2021 ASEE ANNUAL CONFERENCE
Virtual Meeting | July 26–29, 2021 | Pacific Daylight Time
Paper ID #32757

Design and Implementation of Experiential Learning Modules for Reinforced Concrete

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Design and Implementation of Experiential Learning Modules for Reinforced Concrete Design

Abstract

Most undergraduate civil engineering programs include an introductory course in reinforced concrete design. The course generally includes an introduction to the fundamentals of reinforced concrete behavior, the design of simple beams and one-way slabs to resist shear and flexure, and the design of short columns. Because of the scale of typical civil engineering structures, students commonly do not get to experience large or full-scale structural behavior as a part of an undergraduate reinforced concrete course. Rather, students typically learn fundamental concepts through theoretical discussions, small demonstrations, or pictures and images. Without the interaction with full-scale structural members, students can struggle to develop a clear understanding of the fundamental behavior of these systems such as the differences in behavior of an over or under-reinforced beam. Additionally, students do not build an appreciation for the variations between as-built versus theoretical designs. Large-scale models can illustrate such behavior and enhance student understanding, but most civil engineering programs lack the physical equipment to perform testing at this scale. The authors from St. Louis University (SLU) and Rose-Hulman Institute of Technology (RHIT) have designed and implemented large-scale tests for in-class use that allow students to experience fundamental reinforced concrete behavior. Students design and test several reinforced concrete members using a modular strong-block testing system.

This paper provides a detailed overview of the design, fabrication, and implementation of three large-scale experiential learning modules for an undergraduate reinforced concrete design course. The first module focuses on service load and deflections of a reinforced concrete beam. The first and second modules also focus on flexural failure modes and ductility. The third module focuses on shear design and failure modes. Each module uses a large scale reinforced concrete beam (Flexure specimens: 12 in. x 14 in. x 19 ft, Shear specimens: 12 in. x 14 in. x 10 ft.) that was tested on a modular strong-block testing system. The three modules were used throughout the reinforced concrete design course at SLU and RHIT to illustrate behavior concurrent to the presentation of various reinforced concrete design concepts.

Introduction

Reinforced Concrete Design is often the first technical design course that civil engineering students experience as a part of their curriculum, specifically students pursuing the structural engineering subdiscipline. An introductory course in reinforced concrete design typically focuses on analysis and design of primary members. Students learn how to select beam or column dimensions and an appropriate amount and location of reinforcement to satisfy shear, flexure, and/or axial demands. Students may also learn how to calculate deflections of reinforced concrete beams to meet serviceability requirements. Because a good design meets code requirements and preferences ductile failure modes, students need to develop a foundational understanding of the behavior of these members. Mastery of the course material also requires students to successfully aggregate and apply prerequisite knowledge from statics, mechanics of materials, civil engineering materials, and structural analysis. Instructors often use illustrations, small demonstrations, or videos to illustrate different failure modes and emphasize fundamental behavior. However, students rarely have the opportunity to experience full-scale behavior firsthand. Testing large scale members requires specialized equipment, and many engineering programs do not have access to the necessary facilities or resources to incorporate full-scale testing into the undergraduate classroom.

As a part of a multi-course, experiential learning project, St. Louis University (SLU) and Rose-Hulman Institute of Technology (RHIT) have developed three full-scale experiential learning modules to be used during an introductory reinforced concrete design course. Each module was implemented on the Modular Strong-block Testing System [1]: a self-contained system that provides an affordable alternative for testing larger-scale specimens. The three experiential learning modules were designed to illustrate fundamental behavior of reinforced concrete beams: Module 1 – Tension Controlled Failure, Module 2 – Compression Controlled Failure, and Module 3 – Shear Analysis and Design. Each module supports critical learning outcomes for a traditional reinforced concrete course. The following sections provide some background about the overall project along with the design and implementation of the experiential learning modules. There is also a brief discussion about assessment efforts on the project and lesson learned by the project team thus far.

Project Background

SLU and *RHIT* are both private, highly residential, four-year institutions located in the Midwest. *SLU* is a large, PhD granting university and *RHIT* is a small, primarily undergraduate institution. In the 2017-2018 academic year, *SLU* and *RHIT* began the implementation of a joint experiential learning project for courses in structural engineering [2]. The project includes a suite of learning modules across four different courses: structural analysis [3], reinforced concrete, steel design, and geotechnical engineering [4]. Each module is designed to provide students with hands-on experiences with large-scale, interactive tests. This paper is the second in a series and covers the design and implementation of the experiential learning modules for reinforced concrete design at both institutions.

Reinforced concrete design is required course content for third-year students at *SLU* and *RHIT*. The course at *SLU* is a semester long introduction to structural design that covers both reinforced concrete and steel design. The course meets twice a week for an hour and 15 minutes. Reinforced concrete is covered for seven weeks of the semester. The course at *SLU* is also accompanied by a structural design lab that meets for one hour and 50 minutes each week during the semester, which is a separate course, and that time is not used for this project. Each year, the introduction to structural design course includes approximately 20-30 students. Students meet in a learning studio classroom equipped with mobile seating and flat-panel monitors distributed around the perimeter of the room. The instructor employs various active learning techniques including the use of skeleton notes, group problem sessions, classroom demonstrations, and facilitated discussions.

The course at *RHIT* is a 10-week course dedicated exclusively to the structural design of reinforced concrete. Students meet three times per week for 50 minutes. There is no separate lab component for the course at *RHIT*. Each year, this course includes approximately 25-40 students. The class meets in a classroom that serves dual purposes as a classroom and small structural engineering laboratory. The room is equipped with flattop tables and is arranged in a traditional lecture format: chalkboard at the front of the room and tables in rows. The back of the room is equipped with a small load frame and tensile testing machine. The instructor uses active learning techniques during class lectures. Each class meeting includes a short lecture introduction to the content for the day supported by skeleton notes, then students work example problems, engage in group reflections, or participate in a demonstration. While both institutions incorporated some demonstrations in their classroom activities, prior to the 2019-2020 academic year, neither institution was equipped with large-scale testing equipment.

The reinforced concrete design content covered in the *SLU* and *RHIT* courses is similar. Both courses include uncracked and cracked section analysis for beams, flexural analysis of beams with rectangular and non-rectangular cross-sections, design of beams to satisfy shear and flexural effects, service load deflections of beams, and analysis and design of short columns. The authors share a common observation that students tend to struggle with similar topics at both institutions. Specifically, students struggle with topics that require a deeper understanding of the behavior of elements subjected to loading, as well as applying course content to new contexts rather than following rote procedure. Common struggle areas include calculating service load deflections, flexural analysis of beams, and flexural and shear design of beams.

In addition to instructor perception, students at both *SLU* and *RHIT* were asked to complete a course content survey to evaluate their perception of the topics most difficult to understand during years 1 and 2, prior to the implementation of the experiential learning modules. The survey used a standard five-point Likert scale where 1 = Very difficult, 2 = Difficult, 3 = Neutral, 4 = Easy, and 5 = Very easy. Over the course of two years, 90 students at the two schools participated in the survey, the results of which are shown in Table 1. Four topics, highlighted in grey, indicate an average response less than 3.0, two of which (Topics 17 and 18) align very well with the topics identified by the instructors. Topics 17 and 18 also had modes of 2.0, indicating that a significant number of students selected “Difficult” on the survey. The results of the survey were fairly consistent across universities and it was not surprising that topics 17 and 18 had the lowest scores. Topics 3, 4, 8, and 16 had higher scores than expected, but student exam performance consistently shows a lack of understanding of these topics.

Table 1—Students' perception of the most difficult topics in reinforced concrete design [2].

#	Topic	SLU			RHIT			Total		
		Mode	Avg.	SD	Mode	Avg.	SD	Mode	Avg.	SD
1	Concrete Material Properties	4.00	3.58	0.94	4.00	3.81	0.65	4.00	3.72	0.78
2	Uncracked Elastic Section (gross transformed section properties)	3.00	3.31	0.92	4.00	3.43	0.86	4.00	3.38	0.88
3	Cracked Elastic Section (cracked transformed section properties)	3.00	3.11	0.85	4.00	3.15	0.82	4.00	3.13	0.83
4	Deflections (effective moment of inertia)	3.00	3.19	0.89	3.00	3.35	0.72	3.00	3.28	0.80
5	Equivalent Rectangular Stress Block (a, β_1)	3.00	3.61	0.93	4.00	3.57	0.80	4.00	3.58	0.85
6	Tension controlled flexural failure	3.00 & 4.00	3.39	0.80	4.00	3.46	0.79	4.00	3.43	0.79
7	Transition flexural failure	3.00	3.31	0.80	4.00	3.23	0.81	3.00 & 4.00	3.27	0.80
8	Compression controlled flexural failure	3.00	3.28	0.78	4.00	3.40	0.82	3.00	3.35	0.80
9	Strength reduction factors for flexural failures	4.00	3.61	0.96	4.00	3.40	0.79	4.00	3.48	0.87
10	Beam design (b&h known)	4.00	3.25	0.97	4.00	3.69	0.95	4.00	3.51	0.97
11	Beam design (b&h unknown)	3.00	2.61	1.05	4.00	3.20	1.02	3.00 & 4.00	2.97	1.06
12	Flexural strength of beams with compression steel that yields	4.00	3.42	0.91	4.00	3.26	0.81	4.00	3.33	0.85
13	Flexural strength of beams with compression steel that **does not** yield	4.00	3.34	1.06	4.00	3.12	0.80	4.00	3.21	0.91
14	Flexural strength of "T-beams"	3.00	2.94	0.86	4.00	2.91	0.94	3.00 & 4.00	2.92	0.90
15	One-way slab design/continuous beams	3.00	3.06	1.00	3.00	3.36	0.81	3.00	3.29	0.86
16	Analysis of beams in shear	3.00 4.00	3.00	0.99	4.00	3.41	0.84	4.00	3.24	0.92
17	Shear design of beams (uniform stirrup spacing)	2.00 3.00	2.94	0.97	4.00	3.43	0.88	4.00	3.24	0.94
18	Shear design of beams (variable stirrup spacing)	2.00	2.64	1.05	4.00	3.33	0.87	2.00 & 3.00	3.06	1.00
19	Column interaction diagram	3.00	3.08	1.08	2.00 & 4.00	3.11	0.95	4.00	3.10	1.00
20	Column design	4.00	3.08	1.11	4.00	3.34	0.90	4.00	3.24	0.99

Design and Implementation of Experiential Learning Modules

The primary objective of this project is to develop and implement experiential learning modules that allow students to visualize the behavior and accurately predict the failure loads and mechanisms of reinforced concrete beams in flexural and shear. This paper focuses on three experiential learning modules for reinforced concrete design courses that illustrate service load behavior and structural failure mechanisms. The three modules focus on 1) Tension-controlled Flexural Failures, 2) Compression-controlled Flexural Failures, and 3) Shear Analysis and Design. Each of the following sections contain a description of the design, fabrication, and implementation for each module at *SLU* and *RHIT* during the third and fourth years of the project.

Design

The test specimen for each of the three modules was subject to three primary design considerations. First, the dimensions of the test specimen should be large enough to illustrate typical reinforced concrete beams. Second, the selected cross-section and material properties would be identical for each of the three modules so students could compare behavior and capacity. Finally, the length of each beam would correspond to a required load that would generate the moment necessary to fail each beam in the desired mode while not exceeding the capacity of the testing system [1]. The resulting cross-section was a 12 in. wide and 14 in. deep assuming the concrete compressive strength would be between 4,000 and 5,000 psi at the time of testing.

The beam For Module 1 – Tension Controlled Flexural Failure was 19 ft long and called for four No. 7 bars located 2 in. from the bottom of the beam along with No. 3 stirrups spaced on center at 6 in. throughout the length of the beam. Two No. 4 bars were placed near the top of the beam for constructability. The capacity of the beam varies depending on the actual compressive strength of the concrete, but the concrete compressive strength must be at least 3,700 psi to develop a tensile strain of 0.005 in the bottom layer of steel (ε_t) and ensure a tension-controlled failure. Figure 1 shows the cross-section of the beam and a three-dimensional schematic of the reinforcing cage.

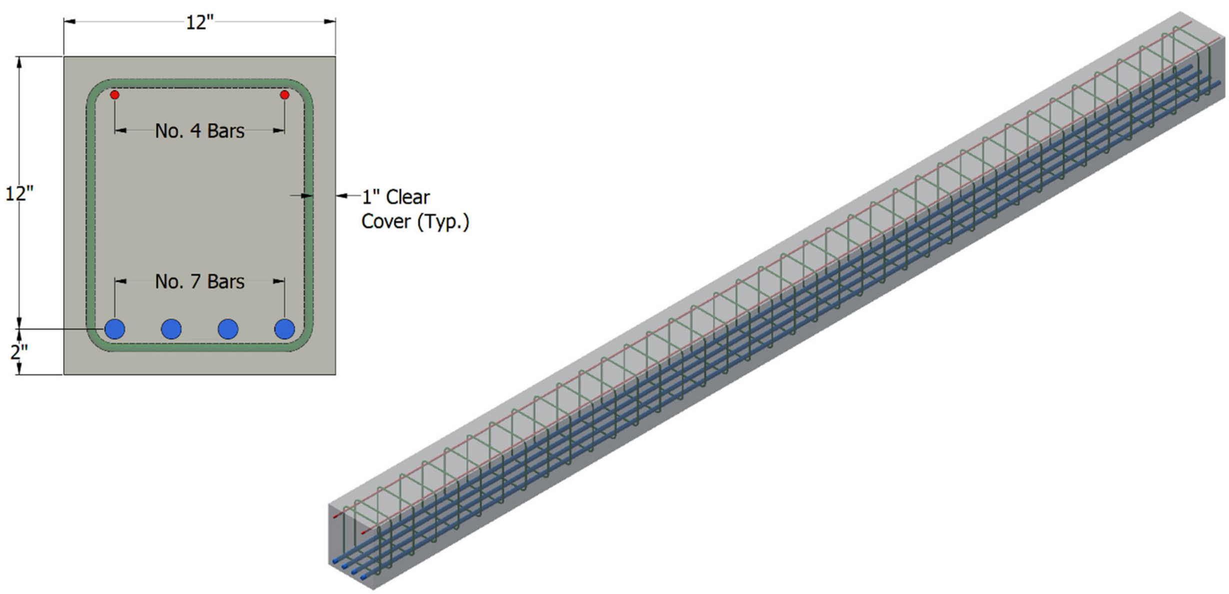


Figure 1—Tension-controlled beam cross section rebar cage schematic.

The beam for Module 2 – Compression-controlled Flexural Failure was also 19 ft long, but the amount of tensile reinforcement was increased to eight No. 8 bars in two layers with the bottom layer located 2 in. from the bottom of the beam. No. 3 stirrups spaced on center at 6 in. throughout the length of the beam was again used for the shear reinforcement along with two No. 4 bars placed near the top of the beam for constructability. The capacity of the beam varies depending on the actual compressive strength of the concrete, but the concrete compressive strength must not exceed 5,300 psi to ensure that the bottom layer of steel does not yield ($\varepsilon_t <$ 0.00207). Figure 2 shows the cross-section of the beam and a three-dimensional schematic of the reinforcing cage.

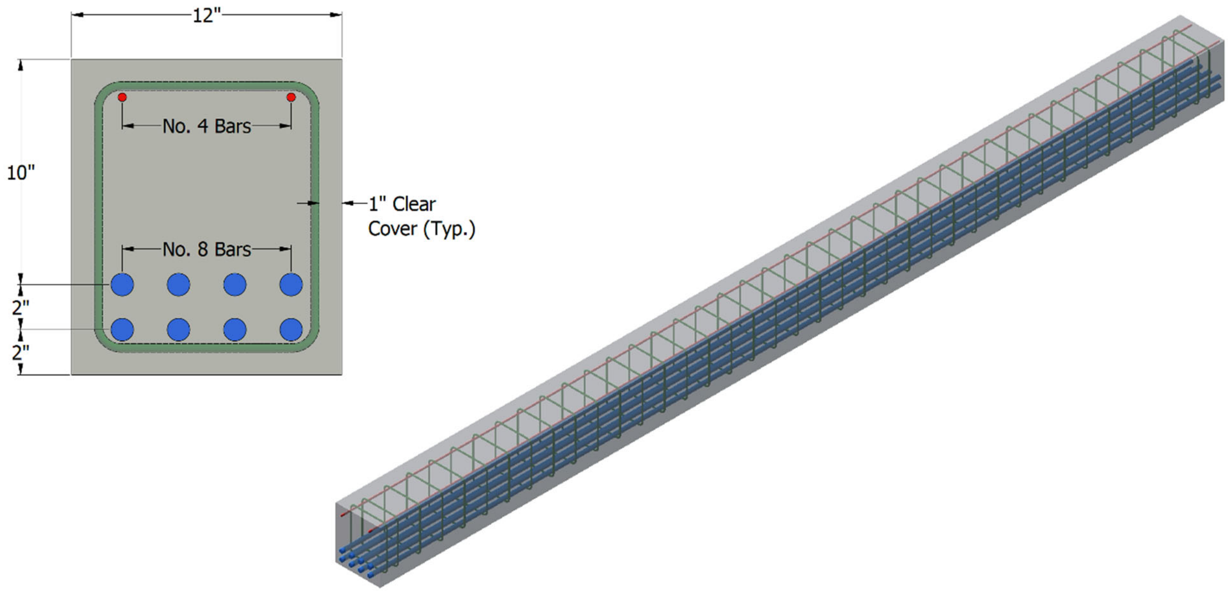
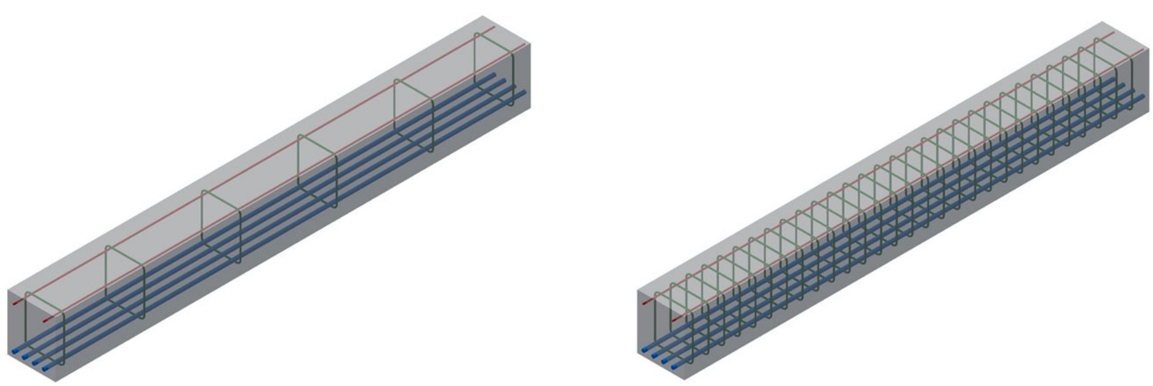


Figure 2—Compression-controlled beam cross section and rebar cage schematic.

The beams for Module 3 – Shear Analysis and Design were 10 ft long and the amount and location of tensile reinforcement was identical to the Module 1 beam. However, the spacing of shear reinforcement was altered. The first beam at SLU had No. 3 stirrups spaced at 24 in. on center, which is four times the maximum allowable spacing of 6 in. per ACI 318-19 geometry requirements [5]. The second beam at SLU had No. 3 stirrups spaced at 4 in. on center, which would ensure a flexural failure of the specimen. SLU used the shorter beam to help ensure the beam would fail in shear and prevent a flexural failure from occurring. At RHIT, the decision was made to use a single 19 ft long beam, identical to the first two modules. However, for this beam the stirrups were omitted altogether. Figure 3 (a) shows a schematic of the SLU beam with design flaws and Figure 3 (b) shows the schematic of the correctly designed beam.



(a) (b)

Figure 3—Rebar cage schematics for (a) beam with design flaws and (b) correctly designed beam.

Fabrication

The formwork for the beam specimens at SLU was constructed from 2x4s and High Density Overlay (HDO) plywood in sections no longer than 8 ft for storage purposes. A 2x4 ran along the top and bottom of each section throughout the entire length with 2x4 studs spaced at roughly 12 in. on center. All pieces were attached with various sizes of drywall screws. The top longitudinal 2x4 was placed 1.5 in. below the top edge of the HDO plywood to make finishing easier and to allow for threaded rods to pass through the plywood near the top edge. One-quarter inch diameter threaded rods were placed through the HDO plywood near the top edge about every 2 ft to support the rebar cage and provide lateral ties for the forms. Additionally, each end plate included a hole pattern that mimicked the rebar pattern to also help with cage construction and alignment. The longitudinal bars were slid through one end plates and stirrups added. The No. 4 bars were tied to the threaded rods and then stirrups tied in place to the top steel and tensile reinforcement. A local ready-mix company supplied 3 yd^3 of concrete, which was placed using a concrete bucket connected to an overhead gantry crane. The beams were left to cure for a few days before removing the formwork. The beams were covered with wet burlap and plastic to continue moist curing the beams for about two weeks. Figure 4 shows exploded views of the formwork for the 19 ft and 10 ft specimens; Tables 2-4 list the materials needed for Modules 1-3, respectively; and Figure 5 illustrates three steps in the casting process.

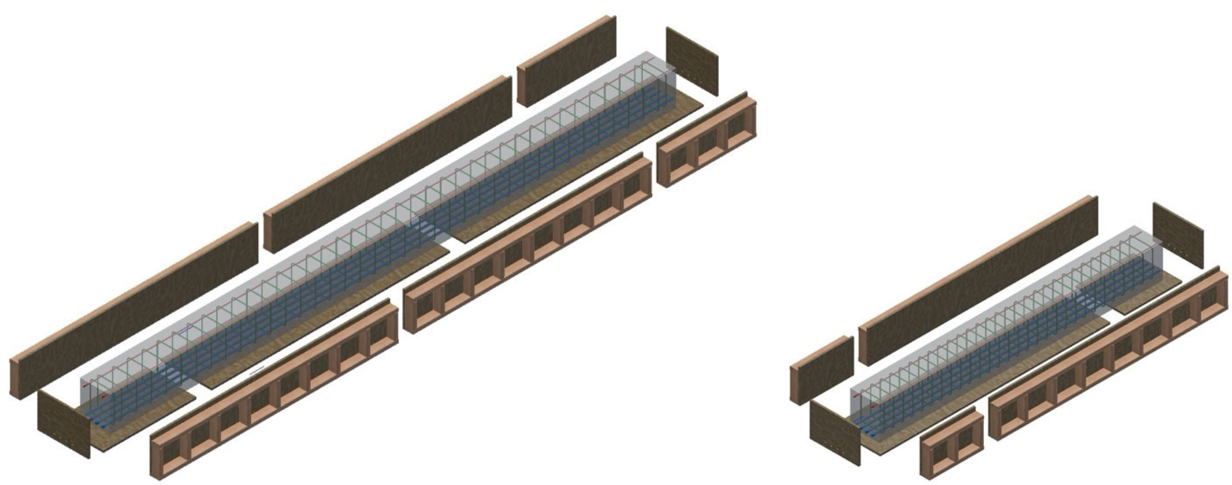


Figure 4—Exploded view of formwork for flexural beam and shear beam.

Table 2—Tension-controlled failure specimen material takeoff

Item	Dimensions	Quantity
¾ in. HDO plyform base piece	16.5 in. x 96 in.	2
¾ in. HDO plyform base piece	16.5 in. x 37.5 in.	1
¾ in. HDO plyform side piece	14 in. x 96 in.	4
¾ in. HDO plyform side piece	14 in. x 36 in.	2
¾ in. HDO plyform end piece	14 in. x 16.5 in.	2
No. 2 southern pine 2x4	8 ft	8
No. 2 southern pine 2x4	3 ft	4
No. 2 southern pine 2x4	9.5 in.	44
Drywall screws	3 in.	1-5 lb box
Drywall screws	2 in.	1-2 lb box
Drywall Screws	1-5/8 in.	1-5 lb box
¼ in. threaded rod	17 in.	10
nuts	¼ in.-20	40
washers	¼ in.	40
No. 7 GR 60 reinforcing bars	19 ft 2 in.	4
No. 4 GR 60 reinforcing bars	10 ft 2 in.	2
No. 3 GR 60 reinforcing bars	4 ft 4 in.	39
Rebar ties	6 in.	1 bundle

Table 3—Compression-controlled failure specimen material takeoff

Item	Dimensions	Quantity
¾ in. HDO plyform base piece	16.5 in. x 96 in.	2
¾ in. HDO plyform base piece	16.5 in. x 37.5 in.	1
¾ in. HDO plyform side piece	14 in. x 96 in.	4
¾ in. HDO plyform side piece	14 in. x 36 in.	2
¾ in. HDO plyform end piece	14 in. x 16.5 in.	2
No. 2 southern pine 2x4	8 ft	8
No. 2 southern pine 2x4	3 ft	4
No. 2 southern pine 2x4	9.5 in.	44
Drywall screws	3 in.	1-5 lb box
Drywall screws	2 in.	1-2 lb box
Drywall Screws	1-5/8 in.	1-5 lb box
¼ in. threaded rod	17 in.	10
nuts	¼ in.-20	40
washers	¼ in.	40
No. 8 GR 60 reinforcing bars	19 ft 2 in.	8
No. 4 GR 60 reinforcing bars	19 ft 2 in.	2
No. 3 GR 60 reinforcing bars	4 ft 4 in.	39
Rebar ties	6 in.	1 bundle

Table 4—Shear Analysis and Design specimen material takeoff

Item	Dimensions	Quantity
¾ in. HDO plyform base piece	16.5 in. x 96 in.	2
¾ in. HDO plyform base piece	16.5 in. x 24 in.	2
¾ in. HDO plyform side piece	14 in. x 96 in.	4
¾ in. HDO plyform side piece	14 in. x 22.5 in.	4
¾ in. HDO plyform end piece	14 in. x 16.5 in.	4
No. 2 southern pine 2x4	8 ft	8
No. 2 southern pine 2x4	2 ft	8
No. 2 southern pine 2x4	9.5 in.	48
Drywall screws	3 in.	1-5 lb box
Drywall screws	2 in.	1-2 lb box
Drywall Screws	1-5/8 in.	1-5 lb box
¼ in. threaded rod	17 in.	12
nuts	¼ in.-20	48
washers	¼ in.	48
No. 7 GR 60 reinforcing bars	10 ft	8
No. 4 GR 60 reinforcing bars	10 ft	4
No. 3 GR 60 reinforcing bars	4 ft 4 in.	39
Rebar ties	6 in.	1 bundle

(a) (b) (c)

Figure 5—(a) Formwork assembly; (b) completed rebar cages in formwork; and (c) just after placing the concrete.

Fabrication of the three specimens at RHIT required three rebar cages and formwork for each beam. Each rebar cage was constructed to satisfy the reinforcement amount and spacing established in the previous section. Stirrups were secured to the longitudinal tension reinforcement using rebar ties (Figure 6). Due to the weight of the reinforcement cages, particularly for the compression-controlled beam, it is recommended to use a lifting device when moving or placing the reinforcement cage.

The formwork for each beam was built to ensure a 14 in. by 12 in. cross-section with and overall beam length of 19-feet. The span length of the test specimen is 18-ft, and the additional foot accommodated the placement of supports during the actual test. SLU elected to construct three identical and separate beam forms using plywood and dimensional lumber. RHIT decided to construct a single set of beam forms with shared walls (Figure 4 (b)). At least four weeks prior to the first testing date, the concrete was placed in the forms (Figure 4(c)). Form liner was used on the forms to aid in the ease of removal. Mechanical vibrators were used to prevent voids in the beam. The beams were covered and left to cure for 7 days. After 7 days, the forms were removed, and the beams were set aside until the corresponding testing date. In addition to the beams, a minimum of 3 - 4 in. diameter cylinders were cast for material testing at a later date.

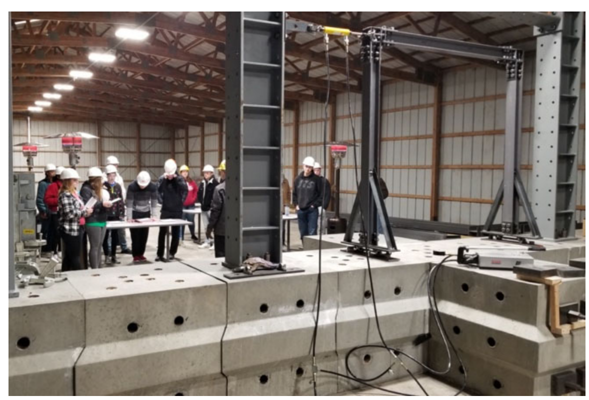
It was decided that each of these specimens be constructed not as a part of required activities for the class. While SLU does have a lab component, RHIT does not have a dedicated lab component. Since many institutions do not have laboratory components associated with their design class, this project was implemented to see how these modules could be incorporated into typical class. Additionally, the time required to fabricate and cure the concrete specimen did not accommodate being complete in the time allotted for class during the semester/quarter. Accordingly, each instructor utilized graduate student assistance in fabricating the specimen outside of class. While students did get to see and handle the material used in constructing the beams, students in the classes did not participate in the fabrication. To assist other instructors in implementing these modules, the materials required for Module 1 through Module 3 are shown in Table 2, Table 3, and Table 4, respectively. Each module's material list is listed separately to accommodate adoption of only a single module if desired. The list of materials represents the specific material used by SLU.

Figure 6—Rebar ties used to connect stirrups with longitudinal reinforcement.

Implementation

As was stated previously, neither program was equipped with large scale testing equipment prior to the 2017-2018 academic year. The size of the beams and the anticipated capacity of the specimen for each of the three modules require structural testing equipment. It would be ideal to utilize a structural testing facility, but most small programs do not have access to these types of facilities. To demonstrate how a smaller institution can implement these modules, this project utilizes the Modular Strong-block Testing System [1], a versatile and affordable large-scale testing alternative. Figure 7 (a) and (b) show the system in use.

(a)



(b)

Figure 7—The Modular Strong-block Testing System setup for (a) a beam test and (b) a frame test.

Module 1—Tension-controlled Failure

The order of course material in the ***SLU*** course begins with the uncracked elastic section analysis, cracked elastic section analysis, and service load behavior and naturally progresses to ultimate strength of rectangular sections. The instructor spends a day discussing the equivalent rectangular stress block and doing a visual learning activity with the students before moving on to tension-controlled failures, then used the same cross-section for uncracked elastic, cracked elastic, service load behavior, and ultimate strength discussions. The instructor decided to flip the class using a short video lecture focused on tension-controlled failures and use the in-class time for the new module activities. The video lecture included a review of the flexural stages, the elastic properties, and service load deflection calculations from previous classes, which gradually transitioned to the nominal and ultimate strength calculations, all of which assumed a concrete compressive strength of 4,000 psi.

The following day students went straight to the structures lab where high-top tables were setup for class. Students were given a handout and asked the question, "What happens to the resultant compressive forces if b (width of beam), A_s (area of tensile reinforcement), and f_y (yield strength of tensile reinforcement) all stay the same, but the concrete strength increases?" The students then preceded to calculate the strength of the beam with the actual concrete strength, which varies each year. At that point in class, the beam was gradually tested, and the students manually plotted the load and deflection for each load step up until the point of failure and compared those values to the predicted values for service load deflections and ultimate capacity. The instructor explained each key point in the load process and two graduate students marked cracks with Sharpie markers so the students could see the progression of cracks (Figure 8 (a)). After the test was complete, the students were asked five reflection questions:

1. What effect did the increase in concrete strength have on the depth of the neutral axis (c)? Why?
2. What effect did the increase in concrete strength have on the resultant forces C and T?
3. What effect did the increase in concrete strength have on the nominal moment capacity? Why? Is the difference significant?
4. What effect did the increase in concrete strength have on the tensile strain in the bottom layer of steel? Why? Is the difference significant?
5. Did you find anything surprising about the physical behavior of the beam?

The course material at *RHIT* follows a similar sequence to that of *SLU*. In the first week of class, students work with the instructor to define a simply-supported beam with a rectangular cross-section subjected to a point load at center-span. To illustrate flexural behavior to the students, it is explained that we are going to analyze the beam at several stages as it is subjected to a loading progression. Over the following week, students work to perform uncracked analysis, calculate the cracking moment, perform a cracked section analysis, calculate deflections, and calculate the nominal capacity all for the same defined cross-section. During these lectures, students are introduced to the rectangular stress block, tension-controlled versus compression-controlled failures, and a demonstration highlighting the difference between reinforced and unreinforced concrete. In-class activities are supported by homework and quizzes requiring students to apply a similar loading progression to a non-rectangular section and a parametric study of a rectangular beam.

Students are then provided with the Module 1 beam dimensions including nominal cross-section, length, loading condition and material properties. Prior to participating in the test, students were asked to prepare a predicted load versus deflection plot. Specifically, students were expected to estimate the load and deflection at cracking, at first yield of the tension reinforcement, and at ultimate capacity. This activity serves as a summary assignment for the beam analysis and design portion of the class.

The test of the tension-controlled member was conducted during a single class period. During the test, students were provided with the actual concrete strength based on a cylinder compressive test completed the same day. Students were then asked to measure the beam's cross-section and length and comment upon any discrepancies. Students took turns loading the beam, marking concrete cracks, and recording data points (Figure 8 (b)). The instructor took pauses during the loading sequence to ask targeted behavior questions. Students were asked to describe where they expect the first crack to occur, articulate observations about the crack pattern, and describe the failure mechanism. The beam was loaded to failure, and after the test, students were required to produce a report that included the following information:

1. A summary of the behavior and failure mechanism of the beam along with a load-deflection plot.
2. An analysis of the expected performance of each beam using measured properties and dimensions
3. A discussion of why the expected performance differed from the actual performance
4. A discussion of the desired type of beam behavior.

(a) (b)

Figure 8—(a) The tension-controlled beam is loaded during class at ***SLU*** as the instructor describes what is taking place and (b) Students at ***RHIT*** verifying the cracking moment by locating the first flexural crack in the beam.

Module 2—Compression-controlled Flexural Failure

The process for implementing the second module at SLU used essentially the same format as the first Module. The instructor flipped the class using a short video lecture focused on compression-controlled failures and used the in-class time for the new module activities. The video lecture included a review of the flexural stages, the elastic properties, and service load deflection calculations from previous classes, which again gradually transitioned to the nominal and ultimate strength calculations for the compression-controlled beam.

The following day, students again went straight to the structures lab where high-top tables were setup for class. Students were given a handout with the load versus deflection plot for the tension-controlled beam that also included the predicted values for the compression-controlled beam. After some brief review about compression-controlled failures, the beam was gradually tested, and the students manually plotted the load and deflection for each load step up until the point of failure. Figure 9 (b) shows the depth of the compression zone. They compared those values to the predicted values for service load deflections and ultimate capacity along with the general shape compared to the tension-controlled beam from the previous class. In addition to plotting the load versus deflection values, each student also had the opportunity to look for and mark cracks with a Sharpie marker during the loading process. After the test was complete, the students were asked six reflection questions:

1. What effect did the increase in area of tensile steel have on the depth of the equivalent rectangular stress block (a)? Why?
2. What effect did the increase in concrete strength have on the resultant forces C and T?
3. What effect did the increase in area of tensile steel have on the nominal moment capacity compared to the first beam? Why? Is the difference significant?
4. What effect did the increase in area of tensile steel have on the tensile strain in the bottom layer of steel compared to the first beam? Why? Is the difference significant?
5. Did you find anything surprising about the physical behavior of the beam?
6. How did the behavior of this beam compare to the behavior of the first (Module 1) beam? What stood out to you the most?

The second module for *RHIT* was tested one week after the first module. At this point during the term, the class had completed flexural analysis and design and had just started shear analysis and design. Similar to the previous test, students were provided nominal material properties and dimensions for the test specimen. Students were asked to estimate the cracking moment, the point of first yield, and the ultimate capacity of the member. The test of the compression-controlled member was also conducted during a single class period. During the test, students were provided with the actual material properties and beam dimensions. Students took turns loading the beam, marking concrete cracks, and recording data points. The instructor also prompted students with discussion questions. The instructor asked if the cracking moment should be similar to the first specimen. Students were also asked to describe any observed changes in behavior. After the beam had failed, students observed the failure location and were asked to discuss the difference in failure modes (Figure 9 (b)). Students were required to produce an additional section to their report following identical prompts for the second specimen.

(a) (b)

Figure 9—(a) Depth of compression zone of SLU beam and (b) the resulting failure location of RHIT beam.

Module 3—Shear Analysis and Design

The third module included two specimens and took two separate class periods to complete at SLU. The instructor flipped both classes to ensure adequate time during class to complete both beam tests. The first video lecture included a review of Mohr's circle and principle stresses followed by an introduction to shear strength based on ACI 318-18 [5]. When students arrived in class the following day, they were presented with a live load to be applied at mid-span in addition to the self-weight of the beam and asked to compute the ultimate moment and shear (at the critical section) using the appropriate load combination. They were asked to check the flexural strength and then select a spacing for the stirrups to satisfy strength requirements based on the given load. The problem works out such that students calculate a spacing just larger than 24 in., which is the spacing used in the first beam. There was no discussion about geometry and other spacing limitations before the beam test. Students were then presented with a scenario where the concentrated live load was moved from mid-span to a third-point by the contractor due to an on-site change without notifying the design engineer and asked to describe what could happen. The purpose is to highlight the importance of considering any variations in load location.

After students calculated the spacing and discuss the potential effects of moving the load, the beam was gradually tested to the point of failure. The cracks were marked throughout the process, specifically noting orientation and how the cracks occurred in between the stirrups spaced at 24 in. Figure 10 (a) shows the specimen after testing. After the test was complete, there was additional discussion about spacing limitations to prevent such events from occurring and the students were asked four reflection questions:

1. Sketch the crack pattern you observed.
2. Describe the progression of cracks that occurred during the test.
3. Describe the final failure mechanism. Was it ductile or brittle? Explain.
4. What critical errors did you, the designer, and the contractor make?

The second video lecture presented the design process for variable spacing of stirrups, which included discussion of spacing limitations for geometry, along with minimum and maximum steel requirements. When students arrived in class for the second day, they were presented with a scenario where a concentrated live load was applied at the third point along with the maximum possible magnitude of that load to result in a flexural failure based on the appropriate load combinations. They were then asked to select a spacing for stirrups to satisfy strength requirements based on the given load. This problem works out such that students calculate a spacing just larger than 5 in.; the actual spacing in the beam was 4 in. The students were then presented with the actual load that would cause a flexural failure based on the nominal strength, neglecting load factors and were asked to estimate the nominal shear strength based on the actual spacing of stirrups in the beam. The purpose was for students to compare the design values with the nominal values to illustrate the effects of load and strength reduction factors.

After students completed the calculations, the beam was gradually tested to the point of failure. Each student had the opportunity apply one increment of load and look for and mark cracks with a Sharpie marker. As students progressed through the loading process, the instructor discussed the progression of cracks specifically noting orientation and which crack was a flexural, flexural-shear, and shear crack. After the test was complete, the students were asked four reflection questions:

1. Sketch the crack pattern you observed.
2. Describe the progression of cracks that occurred during the test.
3. Describe the final failure mechanism. Was it ductile or brittle? Explain.
4. What differences in behavior did you notice between the beam from last class and this one?

The third module for *RHIT* was tested one week after the second module. At this point during the term, the class had just finished the shear analysis and design component covered in class material. As with the previous two specimens, students were provided nominal material properties and dimensions for the test specimen, and each student was asked to estimate the cracking moment, the point of first yield, and the ultimate capacity of the member. Students were reminded that for this specimen they needed to consider shear capacity in addition to flexural capacity. The test of the shear critical member was also conducted during a single class period. During the test, students were provided with the actual material properties and beam dimensions. Students took turns loading the beam, marking concrete cracks, and recording data points. The instructor also prompted students with discussion questions. The instructor asked if the cracking moment should be similar to the first two specimen. Students were also asked to describe the expected crack pattern and failure mode. Throughout the test, the instructor asked students to articulate differences in behavior. After the beam had failed, students observed the failure location and were asked to discuss the difference in failure modes (Figure 8 (b)). Unfortunately, the RHIT beam did not have a classical shear failure. The instructor used the opportunity to articulate the observed failure mode. Finally, students were required to produce the third addition to their report following the same prompts for the first two specimen.

(a) (b)

Figure 10—(a) Shear Analysis and Design Specimen at *SLU* with intentional design flaws and (b) the final resulting failure location (a delamination failure) of the shear specimen at *RHIT*

Lessons Learned and Recommendations

The full-scale tests were extremely engaging and provided an excellent teaching tool for the instructors. The time spent on the modules was interactive, students were able to experience real behavior, and the instructors were able to facilitate meaningful discussions on the behavior of these elements. However, as might be expected, these activities demanded a great deal of time. First, the fabrication of the beams added a great deal of "class prep." Since students in the class are not fabricating the beam, the instructor must accommodate the fabrication. The construction of the concrete beams also requires significant lead time as well. Additionally, the actual tests take a significant amount of time as well. The tests required three and four classroom days, respectively at SLU and RHIT. This substitution required for content to be delivered differently or skipped altogether. It is necessary for instructors to weigh critical learning elements with the benefits of experiential learning activities.

Instructors need to carefully assign responsibilities and safety protocols during the test. With the number of students participating with the tests, it was necessary for the instructor to be intentional about assigning students with active roles. Some students left to their own means tended to withdraw and not participate. Having reflection sheets or prepared questions can help to actively engage the students. Additionally, the impact of the restrictions resulting from the COVID-19 pandemic for social distancing resulted in some students being online. Using a smartphone on Zoom can provide good views for students who were online, and coincidentally, using Zoom sparked a new idea for how to also lecture in a lab that does not have projection capabilities. The students can still see and class annotations on Zoom when the instructor uses a tablet coupled with skeleton notes. This method will likely stay a part of this teaching approach post-pandemic to effectively mix in some lecture in a lab setting.

Finally, with regards to the test performance, it is critical that the concrete compressive strength remain between 4000 and 5000 psi. Using the defined dimensions, the beams will not reach true tension-controlled and/or compression-controlled failure due to the reduced and/or increased concrete compressive strength for a specimen. The instructors recommend working closely with a ready-mix plant to ensure the strength of their concrete mix. Also, the SLU setup for Module 3 – Shear Analysis and Design was much more effective at demonstrating shear behavior than the RHIT setup. The performance of the beam reflected a more typical shear failure, but the beam does require much higher loads to fail the beam that is correctly designed.

Future Assessment

Assessment of the project includes both qualitative and quantitative assessments. The qualitative assessment includes the Student Response to Instructional Practices (StRIP) survey [6], a course content survey, and a series of open-ended questions about the experiential learning modules (post-test only). The assessment includes a series of exam questions related to each module: 1) a question requiring the determination of the cracking moment and verification of the size of an equivalent rectangular stress block for a beam, 2) a question soliciting a description of the difference between tension-controlled and compression-controlled behavior of flexural members, and 3) a question about the required spacing of shear stirrups and a description of the crack pattern of a beam with an impending shear failure. The students at both universities in Year 1 and 2 were the control group and the students in Year 3 and 4 will be the intervention group. The intervention groups are currently in progress at both universities and full assessment is beyond the scope of this paper. However, future dissemination efforts will highlight the effect of the experiential learning modules on student learning, perception of topic difficulty within the course, and instructional practices.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. 1726621. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors would especially like to thank the Breckenridge Materials Corporation, Inc. and, Coreslab Structures, Inc., for their contributions and assistance with specimen fabrication along with Mr. Ben Frieden, Ms. Elise Westhoff, Mr. Keaton Shieffer, Ms. Hana Baban, Ms. Madeline Mueller, Ms. Kelsey Musa, Mr. Jonathan Stodola, Mr. Ranger Caffrey, and Ms. Isabella Marzari for their assistance with fabrication. The authors would also like to thank Wieser Concrete, Superior Steel, Inc., Benchmark Fabricated Steel, and McLaughlin Hoist and Crane for their contributions to the development of the structural engineering laboratories.

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