Design and Implementation of Experiential Learning Modules for Structural Analysis

Alec Colin Derks, Saint Louis University
Dr. J Chris Carroll P.E., Saint Louis University, Parks College of Eng.

Dr. Carroll is an Assistant Professor and the Civil Engineering Program Coordinator in Parks College of Engineering, Aviation and Technology at Saint Louis University. His experimental research interests focus on reinforced and prestressed concrete, while his engineering education research interests focus on experiential learning at both the university and K-12 levels. Dr. Carroll is the chair of ACI Committee S802 - Teaching Methods and Educational Materials and he has been formally engaged in K-12 engineering education for nearly ten years.

Prof. James H. Hanson P.E., Rose-Hulman Institute of Technology

Dr. James Hanson is a Professor of Civil Engineering at the Rose-Hulman Institute of Technology. His teaching emphasis is structural analysis and design. Over the last fifteen years he has conducted research on teaching students how to evaluate the reasonableness of their results. He is the recipient of several best paper awards and teaching awards including the American Concrete Institute's Young Member Award for Professional Achievement and the Walter P. Moore Jr. Faculty Award. He also received the Ferdinand P. Beer and E. Russell Johnston, Jr., Outstanding New Mechanics Educator Award from the Mechanics Division of ASEE.

Professor Hanson brings four years of military and industry experience to the classroom. Upon completing his Ph.D. in structural engineering at Cornell University, he taught for two years at Bucknell University. He is a registered Professional Engineer.

Dr. Matthew D. Lovell P.E., Rose-Hulman Institute of Technology

Matthew Lovell is an Associate Professor in the Civil Engineering Department at Rose-Hulman Institute of Technology, and he currently serves as the Senior Director of Institutional Research, Planning, and Assessment office. He is also serving as the director of the Making Academic Change Happen (MACH) program. He received his Ph.D. from Purdue University, and he holds his PE license in Indiana. Matt is very active with respect to experimentation in the classroom. He greatly enjoys problem-based learning and challenge-based instruction. Matt is the 2018 recipient of the American Concrete Institute's Walter P. Moore, Jr. Faculty Achievement Award. He was awarded Teacher of the Year for the Illinois Indiana section of ASEE in 2017. Also, he was awarded the Daniel V. Terrell Outstanding Paper Award from ASCE. Matt is highly active in ASEE, currently serving as the ASEE CE Division's Freshman Director. In 2014, Matt received the ASEE CE Division Gerald R. Seeley Award for a paper highlighting a portion of his work regarding the development of a Master's Degree at Rose-Hulman.

Dr. Kyle Kershaw P.E., Rose-Hulman Institute of Technology

Dr. Kyle Kershaw is an Assistant Professor in the Department of Civil Engineering at Rose-Hulman Institute of Technology. Kyle's primary teaching duties include courses in geotechnical engineering and construction materials. His research interests include behavior and monitoring of in-place foundations and retaining structures. In addition to his teaching and research duties, Kyle is involved in geotechnical consulting and Engineers Without Borders.

Design and Implementation of Experiential Learning Modules for Structural Analysis

Introduction

Structural analysis is the foundational course of a structural engineer's education, which generally includes topics ranging from basic statics to analyzing complex indeterminate structures. Most courses focus on theoretical approaches to solving and understanding problems with a large focus on determining internal forces, external reactions, and displacements. Additionally, some courses will offer discussion on deflected shapes and actual behavior compared to theoretical assumptions. Visualizations in the form of photos, videos, and simulations are commonly brought into the classroom to help with this discussion, but students rarely have the opportunity to physically feel the differences and experience large-scale models that illustrate such behavior. The rarity of full-scale models in the classroom is mainly due to the cost, fabrication complexity, and material stiffness. Saint Louis University (SLU) and Rose-Hulman Institute of Technology (Rose-Hulman) designed large-scale, lightweight models for the classroom to be used during structural analysis courses. The modules utilize EXTREN® structural shapes which are made out of a flexible fiberglass reinforced polymer (FRP). While this material is regularly used for the design of structural members, it also has advantageous properties for the purpose of these modules in an experiential setting.

The first module focuses on the behavior of beam-to-column connections compared to theoretical assumptions. This module also displays the differences in behavior between different connection types. The second module focuses on load paths and tributary areas related to a typical floor system. This module replicates a real floor system that may be used in a building. The module provides the ability for students to physically see theoretical calculations compared to actual results during a lecture. The third module focuses on the deflected shapes of determinate and indeterminate beams. This module utilizes a channel that is large enough for students to stand on and has multiple configurations that are able to be assembled quickly. Additionally, the third module reinforces virtual work and the force method. The fourth module focuses on the behavior of a portal frame subjected to both vertical and horizontal loads with various support configurations. This module focuses on students visualizing deflected shapes based on the conditions and comparing the theoretical results to the observable deflected shapes in the classroom. Additionally, this module was used to further reinforce virtual work and the force method.

The following sections provide some background about the overall project along with the design and implementation of the experiential learning modules. There is also a brief discussion about assessment efforts on the project and lessons learned by the project team thus far.

Project Background

The project as a whole includes several experiential learning modules covering four courses: structural analysis, reinforced concrete, steel design, and geotechnical engineering (soil mechanics and foundations) as described by Carroll et al. [1]. This paper focuses only on the design and implementation of the experiential learning modules for structural analysis. The experiential learning modules discussed herein use fiberglass reinforced polymer (FRP) structural shapes produced by the Strongwell Corporation. Strongwell produces over 100 structural shapes from an FRP material called EXTREN® that is both lightweight and high strength. EXTREN® is an anisotropic material with directional dependent properties, but the modulus of elasticity for flexural members is determined directly from simple beam bending tests on full sections. The modulus of elasticity is roughly 10% of steel's modulus of elasticity: a value ranging between 2,500 and 2,600 ksi. Its ultimate strength reaches 30,000 psi in the direction of the reinforcement. Therefore, EXTREN® members are much more flexible than steel at much lower stresses. Lastly, EXTREN® structural shapes have a density of about 120 pcf whereas steel has a density of about 490 pcf. Thus, EXTREN® is an ideal product for this project. It is strong and lightweight, yet flexible enough to illustrate structural behavior [2].

Three of the four structural analysis modules require no structural testing facilities and the fourth could also be adjusted to negate the need of structural testing facilities. The structural analysis modules could be implemented at universities with smaller programs that do not have structural engineering laboratories. SLU is a large, private, four-year, highly residential university with doctoral programs and high research activity (R2); Rose-Hulman is a small, private, four-year, highly residential university without doctoral programs, classified as special focus four-year: engineering schools. Neither institution had a structural engineering laboratory prior to this implementation, but both focus heavily on the undergraduate learning experience. The project utilizes the Modular Strong-block Testing System [3] when needed to test larger-scale specimens. While a full structural engineering lab would be ideal to conduct such tests, the self-contained system provides an economical solution for smaller programs. Fig. 1 (a) and (b) show the system in use.

(a) (b)

Fig. 1—The Modular Strong-block Testing System setup for (a) a beam test and (b) a frame test.

All junior-level civil engineering students at SLU and Rose-Hulman take an introductory structural analysis course called Structural Analysis and Structural Mechanics I, respectively. The SLU course takes place in the fall semester and includes roughly 24 students each year. The course meets two times per week over the course of fifteen weeks for one hour and 15 minutes each time. The Structural Analysis course at SLU also includes a separate lab section that meets one time per week for one hour and 50 minutes. The lecture and lab portions of the course are taught in a learning studio type classroom with mobile seating along with two short-throw projectors at the front of the room and five flat-panel televisions spread along the other three walls. Each class is devoted to a specific topic and includes an overview of the day's objectives followed by some theoretical content and an example generally completed using an active learning technique. Students receive a handout in the form of "skeleton files" that features a PowerPoint presentation including most supporting text and the schematic drawings for the examples along with blank spaces for students to fill in and complete examples during class. The instructor uses a Surface Pro 2 computer to present the material wirelessly while roaming around the classroom and facilitating students as they work through examples.

The Rose-Hulman course takes place in the fall quarter and includes roughly 36 students each year. The course meets four times per week over the course of ten weeks for 50 minutes each time. Each class typically includes the following progression of material: presentation of a new analysis method, application of the method through a guided example exercise, and when possible, independent application in an additional exercise with the faculty member moving around the room to help. The instructor uses a Socratic approach asking questions to guide the students to a deeper understanding. The presentation of new material involves frequent active learning techniques to keep the students engaged.

The content of structural analysis courses varies widely among universities and may include topics ranging from load paths all the way to matrix analysis. However, most courses include a core list of topics such as loads and load paths, determinate structures, truss analysis, shear and moment diagrams, deflections, indeterminate structures, and approximate methods of analysis. The prerequisite material for structural analysis courses mainly includes statics and mechanics of solids. Among the topics that students learn, the authors have noted particular student struggles with analysis skills that require deeper understanding and judgement. Some of the particular topics are 1) the difference between theoretical assumptions and actual connection behavior, 2) load paths and load combinations, 3) visualizing the deflected shapes of beams and calculating non-standard deflections, and 4) approximate analysis of braced and rigid frames and visualizing their behavior [4].

Students at both SLU and Rose-Hulman were asked to take a course content survey to evaluate their perception of the topics most difficult to understand. The survey used a standard five-point Likert scale where 1 = Very difficult, 2 = Difficult, 3 = Neutral, 4 = Easy, and 5 = Very easy. Over the course of two years, 94 students at the two schools participated in the structural analysis course content survey, the results of which are shown in Table 1. Eleven topics had an average response less than or equal to 3.0. Furthermore, Topics 14, 16, 19, and 25 had modes of 2, indicating that a significant number of students selected "Difficult" on the survey. The results of the survey were fairly consistent across universities and not surprising. However, topics 2, 3, and 4 had higher scores than expected; students tend to struggle with those concepts, which is discussed in more detail hereafter.

Table 1—Students' perception of the most difficult topics in structural analysis [4].

#	Topic	SLU			Rose-Hulman			Total		
		Mode	Avg.	SD	Mode	Avg.	SD	Mode	Avg.	SD
1	Types of loads (e.g. live, dead, rain, snow, wind, earthquake, etc.)	4.00	3.91	0.81	4.00	3.43	0.92	4.00	3.64	0.90
2	Load paths	4.00	3.52	0.98	3.00	3.21	0.69	3.00	3.35	0.83
3	Structural idealization	3.00	3.25	0.79	3.00	3.25	0.70	3.00	3.25	0.73
4	Predicting results	3.00	3.19	0.75	4.00	3.11	0.99	3.00	3.14	0.89
5	Statically determinate structures	4.00	3.77	1.07	3.00	3.70	0.78	4.00	3.73	0.91
6	Trusses (method of joints)	5.00	4.09	0.97	4.00	3.96	0.88	4.00	4.02	0.91
7	Trusses (method of sections)	4.00	3.86	0.94	4.00	3.82	1.02	4.00	3.84	0.98
8	Internal forces (calculating forces and moments at a section cut)	4.00	3.82	1.01	4.00	3.59	0.89	4.00	3.69	0.94
9	Internal forces (axial force equations/diagrams)	3.00 & 4.00	3.59	1.01	4.00	3.36	1.03	4.00	3.46	1.01
10	Internal forces (shear and moment equations)	4.00	3.41	1.05	4.00	3.57	1.00	4.00	3.50	1.02
11	Internal forces (shear and moment diagrams)	4.00	3.55	1.06	4.00	3.57	1.00	4.00	3.56	1.01
12	Deflections (virtual work for trusses)	3.00	3.32	0.99	3.00	2.79	0.92	3.00	3.02	0.98
13	Deflections (virtual work for beams)	3.00	3.43	0.98	3.00	2.79	0.92	3.00	3.06	0.99
14	Deflections (virtual work for frames)	2.00 & 3.00	3.05	1.09	3.00	2.63	0.84	3.00	2.82	0.97
15	Deflections (conjugate beam method)	3.00	2.91	0.97	-	-	-	-	-	-
16	Deflections (moment-area method)	2.00	2.80	0.77	-	-	-	-	-	-
17	Deflections (double integration method)	-	-	-	4.00	3.19	0.83	-	-	-
18	Indeterminate beams (force method)	3.00	2.68	0.84	-	-	-	-	-	-
19	Indeterminate frames (force method)	2.00	2.55	0.86	-	-	-	-	-	-
20	Indeterminate composite structures (method of compatibility)	4.00	2.50	0.86	-	-	-	-	-	-
21	Influence lines (determinate structures)	4.00	3.27	0.94	-	-	-	-	-	-
22	Influence lines (indeterminate structures)	4.00	3.18	1.14	-	-	-	-	-	-
23	Approximate analysis (indeterminate trusses)	3.00	2.91	1.02	3.00	2.79	0.69	3.00	2.84	0.84
24	Approximate analysis (indeterminate beams)	3.00	3.00	1.07	3.00	2.69	0.68	3.00	2.83	0.88
25	Approximate analysis (braced frames)	2.00	2.73	1.03	3.00	2.61	0.57	3.00	2.66	0.80
26	Approximate analysis (unbraced frames)	3.00	3.00	1.07	3.00	2.58	0.58	3.00	2.77	0.86
27	Matrix analysis (trusses)	3.00	3.41	1.05	-	-	-	-	-	-
28	Matrix analysis (beams)	3.00 & 4.00	3.41	1.05	-	-	-	-	-	-
29	Matrix analysis (frames)	3.00	3.27	1.08	-	-	-	-	-	-

Design and Implementation of Experiential Learning Modules

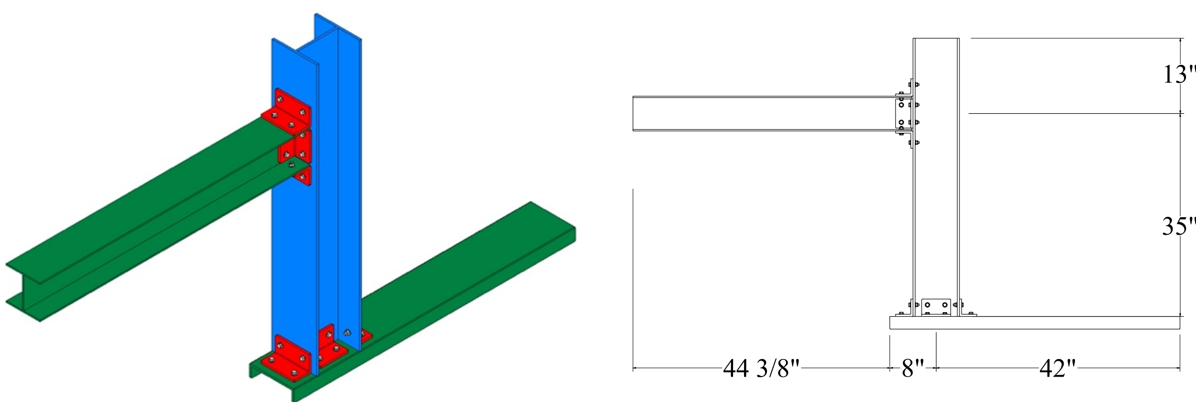
The primary objective of this project as a whole is to develop and implement experiential learning modules that allow students to visualize the behavior and accurately predict the effects of loads on structural systems and components. This paper focuses on four experiential learning modules for structural analysis courses that illustrate structural behavior. The four modules focus on 1) Connections, 2) Load Paths, 3) Deflections of Beams, and 4) Deflections of Frames.

Each of the following sections contain a description of each module's design, fabrication, and their implementation at SLU and Rose-Hulman during the third year of the project.

Module 1—Connections

Design

The purpose of the *Connections Module* is to demonstrate the behavior of beam-to-column connections compared to theoretical assumptions. The module highlights three types of connections: rigid, semi-rigid, and pinned and was designed like a "science center style exhibit" so students could physically feel and see the difference among the connection types. The design includes three initial considerations. First, the module should be free-standing; second, the module should be stable when students apply load; and third, the connection should be easily switched. The resulting design was fabricated from EXTREN® structural members including an 8 in. wide channel for the base, an 8 in. deep wide-flange (W8) beam for the column, and a 6 in. deep wide-flange (W6) beam for the cantilever beam. The structure was bolted together using EXTREN® angles and 3/8 in. diameter Grade 5 bolts. The connection can be adjusted to simulate various levels of rigidity. Fig. 2 shows the final design along with the overall dimensions.



(a) (b)

Fig. 2—(a) Connection module design and (b) overall dimensions.

The first design consideration was that the module should be free-standing, while the second was stability under loading. The column height was first selected so a student could hold the flange at the top of the column to support the column horizontally when another student applied a vertical load to the end of the cantilever beam. The cantilever beam length was arbitrarily chosen to illustrate a beam framing into a column. The channel was selected for the base for two reasons. First, the channel's stiffness is adequate to resist the resulting moment within the system when a student applies a vertical force at the end of the cantilever beam. Second, the elevated web provided clearance for the vertical bolts attaching the channel to the column. The orientation of the channel was selected so a student can stand on the opposite side of the column to counteract the force being applied to the end of the beam by another student. The length of the channel was selected to adequately balance the structure when no one is using it. The third design consideration was that the connection type could be easily changed. Therefore, the beam to column connection was designed using only angles and bolts. Additional design considerations taken into account were the hole locations for simplicity of fabrication. Holes on the shear tabs were able to be completed on a mill, so it was easy to achieve precise dimensions. The holes on the channel and wide flange beams were done by hand, so straightforward bolt patterns were followed on these members. Thus, the hole locations on the channel and the wide flange beams controlled the design, and the shear tabs' holes were designed in accordance with those locations.

Fabrication

Fabrication of the *Connections Module* began with selecting the required materials for one structure as previously discussed (shown in Table 1) and cutting all of the members to length. The EXTREN® shapes are made from fiberglass reinforced polymer. Thus, it was important to wear appropriate personal protective equipment (PPE) when working with the material. Once materials were cut down to size, the next step was to mark hole locations and drill the holes in all members. All of the connections used 3/8 in. diameter Grade 5 bolts, so all of the holes were sized 1/16 in. larger for a diameter of 7/16 in. All bolts used two washers (one on each side) and a nut. Assembly of the *Connections Module* was a simple process. The channel connected to the column using four angles that attach to the column's flanges and web, creating a rigid connection. The cantilever beam connected to the column in the same manner. Four angles attach the flanges and web of the beam to the flange of the column. Each angle holding the cantilever beam in place can be removed from the top and bottom flange to create the semi-rigid or pinned connection. Fig. 3 shows an exploded view of the assembled *Connections Module*.

Table 1—Connections module material takeoff

Item	Length	Quantity
8x8x3/8 EXTREN® wide flange beam	48 in.	1
6x6x1/4 EXTREN® wide flange beam	48 in.	1
EXTREN® 8x3/8 channel	50 in.	1
EXTREN® 3x3x3/8 angle	5 in.	4
EXTREN® 3x3x3/8 angle	6 in.	4
3/8 in. Diameter Grade 5 bolts (2 Washers, 1 Nut per bolt)	1 ½ in.	24
3/8 in. Diameter Grade 5 bolts (2 Washers, 1 Nut per bolt)	1 ¾ in.	4

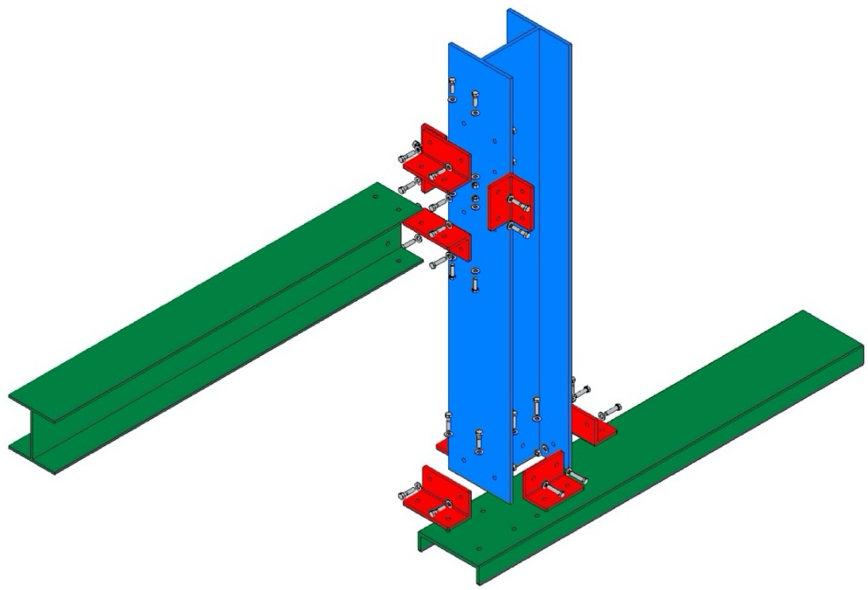


Fig. 3—Exploded view of connection module

Implementation

The connections module demonstrates the difference between pin-connected and rigid-connected members. Identifying the most appropriate idealization for a connection is a skill that students must develop before they can begin analyzing a structure. Describing the difference between the two types of connections with words is marginally effective. The approach to implement the connections modules will vary and is dependent on the instructor, the course content, and the learning objectives, but the overall goal is the same: help students understand the behavior of connections.

In the past, the SLU course simply included a brief discussion about support connections and the differences between theoretical assumptions and actual behavior. The discussion included sketches of pinned and rigid steel connections and a roller support and rigid connection for reinforced concrete. The Connections Modules began with a similar introduction that included an added discussion of how analysis programs account for the differences between theoretical assumptions and actual behavior. The connection was first rigid with shear tabs on both sides of the web as well as the top and bottom flanges of the cantilever beam. Each student had the opportunity to feel how the rigid connection behaves due to an applied force. After returning to their tables, the students were asked to individually describe on their notes what they experienced. The teaching assistants removed the top angle from the cantilever beam to create a semi-rigid connection. The students again pulled up and pushed down on the end of the beam to feel the connection's behavior. After returning to their tables, the students were asked to individually describe on their notes what they experienced. The teaching assistants lastly removed the bottom angle from the cantilever beam to create a pinned connection. Once more, the students pulled up and pushed down on the end of the beam to feel the connection's behavior. After returning to their tables, the students were asked to individually describe on their notes what they experienced. After the demonstration, each table worked together to describe the differences between the three connection types.

In the past, the Rose-Hulman course included photographs to show the different connections types. That did not demonstrate the fundamental differences in behavior: a pin connection allows members to rotate relative to each other, and a rigid connection restrains the two members to rotate together. Therefore, the connections modules allowed the students to manipulate, to see, and to feel the presence or absence of relative movement. Implementing the new module required little change in course delivery. Instead of trying to explain the behavior with photos, the time was spent experiencing the behavior in person right there in the classroom. Fig. 4 shows two students working through the module and a close-up view of the beam to column connection.

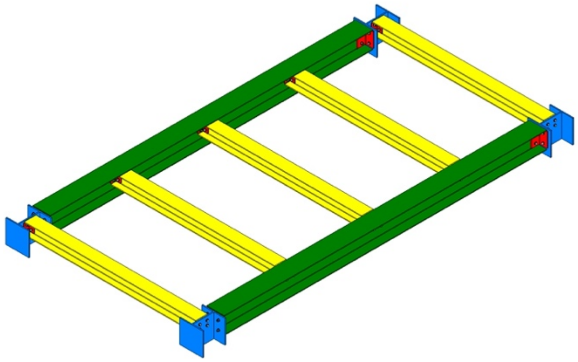
(a) (b)

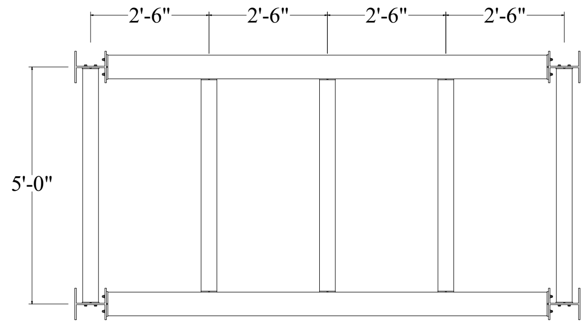
Fig. 4—(a) Students hold and load the structure and (b) a close-up view of the "rigid" connection.

Module 2—Load Paths

Design

The purpose of the *Load Paths Module* is to demonstrate load paths and tributary areas related to a typical floor system. The module mimics an actual floor system through the use of beams, girders, and short columns. The design includes three initial considerations. First, the dimensions of the floor system should be large enough to be realistic, but small enough to be practical; second, the aspect ratio of the spans should provide effectively one-way slab behavior; and third, the structure should be structurally sufficient and provide smooth transitions from beams to girders to columns. The resulting design was fabricated from EXTREN® structural members including 6 in. deep wide-flange (W6) beams for the girders; 4 in. deep wide-flange (W4) beams for the beams, and 8 in. deep wide-flange (W8) beams for the columns. The structure was bolted together using 2x2x1/4 EXTREN® angles and 3/8 in. diameter Grade 5 bolts. The overall nominal dimensions of the interactive floor system are 10 ft long, 5 ft wide, and 8 in. tall with a beam spacing of 2.5 ft. The four columns sat atop four postage scales to show the forces in each column. Fig. 5 shows the final design along with the overall dimensions.





(a) (b)

Fig. 5—(a) Load paths module design and (b) overall dimensions.

The first design consideration was that the floor system should be large enough to be realistic, but small enough to be practical and the second design consideration was that the aspect ratio of the spans should provide effectively one-way slab behavior. The EXTREN® shapes are available in 20 ft lengths. Therefore, a length of 10 ft was the maximum, yet most efficient length for the floor system. Likewise, a width of 5 ft provided the most efficient width for the beams allowing four per stock member. Lastly, a beam spacing of 2.5 ft provided a length to width ratio of 2:1 ensuring that a deck slab would exhibit effectively one-way slab behavior. The third design consideration was that the structure should be structurally sufficient and provide smooth transitions from beams to girders to columns. The member sizes were selected based on anticipated loads from students standing on the floor system and constructability considerations, which resulted in the W6 and W4 members. Three of the W4 members were bolted to the webs of the W6 members using 2x2x1/4 double EXTREN® angles with six 3/8 in. diameter Grade 5 bolts, while the other were bolted directly to the web of the W8 columns. The W6 members were bolted to the flanges of the W8 columns using 3x3x3/8 double EXTREN® angles with six 3/8 in. diameter Grade 5 bolts. Furthermore, the top flanges of the three W4 members were coped to ensure the top flanges of the W4 and W6 members were all flush so the decking could lay flat for smooth load transitions.

Fabrication

Fabrication of the *Load Paths Module* began with selecting the required materials as previously discussed (shown in Table 2) and cutting all of the members to length. The member lengths were reduced based on the connections to ensure the aforementioned center-to-center spacings (e.g the W6 beam was cut to 9 ft 3-1/4 in. to account for the columns and connecting angle). Like the *Connections Module*, the *Load Paths Module* used 3/8 in. diameter Grade 5 bolts. Therefore, all of the holes were 1/16 in. larger resulting in a diameter of 7/16 in. Most of the holes were drilled using a milling machine, which provided an efficient method for drilling repetitious holes quickly, precisely, and accurately. The only member that required hand drilling was the W6 girders due to the long length. Each of the hole locations were marked very carefully and were predrilled with a smaller drill bit before increasing to the 7/16 in. hole diameter to ensure everything fit together properly. The next step was to cope the interior beams using a vertical band saw. The coped ends provided ¼ in. spaces between the flanges of the W4 and W6 beams. Lastly, any jagged edges were cleaned up with a handheld sander. Assembly of the Floor System was a simple process with two people and requires about 30-45 minutes to complete. The first step to assemble the outer perimeter including the un-coped beams, the column members, and the girders followed by the interior coped beams. All of the bolts in the initial assembly were placed hand tight and later securely tightened after all of the members and bolts were in place. During final tightening of the bolts, special care was given to ensure the tops of all members were flush. The resulting module weighs approximately 275 lbs. Fig. 6 shows an exploded view of the assembled *Load Paths Module*.

Table 2—Load paths module material takeoff

Item	Length	Quantity
8x8x3/8 EXTREN® wide flange beam	8 in.	4
6x6x1/4 EXTREN® wide flange beam	9 ft 3-¼ in.	2
4x4x1/4 EXTREN® wide flange beam	4 ft 11-¼ in.	3
4x4x1/4 EXTREN® wide flange beam	4 ft 11-1/8 in.	2
EXTREN® 2x2x1/4 angle	3 in.	20
EXTREN® 3x3x3/8 angle	5 in.	8
3/8 in. diameter Grade 5 bolts (2 Washers, 1 Nut per bolt)	1-¼ in.	40
3/8 in. diameter Grade 5 bolts (2 Washers, 1 Nut per bolt)	1-½ in.	36
3/8 in. diameter Grade 5 bolts (2 Washers, 1 Nut per bolt)	2 in.	8
Postal scales	N/a	4

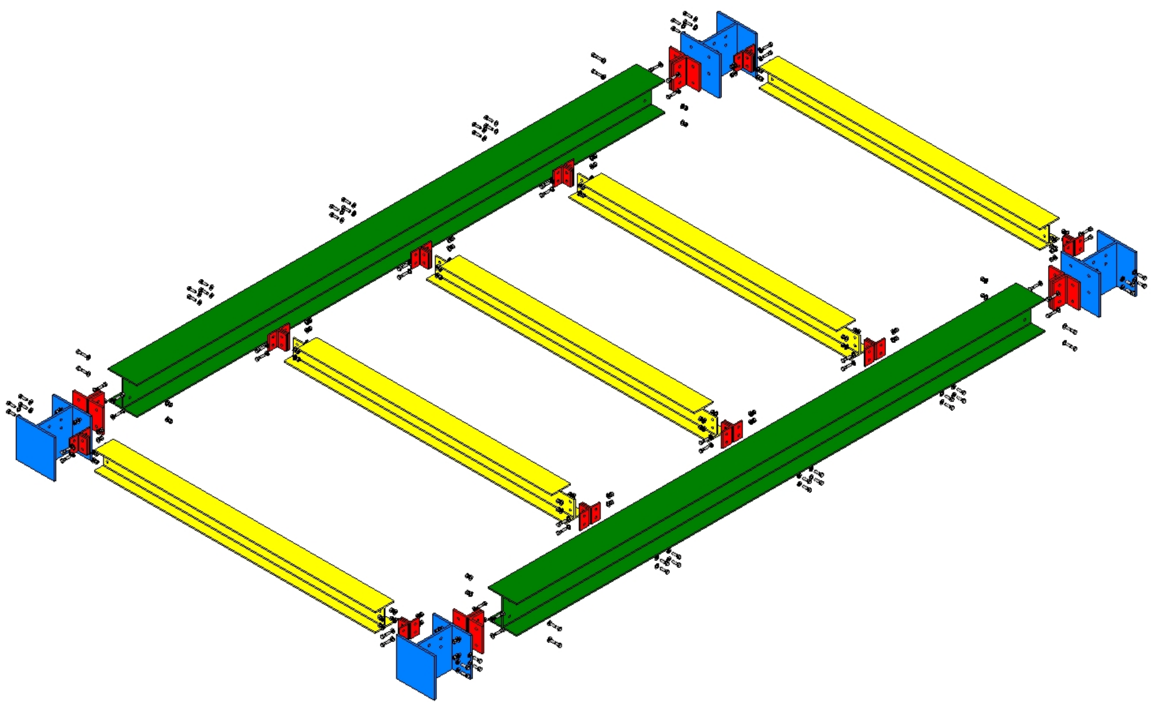
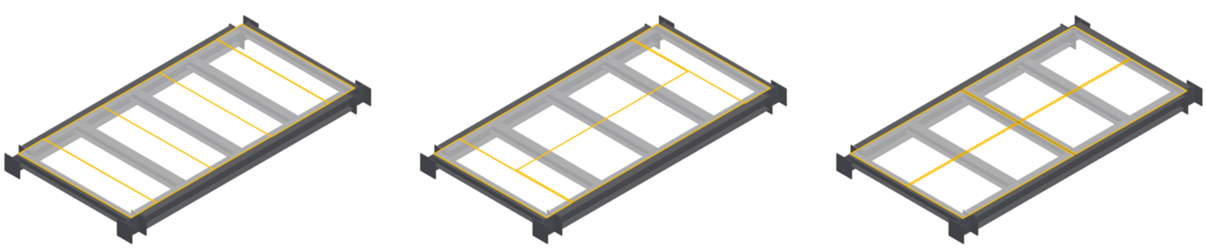


Fig. 6—Exploded view of Load Paths Module

Implementation

The class at SLU began with a brief overview of load paths throughout a one-way floor system followed by a discussion of tributary areas and how to convert a pressure to a uniformly distributed load along a member. Fig. 7 shows an example of the visuals used to discuss tributary areas assuming one-way slab behavior. The floor system started without decking so the students could clearly see the arrangement of beams and girders and the instructor discussed how static point loads would transfer from a beam, to a girder, and ultimately to the columns. Next, the decking was placed on top of the floor system and the teaching assistants added EverBlock walls with known weights to simulate a uniformly distributed load along with a linearly varying distributed load along the length of two intermediate beams. Fig. 8 (a) shows the floor system at SLU with EverBlocks stacked on top of the decking to illustrate the aforementioned loads. The TAs then stood on the middle beam 1.5 ft from the girders with 2 ft between them to represent two point loads. The students then worked through a series of loads placed on the decking to determine what the forces would be in each column. The instructor guided the students through each step of the analysis including calculating the equivalent distributed loads resulting from the decking followed by the resultant forces of each distributed load, beam support reactions, and subsequent girder support reactions. The conclusion of the class consisted of students comparing their theoretical calculations with the actual readings of the postal scales.



(a) (b) (c)

Fig. 7—(a) Beam tributary areas; (b) girder tributary areas; and (c) column tributary areas.

The Rose-Hulman course included an early discussion of load paths for gravity loads on a floor system. Students learn how to idealize the floor pressures onto the supporting beams, and then how to track the load from the beams to the girders to the columns. Previously this was taught exclusively through example problems. The module allowed students to test the validity of the approach taught in class. The instructor reduced the last example problem by 10 minutes to insert the module. At the end of the example problem the instructor took the students to an adjacent lab where there was enough room to have the model floor system set up and waiting. The instructor had a volunteer weigh themselves and announce their weight to the class. The instructor then had the class calculate what the four reactions should be if the volunteer stood at a specific location, Fig. 8 (b). Once the class had made the quick calculations, the volunteer moved to that point and the class verified their calculation results. The class and instructor discussed how they made their calculations in case any students were making mistakes or struggling to implement the skills. The instructor moved the volunteer two more times, each time to a progressively more challenging location for calculating reactions. Each time the results closely matched the student predictions and the class debriefed.

(a) (b)

Fig. 8—(a) Floor system with decking and EverBlock walls and (b) floor system without decking to visualize load paths of point loads.

Module 3—Deflections of Beams

Design

The purpose of the *Deflections of Beams Module* is to illustrate the deflected shapes of determinate and indeterminate beams and reinforce the method of virtual work and the force method. The design considerations for this module were simple: 1) the members should be easy for a student to stand on and be stable, 2) the members should be flexible yet strong enough to support the weight of multiple students, and 3) the members should be sized to efficiently use the stock material. The resulting design was EXTREN® 8x8x3/8 channel for the beams. The channel provides a flat surface to stand on; the channel is very flexible for bending about its weak axis, but the stresses remain around 50% of the material's ultimate strength when loaded; and the long members were 12 ft 4 in. long, while the short members were 6 ft 4 in. long to minimize waste material and provide 12 ft and 6 ft center-to-center spans when supported at the ends.

Fabrication

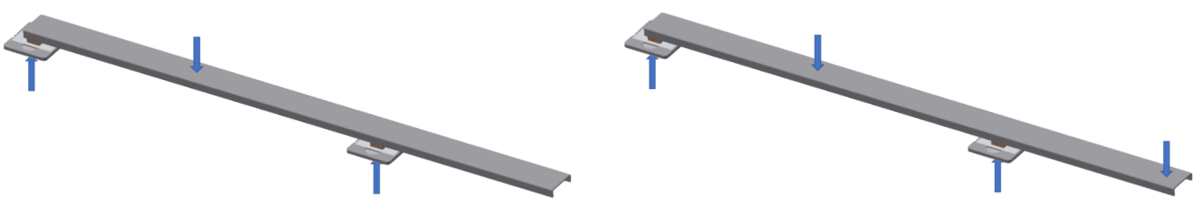
Fabrication of the *Deflection of Beams Module* was very straightforward: select the required materials as previously discussed (shown in Table 3) and cut all of the members to length. The extra 4 in. on each member provided space for the members to rest on wooden support blocks, while still maintaining the specified center-to-center span lengths. The support blocks were 6 in. long 2x4 wooden blocks that also increased the height of the channels from the ground to allow for full deflection. The final step in fabrication was to mark 1 ft increments on the channels with a permanent marker along their lengths. These marks were added so students could easily identify the exact points to stand while completing the activity.

Table 3—Deflections of Beams Module material takeoff

Item	Length	Quantity
8x3x3/8 channel	12 ft 4 in.	1
8x3x3/8 channel	6 ft 4 in.	2
2x4 wooden blocks	6 in.	12
Postal scales	N/a	3

Implementation

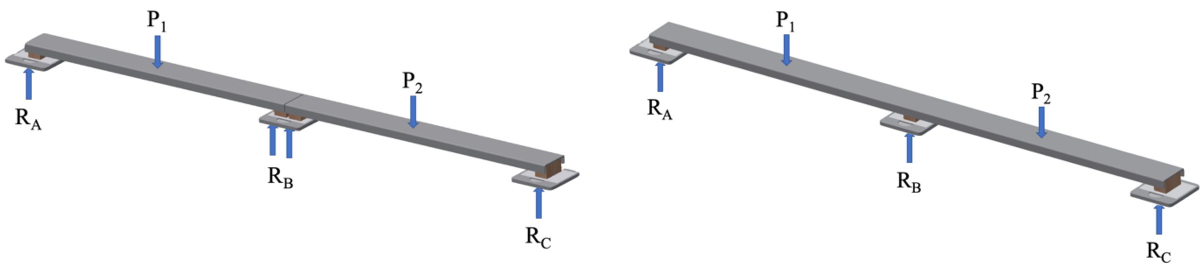
In past semesters, the method of virtual work for beams and frames was taught in the same class in the SLU course. The instructor introduced the method of virtual work with a basic beam example followed by a second example with time for students to work through a beam problem in groups. In the same class, the instructor also presented a frame example followed by time for students to work through a frame problem in groups. The class was split into two classes during this semester: one focused on virtual work of beams and another focused on virtual work of frames, the latter of which is discussed in the next section. As a result, the instructor removed the moment-area method from the course. The instructor decided to flip the class focused on the method of virtual work for beams and use the in-class time for the new module activities. Two of the 12 ft channels were setup as shown in Fig. 9 with a center-to-center span of 8 ft and a cantilever span of 4 ft. The instructor first had the students calculate the vertical deflections at the end of the beam and at mid-span due to a single point load at mid-span of the 8 ft span. The instructor then repeated the process with the combination of point loads at mid-span of the 8 ft span and at the end of the cantilever beam. The point loads were the resulting weights of two student volunteers. The larger of the two loads was placed at mid-span to prevent lift-off of the support reaction at the opposite end. Fig. 11 (a) shows the activity.



(a) (b)

Fig. 9—(a) Beam with single point load at mid-span and (b) beam with point loads at mid-span and at the end of the cantilever.

The SLU course also includes indeterminate structures and the force method. A separate class was devoted to the force method for beams, which built upon the class devoted to virtual work. Rather than using a video lecture, the handout provided for the students included all of the derivation for the method of virtual work on a determinate structure with a vertical point load. The handout included reactions and moment diagrams. First, students were asked to sketch the deflected shape of the two simply-supported beams shown in Fig. 10 (a) and draw the shear and moment diagrams along with the point of maximum moment. Second, students were asked to sketch the deflected shape of the continuous beam shown in Fig. 10 (b) and mark the points of maximum deflection. The students were then guided through the process of virtual work. First, the middle support was removed and two students with similar weight stood at the quarter points. Another student measured the actual deflection at mid-span, Fig. 11 (b); they also calculated the theoretical deflections to compare. Second, the students were asked to calculate the vertical deflection due to a 1 lb load at mid-span. After solving for the deflection, the students were able to solve for the redundant reaction, R_B followed by R_A and R_C. They were then able to draw the shear and moment diagrams. Third, the students stood on the indeterminate beam and compared their results to their calculations, all of which were comparable. Lastly, the students were asked to describe the differences in the deflected shapes for the two types of beams and the differences in the reactions and maximum moments for the two types of beams.



(a) (b)

Fig. 10—(a) Two 6 ft simple span beams and (b) single 12 ft continuous beam.

In the Rose-Hulman course, the instructor covers skills for predicting analysis results. Traditionally the instructor used a six-foot flexible foam beam to qualitatively demonstrate the behavior of a continuous beam on three supports. The new module, however, allowed the students to compare approximate calculations with actual results. The setup was the same as Fig. 10 with two 6-ft beams that supported in series on three scales and a 12-ft beam that supported at the ends and midspan with scales. When it is time to do the simple calculation example in class, the instructor asked for two volunteers who were willing to be weighed and share their weights with the class. The students then made a simplified prediction of the vertical reactions of the continuous beam with the two volunteers. The students then stood on the continuous beam and read off the actual reactions. To show the students what they assumed in making their simplifying prediction, the volunteers stood on the two beams in series and measured the actual reactions. Those values matched the student predictions almost exactly because when making their prediction, they effectively assumed each span behaves independently. The new module required less than 10 minutes and is done right in the classroom. The instructor did not have to sacrifice any content. Instead, the instructor just shifted time from trying to explain the concept with drawings on the board to demonstrating the concept real-time.

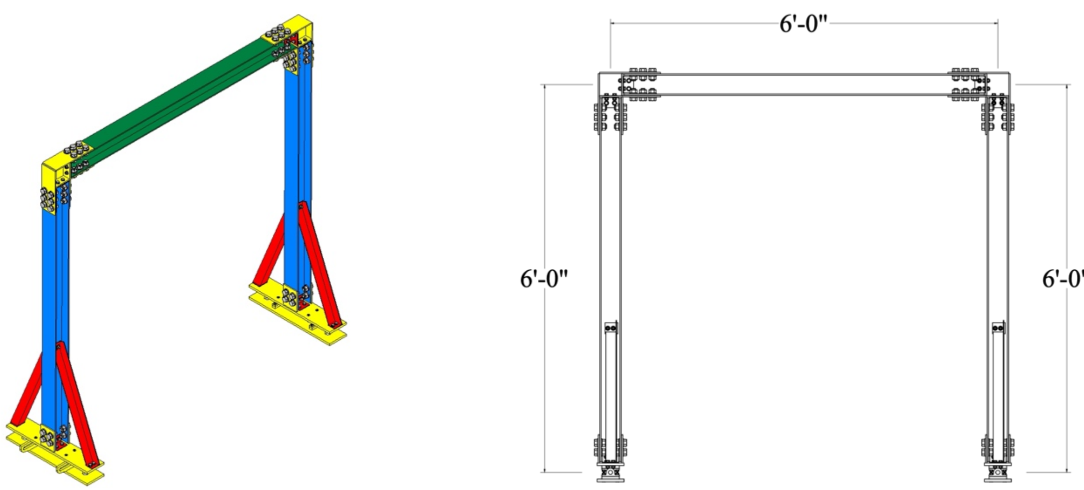
(a) (b)

Fig. 11—(a) Students load a beam to measure the deflection at the end and (b) students measure the deflection at mid-span due to two point loads applied at the quarter points.

Module 4—Deflections of Frames

Design

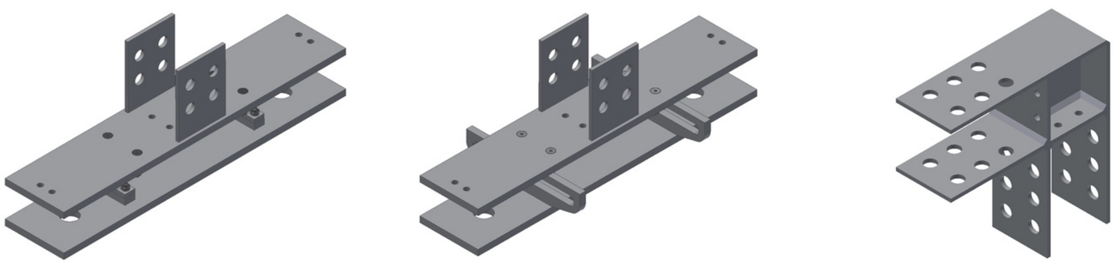
The purpose of the *Deflections of Frames Module* was to demonstrate the behavior of a portal frame subjected to both vertical and horizontal loads with various support configurations. A portal frame has rigid joints, so steel was selected to be used for the knee joints. However, EXTREN® structural members would be used for the columns and beam member in order to show deflected shapes. It was determined that using 4 in. deep (W4) EXTREN® beams and columns in combination with 1/4-inch-thick steel knee joints, shown in Fig. 13 (c), would allow the joints to be rigid while still allowing the beams and columns to deflect without exceeding the ultimate stress capacity of the EXTREN® material. The last notable part of the design is the diagonal bracings that were added to the base supports. These were added to restrict the frame from moving out of plane while being loaded vertically. The frame also used steel base connections that had the ability to tie down into the testing system that both SLU and Rose-Hulman have in place. The overall design of the Portal frame module is shown Fig. 12.



(a) (b)

Fig. 12—(a) Deflections of Frames module design and (b) overall dimensions.

As previously mentioned, the *Deflections of Frames Module* utilizes various support conditions. The module would use a Pin-Pin support condition as well as a Pin-Roller support condition. To create a true pin connection, roller bearings in combination with a high strength steel rod was used (shown in Fig. 13 (a)). To create a true roller connection, two roller bearings were used to connect to the column base plate with a high strength steel rod. This is the same configuration was designed for the pin connection. The change made for the roller connection was the base plate that ties down to the testing system. The new plate utilized a vertical-standing slotted roller that was welded to the base plate as shown in Fig. 13 (b).



(a) (b) (c)

Fig. 13—(a) Pin support; (b) roller support; and (c) rigid knee joint.

Fabrication

Fabrication of the *Deflections of Frames Module* began with selecting the required materials as previously discussed (shown in Table 4) and cutting all of the members to length. The member lengths of the beam and column members were reduced based on the connections to ensure the aforementioned 6 ft. center-to-center spacings (e.g the W4 beam was cut to 66-15/16 in. to account for the steel angles and knee joints). The *Deflections of Frames Module* used mostly 3/8 in. diameter Grade 5 bolts. Therefore, all of the holes were 1/16 in. larger resulting in a diameter of 7/16 in. The points of connection to the flanges of the beams and columns required, larger, 3/4 in. diameter structural steel bolts to reduce the bearing on the holes in the EXTREN® Structural Members. Therefore, these holes were 1/16 in. larger resulting in a diameter of 13/16 in. All of the holes were drilled using a milling machine, which provided an efficient method for drilling repetitious holes quickly, precisely, and accurately. All measurements were made from one end towards the other to eliminate any inaccuracies from the initial cutting on the band saw.

Table 4—Deflections of Frame Module material takeoff

Item	Length	Quantity
4x4x1/4" FRP Wide Flange Beams	67 11/16"	2
4x4x1/4" FRP Wide Flange Beams	66 15/16"	1
3x3x1/8" Steel Angle	3"	12
Steel Knee Joints	N/a	2
Steel Pin Connection	N/a	2
Steel Roller Connection	N/a	1
Lateral Support Bracing	N/a	4
3/4" Dia. Structural Steel Bolts (1 Nut, 2 Washers per bolt)	1 3/4"	64
3/8" Dia. Grade 5 Bolts (1 Nut, 2 Washers per bolt)	1 1/2"	36

Another important step of fabrication was the knee joint. With all of the members cut and holes drilled, the final step in fabrication of the knee joints was welding. While welding the knee joint together, it was important to ensure that all of the bolt holes were concentric with one another. This was an important step to make sure both before the start of welding as well as during and after each weld. Failure to make the holes concentric would have caused significant issues during assembly of the frame. Welding was also required during the fabrication of the base plates that would connect to the column as well as the roller connection base plate. Cautious strategies were also taken during these steps to ensure simplicity during assembly. A final exploded view of the assembly orientation for the *Deflections of Frame Module* is in Fig. 14.

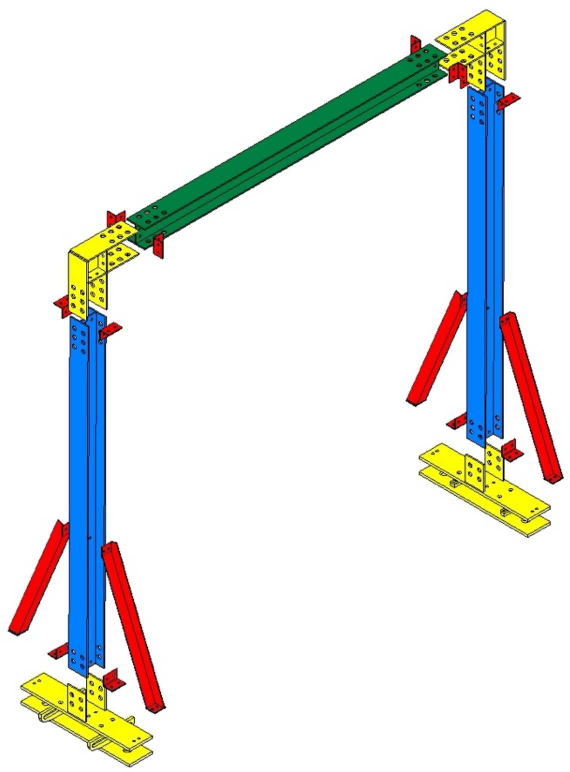


Fig 14—Exploded View of Deflections of Frame Module

Implementation

As previously mentioned, the method of virtual work for beams and frames were taught in the same course at SLU. The topic was split into two classes during this semester: one focused on virtual work of beams and another focused on virtual work of frames. The frame was used for two purposes in the class, the first of which focused on the lateral displacement of the roller support using virtual work and the second focused on calculating the reactions using the force method. One day was devoted to the lateral displacement of the frame. The instructor provided a video lecture containing the theoretical content behind virtual work of frames and the calculations for the reactions of the frame for a vertical point load applied at mid-span of the beam and a horizontal load applied at the knee joint as shown in Fig. 15 (a) and (b) respectively. The students began class by finishing their virtual work calculations to predict the horizontal deflection of the frame due to the vertical point load. Afterwards, the instructor and teaching assistants applied the vertical load to the frame with a hydraulic ram and the students were asked to sketch the deflected shape. Next, the students finished their virtual work calculations to predict the horizontal deflection of the frame due to the horizontal point load. Afterwards, the instructor and teaching assistants applied the horizontal load to the frame with a weight and pulley. The students were again asked to sketch the deflected shape.

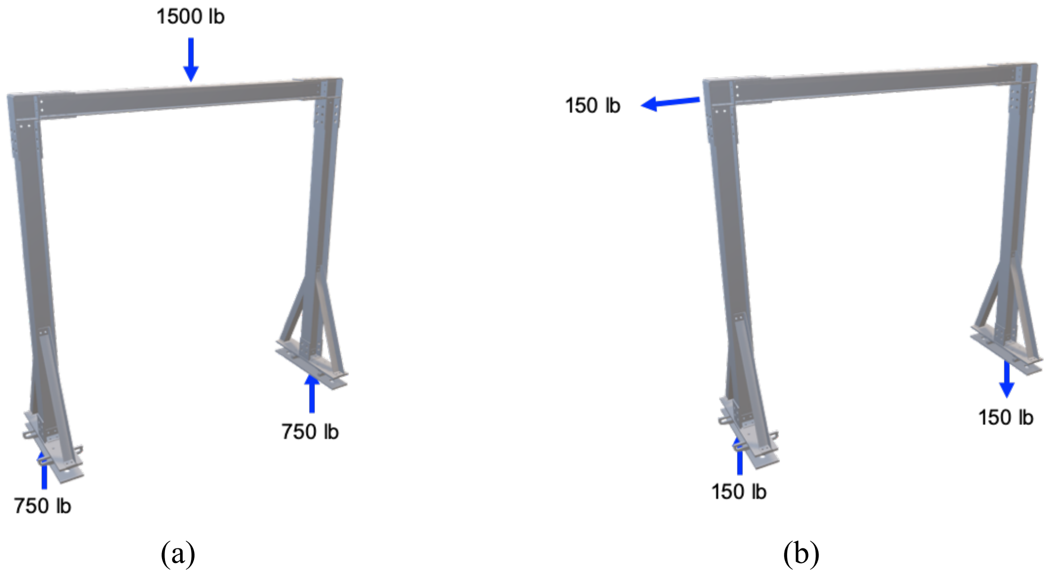
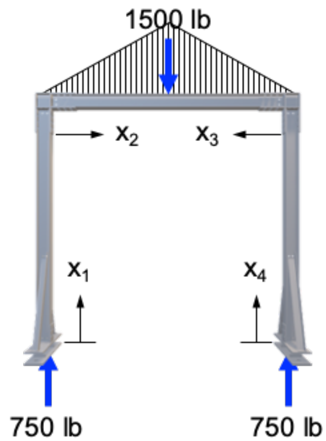
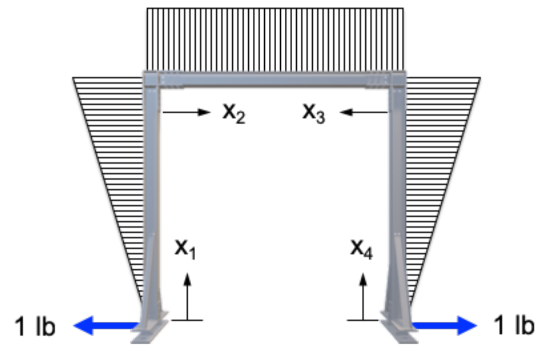


Fig. 15—Simply supported frame with (a) vertical point load and (b) horizontal point load.

As previously mentioned, the SLU course also includes indeterminate structures and the forced method. A separate class was devoted to the force method using the frame with pinned-pinned connections, which built upon the class devoted to virtual work. Rather than using a video lecture, the handout provided for the students included all of the derivation for the method of virtual work on the determinate structure with a vertical point load applied complete with reactions and moment diagrams as shown in Fig. 16. The students completed the virtual work calculations and solved for the redundant support reaction. Afterwards, the frame was loaded and the students were asked to sketch the deflected shape. The process was repeated for a horizontal load of 500 lb applied in the same location shown in Fig. 15 (b). Students worked through the process of virtual work and the force method to find the redundant reaction. Again, the frame was loaded and the student were asked to sketch the deflected shape.



(a)



(b)

Fig. 16—(a) Real structure with actual load and corresponding moment diagram and (b) vertical point load and (b) horizontal point load.

In the Rose-Hulman course, the instructor traditionally starts by introducing the assumptions made for approximate analysis of rigid frames subjected to lateral loads. Previously the instructor used table-top scale models to show where to anticipate inflection points in the displaced shape, the key assumptions. The test system is in a different building from the classroom, so the instructor used the full class period at the test facility. When the students arrived, the frame had one pin and one roller support. The students were given a handout showing an idealized drawing of the frame and were asked to sketch the anticipated displaced shape given what they knew about the types of connections, types of supports, and direction of loading. The frame was then loaded, and students were able to sketch the actual displaced shape. The handout had room for both sketches so they could metacognitively reflect on the difference. A rigid frame on pin and roller supports is determinate, but the point of this part of the course is to make assumptions to analyze indeterminate frames. Therefore, the instructor used the module to show the behavior of a rigid frame with pin supports on both sides as shown in Fig. 17 (b). Switching the support on the full-size frame takes about five minutes, so the instructor had the students practice previous material between demonstrations. The handout had places for the students to create axial, shear, and moment diagrams for the rigid frame with pin and roller supports. Once the support had been changed, the instructor debriefed the internal force diagrams and provided a second handout: one with the pin supports. The students predicted the displaced shape, then the instructor loaded the frame. While students sketched the actual displaced shape, the instructor debriefed the key features.

(a) (b)

Fig. 17—(a) Simply supported frame with small load applied via pulley and (b) pinned-pinned frame with larger load applied with hydraulic ram.

Lessons Learned and Recommendations

The most important lessons learned by the instructors were about time management. Predicting how much class time each module would use started as an educated guess. In some cases, the instructors over-predicted and in some cases under-predicted. Another important lesson is expectation management. Some students assumed they would be passively watching. In the future the instructor will advise students to bring notebooks, pencils and calculators. For the fourth module, the large portal frame, the instructors both noticed inelastic deformation building up in the steel knee joints in the top corners of the FRP frame when larger lateral forces were applied. The FRP members remain elastic, but the steel plates in the rigid connections are vulnerable and will be tweaked in the coming months. The implementation was an overall success from the perspectives of both instructors.

Future Assessment

Assessment of the project includes both qualitative and quantitative assessments. The qualitative assessment includes the Student Response to Instructional Practices (StRIP) survey [5], a course content survey, and a series of open ended questions about the experiential learning modules (post-test only). The quantitative assessment includes a series of exam questions related to each module: 1) a question about connections, a question about deflected shapes of beams, and 3) a question about the deflected shapes of frames. The students at both universities in Year 1 and 2 were the control group and the students in Year 3 and 4 will be the intervention group. The intervention groups are currently in progress at both universities and full assessment is beyond the scope of this paper. However, future dissemination efforts will highlight the effect of the experiential learning modules on student learning, perception of topic difficulty within the course, and instructional practices.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. 1726621. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors would especially like to thank the Strongwell Corporation for their contributions and assistance with module design and fabrication along with Mr. Ben Frieden and Ms. Elise Westhoff for their assistance with fabrication. The authors would also like to thank Wieser Concrete, Superior Steel, Inc., Benchmark Fabricated Steel, and McLaughlin Hoist and Crane for their contributions to the development of the structural engineering laboratories.

References

1. Carroll, J.C., et al., *Rationale and Design Approach for Full-scale Experiential Learning Opportunities in Structural Engineering*, in *2020 ASEE Virtual Conference*. 2020, American Society for Engineering Education.

2. Strongwell Corporation, *Design Manual*. 2007, Strongwell Corporation: Bristol, VA.

3. Carroll, J.C. and J.W. Benton, *Design, Construction, and Performance of the Modular Strong-block Testing System.* Journal of Performance of Constructed Facilities, 2018. **32**(5).

4. Carroll, J.C., et al., *Rationale and Design Approach for Full-scale Experiential Learning Opportunities in Structural Engineering*, in *2020 ASEE Annual Conference and Exposition*. 2020, American Society for Engineering Education: Montreal, Quebec, Canada.

5. DeMonbrun, M., et al., *Creating an Instrument to Measure Student Response to Instructional Practices.* Journal of Engineering Education, 2017. **106**(2): p. 273-298.