**Physical Models in the Reinforced Concrete Design Classroom**

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3-D visualization tools can enhance students' understanding of design issues

Though it has been 6 years since my undergraduate reinforced concrete design course, I still vividly recall the first day. Our instructor brought in two polystyrene beams, each about 1.5 ft (0.46 m) in length: one with duct tape running along the bottom face and the other without. He explained to us that the first beam was "reinforced concrete" and the other was "plain concrete." Without any warning, he bent the "plain concrete" beam and it failed suddenly with a jarring snap. He then challenged us to do the same to the "reinforced concrete" beam. Even the strongest students in the class failed to cause more than a modest amount of deformation. Ultimately we surrendered, and feeling defeated, we passed the intact beam back to the instructor. Immediately, he flipped the beam over so the taped face was on top, bent it slightly, and it snapped just as dramatically as the first beam. Since that day, I have never forgotten that reinforcement must be placed in the tension region of a beam to achieve a ductile response; otherwise one may as well design using plain concrete because the failure would be just as brittle.

My objective with this anecdote is to highlight that integrating even simple physical models and interactive activities can play a significant role in clarifying and engraining fundamental concepts. During multiple semesters of my graduate studies, I have served as a teaching assistant for an introductory reinforced concrete design course. This has allowed me to engage personally with students to identify topics in the curriculum that they find challenging and to investigate the particular aspects that cause confusion. In the Spring 2015 semester, as a primary instructor for this course, I began developing and implementing topic-specific physical models. My goal was to attempt to address those areas of struggle. But more than that, I hoped to create new and stimulating learning experiences that would leave a lasting imprint, like the one that remains in my memory from 6 years ago.

The following is an overview of the various physical demonstration tools intended to supplement lectures in topic areas that students consistently identify as being troublesome. The design, fabrication, and implementation of the classroom models was part of a larger research study, "Use of Physical Models in an Introductory Reinforced Concrete Design Course," through which I was able to survey and interview students on their perceptions of the physical models that they had been exposed to in the course.

Flexural Analysis of Rectangular Beams

Every semester when we teach students about flexural analysis of beams, we focus on the critical points of the moment-curvature plot-cracking, yielding, and nominal moment capacity. Moving along this curve we typically observe that the stress in the concrete is linear under low moments, and then becomes parabolic as the moment increases. In learning this, the predominant question from the students was: "What are the formulas we have to memorize to calculate the force due to concrete in compression?" I have always been an opponent of rote memorization, and so I explain to the students that the force is the volume of the three-dimensional (3-D) concrete stress block. However, it is difficult for some students to visualize 3-D stress blocks based on the two-dimensional (2-D) strain-stress-force diagrams shown in the typical lecture (Fig. 1).

To clarify the concepts, I have created a set of physical models for various stress conditions in rectangular beams (Fig. 2). The models display flexural stresses when:

* Concrete compressive stress is less than 0.5 to 0.6 fc ? and is

* Concrete compressive stress is greater than 0.6 fc ? and is

* The equivalent rectangular (Whitney) stress block, as

These models can be used in explanations of force equilibrium and calculation of the depth of the compression stress for a particular stress condition on the beam. In this process, the volume of the compressive stress in the concrete (blue) is set equal to the volume of the tensile stress in the steel reinforcement (red). The model also helps students visualize how to calculate the moment arm between the concrete compression and steel tensile forces. Being able to see the geometry of the concrete compressive stress block helps in calculating the centroid of this volume, where the force would act.

These models are fabricated from 3 x 4 x 8 in. (76 x 102 x 203 mm) polystyrene blocks (sold at most craft stores for making floral arrangements) and 3/8 in. (10 mm) diameter wooden dowels. In addition to using paint to differentiate compressive versus tensile forces, the models can be labeled with relevant variables so students can connect various aspects of the physical models to the strain-stress-force diagrams they draw as part of the flexural analysis procedure. The success of these models has been clear, as the students' questions no longer focus on "formulas" but instead are directed toward the variations in the geometries of the stress blocks.

Flexural Analysis (Nominal Moment) of Flanged Beams

After covering flexural analysis of rectangular beam sections, we continue on to calculating the nominal moment capacity of flanged beams (T-beams). This type of structural member is prevalent in slab systems where the slab functions as the beam flange and the portion of the beam extending below the slab forms the web. The challenge for many students in determining the positive flexural capacity of the section is recognizing that the concrete compression force varies if the compression zone lies only in the flange or also extends into the web. Furthermore, they must recognize that when evaluating negative flexural capacity, the compression zone is solely in the web (Fig. 3). With this, I have observed students trying to memorize each case and the associated formulas for the concrete compression force. This learning approach is dangerous because if students are faced with a flanged beam other than a T-beam, their memorized formulas do not apply and they may not have the conceptual understanding to analyze these members.

By seeing the shape of a 3-D equivalent rectangular (Whitney) stress block for different depths of compression in a flanged section, students gain the conceptual understanding needed to determine the concrete compressive force necessary in their flexural capacity calculations (Fig. 4). This is especially important in the case of positive flexure where the concrete compression depth extends into the web-the 3-D stress block needs to be divided into various parts to evaluate the force in the concrete.

During the course, homework and exams provided opportunities to evaluate students' understanding of flexural analysis of flanged beams (such as bulb-tee or hollow-core square sections). Students were able to successfully recognize that they must apply their conceptual understanding of stress blocks to develop expressions for concrete compression force, rather than resorting to memorized formulas for T-beams.

One-Way Slab Model

In learning about one-way slabs, students generally accept the fact that bending primary occurs in the direction parallel to the short side of a bay (when the slab has an aspect ratio greater than or equal to 2:1). This is well illustrated by a physical model developed by Jones2 that consists of a foam slab stretched over a wooden frame. However, there are some aspects of one-way slabs that students remain uncertain about that could be clarified with slight modifications to this existing model.

The first point of confusion is related to the strip method, where students design a slab for flexure as if it were a 12 in. (305 mm) wide beam. Although most students will correctly calculate an area of steel per foot (in.2/ft) based on the flexural demands, it is common for students to incorrectly select a bar size and spacing based on satisfying horizontal cover requirements for the 12 in. (305 mm) wide section. In other words, many students treat the strip as an isolated beam section rather than as a design unit that will be spread uniformly across the entire one-way slab.

Another issue is that students will place their flexural reinforcement perpendicular to the primary direction of bending. Shrinkage/temperature reinforcement is therefore placed parallel to the primary direction of bending, providing insufficient flexural capacity. This can be resolved by clearly highlighting the 1 ft (0.30 m) wide design strip in respect to the entire slab (Fig. 5(a)).

With the one-way slab model, it also is important to provide students with a sample two-way slab model, so they can observe what it means to have significant bending in both directions and to distinguish the variance in slab aspect ratio that results in this behavior (Fig. 5(b)). This semester, I passed both one- and two-way slab models around the classroom so that each student could load the two slabs and observe the difference in deformation. Students commented that this helped them understand and remember the behavior between the slab types.

Flexure and Shear Design of Beams

In teaching flexure and shear design, I have noticed that students are able to rather easily pick up the calculation procedure to determine the amount of reinforcement to meet the respective demands for a given beam. However, those without on-site construction experience have a cloudy understanding of what their resulting beam design looks like in 3-D. In the past, I have tried to overcome this by providing students with transparent renderings of beams, but it is often difficult for them to visually interpret a 2-D image of a 3-D object when they have never seen the original reference object.

To address this concern, I designed a half-scale beam model from transparent acrylic that has two "legs" in the shape of the beam cross section (it can be rectangular, flanged, and so on based on the instructional needs). The "legs" have shallow shelves where flexural reinforcement-wooden dowels of different diameters-can rest. The shelves are positioned to provide sufficient vertical and horizontal cover to the bars. The two-legged stirrups are formed from mild steel threaded rod and they can be spaced along the flexural reinforcement as desired.

This model allows for various arrangements of flexural and shear reinforcement. Moreover, instructors or students can write directly on the model with dry-erase markers to label relevant variables, cross-hatch the concrete compression zone, and draw cracking diagrams, among other possibilities (Fig. 6). The reinforcement configurations shown in the figure exhibit large negative flexural capacities. This can be easily modified to suit the particular design problem the students are considering. Reflecting on the beam model, one of the students commented on their improved understanding of beam design: "[it] helped seeing a 3-D 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."

One-Way Slab System Model

The semester builds up to a final team project that involves designing a multi-bay, two-story building that uses a one-way slab system. The project, as a multi-bay system with varying bay spans and loads, requires students to not only consider load path but also the physical interaction between all of the structural elements. To design this system effectively, they must be able to clearly visualize how everything comes together-not an insignificant task if you have previously only been exposed to 2-D drawings of individual members. Also, while students have already become confident in each of the individual topic areas of reinforced concrete material behavior, flexural and shear design of beams and slabs, and axial load-flexure design of columns, the problems they have faced before in homework and exams involved isolated components. The design process for this project requires that they are able to assemble all the knowledge they have gained.

To help students understand the interaction between the various structural components in a one-way slab system, particularly reinforcements and their relative placements in this structure, a transparent model (nominally 28 x 28 x 12 in. [711 x 711 x 305 mm]) was constructed as shown in Fig. 7.

The model was fabricated by the University of Illinois Civil and Environmental Engineering Machine Shop to achieve the highest level of realism possible so that students would have a physical reference for everything they had learned during the course. The students are able to examine the flexural (copper) and shrinkage/temperature steel (blue) in the slab (Fig. 8(a)), flexural (black) and shear (red) reinforcement in the interior and edge beams (Fig. 8(b)), and vertical (gray) and tie (green) reinforcement in the columns (Fig. 8(c)). Perhaps the best way to describe the model is as if a real one-way reinforced concrete slab system-complete with steel reinforcing bar ties and bar chairs-was shrunk to Lilliputian dimensions (Fig. 8).

As with the transparent beam model, the one-way slab model can be marked so that students can, for example:

* Use arrows to illustrate load paths and flow of forces;

* Cross-hatch tributary areas for different elements;

* Note relevant variable names;

* Outline the L- versus T-shapes of edge and interior beam

* Indicate where tension or compression forces occur in the

Furthermore, the model can be used to facilitate discussions about economizing in design, such as using bar cutoffs for flexural steel or varying stirrup spacing in beams.

Beyond the instructional value of this tool, there is a level of excitement that students exhibit upon seeing and interacting with a model unlike anything that they had seen in any other class. One student indicated in their post-semester survey: "The major strengths [in the course] are the visuals. The detail in the mini slab/column model is incredible..." Another wrote in response to improvements suggested for the course: "More physical models. The slab model is so cool!" It is the hope that this technically accurate and intriguing physical model will leave a lasting imprint on the students, and help them retain some part of what they learned in the course as practicing engineers.

Summary

Perhaps the best summary I can provide is a quote from a student interview-a call to action for reinforced concrete design instructors on the use of physical models in the classroom: "Stay on it with the physical demos...because a lot of people don't have visualization skills that they need. And that's how you develop them, by seeing things work and then by developing that kind of spatial intelligence. Anything that you can do to help improve that would be great because that's way underrated in terms of things that you use when you're designing; your being able to visualize things."

I hope this discussion of physical models is useful for other educators teaching introductory reinforced concrete design courses, and I look forward to hearing about topic areas that other instructors have found challenging for their students, so we can discuss how those difficulties might be addressed via physical models. Individuals who are interested in the fabrication details or lecture materials related to any of the teaching tools described in this article can contact me at behrouz2@illinois.edu.

A final comment-as an undergraduate student, I appreciated my reinforced concrete instructor for not only helping us develop a physical appreciation for concrete behavior but also for generating an enthusiasm that made us want to come to class each day and see what he was going to share with us. Looking back on how we were duped with the "reinforced" concrete beam on the first day, it amuses me to imagine what would have happened had I known then what I know now. I may not have been the strongest person in the class, but I certainly would have been able to snap that beam with ease!

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