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education sciences

Article

Embedding Civil Engineering Understanding through the Use of Interactive Virtual Reality

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Abstract: Recent skills surveys of engineering graduates have highlighted a deficit in critical thinking among graduates. A possible solution to this is to increase the number of hands-on exercises in the curriculum. This could be carried out through the integration of 3D learning tools, specifically a virtual reality (VR) program, to effectively teach civil engineering practical studies and allow repeatable and measurable exercises for students. This study aims to assess the suitability of the VR program as an additional resource alongside existing learning exercises or a substitute for hands-on experiments when needed. The methodology involved creating a VR program, compatible with VR headsets to replicate an engineering experiment, namely the loading of a concrete beam to observe its failure. Students' understanding of the virtual experiment was evaluated through end-of-experiment questions. The findings indicate that the VR learning tool was successful in enhancing students' understanding of the civil engineering experiment. The immersive and interactive nature of VR contributed to a solid grasp of the concepts presented, proving its potential as a valuable educational resource. By leveraging VR technology, educational institutions can provide an engaging and effective alternative to traditional laboratory sessions, ensuring uninterrupted and high-quality learning experiences for civil engineering students.

Keywords: virtual reality; interactive learning tool; digital modelling

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1. Introduction

The most recent skills survey from the Institution of Engineering and Technology (IET) has revealed that less than half of new engineering recruits have both the necessary technical and soft skills needed for work within the industry. Civil Engineers play a significant role in shaping and designing the world around us and therefore have a significant opportunity to help create a more sustainable world. Approximately 70% of global emissions can be linked to infrastructure, and as the designers, builders, and maintainers of this infrastructure, civil engineers are one of the best-placed professions to reduce carbon emissions and mitigate climate risks globally. Engineering educators need to teach new skills such as critical thinking, social awareness, and creativity to enable future graduates to meet these challenges. This research is focused on the design and implementation of an interactive digital environment supported by immersive technology to enhance student learning and understanding.

The civil engineering undergraduate degree at Queens University Belfast includes a number of physical laboratory investigations and practical exercises, particularly in Stages 1 and 2, where "stages" refers to the year group (i.e., stage 1 is the 1st year and stage 2 is the 2nd year). They are important learning exercises that are required for course accreditation with the Joint Board of Moderators and assist in demonstrating and embedding knowledge and learning. Previous research has highlighted that experimental learning is a key component in engineering education [1,2].

A positive aspect of this format is that students gain hands-on, practical experience, which is often cited as one of the main highlights of the program in end-of-year reviews. A negative aspect of the current format is the poor linkages between previous topics/assignments covered by students relating to physical testing, which ultimately limits student understanding of the significance and consequences of different design choices and their associated impact on sustainability, health and safety, and project management. In practice, civil engineers often need to make quick-fire decisions in construction site conditions. Learning these skills onsite can be extremely resource-intensive (time, money, materials, etc.) and undoubtedly contributes to the significant waste produced by the construction industry. Recent research has suggested that students would greatly benefit from method-based or problem-based teaching in practical engineering labs to enhance the learning experience [3–6]. However, these laboratories require space, consumables, technical support, and academic support. This research explores the suitability of digital technology to equip students with appropriate decision-making skills in a low-risk environment. It was proposed to make these digital environments immersive in nature using inexpensive virtual reality (VR) headsets (Meta Quest 2). Response and learning outcomes were monitored and reported, comparing the student learning outcomes from physical laboratories with those from virtual laboratories. Academic performance and reflective student surveys were used to measure the success of the digital learning environment at Queens University Belfast (QUB).

2. Review of the Literature

The scope for the review of the literature was organized using the method laid out by [7] and is detailed in Table 1. EBSCOhost was used for initial keyword searches, with reverse and forward searching carried out using Connected Papers to create a representative overview of the relevant areas.

Table 1. Literature Review Organization.

Characteristic	**Categories**			
Focus	**Research Outcomes**	**Research Methods**	**Theories**	**Applications**
Goal	Integration	Criticism	Identification of Central Issues	
Perspective	Neutral Representation		Espousal of Position	
Coverage	Exhaustive	Exhaustive/Selective	Representative	Central/Pivot
Organization	Historical	Conceptual	Methodological	
Audience	Specialized Scholars	General Scholars	Practitioners	General Public

2.1. Intro to VR

"Virtual Reality (VR) is an advanced, human-computer interface that simulates a realistic environment. The participants can move around in the virtual world. They can see it from different angles, reach into it, and reshape it" [8].

Since the 1950s, pioneering engineers and technology companies have both been inspired by renowned science fiction authors to turn this technology into tangible systems. One notable figure is Morton Leonard Heilig, a cinematographer who started developing the Sensorama (patented in 1962) [9]—an arcade-style theatre cabinet from the 1950s that simulated multiple senses using a stereoscopic 3D display; speakers; fans; smell generators; and a vibrating chair. Heilig also invented the Telesphere Mask, the first VR Head-Mounted Display (hereinafter called HMD) (patented in 1960) [10]. Another significant contributor is Ivan Sutherland, who, along with his students at Harvard University, created the "Ultimate

Display", the HMD that rendered sequential images based on the viewer's movements, serving as the foundation for modern virtual reality technologies.

Since then, academic institutions and industry organizations like MIT, NASA, and Nintendo have made notable contributions to the underpinning technologies and user experience of head-mounted displays and conducted experimental trials in this field.

2.2. VR as a Method of Teaching

Bell and Fogler [11] state, "Many studies have shown that students learn best when a variety of teaching methods are used and that different students respond best to different methods". This research explores the potential of educational tools for chemical engineering. The authors find that the main strength is the "ability to visualize situations and concepts that could not be otherwise seen". In addition, student interest and enthusiasm are increased as a diversity of learning styles, including active, visual, inductive, and global, is possible. However, several weaknesses are present, such as the visual presentation of textual information like equations and definitions in the environment.

The research performed in [12] involved 39 students in the faculty of life sciences taking part in a VR dissection, which found that VR is much better than only using a textbook, but the actual dissection was best in real life, with VR being a good addition to it.

"Despite the cost of technical support, staff training, and space requirements caused by AR/VR, the need for physical space can be reduced, and areas may be redirected for other purposes". "All of this shows a positive impact on universities, including economic repercussions" [13].

Freina and Ott [14] found that 27% of Immersive VR Education-related papers are in the engineering topic, while 60% of papers are in the computer science topic, which shows there is already some development with the potential for growth in the area. The journal concludes by saying, "Immersive VR can offer great advantages for learning: it allows a direct feeling of objects and events that are physically out of our reach; it supports training in a safe environment, avoiding potential real dangers; and, thanks to the game approach, it increases the learner's involvement and motivation while widening the range of learning styles supported".

2.3. VR in Civil Engineering Education

There have been several applications of virtual reality technology being incorporated in the area of civil engineering instruction. The research on this is generally supportive of VR as a means of instruction [15,16], particularly to replace dangerous or expensive laboratory trials [17] or as a means of increasing situational awareness of engineering environments [18,19].

Early work in this area was carried out by Sampaio et al. in [20], where students were shown a virtual simulation of a bridge under construction to improve their understanding of the concepts involved. The authors indicated that students' understanding increased, but no quantitative data were included to support this. The technology at the time did not allow for very realistic simulations, as the engines used to develop the software were not powerful enough at this time. Further work was conducted by Dinis et al. in [21], where K-12 students were presented with a simple VR application that highlighted areas related to specific disciplines of engineering (structural, construction, hydraulics, etc.) to aid student understanding of basic civil engineering concepts and how they apply to the world around them. The authors used a Likert scale to measure engagement but did not investigate improvement in relation to learning outcomes. This gap between simulation development and learning outcomes was also raised by Liang in [22], as the author raised the concern that there are not close enough links between developers of software and the academic community that will be implementing them, which is something that was a priority during the development of the tool used in this research.

With the release of more powerful tools for developing VR experiences, photorealistic simulations could be integrated into courses. The high-resolution recreation of a construction site in [23] allowed for increased immersion due to the detailed graphics present in the simulation. The qualitative data from this paper indicated that the students enjoyed the experience, but the inability to interact directly with elements of the experience reduced the effectiveness of the simulation as a teaching tool. To address this concern, the digital learning environment presented in this research was developed using a game engine. The functionality available from their original use as an engine for developing games and interactive experiences meant it could be applied to this project, as was also carried out in [24]. Additionally, the low cost of licensing a games engine (Unity, selected for this research, is free for academic use) removed one of the main disadvantages of using VR for education, as stated by Zacher in [25].

This research carried out in this paper was inspired by the work carried out by Try et al. in [26]. This research aims to build upon their work, which is closely tied to learning outcomes and quantitatively and qualitatively measured student engagement, by applying similar methods in the scenarios and testing facilities.

3. Materials and Methods

The hardware specifications of the headsets used will first be defined, followed by the development of the application, the questionnaire, and finally the procedure implemented for the collection of data.

3.1. Hardware Specifications

The headsets used in this research were the Meta Quest 2 All-in-one headsets, which are priced at £299.99 for the 128 GB model [27]. The headsets feature six degrees of freedom tracking, ergonomic controllers, and a high-resolution LCD display per eye. The headset is a standalone unit and is powered by a 3640 mAh rechargeable lithium-ion battery, making it fully portable.

These headsets were chosen because of their affordability and ability to meet the processing requirements of the current application. Further development, like the implementation of more complex testing programs and enhanced laboratory equipment functionality, will require improved hardware, such as the Valve Index or Apple Vision Pro.

3.2. Development of the Application

Beam bending theory threads throughout the civil engineering degree and forms the basis of structural design. Stage 1 civil engineering students at QUB learn composite beam theory in class. To embed and demonstrate the theory in practice, the students are required to manufacture two reinforced concrete (RC) beams with two different amounts of reinforcing steel, which will result in different load-deflection behavior and ultimate moment capacity. These beams are designed in accordance with Eurocode 2 [28]. Observation of the cracking and failure modes is critical to the laboratory. The students then observe a practical exercise in the laboratory whereby RC beams are tested to failure under a three-point loading test, as shown in Figure 1. The beam is arranged in a structural loading frame with both ends simply supported, and a central point load is manually applied via a hydraulic pump. The arrangement of this experiment is illustrated in Figure 1.

Pressure, load, and gauge readings were measured throughout the experiment, and using these results, the students then calculated bending moment capacity, maximum external bending moment at cracking and failure, beam shear capacity, and maximum shear force acting at failure. However, the set-up above is used for small, low-capacity elements, and therefore the exercises are restricted by these limitations. Due to time and resource constraints, only two types of beams, under-reinforced and over-reinforced, with the same dimensions are cast by the students in advance of the lab. Therefore, the students' learning and practical experience of beam bending are limited to a controlled test run by trained demonstrators. This provides a valuable visualization of the theory but does not develop the students' agile problem-solving skills required in real-world design situations. Enhanced flexibility in testing can be obtained through the use of more advanced structural testing equipment. The heavy structures laboratory at QUB is also equipped with a large UKAS-calibrated Dartec loading frame, which replaces the manual hydraulic pump with an electro-hydraulic actuator that can apply a load of 600 kN; this is illustrated in Figure 2. The scale of the Dartec provides greater opportunity to test a wider range of beam sizes under a variety of loading conditions, but it can only be operated by trained technicians within the laboratory. Dartec usage is predominantly limited to this research and commercial development of structural products. The aim of this research was to develop a digital application that would enable the students to gain individual experience of practical beam-bending exercise with the range of testing arrangements provided by Dartec. The application was developed to replicate the testing of RC beams carried out during the practical exercise outlined above. The use of digital technology means the students can retain full control of the beam design, specifying beam size, reinforcement locations, and the placement of sensors to monitor the beam behaviour during the test. The student can also control the loading rate and placement of the beam, replicating the real testing situation in the physical tests carried out using the Dartec.

(**a**) (**b**)

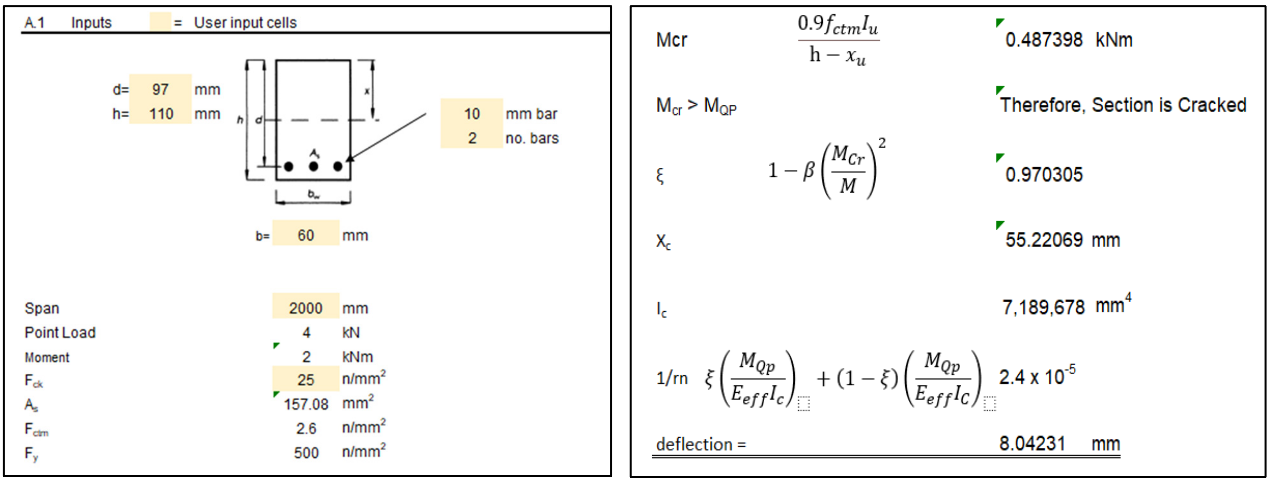
Figure 1. Arrangement of stage 1 RC beam testing experiment (**a**) frame for testing small capacity beams (**b**) hydraulic pump used to apply load to a RC beam.

(**a**) (**b**)

Figure 2. The Dartec used within the heavy structures lab at QUB is (**a**) the Dartec and (**b**) the Dartec testing a concrete element.

For the developed application to be realistic and provide a useful learning tool for student development, the deflection behavior and the deterioration mechanisms had to be modeled accurately for the materials tested. This ensures the learning outcome of the practical is achieved as the students can measure the impact of various loading scenarios and beam geometry. The calculation of the deflection has been carried out in accordance with Eurocode 2 (EC2) [28], the European standard for the design of concrete structures, which is extensively used throughout Europe. The calculation operates based on a simplified approach that uses the total curvature of a RC beam under load, which is based on the curvature of the cracked section and the uncracked section.

A design spreadsheet was developed to provide the numerical values for the structural response of the beam, replicating the examples carried out by the students in class prior to completing the practical. The sheet required six user inputs: the basic beam geometry in terms of height and width, the steel reinforcement bar used within the beam and the depth of this reinforcement bar, the compressive strength of the concrete (F_{ck}), and finally the span of the beam, these inputs are shown in Figure 3a. The input section of the spreadsheet is presented in Figure 3a, where the input cells are cream-coloured, and these can be varied to allow the user to create different configurations of RC beams in terms of geometry and reinforcement to model how the parameters impact the deflection. Following the user inputs, the spreadsheet automatically calculates the concrete properties, including the mean tensile strength of the concrete (F_{ctm}), the 28-day tangent modulus (Ec28), and the creep coefficient (ϕ). Based on these concrete properties, the long-term elastic modulus (E_{eff}), effective modulus (αe), and neutral axes of the uncracked section and cracked section can also be calculated. These parameters are used to calculate the cracking moment (Mcr), which is used to determine if the section is "cracked" or "uncracked", and finally, based on this behavior (i.e., cracked or uncracked), the curvatures can be calculated and the deflection determined based on the total curvatures, as seen in Figure 3b.



(**a**) (**b**)

Figure 3. Extracts from the beam deflection calculation (**a**) Algorithm 1, were user input cells are coloured cream (**b**) deflection output.

The application was then created by the developer, where the calculations described above were coded into the background and the heavy structure lab and Dartec were modeled virtually to allow the students to complete the experiment within the virtual environment. The comparison of the application and the real-world lab is shown in Figure 4.

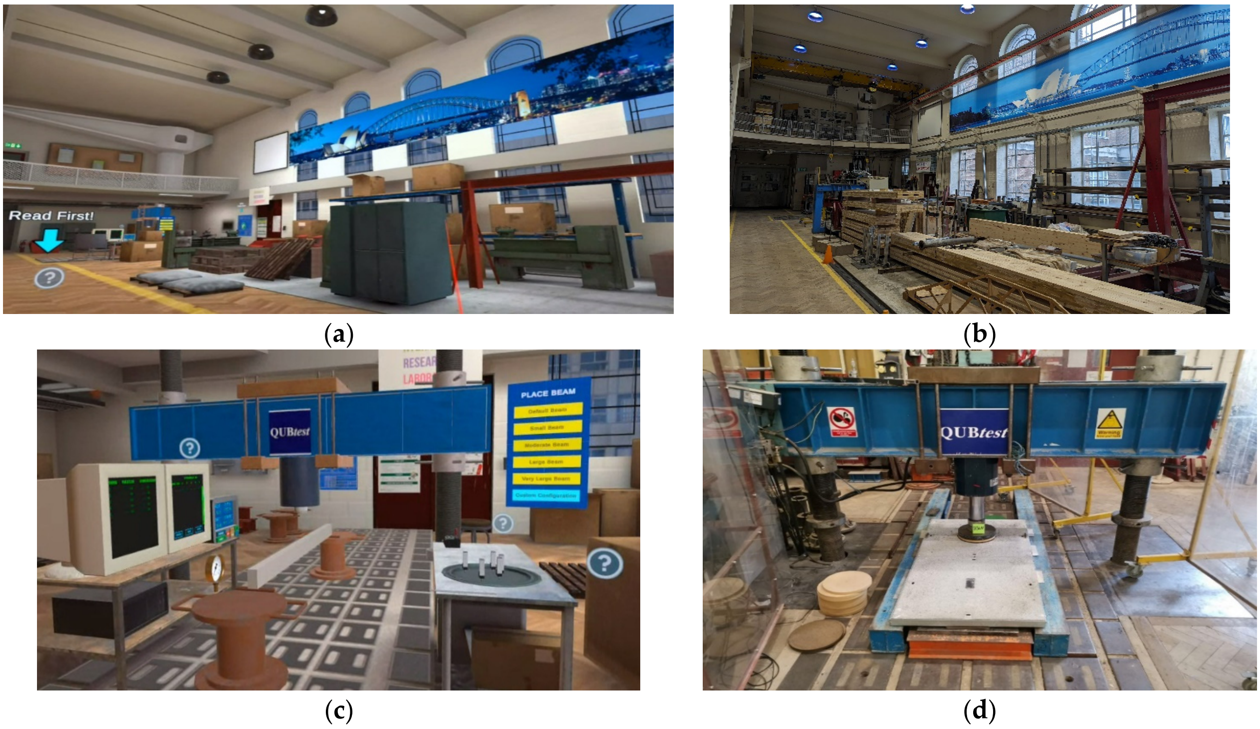


Figure 4. Comparison of a VR lab and a real-world lab (**a**) VR structures lab; (**b**) QUB structures lab; (**c**) VR Dartec; (**d**) QUB Dartec.

3.3. Questionnaire

To measure the efficacy of the application, the authors completed a review of the current literature on user response feedback from VR experiments to identify relevant questions about the user experience. This was combined with a series of questions linked to the learning outcomes of the practical to develop a feedback questionnaire. After the application has been tested by the user, it is important to obtain an idea of the user's feedback based on their interactions throughout the experience. The feedback will be variable, as it will be the individual's perception, which proves to be difficult to measure. This questionnaire was completed by the individual students after the VR experience.

The questionnaire comprised 23 questions, 17 of which were answered using a 5-point Likert scale from strongly agree to strongly disagree; the other 6 questions were answered in text or multiple-choice form. Questions 11–14 consisted of technical questions about the laboratory, which the students answered in text and were added to check if the student understood the laboratory exercise. The students were asked to indicate in which year groups they were currently registered and, in the final question, if they had completed the in-person experiment previously. The complete set of questions contained in the questionnaire can be seen in Table 2.

Table 2. Question sets used in the questionnaire.

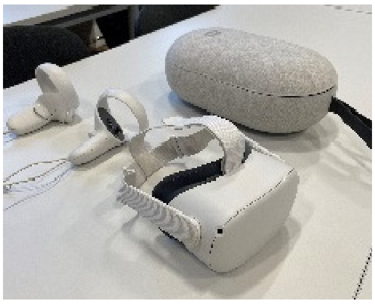
Question No.	Question
1	It is clear what the laboratory is aiming to achieve
2	It is clear how the experiment was set up
3	The experiment was set up in the same way if done in the physical laboratory
4	I could ask for help if I needed it
5	I had the chance to solve problems on my own
6	I was unsure about what I needed to do
7	I understand the results obtained
8	I could apply the knowledge leant in this VR lab to concrete beams in real life

Table 2. *Cont.*

Question No.	Question
9	I have a better understanding of concrete beams
10	I feel more confident about using equations related to concrete beam design
11	What failure mode was present?
12	How does increasing the cross section of steel in the beam affect it?
13	If the area of steel was significantly increased, how would the failure mode change?
14	Concrete in the beam has very low resistance to tension or compression?
15	The VR lab in general was easy to follow
16	The VR lab helped to visualise theory I had been learning about
17	I found the VR controls easy to get used to
18	I would rather watch the experiment in real life from a distance and not participate in a VR simulation
19	I know more about the Dartec actuator which I am normally, not able to use
20	I enjoyed the VR experience in general
21	I would like to do some laboratories in VR like this more often
22	What Civil Engineering year are you in?
23	Have you completed the physical beam testing lab; this experience recreates?

3.4. Collection of Data

Data were collected through random sampling of undergraduate civil engineering students (years 1–4) who volunteered to complete the workshop and questionnaire. A total of three Meta Quest 2 headsets were used throughout the workshop, with the process taking between 30 and 45 min. Figure 5a,b show an example of a head-mounted display used and the area where the workshop was completed. The workshop was run over the course of 13 days between the end of January and the start of March 2023 and allowed 50 students to complete the workshop.



(**a**)

(**b**)

Figure 5. VR workshop arrangement (**a**) Example of HMD used (**b**) area for VR experience to be carried out.

The workshop began with a brief induction about the application, the process, and the questionnaire. followed by headset fitting, and then the students completed the in-application tutorial, where they learned the movements and controls for the application. This section finished with the students putting on virtual personal protection equipment (PPE) before proceeding to the virtual heavy structures lab. Within the virtual heavy structure's lab, students had the opportunity to explore their surroundings and then were instructed by the application to configure different beams based on geometry and reinforcement. The application then instructed students to place virtual sensors to measure displacement on the beams and select a loading rate. The student then triggers the Dartec to apply the load, and they can adjust the loading rate throughout until the failure load is achieved. During testing, the student is reminded to observe the beam response under the applied load, making a note of crack propagation (which was modeled based on the position of the neutral axis determined from the calculations contained in the spreadsheet) and displacement, which load the beams to failure while observing the deterioration load and displacement. Following this, the students then removed their headsets and completed the questionnaire, which was preloaded on nearby computers. This is shown in Figure 5 above.

3.5. Ethical Approval

Ethics approval was considered at the beginning of the project to facilitate the collection of data from undergraduate students. Approval was granted on 1 December 2022, with the faculty REC reference code: EPS 22_399. An ethics amendment form was also completed as changes to the questionnaire were added at a later stage, and this amendment was granted approval on 23 January 2023 with the faculty REC reference code: EPS 22_399—Amendment 1.

4. Results

The questionnaire was completed by 50 students. The breakdown of the year group was as follows: Year 1–12 students, Year 2–16 students, Year 3–19 students, and Year 4+–3 students. The results from the questionnaire were imported into Microsoft Excel to begin data analysis. The results show the average value for questions 1–10 and 15–21. The remaining questions are answered using a text response and will be later analyzed.

4.1. Results of the Questionnaire

Figure 6 shows the average Likert score for each question. The questions were designed so that a higher score correlates to a more positive answer. As seen in Figure 6, all questions were answered very positively by the students. Some of the key questions are broken down and discussed.

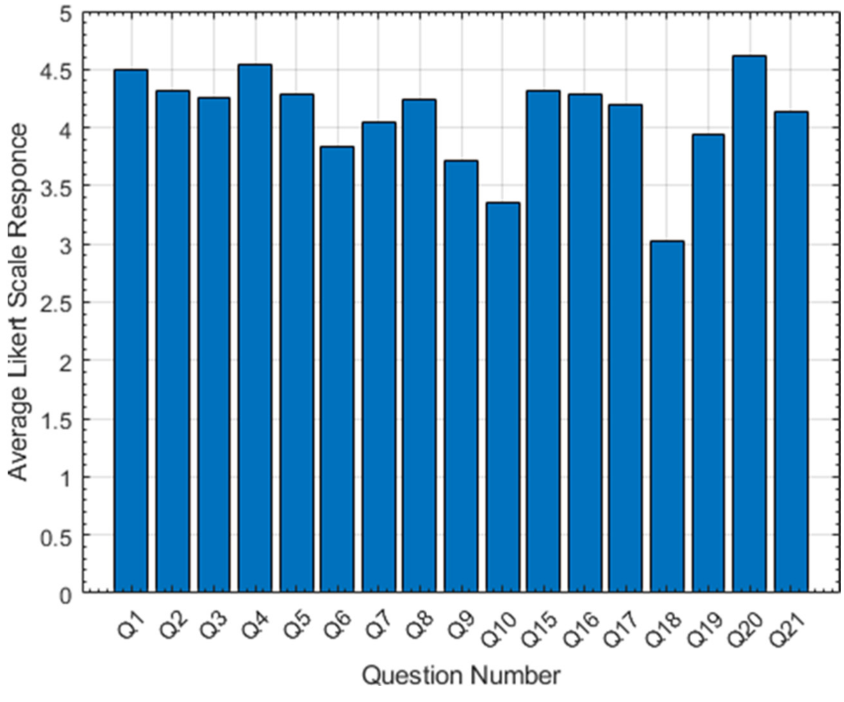


Figure 6. Average Likert score for each question in the questionnaire.

Figure 7 shows the breakdown of results for question 8: 'I could apply the knowledge learnt in this VR lab to concrete beams in real life' where 94% of students agreed to any extent with the question of which 38% of students strongly agreed. One of the main objectives of this 1st year lab is to give the students a foundation in beam beaning theory. The response to this question suggests that the students feel that the knowledge they gained in the VR experience could be transferred to other similar applications. This will hopefully be seen in the subsequent structure modules.

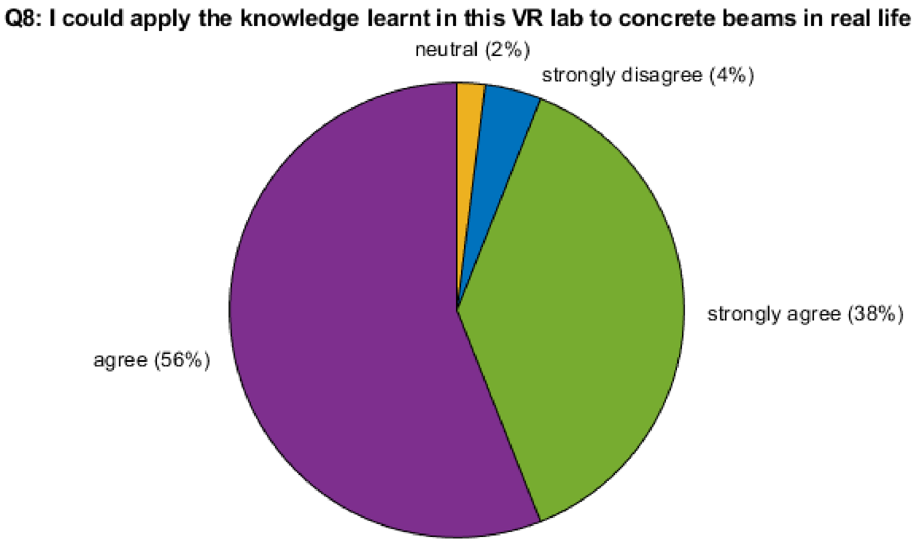


Figure 7. Breakdown of student responses to Question 8.

Figure 8 presents the results of question 10: 'I feel more confident about using equations related to concrete beam design'. It is understandable that more students responded neutrally here compared to other questions, as the beam equations were not explicitly stated in the VR experience. For future iterations of the VR lab, the incorporation of these equations may be delayed.

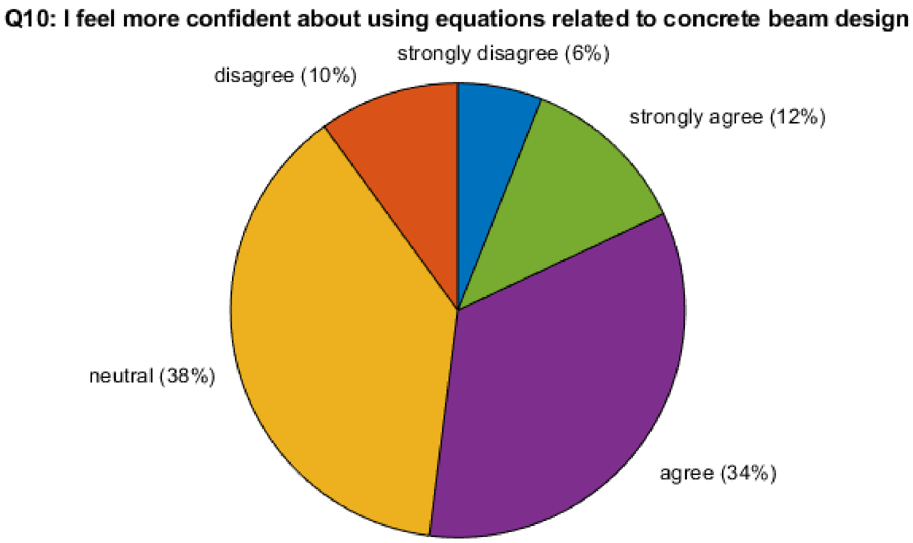


Figure 8. Breakdown of student responses to Question 10.

For question 16: 'The VR lab helped to visualize theory I had been learning' in which 94% of students agreed or strongly agreed. This positive outcome indicates that the VR experience can aid theoretical learning by allowing users to visualize the testing procedure without the use of a physical laboratory.

Figure 9 shows the breakdown of question 18: 'I would rather watch the experiment in real life from a distance and not participate in a VR simulation'. Responses were more mixed, with 32% agreeing to any extent, 32% disagreeing to any extent, and 36% staying neutral. While subjective interpretation may have been an issue in this question, the mixed responses show that the students may not have an inherent preference for a VR simulation over a physical experience. There may also be initial concerns about what is lost by not being physically present during the experiment. An important factor in this question is whether the student has completed the physical lab, as they could make direct comparisons.

Out of the students who answered the questionnaire, only three had previously completed the physical lab. All three of these students responded 'agree' to this question.

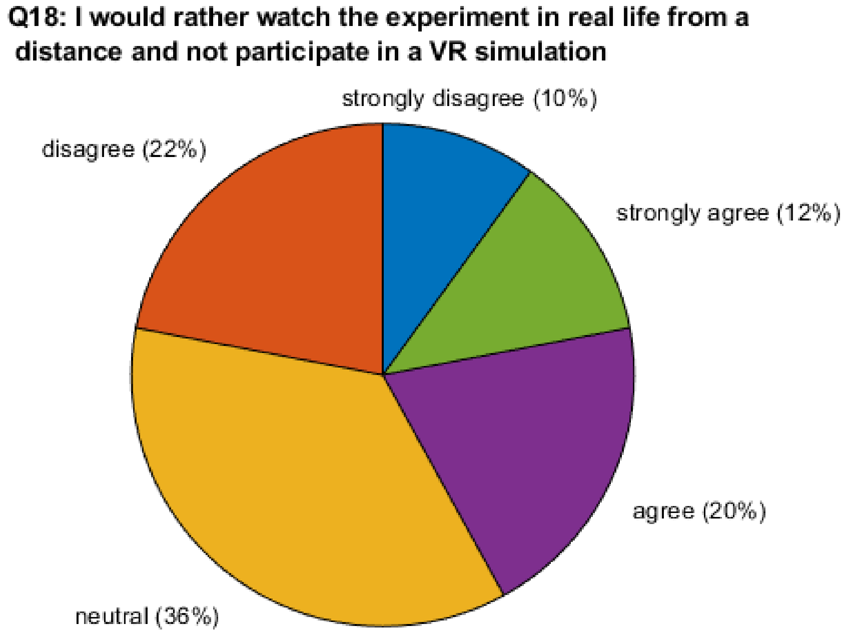


Figure 9. Breakdown of student responses to Question 18.

Finally, Figure 10 presents the results of question 20: 'I enjoyed the VR experience', where 68% strongly agreed to enjoying the experience and 30% agreed to enjoying it. This result is important as the link between a positive view of learning and students being receptive to the material and, in general, higher levels of academic performance has been shown in studies such as [29]. With 98% of students agreeing or strongly agreeing, the authors have confidence in the overall response to the VR experience, which provides encouraging evidence to develop other teaching experiences.

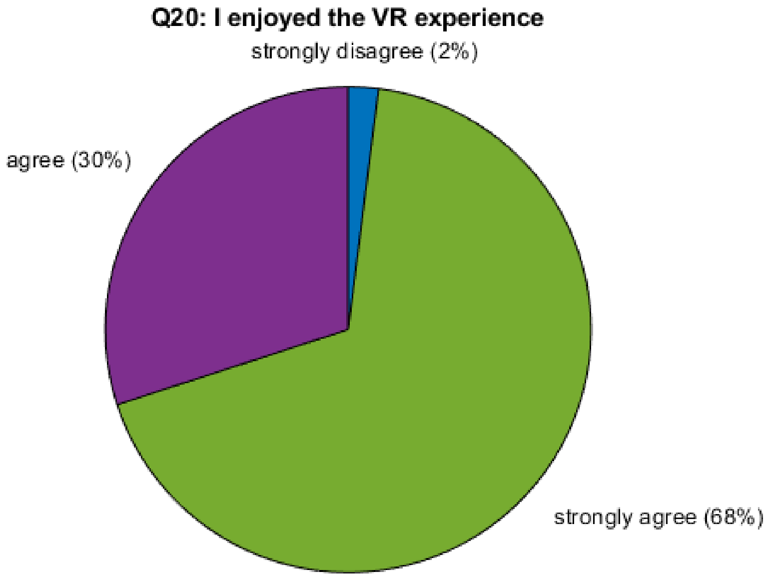


Figure 10. Breakdown of student responses to Question 20.

Questions 11–14 were the text-based answers; these questions were marked manually, and Table 3 illustrates some of the accepted answers. These questions assessed the users' understanding of this study.

Table 3. Accepted answers to technical questions.

Q11	Q12	Q13	Q14
'Explosive' 'Tensile failure'	'The beam will be stronger' 'Higher tensile resistance'	'Less explosive' 'Less sudden'	'Tension'

Q11: (What failure mode was present?)—66% of students input the correct answer.

Q12: (How does increasing the cross-section of steel in the beam affect it?)—92% of students input the correct answer.

Q13: (If the area of steel was significantly increased, how would the failure mode change?)—20% of students input the correct answer. Upon reflection, this question was too vague and is reflected in the responses of the students. It was therefore decided that Q13 is not a suitable measure of the users' understanding.

Q14: (Concrete in the beam has very low resistance to tension or compression?)—86% of students input the correct answer.

Figure 11 visualizes the results from the technical questions broken down by year group. Questions 11 and 14 follow the trend of the percentage correct increasing as the student's year increases, which is to be expected as the students have more experience. Question 12 did not follow this expected trend; however, most students correctly answered it, with 46 out of the 50 students giving a correct response. The average percentage was high. Within the year 1 group of 12 students, only one incorrect answer was submitted. Within the year 2 group, each of the 16 students answered correctly. Within the year 3 group of 19 students, only 2 incorrect answers were submitted, and finally, within the year 4+ group of only 3 students, 1 incorrect answer was submitted. Therefore, the overall percentage of correct answers was 92%, and the graph is only skewed by the relatively low number of year 4+ students. This is clearly evident when comparing the year 1 group with the year 4+ group; both groups only had 1 incorrect answer; however, with the lower number of year 4+ responses, this significantly brings down the average and results in a divergence from the expected trend as mentioned.

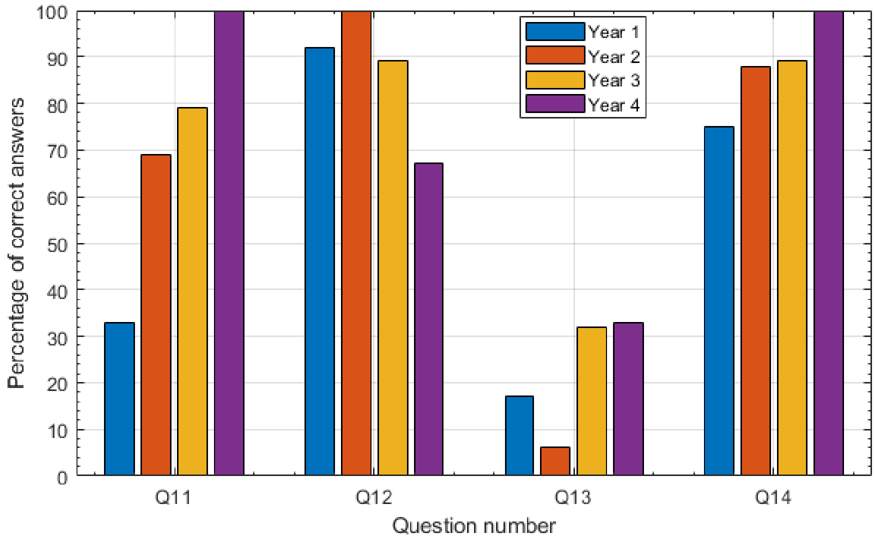


Figure 11. Representation of average correct answers provided for each question by each year group.

Overall, between the technical and opinion-based answers provided by the user, this study was perceived as a positive experience and so would be a useful addition or substitute (if needed) to the users' studies.

4.2. Comparison of Results with the Recorded Lab during 2022–2021 and the In-Person Lab during 2022–2023

In addition to the questionnaire, another measure of the VR workshop effectiveness was investigated by comparing the overall class average with both the in-person physical laboratory experiment carried out during the academic year 2022–2023 and the video-recorded laboratory utilized during the pandemic in the academic year 2020–2021.

For a useful comparison, only the technical questions from the questionnaire were used to determine the class average for the VR workshop, with question 13 removed due to the vague nature of the question and the mixed student response as previously discussed. These class average results are shown in Figure 12. It is clearly evident that the marks were higher for the in-person laboratory, but interestingly, the VR workshop has outperformed the video-recorded laboratory, which clearly shows that the VR workshop has been more successful at engaging the students and enhancing their understanding of the laboratory experiment.

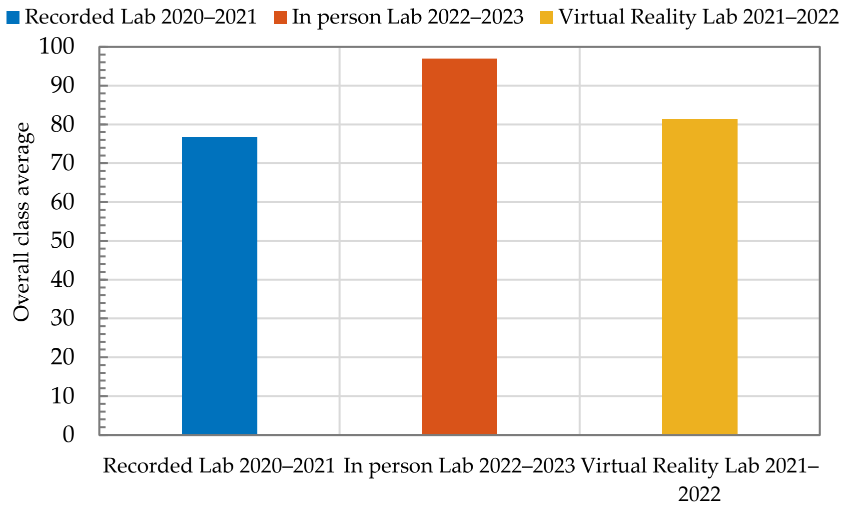


Figure 12. Overall class average compared across the different years and different methods of delivery.

5. Conclusions

The aim of this research was to determine if VR can be successfully implemented as a practical exercise replacement while allowing students to develop their skills without physically completing a practical exercise as well as supporting students within laboratory-based exercises. During this research, the learning tool was designed to replicate the reaction of a concrete beam during point loading. During the exercise, the user was able to see the failure of the beam as a result of the applied load, just as it would fail in reality. Following the exercise, the users completed a questionnaire to evaluate their perceptions of their experience with the program and to evaluate their understanding through a series of technical questions. Overall, the questionnaire showed positive interaction with the program, and based on the technical questions, it proved to provide the students with enough knowledge to enforce a clear understanding of the experiment. In addition, when comparing the results with the video-recorded lab, the VR workshop has proven to be more beneficial to the students' understanding and engagement with the exercise compared with the video-recorded lab. Furthermore, there was only a minor difference in results when comparing the VR workshop with the physical in-person lab, which proves that VR can successfully be implemented as an alternative to traditional laboratory teaching.

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