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Physical Artifacts in Introductory-level Reinforced Concrete Design Instruction

Ms. Anahid Behrouzi, University of Illinois, Urbana-Champaign

Anahid Behrouzi is a doctoral student of civil engineering at the University of Illinois at Urbana-Champaign. She has been involved with STEM education beginning in 2003 as a volunteer and summer instructor with the North Carolina Museum of Life and Science. She has been engaged with undergraduate/ graduate course delivery in the topic areas of engineering problem-solving, structural engineering, and reinforced concrete design at North Carolina State University (2008-2011), the University of Illinois at Urbana-Champaign (2012-2015), and Tufts University (2015-present). She has a BS in civil engineering and BA in Spanish language & literature from North Carolina State University, and a MS in civil engineering from the University of Illinois at Urbana-Champaign.

Physical Artifacts in Introductory-level Reinforced Concrete Design Instruction

Abstract

Incorporating physical models and demonstrations in the introductory-level reinforced concrete design course has shown to be beneficial for students in clarifying and engraining fundamental concepts. The research study conducted at the University of Illinois at Urbana-Champaign during Spring 2015 involved the design, fabrication, and implementation of models to supplement traditional lectures on topics that students have found challenging in prior offerings of the course. The paper includes details intended to enable other civil engineering educators to: fabricate the models, incorporate them in a large-lecture setting, as well as facilitate activities that encourage students to engage with the physical artifacts. The author also presents student feedback on the use of these physical models that was acquired through an IRB-approved human studies research study during Spring 2015. This includes results from mid- and end-term surveys with two class sections of over ninety undergraduate and graduate students. The overall objective of this paper is to provide educators with sample teaching tools to help students better visualize three-dimensional ideas and systems – a skill which is critical as students transition to design industry. In addition, it is intended to stimulate a dialogue with educators about further needs for physical models in reinforced concrete design education, and more generally, in the civil engineering design classroom.

Introduction

When teaching introductory reinforced concrete analysis and design, two of the major challenges are helping students to: (i) develop a conceptual understanding of underlying mechanical theory (rather than rote memorization of formulae or procedures) and (ii) visualize three-dimensional (3-D) structural members/systems. The issue with the former arises since students view prescriptive, code-based design as an exercise of plugging values into equations disregarding that these analysis/design approaches are based on actual physical phenomena – flexure is founded on strain compatibility and shear on the results of countless experimental tests. On the other hand, visualizing structures is typically a problem for students who have not been exposed to the design and construction of reinforced concrete members via laboratory, work-site, or design-office experience. They have no 3-D reference to help them make sense of the many two-dimensional (2-D) figures shown in textbooks, course notes, and the concrete building code.

The question is then: how can a reinforced concrete design instructor modify their teaching to address these common learning challenges? One must start by first examining the learning styles of their students. Felder and Silverman[1] provide a detailed discussion of learning styles, reporting that engineering students are largely sensory and visual learners. Therefore, the traditional teaching approach used in engineering courses which targets intuitive and auditory learners, characterized by lecture/discussion of abstract principles and theories, is not appropriate for most students. Felder and Silverman[1] recommend that instruction should also include concrete facts or data, and that auditory information should be presented visually using images, figures, flow charts, videos, and/or demonstrations.

In particular, a variety of studies have shown that physical hands-on demonstrations are an effective method to help these type of sensory/visual learners achieve a more complete conceptual understanding of engineering topics.[2] Beyond helping students grasp technical ideas, Schaaf and Klosky[3] add that use of demonstrations help students engage as active learners and spark their excitement in course topics. For these reasons, the use of physical models and demonstrations is one of the fundamental approaches in the ExCEEd Teaching Model endorsed by the *American Society of Civil Engineers* to achieve high quality engineering instruction.[4] Some of the most notable work of structural-civil engineering educators in the development and study of physical models have been in the topic areas of: statics[5], structural mechanics[3], general structural engineering[6,7], steel design[8], and reinforced concrete design[9-14].

Examining the hands-on teaching tools and exercises associated only with reinforced concrete design courses, the vast majority involve laboratory testing of beams and/or columns to help students understand structural response.[9-13] These activities often require students to conduct: concrete mix design, flexural/shear design, fabrication, instrumentation, testing of both material samples and structural specimens, data analysis, as well as report writing. While these activities are an outstanding way for students to apply their design knowledge, understand concrete failure mechanisms, and develop a diverse set of auxiliary skills, they can be prohibitive in terms of cost, time, equipment, materials, and instructional support.

An alternative to this approach is presented in Jones[14] which provides an overview of the construction and implementation of hands-on physical models/demonstrations that were integrated into two semesters of a reinforced concrete/masonry design course at the U.S. Military Academy. To engage students in learning, there was a concerted effort to develop activities that had a heavy tactile or visual component. These activities addressed topics as far ranging as the truss analogy for shear design of beams to the examination of various stages of stressing tendons in post-tensioned concrete members. The models/demonstrations presented in Jones[14] were generally simple, inexpensive, transportable, and targeted specific course concepts. Despite these many attractive qualities, there is still a limited set of this type of reinforced concrete table-top classroom models that can be found in literature. Moreover, there is little record of student evaluations for the existing physical models/demonstrations since educators, including Jones[14], tend not to collect or report formal assessment data from student surveys/interviews. Therefore, the motivation for the study described in this paper is twofold: (i) to address the lack of physical models in teaching introductory reinforced concrete design and (ii) to collect student feedback assessing the efficacy of models and potential areas of improvement.

The remainder of this paper will summarize the physical models that were developed and utilized in Spring 2015 to clarify challenging concepts in the introductory reinforced concrete course taught at the University of Illinois. The description for each physical model includes: target concept(s), suggested instructional activities, construction materials, as well as photographs. The paper will conclude with student feedback on the effectiveness of the models based on mid- and end-term course surveys. The overarching objective of this work is to provide other civil engineering educators with sample teaching tools to enhance students' understanding of reinforced concrete analysis/design theory and ability to visualize structural members/systems.

Course Details

Two sections of *CEE 461: Reinforced Concrete Design I* (hereafter *RC1*) were offered in the Spring 2015 semester at the University of Illinois at Urbana-Champaign in the Department of Civil & Environmental Engineering. Of the 89 civil engineering students (82 undergraduates, 7 graduates) in the course, two-thirds had a primary concentration in structural engineering and the remaining one-third was largely in construction management. Students indicated their main motivation to take *RC1* was that it was a core course necessary to complete their primary/ secondary specialization. A significant number of students also indicated they planned to practice as a structural engineer or in some engineering capacity where the class would be an asset. In terms of preparation for *RC1*, nearly all the students had taken undergraduate Structural Engineering, about half of the students had previously taken a Behavior of Materials course where they would have learned about concrete and steel reinforcement properties, and one-third had previous code-based design experience from the introductory Steel Design class.

The *RC1* curriculum covers: material properties of reinforced concrete; behavior, analysis, and design of beams and one-way slabs for both flexure and shear; development, anchorage, and splicing; and behavior, analysis, and design of short columns subject to axial and flexural loads. The physical models were created to address difficult topics within this curriculum which were identified by the author based on three semesters of interacting with students and assessing their performance as a course teaching assistant, and semi-structured interviews with thirteen students would had previously taken the class between Fall 2012 and 2014.

Description of Physical Models

Flexural Analysis of Rectangular Reinforced Concrete Beams

In the *RC1* class, students are taught to analyze the flexural capacity of beams in order to develop a moment-curvature plot that includes the critical limit states of cracking, yielding, and nominal moment. At each of these stages, the 3-D stress in the beam section varies. At low moments, the concrete stress is linear while the steel stress is less than yield; as moment increases, the concrete stress becomes parabolic and the steel stress reaches its yield plateau. For this reason, the idea of using material constitutive models to go from a linear strain distribution to a stress diagram, and then to develop a force diagram (strain-to-stress-to-force) is fundamental in flexural analysis of beams.

Often students do not understand this relationship. They feel it is necessary to memorize the *formulas* for concrete compressive and steel tension forces in order to develop a force equilibrium expression and calculate the depth of compression, c, for each of the cracking, yielding, and nominal moment states. This indicates that they do not fully understand that the expression to describe these forces comes from the fact that stress is applied over an area of the concrete cross-section or steel rebar (referred to herein as “3-D stress block”). Part of the difficulty that students face comes from the fact that most instruction on flexural analysis involves the 2-D strain-to-stress-to-force diagrams shown in Figure 1, and it is difficult to visualize the associated 3-D stress blocks.

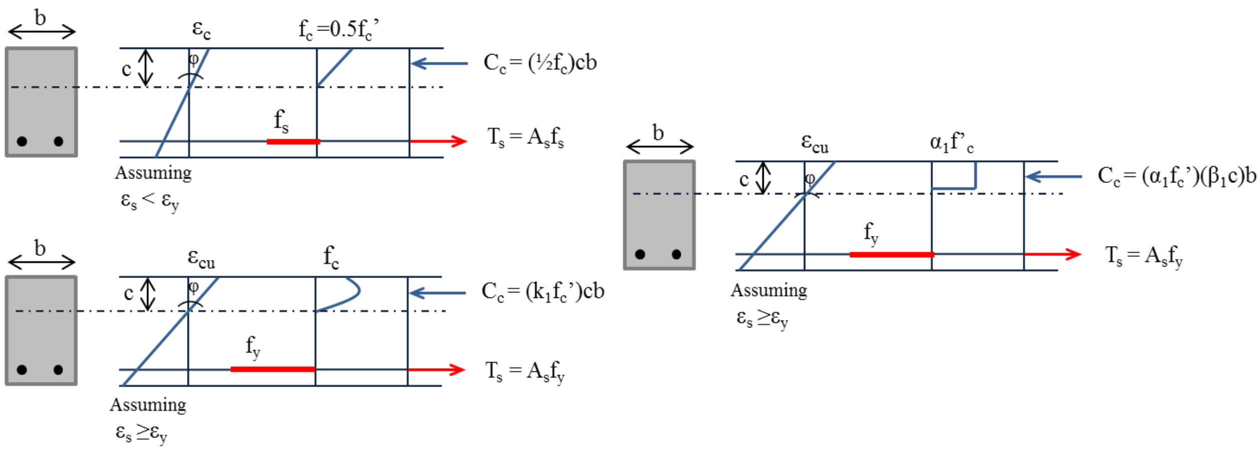


Figure 1. 2-D Strain-to-Stress-to-Force Diagrams for Rectangular Beams subject to Flexure: (Top Left) Linear, (Bottom Left) Parabolic, and (Right) Equivalent Rectangular Stress States

To clarify this concept, a set of physical models for various stress conditions in rectangular beams was created. Figure 2 shows the models associated with:

a) concrete compressive stress at the extreme compression fiber (f_c) is less than $0.5 - 0.6f_c'$ and is assumed to vary linearly,
b) concrete compressive stress (f_c) is greater than $0.6f_c'$ and is assumed to vary parabolically,
c) the equivalent rectangular stress block as described in ACI318-11, Section 10.2.7.[15]

These models are used to show students that the volume of the concrete compressive stress block (blue) is set equal to the volume of the steel tensile stress block(s) (red). Furthermore, the physical models help students calculate the centroid of the compressive stress in the concrete, and subsequently the moment arm between concrete compression and steel tension forces.

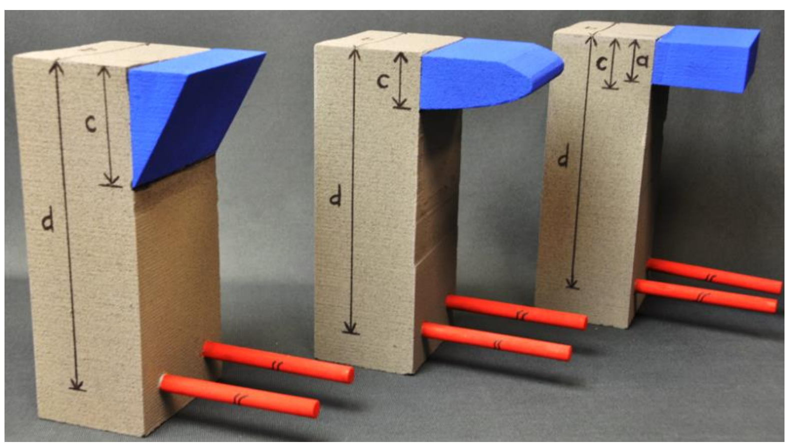


Figure 2. 3-D Physical Models for Rectangular Beams subject to Flexure with: (Left) Linear, (Middle) Parabolic, and (Right) Equivalent Rectangular Stress Blocks

The models were constructed out from 3 x 4 x 8 in. polystyrene blocks and 3/8-in. diameter wooden dowels. Aside from paint color to differentiate compression versus tension stress blocks, relevant variables can be labeled directly on the model so students can relate the 3-D models with the 2-D representations they draw on (Figure 1) as part of their flexural analysis procedure. After implementing these models in the RC1 course, students' questions notably changed from asking about the *formulas* for the different forces and instead focused on understanding the distinct *geometries of the stress blocks*.

Flexural Analysis of Flanged Reinforced Concrete Beams

Following the flexural analysis of rectangular sections, the *RC1* curriculum covers nominal moment capacity of flanged sections. In class the instructors primarily teach students about T-beams since this structural member type is prevalent in monolithically poured slab-beam systems. However, students are expected to be able to draw connections from lecture to homework/exam problems that include other flanged cross-sections.

With the flexural analysis of flanged beams, students often try to *memorize the formulas* to determine forces acting on a T-beam for the nominal moment cases shown in Figure 3:

a) negative flexure when the compression zone consists solely of a portion of the web,
b) positive flexure when the compression zone consists of the flange (or a portion of the flange), and
c) positive flexure when the compression zone consists of the entire flange and a portion of the web.

Taking this rote learning approach is particularly problematic because students do not have the conceptual understanding necessary to analyze bulb-tee, C- or L-shaped sections, as examples. Effectively, the *formulas* used to express forces (and moment arms between forces) on a flanged beam change based on cross-section. Students must adopt a *procedure* to determine these forces (and moment arms) rather than attempting to *memorize expressions* that they may mistakenly believe will be universally applicable to all flanged sections.

An effective method to help students move away from memorization is first have them draw the particular 2-D cross-section they are analyzing (including steel reinforcement and direction of the applied moment), and then create associated strain-to-stress-to-force diagrams. Students can use physical (or later, mental) models like those shown in Figure 4 to visualize the 3-D stress blocks and calculate the volumes of these stress blocks to determine concrete compression and steel tension forces. Having a 3-D reference is especially important for instances, such as the aforementioned Case (c) with T-shaped beams, where the concrete compressive stress block varies in width across its height and should be divided into multiple parts to evaluate the force.

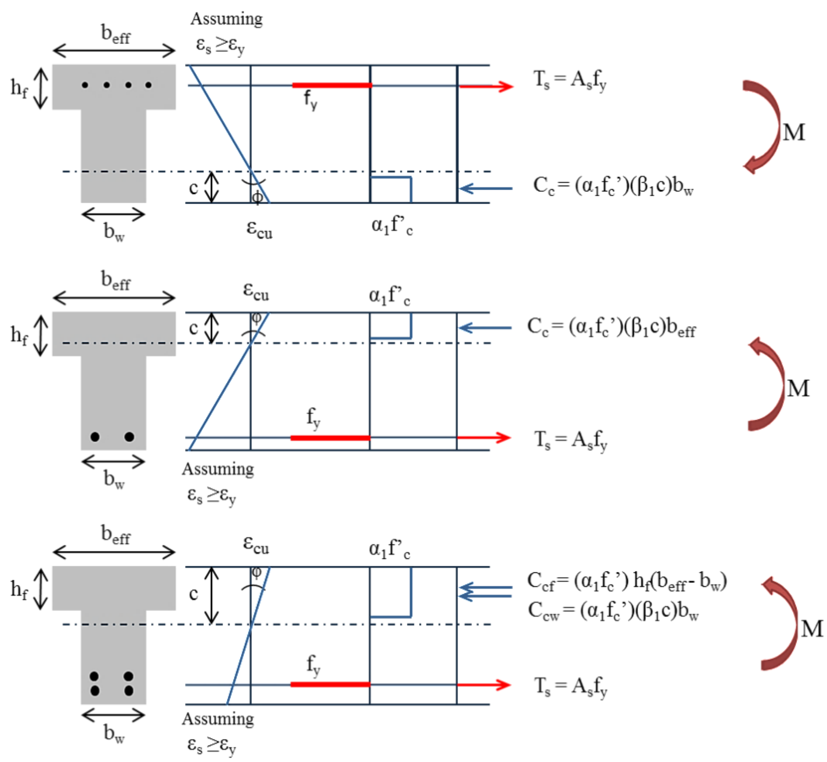
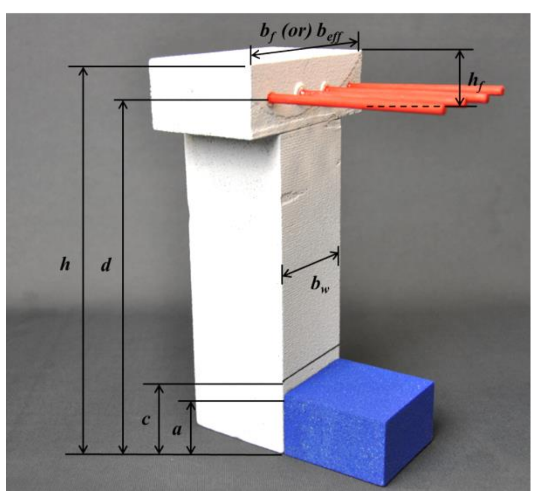


Figure 3. 2-D Strain-to-Stress-to-Force Diagrams for T-Beams at Nominal Flexure: (Top to Bottom) Negative Moment, Positive Flexure – Compression Zone in Flange only, Positive Flexure – Compression Zone in Flange and Web

The flanged beam models presented in Figure 4 appeared to be an effective teaching tool. By the end of the semester a majority of *RC1* students were able to demonstrate a strong conceptual understanding of flexural analysis of flanged sections, beyond T-beams. This assessment is based on reviewing students' hand calculations for L-shaped and hollow-core square sections (in the term project and final exam, respectively) that show their use of stress blocks develop expressions for concrete compression and steel tension forces.



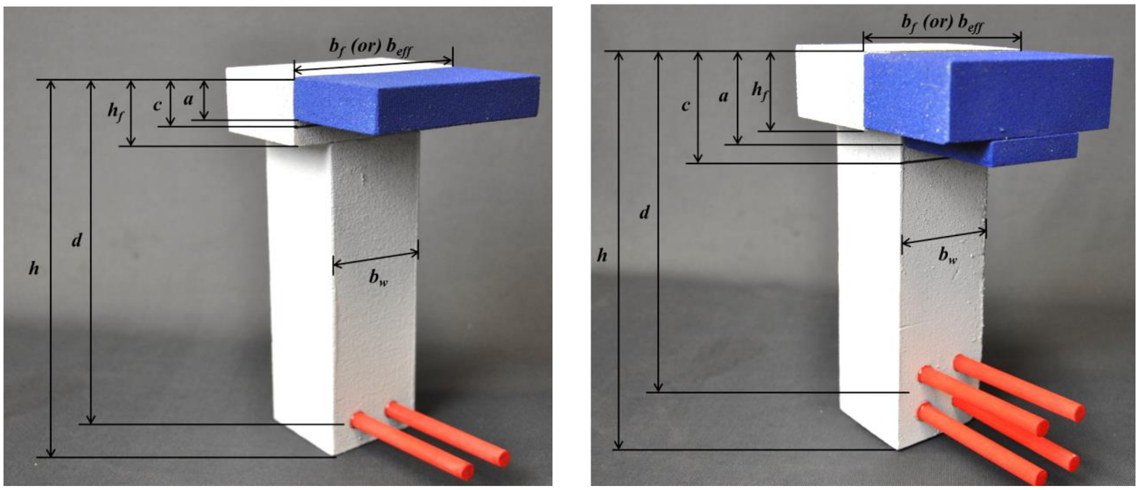


Figure 4. Physical Models for T-Beams at Nominal Flexure:
(Prev. Pg.) Negative Moment, (Bot. Left) Positive Flexure – Compression Zone in Flange only,
(Bot. Right) Positive Flexure – Compression Zone in Flange and Web

One-way Slab Model

Upon first glance, it would appear that flexural design of one-way slabs is rather straightforward, since the strip method simply requires students to design a one foot wide section of the slab as if it were a beam. However, there are other nuances with slab design that are often not clear. Jones[14] proposed a one-way slab model that serves as a starting point for the models shown in Figure 5, which are discussed in this section. With slight modifications, it has been possible to clarify common uncertainties that students have about the design/behavior of the one-way slab system.

The first challenge is providing a clear illustration of the difference in bay aspect ratio and bending behavior between one-way and two-way slabs (where the former has an aspect ratio ≥ 2:1 and the latter < 2:1). It is insufficient for the instructor to simply state that: “for one-way slabs, bending primarily occurs in the direction parallel to the short side of the bay and the amount of bending in the orthogonal direction can be treated as negligible”. The students do not yet have an appreciation for two-way bending where bending in both directions is rather significant. However, passing the two slab models around the *RC1* classroom and allowing students to experiment themselves provided a tangible experience that they commented helped them understand and remember the differences between the slab types.

The second point of confusion is where the strip method diverges from the beam design approach with which students are accustomed. Students will correctly calculate the area of steel reinforcement per foot (in^2/ft) based on the flexural demand (or minimum ACI318 requirements) and then decide they have to select a bar size and number of bars that meet not only spacing but also cover requirements in the *horizontal* direction of the one foot section.[15] Most of the time this leads to a design with larger bar sizes and/or smaller bar spacing than need be. What is often not clear to them is that this design is not isolated to the one foot section but uniformly distributed across the slab parallel to the direction of primary bending.

Another issue that occurs on occasion is that students will place the flexural reinforcement perpendicular to the primary direction of bending and shrinkage/temperature reinforcement orthogonal to that, resulting in insufficient flexure capacity. This can be easily resolved with a simple visual indicator (blue tape) highlighting the one foot wide design strip, with respect to the entire slab, in the appropriate direction that is parallel to the short-side of the bay.

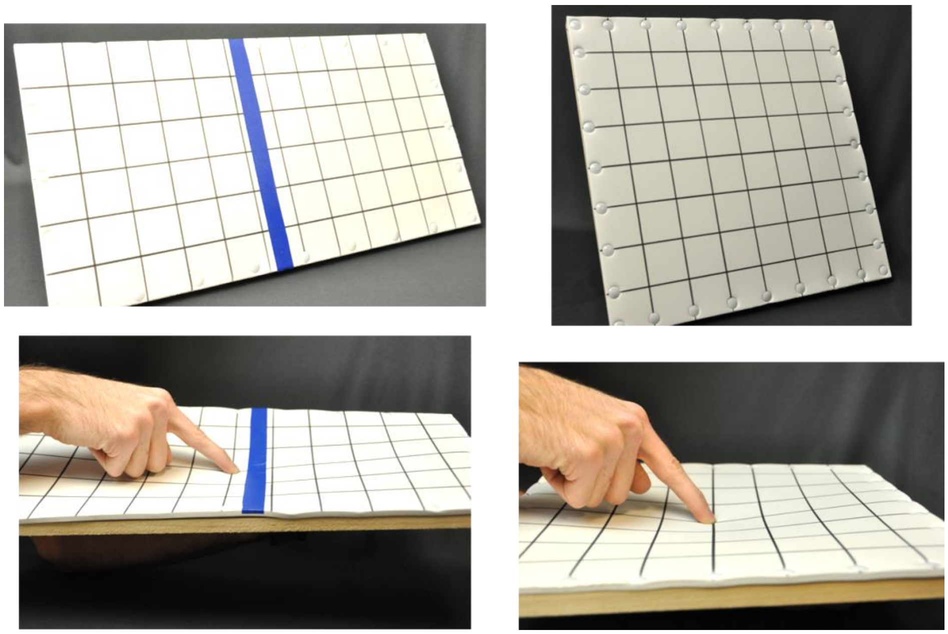


Figure 5. Physical Models for (Left) One-Way and (Right) Two-Way Slabs

The models were constructed with 0.25-in. white foam sheet affixed to a frame constructed from square 3/8 x 3/8 in. wooden dowels with large 13/32-in. diameter thumb tacks. The one-way slab model was 9 x 18 in. and the two-way slab was 12 x 12 in. to achieve the desired bay aspect ratios. Similar to the Jones[14] model the foam is marked with a square grid, so that the effect of bending is apparent when a load is applied to the model. The blue tape indicating the one foot design strip should only be shown on the one-way slab model.

Flexure and Shear Design of Beams

While most students become comfortable with sizing a beam section and selecting adequate reinforcement to meet flexure and shear demands, they have a limited understanding of how their reinforcement configuration appears in 3-D space. This is particularly true of students who have not had the opportunity to observe reinforced concrete construction or examine multi-view design/shop drawings. In past offerings of the *RC1* course, attempts were made to overcome this difficulty with visualization by providing students with 3-D graphics of beams that show the concrete section as transparent so the internal steel can be seen. However, even these images proved to be insufficient as it was difficult for students to reconcile a 3-D object displayed in a 2-D figure with an actual reinforced concrete section.

The two half-scale physical models, shown in Figure 6, were designed not only to assist students in visualizing reinforced concrete beams, but to help them develop skills such as calculating the distance to the centroid of the steel reinforcement, determining the depth of compression, as well as verifying that vertical/horizontal spacing and cover requirements from ACI318 were satisfied.[15] To meet these teaching objectives, the model was designed to be flexible so the user could modify the number and size of rebar in the tension and compression zone; to place, shift the spacing of, and remove stirrups; and to be able make annotations directly on the beam model.

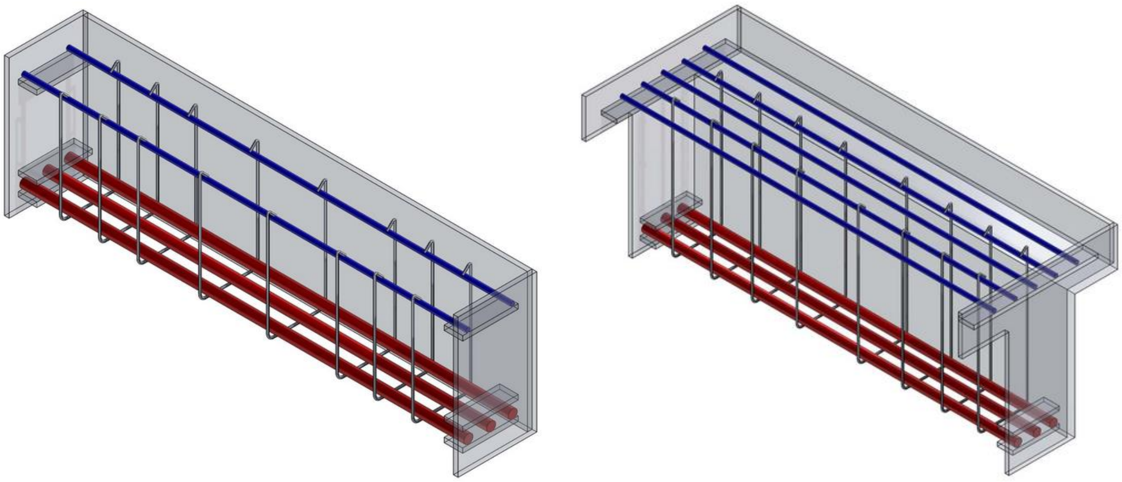


Figure 6. Design Renderings of Physical Models for Flexure and Shear in Beams: (Left) Rectangular, (Right) Flanged Section

A prototype rectangular beam model was fabricated and implemented in the *RC1* course. The kit of materials and a sample reinforcement configuration for this model are shown in Figure 7. The body of the model consists of 1/4-in. thick, transparent acrylic supported by two "legs" in the shape of the beam cross-section. On these "legs" there are shallow acrylic shelves where flexural reinforcement – circular wooden dowels of different diameters (and colors) – can rest. The shelves are placed to provide adequate vertical and horizontal cover/spacing for the bars. Two-legged stirrups were bent from mild steel threaded rod to be easily placed along the beam length.

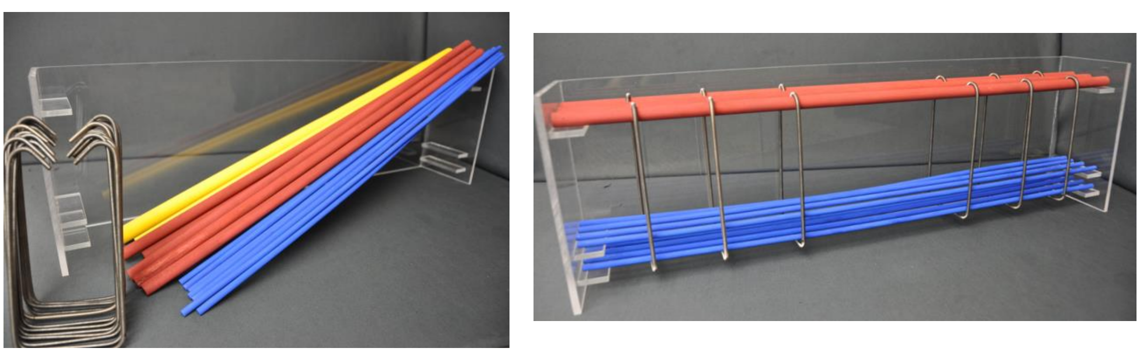


Figure 7. Physical Models for Flexure and Shear in a Rectangular Beam: (Left) Model Kit, (Right) Sample Reinforcement Configuration

The beam model was used as a visual prop in class during design lectures and team exercises, but was found to be more effective in office hours where students were encouraged to actively engage with the model by using dry erase markers to label variables, note the location of the compression zone, or draw cracking diagrams – based on whatever concepts needed clarification.

Students commented that having a physical representation of the beam, over a 2-D cross-section/elevation drawing, helped them make connections to the as-built construction of this member type.

One-way Slab System

After covering topics of flexural/shear beam design, one-way slabs, and flexure-axial design of columns in the *RC1* course, students have the opportunity to assemble this knowledge in their final project by designing a two-story, multi-bay building comprised of a one-way slab system. One of the greatest obstacles with this is having students feel comfortable with load path, and the concept of using tributary widths to determine the distributed line load that should be applied to a beam or tributary areas for the concentrated axial load on a column.

Another aspect that can be confusing is that when the slabs and beams in a structure are cast monolithically. While the beam appears to have a rectangular section, it behaves either as a T- or L-shaped section with the slab acting as the flange. Therefore, it is important for students to design the beams with the understanding that the concrete compression zone varies for positive and negative flexure, as illustrated by the models shown previously in Figure 4.

A final concept that tends to be unclear is how all the reinforcement in a one-way slab system fits together. Throughout the course students have already been tasked with designing slab reinforcement for flexure and shrinkage/ temperature, beam reinforcement for positive/negative flexure and shear, as well as column reinforcement for flexure-axial and shear *individually*. Yet, the interaction or continuity of this reinforcement to tie the entire structural system together is often not well understood, but is critical to the performance of the building's design.

The one-way slab model, shown in Figure 8, aims to clarify all of the aforementioned concepts in a way that directly reflects reinforced concrete design practice and is clear to students. The model was constructed by the University of Illinois Department of Civil & Environmental Engineering (CEE) Machine Shop using funding from the department. It was constructed out of 1/4-in. transparent acrylic and reinforcement is made out of a combination of mild steel welding wire, 16-gauge tie wire, and cold finish steel round wire (based on the desired bar diameter). Reinforcement is tied with 24-gauge copper beading wire and reinforcement chairs are fabricated from notched acrylic tabs to provide adequate "concrete cover" to the reinforcement.

As shown in Figures 9-11, students can view the internal components of the reinforced concrete members in a way that aids their visualization of individual components and connections, as well as how everything comes together at the system level.

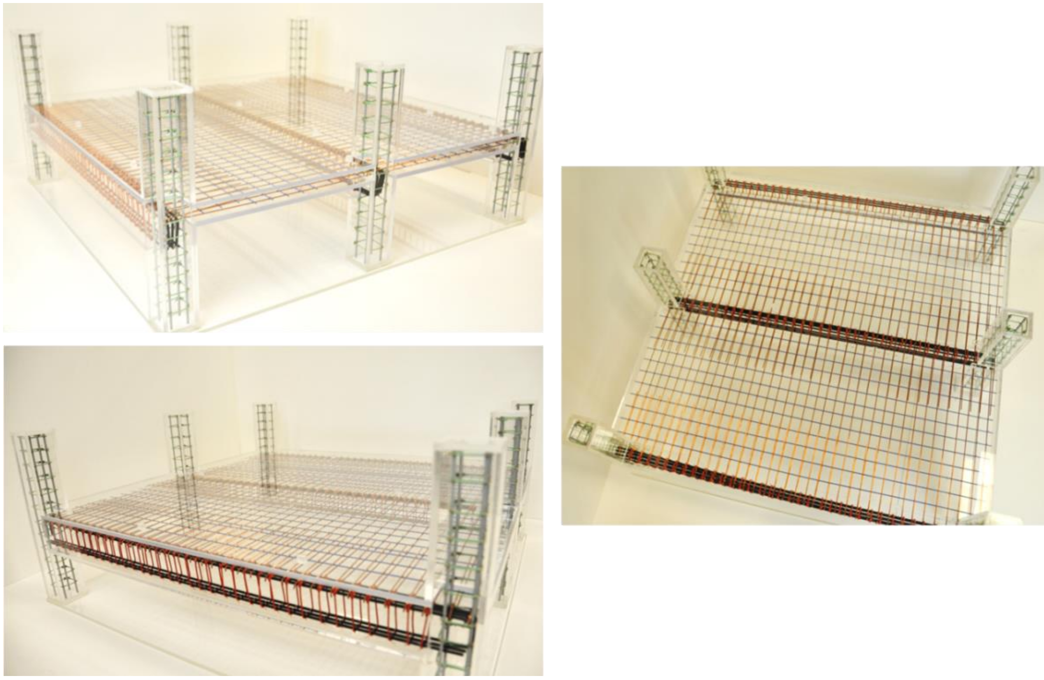


Figure 8. One-way Slab System Model: Overall Images

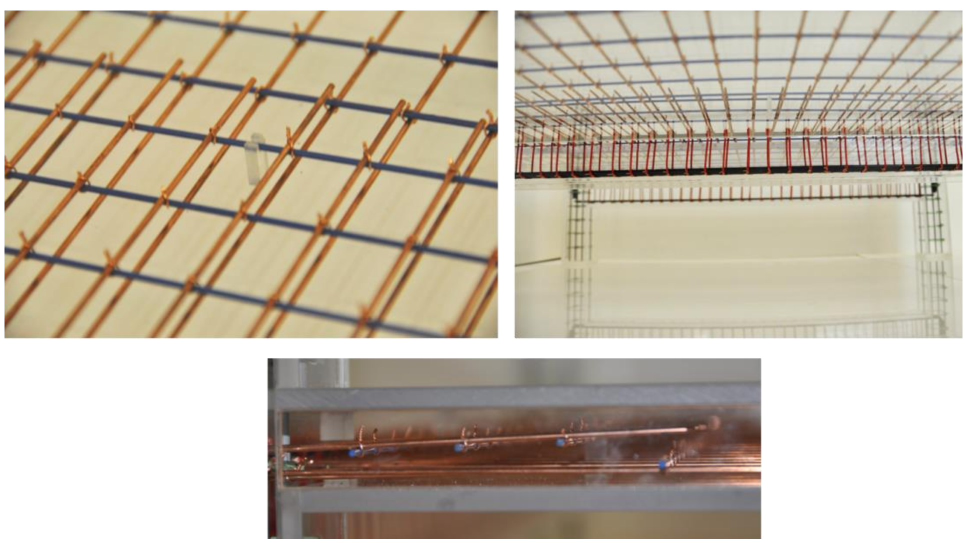


Figure 9. One-way Slab System Model: Slab Reinforcement
(Flexural = Copper, Shrinkage/Temperature = Blue)

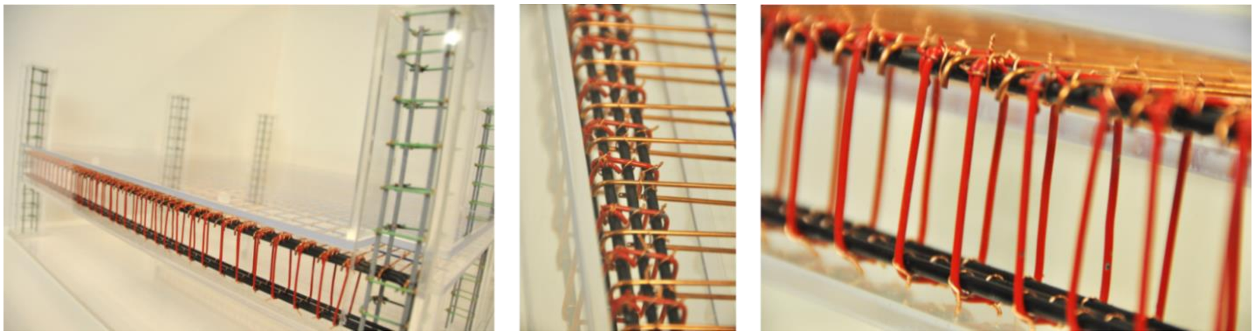


Figure 10. One-way Slab System Model: Beam Reinforcement (Flexural = Black, Shear = Red)

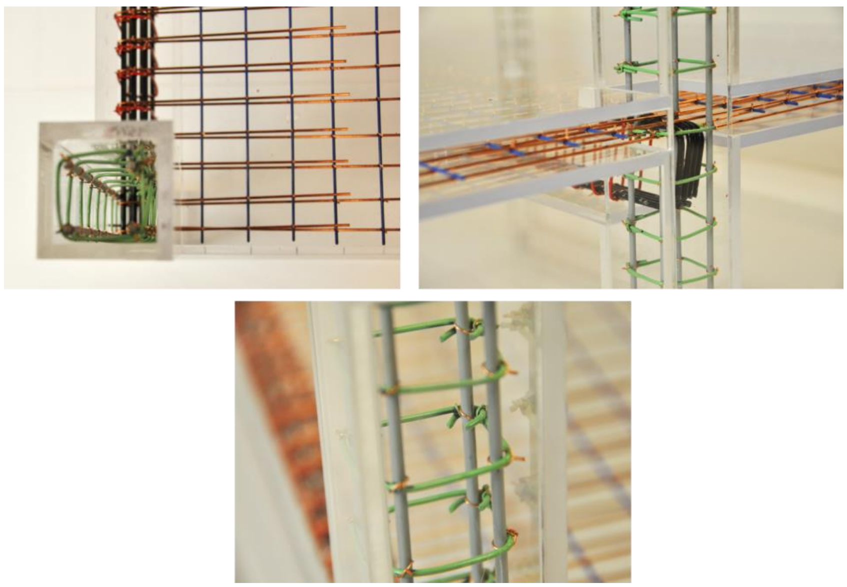


Figure 11. One-way Slab System Model:
Column Reinforcement (Vertical = Gray, Ties = Green)

The one-way slab system model was introduced as a visual prop in class during lecture, and students mostly took advantage of investigating the model and asking questions in office hours over the weeks when they were working on their final projects. Again, the model design aimed to let users write directly on the model with dry erase markers to: draw arrows indicating flow of forces or cross-hatch tributary widths/areas; label relevant variables; outline L- or T-shaped beam cross sections; and so forth. The first response of many students was excitement at such an intricate and unique model. They also developed a more technical appreciation for it as it helped them work through challenges like problem-solving reinforcement conflicts when designing their slab-beam-column connections for the project (something they indicated would otherwise be very difficult to visualize).

Suggested Implementation of Models

Based on cost/effort required, it is suggested that models be implemented in the following order: one- and two-way slabs, 3-D stress blocks, flexure/shear in beams, and one-way slab system.

Student Assessments

Overview of Student Assessments

Both sections of the Spring 2015 *RC1* course where given identical surveys at the middle and end of the semester (beginning of March and end of April, respectively). They were administered by a graduate student on the research team that was not involved in *RC1* course instruction. The survey consisted of eighteen multiple choice and six free-response questions, many of these included questions about the instructors' teaching effectiveness, as well as small group activities, assignments, projects and exams that were integrated into the course. Three of the multiple choice questions and one of the free response questions directly referenced the physical models; two additional free response questions referenced teaching "tools" in a general sense. When given the surveys, students were not originally made aware that the primary interest of this study was on the efficacy of the physical models. They were told that the study was to "understand how civil engineering students learn the concepts of reinforced concrete design" with the intent of limiting student bias in answering questions about the physical models.

Across both course sections the average survey response rate was around 80%, where the average student attendance rate during the semester was around 91%. Of the group that participated in the surveys, around 97% responded to all three multiple choice and 77% to the free response question that directly targeted the efficacy of the physical models.

Before discussing detailed results from the surveys, it should be noted that both course sections were taught on the same date and time (where the codes "MN" stand for the author's and "NP" for the post-doctoral instructor's sections, respectively). Therefore, implementation of models usually occurred in the "MN" section first, with the teaching assistants coming to retrieve the model to use in the "NP" section thereafter. Difficulties with coordination resulted in the "MN" section being exposed to models with slightly more frequency and in a way that may have been better integrated into lecture. Furthermore, there may also be variances in how the models were actually implemented in the sections since there can be difference in using one's own tools and being given another's tools to utilize.

Student Feedback from Surveys: Multiple Choice Survey Questions

The three multiple choice survey questions related to physical model effectiveness that were based on a five-point Likert scale rating included:

1) How well does the instructor coordinate use of physical demonstrations or models in the course? (Response: 1- Rather Poorly/ 5- Very Well)
2) The physical demonstrations or models used in class helped clarify concepts described in class notes and assigned reading material. (Response: 1- Strongly Disagree/ 5- Strongly Agree)
3) The physical demonstrations or models provided a valuable visual reference when completing in class exercises, homework, or exams. (Response: 1- Strongly Disagree/ 5- Strongly Agree)

The average results from these questions are summarized for each of the surveys (mid and end-semester) in Figure 12. In this plot, the mid-semester survey is designated by “March” and the end-semester by “April”. The course sections are denoted with an abbreviated code where “MN” was the author’s section, and “NP” was taught by a post-doctoral researcher. The numbers 1-3 on the x-axis refer to the three multiple choice questions listed above.

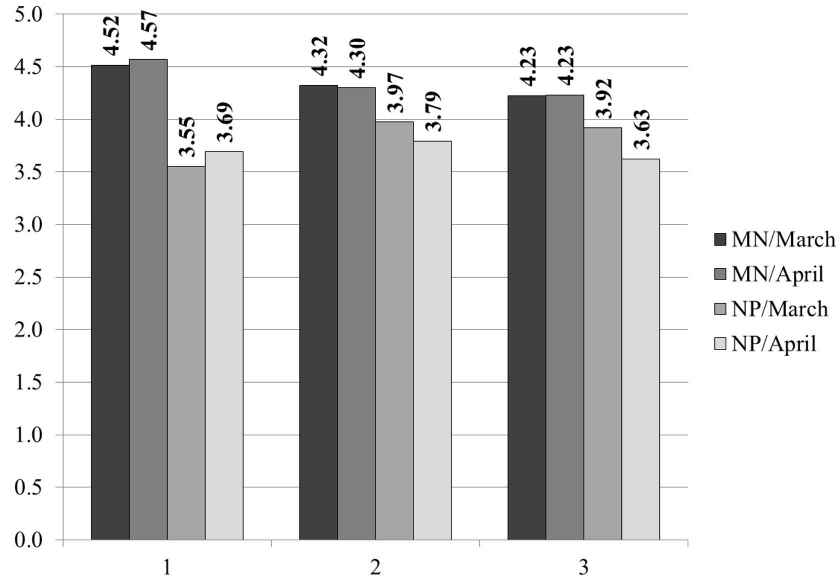


Figure 12. Average Responses to Multiple Choice Questions about Physical Model Efficacy

Examining the results, it can be observed that for all three questions the average scores are higher in section “MN”. The greatest variance between the two class sections occurs in responses to question 1 related to coordination of model use in the classroom. This speaks to the earlier concern raised with frequency and the manner in which models were integrated into the class, since classes were held concurrently and models were consistently used first in section “MN”.

Examining the responses for section “MN” it appears that while students feel that the models are well incorporated into the course (question 1), their perception of how well these visual tools actually help clarify concepts and provide a reference for later design and problem solving is positive (questions 2 and 3), but not as strong. The average responses from section “NP” are slightly lower (for questions 2 and 3), yet it actually appears the value the students see in the visual tools generally exceeds their thoughts on how well the tools were integrated into the class.

However, irrespective of the class section, student response is slightly positive to very positive on the overall use of physical models in the class. A preliminary assessment solely based on student response to the multiple choice questions over the semester indicates the proposed physical models are effective in the instruction of an introductory reinforced concrete class.

Student Feedback from Surveys: Free Response Survey Questions

The survey included one free response question that explicitly probed students about their opinion of the physical models and two other questions that point towards the models indirectly by requesting student comments on teaching “tools” (however, the students could interpret “tools” however they wished).

The questions that elicited responses specifically related to physical models are listed below in the order of the number of relevant responses (this number is a culmination from both the mid and end-semester surveys conducted in both class sections):

- What do you think of the physical models used in class? (Do they aid your understanding, or not? Interesting? Engaging?...And why) – ***108 responses***
- What are the major strengths and weaknesses of the instructor? (What teaching techniques and tools do they employ in class instruction that are effective or ineffective?) – ***14 responses***
- What do you suggest to improve this course? (Do you want things done in class a different way? Are there additional activities or tools the instructor could implement that might help you learn?) – ***8 responses***
- What aspects of this course have been most beneficial to you? (What is helping you learn? What is interesting? What do you want to do more of?) – ***5 responses***

To provide more insight into the types of open-ended responses that students provided, this section of the report will take both qualitative and quantitative approaches to examining their feedback by including a:

1) selection of quotes from student responses to describe a five-point scale of extremely positive to extremely negative student responses, and
2) classification of all student responses by coding responses in relation to the where they fall on the previously mentioned five-point scale using the sample quotes as reference.

1. **Selection of Student Open-Ended Responses**

The following quotes are directly extracted from student surveys from section "MN" to develop a spectrum of student perception of the physical models, they have been placed under the classification of extremely positive to extremely negative.

Extremely Positive:

- "The major strengths [in the course] are the visuals. The detail in the mini slab/column model is incredible…"
- "They're great! I built my own [physical model] (makeshift with a rubber eraser) in order to do a homework."
- "Very helpful, I envision them while doing HWs and tests."
- "Great, really help visualize concepts."
- "More physical models. That slab model is so cool!"

Positive:

- "They were interesting and helped seeing a 3D model rather than the printed examples. This is because it is easier to see and handle, so I know what it looks like in the field."
- "…they help in understanding the concept[s]. Also shows that the professor is well prepared."
- "They are much more fun than anything else. The lectures are very clear. But I imagine that they would be very valuable when someone has trouble with 3D visualization.

Neutral:

- "They help slightly, mostly just to add a 3-D aspect to drawings in notes – otherwise showing the same thing."
- "I'd say they were interesting, but not particularly impactful on my learning. I just learn better working through problems."
- "Yes [they were helpful], but probably not enough to make them worth the cost of constructing them. I'm good at visualizing stuff though."
- "Cool but not necessarily helpful."

Negative:

- "The physical models are not necessary for me personally. I do not think they enhance the learning experience of the class very much."
- "…there are times when the physical models aren't explained well enough to fully visually comprehend."
- "…I wish the explanation of the models were better utilized."

Extremely Negative:

- *No associated responses.* Coding a response as "extremely negative" would require that a student stated they disliked the use of model(s), thought their implementation was a waste of time, and/or that model(s) led to led to increased confusion in learning course material.

Similarly, sample responses from section NP were extracted from student surveys to assign to the same classifications defined above.

Extremely Positive:

- "Excellent, extremely helpful in understanding 3D concepts."
- "Thank[s], models helps a lot esp since most engineers are visual learners."
- "Very useful, and more models please!"

Positive:

- "Interesting and engaging because it helps to visualize in 3D, helps to understand concepts."
- "They are useful for visualization and connecting to reality."
- "They have ranged from interesting, but unnecessary, to very helpful in understanding concepts. It really depends on each model. The most helpful models have been those that illustrate concepts."

Neutral:

- "Good for understanding what the diagrams mean, but not very helpful for assignments, etc."
- "They help somewhat, but I have been in the field, so I can visualize it."
- "We didn't use them much. Had no effect."

Negative:

- "Not many used, but things are explained/drawn well enough I don't feel they're really necessary."
- "Not really [helpful], I did not have a chance to look at them closely."
- "…some features of them seem to be left out (ex. effect of rebar size on model)"
- "Meh. Not that great."

Extremely Negative:

- *No responses.* See commentary from section "MN" related to this category of responses.

It is important to note that frequency of model use in class was a concern expressed by a number of students, stating: (i) a desire for more models, (ii) indication that models were rarely used, or (iii) that there are not many models. In section "MN" this made up 4% of respondents and 40% of respondents in section "NP". Some sample comments:

- "[The instructor] didn't really have visual models. [The other one] did and that helped a lot."
- "[The instructor] has barely used them so we haven't had much exposure to them."
- "We don't have many in this section."
- "[The instructor] doesn't really use them."

2. Quantitative Summary of Student Open-Ended Responses

The surveys yielded 135 individual open-ended responses related to physical models or demonstrations. To get an aggregate sense of the students' perception of the models, a five-point classification scale from extremely positive to extremely negative was established based on the previously provided sample quotes. The results of this classification approach are included in Figure 13.

Any student that ***only*** indicated that the models were used infrequently and had no other comments on the efficacy of the models is not included in the classification included in Figure 13. These plots are intended to provide a metric for the quality (not frequency) of the models and their implementation.

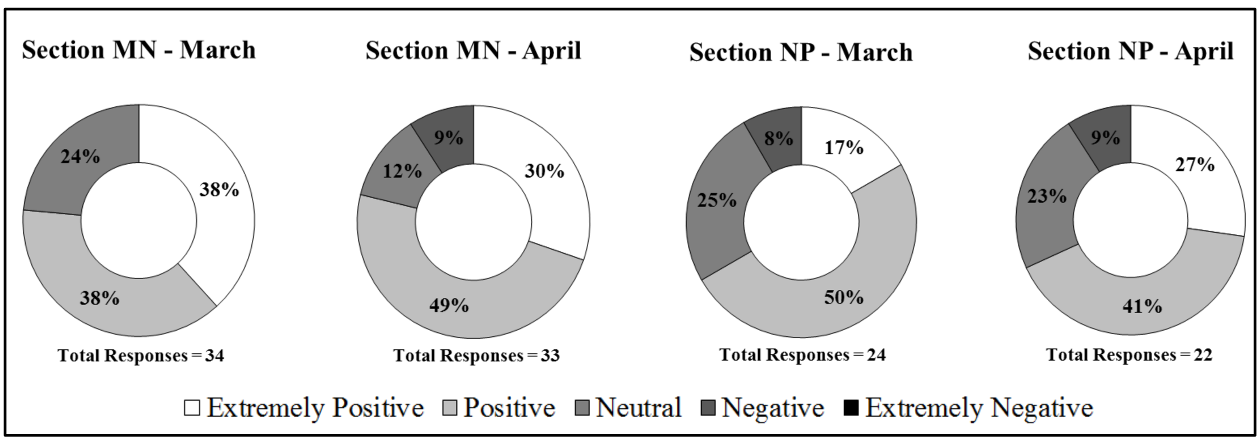


Figure 13. Classification of Free Response Answers related to Physical Model Efficacy

Examining the free-response feedback from students presented in Figure 13, it is important to recognize that physical models will not be universally appreciated by all students (extremely positive/positive comments constituted 67-79% of survey responses while neutral/negative responses were 21-33%). The positive responses where students indicated the models helped them visualize and understand concepts are probably individuals that tend toward sensory/visual/active learning styles. On the other hand, neutral or negative responses from students indicating the models were unnecessary and class notes or textbook figures were sufficient are probably individuals that tend toward intuitive/auditory/reflective learning styles. As Felder and Silverman[1] indicated there is range of learning styles among engineering students. Therefore, it is necessary for educators to employ multiple teaching techniques to reach all the students, and physical models should be seen as only one implement in their teaching toolbox.

Conclusions

Some conclusions – based on a semester of implementing these prototype physical models in two reinforced concrete course sections, soliciting student feedback via surveys and informal discussions, as well as reflection amongst the instruction team – are:

- ***Students are excited by unique models and stay engaged with those that are technically relevant to their learning***. The one-way slab model garnered initial interest because of its miniscule size and accuracy in visualizing a reinforced concrete building. Later students came back to inspect it with greater attention to understand how the structural elements and reinforcement arrangements came together in their final design project.

- ***Students enjoy tangible experiences with models because it adds variety to lecture and helps them more easily remember concepts.*** Many students indicated, after taking a course exam, they thought back to the one- and two-way slabs that were passed around the class to successfully answer a question on slab behavior and aspect ratio. These tangible experiences are only possible if students are allowed to interact directly with the models, not just watch the instructors.
- ***Some students indicated that they feel instructors seem more invested in teaching a course when they put forth effort to make (or use) detailed and explanatory physical models***. Therefore, implementing physical models may be effective for rapport building and classroom engagement.

- ***Students represent diverse learning styles and while sensory/visual/active learners often recognize the benefits of physical models, intuitive/auditory/ reflective learners may feel that they are unnecessary.*** Instructors should be aware of this diversity and insure that they include a range of teaching techniques to address all students' needs. At the same time, they should recognize that physical models can be one of the most effective tools for those in the sensory/visual/active learner group who make up a large portion of engineering students.
- ***Instructors need to find ways to make small, detailed models accessible to all students.*** Small-scale models are preferable in regards to construction cost, storage, and ease of transportation. However, large classrooms make it difficult for students to appreciate the intricacies of small-scale models, and instructors cannot expect that office hours will provide the primary means of exposing students to models. Use of video-projection tools to zoom into certain features could be helpful when explaining concepts related to the models.
- ***Instructors sharing models need to come up with a coordination plan that ensures all students have the same in-class/office hour access to them.*** Models can only be effective if they make it into the classroom, as evidenced by comments of many students in this study.

- ***When designing a new physical model one must prepare a detailed guide for oneself and peer instructors implementing it in class.*** This document (or video) should provide an explicit description of target concepts the model is intended to address, how it can be integrated into existing lecture material, and the type of informal questions that will encourage student observations/learning. This will allow consistency between different educators teaching a single course and to leverage a model to its full potential.
- ***To further improve teaching effectiveness of a physical model one should develop formal guided questions or activities that students can complete in teams.*** This would motivate students to engage with and examine the model more fully, which in turn would likely lead to greater learning gains in the topic areas the particular model is trying to address. It is also an approach to make small, detailed models accessible to all students (see earlier point).
- ***There are many more challenging topics in introductory reinforced concrete design that still need to be addressed using classroom table-top models***. Semi-structured interviews with previous *RC1* students revealed that some unaddressed topics are challenging include: rebar development length and cutoffs, shear behavior, stiffness reduction due to cracking and effects on member performance, and flexure-axial interaction of columns. The work presented in this paper, and the provided references, should be treated simply as a starting point for future work.

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