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Large-scale Timber Shear Wall Experimentation in an Undergraduate Design Course

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Abstract

Despite the widespread use of light-frame timber construction in residential building, wood design courses are typically offered to graduate students and focus on member-level calculations for gravity and lateral systems per the National Design Specification (NDS) for Wood Construction. In years prior, the 10-week advanced undergraduate class described in this paper exposed students through a system-level perspective through a group design project of a multi-story, mixed-use wood building located in a seismic region. A significant course modification in Fall 2020 involved the two class sections constructing and testing large-scale wood shear walls representing a one-story segment of a wall present in their multi-story building project: (i) segmented and (ii) force transfer around openings (FTAO) shear walls. The stages of each shear wall experiment included: design calculations and drawings, fabrication of wall specimens, experimental test set-up, conduct of test, and analysis of data.

This new activity exposed students to additional technical concerns related to constructability and seismic performance of shear walls. Also, it promoted development of skills in project management and teamwork. Feedback collected via surveys of the students indicated that the addition of the timber shear wall experiment allowed students to physically comprehend how these structural components are assembled and behave under loading.

Introduction

In most civil engineering programs, timber design is listed as a graduate course allowing enrollment from upper-division undergraduate students given certain pre-requisites and GPA. The curriculum covers the analysis and design of timber buildings, specifically: (i) determination of gravity and lateral loads using ASCE 7-16 [1] and the International Building Code (IBC) 2018 [2], (ii) gravity system design (tension, compression, and beam members), and (iii) lateral system design (beam-columns, horizontal diaphragms, and shear walls). Typically, the focus is on the structural element and connection, rather than the entire system since many of these courses do not have a culminating final project requiring a comprehensive building design. In the course, students are exposed to strength and serviceability requirements of the 2018 National Design Specification (NDS) for Wood Construction [3] used in the structural engineering industry.

When there are culminating projects within a timber course, these tend to be more limited in scope to theoretical design [4] since there is already a significant amount of new lecture material to cover in the class. In contrast, undergraduate senior projects related to timber (that follow a design course) allows for a longer timeframe and therefore a broader scope that enables the incorporation of construction and physical testing [5-7]. A selection of course and senior projects involving timber design are presented below to provide the reader with a basis for the current state of project-based learning curriculum specifically for design and/or experimentation of timber structures. Literature reviews of project-based learning have been conducted previously for reinforced concrete and steel structural design courses by the authors [8-9].

Course & Senior Projects

Ardakani [4] outlines a group project in an elective timber design course offered to upperclassmen at Ohio Northern University. Teams considered different residential building designs to rebuild the Florida Panhandle region after the 2018 Hurricane Michael. Group tasks were to: (i) determine dead, live, and wind loads per ASCE 7 [1]; (ii) design roof framing, columns, load-bearing walls, diaphragms, and shear walls using commercial software; (iii) produce architectural and structural drawings; and (iv) prepare a report and oral presentation to communicate the team's final design. Survey results indicated that students felt the real-world project motivated them to consider client needs and engage in critical thinking as they interrogated various design options. Students also responded that the project was technically valuable in strengthening their timber design skills.

Zhou & Tanski [5] describes a senior project at Central Connecticut State University to deliver a community pedestrian timber bridge. Tasks included: (i) site survey and mapping, (ii) bridge design using industry standards and modelling using commercial software, (iii) construction and testing for deflection compliance, and (v) installation of the bridge. Students kept bi-weekly progress logs and shared their final project through a written report and oral/poster presentation. Similar senior projects are discussed in Welch & Grant [6] and Welch [7] where student teams at the U.S. Military Academy (USMA) designed and constructed timber foot bridges. The former consisted of two pedestrian bridges at a historic site with rugged terrain near campus, and the latter was a bridge replacement on campus near a maintenance facility. All three projects provided value to student learning of technical (iterative structural design, construction, and physical testing) and professional skills (project scheduling, acquiring funding and materials, communicating with collaborators, and coordinating with community stakeholders).

Research Motivation

This and prior literature reviews [4-9] by the authors on project-based learning in structural design courses indicate that it is more educationally effective and engaging to simulate tasks students will see in the structural engineering industry compared to a lecture-based approach. The characteristics that define the most successful cases of project-based learning address a multi-dimensional problem that enable students to participate in one or more of the following:

- Design a structural system for a building or bridge using code-based approaches and/or commercial software with considerations for strength and serviceability.
- Conduct tasks associated with industry partners: construction management (prepare materials schedule and construction timeline as well as oversee and inspect fabrication), contractors (build structural system based on provided drawings and specifications), materials and systems testing engineers (collect and test material samples, or conduct physical experiments to assess structural system performance), etc.
- Communicate design solution through professional written report (calculations and drawings) and/or oral or poster presentation.

The literature review yielded no similar timber design courses (undergraduate or graduate) which use a multi-dimensional, project-based learning approach to expose students specifically to timber shear walls common in seismic areas. Thus, to address this existing shortcoming, the authors implemented the new design-build-test project described in the remainder of this paper.

Course Details

The Department of Architectural Engineering at Cal Poly is situated on the West Coast and thus places an emphasis on structural seismic design. This training starts in a junior-level structural systems lab course where students use ASCE 7-16 [1] to calculate gravity and lateral loads on buildings and identify load paths. Two quarters later in the curriculum flowchart, students take a lecture course that introduces timber design per the 2018 NDS [3] for structural members subjected to axial, shear, and bending forces, connections, as well as diaphragms and shear walls.

The new projects described in this paper took place in the subsequent course where students are further exposed to timber design, usually during senior year, which is the *ARCE 451 – Timber & Masonry Structures Design and Constructability Laboratory*. Instructors for ARCE 451 are licensed engineers with many years of industry experience who provide lectures and project advising. In past offerings of the course, students designed a 3-story, mixed use wood building during the 10-week quarter where they: conducted a structural analysis, produced calculations for the structural design of the gravity and lateral force resisting systems, and prepared construction drawings. This paper focuses on the Fall 2020 offering of two ARCE 451 sections (16 students each, 9 contact hours per week) where new design-build-test projects of segmented and force transfer around opening, FTAO, shear walls were introduced for a more multi-dimensional student experience involving additional tasks of construction and experimentation.

Project Overview

In Fall 2020, each course section designed, built, and tested one wall specimen type: segmented and FTAO walls. This pairing of wall types was selected to demonstrate the impact that openings have on wall flexibility. The intention of adding the new projects to the course was to expand the student knowledge beyond theoretical design to include construction, physical testing, and data analysis of a common timber lateral force resisting system. The experience also helped students practice professional skills critical to executing a project of this scope and a large team.

In addition to the educational merit to the undergraduate students in the course, the instructors in Fall 2020 have been particularly interested in FTAO shear walls since they are gaining in prevalence in industry, yet current timber design codes do not provide an adequate method to accurately predict their lateral stiffness. Therefore, to utilize the ARCE 451 results for broader industry impact, the first author of this paper was recruited as a graduate researcher to collaborate with undergraduate students during Fall 2020 and conduct more detailed design, experimental set-up, data collection and analysis than what was necessary for the course.

Project Tasks

The project tasks the student teams were responsible for included:

- Design calculations: selection of sheathing, framing, fastening pattern, chord post size, and holdowns to provide sufficient resistance for shear, shear transfer, and uplift;

- Shop drawings: documentation of design including material take-off used to assess against existing material inventory and make purchasing or donation requests;
- Fabrication of wall specimen: assembly of framing and sheathing, installation of wall anchorage into concrete foundation, and straps around window openings (for FTAO);
- Experimental test set-up: construction of loading beam, configuration of support frame, erection of wall, and instrumentation;
- Testing: conducting a cyclic loading protocol to collect data on wall strength and deflection as well as identify damage progression and final failure mechanism;
- Analysis of data: evaluation of experimental results compared to NDS predictions for strength and deflection as well as reflection on anticipated versus observed behavior.

To elaborate on the last point of data analysis, students computed wall shear strength via two approaches: (i) 2015 NDS Special Design Provisions for Wind and Seismic (SDPWS) [10] Section 4.3.3.1 which accounts for sheathing material, thickness and fastener penetration, type, size, edge spacing and (ii) American Plywood Association (APA) Research Report 154 [11] Table A1 using the average experimental results for the walls with a given sheathing material/thickness and fastener type/size/spacing. For the segmented shear wall, students computed deflections utilizing the NDS SDPWS [10] Section C4.3 using the 3-term (bending, shear, tie-down nail slip) and the 4-term equation (also includes nail slip). Specifically, they determined the deflection associated with the predicted design strength and developed load-displacement plots. For the FTAO wall, the deflection calculation was left open-ended. The instructors challenged the students to conduct research, consider how they have calculated wall deflections in their past courses on other structural material types, and propose an approach for coming up with a reasonable estimate for the FTAO wall. The graduate student researcher did pursue a more involved calculation for the FTAO wall type using a technical note and accompanying Excel-based tool available through the APA website [12].

Design

The segmented and FTAO walls were nominally identical with a height of 12’-11” and width of 6’-8”. In order for students in both course sections to practice framing out a window, both the segmented and FTAO walls have top cripple, header, king studs, jack studs around the 3’ by 3’ window ‘opening’. In the segmented wall, the location of the ‘opening’ is filled in with plywood and two infill studs, and for the FTAO it is an actual opening. Along the top and bottom of the FTAO window, Simpson CMSTC16 strap ties were installed. These are 16-gauge galvanized steel metal straps that are 3” in width with two rows of a staggered 3” o.c. hole pattern, which was installed by providing nailing per the manufacturer’s instructions. These straps create a force-transfer mechanism around the window opening between upper to lower panels of the wall. Edge and boundary nailing for the 15/32” plywood consisted of 8d sinker nails at 6” o.c. and field nailing was 12” o.c. At the base of the wall, six 1/2”-dia Titen anchor bolts were utilized as sill bolting and two Simpson HDU14-SDS2.5 holdowns were used at the holdown posts.

The lumber size, length, species, and commercial grade for the various structural elements in the wall is summarized in Table 1, where the abbreviation DF-L stands for Douglas Fir-Larch. The structural elements indicated in this table are labeled in the drawing shown in Figure 1, where black solid lines in the drawing indicate members in both the wall types and red dashed lines represent members that are only in the segmented wall.

Table 1. Lumber Schedule for Timber Shear Walls

Structural Element	**Quanitity**	**Nominal Size [in. x in.]**	**Length [ft]**	**Species**	**Commercial Grade**
Mudsill	1	2 x 6	6'-8"	DF-L	No.1&Btr
Top Plate	2	2 x 6	6'-8"	DF-L	No.2
Sill	2	2 x 6	3'-0"	DF-L	No.1&Btr
Blocking	4	4 x 6	1'-1 1/2"	DF-L	No.1&Btr
Header	1	6 x 6	3'-3"	DF-L	Select Structural
Compression Post	2	6 x 6	12'-6 1/2"	DF-L	No.1
King Stud	2	2 x 6	12'-6 1/2"	DF-L	No.2
Trimmer Stud	2	2 x 6	10'-0 1/2"	DF-L	No.1&Btr
Jack Stud	2	2 x 6	6'-9 1/2"	DF-L	No.1&Btr
Top Cripple	2	2 x 6	2'-0 1/2"	DF-L	No.1&Btr
Infill Stud*	2	2 x 6	3'-0"	DF-L	No.1&Btr

*Segmental wall only

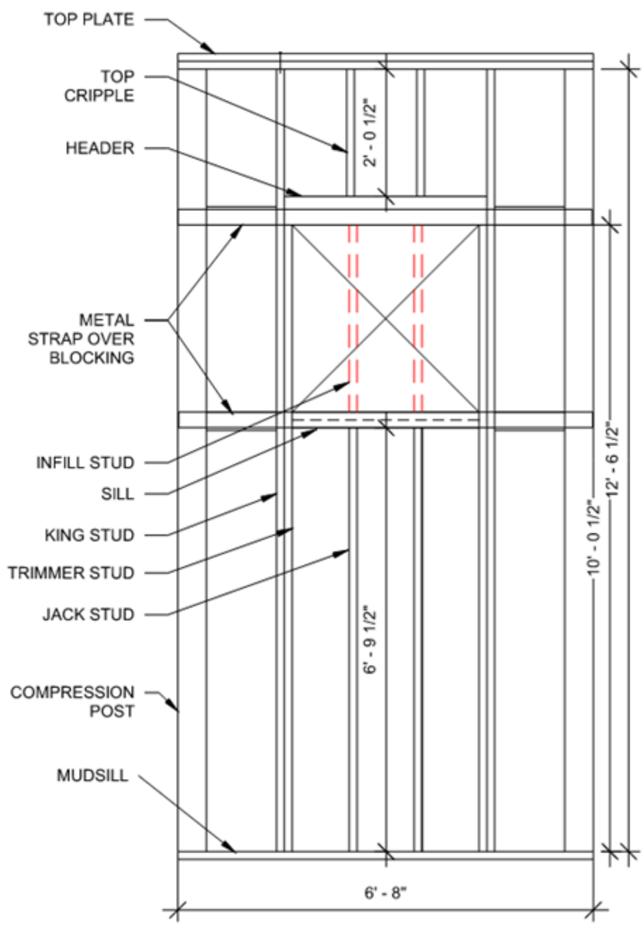


Figure 1. Segmented and FTAO Timber Shear Wall Designs
(Black solid lines = both wall types, red dashed lines = segmented wall only)

Fabrication

Fabrication Facilities: Students completed fabrication activities in the College of Architecture and Environmental Design (CAED) High Bay lab, which includes a wood shop providing access to saws, nail guns, and other handheld tools for wood framing. Shop personnel and course instructors provided safety and training oversight to the students.

Wall Specimen Fabrication: Figure 2 shows the various fabrication tasks that the students were exposed to during the shear wall design-build-test projects: measuring, cutting, and laying out framing members; assembling frame members and attaching plywood (nailing and bolting); installing strap ties, holdowns, and anchor bolts; and fabricating a connection beam to the actuator. The images are provided to demonstrate the scale of the project and extent of student involvement.

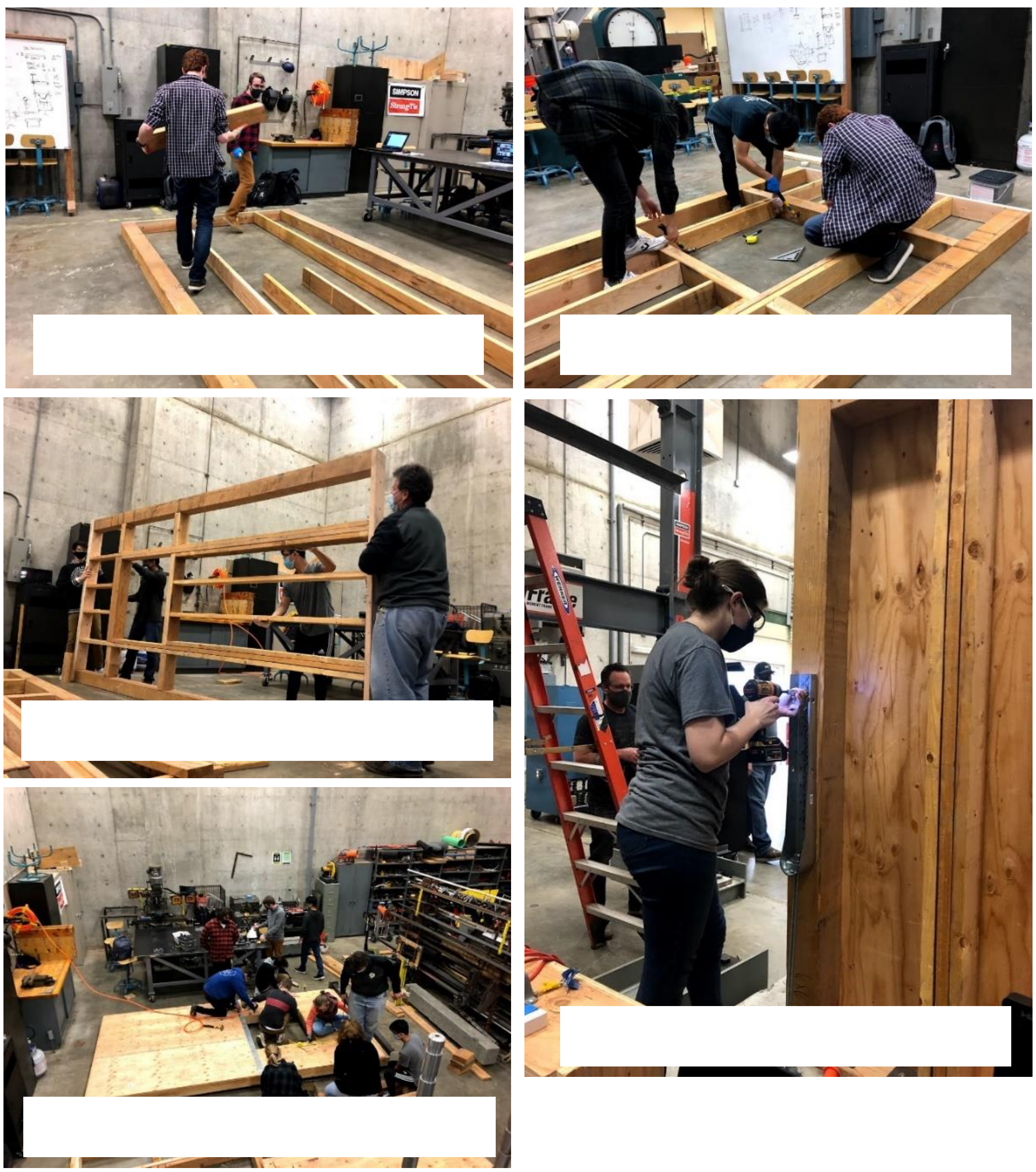


Figure 2. Timber Shear Wall Specimen Fabrication

Experimental Testing

Laboratory Facility: Specimen fabrication and testing took place in the CAED High Bay Lab, shown in Figure 3, where there is a 3-ton Detroit Hoist crane and an Enerpac RR5013 hydraulic actuator with 110 kips compression/23.6 kips tension capacity, as well as a steel reaction frame and strong floor.

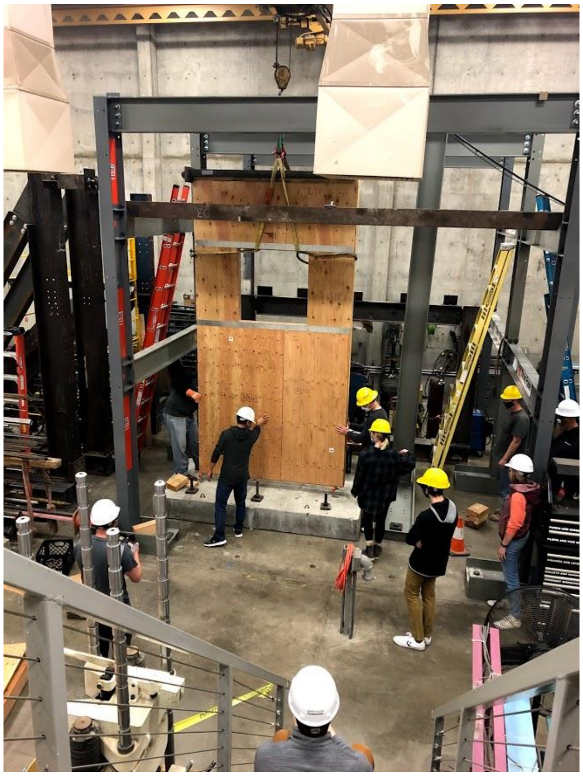
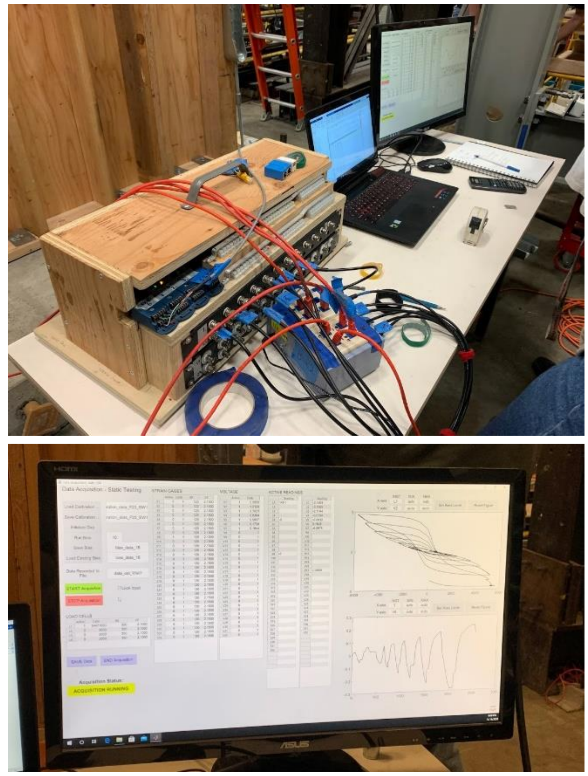


Figure 3. FTAO Timber Shear Wall Specimen Erection in CAED High Bay Lab

Wall Experiments: Both the segmented and FTAO walls were subjected to cyclic loading using a hydraulic actuator attached to the top of the wall with a steel channel. The actuator is outfitted with a load cell to measure the applied lateral force. The wall instrumentation consisted of string potentiometers installed at the top of wall, top and bottom of the window 'opening', and bottom of wall to measure specimen deformation. There was an additional string potentiometer at the base of the foundation to document any slip in the experimental test setup. Linear potentiometers were placed at the location of the two holdowns to investigate uplift during the cycles of loading. Data were recorded and could be visualized in real-time using an in-house data acquisition software. Still and video cameras were utilized to document wall response. The experimental setup and instrumentation of the FTAO wall specimen is shown in Figure 4. These images are provided to provide the reader with a visual understanding of the level of sophistication that the undergraduate students were exposed to in the instrumentation and data acquisition process.

(a) Instrumentation on Front of Wall



(b) Data Acquisition Hardware & Computer

Figure 4. FTAO Wall Instrumentation and Data Acquisition

Student Deliverables

Technical deliverables included a report for both wall specimens with: shop drawings, material schedule, calculations and plots for measured vs. predicted load-deformation behavior (Figure 5), and qualitative documentation of damage (Figure 6) as compared to expectations based on codified shear wall analysis. Additionally, one student compiled a video that documented the entire process of the design-build-test project which is available on YouTube [13].

Figure 5 shows the experimental load-deflection results from the segmented (solid) and FTAO walls as compared to the students' prediction using the 3- and 4-part SDPWS equations for the solid wall [10]. This prediction activity was an important learning experience for the students as the formulas can be difficult to understand and identify all the terms correctly without a complete understanding of wall behavior under loading. The students were able to observe that the actual deflection of the solid wall was underpredicted by both equations by at least 50% at the design shear capacity, and that it is also inappropriate to try to use these equations for the FTAO wall.

This experience illustrated to the students why their faculty instructors and the graduate student researcher assisting with their course project were pursuing further investigations of these calculation approaches for plywood wall deflection. Thus, the experimental portion of this course project will serve as an important datapoint in a larger research study at Cal Poly on solid and FTAO walls with the ultimate intent of addressing the limitations of existing SDPWS equations.

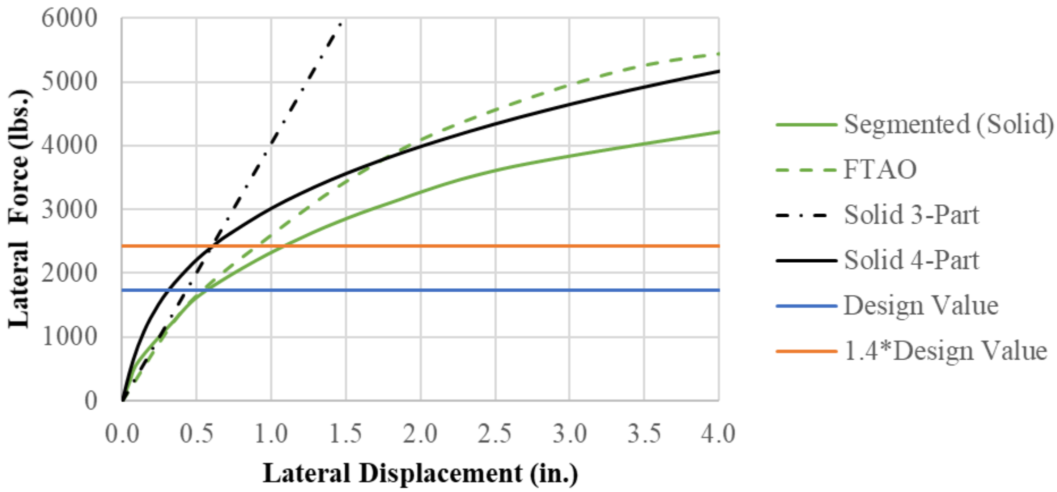


Figure 5. Experimental vs. Predicted Load-deformation Curves for Solid and FTAO Walls (Experimental = Green, Predicted = Black, Design Value = Other Colors)

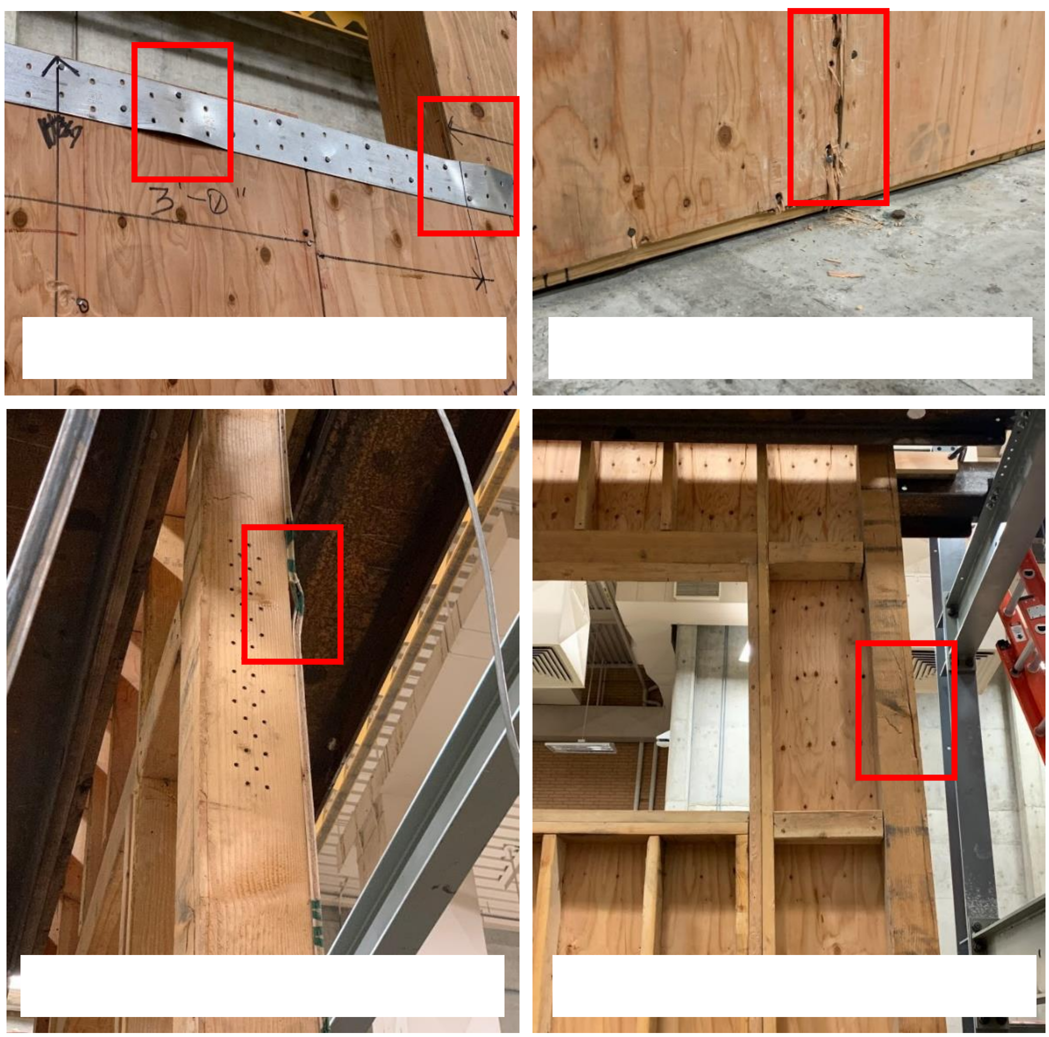


Figure 6. Observed Damage in FTAO Specimen

Student Assessment

Description of Student Survey

Students enrolled in ARCE 451 during the Fall 2020 quarter were asked to complete a survey about the new segmented and FTAO shear wall design-build-test projects. Fourteen students from each of the two course sections responded. Of the 28 students: 15 identified themselves as in-person (participated in design lectures, group activities, construction and testing on campus), 3 as fully virtual (never physically came to campus to participate and were integrated into the course by the faculty and students via Zoom meetings), and 10 as hybrid (some combination of in-person and virtual).

The survey contains 23 standard 5-point Likert scale questions (in some cases N/A could be selected to accommodate responses from in-person, virtual, and hybrid students), and six free response questions. The Likert scale questions asked students to rate the projects on:
(i) educational preparation and feedback provided by the instructors, (ii-iii) exposure to and confidence with various design and fabrication skills, and (iv) overall effectiveness in learning design, fabrication, and testing. The free response section consists of a commentary on the conservatism of the code based on the observed strength and deflection of the physically tested wall, the strengths and weaknesses of the project, the aspects of the course that was most impactful to student learning, as well as overall skills and lessons learned from the experience.

Summary of Student Feedback on Multiple-Choice Questions

Students assessed how effective the instructor was at providing a knowledge background that would enable them to complete the design tasks associated with project. This includes lectures in advance of and feedback during project tasks. Responses are summarized in Figure 7.

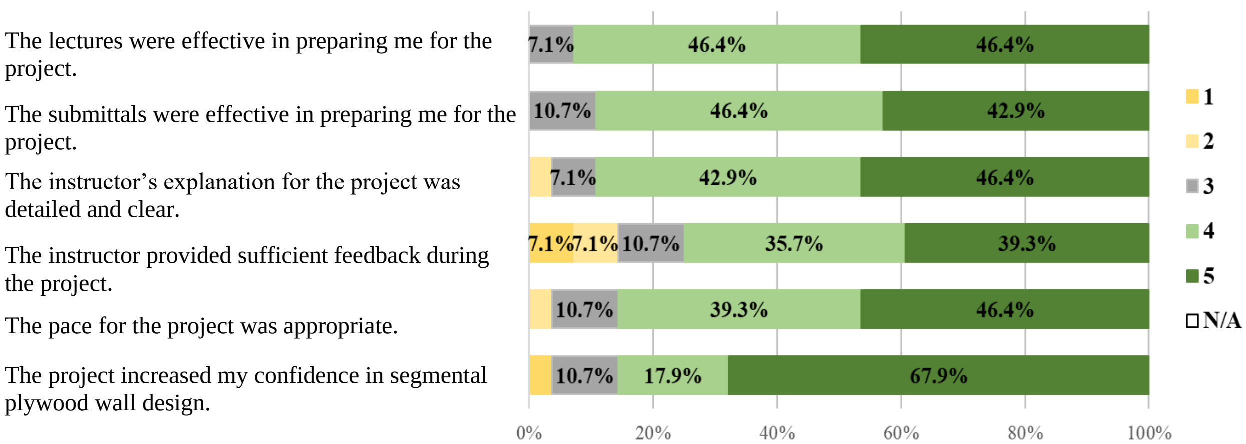


Figure 7. Student Perception of Instructor-Provided Preparation and Feedback
(5 = Strongly Agree, 1 = Strongly Disagree)

Survey results show course lectures and submittals were effective preparation students for the design-build-test project, and that the project cultivated student proficiency in designing timber lateral load resisting systems, specifically segmented plywood walls. One area the survey indicated could use more focus was in consistent, formal feedback through the project.

The survey results shown in Figure 8, provide a general understanding of student sentiment of which portions of the project was most valuable to their learning. Students were asked to rate "The following portions of the project were effective at increasing my understanding of timber wall systems. Select N/A if you did not participate in a particular portion of the project."

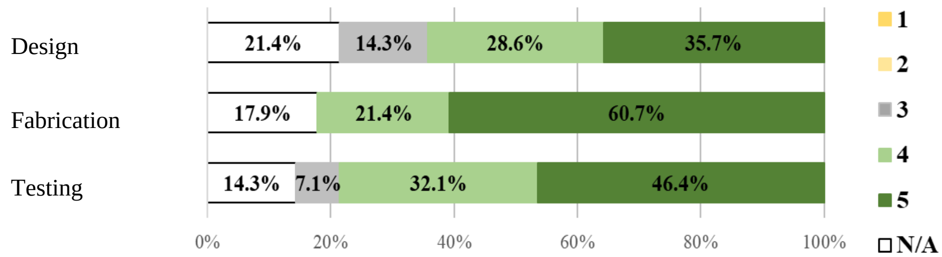


Figure 8. Student Perception of Effectiveness of Different Project Stages were to Understanding Timber Wall Systems (5 = Strongly Agree, 1 = Strongly Disagree)

As a note to interpret the "N/A" responses in Figure 8, 10.7% of the students were fully virtual and another 35.7% were hybrid (partly virtual/in-person). This impacts the availability of those individuals to participate in the hands-on activities of fabrication and testing. Consequently, to have sufficient tasks to engage the virtual/hybrid students the tasks of design, deflection predictions, and data analysis were also distributed accordingly. The students indicated that the greatest learning gains were in the fabrication process (constructability) as a meaningful extension of the design methodology they had learned in the lecture portion of the course. This was followed by the value of experimental testing and finally design. This motivates the reasoning for instructors that already incorporate a multi-dimensional timber design project in their lecture or senior project course to extend this to have some building or testing component.

There were a few follow up questions to assess student confidence related to the specific design processes associated with the segmented wall (shear design, shear transfer design, holdown design, chord design, wall stiffness/deflection prediction), as summarized in Figure 9. Students were asked to rate "The project increased my confidence in:"

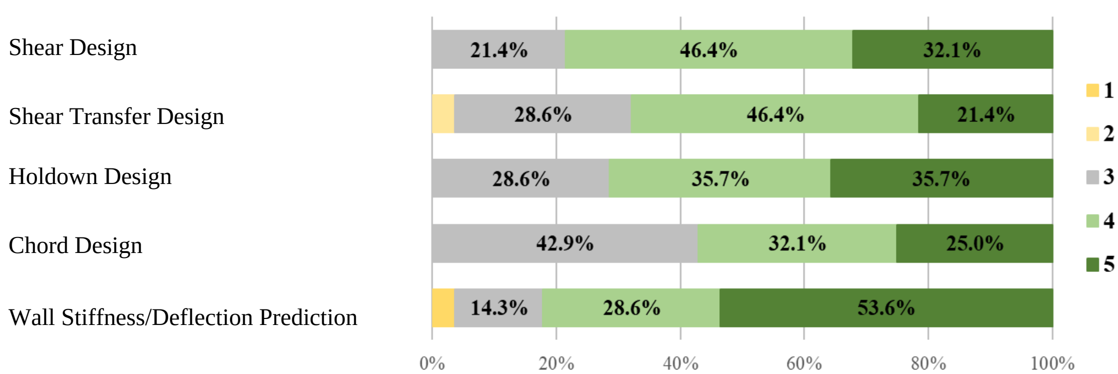


Figure 9. Student Perception of Confidence in the Design Process of Segmented Shear Walls (5 = Strongly Agree, 1 = Strongly Disagree)

The responses shown in Figure 9 indicated students developed a high level of familiarity with wall deflection calculations for segmented walls through use of the 3-part and 4-part SPDWS equations (Avg = 4.3). This was followed by shear and holdown design (Avg = 4.1), and then shear transfer and chord design (Avg = 3.8-3.9). The metrics related to student confidence in the major project topics inform instructors on which topic areas to provide more guidance in the lecture and feedback to student designs during the project in future course offerings.

The survey also investigated student confidence related to various fabrication tasks as shown in Figure 10. Students were the primary individuals responsible for specimen fabrication with training, assistance, and safety oversight from the instructors and shop technicians. As indicated previously 46.4% of the students were virtual/hybrid participants, and as a result a relatively high number of students may have not participated in certain tasks. Students were asked to comment on: "During the project, I participated in and became confident in the following tasks. Select N/A if you did not participate in a particular task or were a virtual student."

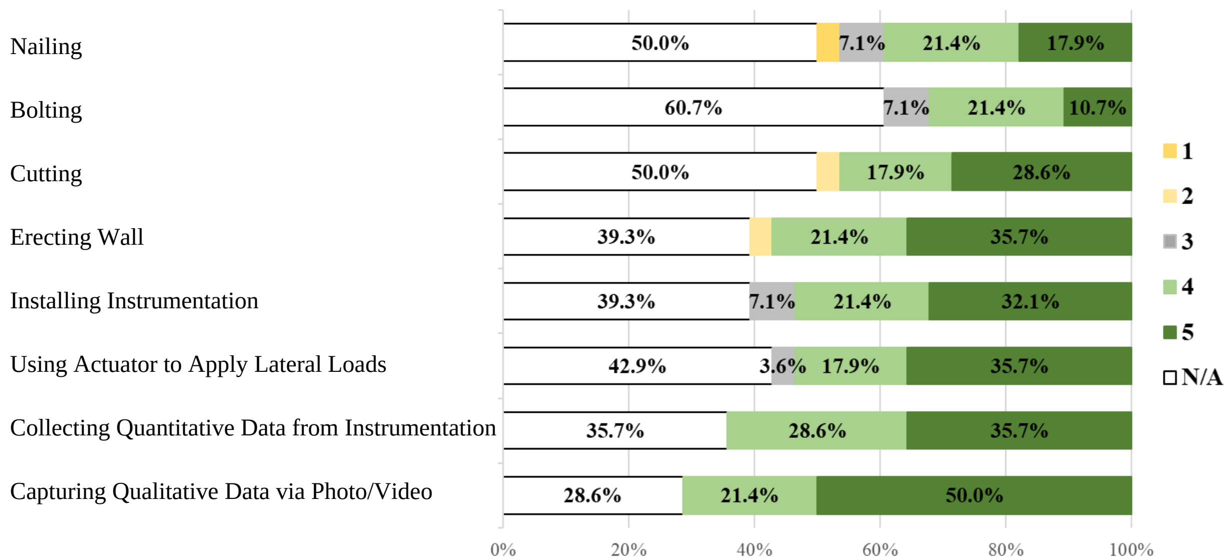


Figure 10. Student Perception of Confidence in the Fabrication Tasks for Shear Walls Projects (5 = Strongly Agree, 1 = Strongly Disagree)

The goal with Figure 10 is to identify construction, instrumentation, and data acquisition tasks that many students have not had much exposure to previously and investigate their level of comfort now having done the course project. The findings show that generally if a student had exposure to one of these tasks during the course project, they developed a high level of confidence in this task. The value of this hands-on learning in the high bay laboratory with construction/machine shop tools, actuator systems, instrumentation, and data acquisition systems should not be underestimated. Through prior studies that the authors have conducted [9], they have observed that through this type of design-build-test projects students have become equipped and interested to the extent where they have gone on to pursue large-scale experimental tests for their senior project or master's thesis research or considering new engineering job paths (like that of forensic engineer that involve in-field and laboratory testing).

Lessons Learned

The following lessons learned are from the perspective of the professors leading the course in Fall 2020 quarter:

- ***The opportunity for hands-on learning (fabrication and experimentation) is significant but requires patience.*** It is critical that students appreciate the constructability of their plywood shear wall designs and develop confidence in methods to assess structural performance. While professors with experience in the trades or large-scale laboratory testing have the advantage of understanding the tasks and timeline for a design-build-test project, they should be empathetic and anticipate student struggles or questions who may not have basic prior construction or experimental experience.

- ***Testing full scale models aids students in visualizing the behavior and failure of lateral force resisting systems.*** Full-scale testing provided students a sense of scale of the structure's size and strength but also an aid to understanding of behavior and failure of various limit states. This tangible experience offered a memorable, alternative approach to the traditional project-based learning activities from prior ARCE 451 offerings.

- ***A lengthier design-build-test schedule would probably create a more desirable learning outcome.*** The project tasks should occur slowly outside of class time over the course of several weeks, rather than compressing in a week, especially if blocks of shop time and staff are limited.

- ***Working as a team is critical for the project success.*** A flexible and engaged shop or laboratory technicians supporting the class project is necessary to help make the activity flow smoothly. Unexpected construction and testing challenges can arise, having multiple perspectives is essential to solving them.

Conclusions

In summary, the objectives of this new project-based learning approach included providing the students with a hands-on opportunity to understand the construction, performance, and failure mechanisms of solid and FTAO plywood shear walls. Knowledge of the construction of a shear wall provides the student with a deeper appreciation for all the working pieces that comprise this structural element. It also aids in their future structural engineering careers in their ability to design walls and develop creative solutions to non-standard situations. The design of the test wall is like what they experience in the lecture portion of the class, yet it enables them to test the structural component at the full-scale and validate their calculations according to theory. Lastly, it allows students to observe the damage progression and ultimate failure of two wall types. They get to witness firsthand various modes of failure and gain a more complete understanding of the design capacity, ultimate capacity, and ductility of the walls.

Based on prior experience of two of the faculty authors, who have taught the course with and without the new project, the addition of the design-build-test project has enabled undergraduate students to develop a deeper insight into plywood wall construction as well as the components that form the gravity and lateral systems of a timber structure. In addition, the hands-on experience provides them with the opportunity to support their understanding of analytical computations with full-scale testing, data analysis, and observation of various failure modes. One of the most rewarding successes of these type of projects that the authors have witnessed are when students progress from not ever holding a hammer to completing a full-scale test of a plywood shear wall. In notable cases, this type of project has provided students with the confidence and desire to pursue further experimental research either through graduate school or an industry position in fields related to structural engineering.

Acknowledgements

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