Virtual Masonry Shear Wall Experiments: Enhancing Understanding of Nonlinear Behavior through Virtual Simulation

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Abstract: In nonlinear structural analysis, civil engineering students are required to understand the structural performance of shear walls under various loading conditions, particularly lateral forces such as those caused by wind or seismic activity. Physical shear wall testing helps engineers to understand damage and failure, which is essential for safe structural design. However, building a shear wall for testing demands time and resources, as the tests are inherently destructive. Additionally, students often lack access to the specialized equipment needed for shear tests, and safety precautions prevent them from conducting experiments unsupervised. As a result, they typically rely on passive learning methods such as lectures or textbooks. In this project, Virtual Reality (VR) Masonry Lab, we created an open-source multiplayer application that allows students to construct and test masonry shear walls in a virtual environment. In the application, students can collaboratively design masonry walls by specifying dimensions and brick size. They then apply horizontal loads to simulate a pushover test, gradually increasing force until the wall fails. The algorithm calculates the wall's deformation, damage, and failure based on the input parameters, and the results are visually rendered in real-time, which allows students to observe how design parameters can influence the structure. This VR-based approach promotes trial-and-error experimentation, allowing students to explore how design parameters affect wall behavior under stress. The digital environment eliminates manual construction and material waste, enabling safe, repeatable testing without time constraints. In a pilot classroom session, students reported that the tool improved their understanding of nonlinear structural behavior and appreciated the ability to virtually repeat the experiment from anywhere and anytime.

Keywords: Virtual Reality, Masonry Shear Walls, Structural Education, Nonlinear Behavior

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1 Introduction

The structural performance of masonry shear walls under lateral loading is a critical topic in earthquake-resistant design [1]. Understanding how these walls respond to seismic forces, including deformation and failure mechanisms, is essential for designing safe and resilient buildings [2]. However, traditional experimental methods used to investigate this behavior are time-consuming, resource-intensive, and often inaccessible to students due to safety and equipment constraints [3].

In civil engineering education, especially in nonlinear structural analysis, students often rely on theoretical knowledge and passive learning tools such as textbooks and lectures [4]. While these approaches convey foundational concepts, they are often insufficient to illustrate complex nonlinear behavior of masonry structures under real loading conditions [5]. This gap limits students' understanding of how design parameters affect structural performance [5].

To address this issue, an open-source Virtual Reality (VR) application called the VR Masonry Lab has been developed. In this system, structural calculations are performed by the EasyFEM finite element framework, while Unity handles the immersive visualization of deformation, crack propagation, and collapse based on user-defined parameters. This allows students to interactively construct walls, apply horizontal loads, and observe the resulting nonlinear behavior in a simulated pushover test.

The VR Masonry Lab builds on the MyScore project, which promotes avatar-based teaching in higher education. MyScore offers an open-source framework that enables interaction via avatars in immersive 3D scenarios [6]. Its modular design, support for real-time feedback and collaborative learning via multiplayer made it an ideal foundation for building the VR Masonry Lab.

Integrating VR into structural education bridges the gap between theory and practice. It enables hands-on exploration in a risk-free digital environment, supporting deeper insight into nonlinear behavior and failure modes. The simulation uses validated numerical models from the EasyFEM to ensure accuracy and relevance. This paper presents the methodology, simulation framework, and educational application of the VR Masonry Lab.

2 Related Work

The use of computer technologies in structural engineering education and research has grown significantly [7], [8], [9]. Among them, VR has shown promise in helping students understand complex structural behavior by interacting with digital environments that simulate real-world responses [7], [9]. Several studies have explored VR in civil engineering education. One study presented a VR beam analysis module where users applied loads and received real-time visual feedback on deformation and stress distribution [9]. Results showed improved learning outcomes compared to traditional lecture [9]. VR labs have been explored as alternatives to physical labs in engineering education [10]. While students valued the accessibility and clarity of VR, challenges remained with hands-on skill transfer [10]. VR has been used in structural design to support parametric modeling of concrete shear walls, enabling visualization of complex geometries and reinforcement details often difficult to handle with conventional tools [8]. Other work has applied VR to assess damage in heritage structures and visualize seismic degradation, aiding both preservation and structural education [7]. Augmented reality

(AR) has also addressed practical issues in masonry construction, such as embed coordination and material planning which help in reducing errors and waste before execution [11].

While prior efforts focus on visualization and design, few platforms allow users to build, load, and observe structural failure interactively. The VR Masonry Lab fills this gap by combining finite element-based simulation with immersive interaction. This application allows students to conduct virtual pushover tests and explore nonlinear behavior under varying design parameters in a safe, repeatable, and collaborative environment.

3 Methodology

The VR Masonry Lab was developed as an open-source application aimed at simulating the nonlinear behavior of masonry shear walls under horizontal loading. The methodology integrates structural simulation, virtual interaction, and educational usability within a single framework. This section outlines the simulation model, virtual interface design, and the workflow for user interaction and analysis.

3.1 Physical Masonry Lab

Masonry shear walls are structural elements commonly used in buildings to resist horizontal loads caused by wind or seismic events [12]. They are typically constructed from bricks or concrete blocks arranged in a regular pattern and bonded together with mortar [12]. These walls provide lateral stiffness and stability of a structure through in-plane shear resistance [2]. In unreinforced masonry, the behavior is highly nonlinear and often brittle, with failure modes that include diagonal tension cracking, corner crushing, and sliding along mortar joints [2]. When properly designed, masonry shear walls can efficiently dissipate energy and limit lateral displacements during seismic activity [12].

In a laboratory setting, masonry shear walls are tested to evaluate their mechanical behavior under horizontal loading conditions, particularly to simulate seismic effects [13]. Figure 1 illustrates a typical experimental setup used for such testing.

The wall specimen is first constructed according to standard geometries and material specifications [2], then mounted onto a strong laboratory floor or reaction frame with rigid boundary conditions at the base. A hydraulic actuator applies lateral forces at the top of the wall and is connected to a steel reaction frame that resists the applied load. In many cases, vertical confinement is also introduced using steel beams to simulate axial forces from upper building stories [12]. Additional instrumentation, such as displacement sensors, load cells, and strain gauges, is installed to monitor the wall's response during testing.

The lateral load is incrementally increased in what is referred to as a pushover test [12] which allows researchers to observe progressive cracking, deformation, and ultimately structural failure. This controlled environment enables the detailed study of load-displacement behavior, crack development, and energy dissipation characteristics, all of which are critical for understanding the seismic performance of masonry walls. To illustrate such failure, figure 2 shows a masonry shear wall after undergoing a lateral loading. Typical shear failure patterns such as diagonal and stepped cracks are visible and have been marked in the image for clarity. This crack pattern is characteristic of in-plane seismic loading, where the wall gradually deforms until failure.

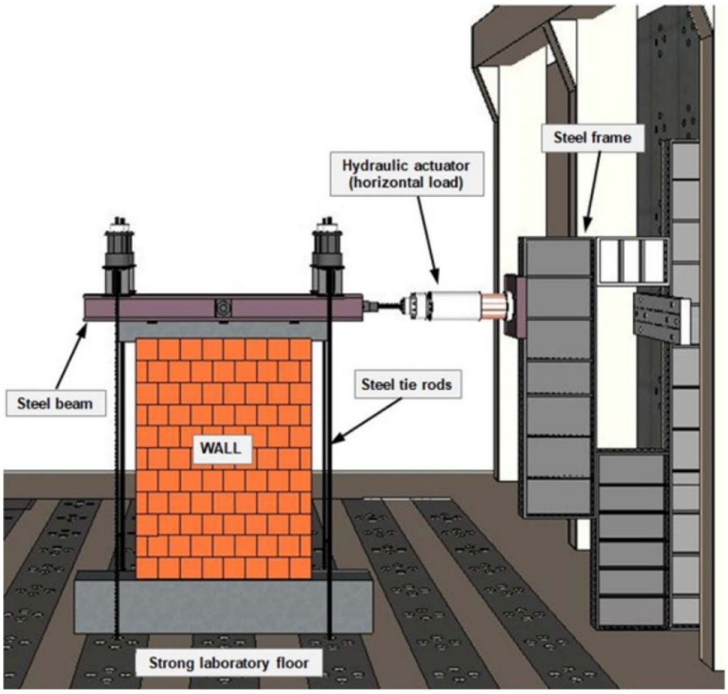

Figure 1: Wall test schematic [12]

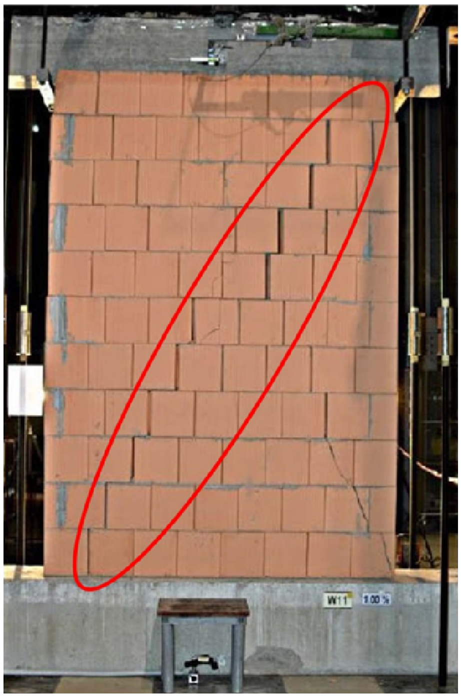

Figure 2: Failed masonry wall [12]

While these tests offer valuable insights, they demand significant equipment, materials, time, and safety precautions. Their destructive nature also limits their suitability for educational settings, where repeated, hands-on experimentation is often preferred [9].

3.2 Virtual Masonry Lab Overview

To address the limitations of physical testing and improve accessibility, the VR Masonry Lab was designed to replicate masonry shear wall experiments within an interactive virtual environment. The application was built using the Unity game engine and is based on the open-source MyScore framework, which supports multi-user, avatar-based learning in immersive 3D spaces. The structural response of the masonry wall was computed using EasyFEM, a finite element library for structural analysis developed by the Chair of Structural Analysis and Dynamics (LBB). Simulation data from EasyFEM is passed to Unity, which visualizes the wall's deformation, cracking, and collapse behavior in real time. This setup ensures accurate structural calculations with an intuitive user interface. The application runs on VR headsets and Windows. Figure 3 shows the virtual lab setup, where two avatars (representing users) are present in the scene. The environment features a masonry shear wall testing rig at the center, along with a control panel for user input and a real-time force-displacement graph. A 360° video of a physical laboratory is embedded in the virtual space to visually connect real and digital environments.

The experiment begins with users specifying brick and wall properties via the control panel, including brick dimensions (height, width, mass) and wall geometry (height and length) as shown in figures 4 and 5. Selected values are summarized on the left panel for review before starting the simulation.

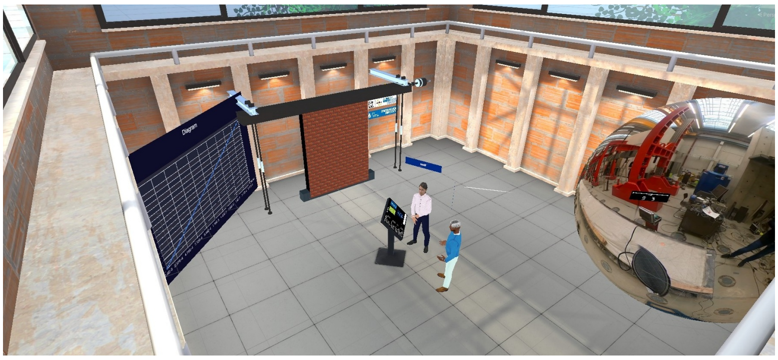

Figure 3: Virtual Masonry laboratory

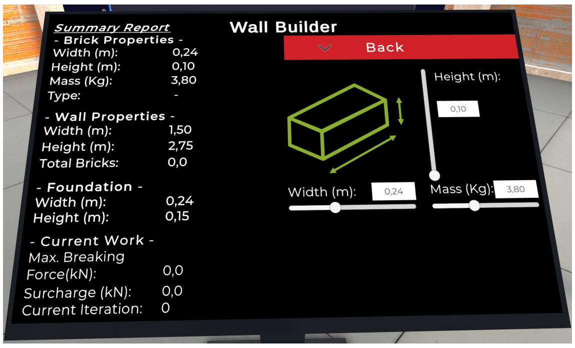

Figure 4: Brick configuration

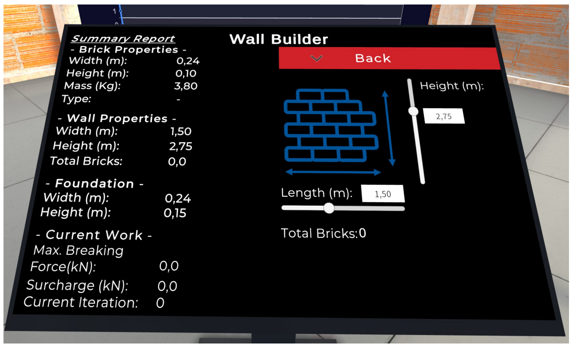

Figure 5: Wall configuration

Currently, the system supports unreinforced clay bricks bonded with mortar. The bricks have a density of approximately 1800 kg/m^3 and an elastic modulus of 3000–5000 MPa. The mortar provides a tensile bond strength between 0.1–0.4 MPa.

Users can then initiate the simulation by selecting the "Build" function as shown in figure 6. The system automatically assembles the wall brick by brick based on the defined specifications. The wall construction animation serves only as a visual feature and does not affect structural calculations.

Figure 6: Constructed virtual wall

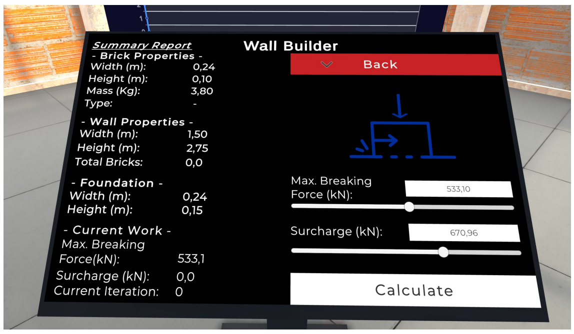

Figure 7: Acting force menu configuration

Afterwards, users can define horizontal loading parameters such as breaking force (kN) and surcharge (kN) via the "Acting Work" menu (figure 7). When the "calculate" function is selected, the configured force will be applied to the top of the wall to perform a virtual pushover test. The EasyFEM engine applies the defined loading to compute internal stresses, displacements, and failure progression.

Next, the simulation engine visualizes wall response through displacement, cracking (figure 8), and eventually, full collapse when the applied force exceeds the wall's load-bearing capacity (figure 9). The simulation stops once the wall exceeds its load-bearing capacity, with broken bricks scattered to indicate failure.

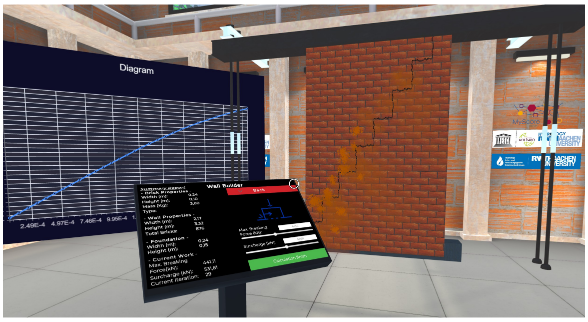

Figure 8: Wall cracking

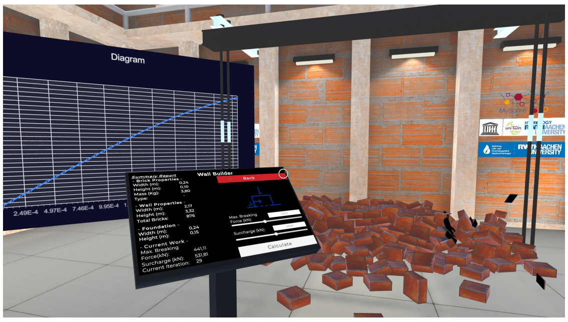

Figure 9: Collapsed wall

A live force-displacement diagram adjacent to the wall illustrates the structural response during loading. Initially, the curve rises steadily, indicating elastic deformation. As loading increases, cracks appear, the curve peaks, and failure is both numerically and visually represented.

To encourage exploration and experimentation, users can repeat the process with different wall configurations. This interactive workflow enables students to test hypotheses and observe how small changes in design or material properties can lead to significant differences in structural behavior. Through its immersive design, the VR Masonry Lab deepens understanding of nonlinear behavior and structural design decisions.

3.3 Student Test

To evaluate the educational potential of the VR Masonry Lab, the application was demonstrated during a lecture session of the "Nonlinear Structural Analysis" course at RWTH Aachen University, with approximately 50 civil engineering students in attendance. The goal was to show how the simulation supports understanding of shear wall behavior and design sensitivity. Although only a few students interacted directly with the system, the entire class followed the simulation via live screen casting from the VR headset to a monitor, allowing everyone to observe the setup, loading process, and wall response. The pilot was conducted in a single-user mode due to classroom logistics. Regardless, the VR Masonry Lab supports true multiplayer functionality, enabling users to collaborate remotely in the same virtual environment.

Students were briefly introduced to VR controls before experimenting with different wall and brick configurations then applied lateral loads and observed force-displacement responses and cracking. Feedback collected at the end of the session was highly positive. Students found the application more intuitive than traditional diagrams and appreciated the ability to repeat experiments without time constraints. Many also valued the flexibility of using the tool on desktop devices and its support for remote collaboration.

Future evaluations will include a structured learning outcome study, comparing groups using traditional methods with those using the VR application. Planned methods include pre- and post-testing, usability surveys, and focus group interviews. These steps aim to assess not only user experience but also the tool's impact on conceptual understanding. Furthermore, students suggested several improvements to the application, including graphical improvement and the ability to define additional parameters such as vertical loads.

Overall, the pilot session demonstrated the advantages of VR simulation in engineering education. By allowing students to build and test structures in a 3D environment, the VR Masonry Lab bridges the gap between theory and practice, supports intuitive understanding of nonlinear behavior, and offers an exploratory learning experience.

4 Conclusions and Future Work

This paper addressed a key challenge in structural education: the limited accessibility of hands-on shear wall testing due to safety, resource, and equipment constraints. As shown in prior research, existing VR tools in engineering education often focus on design visualization but lack real-time simulation or interactive experimentation. The VR Masonry Lab bridges this gap by providing a virtual environment where students can configure, load, and observe the behavior and failure of masonry shear walls.

By simulating a pushover test in an immersive environment, the software enables students to explore nonlinear structural behavior in a repeatable, risk-free format. Unlike purely visual VR tools, the VR Masonry Lab includes real-time structural feedback, enabling a deeper exploration of failure behavior. The pilot classroom test confirmed that students found the tool engaging and educational, offering a more intuitive understanding than traditional methods. The ability to collaborate remotely and experiment with various configurations added further value.

Future work will focus on expanding the simulation capabilities, including the addition of vertical and dynamic loading, additional material types, and refined failure modeling. In parallel, a structured user study will be conducted to evaluate learning outcomes and usability. The study will involve controlled comparison between students using the VR Masonry Lab and those following conventional teaching methods. Assessment will include pre- and post-tests, user satisfaction surveys, and observation of in-VR behavior to measure engagement and conceptual understanding. These results will guide further improvements and validate the educational value of the tool.

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6 Conflict of Interest

The authors declare that this research was carried out without any commercial or financial interests that could be perceived as a potential conflict of interest.

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