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Work in Progress: Developing a Virtual Reality Intervention Activity for Reinforced Concrete Design

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Abstract

This proposal addresses the critical issue of design choice autonomy in undergraduate engineering education, specifically in the context of reinforced concrete design. Students frequently face challenges with spatial reasoning, which complicates their ability to visualize and translate 2D representations of stresses and forces into effective 3D designs. Additionally, the high costs associated with large-scale physical demonstrations often restrict hands-on experimentation, limiting students' opportunities for independent exploration and discovery.

To address these challenges, we propose the development of immersive virtual reality (VR) experiences that provide real-time feedback on design decisions. This approach not only enhances theory-focused instruction but also fosters experiential learning by allowing students to see the immediate consequences of their design choices through 3D visualizations of internal member stresses, strains, and forces. Building on three years of research within the entrepreneurial mindset framework, the proposed module will empower students to investigate design impacts and rapidly iterate on their solutions. The work in progress will detail the framework for the VR module, its development, and the planned assessment strategies in an upper-level reinforced concrete design course. This framework can then be expanded and implemented to a wide range of design courses across engineering disciplines to improve design choice autonomy.

Introduction

In undergraduate engineering programs, student autonomy in making design choices is often overlooked in favor of simplifying summative and cumulative evaluation [1], [2]. As a result, design tasks are frequently reduced to prescriptive procedures rather than exploratory problem-solving experiences. Consequently, students are commonly expected to reason about these design decisions using two-dimensional representations of strain, stress, and internal forces presented in textbooks or computational tools. However, fundamental design decisions—such as selecting appropriate framing members, determining member dimensions, and placing reinforcement—constitute inherently 3D challenges that require spatial reasoning and an understanding of structural behavior in real space. Nonetheless, many engineering students struggle to translate these abstract, 2D depictions into accurate 3D models of physical systems, a difficulty that has been well documented among civil engineering students with underdeveloped spatial visualization skills [3], [4].

Compounding this challenge, undergraduate engineering curricula typically place limited emphasis on physical experimentation, particularly in reinforced concrete design, due in part to the substantial costs and logistical constraints associated with large-scale laboratory demonstrations [2], [5]. Even when such facilities are available, laboratory experiences are often constrained in flexibility and repeatability, limiting students' ability to explore alternative design scenarios or iterate on their own ideas. This lack of accessible, exploratory experimentation restricts opportunities for independent investigation and discovery, potentially hindering deeper conceptual understanding and students' ability to meaningfully engage with authentic design practice.

As a potential solution to these instructional limitations, immersive technologies—such as virtual reality (VR), augmented reality (AR), and interactive simulation environments—offer a cost-effective, scalable, and flexible means to complement theory-focused instruction [6], [7]. These tools enable students to interact with 3D representations of structures, materials, and load responses in ways that are difficult to achieve through static figures or traditional laboratory demonstrations alone. By providing immediate and visual feedback on the consequences of design decisions, immersive environments allow students to iteratively adjust parameters such as member size, reinforcement layout, or framing configuration and directly observe resulting changes in structural behavior, consistent with principles of active and inductive learning [5]. This rapid feedback loop supports experiential learning by linking abstract theoretical concepts to observable outcomes and reinforcing cause-and-effect relationships that are central to engineering design [8]. Prior research has shown that such active, feedback-driven learning environments can enhance conceptual understanding, improve spatial reasoning, and increase student engagement, particularly in domains where 3D thinking is critical [6], [7]. Moreover, immersive technologies lower barriers to exploration by allowing students to test multiple scenarios safely and repeatedly, fostering curiosity-driven experimentation and supporting the transition from passive knowledge acquisition to value-oriented engineering creation [9]. In this way, immersive tools have the potential to bridge the gap between analytical instruction and authentic design practice, while preserving the flexibility needed for student-centered learning across a range of engineering disciplines.

Despite the growing interest in immersive technologies for engineering education, relatively few studies have focused on the development and implementation of VR environments specifically for structural design and analysis [6]. Existing work in civil engineering education has primarily emphasized visualization for construction sequencing, site safety, and general building information modeling (BIM), rather than the explicit representation of structural loads, internal force transfer, and design decision-making [10], [11]. More recent efforts have begun to explore the use of VR to support learning in civil engineering domains such as building systems and load analysis, demonstrating the feasibility and educational value of immersive environments [12]. However, while several VR-based tools have been shown to improve students' ability to visualize structural systems and building configurations, they often present structural behavior in a qualitative or illustrative manner, with limited support for quantitative analysis or iterative design exploration [13]. Studies that incorporate loading conditions frequently rely on predefined scenarios, such as gravity or seismic effects, without enabling students to actively modify member properties, reinforcement layouts, or framing systems and immediately observe resulting changes in structural response [10]. As a result, VR applications in this domain have tended to function primarily as visualization aids rather than interactive design environments that support authentic structural design workflows. Moreover, empirical evaluations of these tools have largely concentrated on student engagement and perception metrics, with fewer studies rigorously examining their impact on students' understanding of load paths, structural behavior, and design reasoning [6], [7]. This gap highlights the need for engineering VR-based educational tools that more directly integrate structural analysis concepts with immersive, feedback-driven design experiences.

One notable contribution in this area is the work by Rodgers et al. [14], which presents the development and implementation of an iterative design VR module focused on structural steel design. In this module, users are able to modify key design parameters, including steel grade, cross-sectional member shape, and member size, and then immediately observe the resulting effects on structural response metrics such as member displacement and utilization ratio within an immersive environment. By coupling real-time visual feedback with quantitative performance indicators, the module enables students to develop a more intuitive understanding of the relationship between design decisions and structural behavior. This interactive approach allows users to rapidly explore alternative solutions and directly compare the consequences of different design choices, supporting deeper engagement with structural design concepts than is typically achieved through static calculations or two-dimensional representations. However, while this work demonstrates the educational value of VR-based iterative design environments for structural engineering, its scope is limited to steel structures. Structural steel represents only one of the primary material systems used in civil engineering practice, and the design considerations, failure modes, and decision-making processes associated with reinforced concrete differ substantially. As a result, there remains a need to extend this type of immersive, feedback-driven VR approach to reinforced concrete design, where concepts such as reinforcement detailing plays a central role in student learning.

Therefore, the primary goal of this work-in-progress is to develop and pilot a set of immersive virtual reality (VR) learning experiences, referred to as a module, that supports student learning in reinforced concrete design through active interaction with real-time design options and immediate visualization of their structural consequences. The proposed VR module is intended to move beyond traditional visualization tools by allowing students to modify key design parameters—such as member geometry, material properties, and reinforcement layout—and directly observe the resulting changes in structural behavior, demand, and performance within an immersive environment. This work builds upon three years of prior research and development by the principal investigators (PIs) focused on the use of VR in civil and structural engineering education, leveraging lessons learned from earlier prototypes and classroom implementations. In particular, the module is grounded in the entrepreneurial mindset learning (EML) framework, which emphasizes curiosity, connections, and value creation, and is used here to encourage students to explore alternative design solutions, evaluate tradeoffs, and iteratively refine their designs in response to feedback. By integrating EML principles with immersive VR technology, the module aims to support more authentic and exploratory design experiences that mirror professional reinforced concrete design workflows. This work-in-progress paper presents the conceptual framework guiding the module development, the technical implementation of the VR environment, and the planned approach for assessing its impact when deployed in an upper-level undergraduate reinforced concrete design course. This framework represents a critical step towards more accessible and immersive educational tools that can be used for engineering design across a range of disciplines to promote a more entrepreneurial mindset.

Methodology & Results

The development of the VR module begins with a clear focus on conceptualization and goal setting. The primary objectives of the module are to enable students to visualize how member size and reinforcement detailing impact the internal stress distribution and internal forces within reinforced concrete members. As such, the module is designed to provide a setup that allows users to select various reinforcement layouts and beam cross-sections and observe the resultant changes in real time.

To fulfill these objectives, two distinct modes were created: narrative mode and interactive mode.

Narrative Mode

The narrative mode guides users through an educational journey focused on single reinforced concrete beam undergoing a maximum crack moment with three types of stress representations: linear, parabolic (non-linear), and the Whitney stress block. This mode features a structured interface that includes a menu, a blackboard, and a 3D model of a reinforced concrete beam with accompanying diagrams.

- The menu provides context and allows users to progress through the learning stages at their own pace.
- The blackboard is utilized to convey essential calculations and diagrams, enhancing understanding of each step.
- The single reinforced concrete beam 3D model is meant to be a generic beam with two steel reinforcement bars near the bottom of the beam with illustrations for the internal strains, stresses, and forces.

Each significant dimension, such as the depth of the bottom reinforcement bar (d) and the depth of stress distribution (a), is also emphasized when necessary. Note, deflection is not reflected in any of these 3D models as that is not the central goal of this mode. The central goal of this mode is to visualize different representations of reinforced concrete internal stresses, strains, and forces when at the maximum cracking moment.

The learning process initiates with the first narrative step as shown in Figure 1, where the user is informed of the learning objectives of the module.

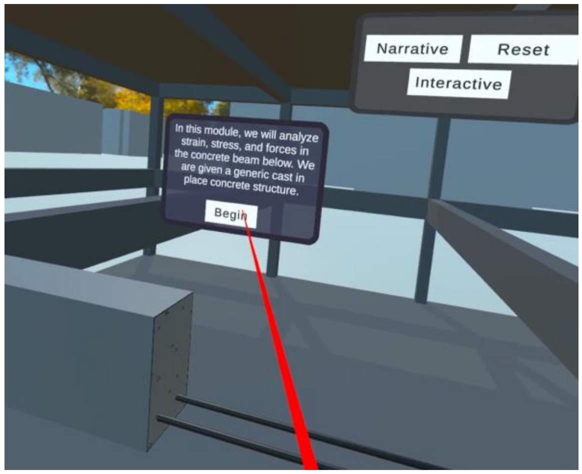
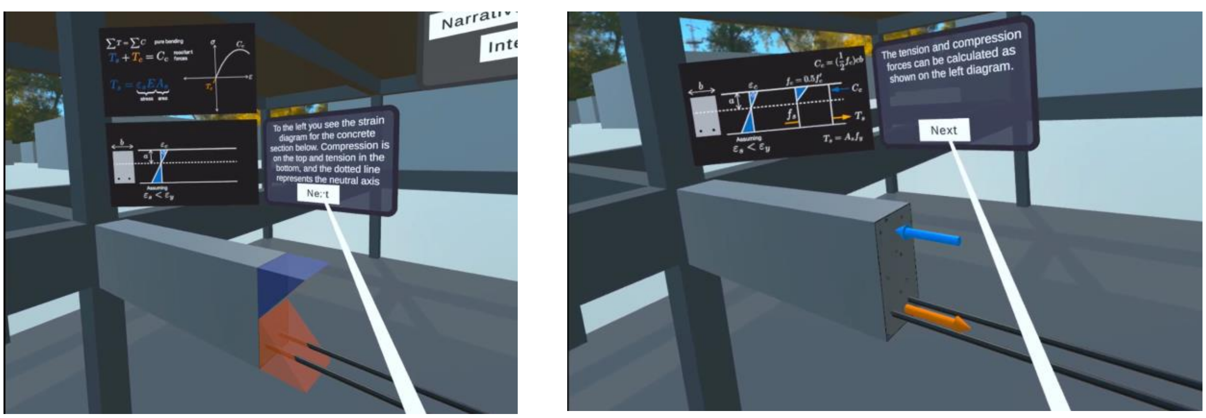


Figure 1. Starting screen of the user's narrative journey on learning reinforced concrete design.

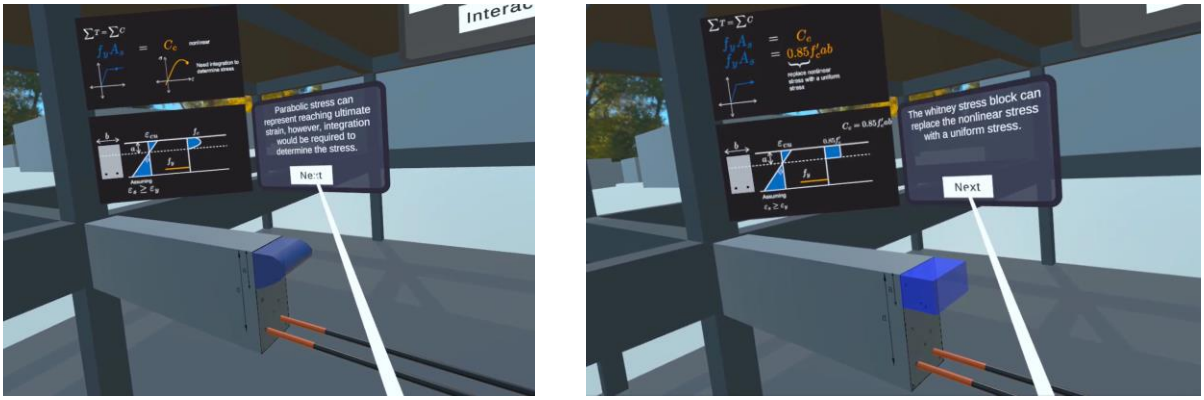
Next, the user learns about the simpler linear stress representation as presented in Figure 2. Here, internal member strains (Figure 2a), stresses, and forces (Figure 2b) for the maximum cracking moment are represented as simple triangular meshes and arrows. The blue meshes and arrows represent compression, while the orange meshes and arrows represent tension. Also, the magnitude of these factors is visually represented in proportion to their significance. Calculations and diagrams for the linear stress, strain, and force representations are shown on the blackboard for the student to visualize in conjunction of the 3D model.



a.) Linear strain diagram b.) Linear force diagram

Figure 2. Screenshots of linear stress representation for a reinforced concrete beam.

Subsequently, Figure 3a presents a parabolic stress representation, providing a more nuanced and nonlinear view of stress distribution. This is accompanied by diagrams and calculations displayed on the chalkboard with a note that integration is required. Following that, Figure 3b introduces the Whitney stress block, which balances the simplicity of the linear model with the enhanced accuracy of the parabolic approach. By beginning with the more straightforward linear representation, students can develop the foundational knowledge necessary to tackle the more complex nonlinear model. This progression will also help them understand the rationale behind the invention of the Whitney stress block and how to effectively utilize all three stress representations.



a.) Parabolic stress diagram b.) Whitney stress block stress diagram

Figure 3. Screenshots of parabolic and Whitney stress presentations.

In the final step, Figure 4 facilitates a comprehensive review, allowing users to revisit earlier parts of the module and consolidate their learning.

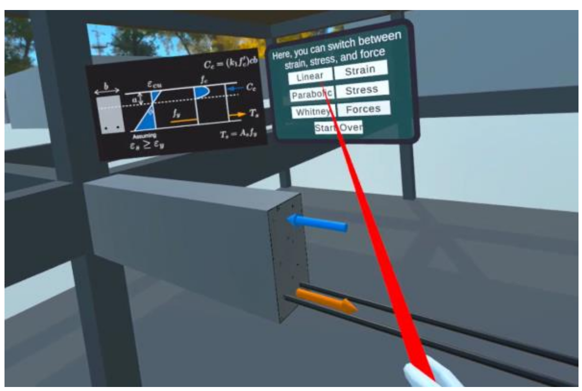


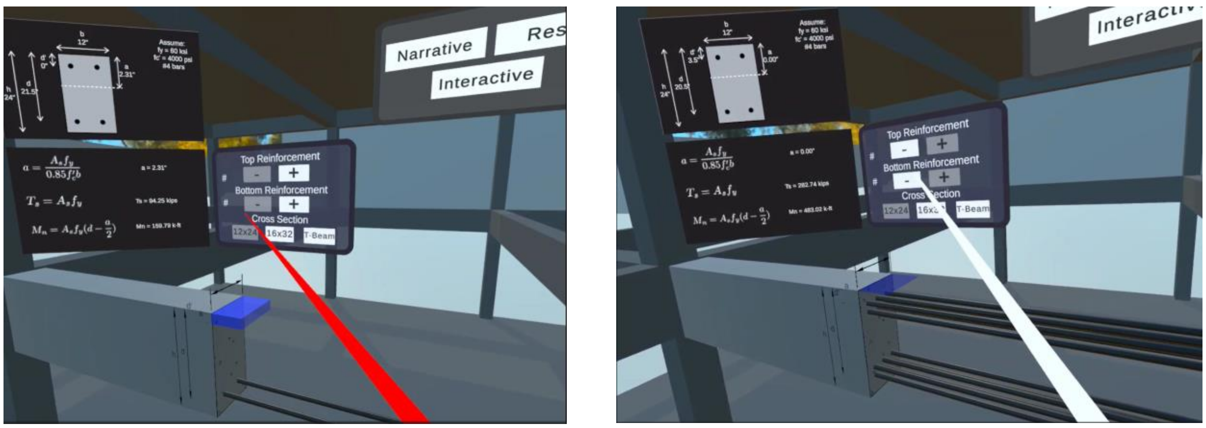
Figure 4. Ending screen of the user's narrative journey on learning reinforced concrete design.

Interactive Mode

In interactive mode, users can manipulate various parameters, such as the number of top and bottom reinforcement bars and the beam cross-section, to observe their effects on stress distribution. For this mode, only the Whitney stress block representation at maximum cracking moment is shown. This mode includes a blackboard for displaying calculations and traditional 2D diagrams, alongside a dynamic menu that allows users to adjust reinforcement configurations and beam cross-sections in real time. Any changes to these parameters trigger instant updates to the

3D beam model and stress block visualizations. It's important to note that, similar to Narrative Mode, deflections are not represented in these 3D models. For this module, users can choose from three size/shape options: a 12 x 24 rectangular beam, a 16 x 32 rectangular beam, and a T-beam.

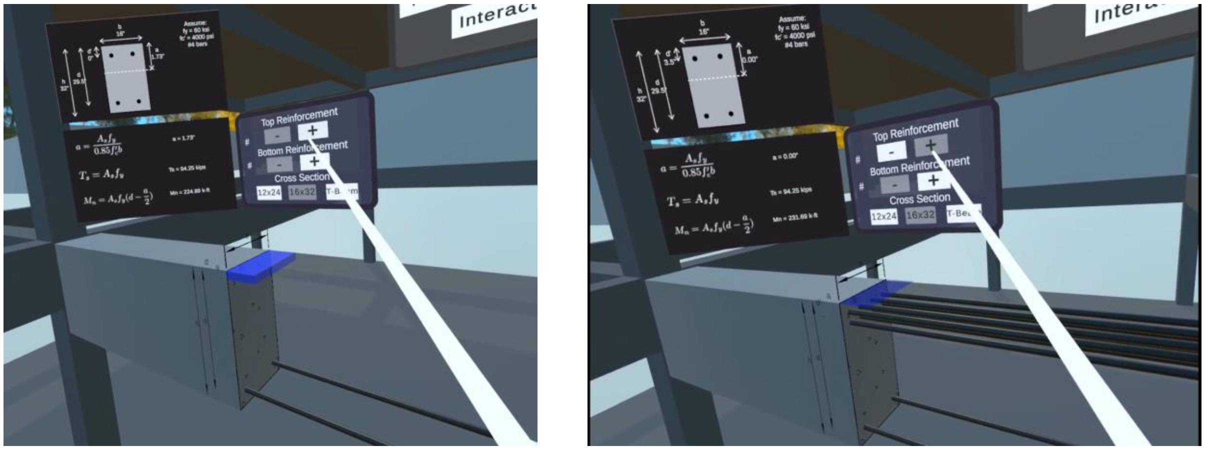
First, Figure 5 presents a 12 x 24 beam with the corresponding Whiteny stress block depth, tensile force, and maximum cracking moment for each reinforcement configuration. The beam for Figure 5a only has two bottom reinforcement bars, while the beam for Figure 5b has six top reinforcement bars and six bottom reinforcement bars. When more bottom and top reinforcement are added, the Whitney stress block depth is decreased, while the tensile force and the maximum cracking moment are increased.



a.) Two bottom bars. b.) Six top bars and six bottom bars.

Figure 5. Screenshots of the interactive mode for a 12 x 24 beam.

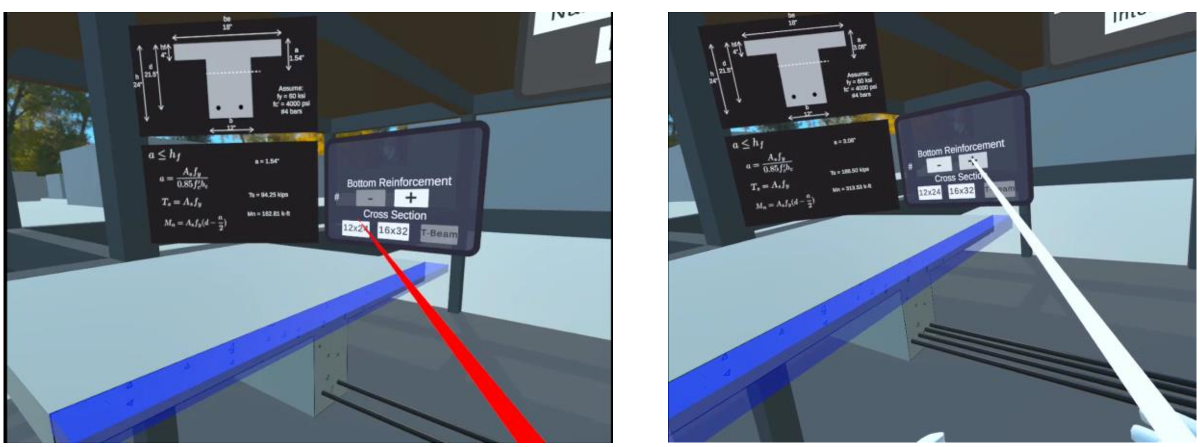
Next, Figure 6 illustrates a 16 x 32 rectangular beam with corresponding calculations. Figure 6a displays a beam with only two bottom reinforcement bars, while Figure 6b features a configuration with two bottom reinforcement bars and six top reinforcement bars. As observed with the 12 x 24 beam, increasing the number of top reinforcement bars reduces the depth of the Whitney stress block while simultaneously increasing both the tensile force and the maximum cracking moment. However, when compared to the 12 x 24 beam with the same reinforcement configuration, the 16 x 32 beam exhibits a shallower Whitney stress block depth and a higher maximum cracking moment, highlighting how size influences internal stresses and forces. It is noteworthy that the tensile forces remain identical for both beam sizes, indicating that tensile force is determined solely by the reinforcement configuration.



a.) Two bottom bars. b.) Six top bars and two bottom bars.

Figure 6. Screenshots of the interactive mode for a 16 x 32 beam.

Finally, Figure 7 illustrates a T-beam along with the relevant diagrams and calculations. Figure 7a displays a beam with two bottom reinforcement bars, while Figure 7b features a configuration with four bottom reinforcement bars. Notably, for this beam shape, users cannot add top reinforcement bars, highlighting the T-beam's design, which is more effective at resisting compression forces compared to rectangular beams. Interestingly, increasing the number of bottom reinforcement bars leads to greater depth of the Whitney stress block, tensile force, and maximum cracking moment. When compared to rectangular beams with similar reinforcement configurations, the T-beam exhibits a shallower Whitney stress block depth and a maximum moment that falls between those of the 12 x 24 beam and the 16 x 32 beam. The tensile force remains consistent across all beam types, underscoring that beam shape does not affect tensile force either; tensile force is solely determined by the reinforcement configuration.



a.) Two bottom bars. b.) Four bottom bars.

Figure 7. Screenshots of the interactive mode for a T-beam.

Development Process

To create the VR module experience, the Unity gaming engine [15] was selected for its versatility and user-friendly attributes. The 3D model of the beam is constructed from a basic rectangular mesh accompanied by a standard concrete material, with reinforcement bars illustrated as simple cylinders. To enhance the immersive quality of the module, an overall building structure was incorporated, avoiding a stark, empty presentation.

Attention was given to the visual simplicity of colors and materials, prioritizing clarity in diagrams and visualizations over hyper-realistic designs. The navigation system was designed for a seated experience, minimizing risks associated with movement in a crowded classroom. Furthermore, the module's interface is crafted to be intuitive and streamlined, facilitating an engaging learning experience.

The blackboard bridges the gap between 2D conceptual understanding and 3D visual representation, allowing students to connect theoretical knowledge to practical application. Collectively, these development choices enhance the module's effectiveness and immerse users in the learning experience of reinforced concrete design.

Future Work

Future work includes implementing and assessing the effectiveness of the VR module in an undergraduate civil engineering reinforced concrete design course. The VR module will be implemented as a one day experience during normal class time at the point in the semester that the students are learning about stress representations. At the beginning of the class, everyone will take a short quiz, called Quiz 1, with questions about sketching stress distributions and forces on 3D beams and determining the Whitney stress block depth, tensile force, and maximum cracking moment for a rectangular beam and a T-beam with varying reinforcement configurations. Afterwards, students will be randomly split into two groups: one control group that will have a paper handout with the lesson and an experimental group that will go through the VR module in turns. After both groups have done their assigned activity, both groups of students will take another short quiz, called Quiz 2, that has similar questions to Quiz 1 but with different numbers / scenarios. The Quiz 1 and Quiz 2 results will then be analyzed between both groups to see how effective the VR module is compared to traditional 2D handouts. After Quiz 2, the control group will have the opportunity to explore the VR module and vice versa for the experimental group. That way, everyone has an opportunity to try the VR module. At the end of class, a short survey will be given out about the students' experiences with the VR module with questions about EML and the Three C's: Curiosity, Connection, and Creating Value. For instance, on a scale of 1 to 5, how curious did the student feel about the different designs? Also, what value tradeoffs did the student notice with the different designs? With this assessment plan, the VR module will be assessed for effectiveness and will be able to be used to enhance the teaching of engineering design courses.

Conclusion

This work in progress aims to address a critical gap in undergraduate engineering education through the development of a VR module focused on reinforced concrete design. Students often struggle to translate 2-D representations of strain, stress, and forces into practical 3-D applications, with traditional assessment methods overlooking the autonomy in design choices—an essential aspect for fostering spatial reasoning and creativity. Furthermore, limited flexibility in laboratory settings constrains hands-on learning experiences, hindering exploration beyond standard frameworks. The developed VR module serves as an innovative solution by enabling students to interact with real-time design options and visualize the consequences of their decisions, in this case for reinforced concrete design. This immersive technology not only provides immediate feedback but also promotes EML, guiding students from curiosity to actionable engineering value. The integration of narrative and interactive modes aims to meet its objectives, enhancing understanding of member sizing and reinforcement detailing while significantly improving student engagement and comprehension. By employing the EML framework, the module encourages independent exploration and rapid iteration of design choices, paving the way for a more dynamic educational approach. As we refine and expand this VR experience, its effectiveness will continue to grow, showcasing the transformative potential of immersive technology in engineering education and promoting more interactive learning methodologies.

AI-Assisted Technologies Disclosure

In this paper, ChatGPT was used to enhance the coherence and flow of ideas presented in the introduction section. This use of AI was limited to improving the connectivity of the text and did not influence the content, interpretation, or conclusions of the research. The final version of this article has been critically reviewed and further refined by the authors, ensuring that the content aligns with the authors' intended scope and scholarly rigor.

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