Structural Engineering Workshop: A Curriculum of Real and Virtual Experiments

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Abstract

Most design procedures for structural components and systems are based on specific behaviors prior to or including an ultimate failure mechanism. One of the critical steps in structural engineering education is to help students understand these behaviors. While some of the behaviors are rather obvious and can easily be described, many are not. To help undergraduates understand the causes and implications of these behaviors, the Structural Engineering Workshop will incorporate laboratory experiments with full-scale structural components into what are traditionally lecture-only upper division courses. Web-based multimedia material will help students place each experiment into context within the course and within the field of study. The Structural Engineering Workshop will also create a new level of continuity within our architectural engineering program, as content will be directed at students in all years of study in graphics, mechanics, analysis, management, and design courses. In addition, students in sophomore construction materials labs and construction methods labs will participate in the fabrication of test specimens.

I. Introduction

The best structural engineers are those that can combine an effective intuitive understanding of structural performance with a strong technical knowledge base. Educators should take advantage of students' intuitive understanding of certain structural principles in the students' first mechanics courses, the sophomore sequence of statics and strength of materials. Students come to these courses having already mastered the *concept* of equilibrium (…the *concept* of equilibrium, not the *application* of equilibrium…) through trial and error construction of block towers. They know Poisson's ratio from Silly Putty. They have known all about basic structural failure theories since Goldilocks overloaded Baby Bear's chair and the big bad wolf created design-level wind events. Unfortunately, it is harder to come up with good analogies in upper division courses. There aren't many fairy tales that include the brittle failure of an over-reinforced concrete beam or plastic redistribution of moments in a continuous structure.

There seems to be a common thought among more experienced engineers that today's college graduates are lacking in intuition. Ferguson[1] presents the observation that engineering programs' emphasis has changed during the past half-century, moving away from drawing studios, labs, shops, and plant visits, and focusing instead on lectures and abstract analysis. The shift has been from active exploring and discovery to passive learning from book and lecture. As a result, students today have "no reason to believe that curiosity about the physical meaning of the subjects they [are] studying [is] necessary." He makes the case, as do Petroski[2] and Backman[3], that some recent high profile engineering failures—as well as innumerable examples of poor design that do not result in catastrophe—are the result of engineers trying to apply theory they don't understand, rather than following an intuitive sense of how structures behave. Parmelee[4] expresses a position that many of his contemporaries seem also to hold – that reliance on a slide rule for calculations during their education and for much of their careers somehow put today's senior generation more "in touch" with their engineering work. He states that "the structural engineer was in complete control of the computations," that "the exercise of 'engineering judgement' was possible at every step," and that the current *modus operandi* is dangerously different.

Note that the views of Ferguson—that what's missing today are physical labs and manual drafting—and Parmelee—that what's missing today are slide rules—both focus on what *used to* work instead of on what might work *today*. These authors therefore offer limited help in solving the problem. We propose that what's actually missing today is effective thinking on how to engage young people to help them learn. This thinking should recognize the role of the computer in our students' backgrounds and in our graduates' jobs, and it should also recognize the power of observation and experimentation in a laboratory. The Structural Engineering Workshop is our attempt to revitalize Ferguson's "curiosity," so students expect that if they look hard enough, they will find a physical (loud, dangerous, surprising) event hidden somewhere in the code's procedure for determining structural capacity.

The objective of the Structural Engineering Workshop is to help students develop their intuitive sense of structural behavior by helping them understand the links between structural behavior, analysis, and design. This will be done with a series of laboratory experiments that are incorporated into upper division structural design courses. The Structural Engineering Workshop will greatly enhance the power of each experiment, however, by providing a rich context for it through a web-based module that will allow students to explore the links between the observed behaviors, basic structural concepts, and structural design procedures. The Structural Engineering Workshop will enhance continuity in our program by including content directed at students in all years of study in graphics, mechanics, analysis, management, and design courses. This will help students understand the relationships between each of their separate courses. This paper describes our plans to implement the Structural Engineering Workshop.

II. Literature Review: Structural Engineering Labs in Undergraduate Education

A review of the literature showed that there have been several significant projects that bring structural experiments into the classroom. None that we are aware of, however, attempts to expand this idea across the curriculum; they are all directed at individual courses. The majority focus on structural design in a generic sense or on structural analysis, whereas the Structural Engineering Workshop focuses on the behavior of real structural components to failure. The "Integrated Teaching and Learning Laboratory" at University of Colorado[5] upends the idea of bringing physical models into the classroom. The building itself is instrumented, so students could conceivably experiment with occupant-induced loadings or see interesting data when the wind off the Front Range is unusually strong. The developers of the lab presumably do not anticipate testing their specimen to failure, however.

Behr, Belarbi, and their colleauges[6,7] describe a structural analysis laboratory that combines physical experiment, computer analysis, and classical methods. They created a format in which teams of students compare analysis results and test results, and then consider the limitations of each phase of the work. The assessment described by Belarbi et al.[7] is much more statistically rigorous than most assessments of educational projects. They show that students using the innovative laboratory maintained comparable performance on traditional tests, and improved performance on non-traditional evaluations requiring synthesis of material from pre-requisite and co-requisite courses. This is a subtle but significant accomplishment – the goal is to have students understand the relations between material in different courses, and to have them synthesize material from a series of courses into a coherent body of knowledge. The work by Behr, Belarbi, and their colleagues indicates that a curriculum with meaningful links between analysis and physical experiments can help reach this goal.

Schmucker[8] is another of those concerned that as curricula become increasingly focused on computerized analysis and design, students will lose what little concept of basic "structural reality" they presently have. The author describes the incorporation of physical experimentation into structural analysis courses, and an enthusiastic student response to the small models used to illustrate moment resisting frames, suspension bridges, and other structures. In addition, Schmucker had the students design, construct, and test small bridges made of pasta and glue. Certain lessons about mechanics and analysis are clearly conveyed by working with these materials, so the project is an appropriate enhancement to the (typically junior-year) analysis course. There is not, however, a good link to the complex material idealizations so critical to the design courses which follow.

Wadia-Fascetti and Tarnowski[9] present another approach to incorporating a lab component into a structural analysis course. The experiments they describe address the concepts covered in the typical junior or senior level structural analysis course, with specialized setups to illustrate such topics as determinate truss analysis, influence lines, etc. Their use of several independent "media" in each lab component is quite interesting. For example, their flexibility method experiment includes a lab setup with dial-gauged beams, traditional hand calculations, and computer analysis with standard commercial software. The most valuable piece of information from this paper is their approach to student reports. The authors ask students for high quality reports that synthesize the data, and they comment that workshops are planned so a faculty member from the technical writing area can help the students improve their writing skills.

Pessiki et al.[10] describe a NSF supported Undergraduate Structural Engineering Laboratory at Lehigh University. Small-scale (bench-top) tests include flexural strength of concrete beams, plastic bending of steel beams, and several non-destructive tests. The authors describe a significant component of course content focusing on the transducers and test setups. In this regard their lab seems to be directed largely toward graduate-level structural research work.

III. Experiments with Full-Scale Structural Components

At MSOE we have developed the capability to conduct tests on full-scale structural components in our Construction Science and Engineering Center Laboratory. The lab includes the sort of equipment in most construction materials laboratories—equipment for mixing and testing concrete, etc. The lab also houses our Construction Methods course, in which sophomore students work in small teams to construct structural assemblies such as a masonry wall, a wood stud wall, a half-scale structural steel frame, and formwork for reinforced concrete. The room has approximately 200 m^2 of floor space (17.5 m by 11.5 m) with a clear height of 11.5 m. There is a large overhead door for truck access and an overhead crane.

The test frame for full-scale structural testing was acquired with a combination of university funding, donations from regional industry, and a 1998 Instrumentation and Laboratory Improvement (ILI) grant from the NSF Division of Undergraduate Education. The test frame in its two main orientations is illustrated in Fig. 1. The frame provides all reactions for the loadings, so it loads the floor only with its own weight and the weight of the specimen. Heavy W18 beam sections and moment-resisting connections minimize the frame's flexibility. The frame was designed by the senior author.

The base of the frame consists of a pair of parallel bottom-beams approximately 1.5 m apart and approximately 9 m long with cross-beams spanning between them every 1 m. The columns are placed 2 m from each end, and each is diagonally braced back to the adjacent bottom-beam end. The only adjustment to be made to this part of the frame—the base and columns—is to move the diagonal braces to the inboard side of the columns or to remove them entirely if they are in the way of a test configuration. Bearing pads located under the bottom-beams below the columns allow the frame to be leveled and fastened to the floor at discrete points. The tops of columns are

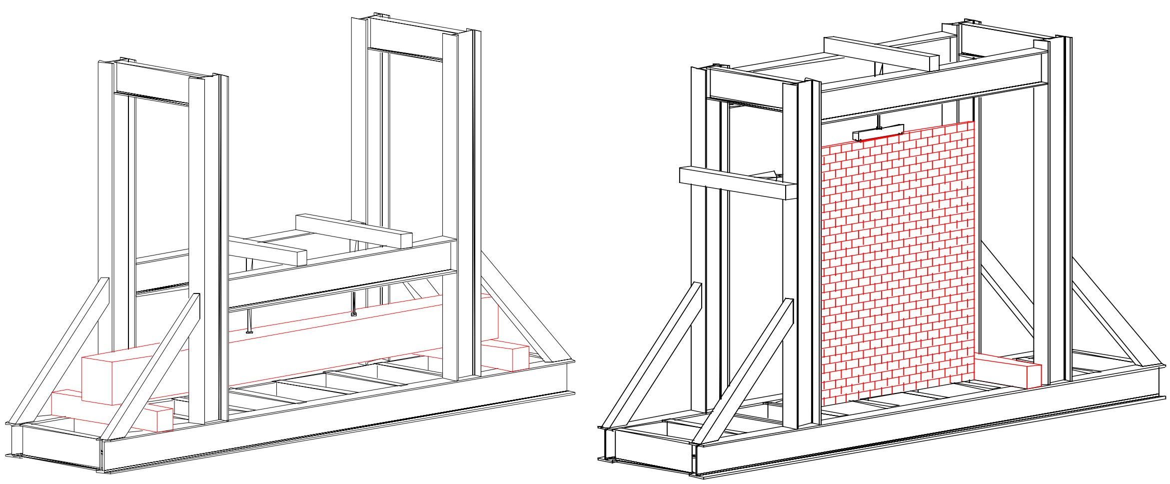

Fig. 1. Load frame with 3.5m square shear wall panel and with 7m simply-supported beam.

joined in the 1.5 m direction by cross-beams welded rigidly into place. The top-beams span approximately 5 m between columns and can be moved up or down and bolted into place—the columns have closely spaced holes to permit almost continuous adjustment. The actuators are mounted on short beams that span between the top-beams (for vertical loads) or between columns (for lateral loads). The specimens can be mounted onto the bottom-beams or cross-beams of the base, all of which have holes at regular spacings. An overhead crane is used to move adjustable pieces and specimens. A crew of two ironworkers can move the pair of top beams in about 45 minutes; a crew of two assistant professors needs a little more time.

The hydraulic loading system from MTS Systems Corp. consists of actuators, hydraulic power source and distribution components, and computerized control system. The actuators have capacities of 160 kN compression and 98 kN tension, with built-in load cells and stroke of 250 mm. They can provide static or low frequency dynamic loadings. The hydraulic power source has been sized for two additional actuators in the future. Control of the hydraulics is provided through MTS TestStar II system and a dedicated computer. This allows us to control the actuators independently by specifying load rate, actuator displacement rate, or an independent strain rate. The system can also act as data acquisition center for strain gauges, extensometers, LVDTs, etc. (it has eight uncommitted analog input channels). Related equipment for the tests includes load cells and LVDTs along with signal conditioners for each, bearings for beams, and fixtures for holding and loading wood and masonry shear walls.

As we now have the equipment in place, we have turned our attention to the strategic issues of obtaining test specimens—and disposing of debris. We will fabricate many of the test specimens as class projects in the sophomore Construction Methods course, and obtain some (precast concrete planks, glue-laminated wood beams and metal-plate-connected wood trusses) through purchase or donation from local fabricators.

IV. Structural Engineering Workshop: An Electronic Book

The Structural Engineering Workshop is a web-based electronic book consisting of a series of modules, each of which focuses on a single structural component, connection, or system. The modules will include extensive background information to help put the behavior into context, and culminate in a multimedia record of one or more full-scale experiments. The electronic format allows a user to search the module for items related to “CAD,” “construction,” or other key words. Specific modules may be developed to describe these behaviors:

- Steel beam: local buckling, plastic hinge, and lateral-torsional buckling.
- Steel connections: simple versus moment connections
- Steel framing system: moment resisting frame vs. braced frame
- Concrete beam flexure: cracking moment, under-reinforced and over-reinforced flexural failures
- Concrete beam shear: effect of shear reinforcement
- Prestressed concrete beam: flexural cracking, flexural failure
- Glulam beam: initial compression failure and ultimate tensile failure
- Wood framed shear wall: panel failure, anchorage failure, diaphragm nail failure
- Masonry shear wall: shear and tensile failures in reinforced and unreinforced walls.

An example module follows this general description of each module’s of four parts:

1. A structural component in context
The goal of this part of the module is to help the user understand the relationships between the component and the structure of which it is a part—to **put the structural component into context**. Information describes what the component physically is, how it is used, and what variations are common.

2. Interactive design calculations
The goal is to fully explore the **idealizations** that are used in analysis and design of the component and the structure of which it is part. Multiple methods of analysis and design (LRFD, ASD, etc.) will be presented when appropriate. The effect of specific assumptions on the results of structural analysis will be illustrated by including multiple analyses.

3. Multimedia record of full-scale experiment
The goal of this section is to present **real physical behavior** of the component. As experiments are repeated over the years a database of results will allow students to explore the ideas of variability and reliability in structures.

4. Summary—with links to the next step
The goal of this section is to present a full discussion of the experimental results, **evaluating observed behaviors of part 3 with regard to the design idealizations of part 2 and the applications of part 1**. Plots derived from the experimental data will be explained. When more than one specimen was used, the significance of differences or random variability will be discussed. Results will be used to evaluate the analysis (for example: "Do measured reactions or displacements match those from analysis? Why/why not?"), the experimental setup (for example: "If we had strain-gauged the rebar…"), and placement of the component in a system (for example: "If the beam were part of a continuous structure how would the behavior change?").

Figure 2. Structural Engineering Workshop—Example Module.

Flexural Behavior of Reinforced Concrete Beams

OVERVIEW
This module illustrates the traditional concept of under- versus over-reinforced concrete beams, and the newer concept of relating the strength reduction factor to the anticipated failure mode—the so-called unified design procedure of Appendix B to the ACI concrete code[11]. In a nutshell, the idea is that a reinforced concrete beam fails in a brittle manner if the compressive strain in the concrete reaches its crushing limit before the tensile strain in the reinforcing steel reaches its yield limit. The design characteristic that controls this, given a set of material properties, is the ratio of steel area to concrete area. The distinction between brittle and ductile failure is critically important: the design code's traditional approach was to prohibit brittle failure modes, and the newer approach is to penalize brittle failure modes with more severe strength reduction factors.

1. A STRUCTURAL COMPONENT IN CONTEXT
This information is intended to be review for upper division students conducting the experiment, and also to be primary information lower division students in the courses noted in parentheses.

STRUCTURAL SYSTEMS
One way systems – beam and slab, joist system with wide beams.
Two way systems – beam and slab, simple span vs. continuous
(Used by students in AE-100 Introduction to Architectural Engineering and Construction Management; AE-308 Basic Concrete Design)

LAYOUT INFORMATION
Locations and applications of flexural members in structures including both floor and wall systems. Will include text, photos, schematic drawings and graphic standards of plans and sections showing dimensions, cover and location of reinforcement, etc.
(AE-100; AE-342 Architectural History; AE-103 Introduction to CAD; AE-130 Architectural Engineering Graphics; AE-308)

Figure 2. Structural Engineering Workshop—Example Module (cont'd.).

CONSTUCTION SYSTEMS AND METHODS

Formwork, reinforcement and concrete placement, concrete curing; shored and unshored construction, photos and videos of construction

(AE-100; AE-123 Building Construction Materials and Methods I; AE 220 Building and Construction Materials and Methods II; CM-310 Construction Issues)

MATERIALS

Conventional steel reinforcement; High strength carbon fiber reinforcement; and other new reinforcement materials. Conventional concrete, lightweight concrete, and high strength concrete.

(AE-123; AE-220; AE-222 Construction Materials Laboratory)

2. INTERACTIVE DESIGN CALCULATIONS

This information is intended to be part review and part new for the students conducting the experiment and primary information for students in lower division courses indicated in parentheses.

DESIGN BASIS

Sketch of column and layout for floor. Design criteria: loads, material properties, etc. Guide for economical span lengths.

(AE-100; AE-308)

MECHANICS

Shear and moment diagrams for generic beam; calculation of deflections.

Stress-strain behavior of flexural members of different materials, composite members.

(AE-200 Statics; AE-201 Strength of Materials; AE-309 Strength of Materials Laboratory; AE-308)

PRELIMINARY DESIGN CALCULATIONS

Calculating tributary width, loading on beam, load factors. Estimating beam size and weight. Structural idealizations and analysis such as simple supported beams, continuous beam on pin supports, continuous beam with columns above and below, effects of pattern loading, and ACI moment coefficients. Comparison of results from different analyses, including approximate analysis methods.

(AE-100; AE-200; AE-201; AE-309; AE-308; AE-305 Structural Analysis I; AE-306 Structural Analysis II)

MATERIAL-SPECIFIC CALCULATIONS

Required reinforcement for moment capacity. ACI approach to ρmin. ACI traditional approach to ρmax. ACI "unified design provisions" of Appendix B. Prediction of load-deflection behavior.

(AE 308; AE-401 Advanced Concrete Design)

3. MULTIMEDIA RECORD OF FULL-SCALE EXPERIMENT

A total of at least three tests will be described in this module. The specimens will have reinforcement below the ACI minimum, within accepted range, and above the ACI maximum.

OVERALL TEST SETUP

Sketches and photos of specimen and frame

Loads at 1/3 points create constant moment region

TEST SPECIMEN

CAD drawings and project specification, rebar shop drawings, concrete mix design, formwork fabrication. Also, photos of fabrication of 20 ft. span beam, 8 in. x 12 in. cross section, by students in AE220 Construction Materials and Methods course.

Calculations and narrative re: predicted capacity and failure mode.

TEST SETUP DETAILS

Load and support points (CAD, photos)

Actuators, load cells, LVDTs (photos, sketches, text, links to manufacturers' sites)

Data acquisition system.

Planned load history and corresponding moment diagrams (text and graph)

TEST

Full load-displacement data from data acquisition system (raw spreadsheet data)

Still images and clips from high speed video showing progression of cracks.

Figure 2. Structural Engineering Workshop—Example Module (cont'd.).

4. SUMMARY AND POST-EXPERIMENT
This information will be used to reinforce the observations to extend the experiment into other upper division courses indicated in parentheses.
DATA ANALYSIS
Annotated load-displacement plots. Comparison of measured and predicted moment-curvature plots. Extrapolated stiffness (E times I) versus stiffness from standard idealizations. Comparison with idealized cracking moment, ACI nominal strength.
CONCLUSIONS
Assessment of the ACI limitations on reinforcement ratio: Was the behavior of the specimen with an "acceptable" amount of reinforcement significantly different? How does the variable resistance factor ϕ of the "unified design provisions" address the different behaviors? If the specimen were placed in a continuous structure how would the behavior change? If the loading were altered how would the behavior change?
(AE-401; AE-301 Basic Steel Design; AE-304 Advanced Steel Design; AE-407 Wood and Masonry Design; AE-306)
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VI. Conclusion

The Structural Engineering Workshop is a work in progress. It is also an ambitious project, aimed at having a significant impact on the entire structural engineering program within MSOE's Architectural Engineering and Building Construction Department. The university recognizes the benefits the physical laboratory presents for educating (and recruiting) students, and it is committed to continued development of the laboratory as a part of our curriculum. The NSF grant which enabled acquisition of the test frame was obviously a pivotal step in development of this lab. The Structural Engineering Workshop's multimedia modules would be an elegant way to incorporate the full-scale testing into the curriculum—by providing a framework to help students place the experiments into context, including a sufficiently broad basis that students from throughout the course of study could use it. Without an infusion of funding to support the development of the modules, however, it is unlikely that they will reach their full potential. The authors plan to seek additional support from NSF's Division of Undergraduate Education, and are interested in discussing the potential for collaboration with educators at other institutions. The Structural Engineering Workshop could become a means for students at several institutions to obtain a mix of real and virtual lab experiences illustrating in a wide range of structural behaviors and concepts.

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