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Physical and Digital Models for Timber Design and Analysis Courses

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Anahid Behrouzi is an associate 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 as well as structural design and analysis at North Carolina State University (2008-2011), the University of Illinois at Urbana-Champaign (2012-2015), Tufts University (2015-2016), and Cal Poly - SLO (2016-present). She has a BS in civil engineering and BA in Spanish language and literature from North Carolina State University, and a MS/PhD in civil engineering from the University of Illinois at Urbana-Champaign.

Abby Lentz

Abby Lentz, P.E. is a project engineer at Studio Prime Engineering with six years of industry experience. She specializes in timber construction and enjoys the never-ending problem solving of the engineering profession. In addition to her full-time engineering responsibilities, she is a part time lecturer at Cal Poly teaching Timber Design in the Architectural Engineering Department.

While in school, she graduated in the top ten percent of her class from the Architectural Engineering program at Cal Poly, Abby Lentz worked as an intern at her current place of employment while simultaneously earning her bachelor's and master's degrees. In school, her senior project in building restoration, master's research in earthquake resiliency, and seismic retrofit work on a school in Nepal with Structural Engineering Students for Humanity added to her passion for engineering.

Miss Lentz believes in structural artistry, that as an engineer her innovative designs add beauty to the built environment and maintain structural fidelity to form and function. Miss Lentz values the integrated design build process and enthusiastically works with the team to achieve balance between complexity of design and simplicity of construction. She strives to produce quality engineering solutions that are cost effective, easy to build, and aesthetically pleasing. For Abby, helping to make dreams a reality is a rewarding part of the engineering service.

Physical and Digital Models for Timber Design and Analysis Courses

Abstract

Among structural engineering education research, there is a limited number of studies on interactive learning tools and activities specifically for the timber design classroom to assist students in visualizing material behavior, vertical and lateral load paths, and construction sequence. Timber design courses within the undergraduate program in the Architectural Engineering department at California Polytechnic State University in San Luis Obispo (Cal Poly), place an emphasis on seismic and wind design. Therefore, the proposed learning tools and activities are intended to pair with an introduction to concepts in the American Wood Council's National Design Specifications (NDS) and Special Design Provisions for Wind and Seismic (SDPWS).

A primary approach implemented in the timber course at Cal Poly was physical and digital models to strengthen student's conceptual understanding of the directional properties of wood, mechanical connections, as well as gravity and lateral load flow. These included:

- Demonstration with drinking straw bundle and sawn lumber to demonstrate difference in behavior due to grain direction and under different types of forces,
- Kit consisting of manufactured lumber (I-joists and laminated-veneer lumber) and hardware samples (shear wall hold-down and joist hanger) sourced from various suppliers to expose students to commercial products available for timber design,
- Laterally braced column model that examines the effects of column section dimensions relative to the unbraced length on buckling load,
- Physical and digital diaphragm models that demonstrate the variations of sheathing layouts, per SDPWS Section 4.2.8, and allows students to investigate the appropriate application of layouts under various loading conditions,
- Digital library of three-dimensional (3-D) components for students to rapidly assemble a stacked shear wall they have designed to be able to investigate load flow and constructability in both 2-D and 3-D views.

Other course material included a homework packet based on a two-story residential project completed by the instructor's firm, a handout that guides students through the analysis of members under bi-axial loading, and presentation material contributed by a firm with an expertise in mass timber (as alternative to hosting a guest presenter). Additional course activities include visits to a local project site and the college's large-scale laboratory to learn about timber construction and behavior from other experts outside of the classroom setting.

Student surveys were conducted for a majority of the various pedagogical techniques implemented in the class to assess effectiveness in achieving the intended educational outcomes including improving student knowledge of material properties, behavior of structural members, load flow and connections, along with context in real-world structural engineering projects.

Introduction

Civil engineering programs that offer a timber materials lecture typically do so at the graduate level (an optional elective for undergraduate students) that introduces material properties, behavior, and the design of isolated members or subassemblies of a structure. In the Cal Poly Architectural Engineering department this is a required undergraduate course followed by a design laboratory with a cumulative project where students prepare a calculation and drawing package for a simple multi-story timber structure. This process starts with determining the configuration of gravity and lateral systems, followed by calculations for sizing and analysis of members as well as the production of construction documents for the framing plans and connection details.

When transitioning from the timber materials lecture to the subsequent design laboratory (or to design in the industry setting) it is critical students understand the context of isolated timber members within the entire structure system. Past studies have shown that by interacting with physical and digital models, students are better able to visualize the behavior and construction of structures (based on literature review of concrete [1], steel [2], and timber design [3] courses previously conducted by one of the authors). However, discussion of these types of demonstration tools are largely absent from publications on timber education at the university level. Therefore, the authors specifically focus on these methods to clarify challenging concepts in the course.

Literature Review

The effort to find existing small-scale physical models and interactive 3-D digital tools on timber design topics was not as fruitful as the authors had hoped. This may result from the fact that if a university offers a course on this material, it is often at the graduate level where perhaps the assumption is that students have developed a high-level of spatial understanding of 2-D drawings and figures. This lack of existing teaching resources underscores the need for tools and activities described in this paper.

Physical Models

The authors' investigation into existing table-top physical demonstrations specific to timber design concepts produced very limited results, which is surprising given that this material is one of the most readily available construction materials at a relatively low cost in any local hardware store (sawn lumber, plywood, typical fasteners, etc.). There was greater success when expanding the search parameters to look for physical models that illustrated topics related to timber member performance that occurs in other material types as well such as column buckling or utilizing 3-D models to visualize a structural system to understand load flow.

Cooke [4] and Flaherty [5] discuss multiple methods of examining strength of materials concepts using the low cost and readily available supplies of pool noodles, masking tape and a black marker. The activity from these sources that is specifically relevant to the context of an introductory timber design lecture is using one (or two noodles taped together) to investigate column buckling. By modifying the braced column length, end restraints, and cross-section's moment of inertia it was possible to illustrate how these parameters affect the buckling load and deformed shape. These lessons apply to all types of building materials but are especially relevant to those where members are often slender and susceptible to buckling. Student feedback from

Cooke [4] for these learning aids was overwhelmingly positive with a clear indication that the demonstrations assisted visualization and understanding of course concepts, while also being an enjoyable learning experience.

On another scale, Schmucker [6] emphasizes the relevancy of three-dimensional visualization of structure and connections through a 10-story office building made with a Girder & Panel Building Set. This model was intended to aid students in learning to identify gravity and lateral systems in steel construction. Students can explore different configurations of members and feel how alternative lateral systems change the building's behavior. Schmucker found the use of this exercise mostly beneficial for students, with many reporting that using the model resulted in clarity of the topic. This model offers a glimpse into load flow for gravity and lateral systems. Load flow is a vital concept in timber design, as there are often more components to gravity and lateral systems than other material types.

Digital Models

Digital models can be used in place of small-scale physical models if fabrication cost/time, storage, or educational flexibility constraints are of concern. Interactive digital tools can be distributed to students for use outside of the classroom, which encourages more prolonged experimentation with the model and allows for use as a learning aid when completing homework assignments. These tools can also model full scale mock-ups of construction subassemblies, which may not be feasible for physical models that the instructor brings to class meetings. As with the physical models, review of existing literature for 3-D models that specifically communicate constructability and load flow concepts related to timber design were limited.

The only tool that was found which is similar to that needed in the timber design course is described in Haque et al. [7] as a website which contains 3-D animations and walkthroughs for the design of concrete formwork fabricated from timber. The website has an interactive flow chart that guides students through the design and analysis process for concrete formwork. Members can be loaded, and the tool provides visualizations of 2-D and 3-D free-body diagrams which allows students to see the effect of loading isolated members. This functionality is useful in developing a basic understanding of constructing timber formwork but does not appear to provide connection details of how members are framed or where hardware is used to fasten framing together. This is an important concept for students to visualize in 2-D and 3-D, as it helps them understand how load is transferred within the system which became one of the major learning goals for the digital model developed by the authors for the Cal Poly timber course.

Virtual Learning Modules & Other Course Instruction Materials

While limited physical and digital models were found during the literature review process, there has been a tremendous effort put into virtual timber design course curriculum for university students and working professionals via the Wood Education Institute [8]. This effort was funded by WoodWorks in 2008 who established an educational partnership with Cal Poly – Pomona. Available resources included lecture presentations and laboratory videos that introduce wood properties, analysis and design (gravity/lateral systems, connections, and fire resistance), construction, behavior, and several case studies. The project website is still available and module descriptions can be accessed; however, the course modules can likely be most easily requested directly from project lead Mikhail Gershfeld, SE at Cal Poly – Pomona. There is a similarly named, yet unaffiliated, organization called The Wood Institute [9] which hosts over a hundred courses that are 1-1.5 hours long and developed through collaboration of professionals with the American Wood Council, ThinkWood, WoodWorks, and the Carbon Leadership Forum. These educational resources are primarily directed towards industry members on specific design principles in timber, rather than for the undergraduate or graduate classroom, but could be useful as instructors develop course modules on niche topics.

Another on-going effort to develop timber design education resources is within the Wood Education subcommittee of the American Society of Civil Engineers Structural Engineering Institute (ASCE-SEI) which falls within the purview of the Wood Technical Administrative Committee. The subcommittee has already developed and distributed sample syllabi that instructors can utilize for a timber design course, and they are in the process of developing a package of course notes, homework assignments, and exam problems that can be distributed to instructors via the ASCE Collaborate online platform. Modules on specialized topics such as timber design for fire and cross-laminated timber are underway by faculty members of the subcommittee whose research expertise is in these areas. At the time of the publication of this paper, the materials can be acquired by or submitted to the project by reaching out to the chair of the Wood Education subcommittee via their website [10]. The ultimate goal of this special education project is to provide the types of materials available through the American Institute of Steel Construction Teaching Aids repository [11].

Course Details

The Cal Poly Architectural Engineering program includes foundational courses before students enter the material lecture and lab series on building materials of steel, concrete, masonry, and timber. The prerequisite courses to timber design include *Structures I and II* on the principles of statics, how to develop free body, shear, and moment diagrams. *Mechanics of Structural Members* covers topics of stresses in beams, plastic bending, combined stresses, buckling, and deflection of beams. *Structural Systems Laboratory* teaches calculation of building loads from ASCE 7 [12] and development of a complete gravity and lateral load path.

The learning aids discussed in this paper are intended for use in the Timber Design Lecture (ARCE 304) that serves as the students' first exposure to the design theory of timber and its unique material properties. This course meets either three times per week for 50 minutes or twice per week for 80 minutes during a ten-week quarter. The class utilizes the 2018 Wood Design package composed of three publications (2018 National Design Specification (NDS) [13], NDS Supplement [14], and 2021 NDS SDPWS [15]) along with the supporting textbook *Design of Wood Structures - ASD/LRFD*, 8th edition [16]. The recommended course outline is presented in Table 1.

Table 1. Recommended Course Schedule

Week	Topic	Textbook Section	Learning Aids
1	Introduction / Overview / Construction/ Wood Properties / ASD / Adjustment Factors	4.1 - 4.21, 4.24	Wood Sample and Straws – Material Properties
2	Beam Design – Sawn Lumber / GLB / I-Joists / Structural Composite Lumber (Fully Braced)	6.1 - 6.9, 5.1 - 5.8, 6.13 - 6.16, 6.19	Manufacturer Samples – I-joist & SCL
3	Beam Design - Stability Factor Axial Design - Tension / Compression	6.3, 7.1 - 7.3, 7.10 - 7.11	Column Buckling Model – Axial Compression
4	Axial - Combined Stress	7.4 - 7.6, 7.8, 7.12 - 7.13	Biaxial Handout – Combined Stress
5	Diaphragms - Material / Gravity / Load Path / Shear / Bending	8.1 – 8.9, 8.11, 8.13, 9.1 - 9.6, 9.9 - 9.10	Diaphragm Layout Model
6	Diaphragms - Collectors / Deflection	9.7 - 9.8, 9.11	
7	Shear Walls – Overview / Shear / Aspect ratio / Overturning / Holdowns	10.1 - 10.3, 10.5 - 10.6, 10.8, 10.10	Introduce Shear Wall Rhino Toolkit – conceptually track load flow
8	Shear Walls - Example / Deflection	10.11	Site Visit1
9	Connections - Overview / Adjustment Factors / Bolts / Lags / Nails	11.1 - 11.7, 12.1 - 12.14, 13.1 - 13.15	Manufacturer Samples – Connections Shear Wall Rhino Toolkit – verify D/C < 1 for each connection
10	Mass Timber / Review		

Foundational and commonly challenging concepts were considered to develop the teaching aids discussed in this paper for the purpose of better communication with students and to improve the class's overall effectiveness. Those concepts include:

- Material directionality of lumber and stress direction with regard to wood fibers.
- Considering slenderness for each principal axis when calculating the column stability factor, C_p, to reduce compression parallel to grain capacity due to column buckling.
- Identifying the compound condition of sheathing layout, orientation to framing, and load direction when choosing diaphragm capacity from the SDPWS.
- Understanding the components of the combined compression and bending check equation in the NDS and how to simplify the equation for different loading conditions.
- Tracking the lateral load path from the roof diaphragm to the foundation and developing connection capacities at each successive step of the load path.
- Visualizing the three-dimensional built environment from two-dimensional drawings including framing assemblies and hardware used at connections.

Description of Physical / Digital Models and Demonstrations

The models and demonstrations are described in this paper in the order they were introduced during the ARCE 304 Timber Design Lecture course. Appendix A contains information on materials used for model fabrication, and Appendix B contains any handouts or lesson plans which accompany the models. Digital model files are available upon request from the authors. Manufacturers also supplied donations and samples of engineered lumber and connector hardware used in the course which are summarized in Appendix A.

Material Property Demonstrations (Physical)

Understanding the anisotropic nature of wood is critical to student's appreciation for the directional differences in timber material properties when utilizing values from Tables 4A and 4D of the NDS Supplement. To address this fundamental concept early in the course, the first class session involves a demonstration where the instructor has a bundle of drinking straws and applies tension, compression, and shear both parallel and perpendicular to grain, Figure 1 shows the demonstration for compression parallel and perpendicular to grain. Cross-referencing each type of stress with design stress values in the NDS helps the class understand the hierarchy of wood strengths relative to force and wood fiber direction. Students can observe the significant difference in capacity based on direction of loading, whether parallel or perpendicular to grain.

To follow that activity and provide an opportunity for the class to directly experience this phenomenon with a wood sample, students are provided with a 2'-6" long segment of 2 x4 sawn lumber and are given a hammer to hit the end grain engaging the specimen in compression parallel to grain and noting the indent size in the wood. Then flipping the specimen to hit the 2x4 and engage compression perpendicular to grain. They will notice a much deeper indentation when employing perpendicular to grain compression. Hammering on the wood is a loud and engaging classroom experience that makes it a memorable way to introduce the topic of material directionality.

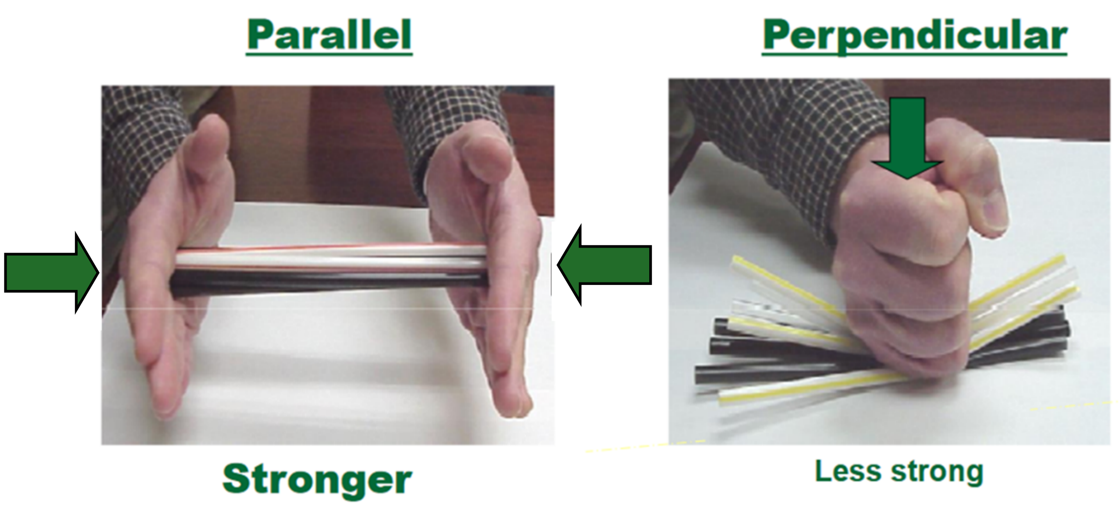


Figure 1. Straw Demonstration – Compression Parallel and Perpendicular to Grain (Photo Credit: John Lawson)

Later during the first week of class, the 2x4 sawn lumber sample from the hammering activity is revisited to explore how applying different types of forces (axial tension, compression, bending) results in different stresses. Two students are chosen, each holding one end of the specimen, and they are told to play tug of war. The class is asked what stress type results and the symbol that is used to represent it (tension parallel to grain, f_t). Next, students are told to push toward each other, repeating the same set of questions (compression parallel to grain, f_c). For the final activity it is necessary to select a third student to assist with the demonstration. The first two hold the wood close to the ends and the third student sits in the middle. The instructor draws a free-body diagram on the board of a simply supported beam with a point load at the center to help students assess what stress type is checked at the middle of the span (bending stress, f_b), at the ends (shear stress, f_v), and at supports (compression perpendicular to grain, $f_{c\perp}$). This exercise helps reiterate the differences in reference design values from the NDS and the directional difference in the material strength of timber.

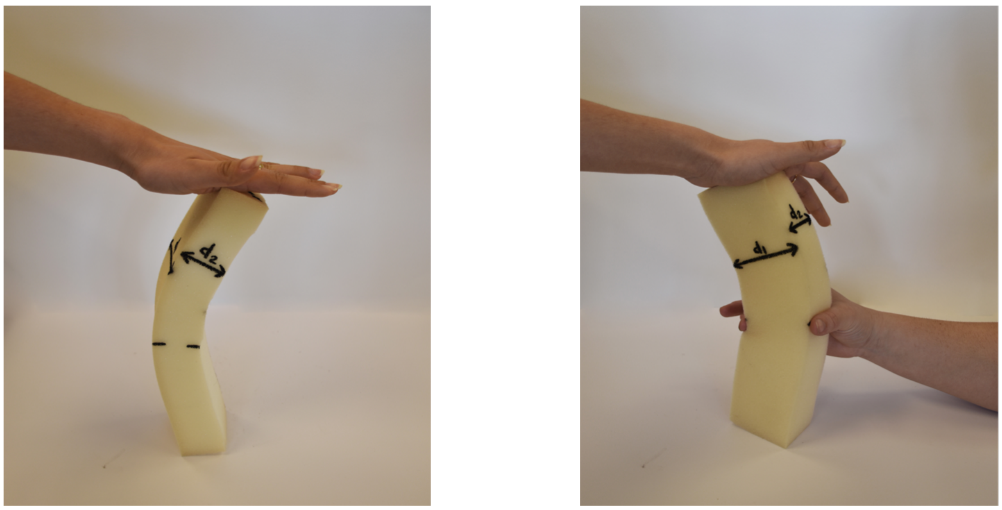
Column Buckling Model (Physical)

A key concept in the design of compression members with a rectangular cross section is the effect of multiple slenderness ratios accounting for strong versus weak-axis buckling, l_{e1}/d_1 and l_{e2}/d_2. A foam column buckling model was designed to demonstrate to students the effects of altering a column's unbraced length to change the slenderness ratio and axis of buckling.

The model was cut from a 3-inch-thick roll of multipurpose foam and was marked along its length and dimensions with black acrylic paint marking the half-way point of the column. The final product consisted of six 1-foot tall desktop models that have 2-inch by 3-inch cross sections, an example can be seen in Figure 2. The markings provide locations for one student to brace the model while the other applies compression. The dimensions used are meant to provide a scaled model as consistent with typical proportions of timber posts or studs as possible while still complying with the material limitations of the foam.

Figure 2. Column Buckling Model

Following the lesson on tension and compression members, small groups of students are presented with the foam model and corresponding handout which is included in Appendix B. Students determined the cross-sectional dimensions and height of the column using a ruler, then calculated slenderness ratios (as defined by NDS 2018 Section 3.7.1.3) [13]. After reflection on how these ratios may affect buckling behavior, students induced two buckling scenarios by pressing on the top of the model to simulate a concentrated axial load as shown in Figure 3. The first scenario involves a completely unbraced length, in which the column buckles along the weak axis in single curvature. The second scenario involves bracing along the weak axis at mid-height, in which the column will buckle along the strong axis in single curvature. The activity concluded with a reflection on how unbraced lengths and slenderness ratios influenced the behavior of the model. An alternate version of this activity was prepared, in which the instructor introduces the concept of slenderness ratios and provides a short demonstration of buckling behaviors. This alternate activity eliminates the need for a handout and involves a short lesson plan that guides instructors through using the model and the different buckling scenarios it is meant to highlight. This lesson plan is also included in Appendix B.



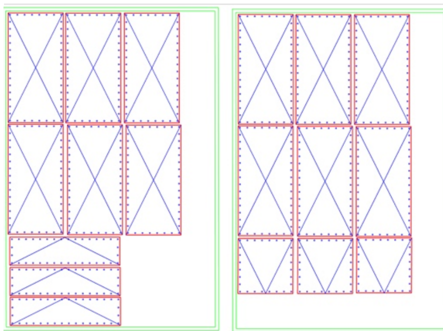
a) Weak-axis Buckling   b) Strong-axis Buckling

Figure 3. Column Buckling Model in Use

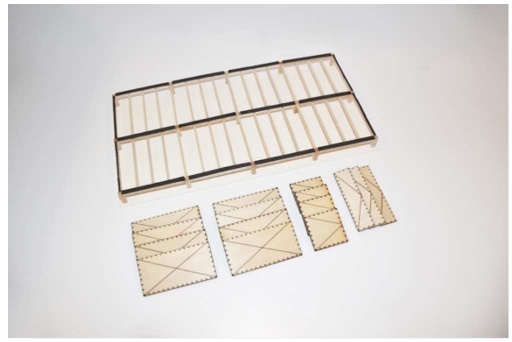
Reflecting on the fabrication process, the authors have two suggestions: (1) utilize a tool long enough to cut through the entire thickness of the foam at once to create a sufficiently straight line and (2) evaluate the appropriate cross-sectional dimensions of the column for the selected foam's stiffness to ensure the model performs as intended. The latter is important as it can be difficult to activate strong axis buckling when the weak axis is braced at mid-height, and instead have double curvature in the weak axis, due to similar slendernesses in each principal direction when bracing the column mid-height.

Diaphragm Layout Model (Physical & Digital)

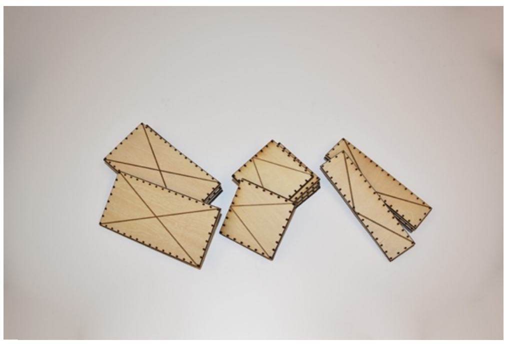
Diaphragm framing layouts vary in their capacity to resist shear loading due to multiple combinations of the panel orientation, layout, and blocking. Figures 4a-f show the tabletop model of a typical framing layout with magnetic "plywood" panels that was designed to help students assemble and visualize all possible framing scenarios for diaphragms as described by SDPWS 2021 Figure 4B [15]. The accompanying exercise in Appendix B also allows students to calculate capacities for different loading and framing scenarios.



a) Diaphragm Cut Sheets

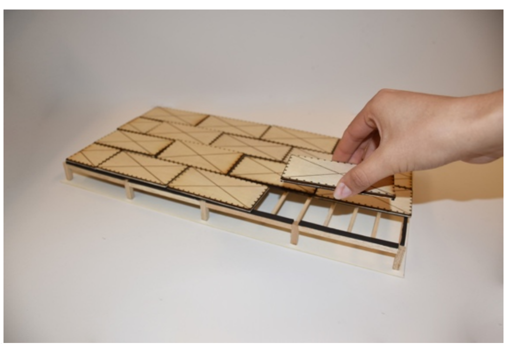


b) Plywood Sheets

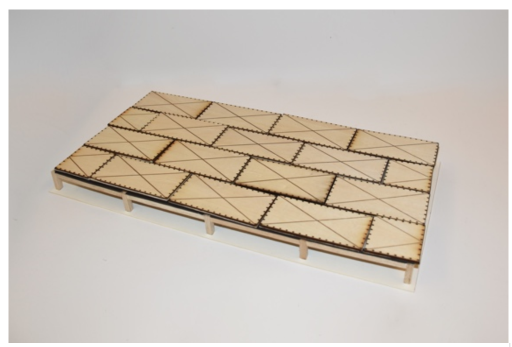


c) Different Panel Sizes

d) Panel With Magnetic Strip



e) Model Assembly



f) Completed Model

Figure 4. Diaphragm Layout Model

The diaphragm panels were laser cut from 1/8" thick basswood sheets using the Cal Poly Digital Fabrication Lab. The cut sheets were created in AutoCAD at a 1 inch:2 feet scale but can be opened in any program that is compatible with Rhino 7. Each typical-sized full panel was 2-inch wide by 4-inch long, with engravings that represent nailing at 6 inches on center along all four panel edges. The diaphragm model provides enough full and half panels (with 4:1, 2:1, and 1:1 aspect ratios) to accommodate all cases described in Figure 4B of the SDPWS 2021. The beams and girders were hand cut from basswood sticks: 1/4-inch square with 8-inch length for the girders and 1/8-inch square with 4-inch length for the beams. The framing members were fastened together with superglue. The perimeter of the framing plan and diaphragm panels were lined with magnetic strips, as well as intermediate beams spaced 4 inches center to center and joists spaced 1 inch on center. This allows the "plywood" panels to be held into place while laying out different panel arrangements. The columns were cut to be 1 inch tall to lift the diaphragm off the working surface. The baseboard that the framing is attached to measures 9 inches by 17 inches.

Students were introduced to this activity following the lesson covering diaphragm layouts and capacities covered in Figure 4B as well as Tables 4.2A and 4.2C of the SDPWS 2021 [15], which describes panel layouts and orientations with their correlated shear capacities. Students are provided with a handout, which is included in Appendix B, that examines the different capacities and reduction factors that apply for various layouts and orientations of the sheathing, nail size and spacing, sheathing thickness, and blocking patterns.

A few remarks to keep in mind when constructing the physical diaphragm model: (1) account for the material's thickness and the laser cutter's capabilities to set appropriate power and speed for full thickness cuts while mitigating scorch marks on the wood, (2) accommodate kerf in the cut sheets to address the thickness lost from the laser width (varies for different material thicknesses), and (3) secure magnetic strips with superglue on the framing members of the model since the adhesive on the magnet may not be sufficient for a strong hold. If an instructor does not have access to a laser cutter, the authors suggest printing the cut sheets to scale to use as a template for cutting the plywood panels with either a band saw or by hand with a precision knife from basswood sheets, cardboard, chipboard, or foamboard.

After reviewing student feedback on this model, it was noted that a digital version would be helpful for students to have access to, as the single tabletop model makes it difficult for all students to interact with it. To address this, a virtual diaphragm model in Rhino 7 was developed that contains all six framing cases from the SDPWS 2021. As an example, one of these six panel orientation cases is pictured in Figure 5a (unblocked) and 5b (blocked). Screenshots of the digital model depicting each framing case can be projected during lecture, while the instructor interacts with the physical model. The virtual model can also be distributed to students to interact with during or after class, where they can drag and drop panels into various layouts and investigate when blocking is necessary, and how the nailing patterns change for each case.

a) Unblocked Case b) Blocked Case

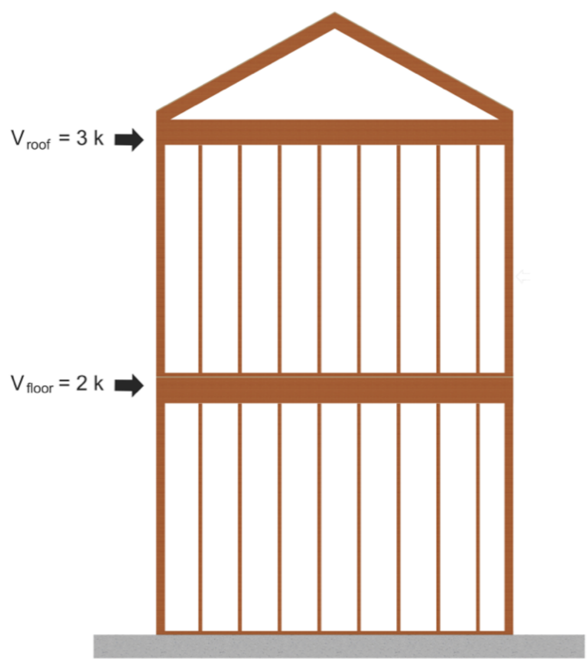
Figure 5. Digital Diaphragm Model

Shear Wall Rhino Toolkit (Digital)

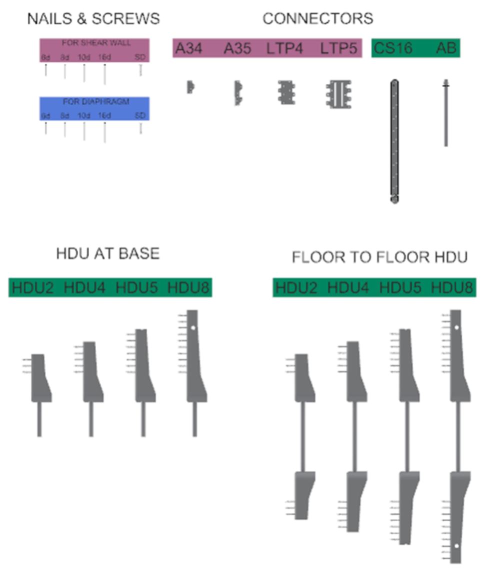
Understanding the transfer of lateral loads through a stacked (multi-story) timber shear wall involves the ability to visualize framing connections and recognize how fasteners and hardware transfer forces between framing components. Students often have difficulty in tracing load flow through connections, especially if they are not familiar with connection details or have not seen shear transfer assemblies in construction.

To help with understanding load flow and constructability in a shear wall, a three-dimensional (3-D) digital toolkit was created within Rhino 7 which allows students to rapidly assemble a shear wall system to examine it in both 2-D and 3-D views. 3-D models of the connectors are available in a digital library through Simpson Strong Tie [17]. Figure 6 shows screen captures of this digital toolkit. Figure 6a displays a perspective view of the partially assembled shear wall, with some plywood panels removed to reveal the framing of the walls. The remaining figures provide more details on the Rhino toolkit: Figure 6b presents an elevation view of the shear wall framing with applied lateral loads at each floor level; Figure 6c displays the various sizes/types of nails, screws, connectors, and holdowns that students will select from based on demand they calculate and place into framing connections; and finally, Figure 6d presents plywood sheathing with 2-inch, 4-inch and 6-inch boundary nail spacing.

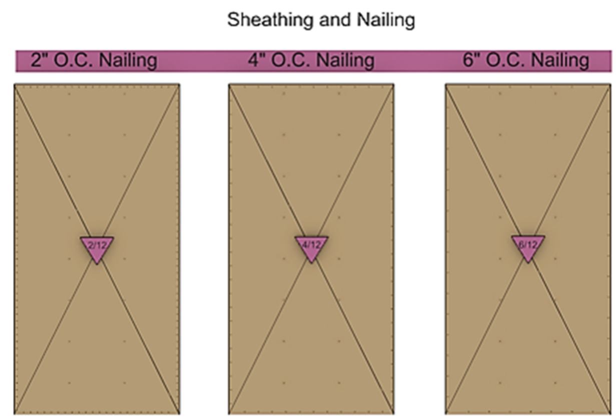
a) Partially Assembled Shear Wall



b) Front View of Shear Wall



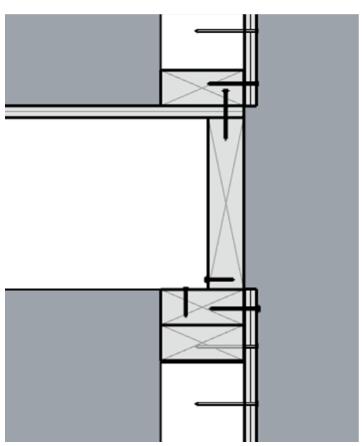
c) Hardware and Fasteners



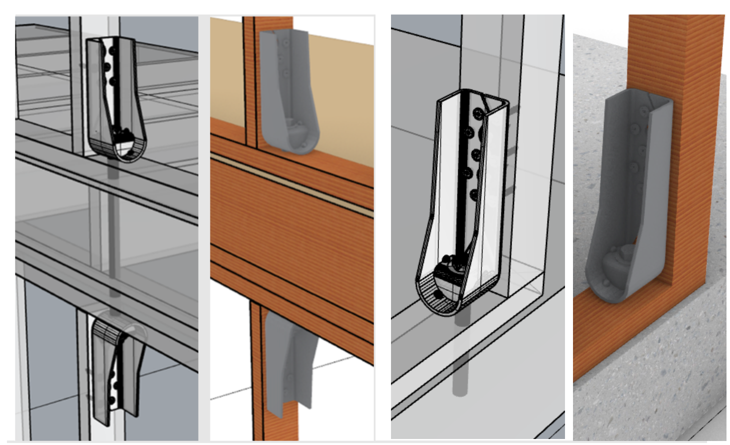
d) Sheathing and Nailing

Figure 6. Shear Wall Rhino Toolkit

Following the lectures on shear wall design, students were provided with a tutorial handout, which is included in Appendix B. This document provides the sizing of all members available in the Rhino toolkit to create the stacked wall system, along with the lateral force at each story they would use to design connections. The handout provides a step-by-step outline for calculations to size and select fasteners and connectors. Each step references specific sections of the NDS [13], SPDWS [15], and Simpson Strong Tie Connector Catalog [18] when calculating demands and checking capacities of components. As students complete their calculations, they use the toolkit to place the fasteners and hardware they had selected into its respective place in the framing. Once assembled, the students can examine the wall system and its connections in multiple 2-D and 3-D views, which clarifies load flow and the constructability of their design. Examples of these connections in 2-D and various 3-D views are shown in Figure 7.



a) Floor to Floor Connection



b) Ghosted and Rendered Views of Hold-down

Figure 7. Toolkit Connection Details

The high level of detail included on the 3-D models of Simpson Strong Tie connectors caused the file size of the toolkit to become quite large and may make it difficult for students to navigate if using a cloud-connected version of Rhino. To prevent lag in the program, it is recommended to use the pre-set rendering settings of the file.

In the case that students do not have access to an educational license for Rhino 7, instructors can direct them to the free 90-day trial provided on Rhino's website. Once the trial expires, they can still view files but will be unable to save any changes. If SolidWorks or SketchUp are more easily accessible, the Rhino toolkit can easily be imported into either program.

Manufacturer Supplied Lumber and Connectors

Students are introduced to engineered lumber, connectors, and fasteners at various points of the course. Yet, many will enter the industry designing details using these materials without having ever seen or held a physical sample of these items. To address this, the student co-authors reached out to manufacturers Simpson Strong-Tie, Boise Cascade, and Roseburg Forest Products to request lumber and connectors. Simpson Strong-Tie sent multiples of 17 products from their catalogues including hangers, straps, and mechanical fasteners. Boise Cascade sent a timber I-joist and laminated wood materials. Roseburg Forest Products provided directions to their website, where it is possible to directly order a pre-arranged sample kit of engineered wood products [19]. These samples are shown in Figure 8, and a list of donated materials can be found in Appendix B, Table 2.

Engineered lumber is introduced during the lectures on I-joists and structural composite lumber flexural design. The manufacturing process is described along with its benefits as compared to sawn lumber. The instructor made use of the Boise Cascade and Roseburg Forest Samples as visual aids during lecture and asked students to pass them around. This interaction with the samples allowed students to see up close the laminations and structure of various engineered lumber. Additionally, framing connections are covered as the last section of the course. During the lecture on connections a select sampling of frequently used hardware provided by Simpson Strong-Tie were placed in a "mystery" box to cultivate student curiosity. Students selected one product from the box at a time and discussed with the class the use of each product. Then they sought out the product and description in the Simpson catalog, its rated capacity, and relevant technical information before passing around the sample.

a) Simpson Strong-Tie b) Boise Cascade c) Roseburg

Figure 8. Manufacturer-Provided Hardware and Lumber Samples

Description of Updated Instruction Materials

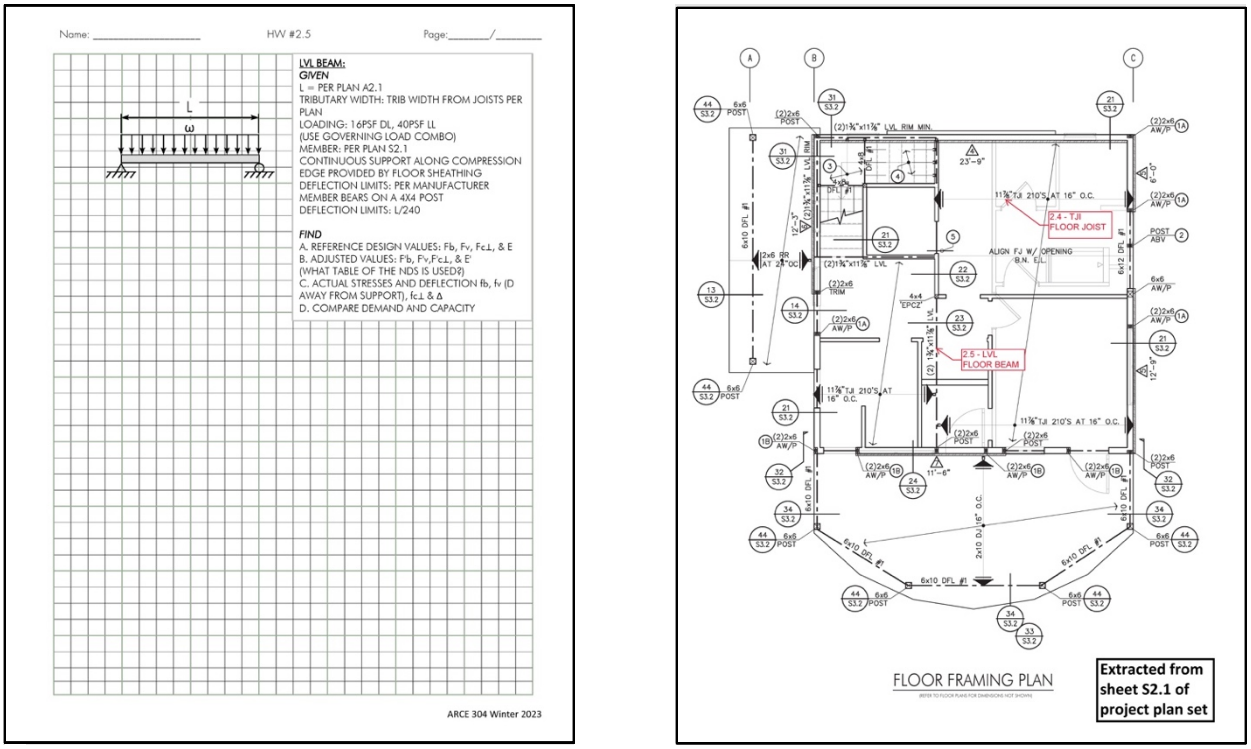
In addition to implementing physical and digital models, a handout detailing combined compression and bending effects along with a revised homework packet were updates to previous teaching materials used by the instructor in previous iterations of the course.

Bi-axial Bending Handout

The course instructor found students struggled to understand the effects of combined compression and bending in applying NDS Equation 3.9-3 [13]. Students tend to be overwhelmed by the number of stress variables in the equation. To help alleviate this issue and make the concepts more digestible, the handout breaks down the equation and purpose behind included moment amplification factors. Figures and a list of variables are provided to connect concepts to the equation. A table summarizes various loading scenarios and describes what sections of the equation will be applicable in each scenario. The handout can be found in Appendix B.

Homework Packet

Outside of class, the main avenue for practicing concepts learned during lecture is homework assignments. Homework is then instrumental in the retention of design knowledge and building engineering skills. The course instructor found students entering industry commonly lacked the skill of ascertaining information needed to formulate design problems from plan sets. To help practice this skill throughout the quarter a homework packet was developed around a simple, two-story, residential unit based on an actual project from her firm. The students referred to this project for weekly homework problems that highlighted one component at a time for analysis. This approach helped students gain a holistic perspective of how each concept related to the design process, rather than traditional textbook problems with an isolated condition, no context to an overall design, and all necessary information given explicitly in a problem statement. A homework packet using a set of architectural and structural drawings helped students gain confidence in their ability to decipher information from building plans such as: geometry to create free body diagrams of framing elements, loading from the tributary area, details for connections, and gravity as well as lateral load path continuity. An example of a homework problem and plan from the packet is shown in Figure 9.



a) Floor Beam Problem Statement b) Floor Framing Plan

Figure 9. Homework Packet Sample Beam Problem

Description of Interactions with Guest Experts

Site Visits

For this course, the instructor is a practitioner at a local firm and was able to organize a site visit to a housing development that showcased residential and commercial light-framed timber construction, shown in Figure 10. The site visit was optional but highly encouraged as an opportunity outside of designated class time. Multiple day and time options were offered to break the two class sections into a small/medium group experience (12-20 people). Carpooling was coordinated between students for transportation to the site. Since the instructor was familiar with both the project and the course topics, she developed a Bingo sheet with twenty-five items that served as a scavenger hunt for the students to complete during the site tour. This appealed to the students' curiosity and competitiveness while also serving as a reference sheet for the instructor to ensure that all the necessary topics were covered during the tour. Students were incentivized to participate with a small amount of extra credit for a single Bingo on the board and double that for a completely filled board. The instructor was one of designers on the project and described the structural engineering aspects, but it was critical to describe to the students the interaction with other disciplines involved in the project and how the structural design is only one component of the overall building function that interacts with other systems, like plumbing, throughout the building.

Figure 10. Site Visit to Light-Framed Timber Construction Project

For other instructors who are not directly involved in industry practice, it would be possible to conduct a similar activity by collaborating with a local engineering or construction firm to schedule a tour of an active project site and to get some background information on the project in advance. A Bingo sheet can be created knowing there are common elements found at wood-framed building job sites that correlate with concepts taught in the class. See Figure C.1 in Appendix C for a sample of the Bingo sheet.

Laboratory Visits

Within the ARCE department, a fellow faculty member has been actively engaged in a large-scale experimental research project involving the strengthening of timber shear walls. Thus, multiple times per year specimens are tested in the college's high bay structural laboratory. The ARCE 304 course instructor was provided with the shear wall testing date during the Winter 2023 quarter so her students could come observe how shear walls they were learning to design realistically behave under lateral loading – what strength that is achieved compared to code predictions and the failure mechanisms that occur. The authors encourage readers who are also educators to reach out to their faculty colleagues to determine what types of experimental research may be going on in their structural laboratory and if it is possible to visit during set-up or testing of a timber experiment (or even wood shoring for fabrication of concrete specimens) so their students can learn more from the research team about their study. Alternatively, remote visits or videos of prior testing from facilities at their university or elsewhere could be informative. Laboratory visits can be effective beyond providing context to timber design concepts, by introducing students to large-scale testing as a future opportunity for senior or master's project work.

Guest Speakers

Other than the instructor bringing their own expertise into the classroom if they are a practitioner or researcher in the timber design field, is to consider reaching out to external experts who work with manufacturers or are industry members, research faculty, and staff engineers at professional organizations actively engaged in wood research and code-writing. This could either involve requesting presentation materials they have already developed that could be adapted by the instructor to implement in a planned teaching model or to invite them to be a guest speaker (in-person or remotely) during the course. Specifically, within the Winter 2023 quarter offering of ARCE 304, a representative from KL&A Engineers & Builders provided the course instructor with an extensive presentation slide-set typically given to industry professionals to further their understanding of mass timber design. This presentation covered topic areas of: fabrication methods, benefits and limitations of mass timber construction, building types, fire protection basics, floor and framing assemblies, code development in relation to cross laminated timber, connection design, and embodied carbon. The course instructor was able to adapt this material to suit the one lecture period discussion on this topic within the undergraduate course. A brief list of additional individuals, firms, and organizations who readers might consider reaching out to for guest presentations or materials on various timber topics are listed in Appendix C, Table 1.

Summary of Student Feedback

Students in the two ARCE 304 sections during the Winter 2023 quarter completed six brief surveys about the physical/digital models as well as the updated course handout and homework packet. Each of the surveys that have been administered using Microsoft Forms and followed a similar structure where there were four to six 5-point Likert scale questions to gauge the effectiveness of the instructor's use of the teaching tool, whether it was useful in completing homework, how it helped students in understanding specific concepts from the timber code documents, and general impact on confidence in the topic area. This was followed by two free response questions to determine how the teaching tool was most impactful to the student's learning and how its implementation might be improved in the course.

Five of the surveys were conducted during class time by the graduate student co-authors on the date by which the instructor indicated the students would have completed the homework on the associated topic. The graduate student co-authors would show a slide with the QR code/link during the class period to direct students to the survey, for which they were given 5-10 minutes to complete the questions. For these in-class surveys it was found to be useful to briefly show students an image of the specific model or handout they were being asked about, to clarify what they were providing feedback on and to remind students that were absent during the class it was used to abstain from responding. The link for the final survey on the shear wall Rhino toolkit was included on the handout sheet for the associated assignment due the day of the final exam. On average there were 42 respondents across the six surveys, with the last survey having the lowest response rate of 34 likely due to being taken outside of class and during the busiest and most stressful portion of the academic quarter given that it was the final exam week.

Likert Scale Survey Questions

Students provided feedback on each of teaching tools described previously in "Description of Physical / Digital Models and Demonstrations" and "Description of Updated Instruction

Materials". Since the questions for each of the surveys were intended to investigate similar qualities about each model or handout, the general form of each statement is given below with specifics that appeared in the location of the bracketed text. The 5-point Likert scale options allowed students to indicate if they Strongly Agreed = 5 to Strongly Disagree = 1 with any of the statements.

Q1. The instructor effectively coordinated the use of the [model/handout and accompanying calculation exercise] in the course.
Q2. The [model/handout] provided a valuable reference when completing the associated homework assignment.
Q3. The [model/handout] improved my understanding of [focus topic].
Q4-6. The [model/handout] improved my ability to [predict member behavior, or, have greater confidence in solving problems related to the focus topic].

A comparison of averages for questions 1 and 2 between teaching tools is included in Figure 11 and a summary of the distribution of the results for each physical model in Figure 12 and digital model or handout in Figure 13. Note that student responses were discarded from the surveys if the student indicated being absent when the physical model or in-class teaching tool was implemented. The nature of the quantitative results is investigated in further detail by reviewing the free responses that accompanied them in the subsequent section of this paper.

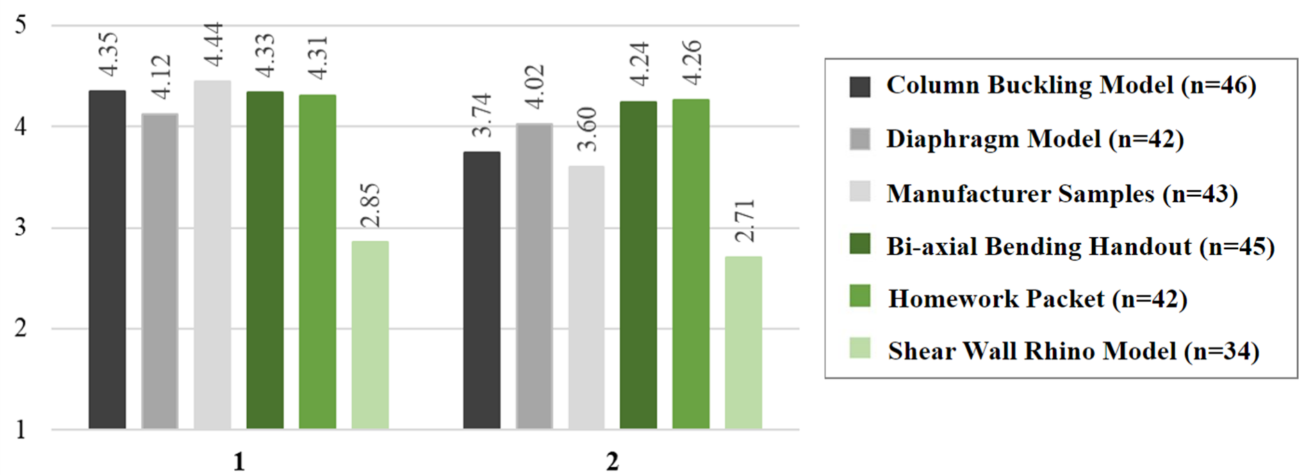


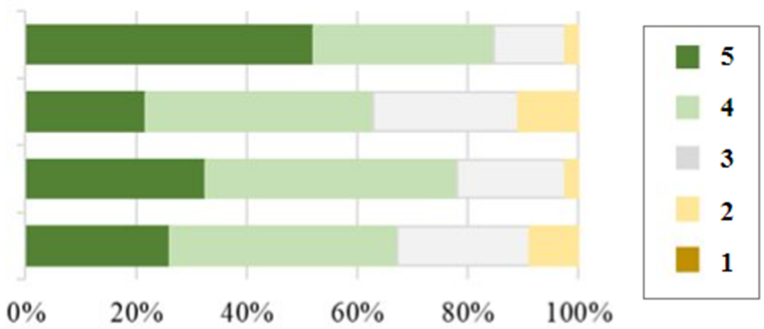
Figure 11. Comparison of Averages of Student Responses to Likert-Scale Questions (5 = Strongly Agree, 1= Strong Disagree)

Q1. The instructor effectively coordinated the use of the column buckling model in the course.

Q2. The column buckling model provided a valuable reference when completing the associated homework assignment.

Q3. The physical model improved my understanding of slenderness ratios, as defined by NDS Section 3.6.

Q4. The capacity calculation exercise improved my ability to predict buckling behavior and direction.



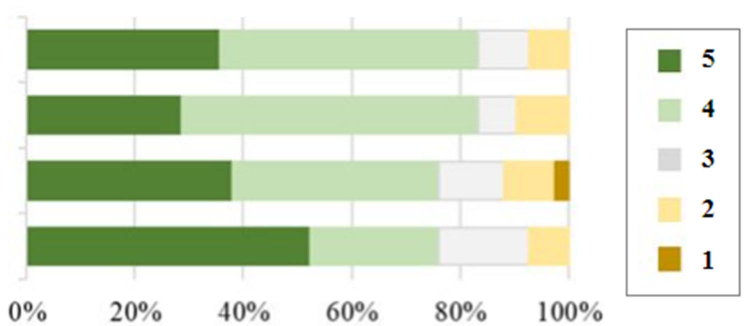
a) Column Buckling Model (5 = Strongly Agree, 1= Strong Disagree)

Q1. The instructor effectively coordinated the use of the diaphragm model and accompanying calculation exercise in the course.

Q2. The diaphragm model and accompanying calculation exercise provided a valuable reference when completing the associated homework assignment.

Q3. The physical model improved my understanding of the various diaphragm framing layouts defined by SDPWS Figure 4B, and the scenarios in which they are implemented.

Q4. The capacity calculation exercise improved my ability to navigate SDPWS Tables 4.2A and 4.2C.



b) Diaphragm Model (5 = Strongly Agree, 1= Strong Disagree)

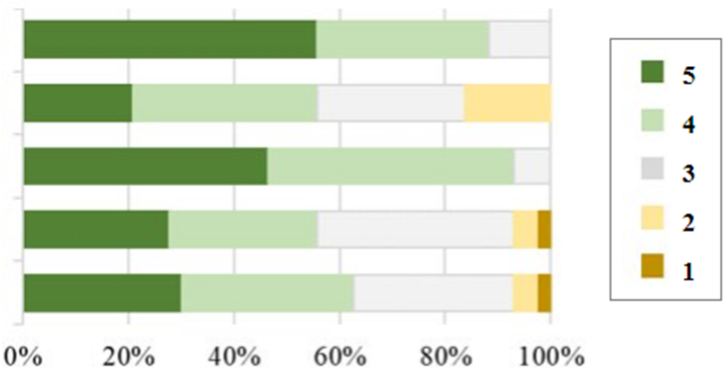
Q1. The instructor effectively coordinated the use of manufacturer samples in the course.

Q2. The samples improved my ability to check connection capacity is greater than demand using manufactured products when completing homework assignments.

Q3. The implementation of ***connection fastener and hardware*** samples improved my understanding of their respective applications.

Q4. The implementation of ***sawn lumber*** samples improved my understanding of their respective manufacturing process, applications, strengths and weaknesses.

Q5. The implementation of ***prefabricated lumber*** samples improved my understanding of their respective manufacturing process, applications, strengths and weaknesses.



c) Manufacturer Samples (5 = Strongly Agree, 1= Strong Disagree)

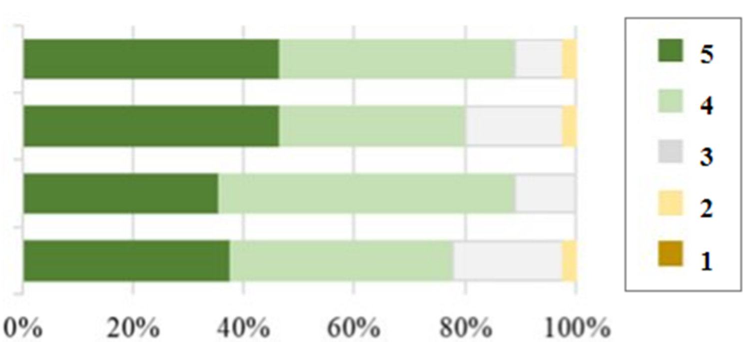
Figure 12. Distribution of Student Responses to Likert-Scale Questions for Physical Models and Manufacturer Samples

Q1. The instructor effectively coordinated the use of the biaxial bending handout in the course.

Q2. The biaxial bending handout provided a valuable reference when completing the associated homework assignment.

Q3. The biaxial bending handout's organization and content helped simplify the concepts of NDS Equation 3.9-3.

Q4. This handout improved my confidence to complete a bi-axial bending problem.



a) Biaxial Bending Handout (5 = Strongly Agree, 1= Strong Disagree)

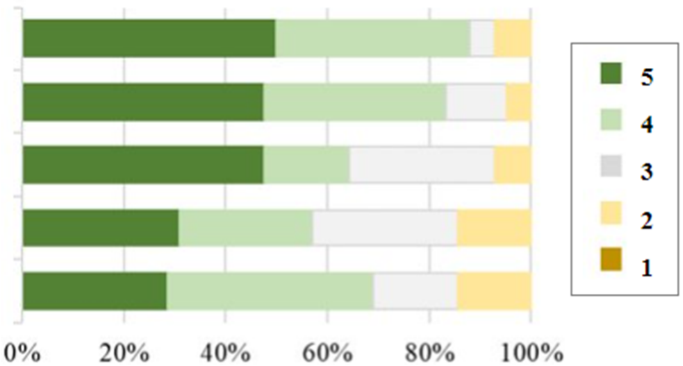
Q1. The instructor effectively coordinated the use of the homework packet in the course.

Q2. The homework packet helped me see how individual concepts relate to timber building design as a whole.

Q3. The homework packet helped improve my ability to zoom in on a single element in a project and zoom out to see the overall structural design intent.

Q4. The homework packet with sample project helped me visualize where ***vertical loading*** is generated and track the load path.

Q5. The homework packet with sample project helped me visualize where ***lateral loading*** is generated and track the load path.



b) Homework Packet (5 = Strongly Agree, 1= Strong Disagree)

Q1. The instructor effectively coordinated the use of the 3-D digital toolkit for timber shear walls in the course.

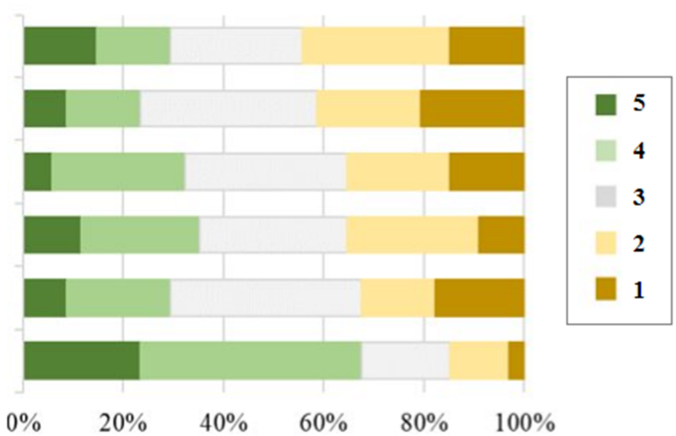
Q2. The 3-D digital toolkit for timber shear walls provided a valuable reference when completing the associated homework assignment.

Q3. The 3-D digital toolkit improved my understanding of shear wall construction and connections.

Q4. The tutorial handout made the 3-D digital toolkit easy to navigate and interact with.

Q5. The 3-D digital toolkit improved my understanding of the lateral force load flow through a stacked timber shear wall - from roof to foundation of a multi-story shear wall.

Q6. The capacity calculation exercise improved my confidence to analyze and design shear walls.



c) Shear Wall Rhino Toolkit (5 = Strongly Agree, 1= Strong Disagree)

Figure 13. Distribution of Student Responses to Likert-Scale Questions for Handouts, Homework, and Digital Models

Free Response Questions

The results from the 5-point Likert scale questions presented in Figures 11-13 indicate that the majority of students found very good to excellent educational value in all the physical models/handouts with lower ratings for the digital shear wall Rhino toolkit. The free response questions are useful to investigate the specific benefits and any areas that the students see shortcomings that can be improved upon. The general form of the two free response questions is listed below. The rest of this section will summarize the responses on each course upgrade, followed by several specific comments in Table 2.

> Q1. Which aspect of the [model/handout] was most beneficial to your learning?
>
> Q2. How could the [model/handout] be improved to better aid in your understanding of relevant concepts? (N/A for no recommended changes)

<u>Column Buckling Model</u>
Students appreciated getting to interact with the model and observing how changing the bracing location modified the effective length for the strong versus weak axis, thus impacting the direction and manner of buckling. Many survey respondents noted that this helped them verify their prediction for column behavior, rather than just imagining it or looking at 2-D drawings on a handout or presentation slide. Yet, the average Q2 and Q4 scores shown in Figure 11 & 12 for this course upgrade are lower than the rest, which is likely due to two causes. First, the type of foam and cross-section to column height dimensions used in the model made it difficult to activate the double curvature in the strong-axis when bracing the weak-axis at the mid-height. Second, the small scale of the model made it difficult to interpret how the column deflected for students who watched their classmates use it but did not interact with it themselves.

<u>Diaphragm Layout Model</u>
The students indicated that having a 3-D physical reference for the different panel layout configurations with respect to other members in the diaphragm system was informative. Specifically, the opportunity to rearrange the pieces to see the layouts and how the components fit together improved their ability to visualize them. Additionally, students commented that the accompanying handout with tables, diagrams, and multiple example problems was a good variety of scenarios to provide context to diaphragm design and helped them with completing the homework assignment. Feedback included that the size of the model made it difficult for all students to see and suggested to either make the model larger, have more models, or have more time to pass around the model and interact with it one-on-one. There was also a comment about the model having too many pieces to rearrange rapidly to look at the different configurations while completing the example problems with possible resolutions being to either make modules with multiple attached pieces or a 3-D animation that could be used on the computer or via a smartphone application (perhaps of a similar nature to the shear wall Rhino toolkit). Other comments included constructing the model to include blocking and in such a way that the sheathing could deform with small springs.

<u>Manufacturer Samples</u>
Many of the students stated they had never seen these connectors in person, and the physical sample was more helpful than a 2-D image or 3-D rendering since it allowed them to look at the labels on the items to find them in manufacturer specification tables and determine capacities; be

able to visualize the geometry/size of each item, necessary mechanical fasteners, and correct orientation to enable load transfer when conducting structural detailing designs; and simply have the tactile experience of getting to hold and examine each component. Students suggested that these samples be shown earlier (and in a more distributed manner) during the course with explicit calculation example to accompany them, rather than the samples being brought to class towards the end of the quarter after the homework assignment on fasteners/connectors was turned in. Multiple students indicated they would have liked to see the fasteners within the context of a detail, with lumber members attached to them, for improved understanding of constructability and load path. Figure 12 indicates that students had more positive interactions with and recollection of the connectors/fasteners while they felt that there was less opportunity to interact with the sawn and pre-fabricated lumber products. Future learning aids could include a demonstration of the geometry factor in connection capacity. This prefabricated sample connection would show end distance, edge distance, spacing between rows, and spacing between fasteners in a row. In addition, how to navigate the geometry factor tables in Chapter 12 of the NDS and how to apply the minimum dimension checks with regard to loading relative to wood grain direction.

Shear Wall Rhino Model

Students liked the visualization aspects of the digital toolkit as it allowed them to inspect how the shear wall components were laid out and take measurements. They suggested the toolkit be introduced at the start of the shear wall unit to have access to investigate and use it for the entire duration rather than just at the end when the homework was assigned. Additionally, several students requested that the shear wall tutorial include a sample detail to reference. Though students felt confident completing calculations for the various portions of the shear wall, they did not know how to assemble their final design in the Rhino toolkit. Aside from this technical feedback, the students identified two major accessibility issues with the Rhino 7 files: most students had Rhino 6 (and it appeared the file was not backward compatible) and the large file size suffered from considerable lag when successfully opened in Rhino 7. This could be resolved by creating a more in-depth tutorial on how to access Rhino 7 or open the file in other software like Google SketchUp. As a note, the shear wall calculation activity with the Rhino toolkit was assigned during the last week of class and due the day of the final exam. Many felt rushed and could not prioritize the activity, which had significant negative impacts on the student experience as shown in the survey results. The authors suggest that the activity be broken into two portions: one that focuses on identifying the load path using the Rhino toolkit and the second that is calculation-based, both portions in advance of the final exam to improve student learning.

Bi-axial Bending Handout

The most common benefit the students indicated in this handout were the 2-D and 3-D diagrams that provided a clear visual of the direction of bending for each loading condition along with explicit indication of which variables were eliminated from the three-part equation (to produce simplified equations) and the appropriate checks to carry out. Multiple students found that separating and defining the various parts of the NDS equation was more digestible and easier to use. Feedback from the students indicated that the associated homework problem was specifically on a square post with an eccentric load. They suggested that some clarification on how to relate that scenario to those listed on the handout, or a worked-out example problem, be included. One student also advocated for a physical model to be made, potentially in reflection on the utility of the prior column buckling model.

Homework Packet

The students found value in the exposure to reading framing plans and detail drawings to extract pertinent information that would be expected of them as structural designers, rather than just reading text as in typical book problems. Having access to view the residential project in its entirety helped students see how each member or connection calculation approach they learned in class connected to the overall project scope. Moreover, as they continued through the quarter and designed subsequent structural members it helped them be able to track the load flow throughout the entire structural system. They found that the organization of the homework packet on different pages with simplified free-body-diagrams, problem statements, and some guidance on what and where givens to find in the drawings made the assignments more easily digestible. There were several comments from students indicating that they needed more support in navigating the plans and that on some occasions it seemed as if there was missing information that they would have to ask the instructor which limited the time they could work on the assignment. As a result, students felt that the difficulty of the homework problems was greater than those presented as in-class examples, and that there were additional challenges beyond trying to apply the course concepts. This could be resolved by spending more time introducing each set of homework problems and identifying potentially missing information early on.

Table 2. Sample Student Free Response Answers

Model/Handout	**Benefits (Q1)**	**Suggestions for Improvement (Q2)**
Column Buckling	"Being able to identify which way the [column] would buckle in regards to bracing. It can be difficult to picture it in 2D pictures"	"Contour or perpendicular lines drawn on the foam would have been helpful to visualize deflections...a better way to indicate zones of Compression/Tension..."
Bi-axial Bending Handout	"The pictures of the different scenarios with the associated equations helped me understand what part of the equation applies to what loading situation."	"An explanation of which parts of the equation are used on a member with a square cross-section...whether it could be considered flatwise or edgewise bending or both."
Diaphragm Layout Model	"Seeing the physical directions of framing and blocking was very helpful to visualize the different cases of sheathing"	"...passing around the model so people can see it more closely" "featured a display of potential loading for a problem statement"
Shear Wall Rhino Model	"…helps with visualizing load flow, making it easier to tell when the load is perpendicular versus parallel." "Being able to measure between members and see connections."	"Maybe include the detail drawings in the model as well" "...helpful to reference the digital toolkit during class instead of just giving it to us to use as reference for the exercise"

Manufacturer Samples	"The connection samples were greatly beneficial as they helped me to better understand load flows through the material." "Seeing the physical scale of each sample."	"Integrate samples into lecture instead of saving them for the end of class" "Have us do a practice calculation with a connection in class..."
Homework Packet	"It was very helpful to see where and how each piece of a project fit in and how we calc it. It was also helpful practice for reading and finding specific things in a plan set."	"There are more small pieces of information needed on multiple problems." "the homework problems didn't always line up exactly with the examples/concepts we learned in class..."

Some of the highest words of praise were from a student when asked how the diaphragm layout model could be improved, they answered "nothing, you guys killed it". This shows their enthusiasm for getting to see and interact with a custom model that was designed and fabricated specifically for their class and that topic, which in some way reminds them of the beloved childhood Lego or K'Nex kits that many of them speak of as inspiration to pursue structural engineering to begin with.

Lessons Learned

General commentary on the benefits of using physical and digital models discussed in this paper:

- ***Student excitement.*** The instructor found that entering a classroom with a model instantly garnered attention, faces brightened, and students sat forward. Just the prospect of getting to interact with, touch, and hold something caused increased engagement.

- ***Prompted more questions.*** Students asked more questions when a model was introduced. The authors hypothesize that being confronted with a physical model tends to activate more critical thinking and thus prompted more questions from the class.

- ***Improved visualization.*** To communicate spatial concepts, typically the information is delivered by an instructor using verbal and 2-D visual communication. Then a student must interpret words and drawings to create a 3-D mental visualization of the spatial concept. If there is a breakdown at any point in this sequence, learning is hindered. Thus, 3-D physical and digital models expedite and aid in the effectiveness of that process.

- ***Formed connections between structural topics.*** By implementing a comprehensive homework packet, students could better connect the different structural systems with one another. The packet also helped to familiarize students with finding information in drawings and learn the typical notation of timber drawings.

Specific feedback on the various demonstration tools so other instructors can implement them most effectively in their own teaching:

- ***Making a larger set of column buckling models gives students equal opportunity to have hands-on interaction.*** Six 1-foot tall models were created for use in class, and students were asked to pass them around. However, with a class of nearly 30 students, some students reported not having much time to use and experiment with the model. Those who did not have a chance to use the model noted that only observing from a distance made it difficult to understand which buckling direction was being activated.

- ***Updating handouts to introduce concepts or have in-class examples that address the types of complexities that students will encounter in the homework problems.*** This was a suggestion for improvement with the bi-axial bending handout where it was not clear to students how to deal with a square cross-section that was subjected to an eccentric load. However, the array of useful in-class problems was identified as one of the successes of the handout that accompanied the diaphragm layout model.

- ***Addressing diaphragm layout model disassembly and reassembly time.*** There are six panel layout cases outlined in the SDPWS, and it would be inefficient to disassemble and reassemble each case during lecture time. It was better used to describe panel orientation to framing, discontinuous versus continuous panel edges, and blocked versus unblocked diaphragms rather than strictly panel layout cases. It is worth rethinking how to implement for students to interact with directly rather than solely observation.

- ***Distributing physical samples throughout the course.*** Physical samples of connectors, fasteners, engineered lumber and sawn lumber were incorporated into lectures during the end of the course. Students found the samples helpful to see and interact with in person and suggested bringing samples into class at various points throughout the course, when their applications are first introduced. Students also proposed doing a sample calculation to introduce how to select connectors given specific loading scenarios.

- ***Additional support for access and use of digital toolkits and models.*** Some of the issues in the digital model usage were due to the inability of some students to easily access or utilize the software necessary to view these models. Once in the model, students needed additional scaffolding to understand how to use the toolkit to assemble the components of the shear wall they had designed.

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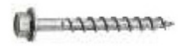
Appendix A

Table A.1. Model Fabrication Materials

Material	Dimensions	Cost	Source
Basswood Sticks	1/8 x 1/8 x 12 in (60 ct)	$8.99	Amazon
Basswood Sticks	1/4 x 1/4 x 12 in (60 ct)	$10.99	Amazon
Basswood Sheets	1/8 in x 200 x 300 mm (3 ct)	$19.94	Amazon
Magnetic Strip	1/16 in x 1/2 in x 15 ft (1 roll)	$7.50	Amazon
Multipurpose Foam	3 x 24 x 72 in (1 roll)	$27.00	Home Depot
Super Glue (2 bottles)	N/A	$10.00	Amazon
Spray Adhesive	N/A	$7.99	Amazon
Wood Glue	N/A	$12.00	Amazon
	Total:	$104.41	

Table A.2. Donated Materials Reference Sheet

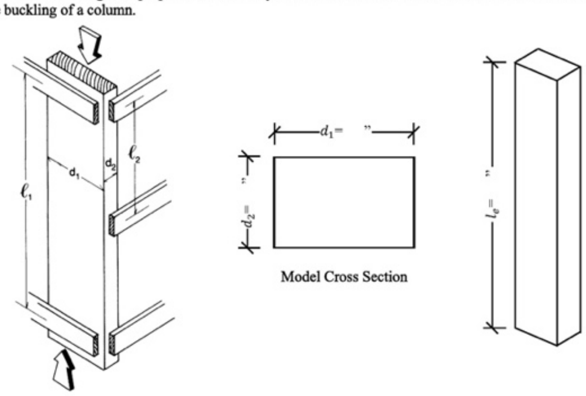
Category	Item	Quantity	Manufacturer	Simpson Catalog page (2021 Version)	Image
LVL	RigidLam LVL	1	Roseburg	N/A	
LVL	RigidRim Rimboard	1	Roseburg	N/A	
I-Joist	RFPI Joist	1	Roseburg	N/A	
Face Mount Hanger	U26	4	Simpson	100	
Face Mount Hanger	LUS26	7	Simpson	102	
Face Mount Hanger	LUS28	3	Simpson	102	
Top Flange Hanger	LB26	4	Simpson	124	
I-Joist Hanger	IUS2.37/11.88	3	Simpson	140	
Hurricane Tie	H1	3	Simpson	276	
Framing Angle	A35	3	Simpson	286	
Framing Angle	LPT4	3	Simpson	286	
Strap Tie	MST824	3	Simpson	268	
Nail	8d SCN Smooth Shank Connector Nails	150	Simpson	21	
Nail	10d SCN Smooth Shank Connector Nails	150	Simpson	21	
Nail	16d SCN Smooth Shank Connector Nails	150	Simpson	21	
Screw	SD Connector Screws	100	Simpson	21	
Screw	#9 SDS Heavy Duty Connector Screws	25	Simpson	21	
Screw	SDW screws	9	Simpson	21	
Anchor Bolt	Anchor Bolt	3	Simpson	42	
Anchor Bolt	SSTB Anchor Bolt	3	Simpson	36	

Appendix B

Column Buckling

Column Buckling Name: ______________________
ARCE 304: Timber Design

This activity is designed to examine the effect on column buckling when columns have different unbraced lengths for each principal axis. The accompanying foam model can be braced at different lengths in each direction of bending. The purpose of the activity is to visualize the effects of different slenderness ratios on the buckling of a column.



NDS 3.6 Figure 3F

Step 1: Determine the cross sectional dimensions and height of the provided foam column model.

Step 2: Calculate slenderness ratios for the column before and after bracing at mid-height in the weak direction ($l_1/d_1, l_1/d_2, l_2/d_2$). Hypothesize how the ratios will influence the buckling behavior of the column before and after bracing.

Step 3: To exhibit the first buckling behavior, leave the length of the model unbraced and press down at the top of the model. Note the buckling shape and direction.

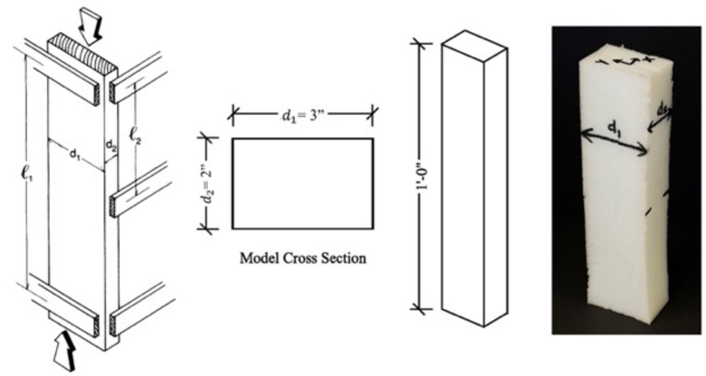
Step 4: To exhibit the second buckling behavior, brace the model at mid-height (at indicated line) along the weak axis and press down at the top of the model.

Step 5: Reflect on your hypothesis and compare it to the results of the activity.

Figure B.1. Column Buckling Handout

Column Buckling Model Lesson

This activity is designed to examine the effect on column buckling when columns have different unbraced lengths for each principal axis. The accompanying foam model can be braced at different lengths in each direction of bending. The purpose of the activity is to visualize the effects of different slenderness ratios on the buckling of a column.



NDS 3.6 Figure 3F

Directions for use in Lecture

Step 1: Direct students to NDS 3.6 Figure 3F (see above), to introduce the idea of multiple slenderness ratios on a single column ($l_1/d_1, l_1/d_2, l_2/d_2$).

Step 2: Divide students into small groups, and provide each group with a foam model. Instruct students to calculate slenderness ratios for the column before and after bracing in the weak direction. Invite students to then hypothesize how the ratios will influence buckling of the models.

$$\frac{l_1}{d_1} = \frac{12"}{3"} = 4 \quad \frac{l_1}{d_2} = \frac{12"}{2"} = 6 \quad \frac{l_2}{d_2} = \frac{6"}{2"} = 3$$

Step 3: To exhibit the first buckling behavior, instruct students to leave the length of the model unbraced and press down at the top of the model. The model should buckle in the weak direction with a single curvature.

Step 4: To exhibit the second buckling behavior, instruct students to brace the model at mid-height (at indicated line) along the weak axis and press down at the top of the model. The model should buckle in the strong direction with single curvature.

Step 5: Invite students to reflect on their hypothesis and compare it to the results of the activity.
Larger ratio > more slender > indicates buckling direction

Figure B.2. Column Buckling Lesson Plan

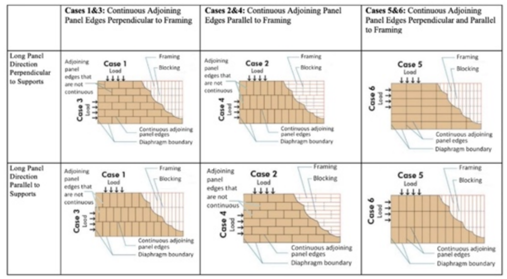
Diaphragm Capacity

Diaphragm Capacities

Name: ____________________

ARCE 304: Timber Design

This activity is designed to determine the capacities of multiple diaphragm framing cases based on the layout and orientation of the structural paneling on the framing (see SDPWS Fig 4B below). Reference SDPWS Tables 4.2A and 4.2C. Assume a sheathing grade of Structural I Plywood for all cases. Arrange the panels in the correct scheme for each scenario.



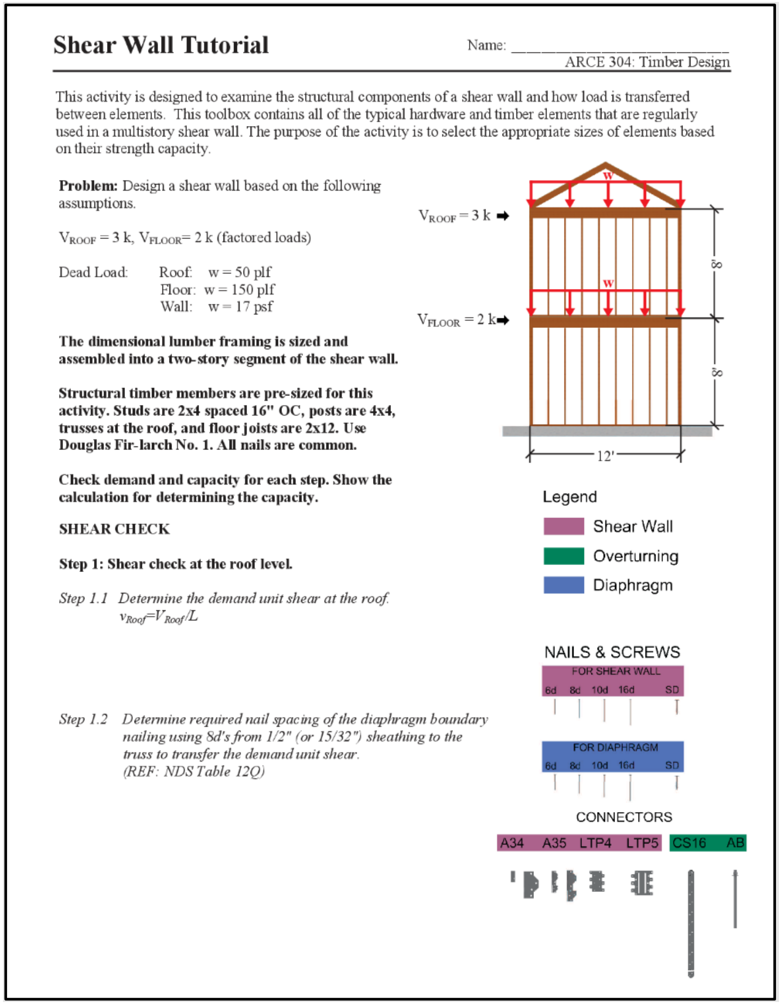
SDPWS Figure 4B

Diaphragm Scenario	Blocking	Force	Sheathing Thickness	Nailing	Supporting Member	Case
A	Unblocked	Seismic	1/2"	8d @ 6" o.c.	Roof trusses	3
B	Unblocked	Seismic	3/4"	10d @ 6" o.c.	TJI floor joists with 2x4 flat top flange	4
C	Blocked	Wind	1/2"	8d @ 6" o.c.	2x roof rafters	1
D	Blocked	Wind	1/2"	8d @ 4" o.c., 6" o.c. at staggered panel edges	2x roof rafters	1
E	Blocked	Seismic	3/4"	10d @ 4" o.c., 6" o.c. at staggered panel edges	2x10 floor joists	2
F	Blocked	Seismic	3/4"	10d @ 2" o.c. , 3" o.c. at staggered panel edges	2x10 floor joists	4

Diaphragm Scenario	Tabulated Capacity (plf)	ASD Reduction Factor	Allowable Capacity (plf)
A			
B			
C			
D			
E			
F			

Figure B.3. Diaphragm Capacity Handout

Shear Wall Tutorial



Shear Wall Tutorial Name: ______________________

ARCE 304: Timber Design

This activity is designed to examine the structural components of a shear wall and how load is transferred between elements. This toolbox contains all of the typical hardware and timber elements that are regularly used in a multistory shear wall. The purpose of the activity is to select the appropriate sizes of elements based on their strength capacity.

Problem: Design a shear wall based on the following assumptions.

V_{ROOF} = 3 k, V_{FLOOR} = 2 k (factored loads)

Dead Load: Roof: w = 50 plf
Floor: w = 150 plf
Wall: w = 17 psf

The dimensional lumber framing is sized and assembled into a two-story segment of the shear wall.

Structural timber members are pre-sized for this activity. Studs are 2x4 spaced 16" OC, posts are 4x4, trusses at the roof, and floor joists are 2x12. Use Douglas Fir-larch No. 1. All nails are common.

Check demand and capacity for each step. Show the calculation for determining the capacity.

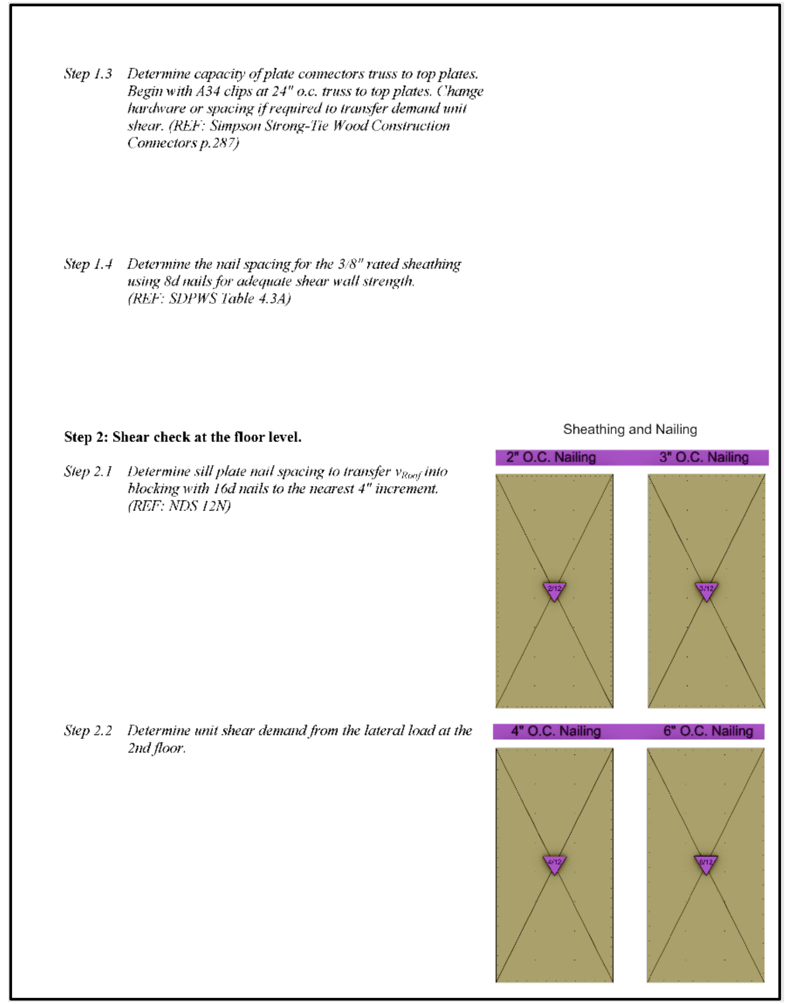
SHEAR CHECK

Step 1: Shear check at the roof level.

Step 1.1 Determine the demand unit shear at the roof.
$v_{Roof} = V_{Roof}/L$

Step 1.2 Determine required nail spacing of the diaphragm boundary nailing using 8d's from 1/2" (or 15/32") sheathing to the truss to transfer the demand unit shear. (REF: NDS Table 12Q)

Figure B.4. Shear Wall Tutorial, Page 1 of



Step 1.3 Determine capacity of plate connectors truss to top plates. Begin with A34 clips at 24" o.c. truss to top plates. Change hardware or spacing if required to transfer demand unit shear. (REF: Simpson Strong-Tie Wood Construction Connectors p.287)

Step 1.4 Determine the nail spacing for the 3/8" rated sheathing using 8d nails for adequate shear wall strength. (REF: SDPWS Table 4.3A)

Step 2: Shear check at the floor level.

Step 2.1 Determine sill plate nail spacing to transfer v_{Roof} into blocking with 16d nails to the nearest 4" increment. (REF: NDS 12N)

Step 2.2 Determine unit shear demand from the lateral load at the 2nd floor.

Figure B.5. Shear Wall Tutorial, Page 2 of

Step 2.3 *Determine unit shear capacity of diaphragm boundary nailing 10d nails spaced at 6" o.c. from 3/4" (23/32") sheathing to blocking to transfer floor unit shear. (REF: NDS Table 12Q)*

Step 2.4 *Determine total unit shear.*

Step 2.5 *Determine plate connector and spacing blocking to top plates to resist the total unit shear starting with A34 clips at 16" o.c. (up-size to an A35 if necessary). (REF: Simpson Strong-Tie Wood Construction Connectors p. 287)*

Step 2.6 *Determine spacing of 8d nails with 3/8" wall sheathing for adequate shear wall strength to resist total unit shear. (REF: SDPWS Table 4.3A)*

Figure B.6. Shear Wall Tutorial, Page 3 of

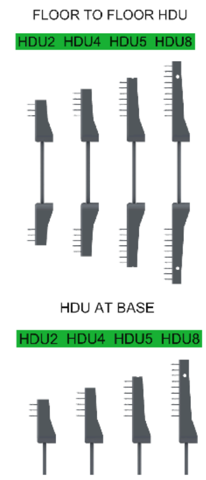
Step 3: Shear check at foundation. Determine spacing of the 5/8" anchor bolts to the nearest 6" increment. (REF: NDS Table 12E)

Step 4: Resolve overturning, determine the size of the wood to wood hold downs and the wood to concrete hold downs.
(REF: Simpson Strong-Tie Wood Construction Connectors p. 53)

Assume load combo $(0.6 - 0.14S_{DS})D + 0.7E$
Recall that lateral forces in problem statement have been factored

$S_{DS} - 1.0$

Step 4.1 *Select hold-downs at 2nd floor.*



Step 4.2 *Select hold-downs at ground floor.*

Figure B.7. Shear Wall Tutorial, Page 4 of

Helpful Rhino Commands

Use these Rhino commands to easily move, copy, and place items into the shear wall framing. Type these commands into the command bar to activate. Rhino will prompt you to insert additional information as needed.

Gumball: Click "Gumball" in the bottom bar of the display to activate the gumball tool. This allows you to move and rotate items along a single axis, which is especially helpful while in perspective view.

Array: Allows you to make copies of an item at equal spacing along single or multiple axes.

Measure: Measure a distance.

Move: Move a selected item a specified distance.

Rotate: Rotate at item at a specific angle along a desired axis.

Copy: Select an item and create a copy.

Paste: Paste a copied item.

Hide: Hide a selected item.

Show: Show hidden items.

EnableClippingPlane: Select desired clipping plane, then adjust clipping plane in order to create sections though elements.

DisableClippingPlane: Select desired clipping plane to undo any section views that have been created.

Methods of Accessing Toolkit

Rhino 7:
Visit https://www.rhino3d.com/download/ and download the 90-day trial of Rhino 7, available for both Mac and Windows.

Rhino 6 or previous versions:
Contact instructor for file compatible with Rhino 6 or previous versions.

SketchUp:
In the File menu, click Open > Insert > Import. Select the .3dm file type and the Rhino toolkit file.
An import option dialog box will appear, ensure that "Mesh" is selected for imported faces, and that the "Edges", "Faces", and "Embed textures" options are checked.

Solidworks:
In the File menu, click Open. Select .3dm under the file type tab and select the Rhino toolkit file. Click Options, and specify surfaces and solids to be imported as features.

Figure B.8. Shear Wall Tutorial, Page 5 of

Combined Compression and Bending Handout

Combined Compression & Bending

Name: ______________________

ARCE 304: Timber Design

This handout is designed to break down the elements of the combined compression and bending equation. It explains the different moment amplification factors and what they account for in the equation.

3 Things to Consider

1. Column Buckling (Column Stability, C_P, accounted for in allowable compressive stress, F'_c)
2. Lateral Torsional Buckling of Beam (Beam Stability, C_L, accounted for in allowable edgewise bending stress, F'_{b1})
3. Column-Beam Stress Interaction

NDS 3.9-3: $$\left(\frac{f_c}{F'_c}\right)^2 + \left(\frac{1}{1-\frac{f_c}{F_{cE1}}}\right)\left(\frac{f_{b1}}{F'_{b1}}\right) + \left(\frac{1}{1-\left(\frac{f_c}{F_{CE2}}\right)-\left(\frac{f_{b1}}{F_{bE}}\right)^2}\right)\left(\frac{f_{b2}}{F'_{b2}}\right) \leq 1.0$$

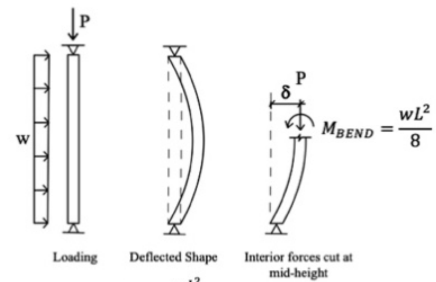
Equation Component	Purpose
$\left(\frac{1}{1-\frac{f_c}{F_{cE1}}}\right)$	Moment Amplification Factor 1 (MAF1) to account for second order P-δ effects of edgewise bending.
$\left(\frac{1}{1-\left(\frac{f_c}{F_{CE2}}\right)-\left(\frac{f_{b1}}{F_{bE}}\right)^2}\right)$	Moment Amplification Factor 2 (MAF2) to account for second order P-δ effects of flatwise bending.
$\left(\frac{f_{b1}}{F_{bE}}\right)^2$	Accounts for amplification of f_{b2} from f_{b1}, based on testing results and analysis

Figure B.9. Combined Compression and Bending Handout, Page 1 of 4

P-δ Effect

δ is not found directly to use in M_{MAX} but accounts for the effect by increasing actual bending stress, f_b, with MAF1 and MAF2

- As P increases, both f_c and MAF1 increase.
- Slenderness, l_e/d, affects the magnitude of δ. F_{cE} is Euler Buckling stress using d, in the direction of bending. As slenderness increases, F_{cE}, decreases and MAF increases.



$$M_{MAX} = \frac{wL^2}{8} + P\delta$$

Compression and Bending Interaction Guide

P_1 induces δ_1 and MAF1, which adds to M_x, edgewise bending moment and corresponds to $\frac{f_c}{F_{cE1}} \leftarrow use\ \frac{l_e}{c}$

P_2 induces δ_2 and MAF2, which adds to M_y, flatwise bending moment and corresponds to $\frac{f_c}{F_{cE2}} \leftarrow use\ \frac{l_e}{d_2}$

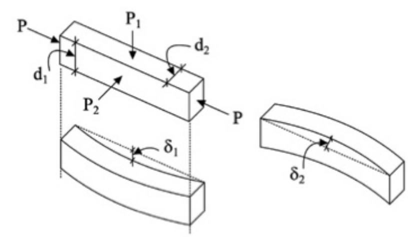
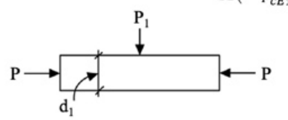


Figure B.10. Combined Compression and Bending Handout, Page 2 of 4

Loading Conditions

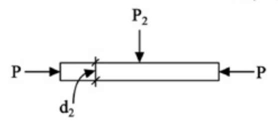
1. No flatwise bending

NDS Eq 3.9-3 (simplified): $\left(\frac{f_c}{F_c'}\right)^2 + \frac{f_{b1}}{F_{b1}'\left(1-\frac{f_c}{F_{cE1}}\right)} \le 1.0$



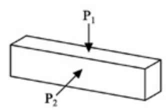
2. No edgewise bending

NDS Eq. 3.9-3 (simplified): $\left(\frac{f_c}{F_c'}\right)^2 + \frac{f_{b2}}{F_{b2}'\left(1-\frac{f_c}{F_{cE2}}\right)} \le 1.0$



3. No compression

NDS Eq. 3.9-3 (simplified): $\frac{f_{b1}}{F_{b1}'} + \frac{f_{b2}}{F_{b2}'\left(1-\left(\frac{f_{b1}}{F_{bE}}\right)^2\right)} \le 1.0$



4. All apply (P, P_1, and P_2)

NDS Eq. 3.9-3 AS IT APPEARS and
NDS Eq. 3.9-4 $\frac{f_c}{F_{cE2}} + \left(\frac{f_{b1}}{F_{bE}}\right)^2 < 1.0$

Checks

A. $f_c < F_{cE1}$
- For uniaxial edgewise and biaxial
- Checks demand compression stress is less than critical buckling stress about strong axis

B. $f_c < F_{cE2}$
- For uniaxial flat and biaxial
- Checks demand compression stress is less than critical buckling stress about weak axis

C. $f_{b1} < F_{bE}$
- Biaxial only
- Checks bending about strong axis is less than critical lateral torsional buckling stress

Figure B.11. Combined Compression and Bending Handout, Page 3 of 4

List of Variables

- f_{b1} = actual edgewise bending stress (bending load applied to narrow face of member), psi
- f_{b2} = actual flatwise bending stress (bending load applied to wide face of member), psi
- F'_{b1} = bending capacity stress (allowable bending load applied to narrow face of member), psi
- F'_{b2} = bending capacity stress (allowable bending load applied to wide face of member), psi
- $F_{bE} = \frac{1.20E_{min}'}{R_B^2}$
- f_c = compression stress (compression load applied to the member), psi
- F'_c = capacity compression stress, psi
- $F_{cE} = \frac{0.822E_{min}'}{\left(l_e/d\right)^2}$
  - $F_{cE1} = \frac{0.822E_{min}'}{\left(l_{e1}/d_1\right)^2}$, applied to narrow face of member, psi
  - $F_{cE2} = \frac{0.822E_{min}'}{\left(l_{e2}/d_2\right)^2}$, applied to wide face of member, psi
- d_1 = wide face dimension, in
- d_2 = narrow face dimension, in

Figure B.12. Combined Compression and Bending Handout, Page 4 of 4

Appendix C

B	I	N	G	O
Find a grading stamp, what information did it tell you?	TJI flange size? Can you use 2x or 3x for diaphragm capacity?	What did you noticed about wood construction that you didn't know before? (Write on back)	What type of foundation is it? Anything special?	Where do we typical allow holes through flexural members?
Find a shear wall with BN less than 4" oc. What is the EN?	Find a collector transferring load to a shear wall. Sketch	What is a member where the incising factor would be applicable?	How do you know if a wall is a partition wall or bearing?	Find an engineered lumber beam what is the type and size? What is it supporting?
What is the spacing between trusses?	Find a member where CL would be a significant factor, describe.	Ask a Question	Shear wall on the second story how do you transfer shear to wall below?	What's the typical anchor bolt spacing?
Find a post (4x min) what is the le/d?	When can you use 2x blocking between trusses and when do you use truss blocking?	How many screw connect a HDU2 holdown to a post?	What do they do at shear wall panel edges? (Vertical seams)	What is the nail spacing of the floor sheathing?
What three members that would get a repetitive member factor?	What elements transfer lateral load from the diaphragm to the top plates?	Shear wall on the second story how do you transfer moment to wall below?	What are the size and spacing of the studs?	Is the roof diaphragm blocked or unblocked?

Figure C.1. Bingo Sheet used for Site Visit to Light-Framed Timber Construction Project

Table C.1 Recommended Companies and Industry Contacts

Focus/Specialty	Companies/Contact
Manufacturers of Wood Products or Fasteners	• Boise Cascade • Simpson Strong-Tie • Roseburg Forest Products
Engineering/Construction Firms Involved in Innovative Wood Building Projects	• Fast + Epp • KL&A Engineers & Builders • Swinerton (Timberlab)
Professional Organizations Affiliated with Wood Products	• American Wood Council [22] • APA – The Engineered Wood Association • WoodWorks
Faculty/Industry Members Engaged in Wood Code Development:	• Erica Fischer with Oregon State University [20],[21] • Kelly Cobeen with Wiss, Janney, Elstner • Shiling Pei with Colorado School of Mines • John Lawson with Cal Poly – San Luis Obispo • Maria Koliou with Texas A & M University