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A Project-Based Learning Approach to Seismic Testing and Damping in Structural Dynamics

Dr. Simin Nasseri, Kennesaw State University

Dr. Simin Nasseri is a distinguished full professor in the department of Mechanical Engineering at Kennesaw State University (KSU). She obtained her Ph.D. in Mechanical Engineering from Sydney University. She has been working at KSU since 2006. She has about 25 years of academic/industry experience. In addition to journal/conference papers and book chapters, she has published a book titled: ”Solving Mechanical Engineering Problems with MATLAB.” Her research experiences are related to Biomechanical engineering (artificial organs and soft tissue rheology), Manufacturing, Rheology and viscoelasticity, Polymer processing, Computational mechanics, Robotics, and Micromachinery. She has won many fellowships, awards and grants. In 2019, she received the KSU distinguished professor award, for excellence in teaching, research and service.

Mohammad Jonaidi, Kennesaw State University

Dr. Jonaidi obtained his Ph.D. from Sydney University and is currently working at Kennesaw State University. During 38 years of research and industry professions, he has been involved in analysis and design of complex structural projects such as: FEA of high-rise buildings/steel structures, Floor vibration for concrete slabs/pedestrian bridges, Serviceability vibration analysis of high-rise buildings, Earthquake Engineering, Post-tensioned concrete structures, Nonlinear and buckling analysis of thin-walled cylinders, Analysis of long span spatial steel structures, Analysis of Glazing façade, Below grade shoring walls, Retrofit of concrete structures using Fiber Reinforced Polymers (FRP), and the strengthening of structures to resist progressive collapse.

Riley Womack, Kennesaw State University

Riley Womack is an undergraduate student in Mechanical and Aerospace Engineering at Kennesaw State University. Expected graduation date: May 2029. He contributed to A Project-Based Learning Approach to Seismic Testing and Damping in Structural Dynamics. He is an active member of many engineering programs through Kennesaw State, having leadership roles in SME, ASME, Kennesaw Aviation Club and the URC. While also being on the Cansat competition team and doing aerospace research on UAS and UAV’s.

A Project-Based Learning Approach to Seismic Testing and Damping in Structural Dynamics

Abstract

This study presents a project-based learning (PBL) framework that integrates Kolb's Experiential Learning Cycle and a Students-as-Partners (SaP) approach to improve student understanding of structural dynamics and seismic resilience. The initiative was implemented through undergraduate and graduate research courses, engaging students through design, experimentation, reflection, and collaboration. The primary educational objectives were to improve student understanding of dynamic response, damping behavior, and seismic excitation, while developing experimental reasoning, computational analysis, and teamwork skills aligned with the engineering curriculum.

The work initiates with the co-development of a custom shake table intended to facilitate controlled base excitation, restricting motion to a single reciprocating degree of freedom. Two initial designs for the shake table's dynamic mechanism (wedge/ball bearing and cylinder-piston functions) were considered and evaluated to achieve efficient operation within limited laboratory space, accommodating various building model sizes. The experimental setup integrates a newly acquired shake table with a data acquisition system comprising a waveform generator, accelerometers, and vibrometers for real-time response monitoring. Acceleration and displacement responses were recorded and analyzed to support interpretation of structural behavior. Two primary composite building prototypes, one with 3D-printed polymeric floors and another with plywood decks, both framed with steel members, were developed to represent mid-rise structures.

The entire process involves initial analysis of a moment-resistant model lacking fluid viscous dampers (using support brackets) and a subsequent phase incorporating fluid viscous dampers positioned diagonally between floors to improve lateral stability and energy dissipation. Through iterative testing, supported by finite element analysis (FEA) and MATLAB-based simulations, students connected theoretical vibration models with empirical data, engaging in experiential learning and reflection consistent with Kolb's model. Preliminary observations and student reflections indicated increased engagement and improved ability to relate analytical predictions to measured structural response.

Key to seismic testing is the refinement and application of scaling equations for frequency range and acceleration to accurately translate laboratory data to real structural conditions. Vibration tests are performed on both the undamped and damped models to evaluate the influence of the fluid viscous dampers on frequency response, amplitude reduction, and mode shape variation. The collaborative PBL setting fostered peer learning, problem-solving, and shared ownership of results, reinforcing SaP principles in engineering education. Implementation challenges, including varying levels of student familiarity with computational tools and hands-on experimental techniques, were addressed through parallel task allocation and iterative

instruction. This educational experiment not only deepened conceptual understanding of dynamic structural behavior but also showed the instructional value of experiential design projects in connecting theory with practice in engineering education.

Key words:

Structural dynamics, Project-based learning, Experiential learning, Students-as-Partners, Seismic testing, Computational modeling.

Introduction

This paper describes an experimental project implemented in mechanical engineering courses (undergraduate course Directed Study, ME 4400, and graduate level course Master's Project, ME 6800) to support student learning in structural dynamics and seismic response, topics central to the design and evaluation of buildings and infrastructure subjected to dynamic loading. While concepts such as base excitation, resonance, damping, and scaling are fundamental, they are often difficult for students to fully grasp through analytical methods alone.

In response to this instructional challenge, the project focused on the design and use of a small-scale shake table and multi-story building models, allowing students to directly monitor and measure dynamic structural behavior. Students participated in developing the experimental setup, conducting vibration tests on structures with and without fluid viscous dampers (FVD), structural components installed between floors, beams, and columns that use a piston-cylinder mechanism filled with viscous fluid to generate a velocity-dependent resisting force, and analyzing measured data to connect theoretical concepts with physical response. As relative motion is induced by base excitation, the dampers dissipate vibrational energy as heat, reducing structural response and sway, and enabling students to directly observe the effect of damping on dynamic behavior (Figure 1).

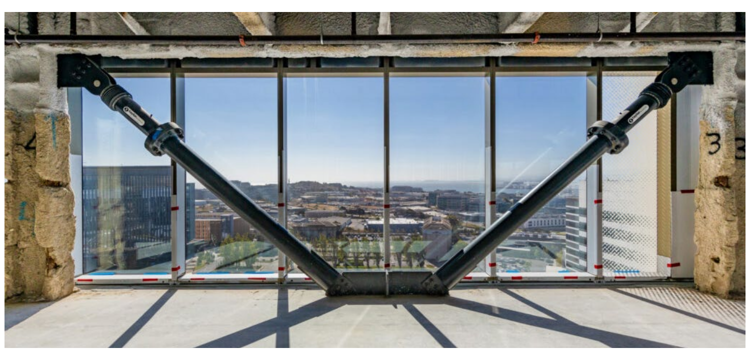

Figure 1. Fluid viscous dampers installed to reduce building vibrations. Picture courtesy of www.taylordevices.com.

The project was supervised collaboratively by two faculty members, one from the Mechanical Engineering Department and one from the Civil and Environmental Engineering Department, and engaged four graduate and eleven undergraduate students. These instructors have a long history of publishing work in engineering education. Their prior publications include multiple papers presented and published through ASEE, addressing topics such as hands-on learning, project-based instruction, laboratory education, and student engagement and have introduced new educational models that support effective teaching and learning in engineering [1- 15]. Consistent with this prior work, the cross-disciplinary, hands-on approach presented in this paper emphasizes collaboration, iterative testing, and applied learning within a course-based engineering context.

Kolb and Kolb [16] formalized “Experiential Learning Theory (ELT)” for higher education and articulated learning as a cyclical process involving experience, reflection, conceptualization, and experimentation (Figure 2). The authors clarified pedagogical design principles for aligning instructional activities with this cycle and provided a theoretical basis for experiential and project-based learning in engineering education across disciplines, including engineering [16].

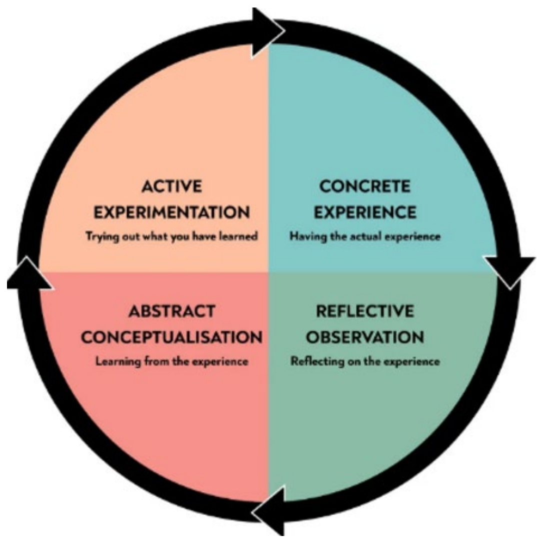

Figure 2. Experiential learning cycle illustrating the progression through active experimentation, concrete experience, abstract conceptualization, and reflective observation, as conceptualized in Experiential Learning Theory or ELT (adapted from Kolb & Kolb, [16]).

Jamison *et al.* [17] conducted a systematic review of experiential learning implementations in undergraduate engineering education and identified common instructional patterns, strategies, and measurable outcomes across diverse contexts. Using Kolb’s experiential learning cycle as an analytical framework, they showed that structured, hands-on activities improved conceptual understanding and problem-solving skills, providing a foundation for integrating project-based learning with theory and reflection. Lin [18] examined an experiential learning project structured around Kolb’s learning cycle and documented student progression through experience, reflection, conceptualization, and experimentation. The study provided course-level evidence supporting Kolb-aligned instructional design and highlighted the role of structured reflection in improving student understanding and engagement [18].

Cook-Sather *et al.* [19] established the conceptual and practical foundations of the “Students-as-Partners (SaP)” approach in higher education and defined how students and faculty can co-create learning experiences and collaborate in teaching, assessment, and curriculum design [19]. Their work synthesized theory and practice to position partnership as a means of increasing student engagement and shared responsibility in learning. Later, Healey *et al.* [20] reviewed Students-as-

Partners practices in higher education and framed partnership as a collaborative model in which students and faculty jointly contribute to learning and teaching, promoting engagement, shared responsibility, and deeper learning [20].

Mercer-Mapstone *et al.* [21] conducted a systematic review of Students-as-Partners (SaP) practices in higher education and categorized partnership models, principles, and reported outcomes. The authors conducted a comprehensive review (using Healey and co-worker's work and others [20]) and showed that student–faculty collaboration in curriculum design, assessment, and research promoted engagement, ownership, and deeper learning, establishing a conceptual basis for SaP-informed instructional and research practices. Figure 3 shows a conceptual Students-as-Partners (SaP) framework, illustrating a partnership learning community in which students and faculty collaboratively engage in course design, experimentation, and reflection, providing context for the Students-as-Partners literature discussed by Healey *et al.* [20] and evaluated in the work by Mercer-Mapstone *et al.* [21].

Figure 3. Conceptual Students-as-Partners (SaP) framework emphasizing shared responsibility and collaborative learning (Courtesy of Healey *et al,* [20]).

Lavado-Anguera *et al.* [22] synthesized recent literature on "Project-Based Learning (PBL)" in engineering education and examined its alignment with experiential learning principles and real-world problem solving. The authors identified recurring instructional strategies, assessment methods, and learning outcomes, reinforcing PBL as an effective approach for integrating theory, experimentation, and collaboration in engineering curricula. Previously, Khraishi *et al.* [23] designed and assessed problem-based learning experiments within an undergraduate dynamics course and evaluated their impact on student learning. The researchers demonstrated that student-driven experimentation closely linked to theoretical content increased engagement and conceptual mastery, supporting the effectiveness of hands-on mechanics activities in engineering education.

Xu *et al.* [24] presented theoretical analysis and shaking-table validation of a novel variable-damping viscous fluid damper. Experimental results confirmed the damper's ability to adaptively control seismic response and provided insight into advanced damping strategies applicable both research-oriented and scaled instructional structural models.

Su *et al.* [25] combined numerical modeling and experimental testing to investigate seismic response control using winding-rope fluid viscous dampers. The researchers reported significant reductions in structural response and increased energy dissipation, contributing to the understanding of nontraditional viscous damping configurations for seismic mitigation.

Lan *et al.* [26] conducted shaking-table experiments to evaluate the seismic performance of structures (two-story steel frame with each story 3.6 *m* tall and 3 *m* span in plan) equipped with fluid viscous dampers (Figure 4). By comparing damped and undamped configurations, they quantified improvements in energy dissipation, response reduction, and vibration control, demonstrating the effectiveness of viscous damping systems for mitigating structural dynamic response under seismic excitation.

Figure 4. Damping structural model in the work of Lan *et al*., [26].

Previous studies have shown that hands-on learning, project-based activities, and student–faculty collaboration can improve learning in engineering courses. Separate research has also demonstrated the value of shake-table testing and damping devices for studying structural behavior under dynamic loading. However, these two areas of work have mostly developed independently, with limited effort to combine educational approaches and physical experimentation into a single instructional model.

Most educational studies focus on course design, student engagement, and reflection, but often rely on simplified or abstract activities rather than realistic experiments that connect theory to measured structural response. In contrast, experimental studies using shake tables and damping systems typically emphasize technical performance and validation, with little attention to how these experiments can be used effectively in undergraduate classrooms. Although experiential learning frameworks such as Kolb's learning cycle are frequently cited, they are rarely implemented in full within one sustained project that includes design, testing, reflection, and iteration. Likewise, while student–faculty collaboration is well discussed in the literature, students are seldom involved in the design and development of experimental equipment used in core engineering courses (Figure 5).

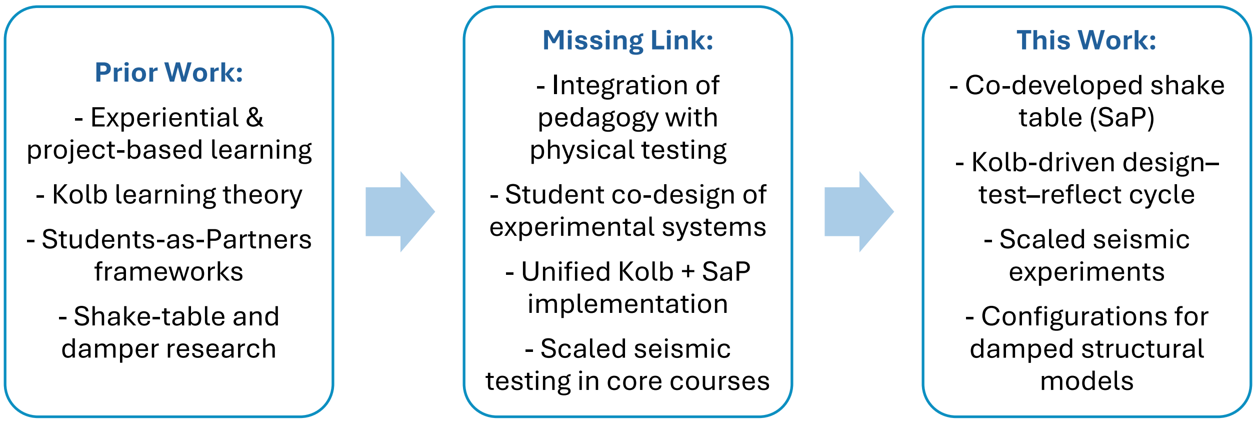

Figure 5. Relationship between prior work, identified gaps, and the focus of this study.

This work addresses these gaps by presenting an integrated learning approach in which students help design the experimental setup, conduct scaled shake-table tests, and analyze the behavior of structures with and without damping devices. By combining hands-on experimentation with structured reflection and collaboration, the study connects classroom concepts with real structural behavior and provides a more complete learning experience in structural dynamics (Figure 6).

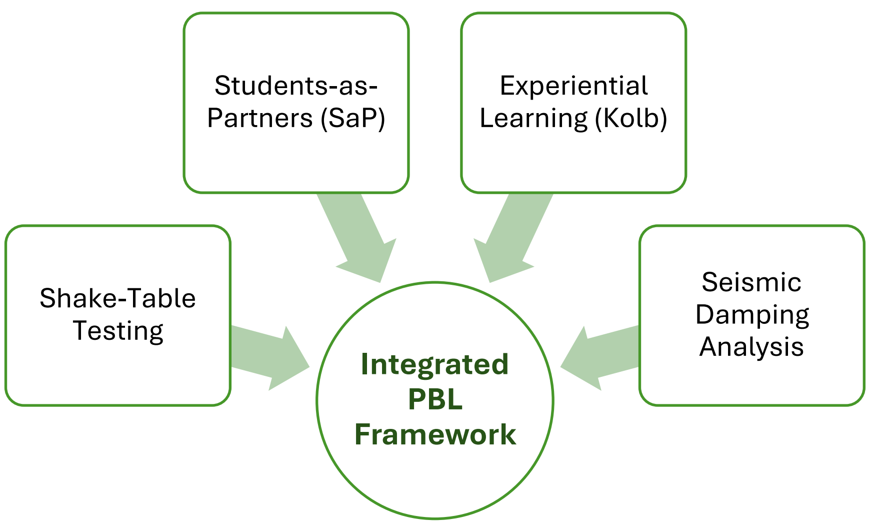

Figure 6. Integrated project-based learning framework used in this study.

Experimental and Computational Project Overview and Learning Objectives

The project was conducted within undergraduate Directed Study (ME 4400) and the graduate research-based Master's Project course (ME 6800), which are designed to support advanced, individualized work under faculty supervision rather than a fixed prerequisite sequence. As such, no formal prerequisites in Finite Element Analysis (FEA), MATLAB, or additive manufacturing were required. Student assessment was based on multiple components rather than a single project grade, including completion of FEA assignments, participation in model fabrication and experimental setup phases, execution of vibration tests, data processing and interpretation tasks, and reflective contributions throughout the project. Graduate students participated alongside undergraduates and played an active mentoring role by providing guidance on advanced finite element modeling and 3D printing techniques, answering technical questions, and supporting troubleshooting during both computational and experimental phases. This structure allowed students with different backgrounds to develop required skills progressively while maintaining consistent evaluation criteria across project activities.

The project was structured in two primary phases. In the initial phase, students examined the dynamic behavior of a three-story, 1:10-scale building model without supplemental damping, using experimental measurements alongside FEA simulations and MATLAB post-processing (Figure 7). This phase introduced concepts such as degrees of freedom, base excitation, frequency response, and modal behavior, while noting differences between idealized analytical models, numerical predictions, and measured physical response. Students examined how structural stiffness, mass distribution, and boundary conditions influenced vibration characteristics through integrated experimental and computational analysis.

In the second phase, students extended the experimental framework by incorporating fluid viscous dampers into one of the building models and comparing its response to an undamped baseline structure. Through this comparison, students observed how energy dissipation mechanisms altered system response, including reductions in vibration amplitude and changes in frequency response. This phase reinforced the concept of damping as a physical phenomenon and helped students connect theoretical damping models to real structural behavior.

Across both phases, students were responsible for assembling test specimens, mounting sensors, conducting vibration tests with varying input frequencies and accelerations, and processing experimental data using MATLAB. These activities were planned to help students develop skills in experimental planning, data acquisition, signal interpretation, and critical evaluation of results. By iteratively testing and refining their setups, students gained experience with experimental uncertainty, sensor placement effects, and the challenges of scaling laboratory results to real structures.

Overall, the project aimed to move beyond demonstration-based laboratories by involving students in an experimental process. The learning objectives emphasized not only technical knowledge in structural dynamics and seismic response, but also the development of problem-solving skills, collaborative work practices, and the ability to link theory with physical evidence in an engineering context.

A common rubric was used that evaluated students on technical accuracy, quality of data analysis, clarity of interpretation, and participation in teamwork and reflection across all project components (experimental work, and computational tasks).

Figure 7. Undergraduate and graduate students engaged in hands-on experimental activities, including 3D printing, model fabrication, instrumentation, vibration testing, and finite element analysis (FEA).

Shake Table Design and Student Involvement

A central component of the experimental project was the design, evaluation, and use of a custom shake table to provide controlled base excitation for scaled structural models. Rather than using a pre-packaged instructional device, students were actively involved in understanding the functional requirements, constraints, and trade-offs associated with shake table design. This approach was intended to deepen student comprehension of how experimental hardware influences measured dynamic response.

Students examined two alternative mechanisms for generating uniaxial motion: a wedge-and-ball-bearing system and a cylinder–piston-based configuration. Through this comparison, students learned how mechanical design choices affect motion smoothness, load capacity, controllability, and system footprint. Evaluating these alternatives required students to consider practical constraints such as cost, manufacturability, available workspace, and compatibility with different building model sizes, reinforcing the role of engineering decision-making in experimental design.

The final shake table configuration was designed to restrict motion to a single horizontal degree of freedom while limiting the remaining five degrees of freedom. Students learned the importance of constraining unwanted motion to ensure that measured responses could be attributed primarily to base excitation rather than parasitic vibrations or boundary effects. By physically observing the system behavior during testing, students gained insight into how imperfect constraints and structural flexibility can introduce experimental error.

Through internal funding provided by the college, a commercial shake table was obtained and was integrated with accelerometers to record structural response data. This process helped students understand the relationship between base excitation and measured structural response. Through hands-on setup and troubleshooting, students developed practical skills in sensor placement, signal calibration, and synchronization of excitation and response data, skills that are often underemphasized in traditional laboratory exercises.

By involving students directly in the design and operation of the shake table, the project transformed the experimental platform itself into a learning object. Students did not simply operate equipment; they learned how experimental limitations, design decisions, and system constraints influence data quality and interpretation. This experience supported a more realistic understanding of experimental structural dynamics and prepared students to critically evaluate both laboratory results and analytical predictions.

Building Model Construction and Materials Comparison

The construction of the building models was an important learning component of the experimental project, allowing students to explore how material selection, fabrication methods, and structural detailing influence dynamic behavior. Two 1:10 scale, three-story building prototypes were developed using identical steel framing systems but different floor materials, enabling a direct comparison of structural response under identical base excitations.

As shown in Figure 8 (Left), students constructed a baseline moment-resisting frame using 3D-printed polymeric (PLA) floor decks secured to the steel columns with corner brackets. This configuration served as a reference model for subsequent testing while introducing students to the influence of floor flexibility and connection detailing on global structural behavior. Due to printer bed size limitations and assembly constraints, the PLA floors required multiple redesign iterations and multiple printing cycles. Students fabricated the floors in segmented components and bonded them to achieve the required dimensions, gaining practical experience with additive manufacturing challenges such as tolerance control, joint stiffness, and variability introduced during post-processing.

In parallel, students developed a second building model incorporating plywood floor decks as shown in Figure 8 (Right). Compared to the PLA model, the plywood floors were cut and installed with minimal difficulty, providing a relatively stiff and rigid system for comparison. Through fabrication and assembly, students observed how increased floor rigidity and connection simplicity contributed to overall structural stiffness and load transfer between stories, clarifying the relationship between material properties, constructability, and measured dynamic response. This model was further modified to include fluid viscous dampers installed diagonally between floors, enabling students to compare damped and undamped configurations using different floor materials. This comparative setup strengthened student understanding of how damping mechanisms interact with structural stiffness and mass, and how material choices can influence the effectiveness of vibration mitigation strategies.

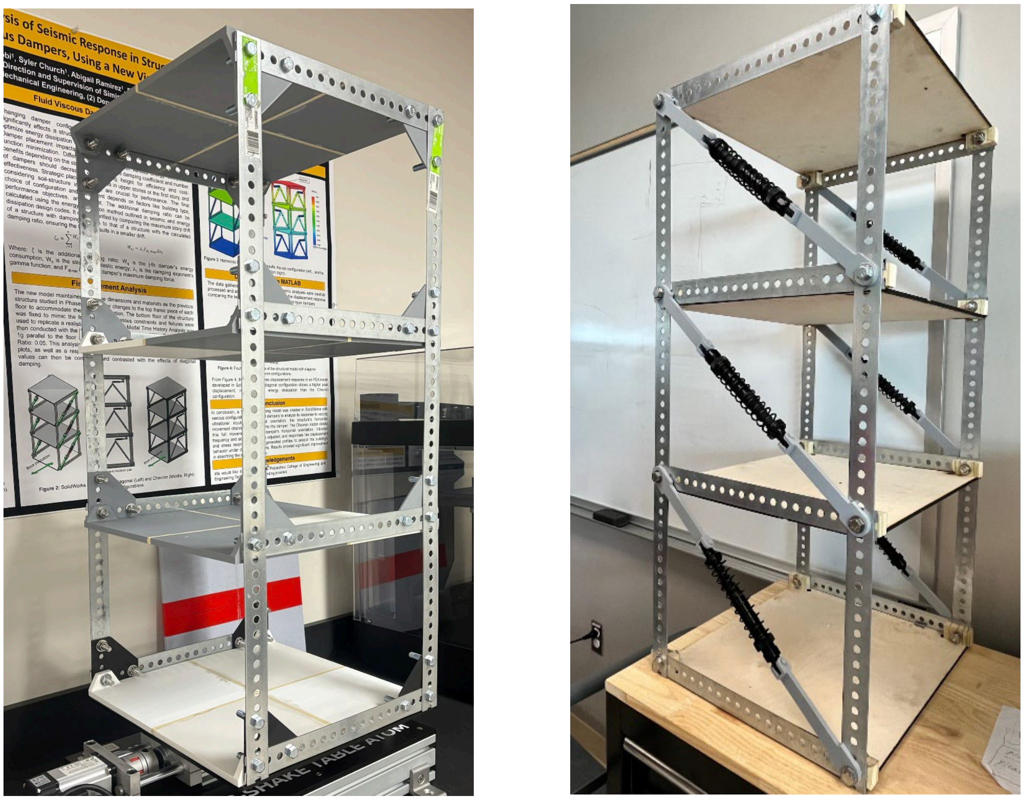

Figure 8. The two building models: The moment-resisting frame configuration with PLA floors (Left) and the fluid viscous damper configuration with Plywood floors (Right).

Comparing the two models allowed students to directly observe how material properties and fabrication methods affected dynamic response. During vibration testing, students noticed differences in flexibility, vibration amplitude, and response consistency between the plywood and PLA floor systems. These observations supported theoretical discussions of mass distribution, stiffness variation, and damping effects, while drawing attention to practical factors not captured by simplified analytical models.

Through the construction and comparison of multi-material building models, students developed practical skills in fabrication, assembly, and quality control, while deepening their conceptual understanding of structural dynamics. The activity emphasized that experimental outcomes are shaped not only by theoretical design but also by material behavior, manufacturing constraints, and construction decisions, an insight essential for both experimental research and real-world engineering practice.

Instrumentation, Sensor Placement, and Data Acquisition

Instrumentation and data acquisition were other important elements of the project, allowing students to directly measure and interpret the dynamic response of scaled building models. Students assembled and operated a data acquisition system that integrated a waveform generator, accelerometers, and vibrometers with the shake table to record real-time response under controlled base excitation.

Accelerometers were mounted at the center of each floor to capture story-level acceleration during testing. Through this process, students learned how sensor location and mounting consistency influence data quality and repeatability. Variations observed across tests helped students identify sources of noise and measurement error and learn the importance of careful experimental setup.

The waveform generator was used to vary excitation frequency and acceleration, enabling students to explore resonance and amplitude-dependent response. By comparing input signals with measured responses, students developed a clearer understanding of dynamic amplification and modal behavior. Response data were processed using MATLAB, where students analyzed time histories and compared the behavior of damped and undamped models.

Overall, this phase improved students' ability to connect physical measurements with theoretical concepts in structural dynamics and encouraged a more critical view of experimental data.

Scaling Laws and Interpretation of Results

Scaling laws were introduced as a key component of the experimental project to help students interpret laboratory measurements in the context of real structural behavior. Because the building models were constructed at a 1:10 geometric scale, students were required to consider how frequency, acceleration, and displacement relationships change with scale when comparing experimental results to full-scale structures.

Rather than focusing on formal derivations, instruction emphasized the physical meaning of scaling relationships. Students examined how reduced structural dimensions influenced natural frequencies and why scaled models typically respond at higher frequencies than their full-scale counterparts. Through experimental observation, students learned that measured responses could not be interpreted directly without accounting for scale effects, highlighting the limitations of intuitive reasoning when analyzing dynamic systems.

Students applied scaling considerations when analyzing acceleration and displacement data obtained from shake-table tests. By comparing responses across different excitation frequencies and amplitudes, they developed an understanding of how resonance behavior shifts with scale and how damping effects manifest differently in scaled models. This process helped students recognize the role of scaling in experimental validation and the challenges associated with translating laboratory results to real-world applications.

The comparison between damped and undamped models further improved student interpretation skills. Students observed that while fluid viscous dampers consistently reduced vibration amplitudes, the magnitude of reduction depended on excitation frequency and model configuration. Interpreting these results required students to consider both scaling effects and material differences, encouraging a broader view of structural response rather than reliance on single performance metrics.

Overall, this section of the project helped students move beyond data collection toward informed interpretation. By integrating scaling concepts with experimental observations, students gained a deeper appreciation for how physical models are used in engineering practice and why careful interpretation is essential when applying experimental results to real structures. Table 1.

summarizes the project components and associated student learning outcomes, illustrating alignment between experimental activities and key concepts in structural dynamics.

Table 1: Project Components and Learning Outcomes

Project Component	**Expected Student Learning**	**Kolb Learning Stage**
Shake table design and operation	Understand how base excitation is generated and how mechanical constraints influence system response	Concrete Experience / Active Experimentation
Building model construction	Recognize the effects of material choice, stiffness, and connections on structural behavior	Concrete Experience
Instrumentation and sensors	Learn proper sensor placement and its impact on data quality and repeatability	Active Experimentation
Data acquisition and analysis	Develop skills in collecting, processing, and interpreting vibration data	Abstract Conceptualization
Scaling laws	Understand how scale affects frequency, acceleration, and displacement responses	Abstract Conceptualization
Damped vs. undamped comparison	Identify how damping mechanisms reduce vibration and alter dynamic response	Active Experimentation
Interpretation of results	Connect experimental observations with theoretical concepts in structural dynamics	Reflective Observation

Student Learning Outcomes and Reflections

Student reflections were collected through short written responses and guided discussions following major experimental phases. These reflections focused on students' understanding of dynamic behavior, challenges encountered during testing and modeling, and perceived value of the hands-on and collaborative learning experience.

The experimental project resulted in clear improvements in student understanding of structural dynamics concepts and increased confidence in applying theory to physical systems. Through direct involvement in design, construction, testing, and data interpretation, students demonstrated a stronger ability to relate analytical models to observed structural response.

One of the most significant learning outcomes was students' improved understanding of dynamic behavior under base excitation. Students reported greater clarity in concepts such as resonance, frequency response, and damping after observing these effects directly during shake-table testing. Comparing responses across different excitation frequencies helped students move beyond equation-based reasoning and develop physical intuition for dynamic systems (Figure 9).

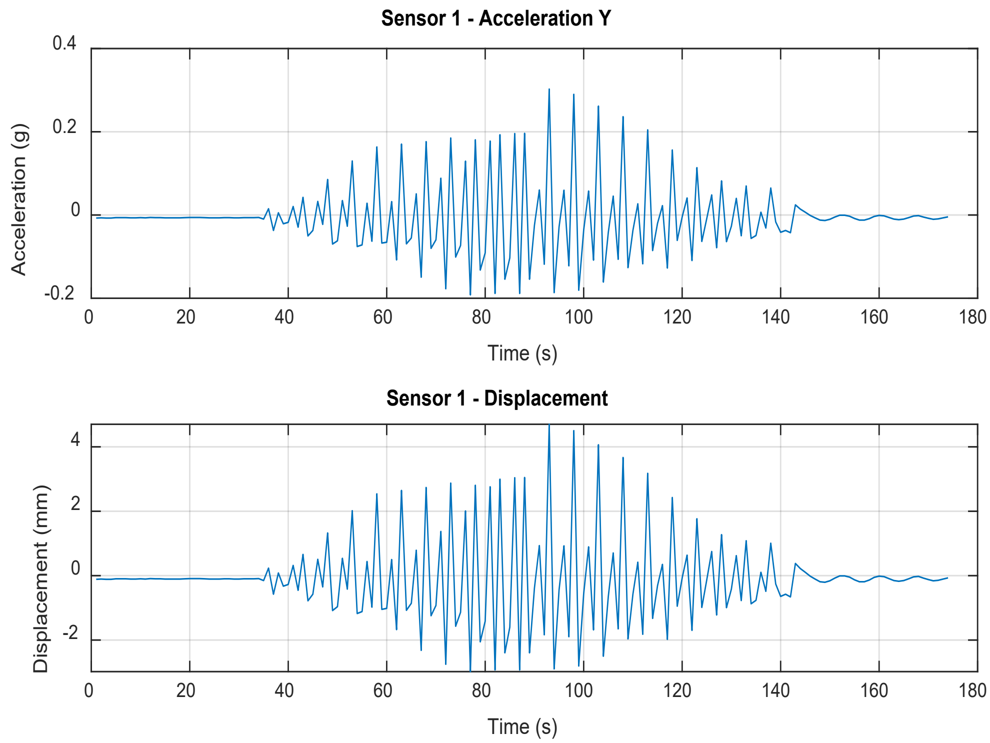

Figure 9. Time-history response of the fourth floor during shake-table testing at 4 Hz excitation frequency and 4 mm amplitude, showing measured acceleration and displacement as functions of time.

Students also showed measurable growth in experimental reasoning skills. Activities involving sensor placement, data collection, and troubleshooting exposed students to experimental uncertainty and variability. As a result, students became more attentive to setup consistency, data quality, and repeatability, recognizing that experimental results depend not only on theory but also on careful implementation and interpretation.

In addition to experimental testing, students used SolidWorks© FEA and MATLAB to model the dynamic behavior of the scaled structure and to compare predicted response with measured shake-table data (Figure 10). Computational results provided estimates of natural frequencies and response trends that closely matched experimental observations, helping students validate their models and recognize sources of discrepancy between idealized simulations and physical behavior. This comparison strengthened students' ability to connect analytical predictions, numerical tools, and experimental evidence when evaluating structural dynamic response.

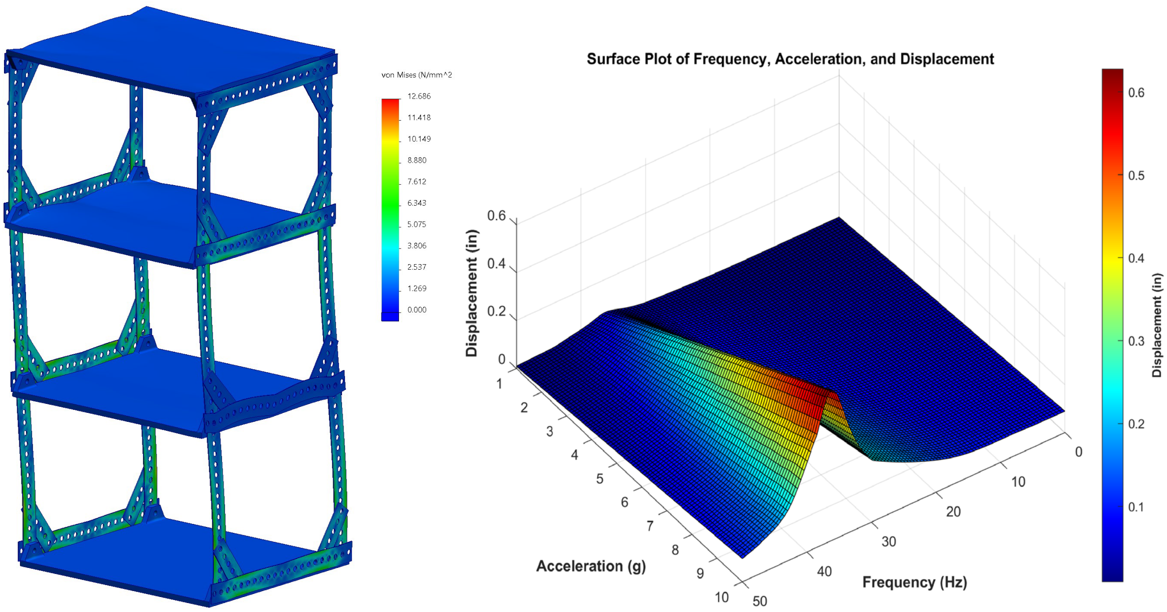

Figure 10. Computational results obtained from SolidWorks© finite element analysis (Left) and MATLAB simulations (Right) showing the dynamic behavior of the scaled building model.

The comparison of damped and undamped models further reinforced learning related to energy dissipation and vibration mitigation. Students were able to articulate how fluid viscous dampers influenced system response and why damping effectiveness varied with excitation conditions. This comparison strengthened their ability to evaluate engineering solutions using experimental evidence rather than assumptions alone.

Student reflections indicated that participation in the design and operation of the shake table increased engagement and ownership of the learning process. Rather than viewing the experiment as a prescribed laboratory task, students perceived it as an open-ended engineering problem that required judgment, iteration, and collaboration. This sense of ownership contributed to increased motivation and deeper engagement throughout the project.

Overall, the project supported learning outcomes aligned with both technical knowledge and professional skills. Students developed a more integrated understanding of structural dynamics, gained hands-on experience with experimental methods, and improved their ability to interpret real-world data, outcomes that are difficult to achieve through traditional lecture-based instruction alone.

Discussion and Lessons Learned

The implementation of a multi-phase, experiment-based project provided useful insights into the role of hands-on activities in undergraduate and graduate engineering courses (Directed Study, ME 4400, and Master's Project, ME 6800). One key lesson was that working with the same experimental system across multiple stages was more effective than short, isolated laboratory exercises. Repeated use of the same structural models and test setup allowed students to gradually build understanding and better connect design choices, measured response, and underlying theory.

Student involvement in the design and operation of the shake table proved very valuable. Allowing students to engage with the experimental hardware increased their awareness of practical constraints, such as mechanical tolerances, sensor limitations, and setup variability. However, this approach also required additional instructional support, especially during early stages, to ensure that experimental complexity did not distract from learning objectives. Clear guidance and structured milestones were essential to maintaining focus on conceptual learning rather than procedural difficulty.

Material selection and fabrication introduced important learning opportunities but also presented challenges. While the use of both plywood and 3D-printed PLA floors expanded the comparison of structural behavior, differences in fabrication effort and consistency affected testing efficiency. These challenges highlighted the need to balance realism with practicality when incorporating advanced manufacturing methods into instructional experiments. Furthermore, during the fabrication process, students identified dimensional errors in the initial building model design and recognized that the full-size floor components could not be printed as single pieces due to 3D printer size limitations. To address this, the floors were redesigned, printed in four interlocking sections, and assembled using adhesive, allowing students to correct the model geometry while maintaining structural continuity.

Another lesson emerged from early testing, when students observed unwanted vibration caused by the shake table not being securely fixed to the laboratory bench. Because permanent attachment was not permitted, students were guided on how to use clamps in special ways and temporary restraints to stabilize the system without damaging the bench. Addressing this issue helped students recognize how setup conditions and boundary constraints can influence measured response. Students initially tended to interpret results as directly representative of full-scale behavior, and guided discussion was needed to help them consider the effects of scale, support conditions, and experimental limitations. This experience emphasized the importance of carefully interpreting experimental data rather than relying on initial assumptions.

From an instructional perspective, the project required more time than traditional laboratory exercises but resulted in deeper learning outcomes. Part of this added value came from a peer-mentoring structure in which graduate students supported undergraduate students by answering questions related to advanced FEA and more complex 3D printing techniques. This interaction helped undergraduates progress more efficiently while reinforcing graduate students' own understanding. Although the project demanded additional time, this investment was balanced by higher student engagement, more productive discussions, and clearer connections between theory and practice. For instructors considering similar projects, careful planning, modular activities, and flexible scheduling are recommended to support iterative experimentation, reflection, and peer learning.

At the Symposiums of Student Scholars, students presented Phases I and II of the project, focusing on seismic testing and damping behavior in structural dynamics using a 1:10-scale, multi-story building model (approximately 30 cm × 40 cm × 90 cm) tested on a shake table (Figure 11). The presentations emphasized the development of a controlled experimental framework to evaluate how different damping configurations affect structural response under simulated seismic base excitation, supported by finite element analysis (FEA) and data interpretation using MATLAB to model system behavior and interpret experimental trends.

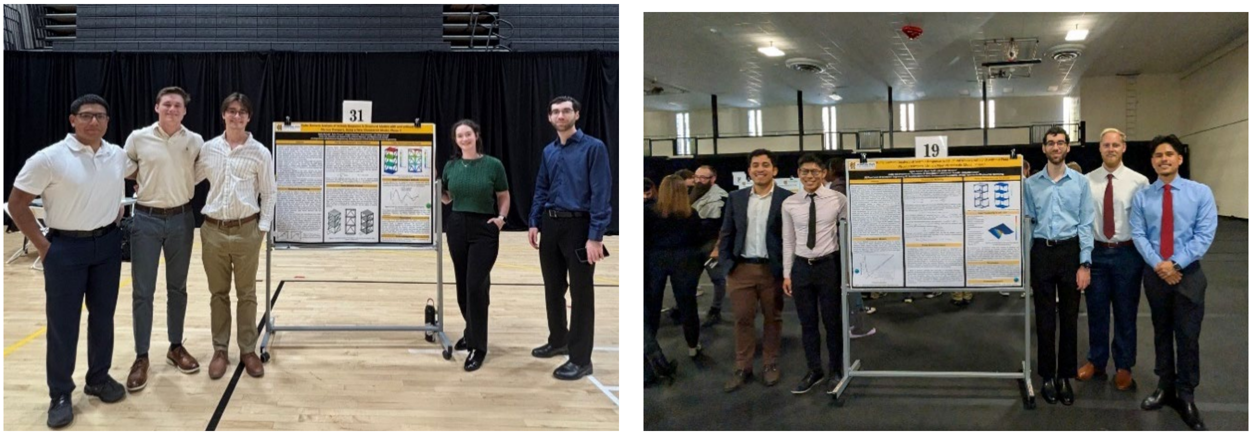

Figure 11. Students presented Phases I and II of the project at symposiums of student scholars. Posters presented in both the undergraduate and graduate categories received first runner-up awards.

Preliminary vibration tests conducted over a range of excitation frequencies relevant to low-rise buildings showed measurable trends in displacement reduction and energy dissipation when fluid viscous dampers were introduced. Although the results were exploratory, the work established a methodological foundation for future refinement, including improved instrumentation, expanded frequency-response analysis, and incorporation of nonlinear dynamic effects. Feedback from faculty, students, and industry attendees helped place the early findings within broader structural resilience research and confirmed the project's potential for seismic mitigation studies.

Overall, the project demonstrated that integrating experimental design, physical testing, and data interpretation within a collaborative learning framework can significantly enhance student learning in structural dynamics. The lessons learned from this implementation provide useful guidance for adapting similar approaches in other engineering courses.

Differences in student performance were associated with prior preparation, level of engagement, and approach to problem solving. Students who performed more strongly tended to take initiative in troubleshooting, relating experimental observations to underlying concepts, and refining designs, while others relied more heavily on guided instruction. Limited proficiency with tools such as SolidWorks© for FEA, 3D printing workflows, and MATLAB initially slowed progress; however, tasks were reorganized and assigned to parallel student groups, allowing skill development and project momentum to continue simultaneously.

The project supported the development of both technical and professional skills, including understanding structural dynamics, conducting experiments, interpreting data, fabricating components, teamwork, and communication. Students joined the research group due to interest in hands-on structural engineering research, curiosity about experimental work, and the desire to gain experience beyond standard coursework. These experiences are valuable for future academic and professional paths, as students gained confidence in working with complex systems, managing open-ended problems, and communicating results; skills directly transferable to engineering practice and collaborative research environments.

Conclusions and Future Work

This paper presented a course-based experimental project designed to improve student learning in structural dynamics through hands-on shake-table testing and collaborative work. By involving students in the design, construction, instrumentation, and testing of scaled building models, the project provided a clear link that connected theoretical concepts with observed physical behavior.

The results showed that working with the same experimental system throughout the course improved student understanding of dynamic response, damping effects, and scaling issues. Students demonstrated stronger ability to interpret experimental data, recognize the influence of material and design choices, and apply theoretical knowledge in a realistic engineering setting. The integration of student involvement in experimental setup further increased engagement, ownership, and learning depth.

From an instructional standpoint, the project demonstrated the value of combining hands-on experimentation with project-based instruction and student–faculty collaboration in mechanical engineering courses (Directed Study, ME 4400, and Master's Project, ME 6800). The approach moved beyond traditional laboratory demonstrations by focusing on iterative experimentation, data-driven interpretation, and reflection, all of which contributed to stronger learning outcomes. Table 2 summarizes the major activities completed by students during the project and the corresponding learning outcomes observed by the end of the course.

Table 2: Student Activities and Learning Outcomes by Category

Category	**Student Work**	**Learning Outcome**
Experimental design	Evaluated shake table mechanisms	Understood how hardware design affects system response
Model fabrication	Built multi-material building models	Recognized effects of material and stiffness on behavior
Instrumentation	Installed sensors and DAQ components	Learned how measurement choices affect data quality
Dynamic testing	Conducted shake-table experiments	Understood resonance and base-excited response
Vibration control	Compared damped and undamped models	Identified how damping alters dynamic response

Category	Student Work	Learning Outcome
Data interpretation	Analyzed experimental data	Interpreted results using scaling considerations
Reflection	Evaluated setup limitations	Recognized sources of uncertainty in experiments
Computational modeling	Built and refined FEA and MATLAB models	Linked numerical predictions to experimental response and identified modeling limitations

Through this project, students developed practical 3D printing skills, including creating and modifying CAD models to meet functional needs, selecting materials, and adjusting print settings for accuracy and strength. They learned to operate and troubleshoot printers, address common issues such as warping or print defects, and perform basic post-processing to prepare components for testing. Students also evaluated how printed parts performed during experiments, refined designs to improve fit and durability, and integrated printed components with other materials. These activities strengthened hands-on problem-solving skills relevant to modern engineering practice.

A direct comparison with students who did not participate in this project was not conducted; however, future offerings will include comparative assessment to better evaluate learning differences. Student assessment in the current implementation was based on multiple experimental, computational, and reflective components rather than a single project outcome, allowing evaluation of technical understanding and engagement across the course. While this limits direct comparison at present, it provides a clear structure for future assessment and refinement.

Future work will expand the experimental framework to include additional structural configurations, alternative damping devices, and a wider range of excitation conditions. Planned improvements also include more formal assessment of student learning outcomes using surveys and performance metrics, as well as adaptation of the project for use in other engineering courses and interdisciplinary settings.

Overall, the project provides a practical example for integrating extended experimentation into engineering education. The framework described here can be adapted to different course formats and provides an approach for incorporating hands-on experimentation, computation, and collaboration into mechanical engineering education, supporting the broader adoption of student-centered learning in structural dynamics and related fields.

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