Critical Thinking for Open-Ended Engineering Problems Through Written Reflection: A Case Study

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Abstract

Engineering classes are frequently assessed with closed-ended, well-defined problems with a "correct" answer. Open-ended and more complex problems complement this approach, and can develop an ability to synthesize and contextualize information, and to develop critical thinking skills. Assessing open-ended problems can prove challenging, as traditional grading methods for closed-ended problems are generally not feasible. One method to assess open-ended problems is to implement written homework reflections. This paper compares two offerings of a graduate course in structural engineering: the homework problems were similar, but written reflections were incorporated in the most recent offering. Student feedback revealed that the written reflections developed critical thinking and were an important component of the success of the course. The purpose of this paper is to stimulate discussion in the use of written engineering reflections for assessment of open-ended engineering problems and to provide grading strategies for faculty interested in adopting this technique.

Keywords

Written Reflection, Open-Ended Problems, Pedagogy, Critical Thinking

Introduction

Engineering courses generally assess course learning outcomes on homework assignments and exams through the use of closed-ended, well-defined problems that are characterized by having a single correct answer. These types of problems provide certain advantages for the instructor. For example, they may be graded rapidly and equitably through the use of a grading rubric that targets common mistakes and misunderstandings.

While these types of problems are certainly a necessary component of engineering education, student learning can be further enhanced through the use of problems that are open-ended and more complex than the well-defined problems. In these types of problems, students practice the art of making assumptions, which lays the groundwork for the development of engineering judgment.

Open-ended problems may certainly be related to design projects and project-based-learning, but are also readily incorporated in lower-level courses traditionally taught with closed-ended problems. Table 1 contrasts closed-ended and open-ended problems that are appropriate for a sophomore-level Mechanics of Materials course.

Table 1. Sample Closed-Ended and Open-Ended Problems in a Foundational Engineering Course

Sample closed-ended problem	**Sample open-ended problem**
A swing in a playground is suspended from a steel frame. The cables that support the swing are composed of a chain of connected oval steel links made of A-36 steel, each with a cross-sectional diameter of 1/4 inch. If a 50-pound child sits on the swing, what is the factor of safety with respect to tensile yielding of the steel that composes the connected oval links?	Find a piece of playground equipment that can be used to illustrate concepts of basic connection design covered in this course. Draw a free-body diagram of the piece of playground equipment when subjected to forces caused by children playing. Use appropriate factors of safety to investigate at least 3 different aspects of the design's components and connections, and speculate on the probable properties of the materials used in the construction.

The open-ended problem is more likely to increase student engagement, broaden perspective on the course's engineering topics, and develop critical thinking skills. Additionally, these types of problems can robustly support the attainment of several ABET student learning outcomes: "an ability to identify, formulate, and solve engineering problems," "the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context," and "a recognition of the need for, and an ability to engage in life-long learning."

However, it is challenging to assess and grade open-ended problems fairly, equitably, and efficiently. It is apparent from the example above that traditional grading methods for closed-ended problems lose applicability to open-ended problems. The different solutions are both too time-consuming to be graded by the instructor in detail and too complex to be graded by a teaching assistant.

Reflection as a pedagogical technique

Reflection (also called *reflective learning* or *reflective practice*) is a pedagogical technique that can be used to close the loop on the learning process and to allow the learner to connect the content to a variety of other concepts and experiences. Through reflection, students "intentionally make meaning of experiences in service of future action."[1]

J. A. Turns, et al.[1] have consolidated and integrated a number of publications related to reflection practices in adult learning. The work of four theorists is emphasized: Dewey, Kolb, Schon, and Mezirow[1,2,3,4,5,6].

The practice of reflection can take many forms. In this paper, it refers to written mini-essays written by students after performing computational homework assignments in response to specific prompts provided by the instructor. Reflective learning can also be evaluated through other activities, such as survey questions, activities that are computational in nature, and graphic presentations[7,8].

In this paper, two approaches to assessment of open-ended problems are compared in a case study. This study illustrates the value of written reflections coupled with open-ended engineering problems – especially the utility of the reflections to help students develop and enhance their critical thinking skills.

Description of case study

Structural Preservation of Existing and Historic Buildings was taught by the author at Colorado School of Mines in two semesters: Spring 2013 (S13) and Fall 2015 (F15). A graduate-level Structural Engineering elective, this course builds on the typical design classes of Steel, Concrete, Timber, and Masonry, exposes students to archaic structural materials and methods, and gives them a set of tools for the structural analysis and intervention of buildings that contain such materials and methods.

Generally, the field of structural preservation requires more critical thinking than the contemporary structural design of new structures. Structural design, as taught in the academy, is akin to a cookie-cutter process, highly codified and constrained by building code requirements and procedures. Students are taught to apply building code provisions so that their design meets the applicable criteria. In contrast, the building codes for existing and historic buildings emphasize the importance of judgment and the ability to make appropriate assumptions when assessing these buildings. Accordingly, the course learning outcomes require students to:

> *(1) select and apply appropriate contemporary and historic analytical methods for a given structural condition;*
>
> *(2) propose structural interventions that are sensitive to life safety, engineering principles, material conservation, building code requirements, sustainable retrofit practices, and preservation principles; and*
>
> *(3) leverage improved proficiency in critical thinking skills, technical writing skills, and graphic communication skills.*

S13 Course Structure, Assignments, Grading System, and Student Feedback

In S13, the course enrollment consisted of twenty-two students. The course structure was primarily composed of traditional lecture slides and commentary, with one week of mini-field trips on-campus, where the instructor showed the students specific structural systems in campus buildings, and led interactive sketching and pair-share activities.

The final course grade was assigned based on the following weights:

10% Class Participation
15% Homework
20% Quizzes
35% Final Project
20% Final Exam

The homework assignments from S13 and F15 were very similar in content and structure; some assignments were identical. In both semesters, reading assignments and in-class lectures and presentations supplied students with a broad and general framework for the homework assignments. However, unlike most engineering courses, a nearly-identical problem was not supplied to the students. In both offerings, students were encouraged to make assumptions and to select appropriate analysis techniques. The instructor indicated that answers were expected to vary. Unlike closed-ended problems with "right" and "wrong" answers, solutions to open-ended problems are considered satisfactory (based on reasonable assumptions and without conceptual errors) or unsatisfactory. Variation in student responses was expected due to the simplicity or complexity of the analysis model and the assumptions made in the problem-definition stage.

Although the problems were similar in the two offerings, the assessment mechanisms varied greatly. The assessment mechanism for the homework in S13 did not include written reflection. Instead, a check / check-minus / check-plus system was implemented. The description of this grading method as issued in the course syllabus is as follows:

> *0 points: Student does not submit the assignment, or submits extremely poor work.*
>
> *CHECK-MINUS (1 point): homework does not minimally fulfill the assignment requirement, or is sloppy, or is unprofessional, or contains major conceptual errors.*
>
> *CHECK (2 points): homework minimally fulfills the assignment requirements, does not contain conceptual errors, and is neatly presented.*
>
> *CHECK-PLUS (3 points): homework surpasses the assignment requirements and is exceptionally well-presented and professional.*
>
> *The average of the scores (n) will be converted into percentage points per this function:*
>
> $$\textit{average in percentage points} = \left(\frac{20}{3}\right)n^3 - \left(\frac{85}{2}\right)n^2 + \left(\frac{605}{6}\right)n$$
>
> *Thus, scoring all 3's is equivalent to a 100%; scoring all 2's is equivalent to an 85%; and scoring all 1's is equivalent to a 65%.*

From the instructor's point of view, this was a liberating grading system that allowed relatively efficient grading by partitioning the student responses into three bins: a minority of students that submitted impressive work, the majority of the students that satisfactorily completed the assignment, and a minority of students (if any) that submitted low-quality work. Unfortunately, the student perception was very different, leading to seventeen of twenty-two students giving negative feedback on the course evaluations (minor spelling and grammar errors have corrected):

- ***Homework is too ambiguous; additional instruction or examples requested*** (seven of twenty-two students)
  - "Provide more instruction in homework and be more clear about assignment prompts (even when you don't think it needs further clarification) – you are trying to make us think on our own, but without the background it's nearly impossible to start."

  - "Homework is way too ambiguous. We are told to "just try it" and then penalized for an incorrect answer."
  - "…all actual calculations and interpretation in this class is left for us to figure out on our own in homework, you haven't taught us anything."
- ***Grading system for homework is unfair or flawed*** (five of twenty-two students)
  - "Actually grade the homework."
  - "The only way to successfully achieve a check-plus as opposed to a check or check-minus on the homework is to have prior knowledge on the subject, but then, why take the class?"
- ***Homework is too time-consuming*** (three of twenty-two students)
  - "I devoted far too much time to busy work (homework) with little improvement in knowledge."
  - "Don't make the homework worth almost nothing (check system) and then make it a huge work load."

This negative feedback was the primary impetus towards revising the homework assessment model in the F15 offering.

F15 Course Structure, Assignments, Grading System, and Student Feedback

In F15, the enrollment consisted of ten students. In response to the course evaluation comments from S13, the course structure was modified to increase the proportion of the mini-field trips from one week to six weeks. These field visits were accompanied by traditional lecture slides and commentary, as well as other interactive in-class exercises, such as group work and pin-ups with discussion.

The homework weighting was significantly increased from 15% to 50%, written reflections were incorporated, the check / check-plus / check-minus grading model was discarded, and the instructor sought student buy-in by emphasizing the learning outcomes in class and in the syllabus, excerpted as:

> *Engineering education research maintains that students internalize and retain concepts better if they are given time to reflect on what they have learned, thereby contextualizing the technical material. The technical work in this course will be initialized during class in pairs, and guided / supported by the instructor. Work that is not completed in the class shall be completed by individuals or groups of students after class. On Thursdays after class, the Instructor will email a series of reflection prompts. Reflections are due at the beginning of class on Tuesday. It is permissible to work on the technical assignment with another student, but each student must submit their own original reflection. Submit the typed reflection (generally 1-2 single-spaced pages) as the cover sheet and append the technical work. The Consortium to Promote Reflection in Engineering Education (cpree.uw.edu) says that "Reflection may take a little of your time, but the outcomes are generally positive. The chance to reflect can help you identify concepts that you may misunderstand, help you consider your identity as an engineering student, and inform your path going forward. Reflection is also a different type of learning experience that*

provides you an opportunity to explain and make sense of what you know, or may not know. The exercise also helps improve communication with others about your knowledge and ability."

The final course grade was assigned based on the following weights:

50% Homework Reflections
10% Presentation
15% Condition Assessment
25% Final Project

The problems worked by the students in F15 were similar and in some cases identical to the problems worked in S13, but the students' perception was dramatically different, as evidenced in course evaluation comments (minor spelling and grammar errors have again been corrected):

- ***Critical thinking was enhanced through open-ended problems*** (five of seven students)
    - "The class fostered critical thinking and integrated analysis that we used in previous classes."
    - "… [the] class really strikes the right balance of coming up with realistic problems that aren't so open-ended that there's no wrong answer, but still allowing us to really think about the problem."
- ***The reflections were effective / enjoyable*** (four of seven students)
    - "I really enjoy the reflection homework because they are doing what they're meant to do and that is to make us think. I believe that taking time to reflect on what we've learned does much more for us than just plugging and chugging homework problems can ever do."
    - "…I actually really liked the homework reflections. While I was hesitant about them at the beginning of the semester, they provided a nice chance to actually articulate my thoughts and think about things on my own time."
    - "…Even though the reflections were sometimes long and tedious, it definitely got me thinking about more than writing out equations or solving problems."

Comparison of student evaluations of teaching

Student evaluations of teaching can be used to characterize the students' satisfaction with the course. In S13, the participation rate was 100%; seven of ten completed the evaluations in F15. (The reduced response rate is attributed to the change from in-class evaluations to an online survey.) The students' responses to the following eleven ranking questions can be compared in Fig. 1 and 2.

- Question 1. The teaching methods used in this course are effective for promoting student learning.
- Question 2. The instructor explains the material clearly.
- Question 3. The instructor is available during office hours.
- Question 4. The instructor creates an environment that fosters student involvement in the learning process.
- Question 5. The instructor demonstrates a positive attitude toward helping students.

- Question 6. The instructor facilitates student learning.
- Question 7. Graded work reflects the content of the course.
- Question 8. The stated grading policies for this course are fair.
- Question 9. The course goals are clearly stated.
- Question 10. The course goals are being met.
- Question 11. Overall, this instructor is effective.

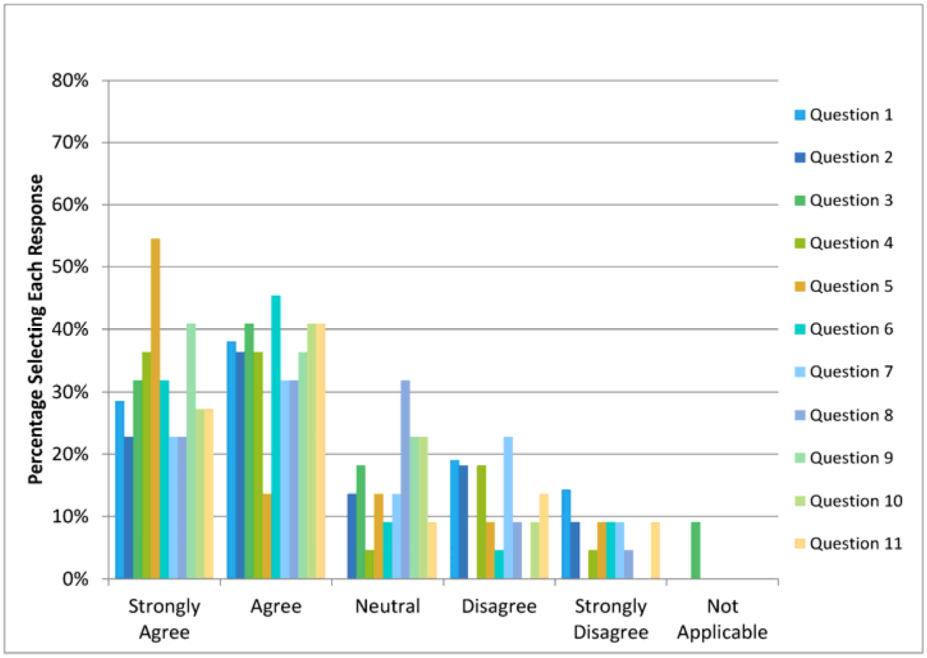


Figure 1. Course evaluation data, S13

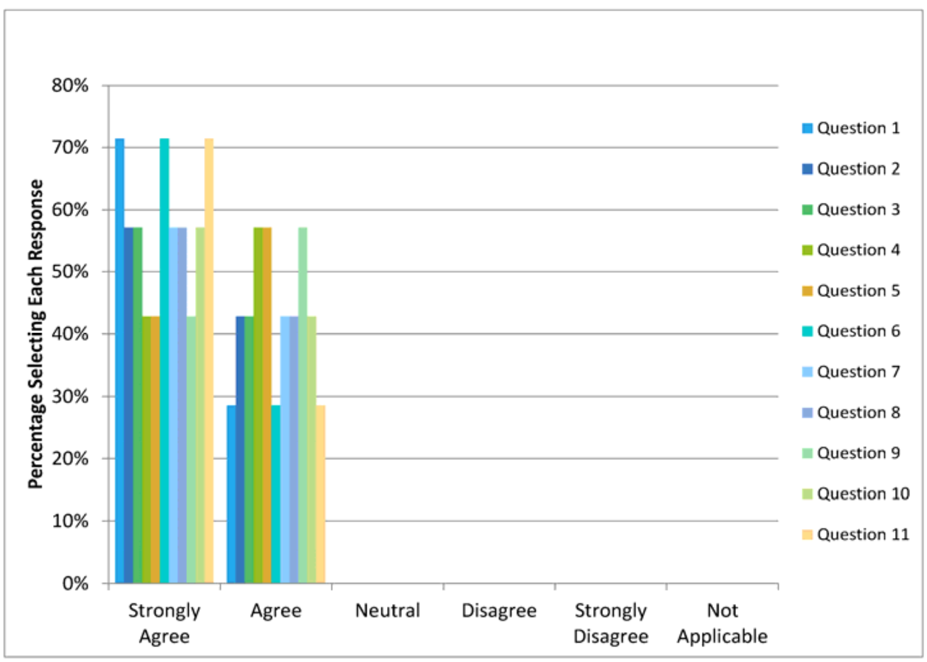


Figure 2. Course evaluation data, F15

The course evaluation form also contains three open-ended questions that ask students to specify the aspects of instruction in the course that are effective for learning, to make recommendations to improve the instruction, and to input any additional comments that the student may have.

In S13, there were few overarching comments on the course. Some students did have a positive impression on the course, but many did not, such as one student who stated “This is not a course for grad students.”

However, the comments in F15 were universally positive, including:

- “Fantastic class. This is the type of class I expected to be taking in graduate school.”
- “I really enjoyed this class! It’s very different than other classes offered at Mines. Instead of it being extremely heavy in theory, codes, and calculations, this class was more critical thinking and applying our knowledge and understanding of structures to figure them out and analyze them.”
- “I just have to say that this was one of my favorite classes that I’ve taken in all my years at Mines as an undergrad and a grad student. I think the main reason for that is that we were expected to work on truly open-ended problems. We were able to make assumptions (and defend them) and come to conclusions for a problem that had no ‘right answer.’ While other classes try to do similar things to this, I think Susan’s class really strikes the right balance of coming up with realistic problems that aren’t so open ended that there’s no wrong answer, but still allowing us to really think about the problem.”

The overall positive experience of students in this offering might be attributed to self-selection bias (only seven of ten chose to fill out the survey), or the smaller section size and improved student-to-teacher ratio, or the increased number of field trips (a course improvement undertaken due to student feedback in the S13 offering that was also mentioned frequently in the course evaluation comments). However, it can be inferred from the comments of the seven participants that the written reflections seem to be an important component of the success of the course.

Sample Reflections and Grading Procedures

Each weekly reflection prompt consisted of three or four bullets from the instructor – most of which were multi-modal. That is, instead of having the students frame and solve the problem in just one mode (the *computational mode* that is typical in engineering education), a given prompt would also tie in other modes of evaluation and understanding.

In the *comprehension and evaluation* mode, students performed a reading or viewed a video and summarized key points, drew conclusions, and analyzed information. In the *site analysis and evaluation* mode, students were asked to visit a physical site (often a building on campus), and interpret that site through drawings and discussion. In the *professional* mode, students reflected on a wide range of professional skills, such as oral communication skills, written communication skills, cost analysis, ethics, design priorities, decision methods, etc. Reflection prompts can also be categorized as *exercise effectiveness*. In this mode, the instructor directly asks the students whether or not specific course activities are effective. These modes of evaluation and understanding are best illustrated through examples, as shown in Table 2.

Table 2. Sample Multi-modal Reflection Prompts

	Mode				
Prompt	Comprehension and Evaluation	Site Analysis and Evaluation	Computational	Professional	Exercise Effectiveness
Read Rabun pg. 151-161. Complete the stress analysis of the unreinforced masonry wall under the gravity loads introduced in lecture on Tuesday 11/3. Use a graphic method similar to the diagrams in the textbook to plot the tension and compression stresses that you calculate on the exterior and interior faces of the wall. Tabulate key stresses from the top of the parapet down to the top of the footing and linearly interpolate between those values. Do you have any observations or comments on this exercise? Was this a useful exercise for you, or too simplistic?	x		x		x
What assumptions did you have to make in your analysis of the John Cabin Bridge? What sources did you use to develop the assumptions? What is the role of conservatism in making assumptions for historic structures?			x	x	
On Thursday, we visited the Chauvenet Hall basement. List 3 "nuggets" (useful pieces of information) that you learned from the site visit. These could range from technical observations ("I learned that rising damp can cause paint on bricks to blister") or skills/techniques ("I learned to always open louvers") or site logistics ("I learned that it is better to review the floor plans thoroughly before a site visit"), etc. In other words, what did you learn on the site visit that wouldn't have been learned in a traditional lecture format?		x			x
In the YouTube link previously distributed, describe the problem that Robert Silman & Associates was hired to address. What are the pros and cons of the solution presented? Give at least one example of how the speaker used tone and language to communicate technical concepts to a layperson audience.	x			x	
Last week you drew a section through a steel beam and composite slab in the 3rd floor BBW corridor where you observed cracks perpendicular to the axis of the corridor. Say that you were the original designer, and that you knew about the architect's desire for ornamental sawcuts in the top of the slab. Describe your design approach to mitigate (or disguise) cracking and provide section drawings that illustrate your ideas. What are the rough cost implications of the decisions you made (a cost estimate is not required, just a discussion of what cost might be added to the project due to your design)?		x	x	x	

For further illustration, here is the way that two different students responded to a specific reflection prompt in the *comprehension and evaluation* mode and the *exercise effectiveness* mode (minor spelling and grammar errors have been corrected):

> Prompt: "Access the 2012 IEBC (International Existing Building Code) online. Familiarize yourself with the document by browsing the table of contents. Select one appendix related to structural analysis (A1, A2, A3, A4, A5, etc.). Browse the appendix to gain a rough understanding of the contents. Summarize the contents of the Appendix. Did you find this exercise interesting or surprising? Why or why not?"
>
> Student A: "Section A5 of the International Existing Building Code focuses on 'Earthquake Hazard Reduction in Existing Concrete Buildings.' This section dictates a three-tiered approach to the analysis of existing concrete buildings for seismic deficiencies. The first tier is simply a report: a relative succinct summary of the building, observations from the design professional, earthquake design values, 'quick-check analysis calculations,' and a summary of all structural deficiencies. Tier 2 describes a more in-depth analysis of the building, including mathematical models, stiffness calculations, and other analyses that closely match modern day seismic design techniques. The code is very explicit about which buildings can and can't be designed using a Tier 2 analysis. Any building that is too large or too irregular to be designed with Tier 2 must use Tier 3. Tier 3 is simply a reference to a particular section of ASCE 41. This section is a nonlinear analysis procedure that the IEBC requires for irregular, existing concrete structures.
>
> I don't know if I can say I found reading through the code *interesting*, but I do think it was a useful exercise to spend a bit of time on. I don't think I've ever actually read through the code before. I've used a number of different codes in different design classes, but only as a place to get equations, limits, etc. from. I've never just read the sections from start to end. So in that way it was interesting, if a bit dry."
>
> Student B: "I chose to browse through 'Appendix A5 – Earthquake Hazard Reduction in Existing Concrete Buildings.' This appendix is, as the title suggests, meant to address the minimum standards for seismic resistance in existing concrete and concrete frame buildings. The first section, A501, mainly states that the purpose of the appendix is to 'promote public safety and welfare by reducing the risk of death or injury that may result from the effects of earthquakes on concrete buildings.' Section A502 describes specific characteristics of the type of concrete buildings this appendix applies to. Buildings with flexible diaphragms or a Seismic Design Category A do not apply. This section also lists the design codes that previously met the standards required of the appendix, meaning that if those codes were used for the design, the building complies with the requirements of the 2012 IEBC. Section A503 describes the three-tier procedure that is used for analysis in A5. Material properties and structural testing, observation, and inspection are briefly addressed in this section as well. The site ground motions to be used for each tier are discussed in Section A504. Sections A505, A506, and A507 each provide the methods required for analysis of a conforming building, one requiring linear methods of seismic analysis, and one requiring nonlinear methods of seismic analysis, respectively.

I found this exercise to be interesting. The code seems to make statements or requirements that contradict each other, allowing for many possible loopholes. I believe that one engineer could interpret the code differently than another engineer, which could cause conflict, or as I mentioned, allow for loopholes to be found in the code."

Figures 3, 4, and 5 illustrate sample reflections from students in some of the other modes of evaluation and understanding.

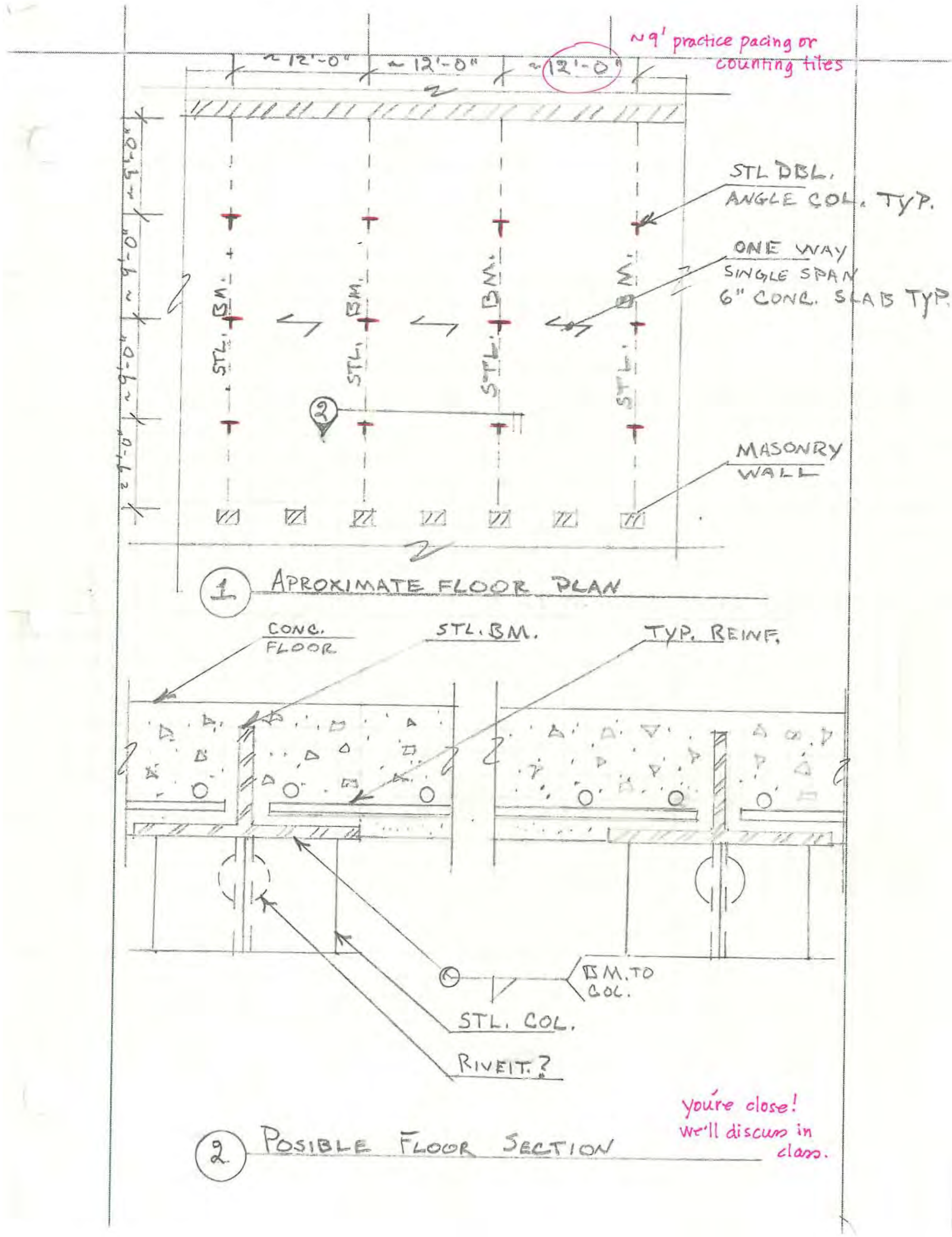


Figure 3 – Sample Reflection, *Site Analysis and Evaluation* Mode

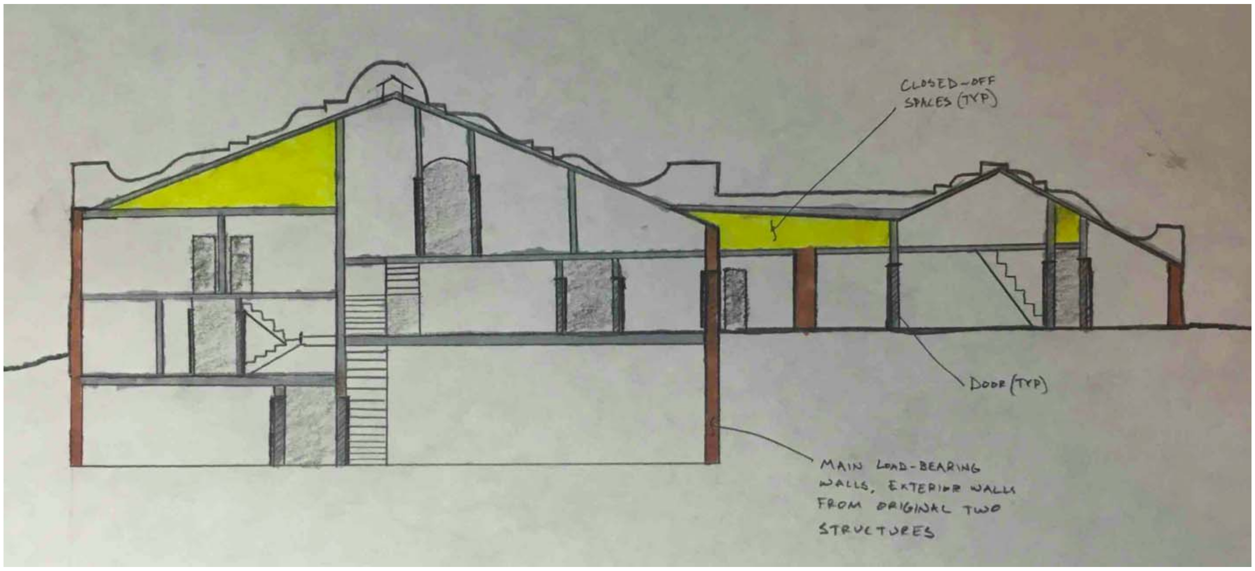


Figure 4 –Sample Reflection, *Site Analysis and Evaluation* Mode

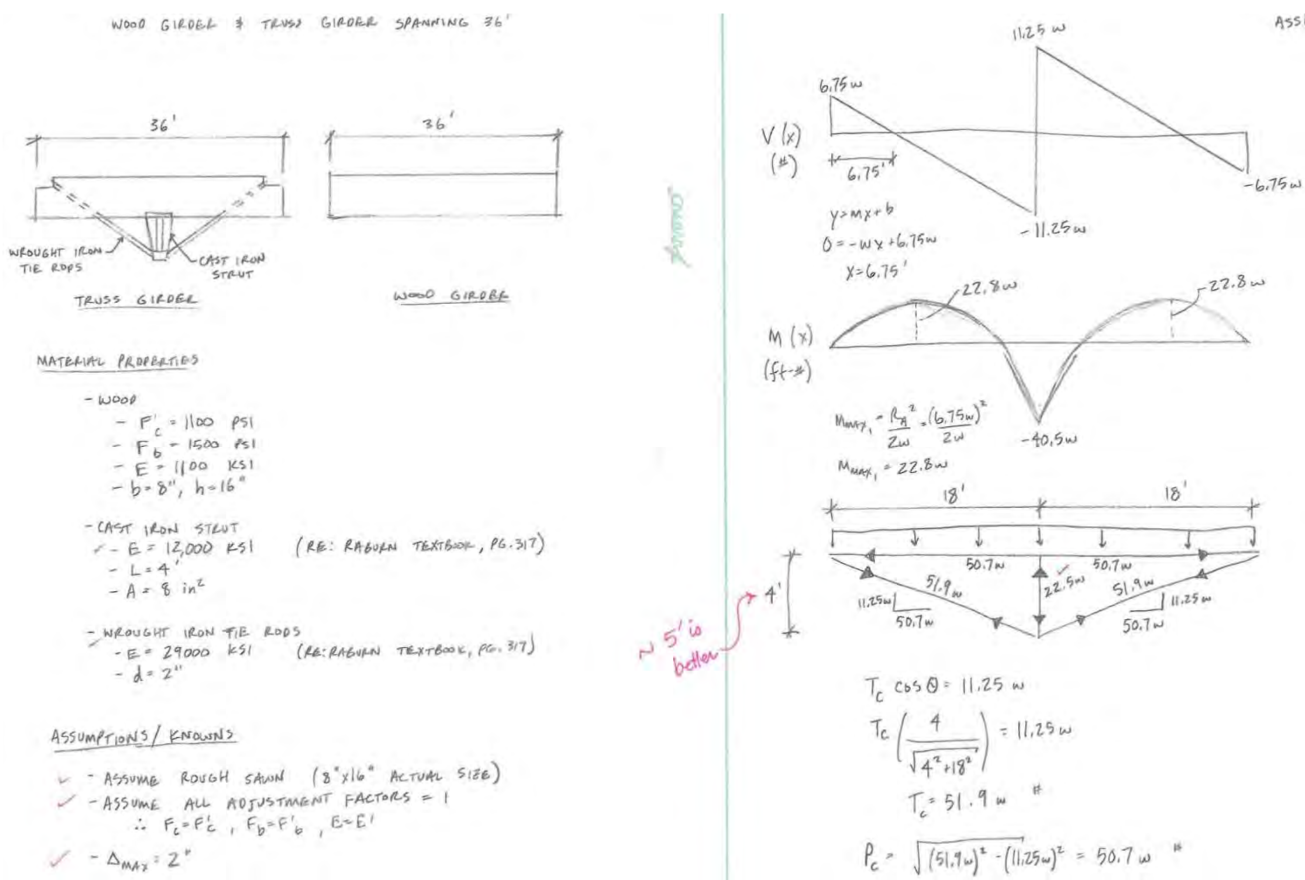
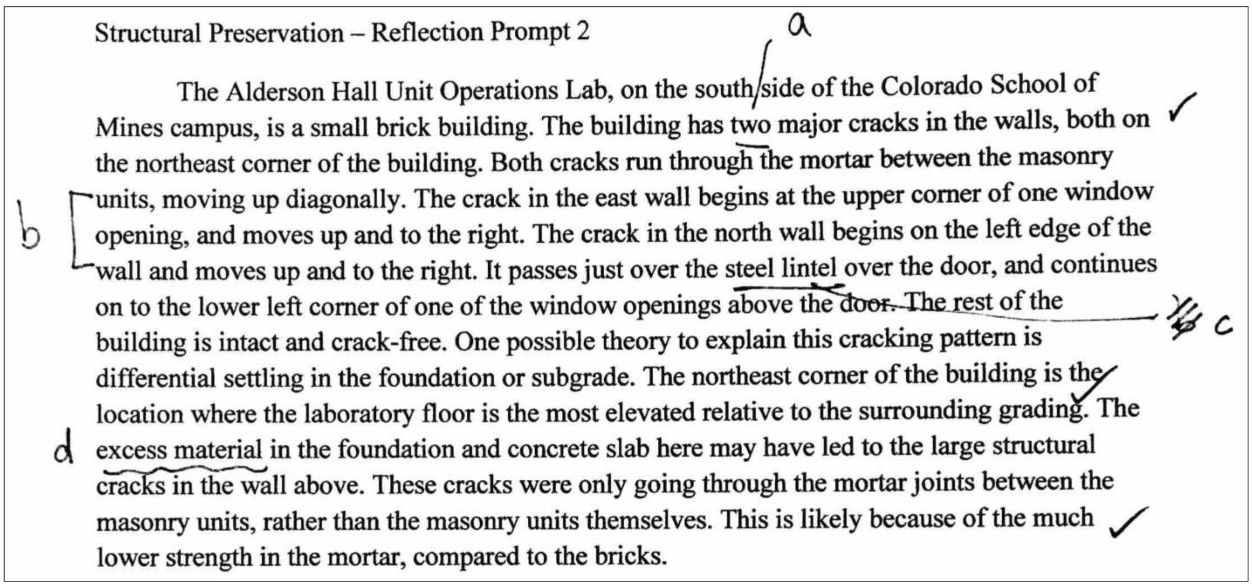


Figure 5 –Sample Reflection, *Computational* Mode

The grading procedure for the reflections is dissimilar to standard procedures for closed-ended problems, which typically consist of the creation of a rubric that specifies a point deduction for each error. Instead, a summative assessment of the student's understanding was conducted by the instructor in two steps: a thorough reading, critique, and commentary on the written reflection, and an abbreviated skim through the supporting calculations and drawings. Depending on the class size, this approach can actually take less time than grading a closed-ended problem, after accounting for the time required to create a solution and rubric. The reflections were compared and partitioned into three or four tiers: oftentimes a tier for 95%, a tier for 85%, and a tier for 75%. Truly exceptional work was awarded 100%, and the tiers for a given week were adjusted according to student performance. The students are very appreciative of individual feedback from the instructor, and the course evaluation comments revealed that they perceive this activity to be more time-consuming than it actually is. Individual feedback to each student was typed in an electronic document that was keyed to the hard-copy submission. This method was quick and effective, in that it facilitated the ability to repeatedly copy and paste certain comments that applied to multiple students. The instructor printed the word document, cut out the personalized comments for each student, and stapled them to their submission, as shown in Figures 6 and 7.


Structural Preservation – Reflection Prompt 2

a

The Alderson Hall Unit Operations Lab, on the south side of the Colorado School of Mines campus, is a small brick building. The building has two major cracks in the walls, both on the northeast corner of the building. Both cracks run through the mortar between the masonry units, moving up diagonally. The crack in the east wall begins at the upper corner of one window opening, and moves up and to the right. The crack in the north wall begins on the left edge of the wall and moves up and to the right. It passes just over the steel lintel over the door, and continues on to the lower left corner of one of the window openings above the ~~door.~~ The rest of the building is intact and crack-free. One possible theory to explain this cracking pattern is differential settling in the foundation or subgrade. The northeast corner of the building is the location where the laboratory floor is the most elevated relative to the surrounding grading. The excess material in the foundation and concrete slab here may have led to the large structural cracks in the wall above. These cracks were only going through the mortar joints between the masonry units, rather than the masonry units themselves. This is likely because of the much lower strength in the mortar, compared to the bricks.

b

c

d

Figure 6 – Sample Student Reflection with Keyed Grading Notes

a) Are they 2 cracks or could you say that they are 2 portions of one large crack?
b) When you find yourself going to this level of detail in your description of a spatial phenomenon, you are probably better off just referring the reader to a sketch or annotated photo.
c) Good observation.
d) You are correct that the lower elevation of the surrounding paving is probably a contributing factor. But I wouldn't attribute it to the additional subfloor constructed dead load that you reference. More on this in class…

Figure 7 –Key for Grading Notes for the Sample Student Reflection

Conclusions

The purpose of this paper is to stimulate discussion in the use of written engineering reflections for assessment of open-ended engineering problems and to provide grading strategies for faculty interested in adopting this technique. A comparison of the students' responses on course evaluation forms in in S13 and F15 yielded insight on how the pedagogical change impacted student learning.

Faculty that wish to adapt this technique to their courses are encouraged to provide timely personalized feedback to the students. The students seem to appreciate the feedback on the reflections more than the grade, as shown on the F15 course evaluation comments:

- "I don't think this style of homework would work in a class with more students, but since Susan found the time to thoughtfully comment on all of our reflections, it became very useful."
- "The feedback that you give us takes a lot of time on your end but is EXTREMELY helpful because it allows me to reflect on ideas / observations I may have missed."
- "It was also nice that Susan gave specific feedback on these so we could see how we were doing on our understanding of the material."

Faculty that wish to adapt this pedagogy to their own courses should also endeavor to establish a classroom culture in which students have freedom to learn through failure and to learn from peers while de-emphasizing grades. At the graduate level in particular, students want the freedom to make mistakes, to learn from the experience, and to gain confidence in their abilities. It is important to get student buy-in on the unconventional evaluation process on the first day of class by referencing a trust model: the instructor must trust the students to give 100% effort and commit to learning for the sake of learning, and the students must trust the instructor to evaluate them fairly and issue grades accordingly.

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