Undergraduate Student Experience in a Multidisciplinary Architecture-Civil Engineering Research Project

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Abstract

This paper examines the learning experiences of undergraduate students who conducted research as part of a multidisciplinary team. The research project involved five undergraduate students with different backgrounds in engineering as well as in arts and sciences, supervised by four architecture and civil engineering faculty and their three PhD students. The research investigates the behavior of new Tessellated Structural-Architectural (TeSA) systems made of repetitive patterns of tiles (tessellations) that are both aesthetically appealing and load bearing. The undergraduate students worked on three tasks: (1) studying the behavior of TeSA shear walls using small scale earthquake simulator tests, (2) studying the shear capacity of reinforced concrete TeSA tiles, and (3) studying the effect of different shapes and interlocking patterns on the performance of small scale TeSA beams. The undergraduate students used hands-on experiments and laboratory testing to study the performance of 3D printed or prefabricated interlocking tessellations. This paper discusses the technical skills, fundamental concepts, and power skills (communicating, writing, presenting, etc.) that the students obtained, as well as the challenges that they encountered. The students found the process of developing and executing hands-on experiments and analyzing experimental results effective for learning new technologies and fundamental concepts. These concepts included 3D printing methods, natural frequency of a structure, and structural response subjected to a shear force. Peer learning, collaboration between students with different backgrounds, and group discussions with all the team members facilitated a deeper understanding and broader perspective on design, performance, and construction of TeSA systems. The project took place during the COVID-19 pandemic, and the students found working and meeting remotely challenging at times. Proper guidance and timely feedback by the project investigators and their PhD students helped with resolving the challenges.

Keywords

High impact practice, lessons learned, undergraduate research, architecture/engineering, collaboration

Introduction and Background

High-Impact Educational Practices (HIPs) have become a gold standard by which the quality of the undergraduate experience can be measured. Kuh[1] suggests that all undergraduate students participate in at least two of these educational opportunities before graduating. Kuh presents evidence that participation in HIPs provides students with greater opportunities for deep learning and self-reported gains, particularly students belonging to historically marginalized groups. This paper will discuss a series of research projects for undergraduate students that fall under the category of two of the HIPs suggested by Kuh: “Collaborative Assignments and Projects” and “Undergraduate Research.”

The National Science Foundation provides an opportunity for undergraduate students interested in research to get involved in existing NSF-funded projects by participating in a Research Experience for Undergraduates (REU). In this paper, we will examine the experiences of five REU participants who were involved in an interdisciplinary architectural and civil engineering research project at two universities during the summer of 2021. These REU students were advised and mentored by four architecture and civil engineering faculty members and three PhD students, whose experiences will also be discussed.

Each of the REU students participated in one of three small research projects which were conducted as part of the larger interdisciplinary project mentioned above. The objective of this larger project is to examine the behavior of Tessellated Structural-Architectural (TeSA) systems. Tessellations are mathematically defined as patterns of repeating geometric shapes with no gaps or overlap. These tessellated patterns have been used for centuries as architectural features in structures; however, they rarely serve any structural purpose. Unlike existing tessellated building components, TeSA systems are load-bearing systems, such as beams and shear walls, and are comprised of individual tiles in a tessellated pattern. Such a system combines the appeal of architecturally striking forms with some unique and desirable structural qualities. TeSA systems offer resilience by isolating damage in the system to a small number of discrete tiles, providing the opportunity for rapid repair by replacing these damaged tiles. TeSA systems may also be a sustainable option because of their potential to be quickly and easily disassembled and reused elsewhere. Additionally, a TeSA system would make an ideal candidate for automated fabrication and construction due to the repetitive nature of the tiles[2].

The three research projects which will be discussed in this paper all address some aspect of the design and structural behavior of TeSA systems. Due to the highly interdisciplinary nature of TeSA design, students with research interests in both civil engineering and architecture were selected to participate in this research. The impact of their interdisciplinary collaboration will be examined, as well as the challenges encountered due to the COVID-19 pandemic. Lessons learned from this experience, as well as some advice for future REU participants, will also be presented.

Meet the Participants

Katie Bender: Katie is a junior bioengineering major with an emphasis in biomaterials at Clemson University. While she has been involved in bioengineering research projects in the past, she is very interested in exploring research opportunities outside her direct field of study. Currently, Katie is a REU student who is researching the shear capacity of precast concrete TeSA systems.

Riley Blasiak: Riley is a senior double major in civil and environmental engineering at the University at Buffalo. Riley is an active member in the American Society of Civil Engineers (ASCE) and has acted as project manager for both the concrete canoe and steel bridge design teams. Currently, Riley is researching the dynamic behavior of TeSA walls using small scale tests as part of a REU.

James Lang: James is a senior civil engineering student studying at the University at Buffalo. James has previously served as a student assistant for statics for two semesters. This role entailed the creating and conducting of recitations, holding office hours, and grading. James is currently a REU student who is researching the dynamic behavior of TeSA walls using small scale tests.

Seth Moore: Seth is a junior architecture major with a minor in English at Clemson University. This project is his first experience in research, something he has always found an interest in. Currently, Seth is an REU student who is researching the design and fabrication of TeSA beams at a mid-size scale.

Olivia Wright: Olivia is a senior architecture major at Clemson University. Olivia will be spending several months studying abroad to explore the architecture of Spain. Olivia is researching the effect of different shapes and patterns on the behavior of small scale TeSA beams as part of her REU experience.

Grace F. Crocker: Grace is a PhD candidate in the Glenn Department of Civil Engineering at Clemson University. She received her M.S. in Civil Engineering from Clemson University in 2019. Her dissertation project focuses on the behavior of tessellated structures, as well as investigating interdisciplinary collaboration between architects and structural engineers.

Sida Dai: Sida is a PhD candidate in the Planning, Design and the Built Environment (PDBE) program at Clemson University. He received his M.Arch. from University of Virginia in 2017. His current research interests are generative design, artificial intelligence, tessellation, tangible, and origami.

Mohammad Syed: Mohammad is a PhD candidate in the Department of Civil, Structural and Environmental Engineering at University at Buffalo. He received his M.S. in Structural and Earthquake Engineering from University at Buffalo in 2019. His research interests include concrete structures, resilient infrastructure, and performance-based structural engineering.

Negar Elhami Khorasani: Dr. Khorasani is an Assistant Professor in the Department of Civil, Structural and Environmental Engineering at the University at Buffalo. She obtained her PhD degree from Princeton University. Her research interests include performance-based design, resilient communities, and risk assessment.

Michael Carlos Kleiss: Dr. Kleiss is an Associate Professor of Architecture at Clemson University. He received his PhD from the Massachusetts Institute of Technology. His primary interest is in the use of computers to aid designers throughout the architectural design process. He also focuses on morphology, biomorphic and bio-mimetic design, parametric design, shape grammars, and origami.

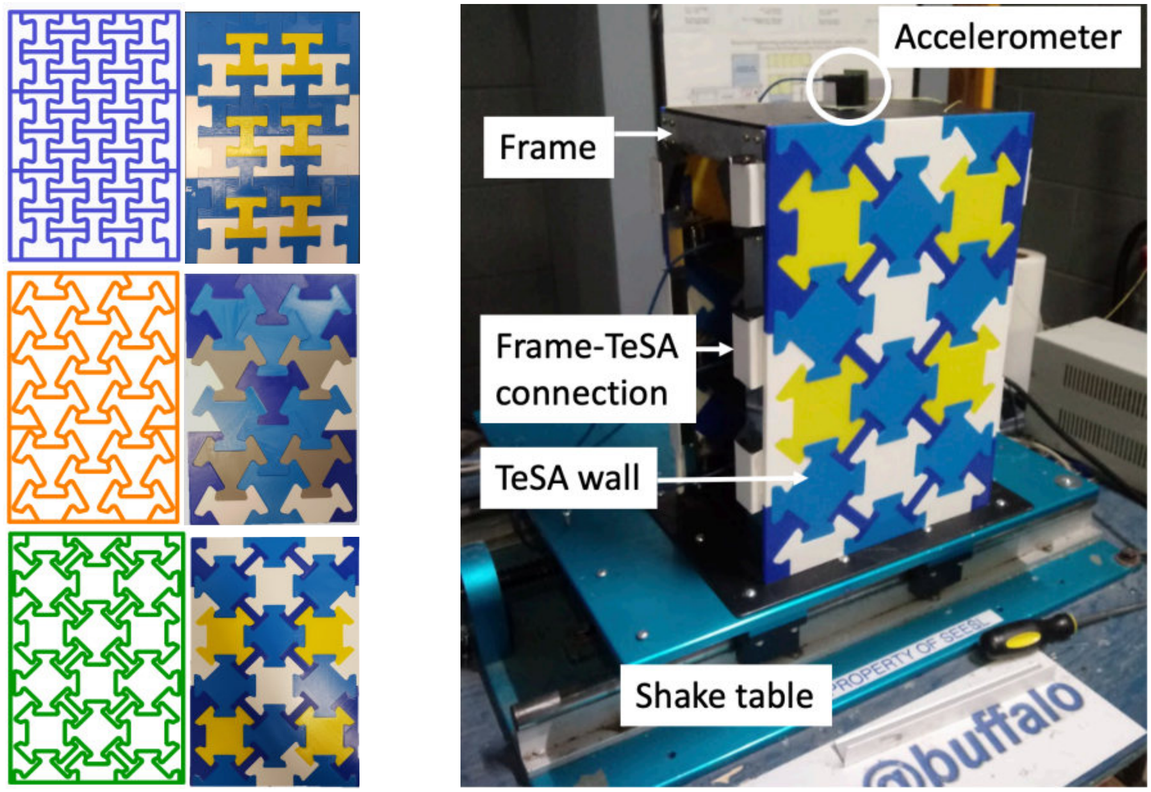
Pinar Okumus: Dr. Okumus is an Associate Professor in the Department of Civil, Structural and Environmental Engineering at University at Buffalo. She received her PhD degree from University of Wisconsin, Madison. Her research focuses on infrastructure resiliency and longevity as applied to reinforced and prestressed concrete structures.

Brandon E. Ross: Dr. Ross is the Cottingham Associate Professor in the Glenn Department of Civil Engineering at Clemson University. He received his PhD from the University of Florida. His research interests vary from adaptable building design to low-cost housing systems for developing communities.

Research Projects

Project 1: *Understanding the Dynamic Response of Tessellated-Structural Architectural (TeSA) Shear Walls Using Small Scale Shake Table Tests*

This research project investigated the seismic performance TeSA shear wall systems through small-scale testing. Additive manufacturing methods were studied to identify suitable approaches for building small-scale TeSA walls. A three-dimensional steel frame with shear walls composed of 3D printed tiles was tested on an earthquake simulator. The shear walls included solid walls and TeSA walls with different tile patterns (I-shape, triangle-shape, and square-shape). The walls were 12.875 inches tall, 8.75 inches long, and 0.22 inches thick with individual tiles whose sizes ranged from 2 inches by 2 inches to 3 inches by 3 inches. Figure 1 shows the CAD drawings and photographs of 3D printed TeSA walls, as well as a photograph of the experimental setup. The solid (non-tessellated) wall tested as a control specimen is not shown. Different frame-to-wall connection types were considered: (1) walls connected to the frame at columns only, (2) walls connected to the frame at columns and slabs, and (3) walls connected to the frame at the columns, slabs, and foundation level. Peak accelerations at floor levels of frames with TeSA and solid shear walls were measured during earthquake simulations and compared to each other. Free vibration tests were performed to determine the relative stiffness of each tessellation type compared to each other and to the solid shear wall. Damage observed during simulations was documented and categorized into groups to understand differences in performance between TeSA walls.

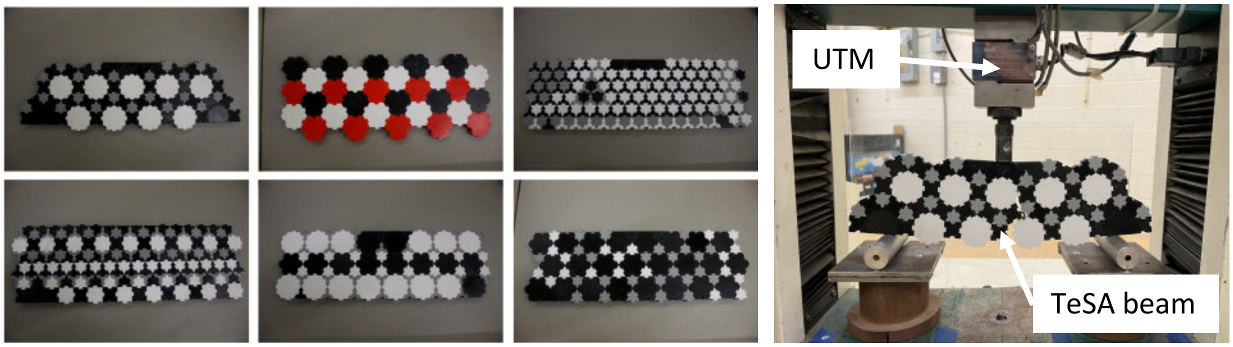


(a) (b)

Figure 1: (a) Drawings and photographs of various tested wall designs, (b) photograph of shake table test setup.

Project 2: *Investigating the Effects of Varying Tessellation Patterns on the Behavior of 3D Printed TeSA Beams in Flexure*

In this project, a variety of different tile shapes and interlocking patterns were used to design small scale TeSA beams. The student-designed patterns included different classes of tessellations. The tiles were individually 3D printed and assembled to create each small beam. The beams were approximately 4 inches deep, 12 inches long, and 0.375 inches thick with individual tiles with dimensions ranging from 0.5 inches by 0.5 inches to 1.5 inches by 1.5 inches. The beams were tested in 3-point bending using a Universal Testing Machine (UTM). Each beam was loaded to failure using displacement-controlled testing. Load-displacement data was collected for each beam, and the various peak loads, peak displacements, stiffnesses, and general load-displacement responses were compared. Beams were categorized as having brittle, ductile, or pseudo-ductile behavior. Examples of tested designs and a photograph of the test setup can be found in Figure 2.

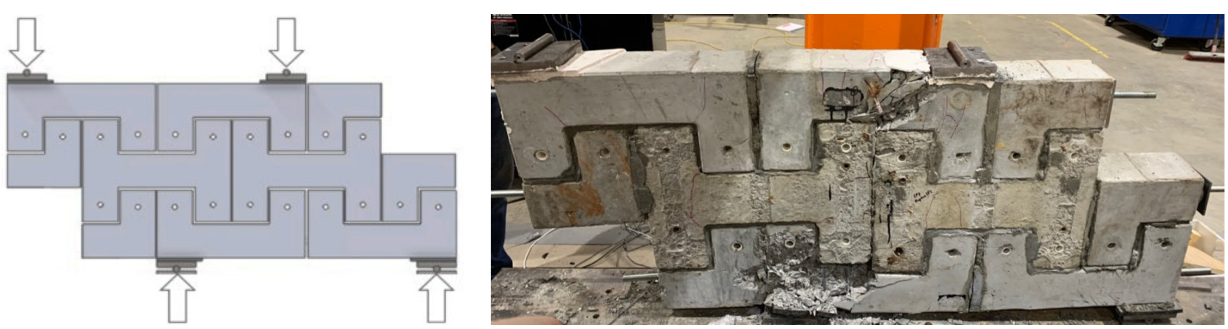


(a) (b)

Figure 2: (a) Photographs of various tested 3D printed beam designs, (b) photograph of 3-point bending test setup.

Project 3: *Measuring the Shear Capacity of a Precast TeSA Specimen*

This project involved the test of a large scale precast reinforced concrete TeSA specimen to determine its shear capacity. Ten precast tiles, which were each roughly 2 feet long, 16 inches tall, and 6 inches thick, were configured in a tessellation to construct a beam-like specimen for testing. A digital rendering and photograph of the specimen can be found in Figure 3. The specimen was tested for direct shear capacity using a modified version of Iosipescu's four-point loading scheme[3]. Two tests were conducted: one with horizontal post-tensioned (PT) steel through the tiles and one without. The first test (with PT) was primarily intended to establish approximately linear-elastic behavior of the specimen, and the second test (without PT) was a test to failure. Redundant instrumentation was installed to ensure accurate collection of load data as well as measurements of global vertical displacement, shear slip at tile interfaces, and gap openings between tiles. Strain data was also collected in various locations. Following testing, the collected data was analyzed to determine the loads at which minor and major cracking occurred, as well as ultimate failure in shear. Visible damage can be seen in Figure 3. Finally, a proposed theoretical model for shear capacity of reinforced concrete was compared to the experimental results.



(a) (b)

Figure 3: (a) Digital rendering of specimen with applied loads and supports, (b) photograph of specimen following testing to failure.

Goals and Operation

All of the projects were planned with the mutual goals that REU participants would develop (1) technical research skills, (2) an understanding of fundamental engineering concepts, and (3) power skills such as writing, presenting, and working with a team. Activities, such as group meetings, were organized to promote interaction and facilitate cooperative learning.

Project 1 was conducted at the University at Buffalo. The experimental work was primarily carried out by Riley and James under the guidance of Mohammad, Dr. Okumus, and Dr. Khorasani. Much of this work was conducted virtually due to COVID-19 restrictions.

Project 2 was conducted at Clemson University. The experimental work was carried out by Seth and Olivia under direct supervision of Sida. Dr. Kleiss oversaw Project 2. The majority of this work was conducted in person at the laboratory.

Project 3 was also conducted at Clemson University. The experimental work was carried out by Katie under direct supervision of Grace. Seth also assisted with Project 3 when available. Dr. Ross oversaw this portion of the research. This project was primarily conducted in person at the laboratory.

The REU students at UB and Clemson planned and organized weekly meetings for the entire research team during the second half of the summer to present their work via online meetings. This gave students the opportunity to see the broad spectrum of research being performed collaboratively and engage with each other to gain a deeper understanding of their own projects. Additionally, PhD students reported directly to the faculty members to keep them updated on the progress of each project throughout the summer. This provided the PhD students with the opportunity to directly mentor undergraduates, while faculty members provided oversight to ensure that everyone was staying on task and on schedule.

Challenges and Lessons Learned

At the end of the summer, all REU students, PhD students, and faculty members convened for a debriefing regarding their experience throughout the research projects. The challenges and lessons learned discussed by the participants were examined for common themes which will be discussed in detail in this section.

Scheduling and Documentation

Students learned to schedule “float time” for unforeseen technical difficulties and conflicting equipment needs. For example, students working on Project 1 reported that research tasks had to be completed in coordination with facilities such as the structural engineering laboratory and the 3D printing center. In the laboratory, several experiments were being carried out at the same time for multiple projects and by various investigators. Thus, working with people outside of their team and coordinating with the laboratory schedule slowed the course of the project. In the original project schedule, possible delays caused by other projects happening in the laboratory space or issues arising from laboratory or production equipment were not considered to the extent that was experienced. New printers were being configured in the 3D printing center at the time of the project. This caused the time for the 3D printing to be delayed, setting back all other parts of the project afterwards. Similar to the laboratory delays, the potential setbacks from the 3D printing center were not considered.

Similarly, those working on Project 3 found that their planned schedule did not allow enough time for setting up and testing instrumentation. Testing was delayed to ensure that valid data was collected. Fortunately, testing was still completed before the end of the summer; however, in the future these students would recommend planning more time than is expected to be necessary for this step of the experimental process.

Students also discovered the importance of keeping detailed documentation of experimental work. All of the REU students came to the consensus that taking detailed notes, many pictures, and supplementary videos of their experiments was crucial for their success. For example, students involved with Project 2 took multiple “before”, “during”, and “after” photos of every beam throughout the testing process in addition to a video. This detailed visual documentation allowed students to retrospectively analyze the failure mechanism of each beam. In addition to discussing the importance of taking detailed experimental notes, pictures, and videos, one student specifically noted the importance of writing short reflections after performing tests to ensure their own understanding of “what was done, why it was important, and what needs to be done next” and claimed that this helped them stay on track with their work.

Technical Skills

All of the REU students reported learning new technical skills during their work at the laboratory. The students working on Project 1 learned about fast Fourier transform, how to apply the fast Fourier transform to available data, the meaning of natural frequency, how to obtain the natural frequency as part of a free vibration analysis, and how to interpret the results of shake table and free vibration tests. The analysis of the natural frequency of the structure was new to the REU students. They had not taken a course on dynamics. They spent time developing a MATLAB code that would convert acceleration data into the frequency domain. In the end, the students researched the existing literature and found available codes, tools and resources, which helped them understand the required inputs and outputs for the conversion process. Understanding the results of the obtained data from experiments was another challenge. The students reviewed several scholarly sources to understand the natural frequency, and the external factors that could be contributing to peaks in the natural frequency data.

The students working on Projects 1 and 2 learned about 3D printing processes, tolerances required for interlocking tiles, and warping and shrinking caused by the printing process. These students also learned about 3D printing materials. Prior to the projects, the students had either very little materials knowledge or a background in civil engineering materials; thus, they were able to learn a whole host of things about 3D printing materials and how they differ from traditional civil engineering materials. The students involved in Project 2 also learned how to operate a UTM to perform 3-point bending tests, as well as analyze the load-displacement data they collected.

The REU students participating in Project 3 learned about installing instrumentation and operating data acquisition software. The REU students had no experience with such instrumentation; they worked closely with Grace to learn how these instruments worked, where they should be located, and how they should be installed. Students also learned how to check if all instruments were operating and troubleshoot when a problem was encountered. The "fundamental questions" of electronics were learned: Is it plugged in? Is it turned on? After testing, Katie learned how to analyze the load, displacement, and strain data collected during testing. Katie also learned the fundamental concepts involved in reinforced concrete mechanics; since her experience was strictly in biomaterials prior to this project, she was required to study this topic independently and through mini-lectures with Grace and Dr. Ross to understand the goals and outcomes of Project 3.

Thinking Like a Researcher

This section will discuss some of ways that the students learned to approach research. Firstly, all of the REU students agreed that this experience taught them the importance of being adaptable throughout the research process. They found it helpful to be open to change, and to listen to feedback from mentors and advisors and make adjustments to their work accordingly.

Students also discovered the value of taking the time to ensure collected data is valid before moving on to the next experiment, especially when many experiments were being performed. Students involved in all projects found that it was important to make sure all data measurement devices were working correctly before completing experiments by having intermediate checks along the way to observe and correct any mistakes. Students also reported that they learned to anticipate the expected results of their experiments based on theory. The REU students learned how to consider the possible outcomes of their research and reflect on the results to consider why the actual outcome may differ from the anticipated response.

One challenge encountered by all of the REU students was that of reading and understanding technical papers. The undergraduate students had limited experience with such literature and found it challenging to synthesize the pages of research into useful information. Students reported that they found it beneficial to read these papers, but it was helpful to ask their peers and advisors for assistance in understanding them when needed.

Learning How to Learn

During the debriefing, REU students were asked to reflect on the methods which they found most useful for learning information relevant to their project. For example, Katie learned from reading technical papers and having lecture-based discussions with Grace and Dr. Ross. These informal discussions provided her with more in-depth knowledge of the specific part of the research she was expected to do. James learned a lot from online sources that provided basic knowledge on the topics that he was working within. Seth learned similarly, since he was tasked with work in several different aspects of the research. He filled in the knowledge gaps he had from sources providing fundamental information needed for Projects 2 and 3.

Students also spent time in the debriefing discussing the differences between learning new information in the traditional classroom environment as opposed to the hands-on research environment. Students commented that information that traditionally provided by the instructor in the classroom had to be discovered in the laboratory setting. Additionally, the REU students pointed out that during their research experience they got to focus on one topic for an extended period of time and gain a deep understanding of it. In contrast, topics are often briefly discussed in the classroom to address the essential information, but time constraints prevent deep understanding. Another quality of the projects that the students reflected positively on was the interdisciplinary collaboration they were engaging in. The participation by students from various fields of study mimicked the professional environment and increased the opportunity for peer learning. Students also noted that executing the research process was similar to a design process in the sense that both are iterative processes in which adjustments must frequently be made to achieve the goal. As mentioned above, being adaptable is a valuable quality in a researcher, and this is also true of a professional engineer or architect. Overall, the students responded well to the active learning environment in lieu of traditional lecture strategies.

Power Skills

One of the goals shared by all three research projects was to help students improve their power skills such as writing, communicating, working in a team, and giving presentations. To this end, several of the students have begun working on technical papers based on their summer research. Additionally, one of the most valuable experiences over the summer was the symposium organized by the REU students. Each student virtually presented their REU research in a conference-style forum. This gave students an opportunity to practice designing and delivering a technical presentation. Being able to present their work at the symposium allowed them to reflect on what they truly learned from the research process. The symposium also gave students the chance to present their own learning in a way that those unfamiliar with the work would be able to understand. The students found that teaching and explaining their work to others was an effective way to cement their own learning.

One challenge, particularly for those involved with Project 1, was the communication between the REU students, advisors, and mentors. The work was completed during the COVID-19 pandemic with much of the communication taking place virtually (Projects 2 and 3 were conducted at Clemson in a time when in-person interaction was permitted). Thus, it was difficult to explain and discuss the research work and experimental setup. At the beginning of the project, the REU students working on Project 1 explored multiple research directions related to 3D printing and testing with the earthquake simulator. In this exploration period, the students had trouble describing the kind of help they needed without showing the mentors their problems. As the project progressed, the students ran into technical problems due to a lack of knowledge on running Fast Fourier Transforms (FFT) and the dynamic movements for structures subjected to seismic motion. At this point, the REU students reached out to Mohammad to utilize all their resources. With the supplemental discussions, the REU students were able to resolve the issues and learn about the technical aspects of the project, such as determining the natural frequency of the structure, dynamics of a structure, and programming required to run an FFT.

Conclusions

Three research projects based on the design and behavior of TeSA systems were executed by five REU students, three PhD mentors, and four faculty advisors. A variety of challenges were encountered and resolved throughout the research process, and many lessons were learned by all of the research participants. After a debriefing, students, mentors, and advisors compiled the following conclusions in the form of advice for future undergraduate researchers:

- When making a schedule, it is important to include extra time to account for events out of the control of the research team. This will prevent significant departures from the planned task order and time.
- It is essential to take detailed notes, as well as more pictures and videos than might be considered necessary, during any laboratory experiment. Detailed documentation provides a valuable reference for later use.
- It is important to be open to change. Feedback from mentors and advisors should be used to make positive changes to the work being reviewed.
- When reading complex technical papers, reaching out to peers and mentors for help can alleviate the frustration caused by misunderstanding jargon or advanced material.
- The active learning strategies implemented via experimental work are a unique and effective way to learn new concepts. Students may enjoy the focus on one particular topic of study, which is a defining aspect of research work. Students may also find it useful to supplement their work in the laboratory with independent study of relevant literature or discussions of relevant technical content with peers and mentors.
- Working in a diverse group of peers from different backgrounds and disciplines may encourage peer learning and allow students to improve their teamwork and communication skills.
- Presenting work to a group of peers, whether the work is ongoing or completed, is highly recommended to foster deep learning for both the presenter and the audience.
- In case of remote coordination and meetings, students may find it helpful to explore and use alternative methods to communicate the research work effectively, such as using several clear photographs to discuss the experimental setup, displaying results in an understandable format, and providing relevant background for any of the discussion topics. Effective communication helps with scheduling, planning, and addressing any issues before they become too large of a problem.

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Grace is a PhD candidate in the Glenn Department of Civil Engineering at Clemson University. She received her M.S. in Civil Engineering from Clemson University in 2019. Her dissertation project focuses on the behavior of tessellated structures, as well as investigating interdisciplinary collaboration between architects and structural engineers.

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