

## **Exposing Undergraduates to Design, Fabrication, and Large-Scale Experimentation in a Structural Steel Design Course**

**Jenna Williams, California Polytechnic State University, San Luis Obispo**

Jenna Williams is an undergraduate architectural engineering student at California Polytechnic State University – San Luis Obispo. She has been engaged in structural engineering through leadership roles in Cal Poly's Structural Engineers Association of California (SEAOC) student chapter, the Earthquake Engineering Research Institute (EERI) Undergraduate Seismic Design Competition team, and the Structural Engineering Students for Humanity (SESH) which assists with post-earthquake recovery in developing nations. In addition, she has previously been engaged in Cal Poly's Society of Women Engineers collegiate chapter as a leader and as an advocate for women in STEM to elementary school, middle school, and high school students in California. After graduation, she plans to pursue a masters degree in structural engineering to further her understanding of the interaction between architecture, structures, and construction.

**Mr. Mark William Wright LEED Green Associate, California Polytechnic State University, San Luis Obispo**

Mark Wright is an undergraduate architectural engineering student at California Polytechnic State University, San Luis Obispo. He has held leadership roles in Cal Poly's Structural Engineering Association of California (SEAOC)/Architectural Engineering Institute (AEI) student chapter and the National Student Organization of the Architectural Engineering Institute (AEI NSO). Additionally, he has assisted with Cal Poly's Earthquake Engineering Research Institute (EERI) Undergraduate Seismic Design Competition team, AEI Student Design Competition team, and post-earthquake disaster relief with Structural Engineering Students for Humanity (SESH). After graduation, he seeks to practice structural engineering in the United States and pursue disaster relief outside of work.

**Mr. Michael James Deigert, California Polytechnic State University**

**Dr. Anahid Behrouzi, California Polytechnic State University, San Luis Obispo**

Anahid Behrouzi is an assistant professor of architectural engineering at California Polytechnic State University - San Luis Obispo. 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 and structural engineering at North Carolina State University (2008-2011), the University of Illinois at Urbana-Champaign (2012-2015), Tufts University (2015-2016), and Cal Poly - San Luis Obispo (2016-present). She has a BS in civil engineering and BA in Spanish language & literature from North Carolina State University, and a MS/PhD in civil engineering from the University of Illinois at Urbana-Champaign.

# **Exposing Undergraduates to Design, Fabrication, and Large-Scale Experimentation in a Structural Steel Design Course**

## **Abstract**

During Fall 2017, Spring and Fall 2018 quarters, various hands-on design, fabrication, and large-scale experimental projects were incorporated into a 10-week undergraduate structural steel design course offered in the Department of Architectural Engineering at California Polytechnic State University – San Luis Obispo. Through these projects students investigated one or two unique steel lateral force resisting systems (LFRS) consisting of either: special moment frame (SMF), special concentric braced frame (SCBF), and/or buckling restrained braced frame (BRBF). Students completed design calculations per the American Institute of Steel Construction steel building and seismic codes, visualized their final design using AutoCAD software, constructed and tested the LFRS specimen. Finally, students compared test results to predictions determined via code equations.

These new projects offer a novel approach for engaging students in the process of learning steel design where they practice the technical structural design and analysis competencies while refining visual/written/oral communication, project management, construction, experimentation, and data analysis skills. Student feedback collected for each course offering indicated that students had a better visual and physical understanding of various steel LFRS systems by undergoing the complete cycle of design, fabrication, testing, and analysis. As a result, students were able to more fully comprehend consequences of their design decisions, lessons which they will hopefully draw on in their future structural engineering career focusing on seismic design.

## **Introduction**

An undergraduate course in structural steel design is typical in the civil (structures focus) and architectural engineering degree track. Common curriculum for this course is the analysis and design of: (i) steel and composite members subject to compression, tension, or axial force and flexure and (ii) bolted or welded connections. Students develop a familiarity with the strength and serviceability requirements of AISC 360 *Specification for Structural Steel Buildings* [1] that is utilized in structural engineering design practice. Traditional methods of steel design lecture involve instruction on the failure modes and design criteria for an individual member or connection type in isolation without exposing students to the systems-level perspective of how these components are integrated into a building structure.

This introduction section explores innovations in the context of these types of traditional structural steel design courses within the groupings of: project-based learning, computer simulation to augment physical models, as well as laboratory and in-field experimentation. This overview provides context for the pedagogical approach discussed in this paper which combines project-based learning and large-scale laboratory experimentation. Based upon a review of published research related to structural steel design instruction, there have been no similar steel design courses which use this teaching approach to expose students to the lateral load resisting frame systems common in seismic areas.

### ***Project-based Learning***

Past engineering pedagogy research has shown that incorporating a project-based approach in a structural steel course, that reflects a task similar to that in industry, is more effective than the traditional lecture approach [2-3]. It exposes students to the complete structural system and encourages students to ask questions as they progress in their design or technical review of a steel structure. Project deliverables include some combination of: an executive summary, calculations, structural analysis model using commercial software, CAD drawings of the structural system and connection details, and/or a material schedule.

Specifically, Tabatabai-Gargari [2] describes a project-based learning approach at the University of Cincinnati where students designed and provided quality assurance/quality control (QA/QC) for a one-story, steel mezzanine structure with a composite deck. Observations of students indicated they had a greater understanding of design theory, appreciation for the relevance of course topics, and sense of enthusiasm about the course. The faculty reflected that his role was one of a consultant who provided information on students' requests as needed throughout the project, rather than as lecturer presenting information in a pre-determined order and without any realistic context.

Phillips [3] outlines an individual design project in an intermediate structural steel design course at Oklahoma State University. Students conducted a structural analysis of a multi-story building and designed a structural system consisting of a composite deck with moment frames in one direction and vertical bracing in the other. Student surveys indicated a high level of excitement and educational value in taking this project-based steel design course. The faculty underscored the importance of each student engaging in every phase of the project to have the skills that necessary for success in future structural engineering courses and ultimately industry.

### ***Computer Simulation to Augment Physical Models***

Use of computer simulations are helpful in a steel design course for a variety of reasons: three-dimensional (3-D) building models illustrate how structures are fabricated and virtual experiments of members, connections, or entire buildings reveal structural response under loading. The former provides students with insights into constructability of the system, while the latter demonstrates the consequences of various failure modes identified in codes of practice. The AISC Web-Enhanced Teaching of Structural Steel Design toolkit addresses both topic areas and has proven an effective teaching aid in courses ranging from statics where students learn about the sources of loads to a senior capstone focusing the design of a steel building [4].

In terms of visualizing 3-D configurations of steel members and connections, one of the standards has been the physical steel sculpture designed by Ellifritt [5] that showcases 48 common connections. While an extremely powerful teaching tool in over 130+ campuses across the United States, this physical model incurs significant expense in fabrication, requires a large permanent display space, and access to expert faculty to provide comprehensive explanations. Moaveni and Chou [6] worked to overcome these challenges by developing a virtual sculpture where each connection is accompanied by a description of failure modes, sample capacity

calculations, in-field applications, and a 3-D finite element model that illustrates internal stresses. Student feedback has been positive related to the virtual sculpture as a learning aid.

At the University of Tennessee, a computer application developed by Williams et al. [7] illustrates the failure modes (tensile yield, tensile fracture, and block shear rupture) and patterns (failure path) of steel tensile members. The instructors provided students with a number of steel test specimens illustrating the original and failure state of steel members, similar in nature to the steel tension connections and static connection models described in Meyer et al. [8]. The computer software intended to expand upon physical models in two ways. Students could witness the damage propagation in the member and study various design parameters (member geometries and grades; bolt sizes, grades, and configurations; failure modes/patterns). Results that are displayed graphically and mathematically enhance student understanding of distinctions in the behavior of tensile member designs without costly experimental testing or involved calculations.

### ***Laboratory and In-Field Experimentation***

Recipient institutions of NSF Instrumentation and Laboratory Improvement grants to support large-scale structural engineering testing have highlighted the value in exposing students to experimental design, fabrication, testing, and data analysis as it helps them develop an understanding of real physical behavior of a structural system [9-10]. One step further is engaging students in the evaluation of an existing structure through inspection, analysis, and testing [11].

Tito-Izquierdo et al. [10-11] documents the success of lab activities incorporated into the steel design course at the University of Houston-Downtown. In an early version of the course, students tested a slender beam to compare experimental and theoretical elastic lateral buckling loads. Students developed a technical report documenting the lab test set-up and prediction calculations, involving use of CAD software and Excel Visual Basic. In a later course offering, students conducted an evaluation of a steel truss pedestrian bridge. They reviewed design documents and examined as-built conditions to produce an accurate CAD drawing. Also, they completed a material take-off and cost estimate, structural analysis with SAP2000 software, dynamic testing to validate the structural model, and verification of steel members. The project culminated in a written report and oral presentation. In exit interviews graduates emphasized lab experience as critical in their interest in their academic program, and student survey results related to the bridge evaluation project indicate that they developed a high level of competency in analyzing and testing steel structures as well as technical communication.

### **Details of Course**

The Department of Architectural Engineering (ARCE) at California Polytechnic State University – San Luis Obispo (Cal Poly – SLO) places a strong focus on the West Coast practice of structural engineering, specifically seismic design. This exposure to earthquake engineering begins in junior year with a structural systems lab course that introduces students to calculation of building loads and development of complete gravity and lateral load path. In the subsequent quarter, students take a lecture course on theory and design in structural steel.

The research described in this paper relates to the next steel course in the junior year progression *ARCE 372: Steel Structures Design Laboratory*. Each ARCE 372 section is taught by a faculty member with significant industry experience and P.E or S.E. licensure who prepares and guides students in a steel-framed building project during the 10-week quarter. Traditionally, students select the structural system type and configuration, conduct a structural analysis to determine gravity and lateral loads, and develop a calculation package that summarizes the structural design as well as construction drawings and specifications for fabrication. In addition, students are expected to integrate building services and architectural design, address constructability issues, and identify relationships between construction methods and cost. As an intensive design course with an engineer-apprentice model, one or two sections of up to 16 students are offered in each of the Fall and Spring quarters with 3 sessions a week at 3 hours per session.

This paper describes a series of new design-build-test projects implemented in ARCE 372 by one of the authors during his course instruction in Fall 2017 (F17), Spring 2018 (S18), and Fall 2018 (F18). Students learned to design ductile lateral framing systems commonly used in seismic applications, including: special moment frame (SMF), special concentrically braced frame (SCBF), and buckling-restrained braced frame (BRBF) as described in AISC 341 *Seismic Provisions for Structural Steel Buildings* [12]. Past offerings of ARCE 372 only involved completing design calculations and drawings for the frame systems, and with the new course format, students additionally worked in a team of 13 to 15 individuals to construct or repair two large-scale experimental frame specimens, conduct a cyclic loading test of each frame, and reflect on observed and measured response to compare SMF, SCBF, and BRBF performance.

The traditional ARCE 372 course leveraged project-based learning to approximate the design office tasks of working in small teams to produce structural calculations based on relevant codes of practice and using computer-aided drafting software to develop construction drawings. The new course format in F17/S18/F18 expands the student experience by transforming an abstract idea, represented by calculations and drawings, to tactile reality. The objectives of the new design-build-test projects are to help students: (i) recognize the real constructability issues that occur in the field as they fabricate their steel frame specimens; (ii) understand differences in seismic response of SMF, SCBF, and BRBF systems based on their experimental test observations and data analysis; as well as (iii) develop project management, teamwork, and communication skills to function in a large team with varied design, construction, experimental testing, and reporting tasks. Appendix B details the FE and PE exam objectives as well as ABET criteria met by the new ARCE 372 course. The remainder of this paper will detail the learning activities associated with the ARCE 372 course projects and student feedback from the first two undergraduate student authors as well as data collected through end-of-quarter course surveys.

## **Project Overview**

Table 1 illustrates the project schedule for the S18 quarter which includes course instruction, design, fabrication, experimental testing, and data analysis tasks for the repair/re-design of an existing SCBF and design of a SMF. Each segment of the project is described in detail below; these descriptions focus on the S18 quarter in which the two student co-authors were enrolled.

### ***Course Instruction***

Course lectures covered design of: floor framing and decking, composite beams, beams and columns, SMF with reduced beam section connection, SCBF design with connection, diaphragm chords and collectors, and welds. Additionally there was general instruction on earthquake loading, seismic design, and detailing. Lectures were planned in advance for timely and organized coverage of the topics necessary for the project. The instructor's experience as a structural engineer and certified welder lent itself to answering student questions that arose during design, fabrication, and testing.

Specifically, during the academic quarter the 3 hour class sessions were divided as follows:

- **Weeks 1 - 3:** 3 hours of lecture on general steel design topics.
- **Weeks 4 - 6:** 2 hours of lecture on design topics related to project, 1 hour project design.
- **Weeks 7 - 9:** 1.5 hours fabricating project; 1.5 hours on project design. Also, small teams of ~4 students completed 2-3 hours per week of project work outside of class.

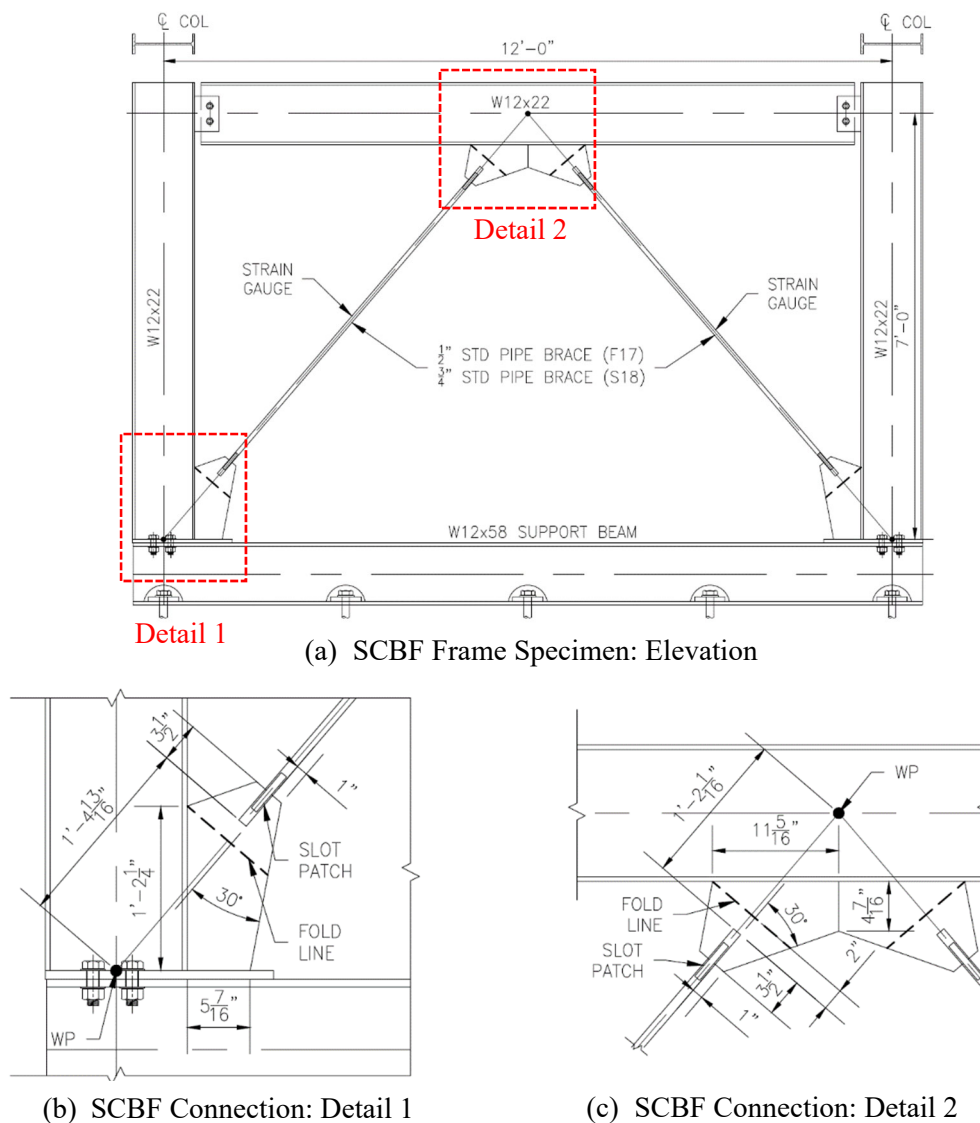
***Table 1.*** Project Schedule for S18 Quarter

Project Milestone Per Category					
Week	Instruction	Design	Fabrication	Testing	Data Analysis
1	Project introduction, review F17 SCBF				
2					
3	Lectures on different SMF and SCBF connections	Select a SMF and SCBF connection			
4	Lectures on SMF and SCBF connection calculations	Complete SMF and SCBF connection calculations			
5	Lectures on proper detailing techniques	Produce AutoCAD drawings and hand sketches of design			
6	Lectures on preparing material take-off for contractor	Develop steel member and bolt schedule	Order steel member and bolts per schedule		
7			Water jet cut plates and cut slots in HSS member		
8	Lectures on bolts		Drill all bolt holes for connections		
9	Lectures on welds	Calculate buckling and failure load of SMF and SCBF	Weld connections and finalize assembly of SMF and SCBF	Apply strain gauges to SMF and SCBF members	
10				Finalize lab set-up and conduct tests of SMF and SCBF	Plot test data and compare to prediction calculations

## Design

### SCBF Design

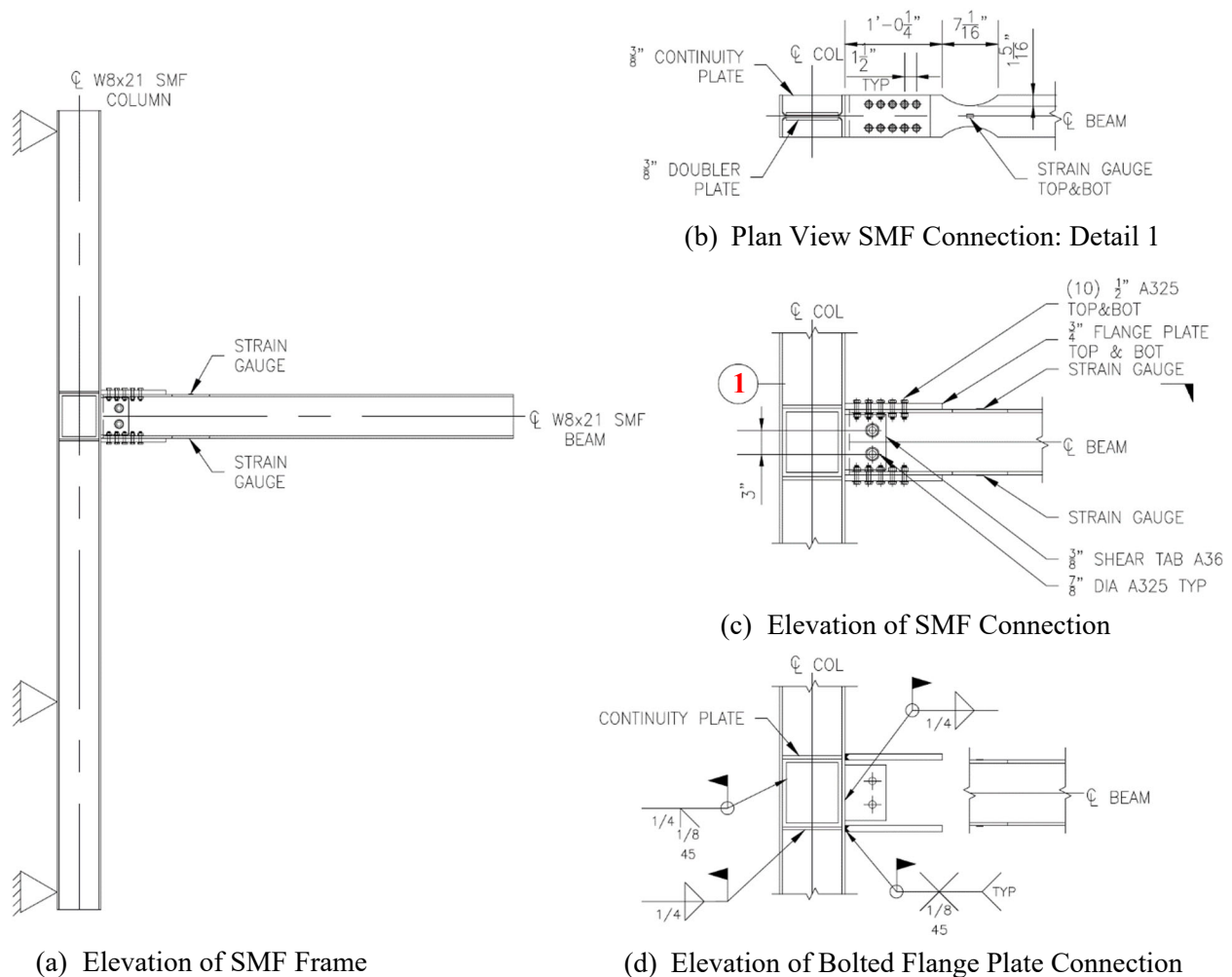
The first step in the SCBF (F17 and S18) design was sizing the brace members for the simple steel frame of W12x22 columns and top beam. The SCBF braces were sized as 1/2-inch and 3/4-inch STD Pipe (F17 and S18 classes, respectively) using a predetermined force of around 13 kips that was the maximum demand that could be reasonably applied by the hydraulic loading jack. Then students determined the gusset plate size based on the weld lengths needed to connect to the columns and base. Students: (i) determined the connection strength required, (ii) checked the brace to gusset connection, (iii) estimated the required gusset plate thickness and width, and (iv) strengthened each brace net section area at the gusset plate in order to prevent rupture in the brace. Figure 1 illustrates the final SCBF specimen and connection details.



**Figure 1.** SCBF Specimen and Connection Details

## SMF Design

The SMF design (S18) began by sizing the beam and column. A W8x21 column was selected as it was one of the smallest W-sections that met that AISC 341 SMF requirements [12]. Students also selected a W8x21 for the beam, and to insure strong column-weak beam behavior they designed a reduced beam section (RBS). Next they selected a moment frame connection that would enable the system to achieve desired strength/ductility while balancing constructability and the desire to reuse the column in future tests. In the connection design process, students reviewed AISC 358, Chapters 5-14 to evaluate the benefits and drawbacks for available moment frame connections [13]. After deliberation, students chose the RBS in conjunction with a bolted flange plate. Figure 2 presents the final SMF specimen and connection details.



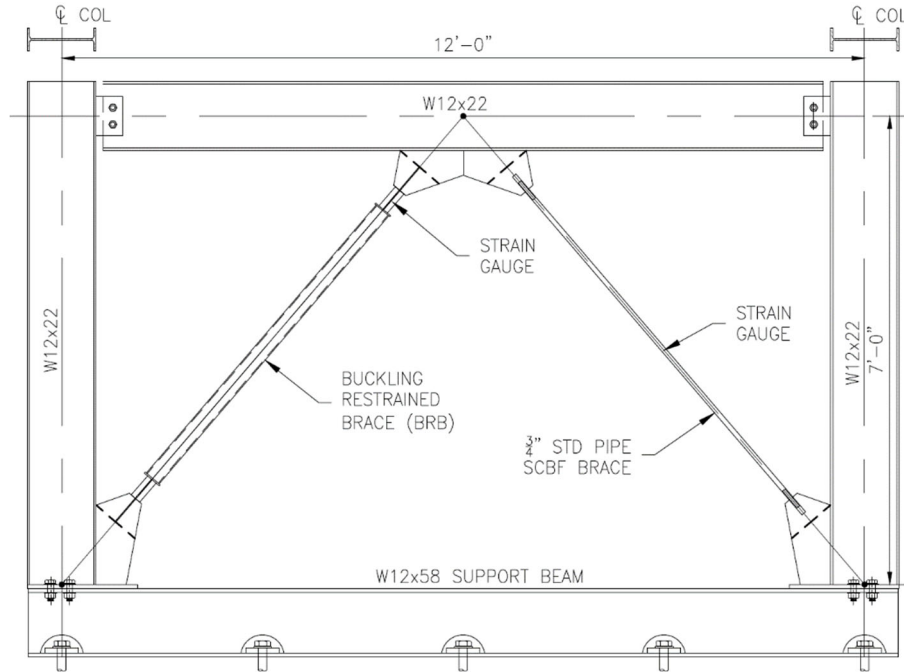
**Figure 2.** SMF Specimen and Connection Details

## BRB Design

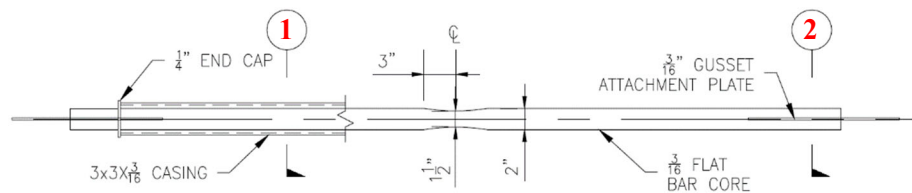
The buckling restrained brace (BRB) design (F18) started with students determining the compression and tension capacity of the SCBF brace, since the BRB would be in the same plane and frame as the SCBF. Students then sized BRB core steel to assure tension and compression



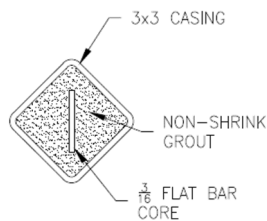
yielding. Next students investigated various casing and core shapes and ultimately selected a 3-inch by 3-inch square tube for the casing and 2-inch wide by 3/16-inch flat bar for the core steel. They then designed a reduced section at the mid-length of the flat bar to insure tension and compression yielding of the core steel. Figure 3 shows the final BRBF/SCBF specimen.



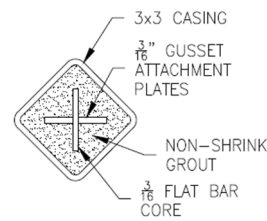
(a) Elevation of BRBF/SCBF



(b) BRB Cross-Section



(c) BRB Core Cross-section: Detail 1



(d) BRB Core Cross-section: Detail 2

**Figure 3.** BRBF/SCBF Combination Specimen and Connection Details

The BRBF/SCBF combination was created as it allowed students to observe the behavior of two bracing systems, while only having to fabricate one specimen. During testing, when the SCBF buckles, the BRBF would be in tension, and vice versa. Thus, this design was for educational purposes only and not does not represent a system that would be implemented in practice.

## ***Fabrication***

### **Facilities, Equipment, and Materials**

Students utilized the College of Architecture and Environmental Design (CAED) Support Shop which includes a metal machine shop with metal band saws, stationary and portable welding machines, grinders, and other metal working tools. Shop supervisors and student technicians guided students in safety and proper fabrication techniques during the projects; necessary personal protection equipment (safety glasses, welding helmet, hard hats, etc.) were provided by the support shop. Students also used the Industrial Design Shop, a student run workshop, for water-jet cutting capabilities.

Appendix A includes an itemized materials list for each project in F17, S18, and F19 as well fabrication, laboratory, instrumentation/data acquisition, and safety equipment.

### **SCBF Fabrication**

The simple frame shown in Figure 1 was fabricated by the F17 class, and has since been reused by the S18 and F18 classes for their SCBF and BRBF/SCBF test respectively. This frame consisted of two columns and a beam, all W12x22, which were cut using a horizontal band saw. The heavy members were held in place with the crane to allow for welds of adequate quality, which exposed students to the difficulty of welding in the field. The gusset plates and braces of the SCBF were added to this existing simple frame.

For SCBF construction, students started by creating AutoCAD files to use as templates to accurately water-jet cut the gusset plates. The gusset plates were then welded at the column-base intersection and mid-span of the beam. The braces, once cut to appropriate length, were slotted using a cutting wheel attached to a grinder and checked against gusset plate thickness for a snug fit. After students verified the braces fit properly in the frame, they welded these to the upper and lower gusset plates. In addition to SCBF specimen construction, students completed two fabrication tasks associated with insuring proper test control: three “shark fins” (sliding slots) to limit out-of-plane motion at the top of frame and two pin connections to mount the hydraulic jack. Photographs of students during the SCBF fabrication process and test set-up are shown in Figure 4.

As an aside about welding that pertains to the SCBF and all subsequent specimen fabrication, students received training from the course instructor who is a certified welder and who also observed all student welding. As a control measure, to account for variability in weld quality produced by the students, welded connections were made longer than necessary and braces were selected to be intentionally small to insure braces were not weld critical. Only the complete penetration weld on the special moment frame end plate connection (bolted plate to column) was completed by the instructor as this was a key element in the fabrication to avoid an undesirable failure of the frame.



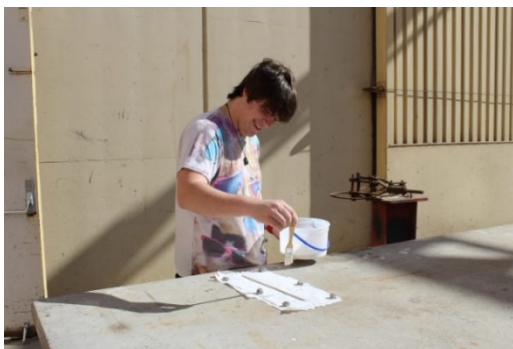
(a) Cutting plate with band saw



(b) Mag drilling holes in beam



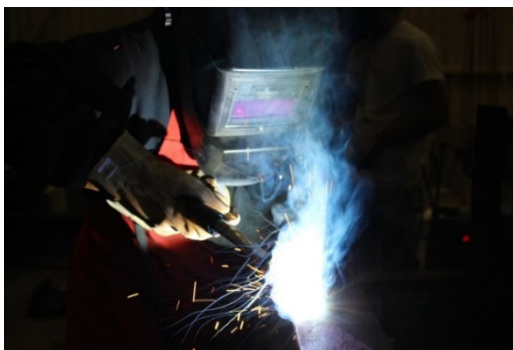
(c) Cutting plate with horizontal band saw



(d) Painting slot patch for brace



(e) Grinding top gusset plate



(f) Welding braces to gusset plates



(g) Grinding a "shark fin"

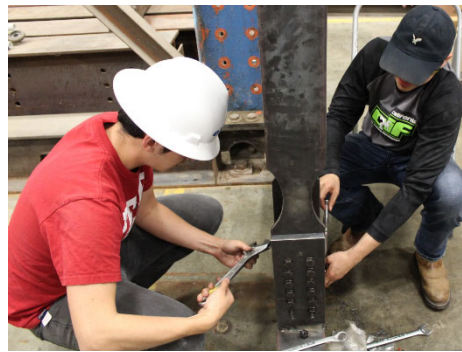


(h) Installing hydraulic actuator

**Figure 4.** Photographs of Students during SCBF Fabrication and Test Set-up

## SMF Fabrication

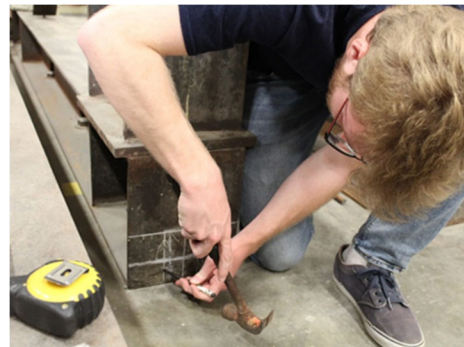
The curved edges of the reduced beam section (RBS) were achieved using a plasma cutter and then smoothed with a grinder. Students are shown bolting the final RBS in Figure 5(a). Another major construction fabrication task for the SMF was adding top and bottom flange plates to the beam as well as a shear plate to the beam web and two shear plates to the column web. All plates were manufactured with the water-jet cutter and bolt holes were produced using a portable magnetic drill. Students then welded the plates in their respective locations. As with the SCBF specimen, additional fabrication tasks were necessary to prepare the SMF test set-up. This included drilling and bolting the strong column of the SMF specimen directly to the reaction frame and constructing a mounting plate (consisting of small beam section, plates, and bolts) to connect the hydraulic jack to the specimen at one end and a concrete reaction block on the other. Photographs of student in various stages of the SMF fabrication and test set-up process are shown in Figure 5.



(a) Bolting RBS connection



(b) Drilling concrete reaction block



(c) Marking holes on reaction frame

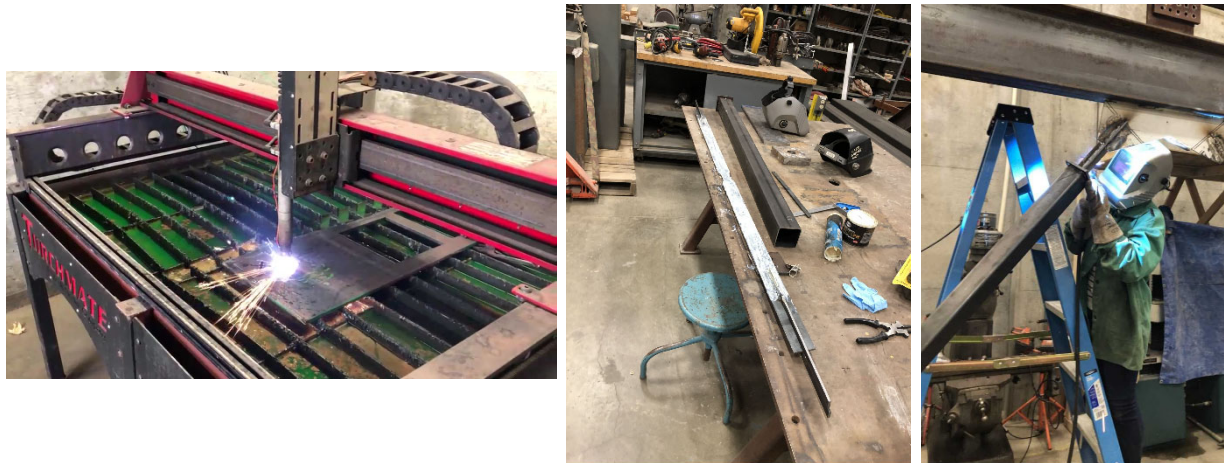
**Figure 5.** Photographs of Students during SMF Fabrication and Test Set-up

## BRB Fabrication

The BRB construction began with the students preparing the core steel: cutting the flat bar on the band saw to the correct length as well as using a small hand grinder for cutting and smoothing out the reduced section at the mid-length. Short stiffening pieces were cut and welded to the ends of the core steel to help prevent the section located outside the casing from buckling when loaded. The flat bar core was prepped with grease and plastic wrap to de-bond it from the grout



that was placed between the casing and the core steel. Once the fabrication of the core steel was complete and the casing cut to length, the students vertically supported the core steel centering it with a shaped plate on one end and proceeded to fill the casing with non-shrink grout. Once the casing was fully grouted, the top end cap was put in place and welded to keep the core steel centered in the casing. After the grout cured the students positioned the BRB in the frame and welded the core steel to the gusset plates. Photographs of various stages of the SCBF/BRBF fabrication process are shown in Figure 6.



(a) Plasma Cutting Core End Caps

(b) Greasing core

(c) Welding BRB to gusset

**Figure 6.** Photographs of Fabricating BRBF/SCBF Combination Specimen

### ***Experimental Testing***

#### **Laboratory Facility**

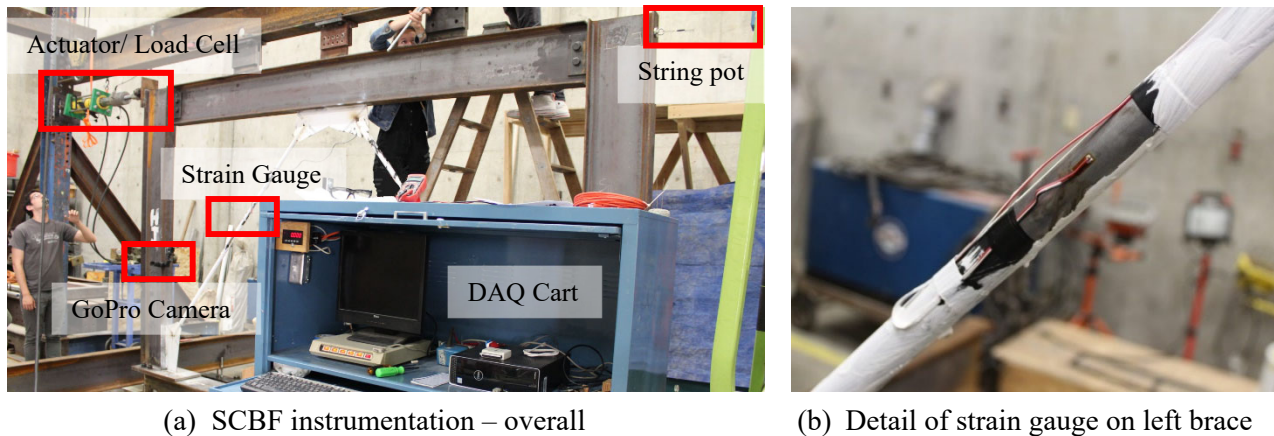
Specimen assembly and testing was conducted in the CAED High Bay Lab, shown in Figure 7. Students had access to a 3-ton Detroit Hoist crane, forklift, and an Enerpac RR5013 hydraulic actuator with 110 kips C/23.6 kips T capacity, as well as a steel reaction frame and strong floor.



**Figure 7.** Photograph of Specimen Assembly in CAED High Bay Lab

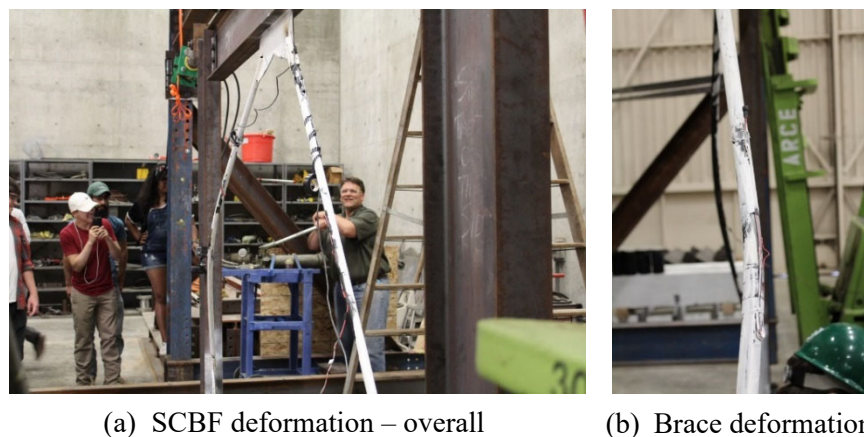
## SCBF Experiment

The SCBF was tested under cyclic loading applied using a hydraulic actuator equipped with a load cell to measure the applied force. In S18 the specimen had a strain gauge installed on each of the brace members and a string potentiometer aligned with the top beam to measure global displacement. Data could be examined in real-time via a computer set-up on the data acquisition (DAQ) cart. A GoPro camera was installed on the column to capture buckling of the braces, and additional still cameras were utilized to document damage progression and final failure mode. The experimental set-up and instrumentation of the SCBF specimen is shown in Figure 8.



**Figure 8.** Photographs of SCBF Experimental Set-up

During testing, students were at first unable to see any change in the system during the initial push. However, upon returning to zero lateral load, they observed the braces had experienced out-of-plane deformation. With additional cycles of increased loading, the braces elongated which provided students with a visual indication of yielding, that they were able to confirm with data collected via strain gauges and the yield strength they had determined for the brace material. Figure 9 illustrates the deformation of the braces. Students noted adequate performance of the brace-to-gusset plate welds (no evidence of tear out) or other significant damage to the gusset plates themselves, and the expected failure mode/limit state of brace yielding.

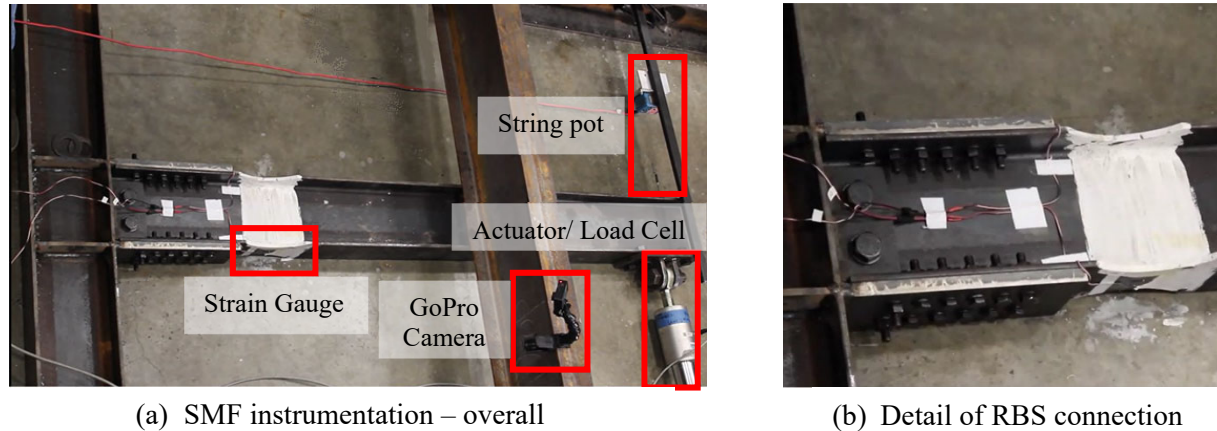


**Figure 9.** Photographs of SCBF Damage



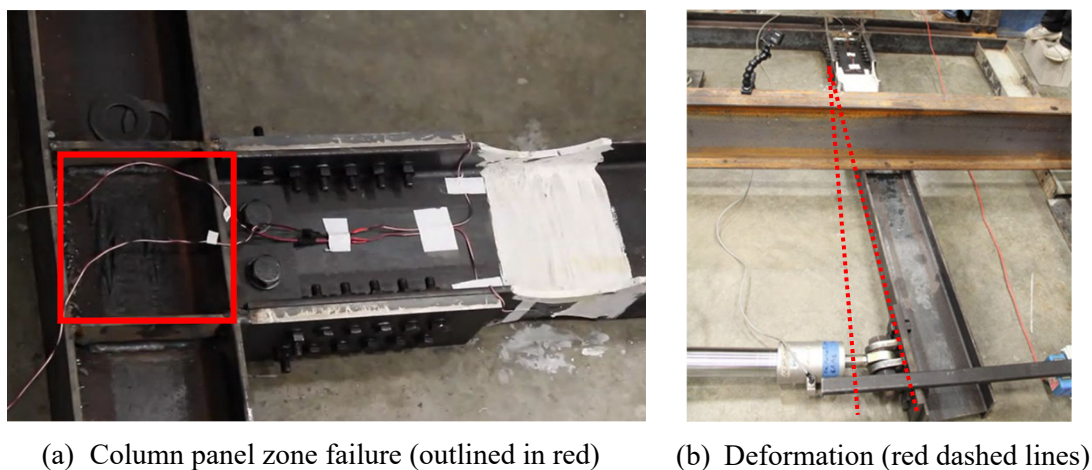
## SMF Experiment

For space accommodation reasons in lab, the SMF system was tested horizontally (parallel to the ground) rather than upright like the SCBF. The SMF was tested under cyclic loading with two strain gauges, one on each flange of the RBS near its narrowest width. A string potentiometer was used to track displacement and a GoPro was mounted on a horizontal W-shape steel section positioned above the SMF. The experimental set-up and instrumentation of the SMF specimen is shown in Figure 10.



**Figure 10.** Photographs of SMF Experimental Set-up

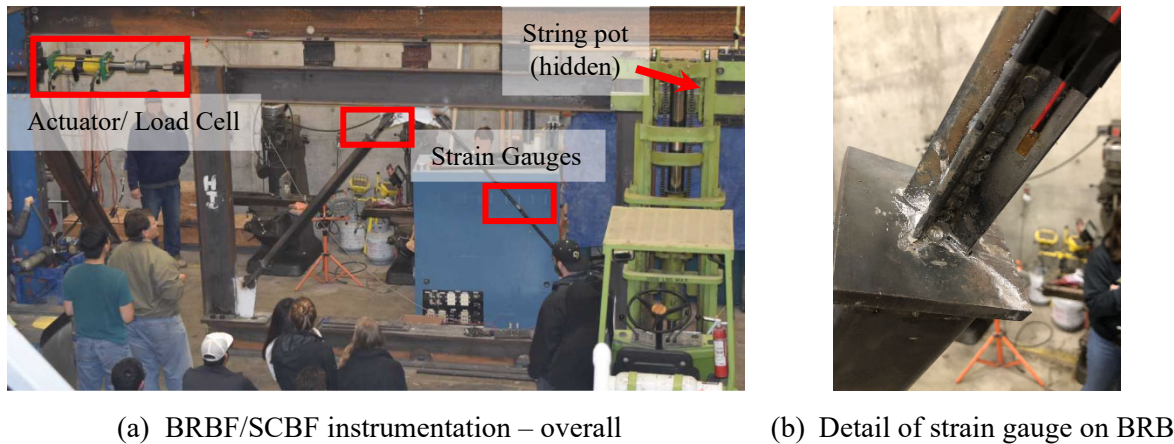
The SMF did not perform as students anticipated: the beam did not yield in the reduced beam section (as evidenced by the fact that none of the white paint chipped off). Instead, students observed the steel coating begin to flake off in diagonal lines at the beam-column joint indicative of a column panel zone failure, as shown in Figure 11. It appeared the load was transferred directly to the column, and instead of the desired strong column-weak beam response, the opposite occurred. Students realized a miscalculation of the effect of the shear plates had generated this structural response. It was a clear demonstration of how a calculation issue could generate issues in design practice and the value of thorough QA/QC. This SMF was re-designed/repaired in the F18 course offering.



**Figure 11.** Photographs of SMF Damage

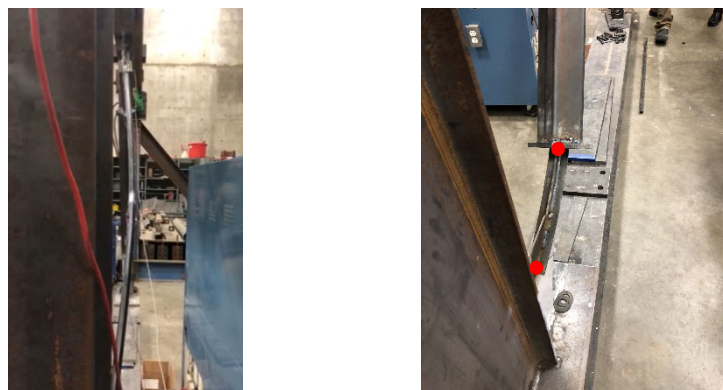
## BRBF/SCBF Combination Experiment

The BRB was tested in the same frame as the SCBF such that one brace of the chevron configuration was designed as a SCBF and the other was a BRB. The frame was cyclically loaded so that BRB and the SCBF were loaded in both tension and compression. Due to the complexity of putting a strain gauge on the encased BRB core, students elected to put the strain gauge on the BRB core steel above the encased region and on the SCBF brace at the mid-length. A string potentiometer aligned with the top beam measured global displacement, and cameras were used to document specimen response. Figure 12 shows the test set-up of the BRBF/SCBF.



**Figure 12.** Photographs of BRBF/SCBF Combination Experimental Set-up

The anticipated response of the BRBF/SCBF was that for the SCBF brace to buckle the BRB brace had to yield in tension; likewise, the BRB had to yield in compression in order for the SCBF brace to yield in tension. During the testing, the SCBF brace buckled and yielded in tension, while the BRB yielded in tension and compression until a bending failure occurred at the gusset plate at the bottom of the BRB. The BRB experienced permanent out-of-plane deflection with three hinges being noted at the: (i) fold line of the bottom gusset plate, (ii) in the bottom end of the core steel as it protruded from the casing, and (iii) at the top end of the core steel as it protruded from the casing. This final damage state is presented in Figure 13.



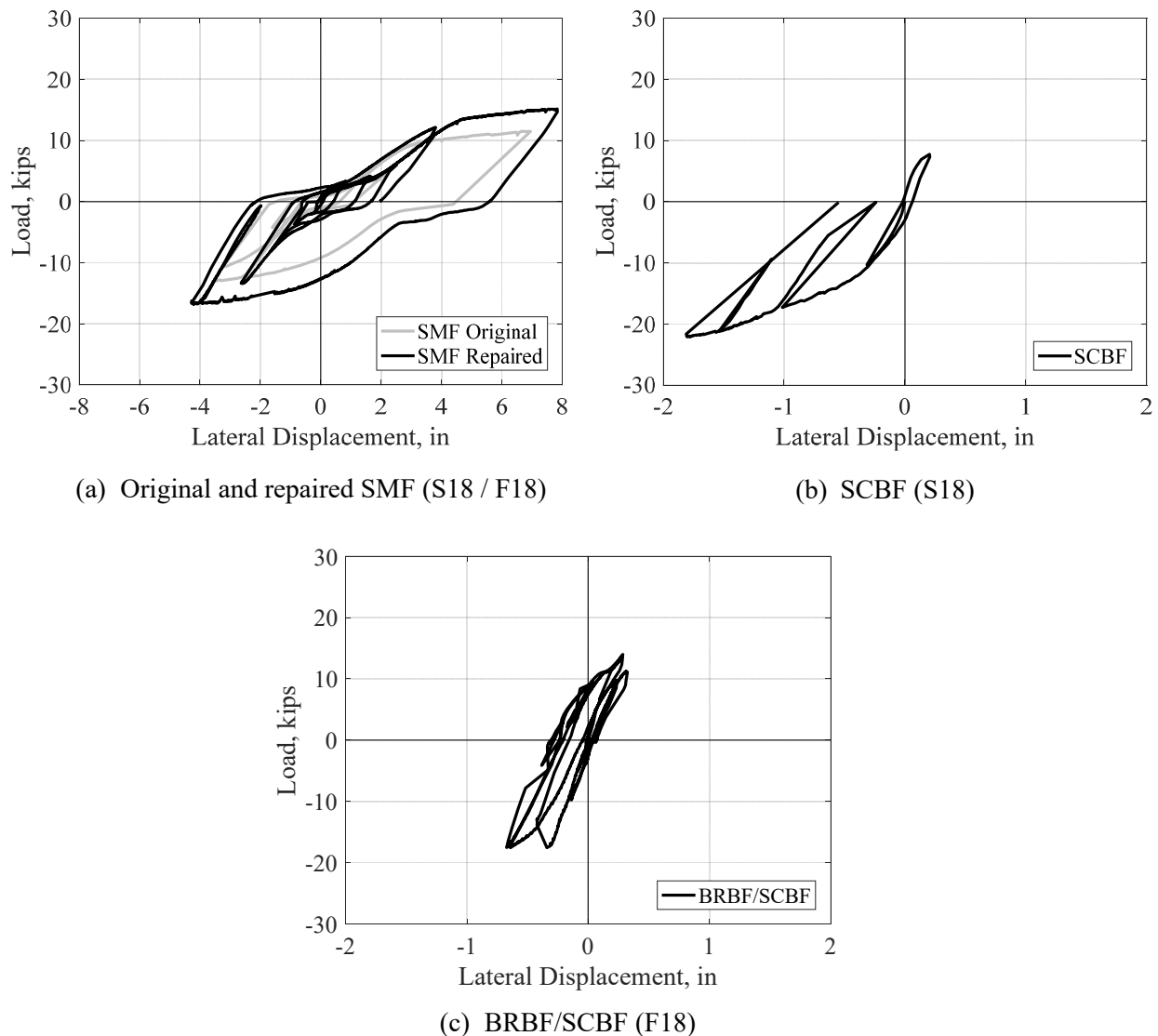
**Figure 13.** Photographs of SCBF/BRBF Damage



A unique opportunity that arose with the BRBF/SCBF testing is that the course instructor was able to arrange for Brandt Saxey, SE, the VP of Preconstruction Sales based out of the Utah office of CoreBrace, LLC to provide a lecture on BRB performance and observe the experimental test of the students' BRBF/SCBF. This industry interaction was meaningful for the students as CoreBrace is responsible for BRB design, inspection, fabrication, testing, and shipping of BRB solutions to projects all over the world.

### ***Data Analysis***

For each LFRS specimen tested, students developed plot of load-deformation behavior, as shown in Figure 14. They then determined the experimental load associated with onset of global yield and failure to compare against calculated values using code equations. Students also reflected on whether damage progression and final failure mode corresponded to design theory. Where behavior diverged from theory, they were asked to comment on source of these differences.



**Figure 14.** Load-deformation curves for LFRS Specimens for S18 and F18 Quarters

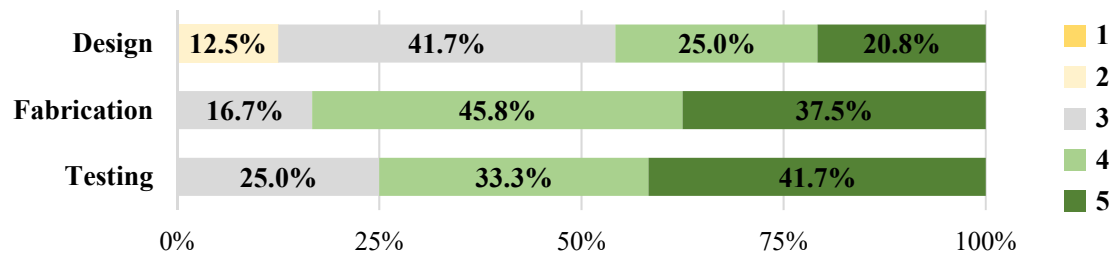
## Student Assessment

### *Description of Student Survey*

Students enrolled in ARCE 372 during the F17, S18, and F18 quarters were asked to complete a survey to evaluate the efficacy of the design, fabrication, and testing projects in learning about various steel LFRS. From the three classes there were 24 survey participants (F17: 4/14, S18: 7/15, F18: 13/13). The survey contains nine standard 5-point Likert scale, nine dual-part 5-point Likert scale, and six (F17 and S18) or seven (F18) free response questions. The Likert scale questions asked students to rate the projects on: (i) instruction, oversight, and feedback from the instructor, (ii) exposure to and confidence with various fabrication skills, and (iii) overall effectiveness in learning about LFRS design and behavior. The free response section consists of a knowledge assessment where students describe SCBF, SMF, and/or BRBF behavior; also, students are asked to reflect on strengths and weaknesses of the projects and how/what skills they gained through the activity. This section summarizes the results of the surveys.

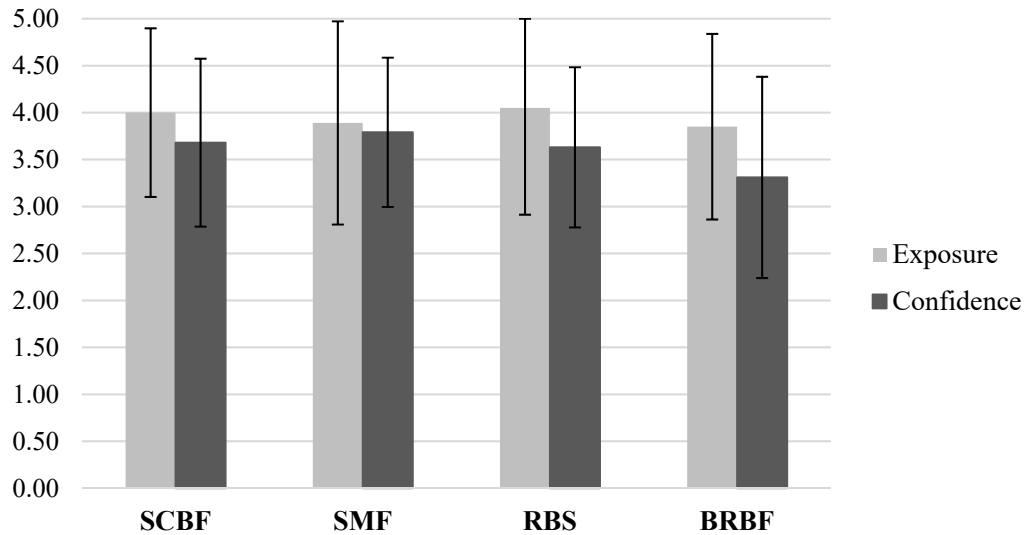
### *Summary of Student Feedback on Multiple-Choice Questions*

Students assessed how effective each project stage of design, fabrication, and testing was at increasing their understanding of steel LFRS (averages: 3.54, 4.21, 4.17 where 5 = very effective and 1 = ineffective). The activities encompassed in the design stage are consistent with project-based activities in previous iterations of the ARCE 372, and traditional steel design courses at other institutions, while fabrication and testing components are new additions. The distribution of responses in Figure 15 indicate students found significant value in the fabrication and testing project stages as an extension of typical design tasks. In interpreting the results, note that the design work was divided among student team members. Thus, each student did not receive direct experience with every task, which may have contributed to lower scores for the design category.



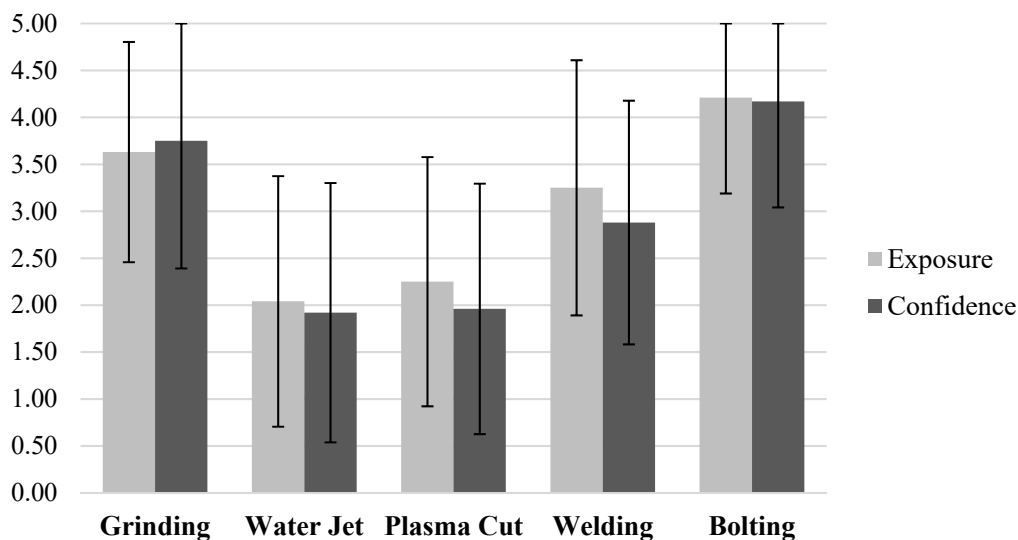
**Figure 15.** Student Perception of Project Stages in Understanding of LFRS  
(5 = very effective, 1 = ineffective)

Follow up questions were utilized to more specifically gauge student exposure and confidence related to the design processes of the various LFRS (SCBF, SMF, RBS, and/or BRBF), as summarized in Figure 16. In this plot, the height of each shaded bar indicates the average ( $\mu$ ) response, and the error bars indicate  $\pm$  one standard deviation ( $\mu \pm \sigma$ ), capped at 5.00. Only F18 students were asked about BRBF as it was only just added to the projects. Students noted moderate to high levels of exposure to each LFRS through course lectures and slightly lower perceptions of their ability to execute these design tasks in assignments and project deliverables. Again, variances in responses in exposure and confidence may be affected by the particular design tasks or checks that a student performed during projects versus those that they did not.



**Figure 16.** Student Perception of Exposure and Confidence to Design Process of LFRS  
(5 = very exposed/confident, 1 = not exposed/confident)

The survey also investigates student exposure and confidence related to various fabrication tasks as shown in Figure 17. For context, freshman architectural engineering students receive basic machine shop training on metal and woodworking equipment, including limited welding under close supervision. For this reason a survey question was included to establish a baseline of students' general fabrication exposure prior to participation in the ARCE 372 course, the average response was 2.79. Due to the nature of the ARCE projects, fabrication was distributed among students and completed with assistance of the instructor and a shop technician. This may account for variances in exposure/confidence responses shown in the plot. On the whole, students indicate a high level of confidence for tasks for which they have significant exposure.



**Figure 17.** Student Perception of Exposure and Confidence to Fabrication Tasks for LFRS  
(5 = very exposed/confident, 1 = not exposed/confident)

### *Summary of Student Feedback on Free Response Questions*

In the free response section of the survey, students were asked the following reflection questions:

- If you were to repeat the project, how would you approach the process differently? What suggestions do you have for the instructor in future course offerings?
- What were the major strengths and weaknesses of the student design and fabrication teams during the completion of the project? Indicate suggested improvements.
- What lecture material, fabrication or other training during the ARCE 372 course offering helped you design and construct the frames? What additional information would you have liked during the design and construction phases?
- What did you learn from constructing a full scale SMF and SCBF? How was this useful in support of your overall understanding of design behavior, and construction of steel lateral force resisting systems?
- Were there other skills you obtained or refined throughout the project?

The authors reviewed responses to these questions and coded them into categories associated with course strength and weaknesses, which are summarized in Figures 18 and 19. These categories are organized into topic groups and displayed in subplots where the answer with the highest response rate appears at the top of each subplot and other answers appear in descending order. This makes it easy to identify the greatest strengths and most pressing areas for improvement in the new projects, so that the instructor can continue to develop these course activities in future offerings.

The following descriptions clarify the types of student responses for each of the project strengths, and are listed in the order of appearance in Figure 18:

#### Fabrication

- **Constructability:** Large-scale specimen fabrication helped students appreciate real-world constructability of their designs.
- **Fabrication:** Learning machining/fabrication skills (band-saw/plasma/water jet cutting and/or welding).
- **Drafting:** Learning additional graphical communication skills (AutoCAD/drafting).

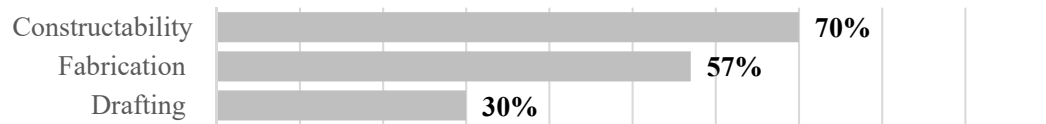
#### Design/Testing

- **LFRS Behavior:** Experiment allowed students visualize how the LFRS behave/fail.
- **Specific Design Calculations:** Learning connection, gusset plate, and/or brace design calculation approaches via lectures.
- **LFRS Design Process:** Learning the entire process of SCBF and/or SMF design as thoughtful, rather than rote, design process.
- **General Design Calculations:** Improving calculation abilities (general, rather than specifically mentioning any of the items in the previous).
- **Load Path:** Experiment allowed students to understand load path.
- **Testing Experience:** Improved understanding of testing through experience.

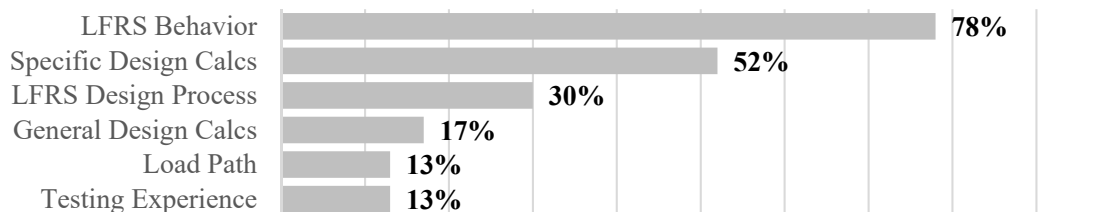
## Professional Skills

- **Teamwork/Communication:** Learning importance of teamwork, collaboration, and/or good communication.
- **Project/Time Management:** Learning importance of time-management and/or project planning.
- **General Problem Solving:** Practicing of general problem solving skills.
- **Other:** Value to students in job interview process (convey hands-on design, construction, and testing experience).

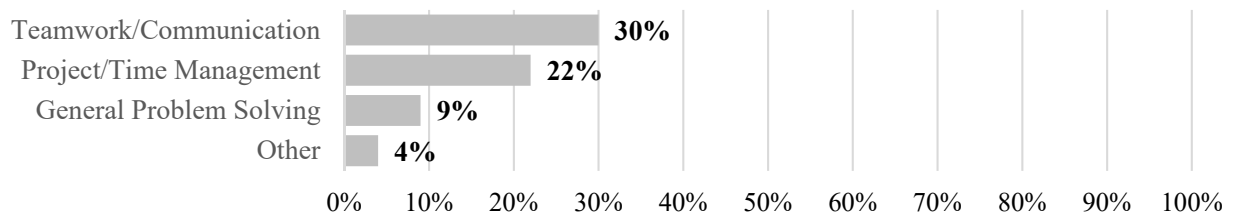
### (a) Fabrication



### (b) Design/Testing



### (c) Professional Skills



**Figure 18.** Classification of Free Response Answers related to Course Strengths  
(Values can sum to over 100% as student can answer in multiple categories)

The most significant student gains are in their understanding of LFRS behavior/failure, knowledge of specific design calculation procedures, and appreciation for constructability of their final design. The following free response highlight the merits of the new course projects.

### Fall 2017 Student Comments:

*“I learned the scope of design to fabrication and all the steps that are involved. I learned the importance of collaboration and good communication. I got to see how a SCBF behaves under lateral loading.”*

*“Overall, this project is a great story to tell employers and shows students' knowledge of lateral systems.”*

### Spring 2018 Student Comments:

*"I learned that there is so much more to the AutoCAD drafts that we produce. It really is impressive to build our own model, and see it actually perform."*

*"It is a lot more difficult to fabricate than it looks but I understand how crucial proper design is to the project, and implementation of that design."*

### Fall 2018 Student Comments:

*"I learned about how to design SMF/SCBF/BRBF. I also learned about project management/construction. It was really valuable to see how each system was built, and then to actually see how they perform when tested. It gives the concept from the book/lectures context for the real-world behavior."*

*"I learned a lot about connections and how everything fits together. I had a pretty good understanding of each, but it was very useful to see the connections to the beam and column. (Also what the core in the BRBF was composed of.) It was helpful when drawing details of our project (in 372)."*

The following descriptions clarify the types of student responses for each of the project weaknesses (or areas of improvement), and are listed in the order of appearance in Figure 19:

#### Fabrication

- **Task Availability:** At times there were insufficient tasks for all students to participate.
- **Fabrication Training:** Need for instructor's assistance caused delay, or students did not feel they had adequate preparation/training to work independently on tasks.
- **Construction Sequence:** Construction sequence was, at times, unclear to students.
- **Other:** Pace of fabrication (too fast or slow), time spent on fabrication was excessive, or instructor should take a more hands-off approach in specimen fabrication.

#### Lectures/Design Calculations

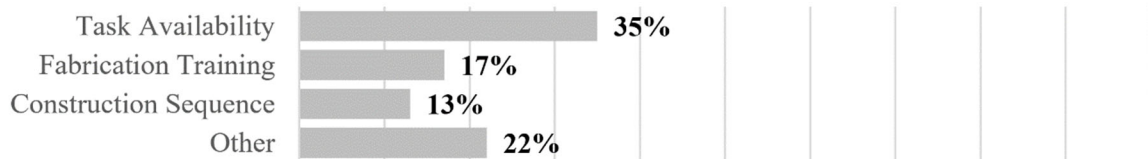
- **Design Lectures:** Requests for additional/more detailed lecture on design topics.
- **Lecture/Feedback Timing:** Lectures on connection, gusset plate, and/or brace design impacted project completion were late in quarter with respect to completing project.
- **Student Participation:** Instructor should engage entire class in design calculations (via QA/QC checks and feedback), so all students gain experience in all LFRS specimens.

#### Project Management

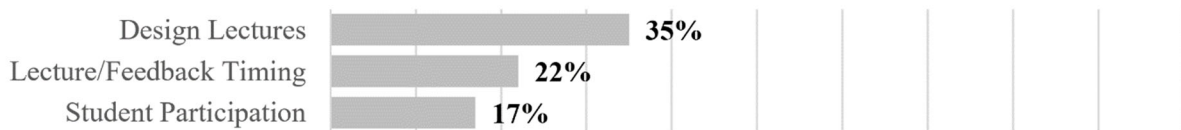
- **Defined Student Roles:** At onset of project, instructor should divide class into groups to assign student roles for calculation/fabrication tasks in an equitable manner
- **Timeline/Milestones:** Provide clear timeline and requirements for deliverable deadlines.
- **Project Start Date:** Start project earlier in the quarter and with more consistent level of work output expected of students.
- **Communication:** Challenges with communication between students on task completion.

- **Student Self-Assembly:** Challenges with project coordination due to lack of student self-assembly into teams and designation of leader.
- **Schedule Coordination:** Challenges coordinating out-of-class worktime for students.
- **Multiple Projects:** Attention divided amongst multiple LFRS projects.

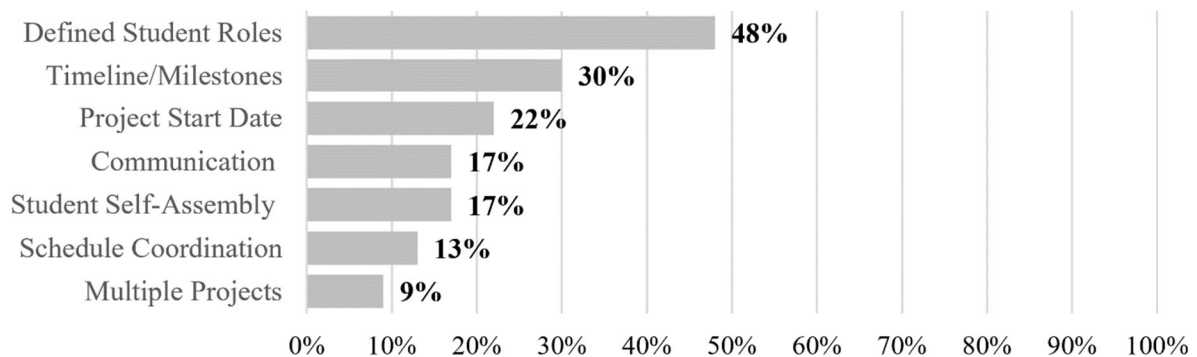
(a) Fabrication



(b) Lectures/Design Calculations



(c) Project Management



**Figure 19.** Classification of Free Response Answers related to Course Weaknesses  
(Values can sum to over 100% as student can answer in multiple categories)

The most critical areas to focus on in coming offerings of the course are helping students assemble into teams, divide project roles, and set milestones. This could be accomplished through a lecture and activity on project management where students list and allocate the design, fabrication, and testing tasks related with consulting from the instructor. Additional care will be taken to better align lectures and feedback with project tasks.

The following free response answers that highlight these suggested areas of improvement:

Spring 2018 Student Comments:

*“There needed to be one leader to manage and delegate roles and tasks for smoother flow and increased productivity. Often the class was too caught up in tasks and lost sight of the overall.”*

## Fall 2018 Student Comments:

*“Next time I would give the students a bit more direction in terms of calculations and fabrication since many of us have done little to no fabrication [experience] before and the material we needed to know to calculate most of these systems was taught very late in the quarter.”*

*“There is only so much that each team can do at a time so there can be people who don’t have much to do. We should have people alternating in tasks and make sure everyone has something to do.”*

## **Summary of Student Knowledge Assessment**

In F17 and S18, students were asked to describe the behavior of a steel SMF and/or SCBF, how they behave differently and how they fail. In F18, students were asked to describe: (i) the behavior of a steel SMF and (ii) how the behavior/failure of a BRBF differs from a SCBF. The coded responses from these student knowledge assessment questions are included in Figure 20.

The knowledge assessment question on SBCFs results indicate that students are aware that the final failure state of this LFRS is out-of-plane buckling of the brace(s) which is often associated with bending of the gusset plate. Brace buckling occurs subsequent to tension yielding in the brace(s). The progression of damage is that yielding in a brace results in elongation of that tension member and horizontal displacement at the top gusset plate, which induces compression in the opposing brace that ultimately leads to buckling. Also, worthy of note is that gusset plates in these systems are intentionally designed so the brace behaves, more or less, as a pin-ended member that is intentionally not restrained against the out-of-plane brace buckling response.

With respect to the SMF, students indicated that the desired behavior is that RBS yields and fails (flanges buckle) to result in a ductile strong column/weak beam behavior. However, in the experimental test during S18 the panel zone (at the beam-column joint) failed due to a design calculation error; this is an undesirable failure from a design perspective but the true response in the case of the test specimen.

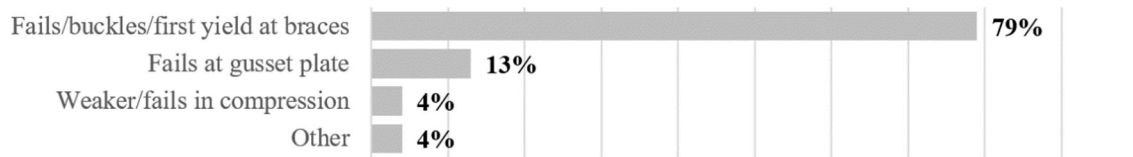
Finally, with the BRBF/SCBF students indicate the BRB is a steel brace is fully encased, but unbonded, along its length with concrete/grout. This configuration is intended to have similar strength and ductility for both compression and tension, and that the steel core yielding controls the response rather than out-of-plane brace buckling. In the BRBF/SCBF combined configuration the damage progression is that the BRBF brace has to yield in tension to allow horizontal displacement at the top gusset plate to induce sufficient compression in the SCBF for it to experience out-of-plane buckling.

Overall it seems that not only do students understand the unique construction of each LFRS configuration and the ultimate desirable/undesirable failure mechanisms, but also the damage progression required to reach that failure. It is this idea of how design effects damage progression to result in a certain failure, that is a significant advantage of conducting and analyzing a large-scale experimental test rather than solely adhering to code equations related to

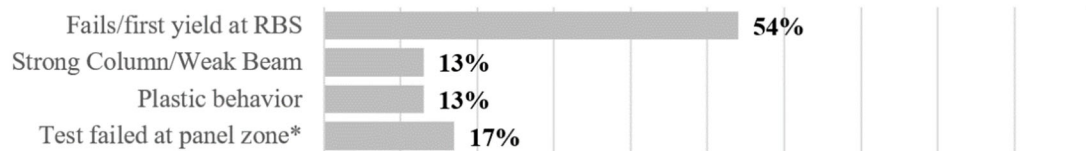


limit states or conducting computer simulations. The student descriptions to the knowledge based questions indicates that witnessing the real performance of an LFRS provides a deeper intuition.

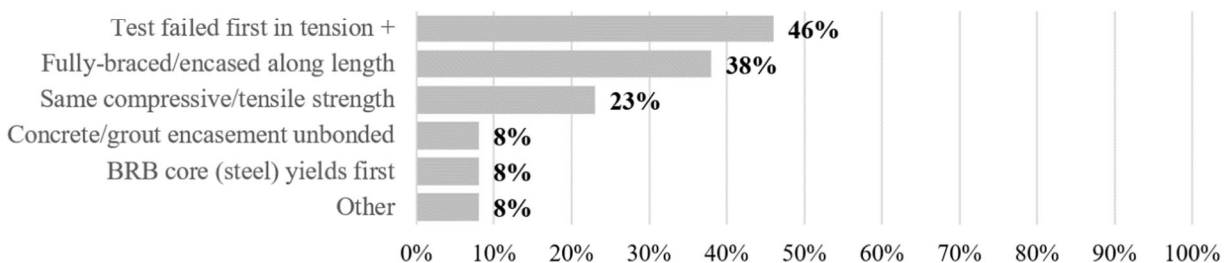
(a) SCBF



(b) SMF



(c) BRBF/SCBF



\*Indicates undesirable SMF behavior students observed in S18 experimental test due to design error.

+ Refer to description of tension yielding in previous paragraph about BRBF/SCBF damage progression

**Figure 20.** Classification of Student Responses on LFRS Behavior/Failure  
(Values can sum to over 100% as student can answer in multiple categories)

## Implementation at Other Institutions

After three iterations of the new format for the ARCE 372 steel design course, the authors conclude that the design-build-test projects described in this paper would be successful at other institutions as a senior capstone project or in an advanced/graduate level structural steel design course. This recommendation is due to two reasons: (i) the complex nature of designing seismic steel LFRS requires previous exposure to the fundamentals of steel design, and (ii) more frequent and/or longer course sessions can accommodate lecture, design, and fabrication without significant out-of-class time investment.

As a resource for other educators, a video of the various stages of these design-build-test projects from the S18 quarter is available on the ARCE Cal Poly YouTube channel:

<https://www.youtube.com/watch?v=Non3PXkMFis> .

## Lessons Learned

The following lessons learned are from the perspective of the student co-authors that participated in the course in S18 quarter and their summary of their peers' survey feedback:

- ***Students gained a greater understanding of the constructability of their designs.*** Students designed and fabricated each LFRS system. Many students expressed a greater appreciation for the construction of these systems and indicated a greater value in providing clear, constructible design details. Additionally, they were able to refine their structural design and detailing abilities.
- ***Students enjoyed testing full scale models because it helps them visualize the behavior and failure of lateral force resisting systems.*** Full-scale testing provided students a visual aid to reinforce understanding of behavior and failure of each system. This tangible experience offered a memorable, alternative approach to the traditional project-based learning activities from previous ARCE 372 offerings.
- ***The hands-off instructional approach presented challenges related to self-assembly of student teams, organization, and communication.*** In a traditional classroom setting, students would be given a specific set of instructions to follow as they complete the project. The course projects described in this paper required students complete design, construction, and testing tasks without explicit instructions. In these types of course projects, the instructor should consider teaching project management skills as well as planning, coordination, and communication to prepare students for the experience.

These next lessons learned are from the point of the view of the faculty co-author that instructed the course in F17, S18, and F18:

- ***Through experimental testing students developed a better understanding of damage progression for each steel LFRS, rather than just the final failure state.*** In their knowledge-based assessment question, students were able to identify intermediate damage states (such as necessary tension yielding of one brace before the opposing brace could buckle), that are beyond the understanding gained through code-based or computer simulation analyses. These pencil and paper / computer approaches do not allow students to track through the onset of damage in the same way as physical experiment.
- ***Students should be given the latitude to make their best informed design decisions, even if those decisions are a “mistake”, so they can understand the physical consequences.*** The instructor, as a consulting engineer, has seen the types of calculation and/or decision errors that students made with the SMF in S18. However, the students realized through physical testing that the RBS did not yield and fail as intended, and instead the damage was concentrated in the beam-column joint panel zone. The learning gained through this was considerable for them as well as the subsequent F18 students who repaired the system.
- ***The laboratory testing/loading set-up can impact the damage progression and final failure of the steel LFRS.*** As an example, some modifications need to be made to avoid the out-of-plane bending that occurred with the repaired SMF test in F18 where the RBS yielded but not fully fail (flange buckling) as intended.

## Acknowledgements

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## Appendix A: Summary of Materials & Equipment

### Materials

Item	Description	Quantity Purchased
<b>Fall 2017 – Frame (\$1000)</b>		
2 columns + 1 beam	W12x22	30'
1 beam	W12x58	15'
Shark fins	3/4" Plate	*found in Cal Poly CAED Machine Shop
Shear tabs	1/4" Plate	*found in Cal Poly CAED Machine Shop
<b>Fall 2017 – SCBF (\$500)</b>		
Braces	1/2" STD Pipe	10'
Gusset Plates	3/16"	4' x 4' sheet
Bolts	A325 7/8"	30 count
<b>Spring 2018 – SCBF (\$500)</b>		
Braces	3/4" STD Pipe	10'
Gusset Plates	3/16" thick	*reused from Fall 2017
Bolts	A325 7/8" Bolts	*reused from Fall 2017
<b>Spring 2018 – SMF (\$500)</b>		
1 column + 1 beam	W8x21	20'
Doubler Plates, Continuity Plates, Shear Tabs	3/8" thick	6" x 10' sheet
Flange Plates	3/4" Plate	6" x 10' sheet
Bolts	A325 7/8"	*reused from Fall 2017
Bolts	A325 1/2"	30 count
<b>Fall 2018 – BRBF/SCBF (\$500)</b>		
Brace	3/4" Pipe	10'
Gusset Plates	3/16" Gusset Plates	2" x 2' sheet
BRBF Casing	3' x 3' x 3/16"	1 count
End Caps	1/4" Plate	4' x 4' sheet
Flat Bar Core	3/16" Flat Bar Core	2" x 10' sheet
BRBF Fill	Non-Shrink Grout	

### Equipment

<b>Fabrication Equipment</b>	<b>Safety Equipment</b>
Basic Hand Tools (Wrench, Hammer, etc)	Safety Glasses
Magnetic Drill	Hard Hats
Vertical Band Saw	Ear Plugs
Horizontal Band Saw	Welding Helmet
CNC Plasma Torch (alternative: acetylene torch)	Welding Gloves
CNC Waterjet (alternative: band saw)	Welding Apron
Metal Grinders	
Miller 210 Welder	
<b>Laboratory Equipment</b>	
3-ton Detroit Hoist Crane	
Forklift	
Enerpac RR5013 hydraulic actuator	
Steel Reaction Frame/Strong Floor	
<b>Instrumentation &amp; Data Acquisition</b>	
Basic Measuring Tools (Tape Measure, Levels, etc)	
Strain Gauges	
String Potentiometer	
Go Pro Cameras	
DSLR Camera w/video capabilities	
Data Acquisition Computer and Hardware	

## Appendix B: Summary of FE, PE, and ABET Criteria Attained

The following tables describe the FE and PE exam objectives and ABET criteria met by ARCE 372.

### *Fundamentals of Engineering (FE) CIVIL CBT Exam Specifications [14]*

<b>3. Computational Tools</b>	
	A. Spreadsheet computations
<b>6. Statics</b>	
	A. Resultants of force systems
	B. Equivalent force systems
	C. Equilibrium of rigid bodies
	D. Frames and trusses
	E. Centroid of area
	F. Area moments of inertia
<b>8. Mechanics of Materials</b>	
	A. Shear and moment diagrams
	B. Stresses and strains (e.g., axial, torsion, bending, shear, thermal)
	C. Deformations (e.g., axial, torsion, bending, thermal)
	D. Combined stresses
	E. Principal stresses
	G. Column analysis (e.g., buckling, boundary conditions)
	H. Composite sections
	I. Elastic and plastic deformations
	J. Stress-strain diagrams
<b>9. Materials</b>	
	B. Test methods and specifications (e.g., steel, concrete, aggregates, asphalt, wood)
<b>12. Structural Analysis</b>	
	A. Analysis of forces in statically determinant beams, trusses, and frames
	B. Deflection of statically determinant beams, trusses, and frames
	C. Structural determinacy and stability analysis of beams, trusses, and frames
	D. Loads and load paths (e.g., dead, live, lateral, influence lines and moving loads, tributary areas)
	E. Elementary statically indeterminate structures
<b>13. Structural Design</b>	
	A. Design of steel components (e.g., codes and design philosophies, beams, columns, beam-columns, tension members, connections)
<b>17. Construction</b>	
	A. Construction documents
	C. Project delivery methods (e.g., design-bid-build, design build, construction management, multiple prime)
	D. Construction operations and methods (e.g., lifting, rigging, dewatering and pumping, equipment production, productivity analysis and improvement, temporary erosion control)
	E. Project scheduling (e.g., CPM, allocation of resources)
	G. Construction safety

***Principles and Practices of Engineering Examination (PE) Civil Breadth Exam Specifications [15]***

<b>IV. Structural Mechanics</b>	
	A. Dead and live loads
	C. Bending (e.g., moments and stresses)
	D. Shear (e.g., forces and stresses)
	E. Axial (e.g., forces and stresses)
	F. Combined stresses
	G. Deflection
	H. Beams
	I. Columns
	J. Slabs
<b>VII. Materials</b>	
	D. Structural steel
	E. Material test methods and specification conformance

***Principles and Practices of Engineering Examination (PE)***  
***Structural Breadth Exam Specifications [15]***

<b>I. Analysis of Structures</b>	
<b>A. Loads and load applications</b>	
1.	Dead loads
2.	Live loads
3.	Construction loads
5.	Seismic loads
10.	Load paths (e.g., lateral and vertical)
11.	Load combinations
12.	Tributary areas
<b>B. Forces and load effects</b>	
1.	Diagrams (e.g., shear and moment)
2.	Axial (e.g., tension and compression)
3.	Shear
4.	Flexure
5.	Deflection
6.	Special topics (e.g., torsion, buckling, fatigue, progressive collapse, thermal deformation, bearing)
<b>II. Design and Details of Structures</b>	
<b>A. Materials and material properties</b>	
2.	Steel (e.g., structural, reinforcing, cold-formed)
<b>B. Component design and detailing</b>	
1.	Horizontal members (e.g., beams, slabs, diaphragms)
2.	Vertical members (e.g., columns, bearing walls, shear walls)
3.	Systems (e.g., trusses, braces, frames, composite construction)
4.	Connections (e.g., bearing, bolted, welded, embedded, anchored)
<b>III. Codes and Construction</b>	
<b>A. Codes, standards, and guidance documents</b>	
1.	International Building Code (IBC)
4.	Steel Construction Manual (AISC)
7.	Minimum Design Loads for Buildings and Other Structures (ASCE 7)
8.	American Welding Society (AWS D1.1, D1.2, and D1.4)
<b>B. Temporary structures and other topics</b>	
1.	Special inspections
2.	Submittals

***Principles and Practices of Engineering Examination (PE)***  
***Seismic Principles Exam Specifications [16] (Page 1 of 2)***

<b>I. Seismic Data and Seismic Design Criteria</b>	
A.	Loads and load applications
B.	Site-related seismic coefficients
C.	Natural period of the structure and the expected period of the seismic ground motion
D.	The seismic design philosophy of the applicable code
E.	Applicable laws, regulations, and codes for civil engineering seismic design and construction
F.	Seismic Design Categories
G.	Building Risk Categories
H.	Seismic importance factors
<b>II. Seismic Characteristics of Engineered System</b>	
A.	The different structural systems and their design parameters
B.	Limitations of different structural systems
E.	Drift and P-Delta effects
F.	Effects of ductility and damping on seismic performance
G.	Effects of redundancy on seismic performance
L.	Buckling or brittle connections in steel braced frame structures
M.	Welded connection failures in steel moment frames
N.	Assessment and identification of post-earthquake damage and risk
Q.	Methods and effects of improving ductility of brittle elements
<b>III. Seismic Forces: Building Structures</b>	
A.	Mass and stiffness
B.	Methods to determine the structure's fundamental period
C.	Selection of seismic factors and coefficients required for design
D.	Static force procedures and formulas
E.	Structural system seismic coefficient application
F.	Design base shear
G.	Vertical force distribution
H.	Design seismic forces on diaphragms
I.	Design seismic forces on structural elements
K.	Design lateral force formulas



***Principles and Practices of Engineering Examination (PE)***  
***Seismic Principles Exam Specifications [16] (Page 2 of 2)***

<b>IV. Seismic Analysis Procedures</b>	
	A. Applicable load combinations
	B. Distribution of internal and external forces
	C. Application of deflection and drift requirements
	D. Diaphragm force distribution to structural elements (e.g., chord forces, drag forces and diaphragm shear)
	E. Methods used to calculate rigidities of structural elements
	F. Distribution of seismic forces based on rigidity
	G. Assumptions controlling the analysis for rigid diaphragms
	H. Methods to determine centers of rigidity and mass
	I. Torsional moment requirements in rigid diaphragms
	J. Assumptions controlling the analysis of flexible diaphragms
<b>VI. Seismic Detailing and Construction Quality Control</b>	
	A. Seismic detailing and inherent seismic performance characteristics for steel
	F. Required building separation and setback
	I. Seismic materials testing requirements
	J. Seismic special inspection requirements
	K. Seismic structural observation requirements

### ***Accreditation Board for Engineering and Technology (ABET) Criteria [17]***

The following ABET Criteria, General Criterion and Program Criteria, are covered by the ARCE 372 project. It should be noted that the ARCE 372 course with new design-build-test projects meets the majority of the ABET Criteria that is required of the Architectural Engineering Department to meet accreditation requirements.

<b>ABET: General Criterion 3. Student Outcomes</b>
1. An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.
2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.
3. An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.
4. An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts
5. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.
<b>ABET: Program Criteria for Architectural Engineering and Similar</b>
These program criteria apply to engineering programs that include “architectural” or similar modifiers in their titles.
<b>1. Curriculum</b>
The program must demonstrate that graduates can apply mathematics through differential equations, calculus-based physics, and chemistry. The four basic architectural engineering curriculum areas are building structures, building mechanical systems, building electrical systems, and construction/construction management. Graduates are expected to reach the synthesis (design) level in one of these areas, the application level in a second area, and the comprehension level in the remaining two areas. The engineering topics required by the general criteria shall support the engineering fundamentals of each of these four areas at the specified level. Graduates are expected to discuss the basic concepts of architecture in a context of architectural design and history.
The design level must be in a context that:
a. Considers the systems or processes from other architectural engineering curricular areas,
b. Works within the overall architectural design,
c. Includes communication and collaboration with other design or construction team members
d. Includes computer-based technology and considers applicable codes and standards, and
e. Considers fundamental attributes of building performance and sustainability.