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Forming Congnitive Connections: Desktop Learning Modules, Structural Analysis Software, and Full-Scale Structures

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Forming Cognitive Connections: Desktop Learning Modules, Structural Analysis Software, and Full-Scale Structures

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Introduction

One of the biggest challenges in teaching civil engineering students a theory-intensive course like structural analysis is helping students make the connection between the engineering mechanics taught at the front of the room and how those concepts define the real behavior of actual engineered structures. According to Montfort et al. [1], "Concept inventories suggest that most students do not truly understand the concepts covered in their STEM courses." This outcome is potentially the result of a complex relationship between teaching methods, assessment methods, and student approaches to learning.

A real, conceptual understanding of a topic includes not just the phenomena underlying a calculation, but also the context, purpose, assumptions, and reasonable expectations [1]. Absent these connections, students will often learn how to successfully perform the mathematical functions on their homework assignments but lack confidence in their ability to apply the same concepts to the analysis or design of an actual structure. Montfort et al. [1] propose that students tend to develop highly methodical approaches that require skill and knowledge, just not necessarily in a way that is correctly related to a conceptual understanding of the topic.

Common ways to try to provide the necessary connections between real-world applications of structural analysis principles and course content include software modeling, the use of small-scale physical models referred to as desktop learning modules (DLMs), or case studies of full-scale structures. Regarding software modeling, modern engineering education serves students well when it incorporates the use of computer applications [2]. Limiting a study of structures to two dimensions may introduce some conceptual challenges, but the use of computer-based analysis and modeling may be used to better aid students in understanding 3D behavior [3]. Students often identify hands-on and lab-based activities, such as the use of physical models, as being engaging and effective parts of an engineering education [4]. Going back to at least as early as 1996, many instructors have implemented activities combining physical models with computer-based models in the structural engineering classroom [5-8]; however, little assessment data has been collected on the efficacy of these approaches. Finally, relating course content and calculations to actual "real-world" structures helps motivate students by showing them what they may eventually be able to do with the content they are learning.

Each of these approaches possesses a significant limitation when it comes to helping students form cognitive connections: software helps provide visualization of engineering mechanics but lacks a connection to actual physical behavior, DLMs often lack adaptability or measurability, and full-scale structures are rarely able to be loaded to produce observable behavior. An ideal learning experience for students would include the synthesis of all of these tools to help students develop cognitive connections between mechanics principles, engineering design tools, and real-world structures through active, constructive, and interactive/collaborative learning.

Pedagogical Theory and Research Methods

Chi [9] defines active learning activities as engaging the learner's attention, constructive learning activities as requiring the learners to produce some outputs which contain some new ideas, and interactive learning activities as participating in dialogue with experts or peers. Furthermore, Chi [9] generalizes that in the order of engagement of cognitive processes during learning activities, interactive > constructive > active > passive. Prince [10] additionally defines collaborative learning activities as students working in groups to achieve a common goal. This study will aim to take advantage of these different methods of cognitive engagement by structuring an activity that is active (students manipulate physical and computer models while learning), constructive (while the activity is guided, synthesis of the different aspects of the activity and related course material is left up to the students), and interactive/collaborative (students work through the activity in groups of two or three, troubleshooting any problems along the way and ultimately drawing conclusions through dialoging).

For effective development to take place during an engineering educational lab, such as the active learning activity proposed in this study, it must address objectives including cognition, psychomotor skills, and behaviors and attitudes [11]. The proposed activity encompasses these categories established by Feisel and Rosa [11] by including aspects of experimentation and theoretical models (cognition), use of engineering tools and observations (psychomotor), and teamwork and learning from failure/mistakes (behaviors and attitudes).

Ultimately, the purpose behind a research effort should drive the choice of research method selected. Quantitative research primarily deals with numerical results and aims to statistically prove or disprove a specific hypothesis; on the other hand, it can have a difficult time capturing complex results or context [12]. Qualitative research is capable of better capturing human perspectives and detailed descriptions; however, it often includes the shortcomings of small sample sizes and researcher bias [13]. Mixed methods research presents a third alternative to the traditional research paradigms of quantitative and qualitative methods of analysis by allowing for the integration of data collected through both methods [12]. Using mixed methods as a research method can be considered "pragmatic" in that it seeks to make use of all available approaches to analyzing a problem, but it may possess a shortcoming in the extent to which the values of the researcher play a role in the interpretation of results [12]. A mixed methods approach, such as the one applied in this study, is often a good fit for engineering educational research due to its ability to collect detailed information concerning a few individuals and generalized information about a broader population [13].

The structure of this study was roughly based on the methods described in a desktop learning modules study by Brown et al. [14].

Purpose of This Study

A popular, recently developed, commercially available structural modeling DLM, referred to as the Mola Structural Kit (see example structure in Figure 1), provides a high enough level of structural simulation and adaptability that it should allow for the kind of learning synthesis that has traditionally been challenging to produce. Using steel spheres for joints, magnetic springs for primary members, and several other magnetic components related to specific structural behaviors, Mola permits students to create a variety of structural models that can reasonably approximate case studies of real structural behaviors in a manner that can be measured and compared to models developed using structural analysis software.

The purpose of this study is to evaluate the effectiveness of an approach combining RISA 3D structural engineering software, the Mola physical model, and examples from actual structural systems at helping students form correct cognitive connections between principles of engineering mechanics and the behaviors of real structures.

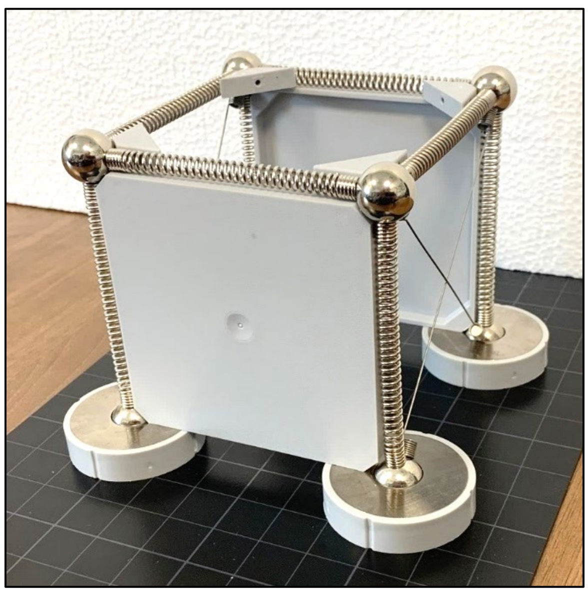


Figure 1 – Example Mola model with a combination of fixed connections, braces, and shear walls

Development of Equipment

The Mola structural kits were purchased from the manufacturer's website at about 160 USD each. While there are three variations of structural kits available, almost all of the activities described in this study can be completed with only Structural Kit 1. Enough kits were procured such that students would not need to work in any groups larger than three for the activities.

In order to provide a means of applying and measuring consistent loading to the structure, a simple physics pulley set (including support bar), a hanger and 250g weight set, magnetic rings, and non-magnetic rulers were purchased to accompany each Mola kit (at a cost of about 40 USD total for each set). The magnetic rings and pulleys are used to redirect a cable connecting a member of the Mola structure to the weight hanger, while a ruler hanging from the pulley support bar provides a convenient location from which to measure the weight hanger displacement. See Figure 2 for an example of the portal frame activity setup and Figure 3 for an example of the lateral force resisting system activity setup.

Figure 2 - Mola model and test setup for portal frames exercise (Activity A)

Figure 3 - Mola model and test setup for lateral force resisting systems exercise (Activity B)

Derivation of Mechanical Parameters for Modeling

The primary structural element in the Mola building kits are coil springs, with magnets in each end. To model these springs as beams, effective beam parameters had to be determined, which resulted from the elastic behavior of the structural element under each type of loading: axial translation (tension/compression), axial rotation (torque), transverse translation (shear), and transverse rotation (bending). These were found using experimentally validated finite element (FE) models.

The FE model constructed for each length of spring consisted of beam elements along a spiral geometry matching the physical spring. The physical springs were fixtured and tested in both pure tension and pure shear, and these results were used to fine-tune the FE model parameters, which were subjected to the same loading in simulation. The two methods agreed to within about 5%. The FE springs were then connected to control points corresponding to the center of the spheres which serve as joints in the Mola system. One control point was fixed in all six degrees of freedom, and the other was fixed in five with a sinusoidal displacement applied to the remaining degree. All six force/moment reactions were linearized, yielding one row of the effective beam's driving point stiffness matrix. This computation was repeated for all six displacement degrees of freedom, yielding the full stiffness matrix, which was then conditioned to ensure symmetry and that only the expected off-diagonal terms corresponding to shear/bending would be non-zero.

Euler beam and shaft theory was applied to relate each non-zero stiffness term with the material and geometric properties, E, G, I, J, A, and L, which are the elastic and shear moduli, bending and polar moments of inertia, cross-sectional area, and effective length, respectively. Since a perfect solution to this mapping does not exist because there are many more stiffness terms than independent parameters, a numerical optimization algorithm was used to identify a reasonable set of parameters. These parameters, given in Table 1, were used to recompute the stiffness terms, which agreed with those from the finite element model to within 10% for almost all terms and for both short and long springs.

Table 1 - Derived parameters for two Mola spring members

Spring	E (MPa)	G (MPa)	A (mm^2)	I (mm^4)	J (mm^4)
Short (7.5 cm)	1.799	0.692	108.1	930	1860
Long (16.5 cm)	1.565	0.601	140.3	1566	3131

Finally, a few example structures making use of the short springs, similar to those shown in Figure 2 and Figure 3, were tested and compared to models created in RISA to validate the derived parameters. With careful measurement of the zero-load deflection and restricting the movement of both the model base and pulley support base, computational results were generally able to match the example physical model results to within 2-20% error.

Development of Activities and Worksheets

The two activities selected for this study were focused on portal frame structures (Activity A) and lateral force resisting systems (Activity B), respectively. These topics were primarily selected because they were based on structural behaviors that the Mola Structural Kits could easily exhibit. These topics were additionally considered appropriate for this study due to the fact that all of the students participating in the study had been at least briefly introduced to them when they had previously taken the Structural Analysis course, but it was still hypothesized by the researchers that at least some students may not possess a clear conceptual understanding of them.

The activities were written up as worksheets for the students to complete without need for instructor guidance. Students completed these activity worksheets in groups of two or three. These worksheets introduced students to the equipment and steps required to complete the activities, but only after first providing written descriptions of the relevant structural concepts along with series of photos of their integration into real-world structures. At this phase of the research, this is the only portion of the activity that is related to full-scale, real-world structures.

After reading about how the topics were related to real-world structures, students were guided through the process of constructing and loading each of their Mola models. For Activity A, students modeled three variations of doubly symmetric square portal frames: (1) fixed at base, pinned joints at beams; (2) pinned at base, rigid joints at beams; and (3) fixed at base, rigid joints at beams. For Activity B, students modeled three variations of singly or doubly symmetric square portal frames with lateral force resisting systems: (1) a moment resisting frame (fixed at base, rigid joints); (2) a braced frame (braced in all vertical bays, rigid joints in horizontal plane); and (3) a shear wall system (shear walls in opposite vertical bays, braces in remaining vertical bays, rigid joints in horizontal plane; see Figure 1). The activity included brief instructions as well as images showing students what how their completed structures should look. Students were next walked through the process of incrementally applying loads to their structures (again, supported by images) and encouraged to make use of Microsoft Excel's plotting tools to determine whether their structures were exhibiting linear behaviors.

Finally, students were guided through creating the members and materials needed for modeling in RISA 3D using the derived parameters. All students in the study had previous experience with RISA 3D, so using it in this application did not present a particular challenge for them. Students were encouraged to visually compare the deflected shapes in RISA 3D (at 1X scale) to the deflected shapes of their Mola models and to numerically compare the calculated maximum deflections with their measured deflections. The activity concluded with a few brief questions about positive and negative observations regarding each of the modeled structural systems, to be discussed and answered as a group.

Development of Assessments

As a quantitative assessment, simple pre- and post-activity questionnaires were developed, distributed to participants, and evaluated according to a scoring rubric. The questions from the pre-activity questionnaire can be seen in Figure 4 and Figure 5. The post-activity questionnaire included questions of identical concepts and similar difficulty, but with each structural diagram in a slightly different configuration. The decision to make the pre- and post-activity questionnaires different was intended to force students to consider each question carefully rather than attempting to answer from memory, particularly since the questionnaires were administered only about 90 minutes apart. This approach was justified based on the methodical nature of the concepts tested; for instance, an understanding of how a fixed joint behaves on a deflected shape diagram should be equally represented on any of several relatively similar structural diagrams. The questions on both pre- and post-activity questionnaires were as follows:

- Question 1 was a control question regarding the calculation of degree of static indeterminacy. As this was not a topic addressed in either of the two activities, there was no reason students' performance on this question should have been shown to improve from the beginning of the activity to the end. This control question was selected based on the fact that students would have learned the concepts required to complete this question at approximately the same point in their education as they would have been introduced to the topics addressed in the activities.
- Question 2a was related to the deflected shape due to vertical loading on a portal frame while Question 2b was related to the deflected shape due to horizontal loading on a lateral force resisting system.
- Question 3 asked students to identify the structural diagrams as stable or unstable in the 2D plane.
- Question 4a asked students to estimate which portal frame would exhibit the smallest relative deflection due to a vertical load while Question 4b asked students to estimate which lateral force resisting system would exhibit the smallest relative deflection due to a horizontal load.

Questions 2a and 4a were considered to be most closely related to concepts explored in Activity A, while Questions 2b and 4b were considered to be most closely related to concepts explored in Activity B. Question 3 was considered to be related to concepts explored in both activities.

Qualitative data was collected through open-ended interviews with a random sample of participants, taking advantage of the opportunity this method offers to ask questions for better explanation and clarity of responses [12]. The interview was conducted in a semi-structured manner: specific questions were asked of each student, but the interviewer had the opportunity to ask for clarification or explanation if desired. Three questions were intended to serve as a direct assessment of students' conceptual understanding of the topic covered in their respective activity and seven questions were intended to serve as an indirect assessment of students' perceptions of their own conceptual gains due to their respective activity. The structured questions can be seen in Table 5 and Table 6 in the results sections below.

The numerical results collected through the quantitative evaluation were considered alongside the narrative results collected through the qualitative evaluation, with the intent of applying a mixed-methods approach. This approach allowed for use of the combination of these results to establish better conclusions related to the effectiveness of the proposed activities at helping students form cognitive connections.

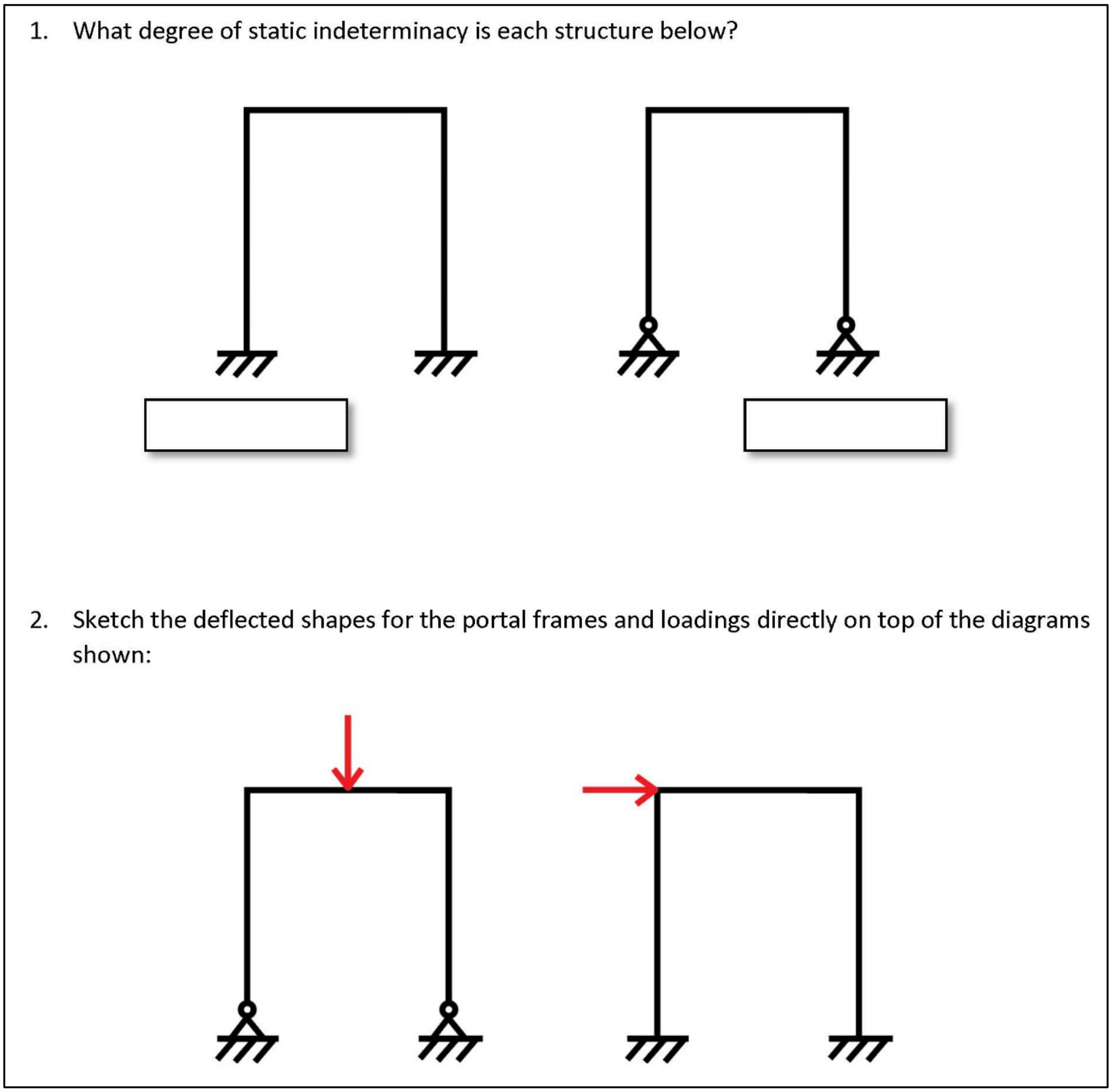
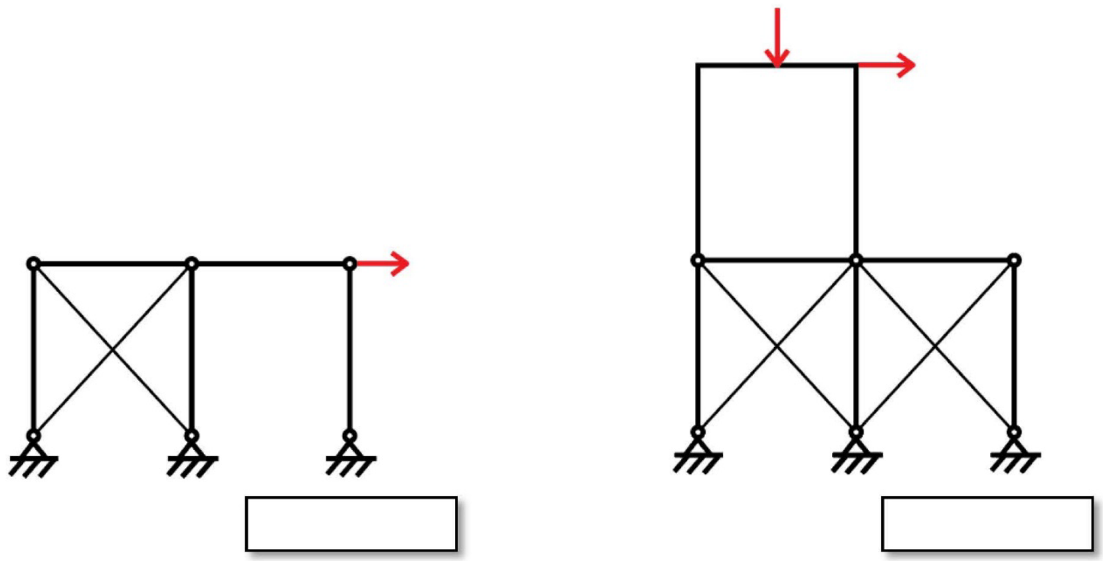


Figure 4 – Questions 1, 2a, and 2b of pre-activity questionnaire

3. Indicate whether each of the frames shown below will be stable or unstable when the indicated vertical and lateral loads are applied:



4. If the only differences between the frames and loadings compared below are the joint and boundary conditions, circle the frame in each group that will be most likely to produce the smallest deflection in the location and direction of the applied load:

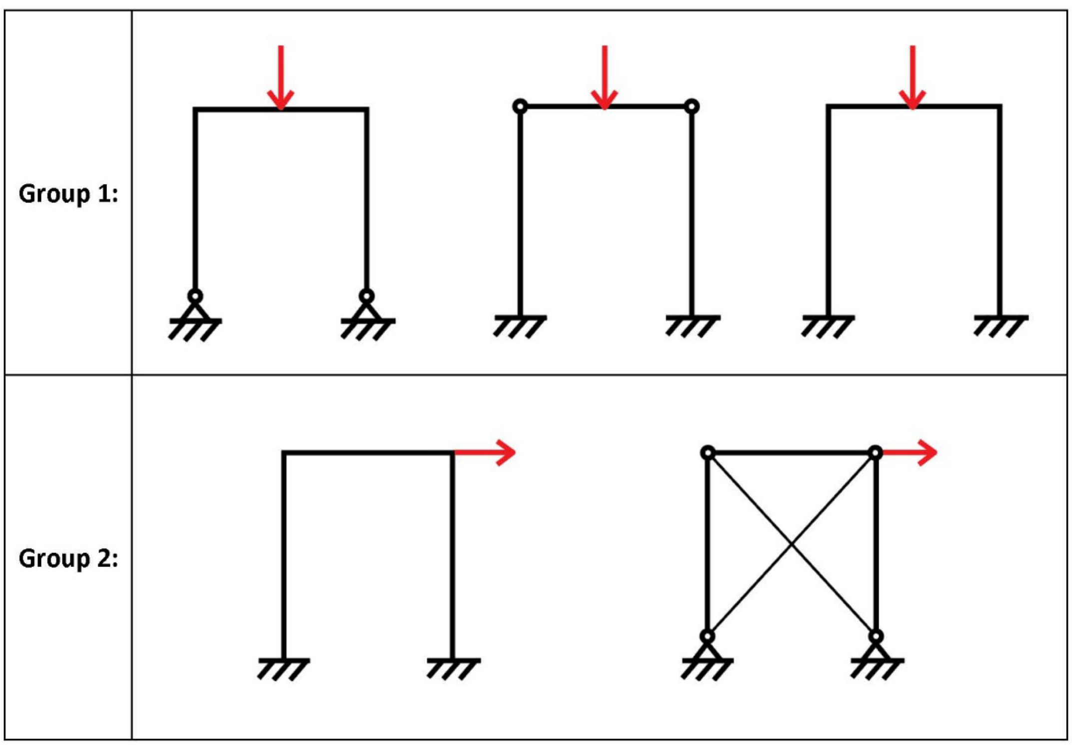


Figure 5 – Questions 3a, 3b, 4a, and 4b of pre-activity questionnaire

Study Implementation

Early in the spring semester of 2022, civil engineering students from the junior-level Design of Steel Structures course and the senior-level Design of Wood Structures course were invited to participate in this research study. Students from these classes were selected as the study population due to their familiarity with the RISA 3D software and related structural concepts, largely introduced through the prerequisite Structural Analysis course. Ten juniors (out of 10; 100% participation) and 11 seniors (out of 15; 73% participation) volunteered, self-selecting a total of nine activity groups that each consisted of two or three students. Based on the classes from which the students were selected and the volunteer nature of the activity, this population of students included only average to high academic performers who also possessed at least some level of personal interest in structural engineering. Due to the relatively uniform nature of this student population and the self-selecting of the activity groups, there did not appear to be any significant disparities between groups based on previous academic performance.

The pre-activity questionnaire was administered immediately prior to beginning the activity, and students completed it individually. Groups were randomly assigned to complete either Activity A (portal frame structures; 5 groups; 12 total students) or Activity B (lateral force resisting systems; 4 groups; 9 total students) and provided with the worksheet, Mola Structural Kits, additional equipment for loading and measuring, and computers with access to the RISA 3D software. On average, students spent about 90 minutes completing the activities and generally had no significant inquiries. Immediately after completion of their group's activity, students completed the post-activity questionnaire individually. Five of the study's participants were selected at random and scheduled to participate in a one-on-one interview within five days of completing the activity.

Quantitative Results

One set of numerical data collected during this study involves the comparison between the measured deflections on the Mola models and the computed deflections on the corresponding RISA 3D models. The average errors the student groups obtained for each individual model (three different models constructed for Activity A and three for Activity B) and across all of the activities are shown in Table 2. As made evident by the relatively high standard deviations, some groups found the models to match much more closely than others. Potential reasons for this high observed error are presented in the discussion of results.

The quantitative results of greater importance to this study are the students' performances on the pre- and post-activity questionnaires. The questionnaires were scored according to a simple rubric: for most questions, a correct answer was worth 1 point, while an incorrect answer was worth 0 points. The only exceptions to this scoring were the deflected shape diagrams from questions 2a and 2b, for which students could score 0.5 points if they were able to draw a deflected shape that was mostly correct.

Table 2 – Average error between students' Mola and RISA deflection results

Model	Avg Deflection Error	Standard Deviation
A1 – Fixed base, pinned joints	31%	38%
A2 – Pinned base, rigid joints	68%	55%
A3 – Fixed/rigid frame	52%	57%
Activity A Avg	**50%**	**45%**
B1 – Moment frame	41%	12%
B2 – Braced frame	72%	17%
B3 – Shear wall frame	176%	90%
Activity B Avg	**89%**	**71%**
All Activities Avg	**67%**	**60%**

Table 3 – Improvement and regression results between pre- and post-activity questionnaires

Exercise Completed	A	B	A	B	A OR B	A OR B
Question Set	**A**		**B**		**Control Q1**	**A&B**
"Opportunities"	9	6	19	11	7	33
"Improvements"	6	3	8	8	1	17
% Improved	**67%**	**50%**	**42%**	**73%**	**14%**	**52%**
"Liabilities"	36	27	32	26	17	100
"Regressions"	4	1	7	3	9	12
% Regressed	**11%**	**4%**	**22%**	**12%**	**53%**	**12%**

Table 3 summarizes one approach to analyzing this data. In this table, results are divided by question set (A = 2a, 3, 4a; B = 2b, 3, 4b, Control = 1) and by the exercise each participant completed for the activity. Within these groupings, any problems that students answered incorrectly on the pre-activity questionnaire are considered "opportunities" for improvement, while any problem that students answered completely correctly are considered potential "liabilities" (on these questions, students could do worse on the post-activity quiz, but it was impossible for them to do better). "Improvements" were then the number of "opportunity" questions the students answered correctly on the post-activity questionnaire while "regressions" were the number of "liability" questions that were subsequently answered incorrectly. For example, the first column of results represents the performance on Question Set A by students who completed Activity A. The students who completed this activity got a total 9 questions from Question Set A either partially or fully incorrect and 36 problems entirely correct. On the post-activity questionnaire, this same group of students "improved" their score on 6 of the 9 corresponding "opportunity" questions while "regressing" on only 4 of the 36 "liability" questions. This same procedure was applied to the rest of the data sets to complete Table 3. The fifth column of data shows the combined results from all students on the control questions (degrees of static indeterminacy) and the last column of data shows the combined results for students who completed either activity on the combination of question sets A and B. Note that this last column is not equal to the sums of the first four columns because Question 3 was counted as a part of both Question Set A and Question Set B due to its relevance to the concepts explored in both activities.

Some of the key takeaways from the above analysis include the following:

- For Question Set A on the post-activity questionnaire, students who completed Activity A improved their scores on 67% of their wrong answers from the pre-activity questionnaire, while students who completed Activity B only improved these same scores by 50%. Students who completed Activity A therefore demonstrated a greater reversal of the incorrect answers that were relevant to the topics of their specific activity than students who completed Activity B.
- For Question Set B on the post-activity questionnaire, students who completed Activity B improved their scores on 73% of their wrong answers from the pre-activity questionnaire, while students who completed Activity A only improved these same scores by 42%. Students who completed Activity B therefore demonstrated a greater reversal of the incorrect answers that were relevant to the topics of their specific activity than students who completed Activity A.
- For both question sets A and B, regardless of the activity completed, there was a greater percent of improvements to incorrectly answered initial problems than regressions from correctly answered initial problems. This suggests that there is at least some conceptual overlap between the two activities, such that completing one activity may also provide improved understanding for the topics of the other activity.
- For the control question that was unrelated to either activity, there was minimal improvement and a much higher rate of regression between the pre-activity and post-activity questionnaires. Since this performance trends in the opposite direction from the other questions, it appears that students did not discuss the questionnaires while working on the activity, at least in such a way that would falsely inflate the post-activity questionnaire results. This performance trend on the control questions lends additional credence to the conclusion that completing the activities improved students' understanding of related concepts.

A different, but common comparison that can be made with quantitative results obtained from two populations (test and control) is the "effect size" [10]. Effect size is simply the quantity of standard deviations of improvement that an educational intervention produces in a test population as compared to the results from a control population. Generally, effect sizes of 0.5 or higher are considered to be at least medium-level indicators of significant improvement [10]. By considering the students who completed Activity A as the test group and the students who completed Activity B as the control group for Question Set A, and then vice versa for Question Set B, the data shown in Table 4 can be calculated. Based on these results, it appears that completing Activity A did not produce a significant improvement on Question Set A (at least compared to the control group that completed Activity B). However, this analysis approach suggests that completing Activity B produced a medium-to-high level of improvement on Question Set B compared to those students who instead completed Activity A.

Table 4 – Evaluation of effect size for improved performance between pre- and post-activity questionnaires

Exercise Completed	**A**	**B**	**A**	**B**
Question Set	**A**		**B**	
Population	Test	Control	Control	Test
Avg. Score Increase	5.0%	8.2%	3.0%	16.4%
Test-over-Control Improvement	-3.2%		13.4%	
St. Dev.	14.2%		18.6%	
Effect Size	**-0.22**		**0.72**	

Qualitative Results

Each of the five interviews were recorded and transcripted, then analyzed for common responses to each question. Given the relatively small quantity and brief nature of the interviews conducted, responses to each question were able to be grouped into only a few select categories. The direct assessment question results in Table 5 indicate the number of students (out of 5) whose responses fell within each category, as well as some representative statements pulled from the transcripts. Note that some students' answers may have included aspects of more than one category.

Based on these categorizations, 40% (2/5) of students were able to express an answer that indicated that they not only made some observations relevant to the main concept during the activity but were also able to make a cognitive connection between those concepts and applications involving real structural systems. However, as was more clearly explained in their answers to the indirect questions, the students possessed at least some prior conceptual understanding, so their answers do not exclusively reflect what was gained during the activity.

The indirect assessment question results in Table 6 indicate the number of students (out of 5) whose responses fell within each category, as well as some representative statements pulled from the transcripts. Note that some students' answers may have included aspects of more than one category.

Table 5 – Categorization of interview results, direct assessment questions (# = students, out of 5)

Direct Assessment Questions	Categorized Responses	#	Representative Statement
Describe the purpose of [A. portal frame structures or B. lateral force resisting systems].	1. General structural behavior from simple observation	3	"Support loads"
	2. Specific structural application	4	"Minimize deflections out of plane"
	3. Both (Correct connection between activity and application)	2	[see above]
In what kinds of situations would you want to use different types of [A or B]?	1. Correct observation from activity (at least some)	4	"Fixed connections obviously had lower deflections"
	2. Correct, clear connection to application (at least some)	2	"What I'm going to assume would be lower overall material costs for the system"
	3. Both (Correct connection(s) between activity and application)	2	[see above]
In what situations would [A. pinned joints or B. moment-resisting frames] be the preferred structural system?	1. Correct observation from activity (at least some)	2	"If you have to fix every single joint...complicate[s] the actual building process"
	2. Correct, clear application (not from activity)	5	"Cost"
	3. Both (Correct connection(s) between activity and application)	2	[see above]

Table 6 – Categorization of interview results, indirect assessment questions (#=5 students)

Indirect Assessment Questions	Categorized Responses	#	Representative Statements
If I had asked you before this activity how well you felt that you understood [A or B], what would you have said?	1. Understanding developed as a result of this exercise	4	"What's a portal frame?"
	2. Prior understanding	1	"Pretty well"
Did you think this activity helped you to better understand some structural principles?	1. No expressed increase in understanding	1	"I feel like I had gotten a good chunk of what I already had from previous classes"
	2. Expressed increase in understanding with identifiable concept	4	[see below]
	2a. Concept gain: joint deflection behavior	3	"It was really helpful to see, as we pulled down on the one member at the top, how that affected the entire system"
	2b. Concept gain: 3D visualization	2	"The ability to visualize in 3-D definitely did help have a greater understanding of 2-D projections"

Indirect Assessment Questions	Categorized Responses	#	Representative Statements
Did the explanations and photos of **real-world structures** contribute to your understanding of the structural principles?	1. Helped understand application	3	"Pictures definitely help you realize it… like visualize it a little more"
	2. May have helped if not already aware of applications	2	"Not as much as if I hadn't seen them previously in the classes and in my own looking into things"
Did constructing and loading the **Mola model** contribute to your understanding of the structural principles?	1. Helped with visualizing deflections in real structural systems	3	"I saw how stuff moved with loading; when you're looking at a real sized building, you don't see the movement"
	2. Helped with understanding joint behaviors	2	"It's easy for me to visualize how each individual member will deflect; it's harder for me to think about how that will influence the next member, like in a fixed connection"
	3. Helped with understanding computer results	1	"We used the physical to go back and check the digital and then they backed each other up"
Did building and evaluating the **RISA model** contribute to your understanding of the structural principles?	1. Didn't contribute to RISA part of activity	3	"One person was designated to actually drawing the RISA stuff"
	2. Contributed to RISA model, but didn't see significant value over Mola model	1	"Similar to the Mola model, maybe a little less helpful"
	3. Saw value in comparing physical and digital model behaviors	1	"Kind of troubleshoot in that way"
Do you see value in **all three parts** (real world structures, Mola model, RISA model) of this activity?	1. Saw value in all three parts of the activity	5	"Yeah"
	1a. Provided coherent explanation of how three parts of activity contributed to understanding	2	"RISA to kind of reproduce what we're seeing in class and learning like on paper, then also to do it with our hands and build it in some fashion; I think all three parts kind of connect"
Did working on this activity **with a partner(s)** help contribute to your understanding of the structural principles?	1. Only helpful for completing activity effectively, not for better understanding of concepts	5	"it's helpful to have other people to bounce ideas off of and be able to take measurements and help build the thing; I'm not sure about contributing to the structural principles; It would have taken way longer if it was just me"

Based on these categorizations, 80% (4/5) students self-identified that they experienced an increase in understanding of a relevant structural concept as a result of the activity they completed. Inquiring further about each of the particular aspects of the activity:

- 60% (3/5) of students believed the examples of real-world structures contributed to their learning; the remaining 40% (2/5) expressed a believe that these examples would have been helpful had they not already been familiar with the applications
- 100% (5/5) of students were able to identify a way the construction of the Mola models helped with their understanding of a structural principle (including the student who previously stated that the activity did not increase their understanding)
- Only 20% (1/5) of students saw significant value in building the computational models in RISA, although this is heavily influenced by the fact that 60% (3/5) of the students admitted that they were not involved in building the RISA models in their groups
- 100% (5/5) of students stated that they saw value in all three components of the project, although only 40% (2/5) provided a coherent explanation behind the value they perceived. When asked a follow-up question to rank the three aspects of their activities in order of the how much they helped contribute to understanding structural concepts, the order was generally the Mola models, then RISA models, then the examples of real-world structures.
- While several of the students initially stated that working with a partner contributed to their understanding of structural principles, their further explanations revealed that 100% (5/5) of the students actually meant that working with a partner simply made the activity go more smoothly and quickly, and none actually experienced any better conceptual understanding as a result of working on their activities in a group.

Discussion of Results

The quantitative results based on comparing the students' displacement measurements to the RISA computed displacements ended up including a much higher error than expected. The amount of error appeared to be highly dependent on the students performing the experiments, though, as several groups had low overall error (<25%) for all three of their exercises and others had very high error (>100%) for their exercises. The sources of the high error experienced by some of the groups appeared to be mostly related to the Mola model displacements, specifically the care they took with keeping the model and pulley support bases stable and the accuracy with which they read their deflection measurements. Despite the measurement errors being higher than expected, there was still good correlation between the physical model and computation model deflected shapes and students seemed to still be able to achieve the main objectives of the activity.

Constructive learning includes not only the creation of new knowledge, but also the repairing or improving of existing knowledge [9]. Through the pre- and post-activity questionnaires, students had an opportunity to demonstrate this constructive repairing of their existing knowledge through an improved ability to interpret the questions related to deflected shapes and stability. Overall, the quantitative results from the questionnaires indicated that the students who completed

Activity B (related to the lateral force resisting systems) seemed to acquire some significant gain in conceptual understanding of the topic as measured by Question Set B. This conclusion is supported by both of the analysis methods applied to the data. The students who completed Activity A (related to portal frames) appeared to acquire some gain in conceptual understanding of the topic as measured by Question Set A using the opportunity-improvement analysis method. The lack of demonstrated effect size for the Activity A / Question Set A students may simply have more to do with the similarity between the concepts explored by the two activities than the ineffectiveness of Activity A. Based on the results of the opportunity-improvement analysis method, it would probably be more accurate to say that both groups of students attained an improved understanding of portal frames than that the portal frame activity was ineffective. Ultimately, compared to their performance on the control question, both populations demonstrated a gain in understanding of the questions related to the modeling activities.

The qualitative results from the student interviews also suggest that the activities were at least partially effective at improving gains of understanding of the activity concepts as well as forming the desired cognitive connections. A few students (40%) were able to elucidate these connections when asked to describe their understanding of the topics, but others struggled to bridge the gap between the activity they completed and real-world applications. The indirect assessment questions revealed that all of the students saw value in the activity, even if they were unable to put into words what they perceived that value to be. Students unanimously saw value in modeling structural behaviors with the Mola Structural Kits and ranked their use as the most effective part of the activity, particularly in their ability to visual structural system behavior and the effects of different joint restraints. Students were less engaged with the explanations and photos of real-world structures and with the modeling in RISA 3D, with several admitting that they left these portions of the activity up to their teammates. The interactive/collaborative component of the activity seemed to provide students with greater satisfaction but appears as though that may have come at the cost of potential gains in understanding.

Conclusions

The activities described in this study were designed to implement pedagogical features of active, constructive, and interactive/collaborative practices. Leveraging students' general appreciation for hands-on and lab-based learning activities, these activities were also intended to help students develop cognition, psychomotor skills, and behaviors and attitudes regarding the structural behaviors of portal frame structures and lateral force resisting systems. The activities included three components: exposure to real-world structures, physical modeling with the Mola Structural Kits, and computational modeling in RISA 3D.

Considering the quantitative and qualitative results together as a mixed method, there is sufficient evidence that students both perceived and experienced that these activities increased their understanding of the related concepts, if not also their ability to connect the concepts displayed by the physical models to the behaviors of the computational models and the applications in real-world structures. However, these gains did not seem to be uniform across all students, and modifications to the activity in future iterations may be able to further increase this and similar activities' effectiveness.

Future Work

The results of this study suggest that there is significant potential for student learning through the described activities. The researchers intend for this approach to be adapted in future structural engineering courses and expanded to include additional and more advanced structural behaviors (such as continuous members, multi-story structures, structural dynamics, etc.). In future implementations of these activities and further research the following improvements are anticipated:

- The presentation of real-world structures prior to the modeling activities would benefit from a more dynamic engagement, either through a video or multi-media experience. Students could also be challenged to develop relationships on their own between real world structural systems and Mola structural models.
- The methods used to derive the mechanical parameters should be expanded to include the additional components included in the Mola Structural Kits as well as to explore the way these parameters are modified due to specific configurations (for example, how a spring's mechanical parameters are changed when magnetically connected to a fixed support, which effectively shortens the spring length, as opposed to a pinned support).
- An improved way for securing the model and pulley support bases and some additional descriptions on how to collect good deflection data are needed in order for students to obtain results that better match between the physical and computational models. Students should also be required to reconsider their testing methodology and rerun their experiments if they observe extremely high error between the physical and software models.
- Additional and more challenging questions should be included on pre- and post-activity questionnaires in order to provide students with a greater number of opportunities to demonstrate increases in conceptual understanding.
- Additional and more in-depth direct assessment questions should be included in the interview process to obtain a fuller narrative of students' conceptual understanding.
- At least one activity involving structural behaviors to which students have not had prior exposure in the classroom should be implemented to evaluate the effectiveness of these activities at introducing new topics.
- The interactive/collaborative components of the activities need to be reconsidered to encourage students to divide work in a way that does not inhibit individual learning and to create opportunities for meaningful discussions between teammates. Presenting the students with more open-ended opportunities for experimentation and "play" may help add value to the interactive/collaborative nature of activities.
- Partnership with instructors at other universities who have already invested in procuring the Mola Structural Kits would help provide a larger and more diverse study population to help strengthen any future conclusions.

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