and academic environments. The final chapter discusses implications of the research findings for engineering education and future research examining the role of concepts in engineering education and practice moving forward.

1.2 Concepts, Conceptual Knowledge, and Conceptual Representations

Concepts are often spoken of in nebulous ways in that most have a sense for what they are, but what constitutes a concept and what does not is more ambiguous. Generally speaking concepts have been defined based on their function within cognition, which is to organize, categorize, and distinguish the parts that make up the whole of a knowledge domain (Rittle-Johnson, 2006). Concepts then, as parts of a knowledge domain, have been described as “units,” “chunks,” or “bits” of knowledge. (Perkins, 2006; Rittle-Johnson, 2006; Streveler, Litzinger, Miller, & Streif, 2008). For example, the knowledge domain of structural theory is often trisected and organized around three units (i.e., concepts): 1) equilibrium, 2) compatibility, and 3) constitutive relationships. These three concepts serve as overarching umbrellas to more specific concepts that envelope even more nuanced concepts creating a hierarchical structure governing the interrelationships amongst concepts. Conceptual knowledge then is our understanding of and ability to navigate and leverage this hierarchy (McCracken & Newstetter, 2001; Rittle-Johnson, 2006).

We represent concepts and by extension our conceptual knowledge through various means including language, symbols, and tools. Therefore the language, symbols, and tools are the conceptual representations we use when learning and applying concepts which shapes our conceptual knowledge (i.e., our mental schemata of the concept hierarchy). For example, Litzinger, Lattuca, Hadgraft, and Newstetter (2011) noted that experts—individuals we would regard with exceptional conceptual knowledge—can categorize and organize their knowledge around “big ideas” or concepts. This is perhaps why our mentors always emphasize focusing on the “big picture” wherein the big picture is an aggregate concept that simplifies the relationship amongst more granular concepts. Therefore, conceptual representations are our way of communicating and formulating our conceptual knowledge to ourselves and others with language, symbols, and tools. “Representations are as representations do” according to Dourish (2001).

1.3 Situated Cognition, Sociomaterial Contexts, and the Engineering Education-Practice Gap

Situated cognition is a learning theory that proposes knowledge as being inextricably linked to the social and material (sociomaterial) contexts of activities wherein said knowledge is first learned and subsequently applied (Greeno, Collins, & Resnick, 1996; Johri & Olds, 2011; Newstetter & Svinicki; 2014). One implication of this theory is that transfer of knowledge across settings may be limited when the sociomaterial contexts of these settings are misaligned (Bransford, Brown, & Cocking, 2000; Carraher & Schliemann, 2002; Lave & Wenger, 1991). Sociomaterial contexts are the people/organizations (social) *and* tools/objects (material) relevant to a setting where knowledge is being formed and/or applied (Greeno et al., 1996; Johri & Olds, 2011; Lemke, 1997). It should be noted that while social contexts may exist in isolation from material ones; material contexts are inseparable from social ones, even when only a single individual is engaged with a material. This is because when we use tools there are the social contexts of how the tool came into being and since been subsequently applied (e.g., when we use a software program, that program was designed by people with a specific intent and we were also trained by people on how to use it). Materials may exist in isolation from social contexts, but once we engage with materials they become inseparable from their innate social heritage (Lemke, 1997); hence, the portmanteau *sociomaterial*.

Situated cognition researchers have demonstrated the role sociomaterial contexts play in cognition. For instance, Carraher and Schliemann (2002) observed that carpenters, farmers, and street vendors demonstrate mastery of geometry, probability, and/or arithmetic within the sociomaterial contexts of their profession (e.g., the street vendor performs arithmetic when negotiating and selling (social) their wares (material)). However, when these same carpenters, farmers, and street venders were presented with similar math problems in the sociomaterial contexts of a school-like setting (e.g., textbook-like math problems with abstract quantities), they found these representations confusing and were unable to demonstrate their mastery of the same mathematical principles (Carraher & Schliemann, 2002).

Similarly, within engineering education research, civil engineering students have generally performed better than practicing civil engineers when answering statics concept inventory questions (i.e., well-structured, textbook-like problems that isolate single concepts to assess conceptual knowledge) (Ha, Brown, & Pitterson, 2017). This does not necessarily mean that students have better conceptual understanding of statics than practicing engineers. Rather, practicing engineers more likely engage with concepts in the sociomaterial contexts of design and are no longer presently embedded in the school-like sociomaterial contexts indicative of the concept inventory questions that students are more familiar with (Brown, Lutz, Perova-Mello, & Ha, 2019). More simply put, "design expertise is a matter of context" (Bucciarelli, 1988, p. 168).

As previously mentioned, conceptual representations are the language, symbols, and tools used to represent concepts. Language, symbols, and tools are sociomaterial contexts and therefore conceptual representations are mediated through these sociomaterial contexts. Thus, when the sociomaterial contexts of two settings are misaligned, representing conceptual knowledge across these settings may be hindered (Litzinger et al., 2011). Engineering education research has noted significant differences in the sociomaterial contexts of the engineering workplace compared to academic settings, such as textbook-based learning with simplified problems compared to complicated problems that require navigating multiple resources, be they people and/or tools (Johri, 2011; Jonassen, Strobel, & Lee, 2006; McCracken & Newstetter, 2001; Stevens, Johri, O'Connor, 2014; Trevelyan, 2010). These differences in context have been identified as broadly contributing to an education-practice gap in engineering, but little to no research has looked at the influence these contexts have on conceptual representations for a specific engineering discipline in both workplace and academic environments.

1.4 Gaps in Existing Research

The work presented in this dissertation addresses multiple gaps in previous engineering education research. First, this study examines *both* engineering practice *and* engineering education through in-situ participation in and observation of both places. Very limited research has examined either setting in situ, let alone via participation and observation. The author believes this research is the first to examine both settings within a single study wherein the researcher not only observes, but also participates in both environments. Second, this study focuses on the specific discipline of structural engineering. Previous research of the engineering workplace or academic environments have primarily focused on engineering more broadly with very few studies that explore the nuance of a specific discipline. Finally, this research explores the relationship between sociomaterial contexts and concepts from a situated cognition perspective. Previous examinations of engineering workplace or academic environments have rarely focused on concepts in these settings, especially from an explicit situative framework that emphasizes the role sociomaterial contexts have on conceptual representations.

1.5 Purpose and Methods

Thus, the purpose of the research presented herein was to explore the sociomaterial contexts of a structural engineering workplace and undergraduate structural engineering courses to gain a deeper understanding of how these contexts influence conceptual representations. While the sociomaterial contexts will differ across other workplace environments and courses, there may be common ways of representing structural engineering concepts across settings that we cannot know for certain until we investigate concepts in more specific settings. The research methodology chosen for this purpose was ethnographic methods. Ethnography is a methodology used to study a group of people and their culture by immersing the researcher(s) within said culture for an extended period of time (Case & Light, 2011; Emerson, Fritz, & Shaw, 2011; Johri, 2014). Therefore, to gain access to and explore the sociomaterial contexts of the workplace and classroom, the author worked as a part-time intern at a medium-sized structural engineering firm and enrolled as a student in four undergraduate structural engineering courses. In both these settings, the author participated in and observed the engineering activities that engineers, instructors, and students engaged in. The discipline of structural engineering was chosen because the author's primary educational focus has been in this discipline, allowing him to more immediately participate in both settings. The author collected field notes, documented artifacts (i.e., tools), and interviewed participants in each setting, using data collected from all three of these sources to provide rich descriptions of the sociomaterial contexts wherein conceptual representations were embedded (Emerson et al., 2011; Johri, 2014, Walther, Sochacka, & Kellam, 2013). The four manuscripts presented in the body of this dissertation represent four distinct foci for the exploration of these settings.

1.5 Overview of Body Chapters and Research Questions

The second chapter of this dissertation is a journal paper submitted to the *Journal of Engineering Education*. This journal is the premier journal in engineering education and the writing of this chapter required the most effort in preparing a manuscript suitable for publication in this journal. The paper has the broadest focus of all the chapters and sought to answer the following research question:

> How are structural engineering concepts that are prevalent in both the workplace and academic environments represented within the sociomaterial contexts of these environments, and how tangible are they?

The *Journal of Engineering Education* has a broad STEM education audience and therefore this paper provides greater explanation of the technical jargon associated with structural engineering than the papers presented in chapters three and four.

Chapters three and four have more concentrated foci based on documentation of two specific types of conceptual representations present across both settings: codes and heuristics. The third chapter is a journal paper submitted to the *Journal of Professional Issues in Engineering Education and Practice* and focuses on the use of codes in both settings to answer the following research question:

> How are structural engineering concepts represented through the sociomaterial contexts of code applications in academic and workplace environments?

The fourth chapter is a journal paper also being submitted to the *Journal of Professional Issues in Engineering Education and Practice* and focused on the use of heuristics in both settings to answer the following research question:

> How are heuristics represented within the social and material contexts of a structural engineering workplace and undergraduate structural engineering courses?

The *Journal of Professional Issues in Engineering Education and Practice* is published by the American Society of Civil Engineers (ASCE) and has an audience primarily made up of civil engineers in industry and academia. Therefore, the papers presented in chapters three and four unpack less of the structural engineering technical jargon than the paper presented in chapter two.

The fifth chapter is a conference paper that was accepted in the refereed conference proceedings of ASEE's Annual Conference and Exposition and was presented at this conference. This paper was written shortly after exiting the workplace environment and early into the stages of data collection in the academic environments and therefore reads as a work-in-progress. The paper does not have an explicit research question and functioned more as a primer for the papers presented in Chapters 2-4. This paper won the 2019 Best Paper Award amongst over 130 papers submitted to the Educational Research and Methods Division of ASEE.

Combined, these four manuscripts make up the body of this dissertation. While all four of these manuscripts function as their own independent papers, they each provided the opportunity to interpret and present the data collected in both environments from unique perspectives. Chapter 6 then concludes this dissertation by explicitly connecting what the findings from these four manuscripts mean as a whole and the implications they have for engineering education and future research.

Chapter 2 – Tangibility of Conceptual Representations in Engineering Courses and the Workplace

2.1 Abstract

Concepts are generally defined as organizers of fundamental principles within specific disciplinary knowledge domains. Situated cognition theory suggests that how we represent concepts and—by extension our conceptual knowledge—are products of the environment wherein we learn and apply concepts. The purpose of this study was to explore a workplace and academic environment to gain an understanding of the tangibility of social and material representations of engineering concepts. The author conducted ethnographic fieldwork at a private engineering firm and in undergraduate engineering courses. Data sources from this fieldwork included the ethnographer's participant-observation field notes, formal and informal interviews, and artifact documentation. Findings from this study demonstrated how conceptual representations are more or less tangible to real-world social and material contexts. Conceptual representations documented in the workplace were found to be tangible to 1) real-world conditions, 2) project/stakeholder constraints, and 3) engineering tools. Conversely, conceptual representations documented in the courses studied exhibited various degrees of tangibility to none, some, or all of these three traits. These findings suggest that the ways in which students are exposed to concepts may not always align with the representations of concepts in the workplace. Specific suggestions for making conceptual representations more tangible to workplace environments are provided based on findings from in the workplace, previous engineering education literature, and best practices observed in the courses studied.

2.2 Introduction

"Too often in engineering classrooms, the instructional activities required of the students are not aligned with the kind of knowledge those activities are intended to foster" (Newstetter & Svinicki, 2014, p. 43). Reinforcing this claim are studies of engineering workplaces noting misalignment between various aspects of engineering education and engineering practice (Johri & Olds, 2011; Jonassen et al., 2006; Trevelyan, 2007, 2010). Workplace studies often attribute the education-practice gap to broad, transferable claims such as how practice requires socially distributed knowledge to solve complex problems, while engineering education trains students to solve textbook-like problems with knowledge that is primarily distributed through textbooks and lectures (Bucciarelli, 1988; Jonassen et al., 2006; Trevelyan, 2010). While these studies have greatly contributed to our broader understanding of the education-practice gap, they provide little to no exploration of the nuances of this gap due to the unique contexts and activities characteristic of different disciplines, courses, and workplace environments.

Situated cognition theory offers a framework that accounts for these unique contexts and activities. Situated cognition theory posits knowledge as being distributed amongst an environment, rather than solely within the minds of individual learners (Greeno et al., 1996; Newstetter & Svinicki, 2014). Here, and throughout the rest of this paper, we operationalize environment to encompass the social and material (sociomaterial) contexts embedded within the activities characteristic of a particular setting. Sociomaterial contexts refer to the people and tools utilized during engineering activities common to engineering courses and workplace settings. It should be noted that the social dimension of sociomaterial contexts is not limited to direct social interaction between two or more people. For example, an individual using an engineering tool has a social context because there is a social interpretation by an agency or profession on how to use said tool. Thus, the combination of social and material contexts into sociomaterial contexts is meant to reflect how the use of materials always has a social context.

Studies of the engineering workplace suggest that engineering concepts are represented through these contexts and that these contexts differ considerably across academic and workplace environments (Johri & Olds, 2011; Jonassen et al., 2006; Newstetter & Svinicki, 2014; Trevelyan, 2010), thus limiting the tangibility of how concepts are represented in academic environments to workplace environments. For example, McCracken and Newstetter (2001) observed that engineering textbooks often provide “diagrammatic representations, assumptions and simplifying details, and possibly queues or hints for solution[s]” (p. 14) that limit opportunities for students to generate their own tangible conceptual representations. By *conceptual representations (CRs)*, we are referring to the ways in which structural engineering concepts are mediated through specific sociomaterial contexts and activities in engineering courses and workplace environments. By *tangibility*, we mean the extent to which CRs are connected to the sociomaterial contexts of real-world conditions, project/stakeholder constraints, and engineering tools.

To capture a more descriptive and nuanced understanding of how engineering concepts are represented within the environment of engineering practice, and how this may differ from engineering courses, additional research needs to be conducted within *both* workplace and academic environments on a disciplinary level. Therefore, we propose an exploratory study of the structural engineering workplace and undergraduate structural engineering courses to answer the following research question:

> How are structural engineering concepts that are prevalent in both the workplace and academic environments represented within the sociomaterial contexts of these environments, and how tangible are they?

To gain access to these environments, we conducted an ethnographic study of four common undergraduate structural engineering courses and an architecture and engineering (A&E) firm specializing in commercial, industrial, and public building design.

2.3 Literature Review

2.3.1 Education-Practice Gap

Many studies of the engineering workplace have claimed that engineering practice is fundamentally different than undergraduate engineering education (Brunhaver, Korte, Barley, & Sheppard, 2017; Sheppard, Colby, Macatangay, & Sullivan, 2007; Trevelyan 2010). This has led to concerns in engineering education and industry that undergraduate engineering programs are inadequately preparing engineering students for professional work (Brunhaver et al., 2017; Johri & Olds, 2011; Jonassen et al., 2006; Litzinger et al., 2011). This education-practice gap has been broadly attributed to the misalignment between an undergraduate engineering education that focuses on applying rigid, fundamental conceptual knowledge to well-structured problems, and engineering practice wherein conceptual knowledge is more nuanced, fluid, and distributed amongst sociomaterial resources in order to solve complex and ill-structured problems (Bucciarelli, 1988; Johri, 2011; Jonassen et al., 2006; Litzinger et al., 2011; McCracken & Newstetter, 2001; Streveler et al., 2008; Trevelyan, 2007, 2010). Differences in how students and practicing engineers engage with concepts influences the formation of their conceptual knowledge, which highlights an important yet limitedly explored area on the gap between education and practice (Davis, Brown, Dixon, Borden, & Montfort, 2012; Bornasal, Brown, Perova-Mello, & Beddoes 2018).

2.3.2 Conceptual Knowledge, Situated Cognition, and Conceptual Representations

Conceptual knowledge, as defined by Rittle-Johnson (2006), is the "understanding of principles governing a domain and the interrelations between units of knowledge in a domain" (p. 2). Within this definition, a "unit of knowledge" is a specific concept, such as force or mass, and an example of an interrelation between these example units of knowledge is Newton's laws (Perkins, 2006; Streveler et al., 2008). Interrelationships between concepts are common in nearly all engineering disciplines, but each discipline has unique and nuanced associations that distinguish their respective knowledge domains from one another. For example, the structural engineer applies Euler's method to concepts of structural stability, whereas an aerospace engineer applies Euler's method to concepts of orbital dynamics. Both are utilizing the same mathematical relationship—that they likely were first exposed to in their undergraduate calculus sequence—but in different ways that are characteristic to their respective disciplines.

Relationships that *represent* concepts can be far more than just laws and equations. Concepts and their interrelationships can be represented within artifacts such as text, diagrams, symbols, etc. (Lemke, 1997; McCracken & Newstetter, 2001), and these representations manifest from the sociomaterial contexts of engineering activities in the workplace and engineering courses (Johri, Olds, & O'Connor, 2014). Therefore, these contexts and activities not only mediate, but shape our conceptual knowledge, which is the general idea behind situated cognition (Johri et al., 2014; Lemke, 1998). Through this lens, how we represent concepts—and by extension our conceptual knowledge—is a product of the environments wherein we first learn and continue to apply said knowledge.

The situated cognition perspective on learning has been demonstrated in a variety of engineering workplace studies (Anderson, Courter, McGlamery, Nathans-Kelly, & Nicometo, 2010; Trevelyan, 2010). Trevelyan (2010) concluded that practicing engineers rarely design and/or perform technical problem-solving on their own; in cases where engineers completed independent problem solving, he or she would still have to engage with others to communicate their technical work while utilizing drawings, specifications, and other deliverable representations. Anderson et al. (2010) performed a cross case analysis of six engineering firms and found that most of the engineers in their study viewed engineering work and their engineering identity as collaborative problem solving. Furthermore, other studies have noted that engineering problem solving in the workplace consists of complex and ill-structured design problems, which is juxtaposed with simpler, well-structured problems common in undergraduate engineering education (Jonassen et al., 2006; Dunkle, Schraw, Bendixen, 1995). These studies have contributed to the general notion that undergraduate engineering programs are not adequately training engineering students for the types of problems in engineering practice and the social collaboration required to solve them (Jonassen et al., 2006; Dunkle et al., 1995; Clancey, 2006; Salzman & Lynn, 2010). Studies like these strengthen the argument for utilizing the lens of situated cognition to analyze CRs in engineering because situated cognition is a framework for understanding the significance of sociomaterial contexts on our learning and application of knowledge (Johri et al., 2014).

Johri and Olds (2011) conceptualize learning as a sociomaterial process, wherein materiality extends beyond just tools and objects, but to representations also. These representations are artifacts that portray a certain meaning to a group of people within a particular context (Lemke, 1997). For example, a stress-strain curve is a representation that conveys meaning to structural engineers about concepts such as stress, strain, plasticity, and/or other material science concepts for an engineering material, and the application of this representation can yield a variety of different looking curves depending on the purpose of the representation within a given context. Therefore, a stress-strain curve is an artifact (i.e., material context) used to represent (i.e., portray meaning of) material science concepts within the social contexts of the engineering activity. Thus, CRs are inextricably linked to both social *and* material contexts. Several studies have demonstrated the importance of being able to fluently navigate multiple CRs in STEM learning and how experts utilize this ability to more readily solve problems in a variety of contexts (Gestson, Barner, Abadi, Hurwitz, & Brown, 2019; McCracken & Newstetter, 2001; Pea, 1993). Therefore, tangibility of CRs—the extent to which CRs are connected to real-world conditions, project/stakeholder constraints, and engineering tools—provides a framework for comparing sociomaterial contexts of CRs that experts (engineers) and novices (students) navigate within their respective workplace and academic environments.

2.3.3 Tangibility

The idea of tangibility has not been explicitly identified in the previous literature, but it can be used to describe findings in similar research. For example, tangibility can be used to further describe the findings from Bornasal et al.'s (2018) exploration of concepts at a transportation engineering firm. Bornasal et al. (2018) observed that engineers recall, form, and apply conceptual knowledge within and through project constraints, negotiation with other engineers and project stakeholders, and the use of material resources. Using our definition of tangibility, it could be said that Bornasal et al. (2018) found that CRs in the workplace are tangible to project/stakeholder constraints, negotiations, and material resources, which can yield a wide variety of CRs.

Gainsburg, Rodriguez-Lluesma, and Bailey's (2010) study of structural engineering workplaces observed and defined fundamental structural engineering design concepts as being the "configuration, operation and performance of elements such as posts, beams, and welds independent of context." *Independent of context* implies that these fundamental concepts are abstract and therefore not tangible according to our definition. However, Gainsburg et al. (2010) observed nine other "types" of structural engineering knowledge in addition to these "fundamental design concepts" including "rules of thumb and estimates" and "design instruments" while also observing the extent to which structural engineers used each type of knowledge throughout different phases in the project. This implies then, that when engineers are representing fundamental design concepts, those CRs are tangible to other types of knowledge such as design instruments (material context) and certain phases of certain projects (social context).

Framing Bornasal et al.'s (2018) five themes and Gainsburg et al.'s (2010) ten knowledge types with how CRs are tangible provides a connection to Johri's (2011) idea of "sociomaterial bricolage." Johri (2011) coined the term "sociomaterial bricolage" to define how software developers make do with the social and material resources at hand to continue making progress on an engineering problem. For example, when we represent concepts in the workplace, these representations can be tangible to engineers' "social negotiation of meaning" and "material resources" (Bornasal et al., 2018), or be tangible to "rules and thumbs and estimates" and "design instruments" within different phases of a project (Gainsburg et al., 2010). Therefore, sociomaterial bricolage can be thought of as a process for how CRs become more tangible to the sociomaterial contexts of real-world conditions, project/stakeholder constraints, and engineering tools.

Tangibility was not only relevant to studies of the engineering workplace; in Stevens, O'Connor, Garrison, Jocuns, and Amos' (2008) observations of four engineering students' curricular path, they noted that the engineering knowledge required of students began with "following a recipe to reach a single, expected result" (p. 3) to upper-level courses where students were more likely to be expected to "generate their own data, either through research or experimentation" (p. 3). Stevens et al. (2008) did not focus on the specific concepts engineering students were learning; however, they did observe increased responsibility to define and bound open-ended problems as engineering students progressed through their majors. To solve these types of problems, Stevens et al. (2008) observed that the engineering students had to find information through research or experimentation that would have been typically given to them in prerequisite courses, and that this exposed students to more " 'real world' conditions" (p. 3). Thus, more open-ended, complex problems required the students to form more tangible CRs to those real-world conditions through the sociomaterial contexts of research and/or experimentation than the CRs that "arose from problems worked under the "'perfect world' conditions of prerequisite courses" (Stevens et al., 2008, p. 3).

The disparity in tangibility of CRs in the workplace and academic environments can be viewed as part of the misalignment between engineering education and practice, but has never been explicitly explored. Ethnography provides a unique methodology for exploring the tangibility of CRs to sociomaterial contexts of the engineering workplace and engineering courses.

2.3.4 Ethnographic Studies in Engineering Practice and Education

Previous research has demonstrated how sociomaterial contexts influences our use and understanding of CRs. Ethnographic methods are well suited for exploring these sociomaterial contexts underpinning CRs in academic and workplace environments because these methods allow for direct observation and active participation in these environments. In engineering education research, only a handful of ethnographies have been conducted to access richer understandings and descriptions of workplace environments, and even fewer for academic environments.

Several studies utilized purely observational ethnographies to examine engineering practice. For example, Vinson, Davis, and Stevens (2017) observed 20 early career engineers within nine different engineering disciplines across five different workplace environments. Gainsburg et al. (2010) conducted a more focused observational study of the engineering workplace by observing 19 structural engineers at three different structural engineering firms. These two studies (Gainsburg et al., 2010; Vinson et al., 2017) relied entirely on observation and interviewing techniques with no participation. Participant-observation ethnographies of the engineering workplace, however, are even more limited because they require the researcher(s) to spend additional time in the field learning how to become a participant. That being said, participation is a worthwhile addition to any ethnography because it can serve as a way of challenging or validating interpretations of observations; thereby adding another layer of credibility and trustworthiness to the data collected and analyzed from field research (Emerson et al., 2011; Walther et al., 2013).

Focusing on how engineers understand and use concepts in the workplace, Bornasal et al. (2018) conducted participant-observation ethnographic fieldwork at a private engineering consulting firm and identified that engineers work with other engineers (social) and artifacts (material) to recall, form, and apply conceptual knowledge within the specific constraints of a project. In another ethnographic study, Johri (2011) observed—but did not participate in—how software developers collaborated with geographically disperse teammates constrained by different time zones. While Johri's (2011) ethnography did not include participation, he did rely on his own past experiences as a software developer to integrate himself as an observer within multiple office environments and to assist in his own understanding of his participants' work.

There are very few ethnographic studies of academic environments, and even fewer, if any, participant-observer ethnographies of said environments. Stevens et al. (2008) conducted a longitudinal ethnographic study following four engineering students at different institutions throughout their entire undergraduate coursework and Godfrey and Parker (2010) provided a holistic description of the culture in a school of engineering at a university in New Zealand with combined insight from junior and senior faculty and students in all four years of their undergraduate study (Godfrey & Parker, 2010). Both Stevens et al. (2008) and Godfrey and Parker (2010) observed the development of a broad engineering identity amongst students as they progressed into their upper-level courses, but with limited exploration into the nuances of specific sociomaterial contexts that influence CRs and subsequent conceptual understanding.

While studies of the engineering courses and the workplace are limited (Johri et al., 2014), what is even more surprising in engineering education research is the limited amount of studies that directly compare the workplace and academic environments with data collected from both environments in a single study. This is surprising because of the amount of studies of the engineering workplace that make broad claims about the nature of the engineering education-practice gap with little to no comparison with actual engineering education environments. In response, Bornasal et al. (2018) noted that more ethnographic research is needed in other workplace environments *and* academic environments for different engineering disciplines to better understand how symbolic representations of concepts differ across these environments.

Based on the previous research presented, the authors conducted a participant-observation ethnography to explore the tangibility of CRs within the sociomaterial contexts of both a workplace and academic environments of a single discipline. Ethnographies wherein the researcher not only observes, but also participates, can offer an even richer understanding of the sociomaterial contexts that influence CRs (Emerson et al., 2011). Immersing oneself within the daily activities of those they are studying allows for a more detailed and descriptive account of participants' experiences through personal exposure and fosters rapport that can be capitalized on in future observations and interviews. Furthermore, being a participant-observer allows the researcher to bounce back and forth between these roles depending on what is the more appropriate data collection method for the respective environment (Emerson et al., 2011).

2.4 Purpose

There is currently no research exploring both academic and workplace environments within a specific engineering discipline characterizing how that discipline represents their fundamental concepts in both environments. Doing such research will provide a more nuanced understanding of CRs in engineering education and allows for a more direct comparison to be made between academic and workplace environments. This, in turn, allows for stronger inferences to be made about how differences in CRs across environments may or may not be contributing to the education-practice gap. We conducted a participant-observer ethnographic methodology to explore an engineering workplace environment and relevant engineering courses to answer the following question:

> How are structural engineering concepts that are prevalent in both the workplace and academic environments represented within the sociomaterial contexts of these environments, and how tangible are they?

2.5 Methods

Structural engineering was chosen for the disciplinary focus of this research for two main reasons. First, it provided a specific engineering knowledge domain to gain a nuanced understanding of and compare with findings from other ethnographic studies of the engineering workplace. Second, the researcher conducting the ethnography (hereto referred to as the ethnographer) has taken extensive coursework in structural engineering for their undergraduate and graduate degrees, but has never practiced structural engineering. This situated the ethnographer squarely in the education-practice gap and allowed him to participate in both environments, with limited bias from previous real-world experience.

2.5.1 Credibility

To improve the credibility of this research, the ethnographer enrolled in four graduate level qualitative research methods courses. These courses focused on qualitative data collection techniques, qualitative data management, and qualitative data analysis methods within sociology, public policy, and science education research. While none of these courses focused solely on ethnographic methods, one required the ethnographer to practice jotting field notes while conducting observations in public settings, and all required the ethnographer to consult with the instructors on the methodology presented herein. Furthermore, two members of the research team have previous experience conducting ethnographic research and consulted the ethnographer before, during, and after collecting data in the field.

The ethnographer also has taken undergraduate and graduate level coursework in structural engineering which provided him with the disciplinary knowledge and technical jargon to understand and participate in the environments he was studying. The ethnographer spent three months in the workplace environment participating in engineering work for approximately 16 hours per week on portions of 18 different projects. When the ethnographer was not performing engineering tasks on one of these projects, he observed and interviewed engineers during design activities. The ethnographer then spent six months participating in and observing four undergraduate structural engineering courses over two quarter-long terms. The ethnographer participated in lectures, labs, office hours, exams, projects, and homework assignments for each course. The study entailed in-depth engagement in the field for nine months (three months in the workplace plus six months in the classroom). This allowed the ethnographer to: collect data from diverse perspectives and experiences (Johri, 2011) through their participation in *and* observation of multiple environments (workplace and four courses), engage diverse participants (students, instructors, and engineers with a variety of experience), and access a myriad of academic and professional engineering activities (group projects, design meetings, etc.).

This may, however, bring to mind issues of bias in conducting a participant-observation ethnography and/or when an ethnographer shares the disciplinary knowledge of their participants. Arguably, attempting to eliminate or reduce bias by trying to enter a research setting with a “blank slate” mindset is impossible and not necessarily desirable (Hammersley & Atkinson, 2007). According to Maxwell (2013), “the goal in qualitative study is not to eliminate this influence [of bias], but to understand it and to use it productively.” (p. 125). Therefore, the argument can be made that an ethnographer with experience in the environment they are studying has their own previous experience (biases) to draw upon as if they were another participant in that environment. These biases then can refute, be rebutted, and/or contribute to the shared interpretations of the data created by the researcher and participants (Guba & Lincoln, 1989).

2.5.2 Site Selection and Description

The workplace environment selected for this study was a private A&E firm located in Oregon that employs structural engineers to perform structural analysis and design of commercial, industrial, and public buildings. The courses selected for this study were located at the ethnographer’s higher education institution. Selection of the workplace and academic sites were based on geographical accessibility (Maxwell, 2013), the firm’s willingness to participate, and instructor approval to participate in and observe their course.

Tables 2-1 and 2-2 summarize demographic information for each site used in the study, which reflect the variety of courses covered and experiential background of the practicing engineers and instructors. The firm studied provides structural engineering services on a variety of new and existing commercial, industrial, and public infrastructure; and the four courses studied make up the backbone of most undergraduate structural engineering programs (Perkins, 2016).

Table 2-1

Demographic Information for Structural Engineers at the Workplace Environment

No. structural engineers	Industry experience in years	No. licensed PEs (SEs)	No. female (male) engineers	No. M.S. / M.Eng. degree holders
20*	0-46 ($\mu = 10.3$)	12 (5)	7 (13)	7

*The firm employed 24 structural engineers across three offices, however only 20 were observed in-depth at the office where the ethnographer was participating.

Table 2-2

Demographic Information for Structural Engineering Courses Studied

Course	No. students	Lecture (recitation) hours/week	Course objective	Instructor teaching (industry) experience in years	Female/male instructor
Structural Analysis I	60	3 (2)	Determinate analysis	30 (12)	Male
Structural Analysis II	50	3 (2)	Indeterminate analysis	36 (29)	Male
Steel Design	67	3 (2)	Beam, column, and brace design	1 (2)	Female
Reinforced Concrete Design	60	4 (0)	Beam design	22 (24)	Male

2.5.3 Transferability

Ethnography emerged out of anthropology as a way to develop richer understandings of cultural practices via immersion within said culture (Case & Light, 2011). Since ethnographies focus on specific cultures and their unique attributes, the goal is not to produce generalizable results, but to frame findings in a way that is meaningful to external customers (e.g., the engineering education community) by guiding future research and positioning findings within broader contexts and the existing literature (Godfrey & Parker, 2010; Walther et al., 2013). Thus, we aimed to enhance the transferability of this research to other engineering environments by providing rich, detailed descriptions of the sociomaterial contexts of CRs in our findings so that others can assess how and to what extent our findings are transferable to broader contexts and within the existing literature (Lincoln & Guba, 1985; Walther et al., 2013). Furthermore, in exploring multiple different types of engineering projects in the workplace and multiple engineering courses that are commonplace in undergraduate structural and civil engineering education—all with engineers and instructors having diverse professional, teaching, and research experiences—we enhanced the opportunities for our findings to resonate with a variety of external customers (Lincoln & Guba, 1985; Walther et al., 2013).

2.5.4 Data Collection

Data collection in ethnographic methods consists of participant-observation, interviewing, and artifact collection (Johri, 2014, Emerson et al., 2011). Collectively, these three methods allowed access to a multitude of interpretations from different perspectives to triangulate the data (Stevens et al., 2008; Walther et al., 2013).

2.5.4.1 Participant-Observation

The ethnographer was able to participate in both environments as a part-time intern with the firm and as an enrolled student in the four courses. Each course spanned a 10-week long quarter-term with a final exam during the 11th week. The ethnographer participated in each course taking notes, completing assignments, attending office hours, and completing activities typical of enrolled students, while observing and documenting the sociomaterial contexts of CRs within the curricular activities the instructors provided for their students.

As a part-time intern at the firm, the ethnographer participated in formal and informal design meetings with engineers and architects, performed design calculations, created and reviewed calculation packages and design drawings, and responded to contractor submittals. The ethnographer also observed other engineers engaging in similar activities when possible. The ethnographer was immersed in participant-observation for 3 months at the firm, arriving at the site each weekday between 7-8 am and leaving the site between 5-6 pm.

Data collected during participant-observations took the form of jottings and field notes during and after activities in which the ethnographer participated or observed. Jottings were quick notes hand-written in the field by the ethnographer while an event was ongoing or immediately after. They were often indecipherable to others, but to the ethnographer provided enough detail to recall significant aspects of an event later when creating field notes. Field notes were the immediate follow up to jottings and ensured that short-hand and abbreviations in the jottings were converted into full sentences and ideas before the ethnographer forgot the meaning behind their jottings (Emerson et al., 2011).

In the courses studied, these jottings were weaved into the lecture notes for the course. In the workplace, jottings were weaved into formal and informal meeting notes. After exiting each environment, the ethnographer immediately reviewed their jottings and converted them into typed field notes. Field notes were organized into episodes for distinctive activities. For example, an episode in the workplace could be a design meeting or a design task that the ethnographer was assigned to work on, and an episode in the academic environment could be a lecture, lab assignment, or office hour visit. This process of converting jottings to typed field notes allowed the ethnographer to stay close to the data, develop formal and informal interview questions to fill in gaps in their notes, and to identify artifacts that needed to be documented and included within each episode.

2.5.4.2 Artifact Collection

Artifact collection consisted of taking pictures of CRs encountered in the activities engaged in within each environment. Typical items documented with pictures included diagrams/sketches drawn by engineers, instructors, or students, screen shots of engineering activities being conducted on a computer, structural drawings/details, design aids, codes/standards/manuals, textbook/homework/exam problems, lab exercises, etc. As previously mentioned, CRs are dependent on sociomaterial contexts and therefore it was not only important to capture the material contexts with pictures, but also to situate them within their synchronous social context. Thus, pictures were integrated into the field notes where appropriate. For example, if a field note episode was about using a design aid during one of the engineering activities at the firm, a picture of the design aid was copied and pasted into the typed field notes, making these episodes an annotated account of the sociomaterial contexts wherein the artifact is being used. Furthermore, social context extends beyond the particular episode wherein a CR is used, but also to how the user(s) understood and interpreted the CR. Accessing interpretations was done through interviews with participants.

2.5.4.3 Interviews

The ethnographer conducted both informal and formal interviews with each engineer located at the office he was interning at and with each instructor for the four courses. Informal interviews included spontaneous discussions with engineers, architects, students, teaching assistants, and instructors before, during, or after an activity. These informal interviews typically consisted of the ethnographer asking brief clarification questions for their field notes. Formal semi-structured interviews with engineers and instructors were recorded when the ethnographer had additional questions arise from their creation and analysis of their field notes. These formal interviews were aimed towards one or more of the following goals: additional clarification, filling missing information in field notes, member checking, accessing participants' interpretations, and/or assessing the reliability of the ethnographer's interpretation of an event/artifact (Emerson et al., 2011; Walther et al., 2013). The recordings of these formal interviews were transcribed by the ethnographer and a third-party transcription service. Following transcription, the ethnographer would revisit their field notes and use information from the transcripts to revise inaccurate or incomplete information in their field notes.

2.5.5 Data Analysis

Data analysis occurred during and after data collection. This allowed the ethnographer to utilize data to guide further inquiry, as well as prevented the ethnographer from being overwhelmed by the amount of data collected and analyzed (Emerson et al., 2011; Johri, 2011; Walther et al., 2013). The ethnographer revisited their field notes and converted any remaining jottings into field notes each day after leaving the field site. Field notes were then merged and combined into episodes of activities that more explicitly identified themes. This process of writing narratives from field notes was a "selective and creative activity [that] functions more as a filter than a mirror reflecting the 'reality' of events" (Emerson et al., 2011, p. 46). If, for some reason, a filter of events was not agreed upon by the participants or research team, the initial field notes and jottings were examined again for re-interpretive analysis (Emerson et al., 2011; Walther et al., 2013). Thus, “[t]he sooner and more explicitly analytic themes are identified, the better able the fieldworker is to 'check out' different alternatives, making and recording observations that can confirm, modify, or reject different interpretations. In these ways, the fieldworker lays the groundwork for developing analyses that are both complex and grounded in the data" (Emerson et al., 2011, p. 126).

Interviewing during and after the data collection process provided the primary means for confirming, modifying, or rejecting interpretations. The analysis of the interview transcripts was synchronous and grounded in the field notes and artifacts collected throughout participant-observation to prevent an overreliance on excerpts out of context (Johri, 2011; Walther et al., 2013). A diagram illustrating this synchronous relationship between data collection and data analysis in the activities of ethnography is provided in Figure 2-1.

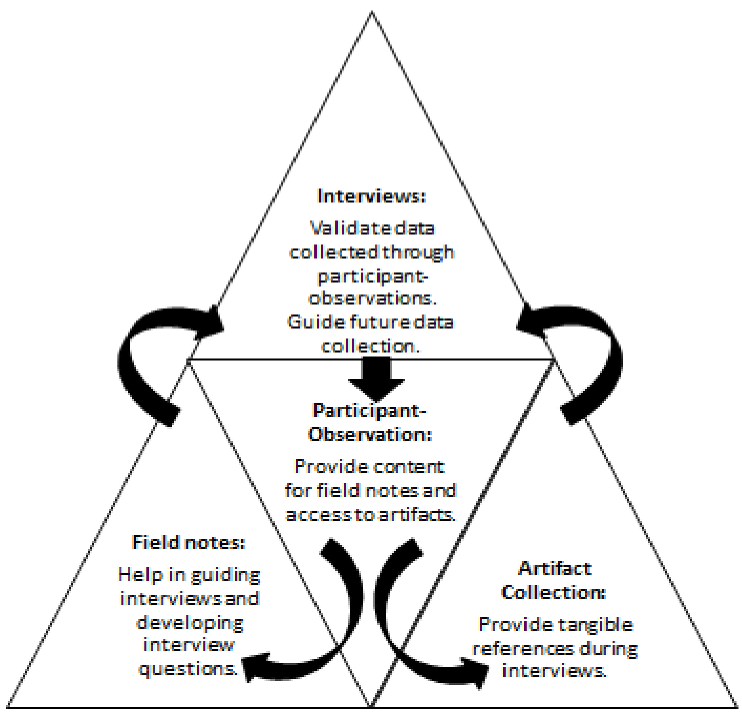


Figure 2-1. Diagram of ethnographic methods.

Figure 2-1 illustrates how interviews were iteratively guided by the other data collection methods. Therefore, coding of the interview transcripts was iterative with initial iterations deductively seeking participants' mentioning of certain concepts that were present in both environments (Miles, Huberman, & Saldana, 2014). These coded excerpts were then inductively coded for emergent themes in tandem with field notes and artifacts to holistically describe the tangibility of CRs in both environments. These concepts and subsequent themes could then be confirmed, refuted, or revised in subsequent coding iterations and additional data collected from participant-observations, field notes, artifacts, and/or later interviews (Emerson et al., 2011; Walther et al., 2013; Miles et al., 2014). Thus, the final analysis of the data consisted of qualitatively assessing the degree of tangibility that a CRs sociomaterial contexts have to real-world conditions, project/stakeholder constraints, and engineering tools.

2.6 Findings

2.6.1 Degrees of Tangibility

The researchers found that structural engineering concepts were represented with varying degrees of tangibility in both workplace and academic environments. CRs that were more tangible were situated within and distributed across more real-world conditions, project/stakeholder constraints and/or engineering tools than less tangible CRs. To illustrate this idea, a spectrum is presented in Figure 2-2 to qualitatively describe how concepts can be represented with more or less tangibility.

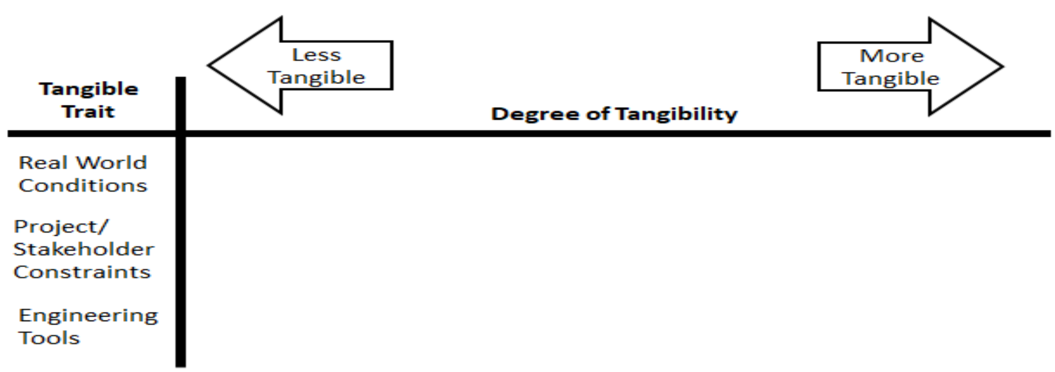


Figure 2-2. Qualitative spectrum for degrees of tangibility.

Throughout the ethnography, several structural engineering concepts were represented in a variety of ways across both environments with varying degrees of tangibility depending on the sociomaterial contexts. Some common concepts frequently observed in both environments were moment, shear, stress, and deflection. However, not all concepts were equally represented across environments due to different academic goals in each course and depending on the nature of work encountered in the workplace. Therefore, it was not only important to identify concepts that were adequately represented in all environments, but that could also be considered a prevalent concept in structural engineering regardless of environment. The structural engineering concept identified by the researchers as best fitting these criteria was the concept of loads.

Loads are the forces that structural engineers design structural systems to resist. Examples include a structure's self-weight (dead loads), occupancy (live loads), and environmental loads (e.g., snow, wind, and earthquakes). In structural engineering, loads are expressed as physical quantities such as pounds or pounds per square foot and are often represented as force vectors acting on a structure. In the workplace environment, load vectors were determined and represented through *real-world conditions* (e.g., snow and/or earthquakes), *project/stakeholder constraints* (e.g., architectural requirements and/or framing options), and *engineering tools* (building codes/standards/manuals and/or engineering drawings/diagrams). The concept of load is ubiquitous to most structural engineering activities, regardless of the structural material being used or whether a structural system is being designed or analyzed. Furthermore, many other important fundamental structural engineering concepts are directly related to loads, such as shear, moment, stress, and deformations. Therefore, loads are a unit of knowledge (i.e., a concept) organized within the knowledge domain of structural engineering that is distinguishable from and interrelated to other units of knowledge in this domain (Rittle-Johnson, 2006; Streveler et al., 2008).

To present findings that are best suited for broader meaning in the structural engineering community in a concise manner, the researchers chose to focus on CRs portraying loads. Furthermore, focusing on CRs for a single concept allows us to showcase a wider variety of sociomaterial contexts and therefore varying degrees of tangibility for each CR.

2.6.2 Conceptual Representations with Varying Degrees of Tangibility

One of the most common engineering tools used for representing loads in the workplace were structural and architectural drawings. Figure 2-3 is an example from the workplace of a roof framing plan illustrating additional loads along the perimeter due to snow drift and ballast loads for a building project.

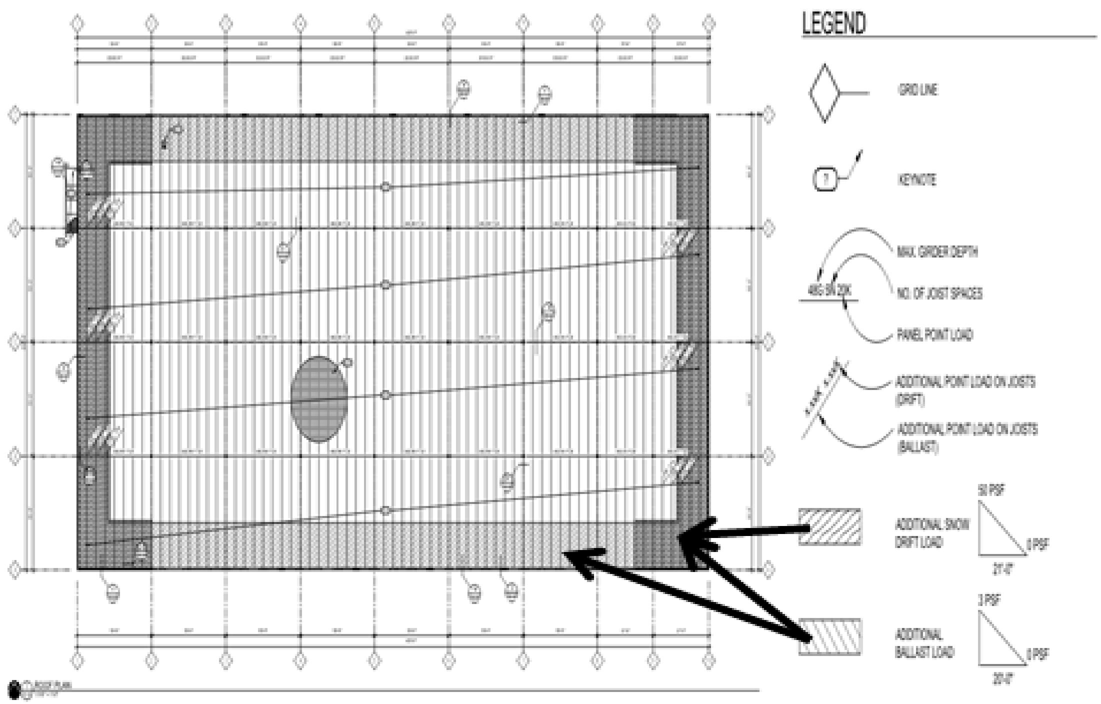


Figure 2-3. Roof framing plan from workplace environment.

The additional snow drift and ballast loads represented in the legend and on the roof framing plan in Figure 2-3 were determined by a structural engineer and could then be used to analyze and design the roof framing. The structural drawing presents loads in a way that are tangible to real-world phenomena (e.g., snow and ballast loads), identifies previous project/stakeholder constraints that influenced the roof framing plan and location of the additional snow drift loads (e.g., column spacing and parapet locations, respectively), and an engineering tool (the structural drawings that they are represented on). Thus, there is a documented history, or paper trail, from where these loads were sourced.

Loads were not always explicitly represented on a drawing as was the case in Figure 2-3, but the ability to read and interpret structural and architectural drawings was still necessary in the workplace environment to obtain dimensions and locations for certain loads. Figure 2-4 shows a wall and post on a floor plan that the ethnographer was tasked with analyzing to ensure it could support the loads of the mezzanine floor above.

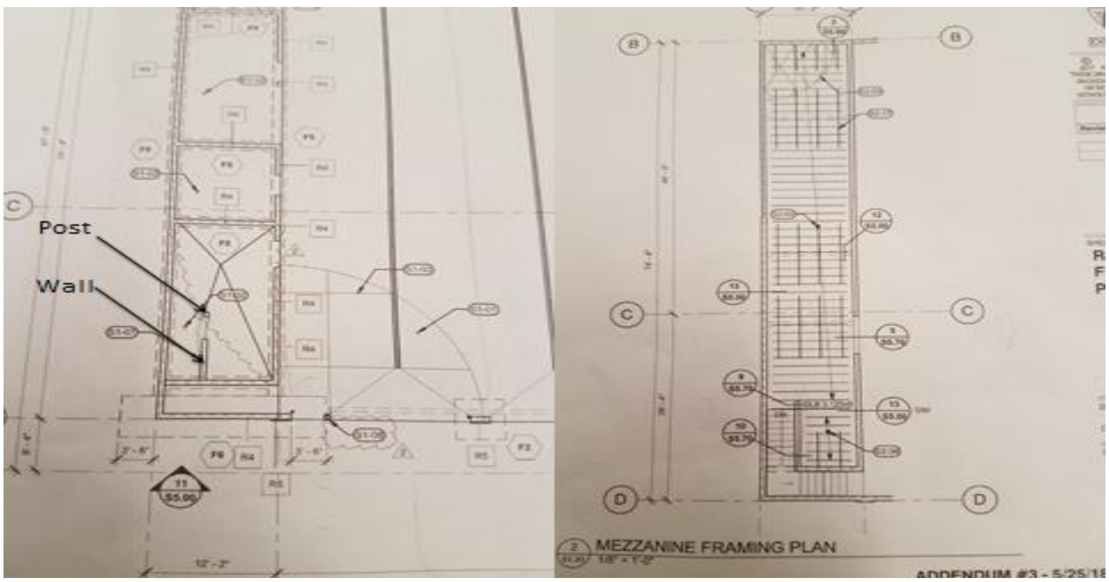


Figure 2-4. Mezzanine framing plan (right image) partially supported by the post and wall (left image).

To determine if the post and wall were sufficient for supporting the mezzanine framing plan, the ethnographer had to determine the live loads for a typical mezzanine floor using a referenced standard (ASCE Standard 7-10), the dead load of the framing materials, and then quantify how much of these loads are distributed to the post and wall by utilizing various dimension values from the structural drawings. Thus, the loads used to assess the demand on the post and wall were tangible to the real-world live and dead loads, the project/stakeholder constraints dictating the function of the space, and to engineering tools including the referenced standard and drawings presented in Figure 2-4.

The spacing of beams and columns in framing plans influences how much of certain loads are applied to each element. These dimensions were sometimes initially determined with the architects and architectural drawings at the workplace. Figure 2-5 shows a practice observed in the workplace environment wherein an initial framing plan was traced on tracing paper over an architectural drawing.

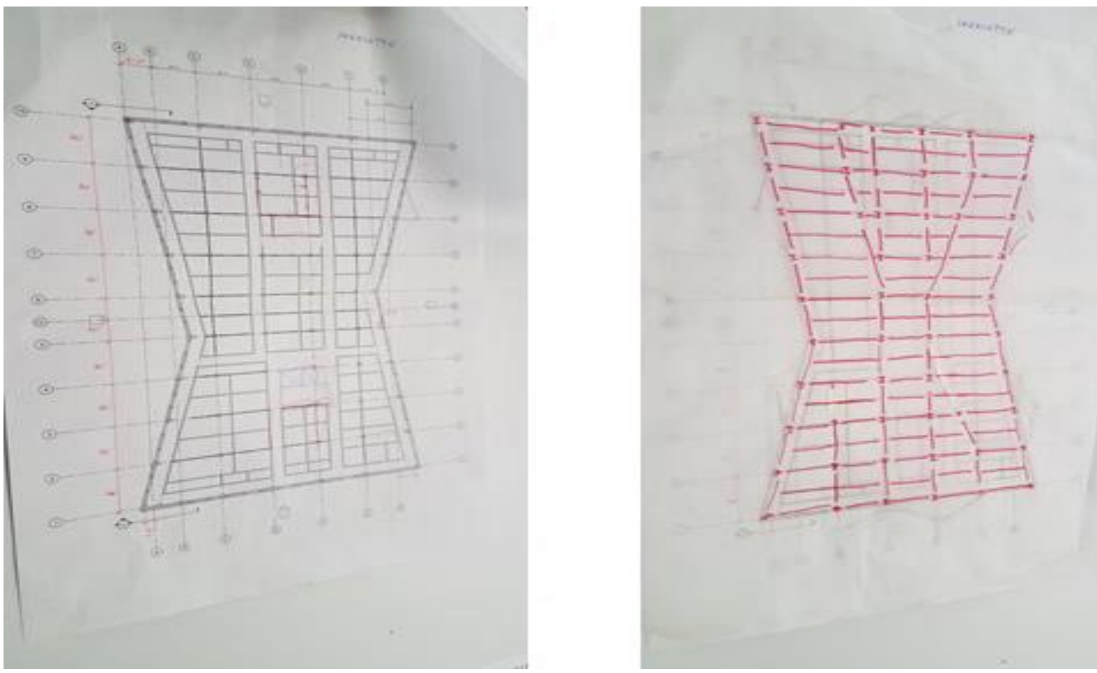


Figure 2-5. Initial framing plan (right image) traced over an architectural floor plan (left image).

When asking one of the structural engineers in an interview about this process of tracing framing plans, he said the following:

> *When you're switching between beams and columns, you can see that distributed load on a beam ends up in two reactions. Those reactions are actually going somewhere, they need columns beneath them to support it. Beneath that you need a footing to support that. Tracing loads down with trace paper […] we do it a lot in schematic design when the architects will bring a building layout and we have to find out where we can put columns and then come up with a framing plan.*

Whatever that final form of the framing plan, it influences the loads that are represented in the design of the beams, columns, and footings. This process of determining a framing plan with the architects and architectural drawings further extended the tangibility, or history of where loads come from and how they were represented.

Aside from loads, many other concepts were represented through and became tangible to the diagrammatic nature of structural/architectural drawings and plan sets. Structural and architectural drawings conveyed meaning, specifically design intent, and thereby helped structural engineers represent many different concepts to other structural engineers and project stakeholders when working through a design problem. Figures 2-3, 2-4, and 2-5 demonstrate how loads can be explicitly represented in drawings (as in Figure 2-3), or implicitly as a result of the framing plan (Figures 2-4 and 2-5). In either case, the loads used in design and analysis were entirely tangible to real-world conditions, project/stakeholder constraints, and engineering tools. This was not always the case for how loads were represented in the academic environments.

Loads in the academic environments were observed to be represented with various degrees of tangibility. To demonstrate this range in tangibility, Figure 2-6 shows a representation with no tangibility, and Figure 2-7 shows a representation that was considerably more tangible and aligned with the representations observed in the workplace.

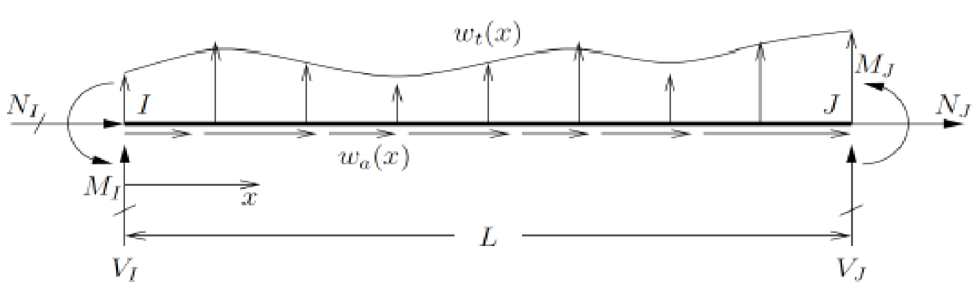


Figure 2-6. Conceptual representation of a distributed load over a beam with each type of support reaction represented on opposite ends.

Figure 2-6 is an abstract representation of a beam exposed to a transverse and axially distributed load and the support reactions at each end. None of the variables have values and the transverse load is represented as having variable magnitude across the span of the beam. Neither the loads nor reactions to those loads were tangible, they were meant to be abstract and ubiquitous. This was a common representation used in this course for introducing notation relevant to more tangible representations presented later in the course.

Conversely, a CR with greater tangibility and therefore further to the right on the spectrum for degrees of tangibility is presented in Figure 2-7, which displays a recitation exercise from the Structural Theory I course.

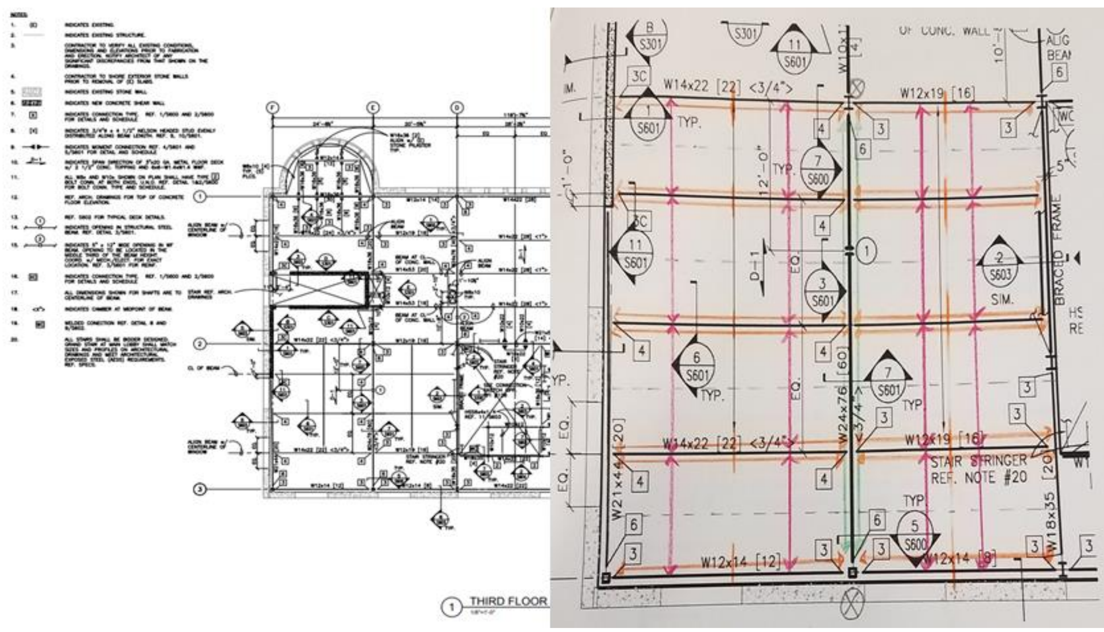


Figure 2-7. Floor framing plan (left image) and conceptual representation of load path being traced over zoomed in portion of floor plan (right image).

For this exercise, students were required to determine the magnitude of the live load from the framing plan notes listed on the far left of Figure 2-7, and then read and interpret the dimensions of the framing plan to trace how much of this load would be distributed to various beams, girders, and columns on the zoomed in framing plan (right image in Figure 2-7). Thus, the loads represented in this exercise were tangible to real-world conditions (live loads for the building their class was in), project/stakeholder constraints (the structure's existing framing and function), and the structural drawings/notes (i.e., engineering tools) for the classroom.

Figures 2-8 and 2-9 are examples of CRs of loads with other various degrees of tangibility.

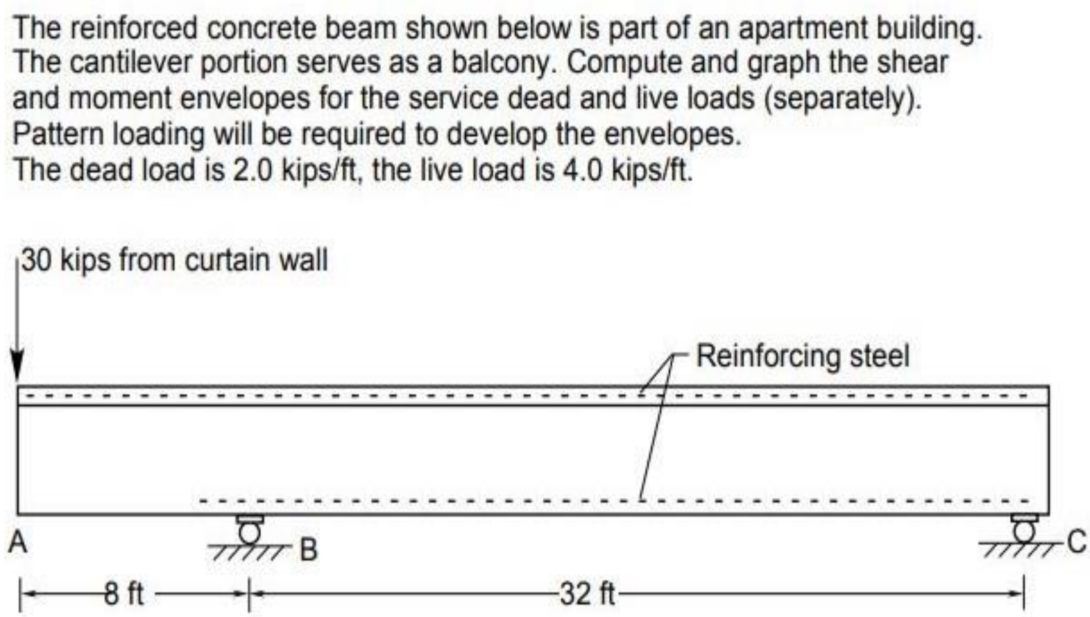


Figure 2-8. Homework problem that asked students to analyze a beam with uniform dead load, a concentrated dead load, and uniform live load due to pattern loading.

In the CR presented in Figure 2-8, the loads were designated with some degree of tangibility to the real-world (i.e., the 30 kips applied at point A is said to be from a curtain wall). The dead and live loads were also given in the problem statement. Students were prompted to consider pattern loading (i.e., determining where the live load needs to be located along the beam to produce the greatest shear and moment demand on the beam) for the problem. While the problem statement provided insight into some project/stakeholder constraints (e.g., the beam being part of an apartment building and supporting a balcony), the loads were limited in their tangibility to these constraints because load values were directly provided rather than determined as a result of those constraints. Similarly, since the loads were given, students were not required to utilize any engineering tools to determine quantity of these loads, further decreasing their tangibility. However, asking students to consider pattern loading and graph the shear and moment envelopes allowed them to create an engineering tool (the shear and moment envelopes) to assess the shear and moment demand on the beam. Therefore, these demands were tangible to those envelopes. These envelopes are presented as another example in Figure 2-15.

Figure 2-9 is a spreadsheet provided to students for a recitation exercise meant to guide students through determining the dead load for a typical column in a given building. Students in this course were encouraged to use the same spreadsheet for a group project wherein they had to design a similar building.

PROJECT: STEEL BUILDING DESIGN CASE STUDY		
SUBJECT: COLUMN DEAD LOAD TAKE OFF		SHEET 6 of 131
LOAD TABLE - COLUMN DEAD LOAD (LB/FT^2)		
COLUMN DEAD LOAD UNDERNEATH TYPICAL FLOOR (LB/FT^2)		**LOADS FROM**
SLAB (4-3/4" Light WT. Concrete)	38	*Slab*
(Lightweight Concrete Density = 96 PCF)		*Mech./Elec./Piping*
MECH./ELEC./PIPING	10	*Ceiling System*
(common practice = 10 psf)		**GO TO**
CEILING SYSTEM (Table C3.1-1a, ASCE 7-16)	5	↓
(Acoustical fiber board & Mechnical Duct allowance)		
JOISTS	3.7	*Joists*
(Assume 11 LB/L.F. @ 3' O.C.)		
GIRDERS		↓
(Assume 85 LB/L.F. @ 36' O.C.)		*Girders*
COLUMNS (36'*30' = 1080 FT.^{2})	1.8	↓
(Assume 150LB./L.F.* 13')/1080FT.^{2}		
OLUMN TOTAL DEAD LOAD – TYPICAL FLOOR (LB/FT^2		
		Columns
COLUMN DEAD LOAD UNDERNEATH ROOF (LB/FT^2)		**LOADS FROM**
ROOF DECK (Table C3.1-1a, ASCE 7-16)	3	*Rigid Insulation*
(Metal, assume 18 gage for estimate)		*Roof Deck*
RIGID INSULATION (Table C3.1-1a, ASCE 7-16)		*Mech./Elec./Piping*
(2" thick) **0.75 psf per 1/2"**		*Roofing (felt & gravel)*
MECH./ELEC./PIPING & CEILING SYSTEM	10	**GO TO**
(Assume 10 psf)		
ROOFING (Table C3.1-1a, ASCE 7-16)		↓
(Five-ply felt & gravel)		*Joists*
JOISTS	3.7	↓
(Assume 11 LB/L.F. @ 3' O.C.)		
GIRDERS		
(Assume 85 LB/L.F. @ 36' O.C.)		*Girders*
COLUMNS (36'*30' = 1080 FT.^{2})	1.8	↓
(Assume 150LB./L.F.* 13')/1080FT.^{2}		
COLUMN TOTAL DEAD LOAD – ROOF (LB/FT^2) =		*Columns*

Figure 2-9. Column dead load takeoff spreadsheet.

The spreadsheet provided tangible sources for each load that contributed to the total dead load on the columns of interest. Some of these loads were provided for the students, while others were left intentionally blank for the students to determine. The representation of dead load in this example would be considered more tangible than the dead load representation in Figure 2-9 because it was more explicit in the real-world conditions (e.g., components of the floor and roof system that contribute to the dead load), project/stakeholder constraints (e.g., slab thickness, member spacing, column sizes), and engineering tools (e.g., references to Table C3.1-1a from ASCE's standard 7-16 in Figure 2-9) that contributed to the quantification of the dead load magnitude. That being said, while the tangible traits of the loads provided in Figure 2-9 were identifiable, the nature of the exercise inevitably guided students to primarily focus their attention on the tangibility of the loads they had to quantify and reduced the tangibility of the load values that were given. For example, the load magnitude given in the spreadsheet where it says to "Assume 10 PSF" for the "Mech./Elec./Piping and Ceiling System," but provides no explanation or reasoning for the derivation of that magnitude limits student exposure to the tangibility of this load.

Quantifying different load types is often one of the first steps in structural engineering design or analysis. Multiple different load types (i.e., dead, live, and earthquake) are then combined using load combination equations that account for the variability of certain load types and the probability of various load types occurring simultaneously. While these load combination equations are necessary for determining the demands on various structural elements (e.g., beams, columns, braces, connections), it is also important to keep different load types separate throughout the design or analysis of a given structural element. This is important for at least two reasons: 1) it allows the structural engineer to express the demand in terms of different load types (i.e., flexural demand due to dead load versus flexural demand due to live load) to easily assess which load types are dominating the total demand, and 2) loads flow throughout a structure from element to element and the load combination that controls the demand for one element may not be the same load combination that controls the demand for an adjacent element. The tangibility of loads not only applies to their initial quantification, but also applies to keeping track of the history of each load type as they flow throughout a structure from element to element.

The following episode from the workplace recalls when the ethnographer was tasked with designing steel stringers for a staircase, and it exemplifies this process and need for separating loads. Stringers are diagonal beam elements that support dead and live loads acting on the stairs and transfer those loads into the base connections and landings for the stairs. It was important for the ethnographer to keep the dead and live loads separate when determining the support reactions at the upper and lower ends of the stringers because these loads would transfer into the base connections and landings and possibly be governed by a different load combination than the one used to determine the demand on the stringers. Figure 2-10 shows a Free Body Diagram (FBD) that the ethnographer drew to analyze the demand on the stringers due to the live and dead loads.

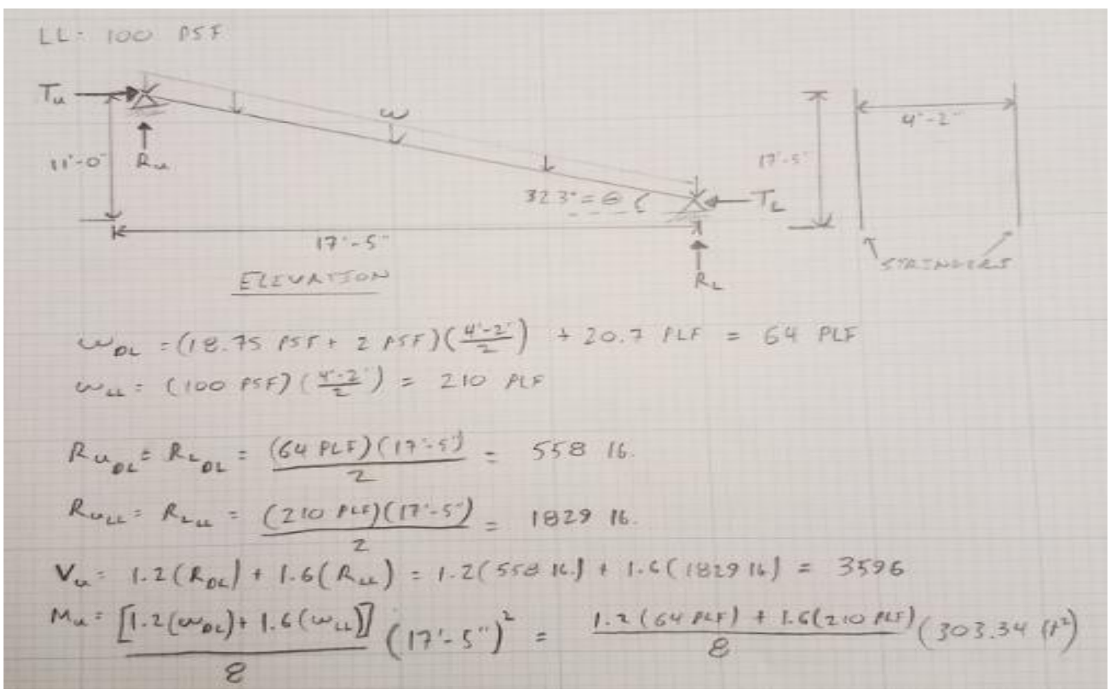


Figure 2-10. Free Body Diagram (FBD) and calculations the ethnographer conducted to determine demand on stair stringers and reactions at upper and lower end of stairs that would transfer into the base plate connections.

Some of the calculations shown in Figure 2-10 illustrate the ethnographer keeping the vertical support reactions due to the dead and live load separate at the upper and lower end of the stringers (e.g., $R_{u_{DL}}$= The upper vertical support reaction (R_u) due to dead load (DL)). These support reaction loads were then used to determine the demands on the connections and landings at the upper and lower end of the stringers. By keeping the loads separate, they had a greater degree of tangibility to the history of the design effort so that the engineer responsible for the design of the stringer connections and landings had a better idea of where the loads acting on those subsequent elements were sourced. Thus, the loads were tangible to the real-world conditions of live and dead loads on stairs and the project/stakeholder constraints of floor height and floor space that dictate the rise and run of the staircase. Furthermore, the loads represented in the subsequent design/analysis of later elements in the load path were tangible to the FBD (an engineering tool), and calculations presented in Figure 2-10.

The following excerpt from an interview with one of the structural engineers further illustrates the importance of keeping the values of different load types separate throughout a design.

> **Engineer:** *You go through it [a design] a couple of times and you have to go back and break apart a [load] value you've been using for your whole calculation. You do that a couple times and you learn that, okay, I just need to keep these [loads] separate.*
>
> **Ethnographer:** *It's worthwhile to do that?*
>
> **Engineer:** *Well there are different load combinations that apply, right? So am I looking to maximize the uplift on my footing? Okay, well that's one load count though. Am I looking to maximize the compression on my footing? Okay, well it's a different load count though. One of those has live load in it, and one of those doesn't have live load in it, and they have different factors on the dead loads, and with the same factors on the earthquake loads. So yeah, you learn, you make the mistake and then you just don't do it in the future.*

Here, the engineer was referring to the analysis and design of a footing. Footings are typically one of the last elements in a structural system designed and their analysis is dependent on the magnitude of the loads that transfer from the super-structure elements (beams and columns) above. The engineer referred to multiple different types of analysis he has to conduct on a footing to determine the demand (uplift/overturning and compression) and how these require consideration for different load combinations, which makes it worthwhile to keep loads separate throughout a design. The excerpt finished with the engineer stating how you learn from the "mistake" of combining load types at the onset and then having to go back and decouple them because of how load combinations change throughout the analysis of various subsequent elements in a structure's load path. Indeed, the ethnographer had actually made this exact mistake on a previous design task and had to go back and redo several calculations to separate their loads. Had the ethnographer not been an active participant in the environments studied, he may not have observed the importance of keeping loads separate and how that influences their representation in the design of subsequent elements. Keeping loads separate in representations was a bookkeeping practice of sorts that makes loads more tangible to their original conception in the real-world conditions, project/stakeholder constraints, and engineering tools applied throughout the design of a structure.

In the academic environments, the tangibility created by keeping loads separate was sometimes limited because the types of loads were not identified and/or elements were often analyzed and designed in isolation from surrounding elements. Exemplifying this was an example problem used during a lecture for one of the courses (Figure 2-11). In this example problem, the instructor demonstrated analyzing a braced frame loaded by gravity and lateral loads by determining the forces these loads induced on the diagonal braces and at the base supports.

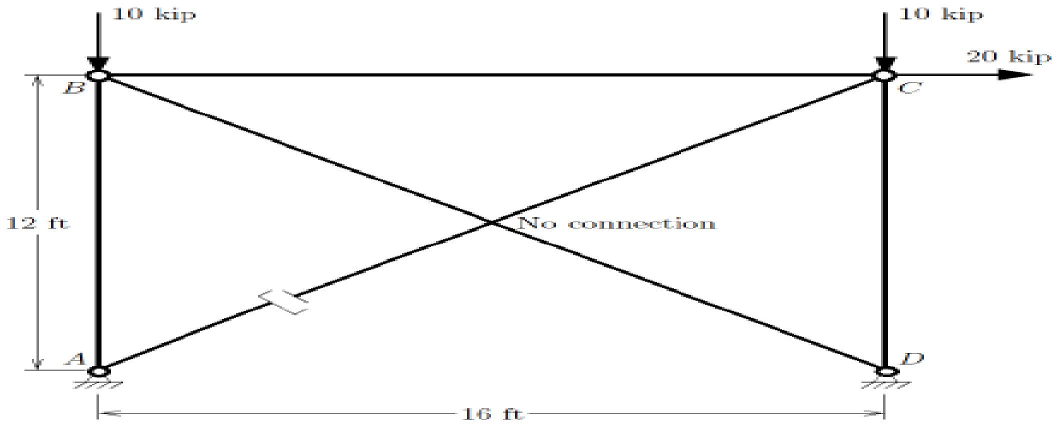
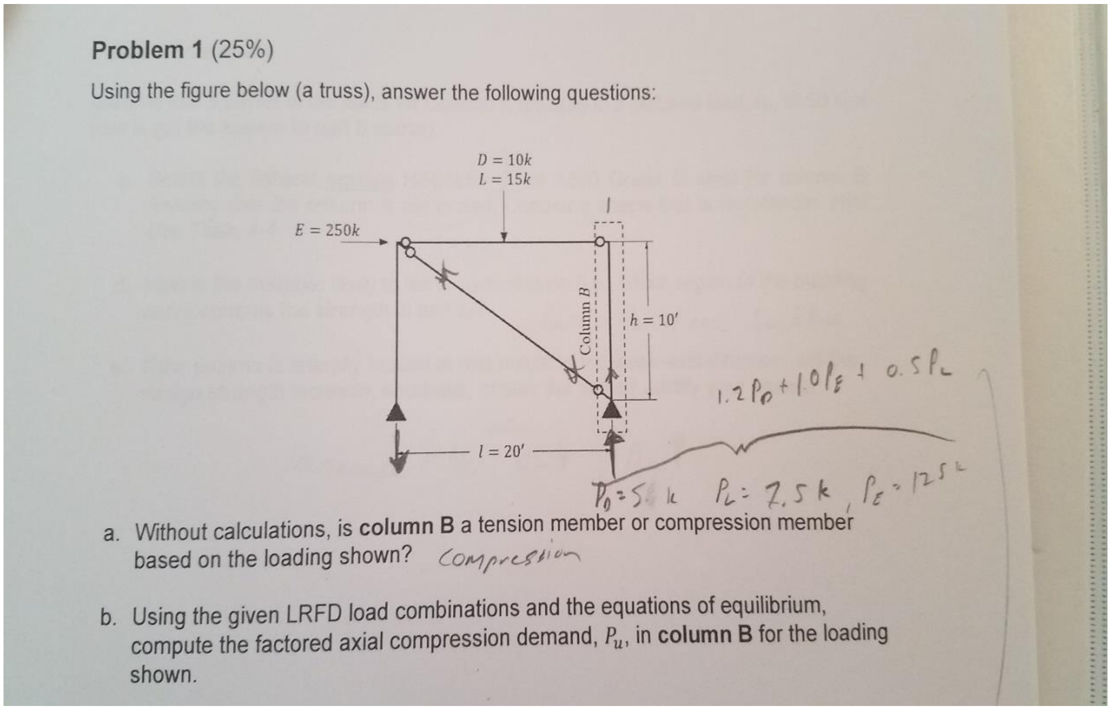


Figure 2-11. An example problem for analyzing a braced frame experiencing both gravity and lateral loads.

The instructor was demonstrating with this example how to determine the axial forces acting on the braces and the necessary vertical and horizontal reactions at the supports A and D due to the 20 kip (1 kip = 1,000 lbs.) lateral load and two 10 kip vertical loads. Since none of these loads were explicitly defined as dead, live, earthquake, wind, etc. loads (although it can be inferred that the lateral load is a product of wind or an earthquake), they were not tangible to anything. This results in the forces being calculated for the braces and the supports not being tangible, nor separated by load type. In the workplace environment, these loads would need to be defined based on their type and kept separate for the purpose of analyzing the brace elements and foundations with the appropriate load combinations.

A similar braced frame from an exam problem in a different course (Figure 2-12) explicitly defines where the loads acting on the frame came from and subsequently asked students to determine the axial force acting on one of the columns.



Problem 1 (25%)

Using the figure below (a truss), answer the following questions:

a. Without calculations, is **column B** a tension member or compression member based on the loading shown?

b. Using the given LRFD load combinations and the equations of equilibrium, compute the factored axial compression demand, P_u, in **column B** for the loading shown.

Figure 2-12. An exam problem that asked students to determine the axial demand in Column B as a result of the combined applied dead, live, and earthquake loads.

In the FBD of the braced frame presented in the exam problem (Figure 2-12), the vertical loads were explicitly defined as dead and live loads and the lateral load was explicitly defined as an earthquake load, making them more tangible to real-world conditions than the loads represented in Figure 2-11. To solve this problem, students had to keep these loads separate and determine how each one individually contributed to the axial demand of the right column. By keeping the loads separate, the students were then able to determine the appropriate load combination for determining the axial compression load acting on the column. Furthermore—even though the students were not asked to do this on the exam problem—it would be important to keep these loads separate for other reasons such as if they were required to determine the demands on the left column, diagonal brace, and/or or foundations supporting both columns. Thus, not only were the loads provided in this problem more tangible, the resulting answer was subsequently more tangible as well. The very act of keeping loads separate as they flow through a structure innately created the paper trail of tangibility to the pre-existing conditions of the structure/problem. This representation would not be considered tangible to any project/stakeholder constraints since the height and width of the truss were given and there was no information connecting the truss to an overarching structure/project. Solving the problem does require using the appropriate load combination, which the students would determine from a design manual or standard, making this representation tangible to an engineering tool.

In the academic environments, loads were sometimes found to be represented in tangible ways to their origin, but then not explicitly left separated when determining the demands induced on supporting structural elements. For example, Figure 2-13 shows a homework problem wherein students were asked to determine the dead load and live load acting on a portion of a floor in an office building and then to determine how much of these loads were transmitted to the reactions of one of the joists, one of the girders, and then to the columns.

This is the office portion of an office building (ignore live load reductions). Obtain loading from the 2014 OSSC. 6" thick reinforced stone concrete slab is reinforced in both directions (150 pcf from ASCE 7-16 Chapter C3). Use combined live + dead load.

a = 12 ft; b = 20 ft

All of the connections are pinned.

Girders (such as ABCDE) are continuous from one end to the other.

FIND:

Draw tributary areas and complete load paths, showing values of the loads.

Draw complete FBDs and calculate reactions for members BF and ABCDE. Show values of the reactions on the FBDs.

Include ALL loads to the columns.

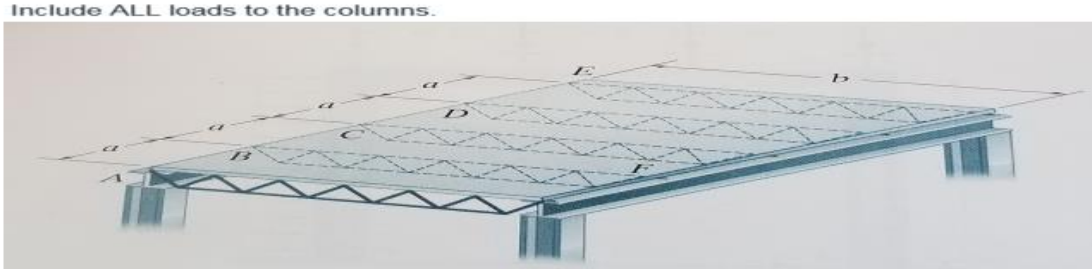


Figure 2-13. Homework problem that asked students to quantify dead and live loads for a portion of a floor in an office building and then trace and quantify these loads through the beams and columns supporting the floor.

This homework problem represented loads acting on the structure with more tangibility to real-world conditions and engineering tools because it required students to determine and combine dead and live loads with references used in practice (e.g., the Oregon Structural Specialty Code (OSSC) and ASCE Standard 7-16 as referenced in the problem statement). The information provided in the problem statement also made this representation more tangible to project/stakeholder constraints because it laid out the framing geometry and functional use of the floor (office space), which influenced the magnitude of the dead and live loads acting on the structural elements. However, it did not explicitly ask students to keep the dead and live loads separate when determining the reactions of the joists and girders or for the load supported by the columns. Again, in the workplace environment, these loads would need to be kept separate to determine the appropriate load combination that control the demand on the joists, girders, and columns, and eventual foundation elements supporting the columns.

Similarly, in another homework problem for a different course (Figure 2-14), students were given the dead and live load acting on a beam and asked to determine the flexural demand (M_u) on the beam as a result of these loads.

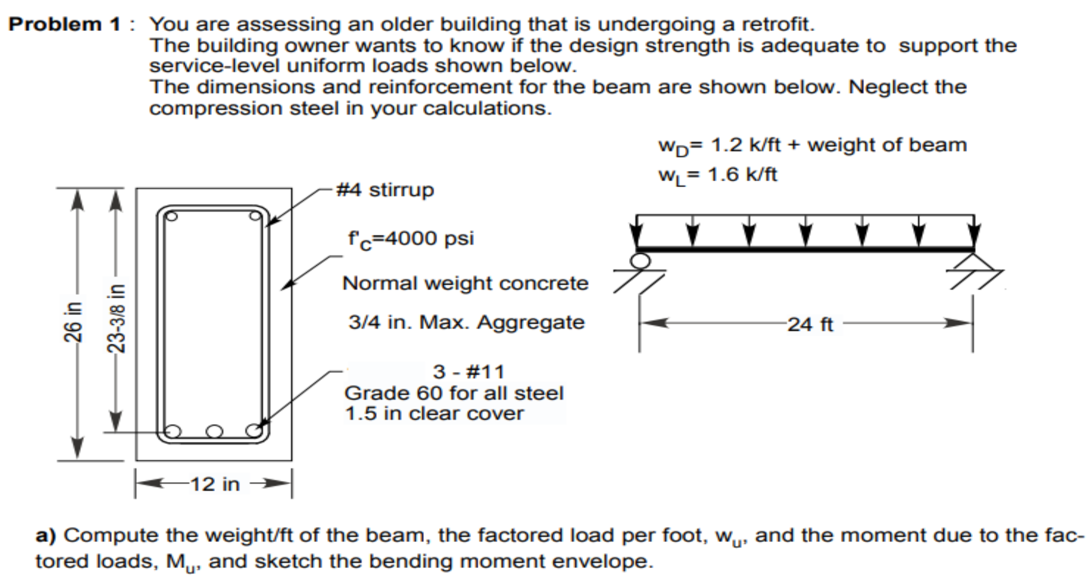


Figure 2-14. Homework problem that asked students to determine the ultimate flexural demand (M_u) of the given beam with the given dead and live loads.

The given loads for the problem in Figure 2-14 were to some extent tangible to the real-world because they were distinguished by their load type (dead versus live). This representation was also somewhat tangible to project/stakeholder constraints via the context provided in the problem statement, as well as in the practice of engaging students to determine total dead load by calculating the self weight of the beam from its existing dimensions. The factored (combined) load that the students were asked to calculate was also tangible to engineering tools because students were required to determine appropriate load combination for the dead and live loads from an engineering standard (ACI 318-14). This representation could be made more tangible to real-world conditions, project/stakeholder constraints, and/or engineering tools by providing even more context to how those tangible traits influenced the magnitude of the dead and live loads. Furthermore, while it was absolutely necessary to combine the loads to determine the flexural demand on this single beam, it would also still be worthwhile to keep the loads separated for determining the reactions supporting either side of the beam so that those loads could be combined with the appropriate load combination if students were asked to analyze the columns supporting the beam.

Thus, Figures 2-13 and 2-14 illustrate that even when loads were initially represented with greater degrees of tangibility, that tangibility can be diminished in subsequent representations if the types of loads were not kept separate throughout the analysis. Furthermore, designing and analyzing elements in isolation from other elements limited the opportunity for students to be exposed to when and why it is important to keep loads separate because when designing an element in isolation the load can be combined at the outset without any consideration for what different load combinations may need to be used for subsequent elements. In structural engineering practice, beams, columns, and other elements do not exist in isolation and so the loads these elements resist are always tangible to adjacent elements and how loads flow through the whole structure.

An example of a subsequent load representation that kept loads separate were the shear and moment envelopes students were asked to create in the problem statement from Figure 2-8. The problem presented in Figure 2-8 asked students to keep dead and live load separate as they determined the flexural and shear demands acting on a beam and while they constructed their shear and moment envelopes.

Figure 2-15 shows the solution for this problem provided by the instructor after the completion of the assignment.

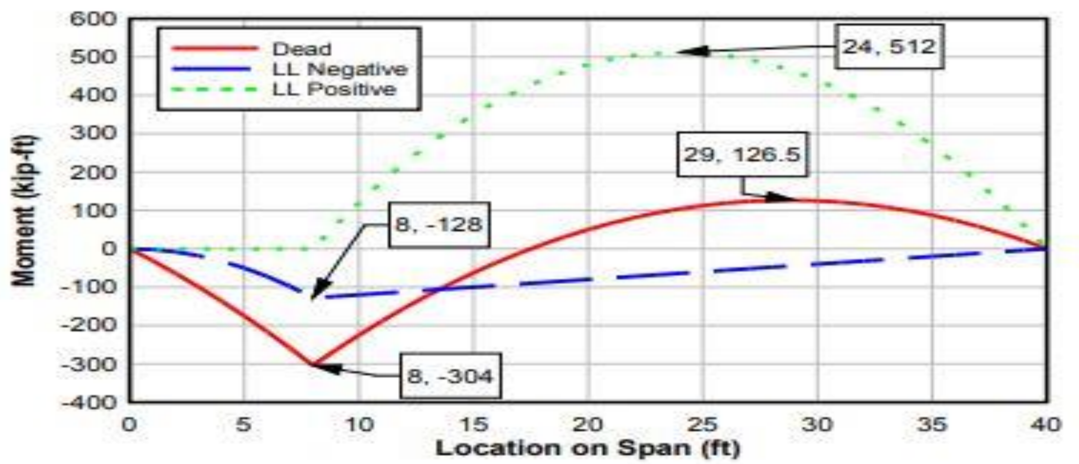


Fig. 1 – Moment diagram for dead load and moment envelopes for live load (all at service levels)

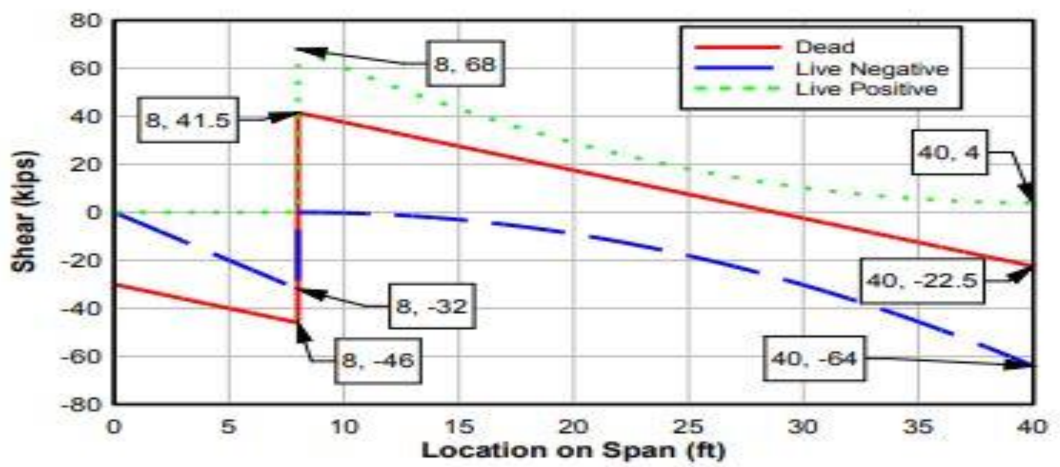


Fig. 2 – Shear diagram for dead load and shear envelopes for live load (all at service levels).

Figure 2-15. Solution to a homework problem that asked students to determine the moment and shear envelopes due to dead and live load acting on a beam.

The top image in Figure 2-15 shows the maximum induced flexural moment across the span of the beam due to dead and live loads separately. The bottom image in Figure 2-15 shows the maximum induced shear across the span of the beam due to dead and live loads separately. Furthermore, for this assignment, students were asked to consider a variety of locations that the live load could be applied along the beam to produce positive and negative moment and shear in the beam (represented by the "Live Negative" vs. "Live Positive" curves in both images in Figure 2-15). This further increased the tangibility of the loads represented in the problem to the real-world because it required students to not only consider differences in load type, but also load location. By asking students to analyze the beam with a variety of live loads separated from dead loads, resulting moment and shear loads represented along the beam in the moment and shear envelopes were more tangible to the initial project/stakeholder constraints presented in the problem statement of Figure 2-8. Conversely, if the loads had been combined and expressed as a single moment and shear diagram, these diagrams would be less tangible to the history of the problem (i.e., the project/stakeholder constraints). Furthermore, having students create and reference these diagrams on future problems made this representation and subsequent representations more tangible to engineering tools because these diagrams were tools students could use to readily determine applied location of live load resulting in the worst case positive and negative moments and shears.

Overall, the examples presented above demonstrate how representations of the concept of load spanned from nearly complete abstract forms to being tangibly connected to real-world conditions, project/stakeholder constraints, and/or engineering tools. Findings from this study indicate that load representations situated in the workplace environment tended to be more tangible to real-world conditions, project/stakeholder constraints, and engineering tools. Load representations situated in the academic environments, on the other hand, were represented with varying degrees of tangibility ranging from having none, some, or all the tangible traits. In the workplace environment, load representations were never provided without context and always had to be formulated by an engineer at some point. This practice of formulation yielded greater tangibility. Conversely, load representations in academic environments were often presented with little to no context, thus yielding varying degrees of tangibility. Figure 2-16 illustrates qualitatively where the academic representations fall on the spectrum of tangibility in relation to one another.

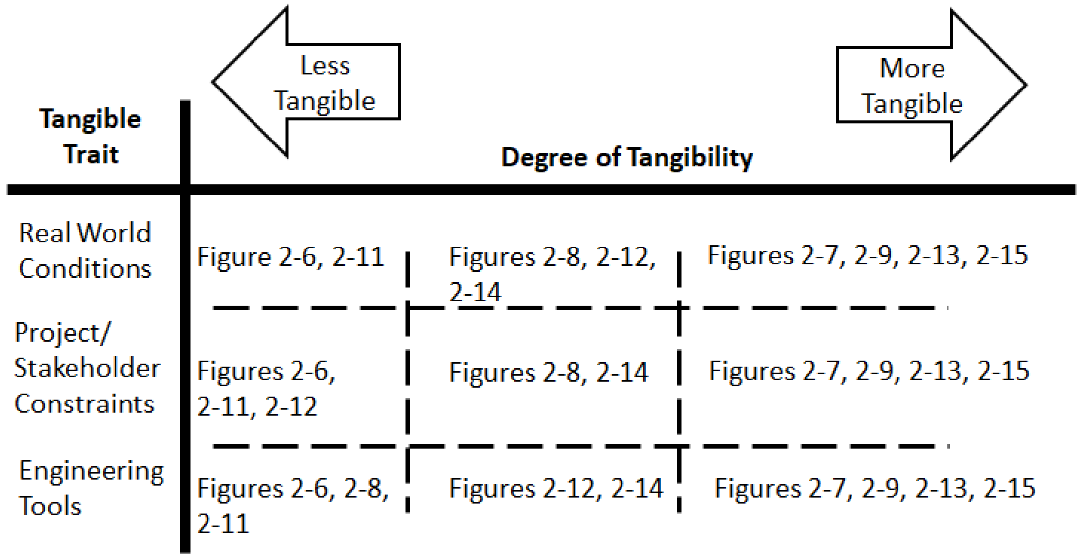


Figure 2-16. Academic representations' degrees of tangibility.

2.7 Discussion

Overall, the findings indicate that the sociomaterial contexts of CRs in the workplace environment made them always tangible to real-world conditions, project/stakeholder constraints, and engineering tools; whereas the sociomaterial contexts of CRs in the academic environments made them typically less tangible to similar real-world conditions, project/stakeholder constraints, and/or engineering tools. Therefore, the degrees of tangibility spectrum can be used as a framework for describing how sociomaterial contexts of CRs in academic environments are aligned with tangible traits of CRs in the workplace environment.

Previous research on the engineering education-practice gap has frequently noted broad differences in the social and material contexts that engineers and students operate within (Brunhaver et al., 2017; Bucciarelli, 1988; Litzinger et al., 2011; Newstetter & Svinicki, 2014; Sheppard et al., 2007; Trevelyan, 2007, 2010), but with little explicit focus on CRs. Since concepts and how we present them to students are such an important consideration in curriculum development (McCracken & Newstetter, 2001; Streveler et al., 2008), it is worthwhile to understand and describe how differences in sociomaterial contexts across workplace and academic environments influence CRs, and thereby contribute to the education-practice gap. Situated cognition has offered the framework for identifying the influence differences in the sociomaterial contexts have on cognition (Johri & Olds, 2011), and tangibility provides a meaningful way of understanding and describing these difference to identify how and when concepts in education can be represented in more authentic sociomaterial contexts to the workplace.

For example, as students engage in engineering activities using less tangible CRs, their conceptual knowledge formation may be limited to decontextualized scenarios thereby limiting their ability to navigate similar CRs within the sociomaterial contexts of the workplace (McCracken & Newstetter, 2001). Similarly, previous research of the engineering workplace demonstrated that practicing engineers' knowledge is distributed across sociomaterial contexts to solve complex problems, while the engineering student primarily gains experience solving simplified and isolated problems (Johri & Olds, 2011; Jonassen et al., 2006; Trevelyan, 2007, 2010) wherein CRs are likely to have a lesser degree of tangibility.

To better prepare students for complex and open-ended problems they will encounter in the workplace, we should consider exposing students to activities that require them to engage with and represent concepts in more tangible ways. Figuring out which ways to represent concepts more tangibly in curricular activities requires in-depth exploration of how concepts are represented during common workplace activities, and that varies across engineering disciplines. Hence, the value of this research, and similar future research of other engineering disciplines, is that it uncovers the uniquely tangible ways engineering concepts are represented within specific disciplinary workplace environments and when and where such representations are appropriate to integrate into academic environments.

That being said, it is important to discuss the purpose of the academic CRs within the context of each course studied and in academia more broadly. The two structural theory courses studied are primarily focused on teaching structural analysis and therefore dedicate significantly more time teaching students how to determine the effects of loads on structures rather than determining the loads acting on the structures. The steel design and reinforced concrete design courses are primarily focused on design and therefore dedicate significantly more time teaching students how to design safe and economic structures for resisting loads and their induced effects rather than determining those loads acting on the structures.

Furthermore, often the activities within these courses and other engineering courses are introducing single or a limited number of concepts at a time and meant to give students initial exposure and practice with those concepts in an isolated, simplified context, which inevitably leads to less tangible representations. By simplifying the contexts of these activities, instructors can expose students to more and a variety of activities (example problems, homework problems, lab exercises, etc.) so that students are provided with multiple opportunities to practice each concept. For example, the homework problem presented in Figure 2-14 is meant to give students practice analyzing the beam that is already designed for them and assessing if it is sufficient in carrying the given applied loads. Asking students to determine those applied loads and then keeping the loads separate so that they could be then used to determine the demand on the columns supporting the beam is beyond the scope of the problem. Asking students to do this would make the problem more robust and authentic to design activities in practice, but would take longer and potentially limit the amount of practice the students get with other beam design and analysis problems and concepts.

One might then ask when students are exposed to the important structural engineering activity of determining loads? Three of the four courses studied dedicated the first couple of weeks to determining loads and using load combination equations, and many of the representations presented in the results came from these earlier weeks in the courses. The other course always represented loads as “Given” values. This is, unfortunately, fairly common in structural and civil engineering curriculum around the country as many courses dedicated strictly to determining loads are offered at the graduate level and/or as electives for undergraduates (Koch, Goff, and

Terpeny, 2010). The institution studied in this paper does offer a 1-credit split level undergraduate/graduate elective course dedicated to determining loads, but limits enrollment to about a dozen students and is offered only one term per year. The ethnographer had previously taken this course in their graduate studies, but the course was not offered during the academic terms when this study was conducted. While an ethnography of this course most likely would have yielded CRs with similar tangibility to those observed in the workplace, it is far more common in structural engineering curriculum across the country for students to be exposed to CRs of loads in courses similar to the four observed in this study (Koch et al., 2010), and therefore these courses provide better access into understanding contributing factors of the education-practice gap.

It could be reasonably inferred that CRs of loads with limited tangibility do not prepare students to think critically about where loads come from and how they permeate throughout the design of an entire structure. For example, when load values are just given with no context as to where they come from, students may not develop a quantitative sense of common, reasonable, and/or acceptable values for certain loads. Thus, we are potentially limiting the opportunities of students' academic training to simultaneously develop engineering intuition for sensible load values.

2.7.1 Recommendations

So how can instructors and curriculum improve the tangibility of loads to enhance the utility of students' academic experiences in preparing them for the workplace? How do we balance valuable time in class for other course outcomes? The following recommendations are presented in order of their ease of adoptability for instructors into their existing curricula. To start, some of the academic examples presented above demonstrate ways for integrating greater degrees of tangibility to the structural engineering concepts students engage with during problem solving. For example, integrating drawings, pattern loading, and determining the load path to subsequent design elements provide students with greater exposure to tangible load representations so that loads are less likely to be a nebulous concept when they enter the workplace.

Another example of tangible representations that aligns with workplace practices is to represent loads in a FBD as itemized values (i.e., explicitly defined as a dead load, live load, or an environmental load). Furthermore, instructors could consider the size, location, and purpose of the structure the FBD is representing to conceptualize a sensible magnitude for the load type acting on the structure. This simple addition to any CR of load adds no additional time for the student in solving the problem, but increases their exposure to different load types and relative magnitudes. Similarly, for engineering problems given to students, the tangibility of the problem can be improved by contextualizing any given numerical value as opposed to those values being represented simply as a number and a unit. Another relatively efficient practice to implement is to reinforce the practice of keeping loads separate throughout and briefly demonstrate how these separate loads transfer to subsequent elements. Combining loads for any element of interest is then a simple matter of arithmetic and can be demonstrated in a short amount of time.

A somewhat more time intensive, but valuable pedagogical activity, exposing students to workplace contexts and activities is with projects entailing design and analysis of full structures. Of the courses included in this study, one included a term-long building design project and another had two smaller projects wherein one dealt with quantifying and locating all the potential loads acting on a structural system. Projects in structural engineering education could revolve around students having to design all the columns and beams (and perhaps other structural elements depending on time) for a 3-4 story building as a group throughout a term. This process would expose students to quantifying and locating all their different loads and keeping those loads separate as they move through designing the elements from the roof down to the ground floor and perhaps even do some preliminary analysis on the foundation elements. Providing students with preliminary architectural drawings for the structure as their starting point would allow students to gain experience reading drawings and grappling with various architectural constraints such as floor heights and clear space, which further enhance the tangibility of their loads and other structural engineering concepts. Such project-based learning has been demonstrated to better prepare students for the workplace environments they will encounter as professionals and improve their conceptual understanding (Prince & Felder, 2006; Thomas, 2000).

Provision of tangible representations, such as structural plan sets of actual structures, and subsequent use of those representations throughout a course may also be beneficial for students. Instead of textbook problems that ask students to analyze and/or design beams, columns, and frames in isolation, the instructor could instead assign analysis and design problems of actual beams, columns, and frames that could be found in the structural drawings. This would expose students to reading and interpreting structural drawings to determine loads and boundary conditions on their FBDs. Such a practice will also expose students to complexities of design, such as architectural changes that require them to go back and reevaluate their loads and demands on previously designed structural elements and determine whether they need to be redesigned. In this way, loads as well as other structural engineering concepts would always be tangible to real-world conditions, project/stakeholder constraints, and engineering tools.

These recommendations are, however, all focused around structural engineering education, but it is important to frame the value of our findings within the broader engineering education community. The idea behind tangibility is not unique to the concept of loads. All engineering concepts can be represented with some degree of tangibility. This is not to say that the purely abstract CR has no purpose, but more of an argument for instructors to consider how concepts are represented after the initial abstract representation is introduced.

Within situated cognition, we can think of tangibility as the extent to which academic CRs are connected to the sociomaterial contexts of the workplace environment. To better understand these workplace contexts, the researchers recommend similar exploratory studies of the workplace within various engineering disciplines. It is unrealistic to expect the curriculum to perfectly mirror the workplace and nor should it as all workplaces are different and not all students will end up at the same workplace. There is value in some degree of abstract ubiquitous curriculum to prepare students for the myriad of professions they might explore in their careers. This is the value behind exploring the workplace of different engineering disciplines, because tangibility begins where the abstractness ends, and tangibility can be different depending on the workplace environment. Through such explorations, we can identify which sociomaterial contexts and activities are common within and across disciplines and begin mapping where tangibility is a worthwhile pursuit in the curriculum.

2.8 Conclusion

The purpose of this research was to explore in depth how loads, a core structural engineering concept, were represented in a workplace environment and multiple structural engineering courses. Previous research has broadly explored the engineering workplace, but little to no research has focused on exploring a specific engineering discipline within both academic and workplace environments for means of comparison. By exploring these environments within a specific discipline using ethnographic methods, we were able to provide a more nuanced description of the education-practice gap unique to structural engineering, but also provide potential value in the broader discussion of improving engineering education. Through this exploration, we developed the notion behind tangibility of loads to express how the concept of loads was represented in tangible ways in the workplace compared with some equivalent or lesser degree of tangibility in the courses studied. Tangibility allows us to qualitatively characterize how the sociomaterial contexts embedded in both the workplace and academic environments influence the ways in which we represent and come to understand certain concepts. It should be noted that the ways in which CRs were described as being tangible in this paper are not exhaustive and CRs can be tangible in other ways that are more or less unique to specific engineering disciplines. Therefore, we suggest that within a situated cognition framework, tangibility of CRs be further explored within other engineering disciplines to better understand how, where, and when concepts can be represented in more tangible ways in the curriculum.

Chapter 3 – Application of Codes in Structural Engineering Practice and Education

3.1 Abstract

Codes and standards are important tools in civil and structural engineering, but how they are applied in the workplace in comparison with how they are taught in undergraduate engineering education has been understudied. The purpose of this research is to explore the social and material contexts wherein codes are applied in a structural engineering workplace and in undergraduate structural engineering courses to better understand the alignment of these two environments. The researchers employed an ethnographic approach to participate in and observe the social and material contexts wherein engineers and students apply codes. Both students and engineers were observed applying codes prescriptively, however engineers also had to apply codes with a more evaluative approach in certain scenarios. Students were never exposed to similar scenarios in their courses. Based on these findings, the authors provide some recommendations for engineering education to provide students with more of an evaluative understanding of codes that is less reliant on a limited prescriptive understanding of code procedures.

3.2 Introduction

Civil engineering curriculum has been considered insufficient in providing undergraduates what they need to know to be successful in the workplace (Aparicio & Ruiz-Teran, 2007; Balogh & Criswell, 2013; Solnosky, Schneider, Kottmeyer, & Zappe, 2017). Common areas of insufficiency cited in engineering education are: communication, teamwork, and leadership, and proficiency with advancing technologies (Brunhaver et al., 2017; Johri & Olds, 2011; Kelly, 2008; Litzinger et al., 2011; Trevelyan, 2007, 2010). Communication, teamwork, and leadership are broader skillsets that apply to all engineering disciplines, while *technologies* vary from discipline to discipline. Within civil engineering, and structural engineering more specifically, *technologies* have been defined as problem solving *tools* (ASCE, 2008; SEI, 2013).

In structural engineering, the word *technologies* might bring to mind software programs for structural analysis, but underlying these programs are a bevy of text-based technologies, such as building codes and standards. Building codes and standards—hereto simply referred to as *codes* for brevity—are *tools* (Batik, 1992) that are constantly advancing and require proficiency from structural engineers to use them appropriately in practice (Solnosky et al., 2017). Proficiency with codes requires comprehension of the structural engineering concepts represented within them (Rumsey, Russell, & Tarhini; 2010; Solnosky et al., 2017). These same concepts, however, are often taught in isolation from codes—if the codes are taught at all—in undergraduate structural engineering education (Kelly, 2008; Koch et al., 2010; Solnosky et al., 2017). This is at least partially due to a commonly perceived educational notion that fundamental conceptual understanding must be established before teaching students how to use technologies; otherwise students will have a "black box" understanding of said technologies (Center for Global Standards Analysis, 2004; Rumsey et al., 2010; SEI, 2013).

While this is a valid educational concern, situated cognition theory posits that our understanding of concepts is bounded within the social and material (sociomaterial) contexts wherein we learn and apply said concepts (Johri & Olds, 2011). Therefore, teaching concepts in isolation from the sociomaterial contexts of codes may be contributing to students' deficiencies with the technologies of codes when entering the workplace, and thereby limiting the application of their fundamental conceptual understanding. An improved understanding of the use of codes in academic and workplace settings would facilitate improving undergraduate education. Thus, the purpose of the research presented herein is to answer the following research question:

How are structural engineering concepts represented through the sociomaterial contexts of code applications in academic and workplace environments?

3.3 Background

Building codes and standards are constantly evolving tools that provide requirements and/or guidance from structural engineers in designing safe structures (SEI, 2013; Solnosky et al., 2017). The terms codes and standards are frequently used interchangeably colloquially by instructors and engineers (Kelly, 2008). The following sections aim to briefly define codes and standards, demonstrate how these tools contain conceptual representations important to structural engineering and what this means in terms of situated cognition, present various opinions on the roles of these tools in engineering education, and then present studies with similar methodologies before outlining our methods.

3.3.1 Codes and Standards

When discussing codes and standards in engineering, there are important differences in their meaning and application across different engineering disciplines (Kelly, 2008). Within civil engineering, standards mostly pertain to design requirements or considerations for public welfare and are frequently referenced by code regulations; which causes many engineers to frequently refer to both standards and codes as simply "codes" even though they are different (Kelly, 2008; Quinn & Albano, 2008).

In the United States, most building codes are modeled off one or more of the International Code Council's (ICC) 15 international codes, such as the International Building Code (IBC), and are administered at the state or local jurisdictional levels (Kelly, 2008). In structural engineering, these codes reference and delegate certain design requirements to the standards for all major structural materials and analysis procedures (Kelly, 2008). For example, "most building codes, which are mandatory regulations in their jurisdiction, reference ASCE's standard for minimum design loads" (i.e., ASCE 7) (Kelly, 2008, p. 61). Building codes have been described as parent-codes to the standards they reference, and these standards are then referred to as child-codes (Solnosky et al; 2017). For clarity and consistency we will refer to building codes and standards as *codes* throughout the rest of this paper.

3.3.2 Situated Cognition and Conceptual Representations in Codes

Codes are written by committees of experts from various fields who over the last century have drafted and published ever expanding codes that have evolved with our knowledge of how structures behave (Kelly, 2008) by establishing newer heuristics and prescriptive requirements (SEI, 2013; Quinn & Albano, 2008). Thus, these tools have drastically changed the profession of structural engineering and how engineers represent fundamental concepts during design activities (SEI, 2013). Concepts are considered units of knowledge that function as hierarchical organizers for a discipline's knowledge domain (Perkins, 2006; Rittle-Johnson, 2006; Streveler et al., 2008). For example, the concept of local buckling is a concept hierarchically organized within the concept of buckling, and encompassing the concept of lateral torsional buckling.

While we might think of concepts residing within the individual's mental schema, we represent concepts in the real-world and thereby demonstrate our conceptual knowledge through the social and material contexts of language, text, diagrams, symbols, equations, etc. (Lemke, 1997; McCracken & Newstetter, 2001). For example, the concept of wind loads acting on a structure are represented through the material context of diagrams, equations, and tables in ASCE 7, and also within the social contexts of the environment ASCE 7 is being applied in and the evolution of this code's development by committees over time. Situated cognition is a learning theory that then argues if sociomaterial contexts mediate our conceptual knowledge, they also shape and are inextricably connected to it (Johri, Olds, & O'Connor, 2014; Lemke, 1998). An implication of this theory then is knowledge transfer to novel contexts is limited (Bransford et al., 2000; Carraher & Schliemann, 2002; Lave & Wenger, 1991). Therefore, the structural engineering profession's use of codes in design is a sociomaterial context wherein structural engineering concepts are represented, and when these sociomaterial contexts differ across academic and workplace environments, engineering education is hindered in its applicability to practice (Johri & Olds, 2011). That being said, there are a variety of opinions on how, if at all, codes should be taught in engineering education.

3.3.3 Codes in Structural Engineering Education

Within structural engineering, certain codes have become commonplace in the curricula while others less so. For example, it is fairly common for material-specific design courses to introduce students to the design codes relevant to that material (e.g., most reinforced concrete design courses expose students to using ACI 318) (Kelly, 2008; Rumsey et al., 2010; Solnosky et al., 2017). However, jurisdictional codes and ASCE 7 often receive little or no attention in undergraduate structural engineering education, causing parent-child code relationships to go unnoticed by students (Koch et al., 2010; Solnosky et al., 2017).

Previous research and changes to both ABET criteria and ASCE's *Body of Knowledge* (BOK) demonstrate a myriad of opinions on whether codes should receive more or less attention in an undergraduate engineering education. For example, Shealy, Kiesling, & Smail (2015) found in a survey of over 120 civil engineering faculty and AEC industry professionals that these two groups both generally believe codes are an important topic to teach in undergraduate education. Conversely, a separate Delphi survey of 32 structural engineers noted that codes should be primarily taught at the master's level and within the first five years of practice (Balogh & Criswell, 2013).

ABET criterion 5 has relegated the incorporation of codes into engineering education to a "curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier coursework" (i.e., a capstone course) (ABET, 2018). ASCE's commentary on ABET criteria for civil engineering programs notes that codes must be integrated into the design component of the curriculum (ASCE, 2019b; Kelly, 2008) and ASCE's second edition of the BOK (BOK2) defines a specific technical outcome (technical outcome 8) that notes students should be able to apply engineering tools, such as codes, to engineering problem solving before entering the profession (ASCE, 2008). However, ASCE's third edition on the BOK (BOK3) removes this technical outcome and uses less explicit language in their more broadly defined outcome of "Design" which simply notes that students "must consider" codes at various stages of the design process (ASCE, 2019a). The Structural Engineering Institute (SEI) noted in their *Vision for the Future of Structural Engineering and Structural Engineers: A case for change* (2013) report an overreliance on prescriptive codes in the profession and a lack of fundamental conceptual knowledge on the behavior of materials in structural engineering education as factors contributing to reducing the role of the profession in society from engineers to technicians. This report does distinguish performance-based codes as a better tool for the future of the profession than prescriptive codes (SEI, 2013). Some codes, such as ASCE 7, have been moving towards performance-based procedures and the SEI report strongly encourages other codes to do so (SEI, 2013).

While the aforementioned surveys, learning outcomes, and reports espouse various beliefs about the roles of codes in education and practice, they all note that codes are prevalent tools used in design and generally should have some role in the curriculum. However, current undergraduate education of codes is believed to be limited due to: time available to cover code related material, codes being taught in isolation from other course/curriculum content, variability in faculty knowledge of codes, limited resources to help faculty teach codes, and codes being taught with passive ad hoc techniques (Center for Global Standards and Analysis, 2004; Kelly, 2008; Moon, 2010; Solnosky et al., 2017). That being said, little to no research has been conducted exploring the sociomaterial contexts wherein codes are applied in workplace and education environments to gain a better understanding of how these contexts can be aligned across environments to better prepare students for the proficiency they will need with codes upon entering the workplace. Exploring these contexts in both environments is well suited for ethnographic methods.

3.3.4 Ethnographic Studies

Ethnographic methods situate a researcher, or team of researchers, within a specific environment where they can gain access to a rich, descriptive understanding of the sociomaterial contexts participants operate within via participation in and/or observations of these contexts (Emerson et al., 2011). This method has been identified as a way to study situated cognition in engineering education (Case & Light, 2011; Johri et al., 2014), but has been seldom used. Furthermore, most ethnographic studies in engineering education have focused on broader engineering education, within either a workplace *or* academic environment, using purely observation techniques and no participation.

For example, Vinson et al. (2017) conducted an ethnography wherein they observed 20 early career engineers from nine different disciplines in five distinct workplace environments. Vinson et al. (2017) observed that as early career engineers become more exposed to codes and other text-based tools in the workplace, they become more likely to use these resources in problem solving as well. Fewer examples of ethnographic studies in academic environments exist. One, however, conducted by Stevens et al. (2008) observed four engineering students in different disciplines throughout their four-year undergraduate experience and noted that lower level courses generally had the students use prescriptive approaches to reach singular right answers, while upper level courses exposed them to more open-ended problems.

One example of an ethnographic study that focused specifically on structural engineering, observed 19 structural engineers at three different workplace environments (Gainsburg et al., 2010). Gainsburg et al. (2010) observed codes being used as repositories of historically established knowledge to meet project time constraints, suggesting they were used in a prescriptive manner. The authors know of only one discipline specific ethnography wherein the researchers participated in the environment they were observing. Bornasal et al. (2018) conducted a participant-observation ethnography of a transportation engineering firm wherein they observed engineers referencing codes to quickly make design decisions. Participation-observation ethnographies allow the researchers to gain a richer understanding of the participants and environments they are studying because the addition of the participation dimension can provide the researcher(s) with additional data for challenging or confirming observations and therefore adds credibility to the ethnography (Emerson et al., 2011; Walther et al., 2013).

All of the previous ethnographic studies mentioned only explored either workplace or academic environments. There are very few engineering education studies employing any methodology that directly compare workplace and academic environments within a single study (Johri et al., 2014). We believe it is worthwhile to do this in the context of our research so that we can expand our understanding of differences in knowledge application across these environments and offer more meaningful recommendations for the application of codes in engineering curriculum. Therefore, we revisit our research question:

> How are structural engineering concepts represented through the sociomaterial contexts of code applications in academic and workplace environments?

3.4 Methods

A participant-observation ethnographic methodology was adopted to answer the research question via observational access of and experience with code applications in academic and workplace environments. The decision to focus on a specific engineering discipline was to gain a more nuanced understanding of code application in education and practice than what has already been documented in the literature. The decision to focus on structural engineering was because the researcher conducting the ethnography—the ethnographer—has an educational background in this discipline and was able to therefore participate more meaningfully in both environments. Furthermore, codes have been identified as a critical tool in structural engineering practice (Balogh & Criswell, 2013; Gainsburg et al., 2010; Koch et al., 2010; SEI, 2013; Rumsey et al., 2010) and therefore this discipline offers significant opportunities to explore the sociomaterial contexts within only a handful of environments.

3.4.1 Site Selection and Transferability

The academic and workplace environments selected for this study were a private architecture and engineering firm and four undergraduate structural engineering courses, respectively. Both sites are located in Oregon to be geographically accessible for the ethnographer. Selection of these sites was based on the firm's willingness to participate and employ the ethnographer as a part-time intern, and instructor permission to participate in and observe their course. As previously mentioned, ethnography situates the researcher(s) in a specific environment to explore and provide in-depth description of the sociomaterial contexts of the environment. Therefore, the goal of ethnographic research is not to find generalizable results, but to provide rich, detailed descriptions of the environment that is meaningful to the research and education community to transfer within their own contexts (Lincoln & Guba, 1985; Walther et al., 2013).

The following tables provide demographic information for additional context on the instructors and their courses, and the structural engineers in the workplace environment.

Table 3-1

Demographic Information for Structural Engineering Courses Studied

Course	No. students	Lecture (recitation) hours/week	Code(s) used	Instructor teaching (industry) experience in years	Female/male instructor
Structural Analysis I	60	3 (2)	Oregon Structural Specialty Code & abridged portions of ASCE 7-16 in textbook	30 (12)	Male
Structural Analysis II	50	3 (2)	None	36 (29)	Male
Steel Design	67	3 (2)	AISC Steel Construction Manual (15th ed.) & printout sections of ASCE 7-16	1 (2)	Female
Reinforced Concrete Design	60	4 (0)	ACI 318-14	22 (24)	Male

Note. Adapted from Barner, Brown, Bornasal, and Linton (2019, in review).

Table 3-2

Demographic Information for Structural Engineers at the Workplace Environment

No. structural engineers	Industry experience in years	No. licensed PEs (SEs)	No. female (male) engineers	No. M.S./M.Eng. degree holders
20*	0-46 ($\mu = 10.3$)	12 (5)	7 (13)	7

*The firm employs 24 structural engineers across three offices, however only 20 were observed in-depth at the office where the ethnographer was participating.
Note. Reprinted from Barner et al. (2019, in review).

All of the instructors that taught a course using a code had sound knowledge of their respective codes and their historical development. All of the codes in the academic environment were observed being used in the workplace environment, albeit the workplace environment more frequently used previous editions. For example, all of the engineers in the workplace environment were observed using ASCE 7-10 over the most recent edition published in 2016. Most engineers were using the 14^{th} edition of AISC's *Steel Construction Manual (SCM)*, while some others were using the 13^{th} edition. One engineer used her own copy of ACI 318-14 while the remaining engineers were using ACI 318-11.

3.4.2 Data Collection, Analysis, and Credibility

Data collection in an ethnography consists of three simultaneous sources: field notes from participant-observations, interviewing, and artifact documentation (i.e., code excerpts) (Johri, 2014; Emerson et al., 2011). During an ethnography, data analysis is occurring simultaneously so that the data collected from these three methods can be used to guide future data collection and triangulate the existing data (Stevens et al., 2008; Walther et al., 2013). Furthermore, the ethnographer consulted two other engineering education researchers familiar with ethnographic methods before, during, and after exiting each environment to improve the credibility of the data collected and analyzed.

Field-notes from participation-observation consisted of the ethnographer initially hand-writing notes of observations during their own use and when others were using or discussing codes. These hand-written notes were immediately typed up following the observation and the ethnographer would develop interview questions for pertinent participants and take pictures of pertinent code excerpts for artifact collection. These pictures were copy and pasted into relevant portions of the field notes to create an annotated description of the episodes wherein codes were discussed and/or applied. Interview questions were asked in formal and informal interviews based on availability of participants. Interview data were used to fill in missing information in the ethnographer's field notes, member checking, and access participant's interpretations of events wherein codes were applied (Emerson et al., 2011; Walther et al., 2013).

Following informal interviews, the ethnographer would revise any relevant field notes. Formal interviews were audio recorded and transcribed by a third party. Following transcription, the ethnographer would review the transcription and initially deductively code excerpts based on specific conceptual representations that participants mentioned pertaining to codes. Following this initial round of coding, the ethnographer would then inductively code transcripts in tandem with field notes and the documented artifacts to create a holistic description of the episodes wherein codes were being discussed and/or applied. At this point, the episodes were descriptive case studies which could then be analyzed and compared with one another to identify common themes across each episode (Yin, 2003). Case studies are considered to be a valuable method for studying and presenting complex phenomena that are indistinguishable from their contexts (Baxter & Jack, 2008; Yin, 2003).

The credibility of the themes derived from the cases was enhanced through participation in *and* observation of both environments for an extended period of time to encounter diverse sociomaterial contexts wherein codes were used (Case & Light, 2011; Johri, 2011). The ethnographer spent three months in the workplace environment arriving at the firm's office each weekday between 7-8 am and leaving between 5-6 pm. The ethnographer worked as an intern for approximately 16 hours per week and conducted observations, interviews, collected artifacts, and analyzed data during the remainder of the work week. As an intern, the ethnographer assisted in 18 different structural engineering projects and observed engineers working on several others within the industrial, commercial, and public sectors.

The ethnographer spent six months in the academic environment over two ten-week terms, enrolling in two classes each term. The ethnographer participated in each class as a normal student would, attending lectures and labs, taking notes, completing homework assignments, and taking exams. Participating in all these activities allowed the ethnographer to gain access to not only how codes were presented in lecture, but also to how students were applying codes on homework, lab assignments, projects, and exams.

3.5 Findings

In general, codes contained several conceptual representations that were used in both environments to prescriptively determine the demand on and/or capacity of various structures. By *prescriptive* we mean that the engineers, students, or instructors utilized a portion of a code to the letter with little to no explicit interpretation of the concepts being represented in their prescriptive approach. Engineering problems encountered in the academic environments typically required students to use a code or codes to find relevant information and apply applicable equations with little to no ambiguity, thus justifying their prescriptive approach. More ambiguous cases that addressed limitations and/or assumptions built into codes were typically only discussed in lecture. Occasionally, students had to assess when more nuanced prescriptive methods in codes needed to be used and then apply them to gain more capacity in their design or reduce their demands. These "sharpening your pencil" calculations, as one instructor frequently put it for using a code's methods for more precise calculations, were also observed in the workplace. However, engineers were more likely to also use evaluative approaches in their application of codes to either reduce their demand, increase their capacity, or to be more conservative than a code's recommendations/requirements. By *evaluative* we mean that the engineers had to rely on sound engineering judgment, skepticism of code provisions, and/or fundamental conceptual knowledge when applying or deciding not to apply aspects of certain codes.

The following subsections present cases from first, the academic environment, and then the workplace environment. The cases presented herein come from field notes of participation-observations in each environment, interview excerpts with engineers and instructors, and artifact documentation of relevant excerpts from codes and design problems for additional context. Not all codes observed in the workplace environment were observed in the academic environments, however all codes used in the academic environment were present in the workplace environment. This is to be expected as there are a substantial amount of codes used in practice that could not all be realistically covered in engineering education. The cases presented are therefore meant to convey broader themes for how codes were applied and interpreted in both environments, rather than make direct comparisons of how a specific code was used in either environment. The cases presented in this section are not meant to be encompassing of all codes, or academic and workplace settings; rather, they are meant to convey themes that can supplement and/or refute existing ideas on the use of codes in engineering education to provide the reader with transferable findings to their own specific contexts.

3.5.1 Academic Environments

In three of the four courses observed, at least one code was utilized by students to some extent when solving structural engineering problems on their homework, recitation assignments, projects, and/or exams. The course that did not use any codes, Structural Analysis II (SA-II), had the primary objective of teaching students how to analyze indeterminate structures using the concepts of equilibrium, compatibility, and constitutive laws. Since this course was not focused on design or determining external loads, it could be argued that there is little to no need for using a code as part of its curriculum. The following subsections therefore present cases from the other three courses wherein a code or codes were presented in lecture and used by students.

3.5.1.1 Academic Case 1 – Strength Reduction Factor and Shear in ACI 318-14

While the SA-II course primarily focused on concepts of equilibrium, compatibility, and constitutive relations, these fundamental concepts are prevalent in any structural engineering course and embedded in many codes. For example, the Reinforced Concrete (RC) Design instructor did mention in lecture that “ACI 318-14 permits us to use equilibrium, compatibility, and constitutive relationships to circumvent the code.” This evaluative approach to ACI 318-14 is further demonstrated within the code itself per section R1.3.2: “The minimum requirements in this Code do not replace sound professional judgment” (ACI, 2014, p. 10). However, no design problems given to the students in this course dealt with a scenario that warranted anything other than a prescriptive application of ACI 318-14.

The instructor for this course did, however, emphasize limitations in ACI 318-14 to provide students with some idea of the assumptions built into this code. For example, in a lecture on shear design of RC beams, the instructor mentioned shear failure is non-ductile and therefore hard to predict. He then stated that ACI 318-14 conservatively accounts for this by reducing the strength reduction factor (Φ) to 0.75 when determining the shear strength of a member. The instructor then mentioned that the AASHTO LRFD Bridge Design Specifications has a better model for equating shear failure than ACI 318-14 does and thus uses a strength reduction factor of Φ = 0.9 for normal weight concrete (AASHTO, 2012, section 5.5.4.2.1). The instructor then presented the class with the equations ACI 318-14 prescribes for calculating the nominal shear strength provided by just the concrete in a RC member, V_c. The instructor noted that the easiest and most common way for calculating V_c is via equation 22.5.5.1 in ACI 318-14 (see Figure 3-1). The instructor then presented the class with Table 22.5.5.1 in ACI 318-14 (also in Figure 3-1) and said that if we want to "sharpen our pencil" for a more detailed calculation and gain more shear capacity, then we can use the least of the equations presented in Table 22.5.5.1. Students were never presented with a design scenario that required them to "sharpen their pencil" and always used equation 22.5.5.1 to determine V_c on homework and exam problems.

22.5.5 V_c *for nonprestressed members without axial force*

22.5.5.1 For nonprestressed members without axial force, V_c shall be calculated by:

$$V_c = 2\lambda\sqrt{f_c'}b_w d \qquad (22.5.5.1)$$

unless a more detailed calculation is made in accordance with Table 22.5.5.1.

Table 22.5.5.1—Detailed method for calculating V_c

	V_c	
Least of (a), (b), and (c):	$\left(1.9\lambda\sqrt{f_c'} + 2500\rho_w \frac{V_u d}{M_u}\right) b_w d$ [1]	(a)
	$(1.9\lambda\sqrt{f_c'} + 2500\rho_w) b_w d$	(b)
	$3.5\lambda\sqrt{f_c'} b_w d$	(c)

[1] M_u occurs simultaneously with V_u at the section considered.

Figure 3-17. Prescribed equations for calculating V_c for nonprestressed members without axial force. Reprinted from ACI 318-14, p. 354.

This case from the RC Design course demonstrates how the instructor clearly identifies a limitation of ACI 318-14 and compares this limitation to a different code (the AASHTO LRFD Bridge Design Specification) so that students are presented with an evaluative understanding for a conservative feature in ACI 318-14. The subsequent presentation on how to prescriptively calculate V_c with the sole emphasis on the more conservative equation—22.5.5.1—for homework and exam problems demonstrates how students are primarily applying a code's prescribed conservative approach with little to no exposure to scenarios that might require a more evaluative approach to justify a less conservative, albeit permitted, solution.

3.5.1.2 Academic Case 2 – Lateral Torsional Buckling Modification Factor in AISC 360-16

Similar to the case presented above, in the Steel Design course, the instructor derived the critical stress equation for the flexural limit state of elastic lateral torsional buckling of wide flange members to illustrate an assumption and factor built into the equation provided in the specification portion (AISC 360) of AISC's *Steel Construction Manual* (*SCM*). To illustrate this case, the following excerpt from an interview with the instructor wherein she was asked: "In what ways do you expose students to assumptions and/or handle limitations in either ASCE 7-16 or the *SCM*?" To which the instructor responded:

> *Yeah, so this is one of the things that I feel like I didn't do that well on, but I think this is one of the big…this is the item. So I did a lot of assumptions, like maybe broken down in almost too much detail, but this is the reason the C_b thing for example, the reason you don't use C_b equals 1.0 is because the lateral torsional buckling equation is based off of the assumption that you have a uniform moment, so that's something built into the equation. […] That is an assumption that's made before it even gets here [points to her SCM], and so I did a lot of that. I limited table use, but I think what I wish I would have done more was maybe that initial review of some strength of materials concepts, some structural analysis concepts, because I think it got to the point where they were just confused. There were too many assumptions floating around, and they didn't know which ones were important and which ones weren't. So, I think…you want to tell them that there are limitations, but you don't want to make them so confused that they don't know which direction to move in.*

Here the instructor is referring to a lecture wherein she derived the ordinary differential equation (ODE) for the critical stress due to elastic lateral torsional buckling (LTB) for the portion of the curve presented in Figure 3-2 where the unbraced length, L_b, is greater than the critical unbraced length corresponding to the development of yield moment, L_r (i.e., $L_b > L_r$).

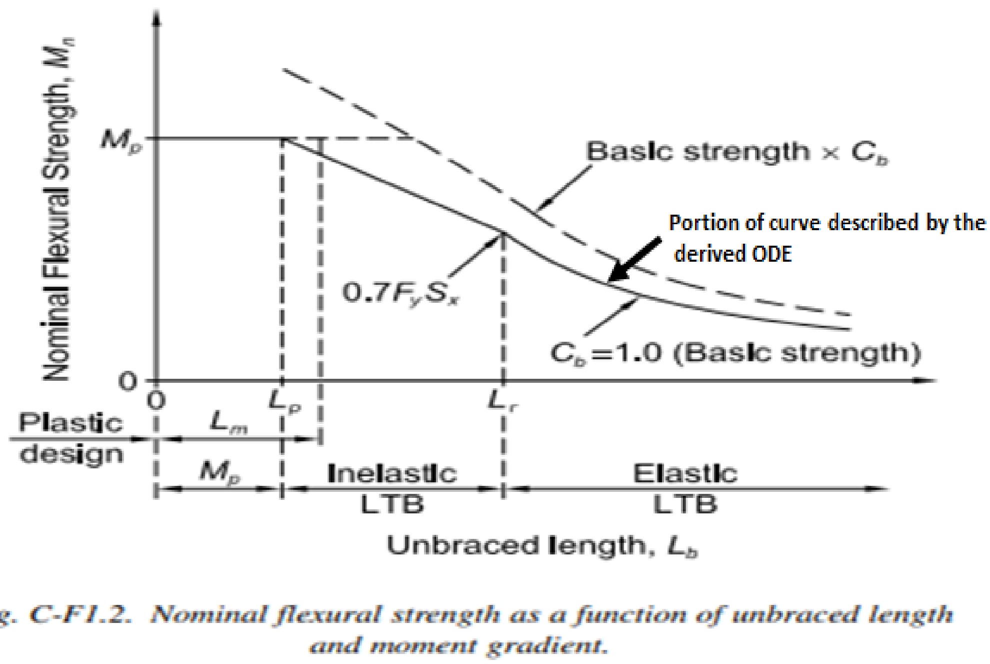


Figure 3-18. Nominal flexural strength and buckling behavior based on unbraced length. Adapted from AISC 360-16, p. 324.

To derive this equation, the instructor mentioned during the lecture that we assumed uniform moment across the beam's unbraced length. However, beams do not always experience uniform moment across their unbraced length and AISC 360 accounts for this by multiplying the derived ordinary differential equation with the factor C_b, where C_b = 1.0 for uniform moment and C_b > 1.0 for non-uniform moment across L_b. The instructor refers to this example in the interview as an example of a time when she broke down an assumption in an ODE derived from theoretical strength of material concepts and how AISC 360 accounts for that assumption with the additional factor, C_b. Students were expected to calculate C_b on a couple of homework problems, but were often told to make the conservative assumption of C_b =

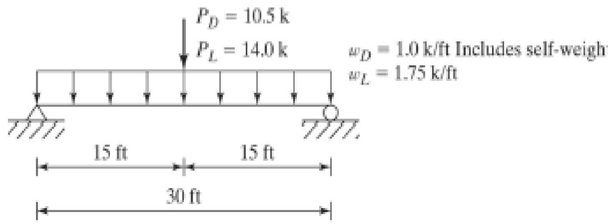
1.0 in their calculations of a wide flange member's nominal moment strength. The instructor mentioned in lecture that most engineers make this same assumption because it is conservative and saves time by not having to calculate a $C_b > 1.0$. The instructor also mentioned in lecture that one of the main reasons she actually taught the class how to calculate C_b was to give students additional practice creating moment diagrams.

This instructor finished her answer to the interview question by noting she wanted to expose students to the limitations and assumptions built into codes, but that she was worried students would be confused if there were too many "assumptions floating around" and subsequently not knowing "which direction to move in" when applying a code. She also mentioned in that interview excerpt that she wants to focus initially on more strength of materials and structural analysis concepts before addressing assumptions and limitations in the codes so that students are less confused as to where these assumptions and limitations come from.

Similar to the previous case, the instructor presented why certain factors exist in their respective codes and the assumptions they are built off of that typically lead to more conservative equations in the codes and how students can prescriptively use the code to perform more detailed, less conservative calculations. Students, however, received little to no practice wherein they were exposed to a scenario that warrants a more detailed and less conservative calculation of C_b since their homework problems either told them when to calculate $C_b > 1.0$ or assume $C_b = 1.0$ with no additional context for why the calculation or assumption should be made. These homework problems came from a single assignment and are portrayed in Figure 3-3 below.

Problem 1

A W24 × 104 beam is used to support the loads shown in the figure below. Lateral bracing of the compression flange is supplied only at the ends. Determine C_b. If $F_y = 50$ ksi, determine if the W24 is adequate to support these loads. Use the equations in Chapter F of the manual to calculate L_p, L_r, and $\phi_b M_n$ and use the appropriate design tables (Table 3-2 and Table 3-10) to check your answers. Check for shear.



Problem 2

A W14×90 of A572 Grade 60 steel ($F_y = 60$ ksi) is used as a beam with lateral support at 10 foot intervals. Assume that $C_b = 1.0$ and compute the nominal flexural strength. (Hint: This is not a standard steel material for wide-flange members. Check local buckling to determine whether it affects M_p.)

Problem 3

Design the lightest W shape beam of 50 ksi steel to support the loads shown in the figure below. Neglect the beam self-weight. The beam has continuous lateral bracing between A and B, but is laterally unbraced between B and C. Determine C_b. Check for shear.

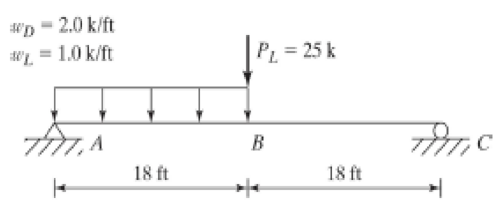
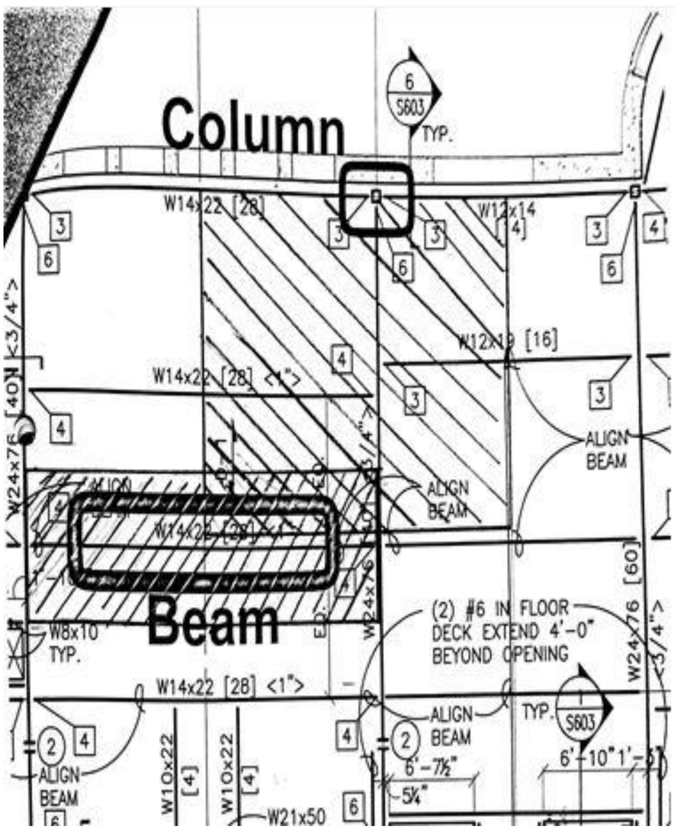


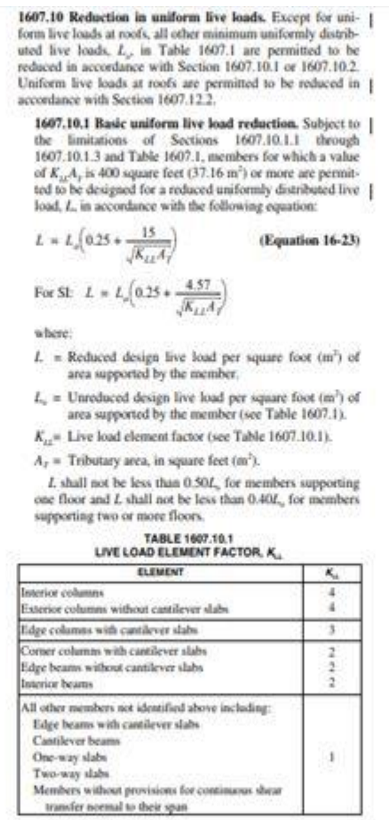
Figure 3-19. Homework assignment for the Steel Design course wherein students had to calculate C_b or assume it was equal to 1.0 in their subsequent calculations for nominal flexural strength (M_n).

This and the previous case from the RC Design course demonstrate how these instructors lectured on limitations and assumptions in their respective codes, while students prescriptively applied their codes on homework assignments and exams with little to no evaluation of these limitations and assumptions. These cases did, however, provide students with some exposure to the importance of reading their respective codes carefully to ensure they were using the appropriate equation prescribed in their codes. The importance of reading codes carefully was emphasized by the instructor of the Structural Analysis I (SA-I) course and demonstrated in the following case.

3.5.1.3 Academic Case 3 – Live Load Reduction in ASCE 7 and OSSC 2014

In the SA-I course, the instructor has some early homework and recitation assignments wherein students were required to navigate the 2014 edition of the Oregon Structural Specialty Code (OSSC) and portions of ASCE 7-16 provided in their textbook for determining live, dead, snow, wind, and earthquake loads. For example, in a recitation exercise, students were expected to use pertinent sections of the OSSC to determine the live load on the column and beam highlighted in Figure 3-4 and if any live load reduction could be applied.





1607.10 Reduction in uniform live loads. Except for uniform live loads at roofs, all other minimum uniformly distributed live loads, L_o, in Table 1607.1 are permitted to be reduced in accordance with Section 1607.10.1 or 1607.10.2. Uniform live loads at roofs are permitted to be reduced in accordance with Section 1607.12.2.

1607.10.1 Basic uniform live load reduction. Subject to the limitations of Sections 1607.10.1.1 through 1607.10.1.3 and Table 1607.1, members for which a value of $K_{LL}A_T$ is 400 square feet (37.16 m²) or more are permitted to be designed for a reduced uniformly distributed live load, L, in accordance with the following equation:

$$L = L_o\left(0.25 + \frac{15}{\sqrt{K_{LL}A_T}}\right) \quad \textbf{(Equation 16-23)}$$

For SI: $L = L_o\left(0.25 + \frac{4.57}{\sqrt{K_{LL}A_T}}\right)$

where:

L = Reduced design live load per square foot (m²) of area supported by the member.

L_o = Unreduced design live load per square foot (m²) of area supported by the member (see Table 1607.1).

K_{LL} = Live load element factor (see Table 1607.10.1).

A_T = Tributary area, in square feet (m²).

L shall not be less than $0.50L_o$ for members supporting one floor and L shall not be less than $0.40L_o$ for members supporting two or more floors.

TABLE 1607.10.1
LIVE LOAD ELEMENT FACTOR, K_{LL}

ELEMENT	K_{LL}
Interior columns Exterior columns without cantilever slabs	4 4
Edge columns with cantilever slabs	3
Corner columns with cantilever slabs Edge beams without cantilever slabs Interior beams	2 2 2
All other members not identified above including: Edge beams with cantilever slabs Cantilever beams One-way slabs Two-way slabs Members without provisions for continuous shear transfer normal to their span	1

Figure 3-20. Recitation assignment in SA-I course wherein students had to determine the live load acting on the highlighted beam and column in (left image) and apply the live load reduction equation from OSSC (2014) (right image) if applicable. Reprinted from OSSC (2014, p. 356).

In an interview with the instructor, he stated that his intention for these assignments was to have students read the codes carefully:

> *And mostly the point there, I guess it's just, it's easy to not read it correctly. I'm not necessarily teaching them in that class how to read ASCE 7, but just making the point that you better read it carefully. […] And then you have to look not just in one place […] So you can't just look in this page right here, there might be relevant information here, here, here, and here.*

Here and in the recitation assignment, the instructor is emphasizing to the students the importance of reading codes carefully and reading all the relevant information before assuming an equation is applicable or not. In the case of the recitation assignment in Figure 3-4 above, students had to carefully read sections of the OSSC to determine if they could reduce the live load demand on the beam and column and then apply Equation 16-23 in the OSSC (2014) correctly. This is the same equation used for live load reduction in ASCE 7-16.

This case is another example of how students were exposed to prescriptively navigating and applying the code to use a more detailed, less conservative equation (live load reduction in this case). Thus, in all three cases provided from the academic environments, students were shown equations in various codes and taught to some extent how they could use more detailed equations subsequently provided in their codes to increase their capacity or reduce their demand. While these cases provided students with some exposure to the assumptions that went into the development of these code equations and their limitations, students were never provided with examples or practice with scenarios where they have to use an evaluative approach to justify using more or less conservative equations from within or outside of their codes. While many of the same codes and equations were observed being used in a similar manner in the workplace, occasional scenarios arose wherein engineers would use an evaluative approach, rather than a prescriptive one, when applying certain provisions in a code.

3.5.2 Workplace Environment

Multiple codes were observed being used in the workplace environment with engineers often navigating more than one code simultaneously in their design activities. In general, the engineers often were using codes to prescriptively calculate loads/demands and check limit states for various structural elements. Other scenarios emerged, however, wherein the engineers had to go beyond prescriptively applying a code and instead had to negotiate an evaluative approach in how they chose to apply certain provisions in various codes. The following cases illustrate these scenarios to provide an overview of what we mean by this evaluative approach and how it differs from the prescriptive applications of codes.

3.5.2.1 Workplace Case 1 – Lateral Stability Factor in NDS 2012

This first case demonstrates a design task wherein the ethnographer had to apply provisions from the American Wood Council's (AWC) *National Design Specification (NDS)* (2012) for lateral stability while designing wood members. For this design task, the ethnographer had to design a hip beam for a canopy structure. When determining the bending capacity of wood beams, a stability factor (C_L) less than or equal to 1.0 must be multiplied to the referenced bending stress capacity of the member. This stability factor potentially reduces the design capacity of the member to account for the effects of LTB. The *NDS* permits $C_L = 1.0$ (no reduction) if the bending member has sufficient lateral support per section 3.3.3.3: "When the compression edge of a bending member is supported throughout its length to prevent lateral displacement, and the ends at points of bearing have lateral support to prevent rotation, $C_L = 1.0$" (AWC, 2012, p. 15). The *NDS* then provides subsequent provisions for calculating C_L based on the geometry and material properties of the member. The ethnographer was not sure if he could safely assume the rafters framing into the hip (see Figure 3-5) provided sufficient lateral support to justify using a $C_L = 1.0$, or if he should be conservative (but spend more time) following the subsequent provisions in the NDS to calculate a $C_L < 1.0$.

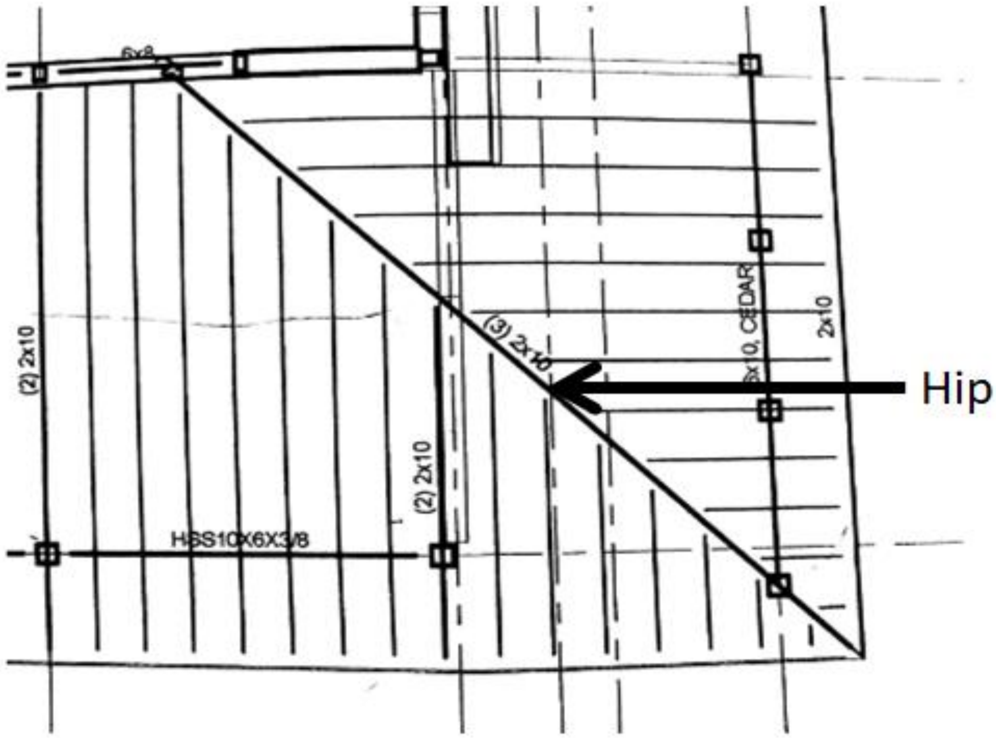


Figure 3-21.Canopy framing plan illustrating rafters framing into the hip of the canopy.

The rafters framed into the hip every 24 inches but the *NDS* does not explicitly address whether this spacing was sufficient lateral support, leaving the ethnographer uncertain. The ethnographer asked a senior engineer whether the rafters provided enough lateral support to merit C_L = 1.0 and the senior engineer said that the rafters provided more than enough lateral support. In a later interview with this same engineer, the ethnographer asked how he was so certain the rafters would provide sufficient lateral support. To answer the question, the engineer shared an anecdote from a field trip to a structures testing lab during a graduate course he had taken wherein he got to observe the amount of force required to prevent LTB in a slender steel beam:

> **Engineer:** *…as the relatively slender beam started to try to laterally torsionally buckle, he [the instructor] said, 'Okay, hand someone a yardstick,' he said, 'Just push on it.' There's several thousand pounds being applied to this and you're just pushing on it with a yardstick, and now it's not laterally torsionally buckling. So that real simple connection of like, 'Oh, this is what a brace force is and oh, doesn't actually take that much.' It's just about restoring equilibrium to make sure that it yields in plane and doesn't buckle out of plane, and actually doesn't require that much force. […]*
>
> **Ethnographer:** *Yeah. And in my head I was even thinking, I was just like, 'I don't feel comfortable saying that these rafters provide lateral stability,' just because I had no concept of…*
>
> **Engineer:** *What it takes.*

This episode demonstrates that since the ethnographer lacked a fundamental conceptual understanding of how much a brace force should be and how frequent one is needed throughout a span to provide lateral stability, he was unable to use an evaluative approach in interpreting the *NDS* for determining $C_{L.}$

3.5.2.2 Workplace Case 2 – Risk Category in ASCE 7

The previous example demonstrates how fundamental conceptual knowledge allows an engineer to take an evaluative approach to a code and justify a less over conservative design. Other cases in the workplace environment conversely demonstrated how engineers sometimes use an evaluative approach to applying codes based on their engineering judgment and/or skepticism of a code's minimum requirements to justify being more conservative than said code's minimum requirements. An example of this type of case comes from an observation of three engineers working on a project that had some uncertain site conditions pertaining to the foundation of a nearby existing structure. One of the engineers quipped after their meeting that their department head "drew the short straw and had to stamp this project" implying that the uncertain site conditions made it a liability for whoever had to stamp the project. The department head overhears this and says, "Wait a minute…" to which the same engineer that made the joke quickly replied that the project was risk category II as defined in ASCE 7. The department head retorts that just because ASCE 7 permits a structure to be risk category II, does not mean that it should not be a higher risk category. Higher risk categories are designed for larger forces and therefore more conservatively designed than lower risk category structures.

The ethnographer asked the department head what he meant by this in a later interview and the department head alluded to a specific excerpt from the commentary in ASCE 7-10 as an example of the code permitting structures containing toxic, highly toxic or explosive substances being classified as risk category II. The excerpt from the interview is provided below for additional clarity:

> *…somebody wrote in the 7-10, some committee, somehow, that said, basically, if you can contain, if you've got chemicals, and you can contain them and they won't spill over to the neighbor after an earthquake, that you're fine. You can be level two. And I just think that is—and it used to be in the commentary that it kind of made that inference that—and it wasn't real super clear. But people would take that exception and go back to the commentary and say, 'You know, this is really what it says.' Well, now it's explicit in the code [ASCE 7-10 C1.5.3, presented in Figure 3-6]. I mean, it just comes right out and says that, 'Hey, if the neighbors aren't affected, you don't have to be a [category] three or four. And what I was saying is that, probably that's coming from the East coast some place. I'm just speculating now, and I don't know this. I doubt this would ever come out in California and if they ever had a big earthquake down in California, is what I was saying […] you'll have chemical plants that will collapse, kill workers. […] I don't think California would let people do this…and in most jurisdictions it would be no way. But let's say they did and some big chemical plant was only a group two, and it was just life safety. They didn't have to go the extra mile, and a bunch of stuff collapses, a bunch of pipes break, and yeah, it doesn't even spill over to the neighbors, but it does a bunch of environmental damage […] and then everybody's going to be up in arms, asking, 'What the hell? Why wasn't this designed as a group four?' Well we just did it to code. And that happened in Northridge […] and you know, there's a lot of stuff in our codes that have been developed since North Ridge and stuff we're even doing since Northridge that probably won't do well. It won't perform well, and our codes will have to change.*

Figure 3-6 provides the portion of the ASCE 7-10 commentary the department head was referring to in this interview.

> Buildings and other structures containing toxic, highly toxic, or explosive substances may be classified as Risk Category II structures if it can be demonstrated that the risk to the public from a release of these materials is minimal. Companies that operate industrial facilities typically perform hazard and operability (HAZOP) studies, conduct quantitative risk assessments, and develop risk management and emergency response plans. Federal regulations and local laws mandate many of these studies and plans (EPA 1999a). Additionally, many industrial facilities are located in areas remote from the public and have restricted access, which further reduces the risk to the public.

Figure 3-22. Excerpt from ASCE 7-10 section C1.5.3. Reprinted from ASCE 7-10 (p. 322).

In the interview excerpt, the department head says that many jurisdictional codes would not permit risk category II for some structures even though ASCE 7-10 does. The regional codes do take precedent over ASCE 7-10, but the department head was using this as an example for when an engineer should use their better judgment to potentially assign a structure a higher risk category, resulting in a lower risk design, even though a code might permit a less conservative design. He emphasized this point by noting how codes evolved after the Northridge earthquake in 1994, and how he was still skeptical of minimum design provisions in the code that he suspected would need to be further updated after another major earthquake event. Thus, this case demonstrated an engineer's overall evaluative approach to a code in the workplace environment wherein they used their judgment and skepticism of codes based on their limitations to be more conservative in their design.

3.5.2.3 Workplace Case 3 – K-rating speeds in FEMA 430

In a similar case, engineers in the workplace environment were observed discussing a project and whether they should apply a code's minimum criteria or use a more evaluative approach to justify a more conservative design. This case was observed during a design meeting for a project installing bollards at an airport to increase security against a potential terrorist attack from a truck being used as a battering ram. The project engineers were designing the bollard system and subsequent load path per the K4 certification outlined in FEMA 430 Section 4.2.2 Barrier Crash Test Standards (see Figure 3-7) based on their client's requirements.

Certification Class	Speed (mph)	Speed (kph)
K12	50 mph	80 kph
K8	40 mph	65 kph
K4	30 mph	48 kph

To become certified with a DOS "K" rating, the 15,000-lb. vehicle must achieve one of the K-rating speeds, and the bed of the truck must not penetrate the barrier by more than 36 inches. The test vehicle is a medium-duty truck such as those that any driver with a commercial license and a credit card can buy or rent. Note that the amount of intrusion is measured to the front of the cargo bed of the truck, where explosives would typically be located (Figure 4-8).

Figure 3-23. FEMA 430 table illustrating differences in the Department of State (DOS) K-rating certification classes. Reprinted from FEMA 430 (p. 4-10).

A couple of engineers mention considering using a higher certification class or adding a factor of safety due to the uncertainty in the impact load (e.g., vehicle weight, speed and angle at impact, explosives, and simultaneous loading scenarios). The engineers working on the project ultimately settled on the original K4 criteria per the client's requests. The existing challenges they were already facing with handling the large forces flowing from the bollards into existing structural elements as a result of a K4 rated impact also influenced their decision to apply the code as indicated. This case demonstrates how even when engineers in the workplace environment do settle on applying a minimal code requirement, there is still some evaluative negotiation based on their engineering judgment and fundamental conceptual understanding for uncertainty in predicting loads.

One of the engineers who suggested using a factor of safety on this design was interviewed later and asked if he could provide an example where he was not comfortable with the uncertainty in a code, particularly when evaluation of the prescribed load led to the use of a more conservative load. The engineer responded with:

> *We do it all the time up front if we're doing a schematic design because we know that variables will change [...] A lot of the times if we're designing a mezzanine or something, or just offices, we'll bump up the weights by 25%. Just because of the unknown and you don't want to have to go back and redesign things.*

ASCE 7-10 prescribes a minimum live load of 50 PSF for typical office spaces and a variety of live loads depending on the occupancy or use of a mezzanine (ASCE, 2013). The values of these minimum loads already have some conservative assumptions underpinning their quantification, but even so, the uncertainty and dynamicity of loads in the real-world resulted in the engineers in the workplace environment taking an evaluative approach when applying the minimum loads provided in ASCE 7.

The three cases presented above exemplify how engineers in the workplace environment sometimes take an evaluative approach when applying and interpreting codes to either justify more or less conservative design assumptions. These cases also exemplify how the sociomaterial contexts of the code being applied and the nature of the project or design task being worked on influences whether or not the engineers used an evaluative or prescriptive approach.

3.6 Discussion

The findings presented in the cases above demonstrate how the sociomaterial contexts of the workplace environment sometimes require an evaluative approach in applying codes. In the academic environments, such evaluative approaches were only alluded to in lecture while students practiced applying the codes in purely prescriptive ways. This resonates with some of what the existing literature has noted as limitations in the way codes are taught in undergraduate education—most notably that information on limitations and assumptions in codes and the need to apply them in an evaluative fashion is mentioned ad hoc in lectures, minimizing student opportunities to engage with this information (Kelly, 2008; Solnosky et al., 2017). Furthermore the courses observed were generally structured around initially presenting conceptual content in lecture, and then students practiced applying codes prescriptively on their homework and/or lab/recitation assignments with minimal explicit connection back to the relevant conceptual content.

Application of codes being isolated from other course content was an additional limitation to instruction of codes identified in the literature (Solnosky et al., 2017). The RC course was somewhat unique in this case because "the core of ACI 318 is built around a subtle and elegant stipulation that all concrete cross-sections meet the requirements of strain compatibility and equilibrium" (Rumsey et al., 2010, p. 1), so these concepts are constantly reinforced through the application of the equations in this code. Conversely, the Steel Design course utilized the *SCM* which represents many concepts through tables that students can apply prescriptively without considerable understanding of the conceptual information represented in them. The steel instructor even shared in an interview how she was initially taught to use these tables:

> *When I learned steel design, I was like a table wizard. I could look up things instantly in tables, but I had no concept of what those tables actually meant. Which means if you got any sort of section that wasn't one of the standard ones, like a wide flange, and it wasn't in the textbook, you had no idea what to do with it. And you didn't know what any of its properties were. There was no intuitive sense of what the section was doing. […] This issue I have with the code and I bet this is the same issue that [other instructors have] with it too…**it causes the students to not critically think.** They just like, it just gives them an answer.*

Here the instructor talked about how she was taught to prescriptively use the tables in the *SCM* without additional evaluation for what they were representing. She also perceives the nature of codes as problematic because they can cause "students to not critically think," which resonates with the concerns raised about prescriptive codes in the SEI (2013) report presented in the Background section. However, based on the cases from the workplace environment, there appears to be an opportunity to use the codes as a medium for teaching fundamental concepts and developing students' critical thinking around those concepts. For example, exposing students to design scenarios wherein they are required to take a more evaluative approach in using the codes like the engineers in the workplace did, gives students more explicit opportunities to think critically about code-based conceptual representations.

While the SEI (2013) report raises concerns about how prescriptive codes limit engineering students' fundamental conceptual knowledge, it does not address the influence of how we teach such codes on said fundamental conceptual knowledge.

According to one of the instructors: “We teach them [codes] as cookbooks, most definitely. We teach them [students] as, you go by the code. You follow these steps. You'll get to the answer.” If students are only provided “cookbook” scenarios wherein they use prescriptive codes with prescriptive approaches, then the SEI (2013) report’s concerns of prescriptive codes on early career professionals is warranted. Take for example this workplace department head’s perspective of the codes upon graduating:

> *When I got out of school, I literally thought […] it [the code] just had tons of research behind it, and just some really super smart people came up with the code, and it's gospel. And, boy, it didn't take long, and I figured, and I was like, "Wait a minute, this isn't necessarily the gospel. There's some stuff kind of messed up in here."*

These two quotes about the codes being cookbooks and gospel exemplify SEI’s (2013) concerns about students being purely taught prescriptive applications of codes and developing an overreliance on codes that limits the application of the fundamental conceptual knowledge we try to emphasize in school. However, when students are taught to apply codes with an evaluative approach there exists an opportunity for students to apply their fundamental knowledge of concepts within a sociomaterial context similar to workplace environments rather than creating a separate set of working knowledge that is purely code based (Rumsey et al., 2010). Such an approach can also foster a healthy skepticism of codes “that attempt to define the design parameters of upwards of 95% of the structures being built today (SEI, 2013, p. 7).

As previously mentioned, codes are written by committee and while the committees are large and full of experts from diverse fields (Kelly, 2008), the codes are still subject to fallacies inherent in human-made objects “designed by committee.” Take for example one of the workplace engineers experience from attending the NCSEA 2018 conference that he shared in an interview with the ethnographer:

> *One of the presenters walked through why certain tenets of the code are in there. Why are you only allowed to design a concrete shear wall building up to 155 (sic) feet? He's like, well it's based on shadow zonings from LA in the '50s. And oh, by the way, it's a typo. It was supposed to say 165, and it's been in every subsequent edition since then. There's no theoretical basis for it. It has to do with zoning and not creating too much shadow on adjacent properties. And then it got codified in engineering standards. So there's no good reason why you can't have a taller building from an engineering standpoint that performs just as well.* ***So his message to everyone was, challenge the code. Use your fundamentals. Use the skills and tools you were taught as an engineer to determine what is a good and prudent practice.***

To clarify, the engineer meant to say 160' instead of 155' and is referring to ASCE 7 height limits on lateral force resisting systems prescribed in Table 12.2.1 in the 2010 version of ASCE 7 (ASCE, 2013). The ethnographer looked into this claim and confirmed that the 160' value was "established by the first [Structural Engineers Association of California (SEAOC)] *Blue Book* to supplement an earlier Los Angeles code requirement for buildings taller than 13 stories. A height limit of 13 stories, approximately 150 or 160 feet, was imposed by Los Angeles zoning regulations since approximately the early 1900's. […] Thus, the 160-foot limit has its origins in this Los Angeles city planning rather than an explicit seismic design rationale" (SEAOC Seismology Committee, 2009).

While it is impossible to expect engineering instructors to know all the limitations and assumptions built into every code, the authors believe that teaching students an evaluative approach to applying codes will develop a healthy skepticism in students of code provisions that they can take into their careers so that they do not think of codes as cookbooks or gospel that can be followed without critical thinking. This is not to say that students should not be taught a prescriptive approach to codes, either. Indeed, these are powerful tools used in industry that students should be taught how to use (Kelly, 2008; Koch et al., 2010; Solnosky et al., 2017). We are merely suggesting that students receive some additional practice applying these codes that goes beyond prescriptive applications. Therefore, the authors have developed the following recommendations for code education within single courses and across the engineering curriculum.

3.6.1 Recommendations

The first recommendation the authors suggest is providing students with design scenarios in homework assignments that require them to consider a more evaluative approach when applying codes. The easiest way to implement this would be occasional homework problems that require students to decide whether they should use a more conservative or detailed “sharpened pencil” calculation prescribed in a code. For example, in RC design, students could be provided with a scenario wherein a hypothetical architect has reduced their allowable beam depth due to desired floor heights. The problem could be set up so that the commonly used conservative equation used for calculating the shear capacity due to the concrete alone in their RC beam results in an insufficient total shear capacity. To resolve this issue, the students would have to understand the conservative assumptions built in that equation and apply the more detailed equations in Table 22.5.5.1 in ACI 318-14 presented in Academic Case 1 to boost their shear capacity with the architecturally constrained geometry of their beam. A similar scenario could be used in a steel design course based around the more detailed calculation of C_b presented in Academic Case 2. And, on the flip side of the capacity versus demand equation, students could be presented with a scenario wherein they need to reduce the demand on an existing structure by using live load reductions, rather than being prescriptively taught how to use the live load reduction equations. These scenarios provide students with experience making the code work for their design, rather than the other way around. These scenarios also give students a better conceptual understanding of what and how sociomaterial contexts play into the variability of determining capacity versus demand as was demonstrated in Workplace Case 3.

Another recommendation is to integrate field trips and/or lab visits wherein students are exposed to how structural materials are put together and behave in the real-world so that their only conception of these things is not solely pictures, diagrams, and equations in codes and textbooks. Observations of construction sites and lab tests allows students to see how constructability and other real-world conditions effect the performance of structures (Koch et al.,

2010) and when possible, the instructor can connect how the code does or does not handle these conditions. This recommendation resonates with Workplace Case 1; wherein the engineer mentoring the ethnographer shared his lessons learned from a field trip visit to a structures lab testing beams. Field trips and/or lab visits may not always be feasible, but there exist several online videos demonstrating lab tests of structures and case studies of prominent structural failures that can be presented in the classroom to emphasize constructability issues and how codes have evolved over time as a result of testing and lessons learned.

The authors are aware that curriculum in nearly all engineering disciplines is considerably full and adopting these recommendations may be considered unfeasible (Solnosky et al., 2017) without sacrificing breadth of other code related topics or focusing on more fundamental conceptual knowledge. In regards to the desire to cover fundamental conceptual knowledge in the abstract prior to learning about codes, the authors believe that fundamental conceptual knowledge can be enhanced and made more engaging when taught through scenario based cases using codes to organize “bigger ideas” about engineering practice and fundamental design principles (Rumsey et al., 2010; Walther, Kellam, Sochacka, and Radcliffe, 2011). In regards to concerns about sacrificing breadth, one recommended practice for mitigating this concern is assigning students or groups of students sections of code(s) to research and present to the class. This allows students to dissect and investigate the underlying tenets and conceptual knowledge in their assigned section of the code and more efficiently expose them to the breadth and depth of codes (Rumsey et al., 2010). Furthermore, when each upper level course in an engineering curriculum provides students with at least one in-depth scenario based exploration of codes that requires an evaluative approach, then the entire onus of teaching the complexities of codes does not fall on a capstone course and better prepares students for the challenges they encounter with applying codes in capstone.

3.7 Conclusion

The purpose of this research was to explore how structural engineering concepts were represented within the sociomaterial contexts of code application in a workplace and academic environments. This research is valuable to the structural engineering community and engineering education community more broadly because of the variety of opinions on the role codes should or should not play within the curriculum. Through the use of ethnographic methods, we were able to capture rich descriptions of how the sociomaterial contexts of the workplace require structural engineers to take an evaluative approach when applying codes and how this contrasts with the sociomaterial contexts of structural engineering courses which instill a primarily prescriptive approach to applying codes. In-depth exploration of these environments offered greater insight into potential avenues for improving code education in structural engineering at the undergraduate level. The authors believe this insight is likely applicable to other civil engineering disciplines and potentially engineering disciplines outside of civil engineering, but encourage similar research investigating the sociomaterial contexts of code application in other fields. Lastly, we began this paper by identifying common areas of insufficiency cited in engineering education literature before focusing in on technological proficiency with codes, specifically. Technological proficiency and the other areas of communication, teamwork, and leadership do not exist in isolation from one another, however. Therefore, when we can improve students' technological proficiency—such as through evaluative approaches to code application—we provide them with opportunities to also demonstrate their proficiency in communication, teamwork, and leadership in the workplace through their technological proficiency.

Chapter 4 – Structural Engineering Heuristics in an Engineering Workplace and Academic Environments

4.1 Abstract

Heuristics are approaches engineers use for solving problems and making decisions with quick, often approximate, calculations and/or judgement calls. Such approaches have become marginalized in structural engineering education to make room for more theoretical and precise approaches. As a result, engineering students are less confident with heuristics and firms believe students are unprepared for using such approaches to solve messy real-world problems. The purpose of this research is to explore how heuristics are represented within the social and material contexts of a structural engineering workplace and undergraduate structural engineering courses to better understand the use of heuristics in these environments. The researchers use ethnographic methods to access these environments and document the social and material contexts wherein heuristics are applied. Findings from this exploration noticed two different types of heuristics: practice-based heuristics and profession-based heuristics. Practice-based heuristics are more dependent on an agency's experience with certain projects and are therefore less transferable across environments. Profession-based heuristics are grounded in a discipline's fundamental concepts and therefore more transferable across environments.

4.2 Introduction

Heuristics are frequently defined as "rules of thumb" that are used to derive quick and/or approximate solutions (Gestson et al., 2019; Ruddy & Ioannides, 2004; Schoenfeld, 1992). Within the profession of structural engineering, designers have developed heuristics over time to solve recurring structural design problems with simple and expedient approaches that were appropriately accurate for their purposes (Ruddy & Ioannides, 2004). The development and application of such heuristics requires engineering judgment and intuition for the concepts that matter most to design (MacRobert, 2018; Ruddy & Ioannides, 2004). Thus, heuristics are a way for structural engineers to selectively and readily represent concepts relevant to solving a problem at hand (MacRobert, 2018; Tversky & Kahneman, 1974), such as having an intuitive sense for the magnitude of loads and the demand they induce on structures to quickly select a preliminary sized member during schematic design (Ruddy & Ioannides, 2004).

Over the last half century, however, structural engineering education has gradually shifted its focus towards more theoretical representations and understanding of fundamental concepts and away from the pragmatic, heuristic representations necessary for solving real-world messy problems (Aparicio & Ruiz-Teran, 2007). This shift has been perceived as contributing to recent engineering graduates lacking the engineering judgment to creatively apply and develop heuristics for solving these messy problems they will encounter in the workplace (Aparicio & Ruiz-Teran; Bernold, 2005; MacRobert, 2018). That being said, the social and material (sociomaterial) contexts wherein heuristics are taught and applied in an academic environment and a workplace environment can considerably influence what is considered a heuristic and how transferable that representation is to other contexts (Johri & Olds, 2011; Tversky & Kahneman, 1974). Thus, the purpose of the research presented in this paper is to answer the following research question:

> How are heuristics represented within the social and material contexts of a structural engineering workplace and undergraduate structural engineering courses?

4.3 Background

4.3.1 Heuristics in Structural Engineering Education and Practice

Heuristics are quick, often approximate, intuitive approaches to solving problems and making decisions when conditions surrounding the problem/decision are uncertain (Gestson et al., 2019; Schoenfeld, 1992; Tversky & Kahneman, 1974). Before the advent of computers, heuristics were a useful resource for structural engineers designing indeterminate structures and for handling frequently reoccurring structural design problems (Aparicio & Ruiz-Teran, 2007; Ruddy & Ioannides, 2004). As computational methods became more prevalent in the profession and allowed for more theoretically precise calculations over the last half century, some historically established heuristics were demonstrated to be wrong or evolved into quick checks of software output (Aparicio & Ruiz-Teran, 2007).

During this same time, structural engineering education progressively focused more on theoretical knowledge and less on the pragmatic, intuitive knowledge and engineering judgment demonstrated through heuristics (Aparicio & Ruiz-Teran, 2007; SEI, 2013). A justification for this transition and continued focus in structural engineering education was that if structural engineering students received sufficient training in the fundamental concepts of mathematics, physics, and mechanics, then they would be prepared for applying those concepts in structural engineering practice (Aparicio & Ruiz-Teran, 2007; Balogh & Criswell, 2013; Robertson, 2002). However, this type of education has also led to the belief that engineering students are uncomfortable and unprepared for handling less precise calculations and the uncertainty of ill-structured real-world problems encountered in the engineering workplace (Aparicio & Ruiz-Teran; Bernold, 2005; Jonassen et al., 2006; MacRobert, 2018; Wirth et al., 2017).

This lack of preparedness can be partially explained by situated cognition theory which posits that our conceptual knowledge is to some extent limited to the social and material contexts wherein said knowledge is learned and applied (Johri & Olds, 2011). Thus, when the social and material contexts of academic environments represent concepts in primarily theoretical formulations and the social and material contexts of workplace environments represent concepts in pragmatic, heuristic applications, students may be stifled in demonstrating their academic knowledge in practice.

4.3.2 Situated Cognition and Heuristics as Conceptual Representations

Situated cognition is a learning theory that emphasizes learning as being inextricably linked to doing (Greeno et al., 1996). Situated cognition, unlike other learning theories, places a greater emphasis on the role of social and material (sociomaterial) contexts wherein learning and knowledge application occurs than on the mind of the individual learner (Johri & Olds, 2011; Newstetter & Svinicki, 2014). Sociomaterial contexts are the people/organizations and objects/tools where learning through doing occurs. For example, Bornasal et al. (2018) observed how practicing transportation engineers' conceptual understanding of sight distance was represented within the negotiation of project constraints with other engineers and project stakeholders (social context) and the use of software and design references (material contexts) on a roundabout project. Thus, when it comes to learning and applying engineering concepts, the sociomaterial contexts wherein said concepts are represented influences and shapes our conceptual understanding (Lemke, 1997; McCracken & Newstetter, 2001). Therefore, conceptual representations are the sociomaterial contexts that mediate our conceptual understanding, such as language, text, diagrams, symbols, equations, etc. (Lemke, 1997; McCracken & Newstetter, 2001).

Heuristics can also be considered conceptual representations since they are a method engineers use to solve problems wherein certain concepts may be simplified and/or given priority over other concepts that are less relevant to or confounding the problem. For example, a structural engineer may opt to qualitatively sketch the deflected shape of a structure based on their intuition of the load path to check software output, rather than perform a complicated hand computation to check the same output. While heuristics are often perceived as being approximate calculations and/or quick judgment decisions, they can also be precise equations grounded in theoretical derivations that engineers use without having to always derive them. The use of heuristics are often based on experience-based intuition and judgment to determine the applicability of certain concepts to a problem and this makes them highly dependent on the sociomaterial contexts wherein they are applied and the experiences where that intuition and judgment were initially honed (Tversky & Kahneman, 1974). One methodology particularly well suited for gaining a deeper understanding of how these sociomaterial contexts influence the conceptual representations of heuristics is ethnography.

4.3.3 Ethnographic Studies of Engineering Workplace and Academic Environments

Ethnography emerged as a methodology from the field of anthropology to access and gain a deeper understanding of cultures by immersing oneself in said culture's environment (Case & Light, 2011). Ethnographies of the engineering workplace environment have broadly observed what situated cognition has already recognized; that knowledge is distributed amongst people (social) and tools (materials) and that the development of said knowledge is highly dependent on these contexts (Bucciarelli, 1988; Trevelyan, 2007, 2010). Thus, ethnography has been demonstrated to provide considerable access into the sociomaterial contexts of engineering environments, but has yet to focus this access towards gaining a deeper understanding of conceptual representations, such as heuristics. Furthermore, very few ethnographies have explored both workplace and academic environments for a specific engineering discipline to understand how heuristics differ across these environments based on sociomaterial contexts (Johri, 2014; Johri, Olds, & O'Connor, 2014).

One ethnographic study of an academic engineering environment occurred at a university in New Zealand, wherein the researchers sought to provide a holistic description of the culture in the university's school of engineering through interviews with and observations of faculty and students at all four years of undergraduate study (Godfrey & Parker, 2010). While this ethnography was not specifically looking for the influence of sociomaterial contexts on heuristics, they did note that the school's culture emphasized an "engineer way of thinking" that focused on solving problems with "best" answers over "right" answers (Godfrey & Parker, 2010). Similarly, heuristics are often used to find the best answer suitable for the problem at hand rather than focusing considerable time and effort on an explicitly right answer (Warren-Myers & Heywood, 2010). This ethnography focused on engineering education at this school in a broad sense and did not look at any specific engineering discipline.

An example of an ethnography of the workplace environment that did focus on a specific discipline is Gainsburg et al. (2010) study, wherein they observed 19 structural engineers at three different workplace environments. Gainsburg et al. (2010) observed these 19 engineers using “rules of thumb and estimates” which consisted of rough, ball park calculations and shortcuts used in the schematic design phase that allowed them to move forward in their design with appropriate, but less precise values. Rules of thumb and estimates are examples of heuristics (Gestson et al., 2019) and Gainsburg et al. (2010) noted these heuristics as being one of the types of structural engineering knowledge important in the workplace environment. While Gainsburg et al. (2010) ethnography is a valuable study in improving our understanding of the types of knowledge used in the structural engineering workplace, it offers little insight into how the sociomaterial contexts of the workplace compare to academic environments beyond traditional lecturing.

Gainsburg et al. (2010) and Godfrey and Parker (2010) only observed the environments they were studying and did not participate in them. Participation in an ethnography provides the researchers with an additional access point to the sociomaterial contexts of the environment being studied, which can confirm or refute findings made through observations alone (Emerson et al., 2011; Walther et al., 2013). Furthermore, the use of heuristics can sometimes be unobservable to an outsider or not made explicit within the contexts it is being used. Participation in the environments being studied allows the researcher to come in direct contact with heuristics and the sociomaterial contexts wherein they are applied.

4.4 Methods

An ethnographic approach consisting of participation and observations was implemented to answer the research question:

> How are heuristics represented within the social and material contexts of a structural engineering workplace and undergraduate structural engineering courses?

To gain access to these contexts the lead author, hereto referred as the ethnographer, worked as a part-time intern at a medium-sized private architecture and engineering firm and enrolled in four undergraduate structural engineering courses over two 10-week long terms. The ethnographer's own undergraduate and graduate studies have focused on structural engineering, providing him with the basic structural engineering knowledge and jargon to participate in both environments. The firm and the courses selected were based on the firm's willingness to employ the ethnographer as a part-time intern and the instructors' willingness to let the ethnographer enroll in their courses. Both environments were located in Oregon to be geographically accessible to the ethnographer.

While at the firm, the ethnographer performed typical work tasks that would be given to an engineer in training (EIT) for ~16 hours per week and then conducted their research for the remaining ~24 hours of the work week. The ethnographer did this for three months and participated in structural engineering activities on 18 different projects. Table 4-1 provides additional demographic info about the structural engineers the ethnographer interacted with at the firm.

Table 4-1

Demographic Information for Structural Engineers at the Workplace Environment

No. structural engineers	Industry experience in years	No. licensed PEs (SEs)	No. female (male) engineers	No. M.S./ M.Eng. degre holders
20*	0-46 ($\mu = 10.3$)	12 (5)	7 (13)	7

*The firm employs 24 structural engineers across three offices, however only 20 were observed in-depth at the office where the ethnographer was participating.
Note. Reprinted from Barner et al. (2019, in review)

For the academic environments, the ethnographer participated in each class as an actual student, attending lectures and recitations, completing homework assignments, and taking exams. Table 4-2 provides additional demographic information about the instructors and their respective courses.

Table 4-2

Demographic Information for Structural Engineering Courses Studied

Course	No. students	Lecture (recitation) hours/week	Course objective	Instructor teaching (industry) experience in years	Female/ma instructo
Structural Analysis I	60	3 (2)	Determinate analysis	30 (12)	Male
Structural Analysis II	50	3 (2)	Indeterminate analysis	36 (29)	Male
Steel Design	67	3 (2)	Beam, column, and brace design	1 (2)	Female
Reinforced Concrete Design	60	4 (0)	Beam design	22 (24)	Male

Note. Reprinted from Barner et al. (2019, in review).

4.4.1 Data Collection

Ethnographic methods rely on three data collections sources: field notes of participant-observations, interviewing, and artifact collection (Johri, 2014; Emerson et al., 2011). Field notes were initial handwritten jottings that the ethnographer documents during and after participating in or observing the use of conceptual representations. These jottings were then converted into completed typed field notes as soon as possible so that the ethnographer did not forget the information being documented in their jottings (Emerson et al., 2011). In the workplace environment, the jottings and subsequent field notes revolved around engineering tasks the ethnographer was assigned as an intern or his observations of an engineer or engineers working on and discussing their design related tasks. In the academic environments, the jottings were integrated into the ethnographer's lecture/recitation notes and then immediately revisited after exiting the classroom to convert into typed field notes. Converting the jottings into typed field notes allowed the ethnographer to identify shortcomings and missed information in their jottings that were used to create interview questions for the instructors and practicing engineers (Emerson et al., 2011).

Formal and informal interviews were conducted with all of the instructors and practicing engineers. When possible, formal interviews were preferred so the ethnographer could record and transcribe the interviews for further analysis. Informal interviews occurred more spontaneously during office hours, following lectures, recitations, design meetings, or after completing an assignment as an intern. Data collected from both formal and informal interviews were reintegrated into the field notes to shore up missing information or revise misinterpretations from observations (Walther et al., 2013). Artifacts were also brought to interviews and integrated into field notes to provide additional information about the sociomaterial contexts in each environment.

Artifacts were physical objects in the field that were relevant to the context of the ethnographer's participation and observations. Artifacts most commonly took the form of diagrams and text that were either created by the ethnographers and/or participants or already existed in a material resource, such as a textbook or design aid. Artifacts were collected with pictures following participant consent and then copy and pasted into the pertinent section of field notes to create an annotated account of the ethnographer's participation and observations. While the artifacts are the primary material context documented in the field, the artifacts do not exist outside of the social context of their creation and application, and therefore must be integrated into the field notes and supplemented with interview data to fully describe the sociomaterial contexts of each environment. Collectively, these three sources of data collection (field notes, interviews, and artifact collection) allow the ethnographer to triangulate the data to confirm or refute data collected from any one source (Walther et al., 2013).

4.4.2 Data Analysis

Data analysis occurs simultaneously with data collection in an ethnography due to the interconnectedness of the data sources and to prevent the ethnographer from becoming overwhelmed by the amount of data collected (Emerson et al., 2011; Johri & Olds, 2011; Walther et al., 2013). The interconnectedness of the data sources requires the ethnographer to constantly synthesize the data collected from each source to create their annotated accounts of how concepts are represented in each environment. The very act of creating these accounts initiates the analysis process by forcing the ethnographer to triangulate the data and begin identifying common themes within and across each environment that can guide further inquiry to challenge or refute the emergent themes (Emerson et al., 2011; Walther et al., 2013).

Interview transcripts from recorded interviews were iteratively coded with the initial iterations deductively seeking participants explicit mentioning of conceptual representations pertaining to specific accounts in the field notes. Coding is the iterative process of constructing categories that describe common excerpts of text relevant to answering the research question (Auerbach & Silverstein, 2003). Subsequent coding iterations were inductive as more transcript data from a variety of participants and contexts became available to begin identifying similarities and differences in conceptual representations across environments (Miles et al., 2014).

4.4.3 Transferability and Credibility

In qualitative interpretive research it is important to provide external customers of the research with sufficient detail so that they can assess the transferability and credibility of the methods and findings (Lincoln & Guba, 1985; Walther et al., 2013). In regards to transferability, the researchers acknowledge that the environments studied are not representative of all structural engineering firms or courses. That being said, the firm studied provides design services on a variety of structures in the public, industrial, and commercial sectors and employs a diverse team of structural engineers as presented in Table 4-1. The courses studied, while somewhat dependent on the instructors' curriculum and teaching style, are four of the most common courses in undergraduate structural engineering education (Perkins, 2016) and have common learning outcomes and curricular materials to similar courses across the United States (Kelly, 2008; Perkins, 2016; Rumsey et al., 2010; Solnosky et al., 2017).

To enhance the credibility of the study, the ethnographer spent nine total months in the field across both environments to expose themselves to multiple sociomaterial contexts via participation and observation (Case & Light, 2011; Johri, 2011). This allowed for initial interpretations of the data within any one environment or specific context to constantly be challenged with alternative interpretations from the sociomaterial contexts of different courses, different projects encountered in the workplace, and different instructors and practicing engineers being interviewed. Participation in both environments was also critical to identifying and documenting heuristics within their sociomaterial contexts as observation alone would not have provided the ethnographer with explicit heuristic applications in the workplace or academic environments.

4.5 Findings

Two different types of heuristics were documented being applied in both environments: practice-based heuristics and profession-based heuristics. *Practice-based heuristics* are heuristics that an agency develops over time based on the sociomaterial contexts they frequently operate within from designing similar structures. These types of heuristics may not be transferable to projects and/or structures the agency is less familiar with and are likely agency-dependent, meaning that they differ from other agency's practice-based heuristics. *Profession-based heuristics* are heuristics that a profession has developed over time that are grounded in the sociomaterial contexts of fundamental structural engineering concepts. These types of heuristics are more likely to be transferable across environments and from project to project.

Practice-based heuristics were mostly observed in the workplace environment and rarely presented in the academic environments. Profession-based heuristics, on the other hand, were prevalent in both environments. The following subsection present some of the practice-based heuristics encountered in the workplace environment with a similar practice-based heuristic presented in one of the academic environments. The subsequent subsection then presents some of the profession-based heuristics represented in the academic environments and their relevancy to the sociomaterial contexts of the workplace environment studied.

4.5.1 Practice-Based Heuristics

Early on in the internship, the ethnographer was tasked with designing additional framing for a roof to support additional HVAC equipment that were being added to said roof. This additional framing would transfer the load of the add-on equipment into the existing roof framing. The engineer mentoring the ethnographer on this design task explained that the dead load for the existing roof framing was 15 PSF and that this was one of their firm's "lineages of ideas." The engineer proceeded to explain what he meant by "lineages of ideas" saying that they are standards of practice that an agency develops over time for frequently encountered problems. The engineer then explained that their firm frequently designs the types of structures this project was related to and has come to learn that 15 PSF dead load for roof materials and framing is an appropriate load estimate that has continuously worked for their practice.

In a later design task, the ethnographer assumed 15 PSF for roof dead load based on the firm's "lineages of ideas" and the same engineer asked how the ethnographer determined that dead load value when checking their calculations. The ethnographer explained that they had assumed it based on what the engineer had previously told him about the firm's "lineages of ideas" and the engineer replied that 15 PSF was an acceptable assumption, but that the ethnographer should understand where that magnitude came from. The engineer then proceeded to print a material weights reference sheet that lists dead loads for components that make up roof and ceiling systems (see Figure 4-1).

Material Weights

Refer to local building code for live load design requirements.

Composition Roofing

2-15 and 1-90 lb.	1.7 psf
3-15 and 1-90 lb.	2.2 psf
3-ply and gravel	5.6 psf
4-ply and gravel	6.0 psf
5-ply and gravel	6.5 psf
Insulated Roof Membrane Assembly (IRMA) 2" thick	13.0 psf
Single-ply roofs (insulation not included)	
Ballasted system	13.0 psf
Mechanically fastened	2.0 psf
Fully adhered	2.0 psf

Douglas Fir Sheathing*
(Based on 36 pcf for plywood, 40 pcf for OSB)

½" plywood	1.5 psf
⅝" plywood	1.8 psf
¾" plywood	2.3 psf
1⅛" plywood	3.4 psf
½" OSB	1.7 psf
⅝" OSB	2.0 psf
¾" OSB	2.5 psf
⅞" OSB	2.9 psf
1⅛" OSB	3.7 psf

Miscellaneous Roofing Materials

Corrugated galvanized steel	
16 ga.	2.9 psf
20 ga.	1.8 psf
22 ga.	1.5 psf
24 ga.	1.3 psf
Asphalt shingles	2.5 psf
Wood shingles	2.0 psf
Clay tile	9.0 to 14.0 psf
Slate (⅜" thick)	15.0 psf

Rigid Insulation (1" thick)

Temlock	1.2 psf
Cork	0.7 psf
Gold bond	1.5 psf
Polystyrene foam	0.2 psf
Foamglass	0.8 psf
Rigid fiberglass	1.5 psf

Roll or Batt Insulation (1" thick)

Rock wool	0.2 psf
Glass wool	0.1 psf

Floors

Hardwood (nominal 1")	4.0 psf
Concrete (1" thick)	
Regular	12.0 psf
Lightweight	8.0 to 10.0 psf
Gypsum concrete (¾" thick)	6.5 psf
Sheet vinyl	0.5 psf
Carpet and pad	1.0 psf
¾" ceramic or quarry tile	10.0 psf

Ceilings

Acoustical fiber tile	1.0 psf
½" gypsum board	2.2 psf
⅝" gypsum board	2.8 psf
Plaster (1" thick)	8.0 psf
Metal suspension system (including tile)	1.8 psf

When calculating total dead load we strongly urge you to use a minimum of 1.5 psf for 'miscellaneous' with all dead loads.

Figure 4-24. Roofing and ceiling material weights from a Truss Joist I-Joist (TJI) manufacturer's manual.

The engineer explained that the roof and ceiling of the structure they were looking at likely consisted of: 3-15 and 1-90 lb. composition roofing (2.2 PSF), 5/8" OSB sheathing (2.0 PSF), asphalt shingles (2.5 PSF), glass wool insulation (0.1 PSF), and 5/8" gypsum board ceilings (2.8 PSF). Each of these components is starred in Figure 4-1. These components all add up to 9.6 PSF and the engineer said that the remaining ~5 PSF covers the existing framing and MEP equipment. In a later interview with the same engineer, he noted where the material weight reference sheet in Figure 4-1 came from:

> *I don't keep it in my head what different building materials weigh, but kind of some sheets. I think the one sheet we use is actually from a TJI manual that someone photocopied, you know, 20 years ago, that pretty much everyone in the department uses.*

The engineer implicitly refers to using the sheet in Figure 4-1 as a heuristic because it allows him to not have to remember what different building materials weigh. The overall approximate 15 PSF dead load demonstrates how the firm developed a practice-based heuristic of estimating roof and ceiling dead loads based on the sociomaterial contexts of a Truss Joist I-Joist (TJI) manufacturer's manual that has continued to work well for the typical roof structures their firm encounters in design. This is a practice-based heuristic because it was developed over time from the firm's practice-based experience, and is not necessarily an appropriate assumption for all roof/ceiling structures or may not be what another company would use/develop in their own practice.

The firm also developed some other practice-based heuristics for common conservative load estimates to account for unknown changes that might emerge after the initial design phase of a project. For example, when designing their roof trusses for certain structures, they accounted for the addition of a 500 lb. floating point load acting within 6 inches of any joint (i.e., panel point) of a truss after installation to account for increases in load like additional HVAC equipment being installed. If the point load had to occur at a location along the truss greater than 6 inches from any panel point then an additional angle member on each side of the joist had to be provided for additional framing per one of the firm's previously developed details (See Figure 4-3). In one instance, the ethnographer was responding to a contractor submittal wherein the contractor was a joist manufacturer with their own specification limiting concentrated point loads to 3 inches away from panel points without installing additional bracing (see Figure 4-2).

NOTED ITEMS	COMMENT
Detail [redacted] gives the project limits for concentrated loads resisted by joist chords before adding field installed strut reinforcing. The detail permits a greater distance from panel points than [redacted] standard 3" away. [redacted] recognizes that the specifying professional authorizes concentrated loads located up to 6" away from panel points to govern field installed reinforcing requirements as shown on the detail. Localized chord bending from concentrated loads within 6" will not be analyzed considering insignificant local chord flexure effects. Concentrated loads not specified	Acceptable. We will revise detail to match [redacted] standards.

Figure 4-25. Contractor's noted item in submittal and ethnographer's comment.

The ethnographer asked an engineer about this discrepancy in the firm's detail and the contractor's specification. The engineer suggests they go ask a more senior engineer where their firm's 6 inches specification came from. The more senior engineer was not certain where that specification had come from, but that it likely came from a previous joist manufacturer's specification. The junior engineer suggests updating their standard detail to 3 inches because of how small the angles are that are used in their detail. The senior engineer says he is comfortable with their detail as is, but agreed to update their detail to 3 inches and then joked that it will eventually become 2 inches based on some other joist manufacturer's specification in the future.

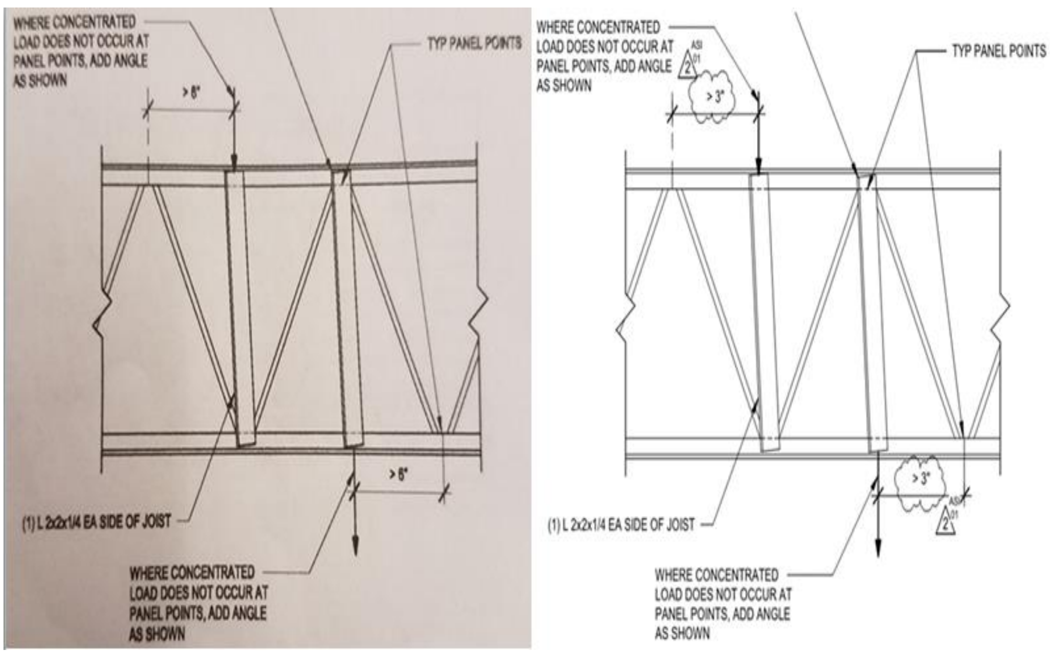


Figure 4-26. Previous standard detail (left) and updated standard detail (right) reflecting change from 6 inches to 3 inches of where a concentrated load can be applied from a panel point without additional bracing.

This is an example of a heuristic based on engineering judgment for how far a concentrated load can safely be applied away from a panel point before additional bracing is needed. The firm had originally developed a standard detail that had historically worked for them, but decided to update their detail and establish a new practice-based heuristic to reflect a more conservative design influenced by the sociomaterial context of a contractor's specification.

The firm's development of standard details in general is another example of a practice-based heuristic because they frequently use the standard details they have developed over time to handle common configurations of structural elements. The performance and load path for these standard details are well understood for the types of structures the firm frequently designed and therefore were practice-based heuristics for expediting commonly designed details that are likely different from the sociomaterial contexts of another agency's frequent projects.

Practice-based heuristics were observed less in the academic environments, but one similar scenario of a load estimate assumption emerged in a recitation exercise for the Steel Design course. In this recitation assignment students were asked to quantify the dead load acting on columns supporting a typical floor and roof for a given structure. The students were given some of the components contributing to the dead load acting on their columns and expected to determine the magnitudes of the remaining components contributing to the dead load (see Figure 4-4).

PROJECT: STEEL BUILDING DESIGN CASE STUDY		
SUBJECT: COLUMN DEAD LOAD TAKE OFF		SHEET 6 of 131
LOAD TABLE - COLUMN DEAD LOAD (LB/FT²)		
COLUMN DEAD LOAD UNDERNEATH TYPICAL FLOOR (LB/FT²)		LOADS FROM
SLAB (4-3/4" Light WT. Concrete)	38	*Slab*
(Lightweight Concrete Density = 96 PCF)		*Mech./Elec./Piping*
MECH./ELEC./PIPING	10	*Ceiling System*
(common practice = 10 psf)		GO TO
CEILING SYSTEM (Table C3.1-1a, ASCE 7-16)	5	↓
(Acoustical fiber board & Mechnical Duct allowance)		
JOISTS	3.7	*Joists*
(Assume 11 LB/L.F. @ 3' O.C.)		↓
GIRDERS		
(Assume 85 LB/L.F. @ 36' O.C.)		*Girders*
COLUMNS (36'*30' = 1080 FT.²)	1.8	↓
(Assume 150LB./L.F.* 13')/1080FT.²		
OLUMN TOTAL DEAD LOAD – TYPICAL FLOOR (LB/FT²		
		Columns
COLUMN DEAD LOAD UNDERNEATH ROOF (LB/FT²)		LOADS FROM
ROOF DECK (Table C3.1-1a, ASCE 7-16)	3	*Rigid Insulation*
(Metal, assume 18 gage for estimate)		*Roof Deck*
RIGID INSULATION (Table C3.1-1a, ASCE 7-16)		*Mech./Elec./Piping*
(2" thick) 0.75 psf per 1/2"		*Roofing (felt & gravel)*
MECH./ELEC./PIPING & CEILING SYSTEM	10	GO TO
(Assume 10 psf)		↓
ROOFING (Table C3.1-1a, ASCE 7-16)		
(Five-ply felt & gravel)		*Joists*
JOISTS	3.7	↓
(Assume 11 LB/L.F. @ 3' O.C.)		
GIRDERS		
(Assume 85 LB/L.F. @ 36' O.C.)		*Girders*
COLUMNS (36'*30' = 1080 FT.²)	1.8	↓
(Assume 150LB./L.F.* 13')/1080FT.²		
COLUMN TOTAL DEAD LOAD – ROOF (LB/FT²) =		*Columns*

Figure 4-27. Recitation exercise for determining total dead load acting on columns.

Note. Adapted from Barner et al. (2019, in review).

The students were told for the column dead load underneath a typical floor that a common practice for mechanical, electrical, and piping (MEP) equipment was 10 PSF and similarly for the column dead load underneath the roof they were told to assume 10 PSF for the MEP and ceiling system. The instructor was asked in a later interview where this heuristic (assumption) came from, to which the instructor replied:

> *It depends. This is one of those things where the loads vary depending on company to company. Companies are going to…they're going to make different assumptions for that, because you know it somewhat depends on what the occupancy category of it, say a warehouse versus an office building.*

Here, the instructor is demonstrating that this heuristic of assuming 10 PSF for MEP equipment is a practice-based heuristic that varies depending on the sociomaterial contexts of the different agencies and the nature of the project.

4.5.2 Profession-Based Heuristics Applicable Across Multiple Companies

In the Structural Analysis II course, students were frequently asked to derive equations for determining the displacements and support reactions for determinate and indeterminate structures. Following the derivation of these equations, students were permitted to use the profession-based heuristic of beam tables to not have to derive an equation each time it was needed. For example in a recitation assignment, the students were asked to use the force (i.e., flexibility) method for deriving the equation for the magnitude of the fixed-end moments for a beam fixed at both ends with a concentrated load at mid-span (see Figure 4-5).

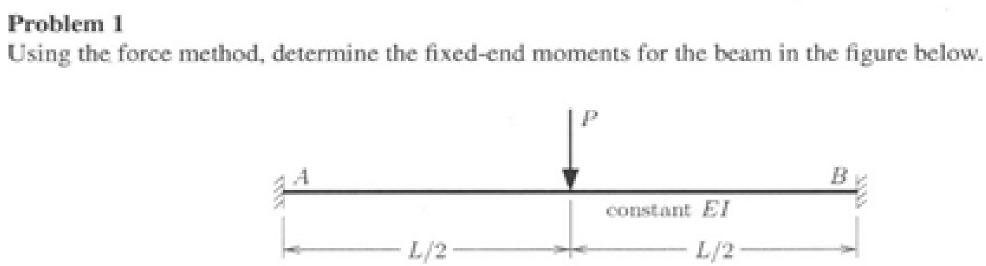


Figure 4-28. Recitation problem from the Structural Theory II course.

The students were informed that they could check their derivation with the beam tables presented in the back of their textbook (see Figure 4-6).

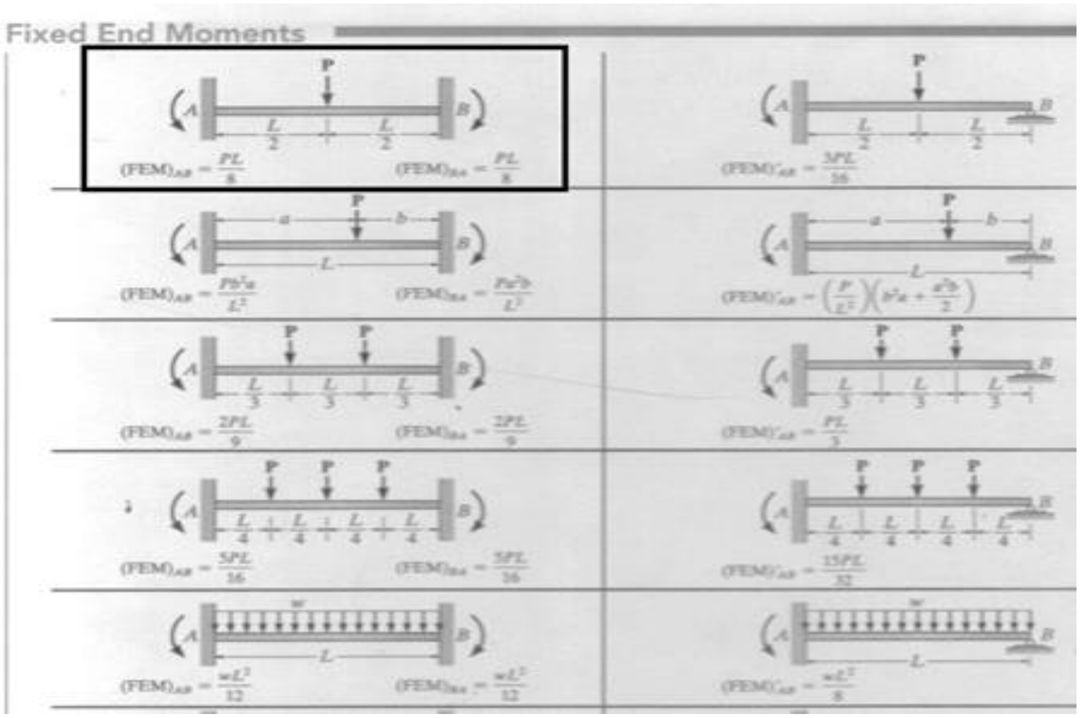


Figure 4-29. Back cover matter reprinted from *Structural Analysis, 10th ed.* (Hibbeler, 2018).

Following this exercise students were permitted to reference the beam tables provided in their course notes and textbook to solve for displacements and support reactions on more complicated indeterminate structures. Similar beam tables exist in design aids such as AISC's *Steel Construction Manual* which an engineer from the workplace mentioned in an interview as being a frequent heuristic him and other engineers use:

> *…the steel manual we just go to because it's so easy to identify beam loading, and we use beam loading all over the place, and various combinations of beam loading. So that's one we use all the time. And only in my career have I started using the tables and the actual manual.*

These beam tables are thus a profession-based heuristic because they are theoretically based equations for exact solutions without having to go through the burden of deriving the equation each time it is needed. In both settings they are represented within the material contexts of design aids such as the course textbook and the *Steel*

Construction Manual with the implied social context that structural engineers know how to derive these equations before applying them as heuristics.

An example of a profession-based heuristic presented in another course that has theoretical underpinnings, but does not provide exact solutions is the portal method used to analyze the demand of lateral loads on building frames. In the Structural Analysis I course, students were presented this method in lecture examples, handouts, and in homework and recitation problems. Figure 4-7 shows a lecture handout provided to students that illustrates the premise of the portal method.

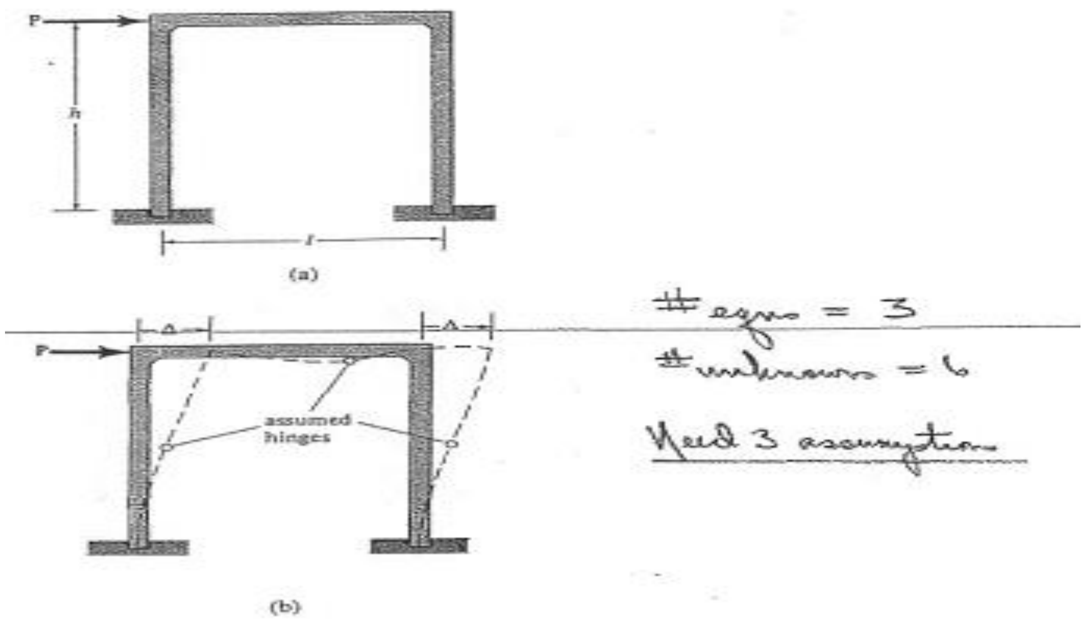


Figure 4-30. Illustration of how the portal method assumes hinge formation in the inflection points of the frame's deflected shape.

Note. Modified from *Structural Analysis, 10th ed.* (Hibbeler, 2018).

The method requires students to draw the deflected shape to identify inflection points in the columns and beam(s) where hinges can be assumed to be located. This provides an additional equilibrium equation for each assumed hinge that can be then used to approximately analyze the original indeterminate structure as a determinate one using equilibrium equations. The portal method and other approximate analysis methods can be defined as a profession-based heuristic because they rely on fundamental concepts of engineering mechanics (e.g., zero internal moment at inflection points) and equilibrium to approximately analyze structures before and/or to check more exact analysis methods (Hibbeler, 2018). The instructor for this course frequently emphasized the value of this and other approximate analysis methods within the sociomaterial contexts of schematic design before member sizes are known and/or as a tool for checking software output.

In the Reinforced Concrete Design course, the instructor provided students with a homework assignment that asked them to determine the moment capacity of multiple different beams and determine which design properties contributed the most and least to increasing the moment capacity of a reinforced concrete beam (see Figure 4-8).

Problem 2: a) Compare ϕM_n for singly reinforced rectangular beams having the following properties:

Beam No.	b (in)	d (in)	Reinforcing Bars	f'c (psi)	fy (ksi)
1	12	24	3-#10	4000	60
2	12	24	3-#10	4000	**40**
3	12	24	3-#10	**5250**	60
4	12	24	**2-#14**	4000	60
5	12	**40**	3-#10	4000	60
6	**24**	24	3-#10	4000	60

b) Taking Beam No. 1 as the reference, discuss the effects of changing, A_s, f_y, f'_c, d, and b on the design strength.

c) What is the most effective way to increase ϕM_n? What is least effective?

Figure 4-31. Homework problem from the Reinforced Concrete Design course.

Upon completion of the assignment, students are expected to identify beam depth (d), steel rebar yield strength (fy) and the cross-sectional area of the reinforcing bars (As) as being the design properties that have the biggest impact on moment capacity; whereas beam width (b) and concrete strength (f'c) have the least impact. This provides students with a heuristic for quickly assessing how changes to certain design properties impact a reinforced concrete beams flexural capacity. This heuristic can be considered profession-based because it is based on the fundamental concepts used in reinforced concrete design (equilibrium and strain compatibility) and in engineering mechanics (second moment of area) and is therefore transferable across agencies and projects.

In an interview with an engineer in the workplace environment, he emphasized this transferability of practice-based heuristics in the following excerpt:

> *I tend to focus on* ***big picture things.*** *I also think it's* ***the most transferable across projects*** *so I'm always focusing on ... I care less if it's what specific beam size it is or I got a number nine rebar and more like what order of magnitude change did this other change cause. So if the architect changes an opening size or span, I'm like well what does that change in percentage of your load? Is it a five percent delta? Because that's not a big change. Is it 200 percent? That's a big change. And* ***that's the sort of stuff you can remember without having to remember specifics*** *and you can use that stuff in client meetings and meetings with consultants to kind of guide discussion and it's less, nobody really wants you to, I mean it's impressive when you can rattle off a beam size and like, "Oh yeah. That's gonna be an 18 by 30." […] But whereas if you can say, "Yeah. If you change that that's gonna double your load or double what we have to do." You aren't necessarily locking yourself into an answer but you still understand what's going on.*

In this excerpt, the engineer never explicitly mentions heuristics, but refers to “big picture things” as being “the most transferable across projects” and “that’s the sort of stuff you can remember without having to remember specifics.” This aligns with our previous definition of heuristics and specifically profession-based heuristics because of transferability. Similar to the homework assignment presented in Figure 4-8, the purpose is not for students to know how a specific beam size or rebar size will perform, but to grasp how changing these things influences the big picture of a design. That way, in the sociomaterial context of when an architect wants to increase floor height, thereby reducing beam depth, the students can draw upon this profession-based heuristic to know that will considerably alter their beam capacity and require a possible re-design.

4.6 Discussion

Previous research has noted that engineering students are uncertain about using engineering judgment and intuition and find it difficult to develop (Koch et al., 2010; Wirth et al., 2017). Engineering judgment and intuition can be considered a type of heuristic used for assessing alternatives and developing appropriately conservative estimates (MacRobert, 2018). This study's description of heuristics as being practice-based or profession-based contributes to previous research on the education of heuristics, like engineering judgment, by distinguishing which types of heuristics have the most utility for students in their engineering education. The findings from this research appear to indicate that engineering judgment and intuition developed through practice-based heuristics is likely best left for the workplace to train, but there may be potential in enhancing students' engineering judgment and intuition through profession-based heuristics.

For example, providing students practice with approximate analysis techniques such as the portal method presented in Figure 4-7 may help students develop intuition for how structures displace. The homework problem for the Reinforced Concrete design course presented in Figure 4-8 is another good profession-based heuristic that provides students with an intuitive sense of how significantly certain design parameters influence an overall design. Ruddy and Ioannides (2004) provide several profession and practice-based heuristics for steel design that can also be used to foster students' intuition for the steel design parameters that matter most in schematic design.

Thus, the differentiation between practice-based heuristics and profession-based heuristics provides a way of describing heuristics that are more or less transferrable to different environments. Practice-based heuristics are more dependent on the sociomaterial contexts of an agency's standards of practice and frequently encountered engineering problems and therefore less transferable across environments. Profession-based heuristics are more dependent on the sociomaterial contexts of a profession's development and standardization of fundamental conceptual knowledge that is transferable across environments. Certain practice-based heuristics may be more common across agencies and projects, but instructors should clarify whether a heuristic presented in the classroom is practice or profession-based and note the limitations and potential errors in applying practice-based heuristics without consideration for the contexts they were developed in. As Fischhoff

(1982) notes, there is “a distinction between education and training […] education develops general capabilities, whereas training develops specific skills.” Practice-based heuristics are specific skills that can be trained in the workplace environments. Profession-based heuristics, however, provide an opportunity to teach students fundamental conceptual knowledge in a way that develops their knowledge and capabilities for multiple workplace environments. Future research could investigate which profession-based heuristics structural engineers prefer for solving certain types of problems and why to identify the profession-based heuristics that are most applicable to structural engineering practice.

4.7 Conclusion

The purpose of this research was to explore how heuristics were represented within the sociomaterial contexts of a structural engineering workplace and academic environments. While previous research has demonstrated the value of heuristics in structural engineering for handling complex, real-world problems, little to no research has explored the sociomaterial contexts of the workplace and academic environments to gain a deeper understanding of how these contexts influence the transferability of certain types of heuristics. The use of ethnographic methods allows for an in-depth exploration of both a workplace and academic environments, which led to the identification of two different types of heuristics. Practice-based and profession-based heuristics provide a framework for identifying heuristics that are more and less dependent, respectively, on the context of their application. Heuristics, overall, had been previously considered prone to error because of their context dependency, however profession-based heuristics provide a unique opportunity for engineering education to connect fundamental concepts with pragmatic approaches that are relevant to the sociomaterial contexts of practice. Future research could consider the use of similar ethnographic methods for exploring other discipline’s profession-based heuristics and more explicitly identify profession-based heuristics used in workplace environments that can be brought into the classroom.

Chapter 5 – Conceptual Representations in the Workplace and Classroom Settings: A Comparative Ethnography

5.1 Abstract

The following is a Theory paper that presents an ethnographic exploration into how concepts are situated in workplace and classroom settings. Situated cognition research demonstrates that different contexts wherein learning occurs and knowledge is applied shape our conceptual understanding. Within engineering education and practice this means that practitioners, students, and instructors demonstrate different ways of representing their conceptual knowledge due to the different contexts wherein they learn and apply engineering concepts. The purpose of this paper is to present themes on how practitioners, students, and instructors represent fundamental structural engineering concepts within the contexts of structural engineering design. By representation of concepts we mean the ways in which practitioners, students, and instructors portray and demonstrate their conceptual understanding of concepts through the social and material contexts of the workplace and classroom environments. Previous research on learning and engineering education has shown the influence that social and material contexts within these environments have on our knowing and understanding. The researchers use ethnographic methods consisting of workplace and classroom observations, interviews with practitioners, students, and instructors, and documentation of workplace and academic artifacts—such as drawings, calculations, and notes—to access practitioners', students', and instructors' conceptual representations. These ethnographic methods are conducted at a private engineering firm and in junior and senior structural engineering courses.

Preliminary results indicate that instructors' conceptual representations in the classroom aim to enhance students' broader understanding of these concepts; whereas students' conceptual representations are focused towards utility in solving homework and exam problems. Practitioners' conceptual representations are more flexible and adapt to project and workplace constraints. These results seem to indicate that even when instructors emphasize broader conceptual knowledge, the academic incentives

behind homework and test scores lead to more academically focused conceptual representations by students. Furthermore, practitioners' conceptual representations indicate the necessity of conceptual fluency in the workplace, which contrasts with the rigidity of conceptual representations that students develop in the classroom. This comparison between workplace and academic conceptual representations enhances our understanding of the extent to which students, instructors, and practitioners share similar or different conceptual representations within the domain of structural engineering. This, in turn, may lead to guided curriculum reform efforts aimed at better preparing structural engineering students for their professional careers.

5.2 Introduction

Several studies of the engineering workplace have demonstrated a gap between engineering education and practice (Johri & Olds, 2011; Jonassen et al., 2006; Trevelyan, 2007, 2010). One reason for this education-practice gap is that "[t]oo often in engineering classrooms, the instructional activities required of the students are not aligned with the kind of knowledge those activities are intended to foster" (Newstetter & Svinicki, 2014). Another proposed reason for this gap is that engineering practice entails solving complex, ill-structured problems with knowledge that is distributed amongst other engineers and engineering tools; whereas engineering students are often trained to solve simple problems with little to no ambiguity using knowledge distributed amongst their instructors, textbooks, and peers (Bucciarelli, 1988; Jonassen et al., 2006; Trevelyan, 2010). Situated cognition theory offers a theoretical framework for studying this education-practice gap in engineering.

Situated cognition theory proposes that the social and material contexts wherein knowledge is learned and applied influences our ability to apply similar knowledge in new contexts (Johri et al., 2014). Engineering education often focuses on transmitting conceptual knowledge to students in abstract formats with the intent of providing students a fundamental understanding of concepts so that they can apply these concepts to unique situations in their future coursework or engineering careers

(Bornasal et al., 2018; Newstetter & Svinicki, 2014). Situated cognition challenges this ubiquitous notion of concepts and our ability to apply conceptual knowledge within novel contexts (Newstetter & Svinicki, 2014). Perhaps then, differences in the social and material contexts of engineering practice and engineering education contribute to different conceptual representations in these settings and make up part of the education-practice gap. By conceptual representations, we mean the ways in which concepts are portrayed in social (dialogue) and material (artifacts) contexts.

Ethnographic methods provide a robust research method for exploring these social and material contexts that influence conceptual representations in professional and academic engineering settings. An ethnography is a qualitative research methodology that aims to gain deeper understandings of cultures by participating in and observing the social and material interactions of these cultures (Case & Light, 2011). Thus, the researchers conducted ethnographic methods at a private structural engineering firm and in structural engineering undergraduate courses to compare the social and material contexts of these settings and how they influenced conceptual representations of fundamental structural engineering concepts.

Structural engineering students in the courses studied were exposed to many of the material resources that practicing structural engineers use in their daily work. The practicing structural engineers at the firm studied often had to negotiate the concepts represented in these material resources and their limitations. However, in the engineering curriculum studied, homework and lab exercises can sometimes over-simplify the concepts present in these material resources and limit the potential for students to develop their own engineering judgment for more complicated applications of these concepts.

5.3 Background

Conceptual knowledge is defined by Rittle-Johnson as the “understanding of principles governing a domain and the interrelation between units of knowledge in a domain” (Rittle-Johnson, 2006). A “unit of knowledge” can be thought of as a specific concept, such as force or mass; and Newton’s laws are an example of the interrelation between these units (Perkins, 2006; Streveler et al., 2008). These relationships, “such as Newton’s laws and the laws of thermodynamics, are part of conceptual knowledge in the engineering domain” and this conceptual knowledge “is central to the practice of engineering” (Streveler et al., 2008). While Newton’s laws and the laws of thermodynamics are in some way important to nearly all engineering disciplines, each engineering discipline has their own unique and nuanced conceptual knowledge that distinguishes their respective disciplines from one another.

Concepts can be represented by more than just laws and equations, however. Especially with engineering, concepts can be represented by artifacts such as text, diagrams, symbols, etc., and these representations are influenced by the social and material contexts of engineering activities done in the classroom and workplace (Johri et al., 2014; Lemke, 1998; McCracken & Newstetter, 2001). An example of a common engineering activity is design and as Bucciarelli states: “design expertise is a matter of context” (Bucciarelli, 1988). According to Lemke, “[i]n these activities, ‘things’ (materials) contribute to solutions every bit as much as ‘minds’ (social) do; information and meaning is coded into configurations of objects, material constraints, and possible environmental options, as well as in verbal routines and formulas or ‘mental operations. […] Our ‘cognition’ is always bound up with, co-dependent with, the participation and activity of Others, be they persons, tools, symbols, processes, or things” (Lemke, 1998). This emphasis of social and material context as being an intrinsic part of cognition is one of the main points of situated cognition (Johri et al., 2014).

Therefore, it is worthwhile to explore the social and material contexts of the design activities performed by practicing engineers and engineering students. Understanding how these contexts might differ across the engineering classroom and workplace could illuminate potential avenues and best practices for bridging the education-practice gap. Ethnographic methods provide a well-suited methodology for exploring in depth the social and material contexts of the engineering workplace and classroom because these methods situate the researcher(s) within these contexts for an extended period of time.

5.4 Methods

The ethnographic methods employed in this study consisted of field notes of activities participated in and observed, artifact documentation, and informal and formal interviews. The research sites where these methods were conducted were within a medium-sized structural engineering department at a private architecture and engineering firm, and in two undergraduate structural engineering courses offered at a large public university. Both the firm and university are located in the Pacific Northwest region of the United States. The researchers decided to focus on the discipline of structural engineering because the researcher conducting the ethnographies has experience in this field and therefore can act as a meaningful participant in both settings. Site selection for both settings was based on geographical access to the researchers and finding a firm and instructors that were willing to participate in the study (Maxwell, 2013). While these settings will undoubtedly have their own unique cultures that do not represent all of structural engineering education and practice, this does not mean that we cannot enhance our understanding of the education-practice gap by focusing on depth over breadth and then situating our findings within existing research.

5.4.1 Data Collection

The data collected during both ethnographies will be field notes from participant-observation, interviews, and artifact documentation (Emerson et al., 2011). As a whole, these methods allow the researchers to triangulate the data to enhance the reliability of their findings (Stevens et al., 2008; Walther et al., 2013). Participant-observation in the workplace setting consisted of the ethnographer working part-time as an intern, assisting in structural design efforts, while also observing design efforts and meetings amongst the other structural engineers. The architecture and engineering firm that participated in the study specializes in design and retrofits of buildings in the commercial, industrial, and public sectors. The firm employs over 20 structural engineers with experience ranging from interns/new-hires to over 30 years of professional experience. The ethnographer worked at this setting for three months.

Participant-observation in the academic setting consisted of the ethnographer enrolling in undergraduate courses as an actual student so that they could actively participate with other students during lecture, labs, on homework, and in studying. The two courses used in this study were an introductory structural analysis course and an introductory steel design course. Both courses are commonly taken in the junior and senior years of undergraduate civil engineering students. These courses met three days per week for a one-hour lecture and one day each week for a two-hour lab. Each course had a term length of 10 weeks. The structural analysis course was taught by an instructor with over 30 years of experience teaching structural engineering. The steel design course was taught by an instructor in their first year working as a professor. Both instructors typically used lecture to introduce new concepts and work example problems, and used lab for group exercises and demonstrations.

The ethnographer wrote field notes on what they did and observed in these settings to capture as much detail in the moment. These field notes serve as an initial bearing for the ethnographer and frequently revisiting them provided the ethnographer with interview questions and what to focus on in later observations.

The ethnographer documented artifacts that they used or created in their participation and that they observed others using/creating. Artifacts were primarily documented through pictures and then integrated into the field notes where the artifacts were noted by the ethnographer during their participation and/or observations. These artifacts help ground the ethnographer’s field notes to tangible, real-world objects that engineers, students, and instructors use to demonstrate their conceptual knowledge. The ethnographer also uses the artifacts to help facilitate interview questions so that participants may use the artifacts to aid in their explanations of concepts.

Formal and informal interviews were conducted with engineers, students, and instructors. Informal interviews occurred spontaneously in the field when the ethnographer had the opportunity to ask clarifying and follow up questions. Formal interview questions are developed for specific participants based on data collected in the field notes and served as a means for member checking the ethnographer's observations and interpretations (Walther et al., 2013).

5.4.2 Data Analysis

Data analysis for an ethnography occurs during and after data collection (Emerson et al., 2011). The ethnographer revisited their field notes after leaving the field site each day to stay close to their data and have it guide them each subsequent day in the field. Frequently revisiting the field notes provided the ethnographer with reminders of artifacts to document and questions to ask participants during interviews. Field notes, pictures of artifacts, and interview excerpts are then synthesized into narratives of activities for the purpose of comparing with narratives of other activities and identifying themes in the data. The ethnographer worked to create these narratives and begin identifying themes while still in the field so that they could continuously check the reliability of their themes and/or develop new ones as more data emerged (Emerson et al., 2011; Walther et al., 2013).

5.5 Results

While many concepts emerged as relevant in both settings, for the purpose of this paper the authors' chose to focus on the concept of loads. Loads are the forces that structural engineers design structures to withstand, such as snow, wind, and seismic. Determining the magnitudes of these loads is an essential step for designing structures and was one of the most frequently documented concept in both settings. This section provides an example of how loads were presented and discussed in the workplace setting and in both course settings to illustrate broader themes about social-material contexts and conceptual representations in these settings.

5.5.1 Workplace Setting

In the workplace setting, structural engineers frequently used a standard published by the American Society of Civil Engineers (ASCE), called *ASCE 7:*

Minimum Design Loads and Associated Criteria for Buildings and Other Structures, for guidance in determining their loads. This standard provides prescriptive methods for calculating load magnitudes such as how many pounds per square foot snow places on the roof of a structure. During one design effort at the workplace setting, two engineers were discussing how to account for the amount of snow blowing over a parapet on the roof of a taller, adjacent structure and onto the roof of a lower structure they were designing. This concept of wind blowing snow from one structure to another is called snow drift and creates concentrated areas with larger snow loads on adjacent structures. ASCE 7 provides methods for determining the magnitude of this snow load when the snow drifts up against an adjacent structure, such as a parapet, but not for how much snow could drift up and over a parapet onto a lower adjacent roof. This lack of nuance in the standard caused the two engineers to question how much snow could blow over the parapet and pile up on their structure's roof below. These two engineers sought a more senior engineer's help on this problem and drew a picture (see Figure 5-1) to explain what they were dealing with. For additional context, Figure 5-2 shows the diagrams used in ASCE 7 for illustrating snow drift.

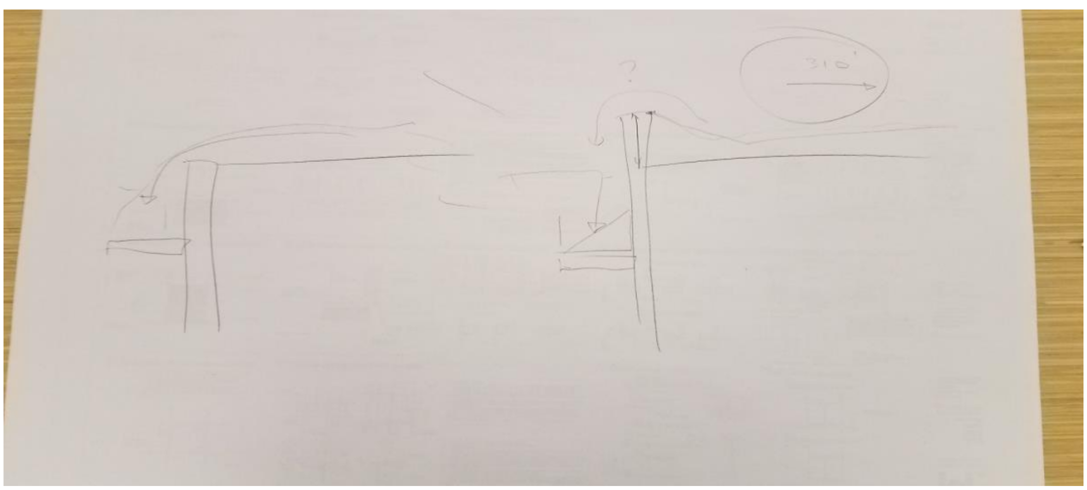


Figure 5-32. An engineer's sketch of snow drift. The left sketch is a diagram of how ASCE 7 presents snow drifting from a higher roof, without a parapet, to a lower one. The right sketch represents the additional nuance of the taller roof having a parapet, and the engineers being unsure how much snow could drift over the parapet and onto the lower roof.

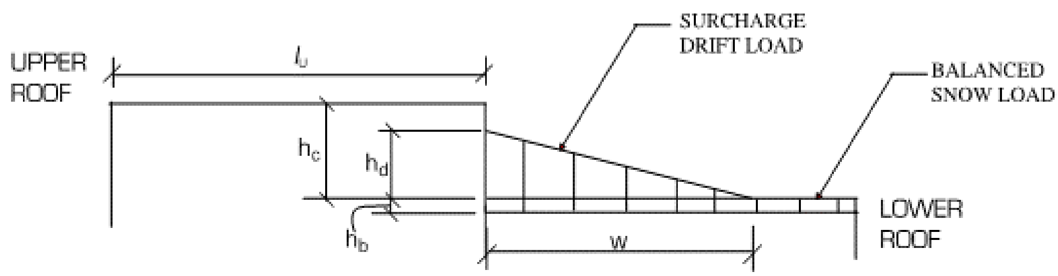


Figure 5-33. Diagram in ASCE 7 depicting the variables that go into accounting for snow drifting from an upper roof to a lower roof.

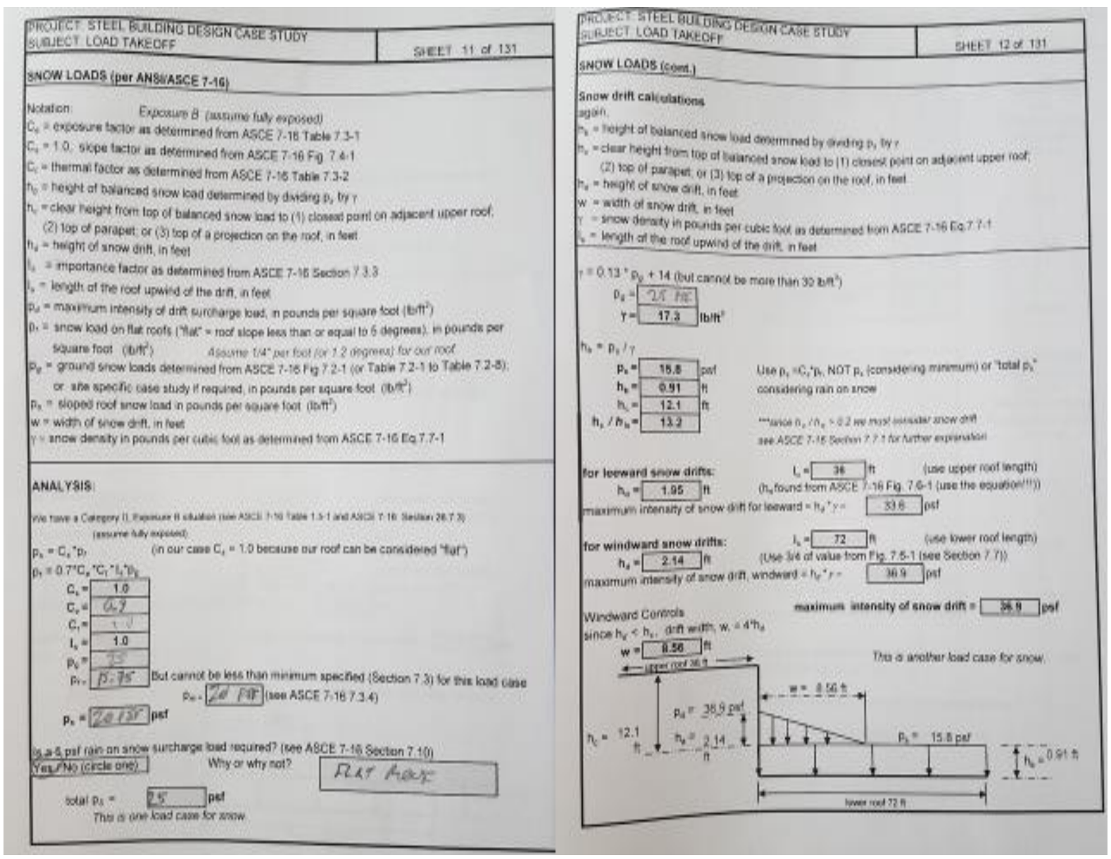
In a later interview with the more senior engineer, the ethnographer asked the senior engineer how they helped the other two engineers resolve this snow drift problem. The senior engineer said:

> *They're [the other two engineers] hung up in the technical portion of it, which is how does the equation work. But the question they should be asking is: how does the principle apply here? Because the equation won't really answer that question. How do I apply drift blowing over a parapet down onto a lower roof? There are cases where you should do that, right? […] The trick becomes […] how can I convince myself as a professional that it's okay to say that this will not have drift on it? I gave you an example of where you shouldn't because it's [the lower roof] seven stories down, six in this case. […] There is no conceivable way for drift to get blown off the side of the building and fall straight down for seven stories and pile up the drift. […] If it has any horizontal force [from wind] at all, it's going to get blown further out. […] So I'm using my judgment when it's six stories down. When it's three stories would I make the same call? Maybe. When it's one story down? No. When it's one story down I put drift on it. There's a gray zone in there where I would have to question myself and either take a conservative approach or really justify to myself why, but the principle…it's not so much about what's the equation, it's what's the underlying principle behind the equation.*

Here the senior engineer discusses the importance of understanding the underlying principles in ASCE 7 in order to be flexible in their application of the concepts represented in the standard and using it in tandem with their engineering judgment when dealing with more complex scenarios.

5.5.2 Academic Setting

In both structural engineering courses, students were taught the tools and procedures for determining snow loads on a structure. In the steel design course, students were assigned a group project for designing the structural steel elements of an office building and in one of their labs were expected to work with their groups to determine the snow loads on their roof. The exercise entailed having the students navigate portions of ASCE 7 to determine a variety of input values for calculating the magnitude of their flat roof snow load and the drift snow load formed from snow being blown up against a penthouse structure on the roof. The lab assignment is presented in Figure 5-3.


PROJECT: STEEL BUILDING DESIGN CASE STUDY
SUBJECT: LOAD TAKEOFF
SHEET 11 of 131

SNOW LOADS (per ANSI/ASCE 7-16)

Notation: *Exposure B (assume fully exposed)*
C_e = exposure factor as determined from ASCE 7-16 Table 7.3-1
C_s = 1.0; slope factor as determined from ASCE 7-16 Fig. 7.4-1
C_t = thermal factor as determined from ASCE 7-16 Table 7.3-2
h_b = height of balanced snow load determined by dividing p_s by γ
h_c = clear height from top of balanced snow load to (1) closest point on adjacent upper roof; (2) top of parapet; or (3) top of a projection on the roof, in feet
h_d = height of snow drift, in feet
I_s = importance factor as determined from ASCE 7-16 Section 7.3.3
l_u = length of the roof upwind of the drift, in feet
p_d = maximum intensity of drift surcharge load, in pounds per square foot (lb/ft²)
p_f = snow load on flat roofs ("flat" = roof slope less than or equal to 5 degrees), in pounds per square foot (lb/ft²) *Assume 1/4" per foot (or 1.2 degrees) for our roof*
p_g = ground snow loads determined from ASCE 7-16 Fig 7.2-1 (or Table 7.2-1 to Table 7.2-8); or site specific case study if required, in pounds per square foot (lb/ft²)
p_s = sloped roof snow load in pounds per square foot (lb/ft²)
w = width of snow drift, in feet
γ = snow density in pounds per cubic foot as determined from ASCE 7-16 Eq 7.7-1

ANALYSIS:

We have a Category II, Exposure B situation (see ASCE 7-16 Table 1.5-1 and ASCE 7-16 Section 26.7.3) (assume fully exposed)
$p_s = C_s * p_f$ (in our case C_s = 1.0 because our roof can be considered "flat")
$p_f = 0.7 * C_e * C_t * I_s * p_g$
C_s = 1.0
C_e = [illegible]
C_t = [illegible]
I_s = 1.0
p_g = [illegible]
p_f = [illegible] But cannot be less than minimum specified (Section 7.3) for this load case
p_m = 20 PSF (see ASCE 7-16 7.3.4)
p_s = 20 / 25 psf

Is a 5 psf rain on snow surcharge load required? (see ASCE 7-16 Section 7.10)
Yes / No (circle one) Why or why not? FLAT ROOF

total p_s = 25 psf
This is one load case for snow.

PROJECT: STEEL BUILDING DESIGN CASE STUDY
SUBJECT: LOAD TAKEOFF
SHEET 12 of 131

SNOW LOADS (cont.)

Snow drift calculations
again,
h_b = height of balanced snow load determined by dividing p_s by γ
h_c = clear height from top of balanced snow load to (1) closest point on adjacent upper roof; (2) top of parapet; or (3) top of a projection on the roof, in feet
h_d = height of snow drift, in feet
w = width of snow drift, in feet
γ = snow density in pounds per cubic foot as determined from ASCE 7-16 Eq 7.7-1
l_u = length of the roof upwind of the drift, in feet

$\gamma = 0.13 * p_g + 14$ (but cannot be more than 30 lb/ft³)
p_g = [illegible]
γ = 17.3 lb/ft³

$h_b = p_s / \gamma$
p_s = 15.8 psf   Use $p_s = C_s * p_f$, NOT p_s (considering minimum) or "total p_s" considering rain on snow
h_b = 0.91 ft
h_c = 12.1 ft
h_c / h_b = 13.2   ***since h_c / h_b > 0.2 we must consider snow drift; see ASCE 7-16 Section 7.7.1 for further explanation

for leeward snow drifts: l_u = 36 ft (use upper roof length)
h_d = 1.95 ft (h_d found from ASCE 7-16 Fig. 7.6-1 (use the equation!!!))
maximum intensity of snow drift for leeward = $h_d * \gamma$ = 33.8 psf

for windward snow drifts: l_u = 72 ft (use lower roof length)
h_d = 2.14 ft (Use 3/4 of value from Fig. 7.6-1 (see Section 7.7))
maximum intensity of snow drift, windward = $h_d * \gamma$ = 36.9 psf

maximum intensity of snow drift = 36.9 psf

Windward Controls
since $h_d < h_c$, drift width, w, = $4 * h_d$
w = 8.56 ft
This is another load case for snow.

Figure 5-34. Load takeoff lab exercise for determining snow loads in the steel design course.

To complete this exercise, students were given print out sections of ASCE 7 relevant to determining snow loads. Students were expected to find the values for various variables pertaining to snow load equations in ASCE 7, write them in where relevant on the sheets shown in Figure 5-3 and work through the procedure outlined for them.

This exercise exposed students to the concepts presented in ASCE 7 that are relevant for determining snow loads and provided them with a relevant resource for navigating step-by-step through ASCE 7's procedure for determining flat roof snow loads and drift snow loads. The student group that the ethnographer worked with on this exercise often navigated the ASCE 7 printouts and filled out the sheets in Figure 5-3 on their own. Students checked their answers within the group each step of the way before moving to the next step. If everyone got the same answer, there was no discussion as they moved to the next step. If someone got a different answer or was unsure where a value was obtained, the students would discuss their interpretations of ASCE 7 and why that led them towards a certain value.

Having the students complete this exercise in groups, for an authentic structure, and using ASCE 7 aligns with many of the social-material contexts present in the workplace. However, the exercise requires little to no exploration of the underlying principles for calculating snow loads in ASCE 7 and becomes more of a plug-and-chug exercise for the students.

In the structural analysis course, students were given a homework problem for calculating snow loads on a high school roof in Portland, Oregon (see Figure 5-4). This problem required students to use and interpret sections of the Oregon Structural Specialty Code (OSSC), a document that practicing engineers in Oregon use in tandem with ASCE 7. ASCE 7 is not a required text for this course, and no handouts of sections of ASCE 7 were provided for students to solve this problem. Instead, pertinent sections of ASCE 7 to snow loading are referenced for the students to know where certain variables and their values are coming from, but with minimal explanation.

Problem #5:
GIVEN: Benson Polytechnic High School in Portland, Oregon. Assume that it has an ordinary flat roof with roof drainage not constrained (roof is able to drain).

FIND:
Design snow load for the roof (psf).

Notes:
- Determine latitude/longitude of this location using Google Maps or Google Earth, for example.
- Snow loads are determined using Section 1608 of the 2014 OSSC.
- Information from the Snow Load Analysis for Oregon published by the Structural Engineers Association of Oregon can be obtained from: http://snowload.seao.org/lookup.html

- Obtain the design ground snow load from this site.
- The Importance Factor for Snow Load, I_S =1.10, as found in ASCE 7-16 Table 1.5-2. A secondary school is in Risk Category III (from OSSC Table 1604.5) if the occupancy load is greater than 250. Benson HS has approximately 1000 students and faculty, plus staff.
- For flat roofs, the design snow load (on the roof) is given by:

a) Hibbeler Equation (1-5) (this is Eq. 7.3-1 in ASCE 7-16)
b) C_e = 0.9 (fully exposed roof in surface roughness B - urban area with numerous closely spaced obstructions) (Table 7.3-1 in ASCE 7-16).
c) C_t = 1.0 for heated building (Table 7.3-2 in ASCE 7-16)

Also, read the Map Usage Notes on Minimum Roof Design Snow Load and apply these as well. If the minimum is greater than the value from Hibbeler Equation (1-5) (this is Eq. 7.3-1 in ASCE 7-16), then the minimum applies. Lastly, include the rain-on-snow surcharge load if appropriate. Explain your logic in considering it.

Figure 5-35. Homework problem on calculating snow loads in the structural analysis course.

Similar to the steel design lab exercise, this homework problem required students to navigate some resources pertinent to structural engineering practice, but most of the problem statement provided students with the remaining inputs and the problem becomes a plug-and-chug process eliminating any considerable need for engineering judgment or thought behind the process.

Both the steel design course lab exercise and this homework assignment for the structural analysis course relegate important concepts pertaining to snow load determination to relevant codes and standards. These exercises help expose students to important resources that will be relevant to them in practice, but represent important concepts as rigid, procedural calculations that limit the opportunity for students to understand the principles behind these procedures and hone their engineering judgment.

It should be noted that the main focus of a structural analysis course is determining the demands on a structure as a result of loads and the main focus of a steel design course is learning to design steel structures with enough capacity to resist such demands. Neither course is meant to spend a considerable amount of time on determining the loads that act on structures. While these curricular constraints limit the amount of time that students can be presented to all the nuances of loads, such constraints should not lead to unresolved oversimplifications.

5.6 Discussion

Previous studies of the engineering workplace have identified the collaborative problem solving and distributed knowledge amongst people and tools required in engineering practice to solve more complex problems than the simplified problems typically asked of students in undergraduate engineering education (Anderson et al., 2010; Dunkle et al., 1995; Gainsburg et al., 2010; Jonassen et al., 2006; Salzman & Lynn, 2010; Trevelyan, 2010). These studies focused on engineering more broadly and not all collected data from engineering classrooms for means of direct comparison. However, our ethnographic research of both workplace and academic settings for structural engineering specifically appear to echo similar findings.

One similar ethnographic study on engineering concepts in a transportation engineering workplace found the following five themes: 1) engineers identify project constraints before applying relevant technical concepts, 2) abstract concepts are contextualized to these project constraints, 3) engineers frequently negotiate meanings of concepts to enhance their own conceptual understanding, 4) concepts manifest in multiple representations in practice, and 5) engineers use material resources to efficiently address complex processes and problems associated with engineering concepts (Bornasal et al., 2018). These themes echo our findings of the structural engineering workplace, implying that regardless of engineering discipline, practicing engineers engage with technical concepts in similar ways. This is promising for a field such as civil engineering because civil engineering students may end up practicing in multiple different sub-disciplines of civil engineering with vastly different technical concepts, but perhaps can all still be trained to engage with these concepts in similar ways.

This is not to say that engineering curriculum can entirely prepare each student for all the problems they will encounter in their career, but that there exist opportunities to enhance the ways students' engage with concepts to prepare them for the complexities and nuances of real-world engineering problems. Group design projects, such as the one used in the steel design course provide students with the opportunity to engage with concepts in similar social-material contexts as practicing engineers. Homework problems and lab exercises, however, that over-simplify engineering concepts into plug-and-chug procedures can make even hand calculations and design guides/manuals as much of a black box as software.

5.7 Conclusion

The purpose of this research was to explore the social and material contexts that influence conceptual representation and understanding in the engineering workplace and academic settings for a specific engineering discipline—structural engineering. The education-practice gap in engineering is a well-documented phenomenon often attributed to some of the differences in these social and material contexts across academic and professional settings, such as the simplicity of textbook-type problems versus the complexity of real-world engineering problems. Little to no research has explored this phenomenon in-depth, in both settings, and in a specific engineering discipline to understand how context influences conceptual representations and subsequent understanding. Using ethnographic methods, the researchers were able to participate with and observe engineers and students in their various design related activities over an extended period of time to enhance our understanding of how differences in social-material contexts and conceptual representations contribute to the education-practice gap. Overall, structural engineers solve real-world engineering problems relying on a variety of material resources, but frequently discuss and negotiate their interpretation and utilizations of the conceptual representations in these resources with other structural engineers. It is important for structural engineering students to be exposed to these material resources so that they are aware of them and know how to use them when entering their careers, but curriculum that encourages students to engage with the limitations of these resources conceptual representations may help develop their engineering judgment for handling the complicated problems encountered in the engineering workplace.

Chapter 6 – Conclusion

6.1 Summary of Findings

The goal of this research was to explore the sociomaterial contexts of an engineering workplace and academic environments to better understand how these contexts influence conceptual representations within the discipline of structural engineering. The findings in Chapter 2 indicated that the concept of loads and other concepts related to loads could be represented with various degrees of tangibility to 1) real-world conditions, 2) project/stakeholder constraints, and 3) engineering tools. How a concept could be tangible to these three traits varied considerable depending on the nature of the engineering activity in the environments studied. Conceptual representations in the workplace environment were always tangible to the three traits to some extent either explicitly or implicitly. Conceptual representations in the academic environments exhibited various degrees of tangibility to none, some, or all three traits depending on the nature of academic activity. These findings resonate with broader engineering education studies which have noted that engineering problems and conceptual representations in academic environments are simplified and isolated from real-world contexts (Johri & Olds, 2011; Jonassen et al., 2006; McCracken & Newstetter, 2001). The three traits of tangibility presented in this paper provided a framework for a more specific description of how conceptual representations in a structural engineering workplace are more complicated and interconnected than their academic counterparts. One of the traits conceptual representations could be tangible to was engineering tools—such as codes—which occasionally required engineers in the workplace environment to evaluate and reconcile their conceptual knowledge with the conceptual representations in these tools, as demonstrated in Chapter 3.

Chapter 3 focused explicitly on how the sociomaterial contexts of these environments studied influenced the conceptual representations within codes. The findings from Chapter 3 indicated that while participants in both settings used codes in prescriptive ways when engaging with the conceptual representations in a code, the engineers in the workplace environment were more likely to encounter scenarios that led them to take a more evaluative approach when engaging with conceptual representations in codes. Instructors in the academic environments studied did mention more evaluative approaches to codes in lecture, but providing no opportunities for students to engage with codes in evaluative ways outside of lecture which resonates with previous literature claims on the passive teaching of codes (Kelly, 2008; Solnosky et al., 2017). Understanding the evaluative ways engineers in the workplace environment engaged with codes offers an approach for teaching codes that addresses the SEI (2013) report's concerns about prescriptive code application reducing the role of the structural engineering profession in society. Some of the evaluative ways engineers in the workplace environment approached codes were products of their practice-based heuristics as demonstrated in Chapter 4, which may be less appropriate for academic environments, however, because of their unique context.

Chapter 4 focused explicitly on conceptual representations that could be considered heuristics and how sociomaterial contexts influenced the development and application of heuristics. Findings from Chapter 4 noted the application of profession-based heuristics across all environments studies, but also noted the use of practice-based heuristics by engineers in the workplace environment. While the use of practice-based heuristics demonstrated experience-based judgment and intuition by the engineers in the workplace environment, the development of these heuristics were also contextually based in the types of projects the firm was frequently contracted to work on. Previous research has noted that engineering students are not confident in their engineering judgment and unprepared for the workplace in this sense (Aparicio & Ruiz-Teran, 2007; MacRobert, 2018; Ruddy & Ioannides, 2004). The findings from Chapter 4 on practice-based heuristics indicate limitations to teaching such heuristics and the engineering judgment associated with them because these heuristics likely vary from workplace to workplace and not all engineering students will end up working in the same environments.

Chapter 5 presented findings that can be described through the lens of either of the previous three chapters' findings. For instance, the example of determining snow drift in the workplace setting demonstrated the tangibility of snow loads, the engineers' evaluative approach to applying ASCE 7 in a unique scenario, and their handling of the scenario with heuristics. Conversely, the examples of determining snow loads presented from the academic settings exhibited a lesser degree of tangibility, required students to prescriptively apply ASCE 7 for a common scenario with profession-based heuristics. Indeed, the distinct interpretive perspectives for Chapters 2-4 emerged from the writing of Chapter 5 and were vetted through the presentation and discussion of Chapter 5 at a national conference with other engineers and educators.

6.2 Contribution to Engineering Education

Considerable amounts of engineering education research have argued that engineering school is not preparing students adequately for the workplace. Relatively broad claims cite lack of communication, teamwork, leadership, significantly different activities in education vs. practice, lack of proficiency with necessary tools in the workplace, oversimplified problems vs. complex real problems (Johri & Olds, 2011; Jonassen et al., 2006; Litzinger et al, 2011; Stevens et al; 2014; Trevelyan, 2010). Very little research has looked at this issue with the focus on engineering concepts, and of those that have, most have not done so at a disciplinary level and/or across both academic and workplace environments (Bornasal et al., 2019; Johri & Olds, 2011; Streveler et al., 2008). The research presented within this dissertation aimed to address this gap in the engineering education literature by focusing on structural engineering conceptual representations within the sociomaterial contexts of a workplace and academic environments.

The ethnographic approach we took to address this gap in the literature allowed us to create unique ways of describing conceptual representations across both workplace and academic environments. For example, while non-abstract representations of concepts have been hinted at having tangibility, our degrees of tangibility framework and traits of tangibility provides an explicit way of describing how conceptual representations are more or less tangible depending on the sociomaterial contexts wherein they are embedded. Furthermore, while codes have been documented as an important tool in engineering practice (Kelly, 2008), various opinions exist on how they should be taught, if at all (Solnosky et al., 2017). Our description and examples of evaluative versus prescriptive code use provides a more nuanced view on the use of codes, and the concepts represented within them, in the sociomaterial contexts of practice and education. Lastly, engineering judgment has been a skillset industry has perceived engineering graduates lacking (Aparicio & Ruiz-Teran, 2007), but has remained poorly described in education literature. Our description and delineation of profession-based versus practice-based heuristics provides a way of identifying heuristics that are more or less transferable across sociomaterial contexts with profession-based heuristics being more transferable and appropriate for teaching engineering judgment in academic environments. While some engineers, instructors, and/or researchers may have already had similar hunches to these findings, our research provided rich descriptions and examples of these hunches to frame the discussion of conceptual representations in engineering education research moving forward.

6.3 Implications for Engineering Education and Future Research

While many of the findings from this research can be connected to similar claims about the distinct nature of engineering practice and education, the research still provides valuable implications for engineering education. For example, the tangibility framework can be used to characterize and better understand conceptual representations within any engineering discipline and across any environment. Future research could explore other workplace and academic workplace environments in structural engineering and other disciplines to examine the comprehensiveness of the tangible traits presented in Chapter 2 and identify other potential tangible traits that are more relevant for different disciplines and workplace environments.

Similarly, while codes are a significant engineering tool in engineering education, other historically developed text-based resources are essential within other disciplinary practices (Kelly, 2008; Solnosky et al., 2017; Vinson et al., 2017). The evaluative versus prescriptive dichotomy for describing code use amongst the structural engineering participants in this research could be used to describe how other text-based resources are applied within other disciplines and environments. Future research could also explore how structural engineers engage with performance-based codes and design to gain a better understanding of how they represent and negotiate concepts in a more open-ended design philosophy.

In regards to engineering judgment and intuition, these nebulous skillsets are challenging to observe, define, and teach (Vick, 2002). Heuristics offer a type of conceptual representation for accessing and describing how and when engineers use their judgment and intuition (Gestson et al., 2019). Further delineating of heuristics as practice-based vs. profession-based provides a way of characterizing heuristics that are more or less appropriate for teaching in academic environments. As more research is conducted in workplace environments, certain practice-based heuristics may be identified as more or less universal across engineering practice. Also, future research could look more explicitly at the types of profession-based heuristics that structural engineers prefer for solving common problems and why to better understand when and where such heuristic are appropriate to teach in undergraduate education. Similar research has already been conducted within water resource engineering (Gestson et al., 2019).

6.4 Conclusion

There may be more common ways of knowing and representing concepts across other engineering workplace environments, but until more studies like this are conducted we cannot say for sure with sufficient detail to make definitive recommendations for engineering education. The author firmly believes based on his experience from this research that more in-depth explorations of specific workplace environments is manageable and appealing for graduate students in any discipline that want to gain industry experience, reinforce what they learned in their undergraduate studies, and gain insight into best teaching practices. Indeed, it will take many ethnographers from a variety of disciplinary backgrounds to gain a more nuanced and descriptive understanding of the engineering education-practice gap. Lastly, when we can better prepare engineering students for the conceptual representations they will encounter in the workplace, we equip them with the skills to demonstrate their conceptual knowledge amongst their mentors and peers in practice, thereby creating opportunities for students to showcase other skills that industry has perceived lacking such as: communication, teamwork, and leadership.

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