Integrated Hazard Vulnerability Assessment and Mitigation Framework with Mixed Reality for Transportation Infrastructures

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A Research Report from the Pacific Southwest Region University Transportation Center

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16. Abstract

The USDOT's top concerns are deterioration of transportation infrastructure and how it affects overall structural performance over time. Transportation infrastructures become more vulnerable to various natural hazards and calamities owing to the structural degradation caused by physical or chemical factors. Accurate assessment of structural performance under extreme events and potential performance degradation due to any damages reported from routine infrastructure inspection is required to increase the resilience of such deteriorating transportation systems. Additionally, information about how the detected defects would impact overall infrastructure performance should be easily accessible for decision-makers and stakeholders to maintain and operate the transportation system properly. To readily check the location of significant damages, their effects on infrastructure hazard vulnerability and the projected economic and life losses from an expected hazard, an enhanced and interactive hazard risk management framework for transportation infrastructures is urgently needed. The objective of this project is to provide an integrated hazard vulnerability assessment and mitigation framework for transportation infrastructures with mixed reality (MR) and progressive vulnerability evaluation. Engineers will be able to monitor damage and degradation propagation over time, reduce hazard risk, predict the remaining lifetime of transportation infrastructure, and optimize maintenance time and cost with the help of the suggested framework. The analysis results from complex structural performance assessment will be more easily accessible and more understandable for decision-makers with the aid of MR technology.

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Contents

About the Pacific Southwest Region University Transportation Center

The Pacific Southwest Region University Transportation Center (UTC) is the Region 9 University Transportation Center funded under the US Department of Transportation's University Transportation Centers Program. Established in 2016, the Pacific Southwest Region UTC (PSR) is led by the University of Southern California and includes seven partners: Long Beach State University; University of California, Davis; University of California, Irvine; University of California, Los Angeles; University of Hawaii; Northern Arizona University; Pima Community College.

The Pacific Southwest Region UTC conducts an integrated, multidisciplinary program of research, education and technology transfer aimed at *improving the mobility of people and goods throughout the region*. Our program is organized around four themes: 1) technology to address transportation problems and improve mobility; 2) improving mobility for vulnerable populations; 3) Improving resilience and protecting the environment, and 4) managing mobility in high-growth areas.

US Department of Transportation (USDOT) Disclaimer

Disclosure

Principal Investigator, Co-Principal Investigator, and two PhD students conducted this research titled, "Integrated Hazard Vulnerability Assessment and Mitigation Framework with Mixed Reality for Transportation Infrastructures " at the Department of Civil and Environmental Engineering, College of Engineering in the University of Hawaii at Manoa. The research took place from August 2021 to August 2022 and was funded by a grant from the Pacific Southwest Region University Transportation Center in the amount of $26,649.48. The research was conducted as part of the Pacific Southwest Region University Transportation Center research program.

Abstract

The USDOT's top concerns are deterioration of transportation infrastructure and how it affects overall structural performance over time. Transportation infrastructures become more vulnerable to various natural hazards and calamities owing to the structural degradation caused by physical or chemical factors. Accurate assessment of structural performance under extreme events and potential performance degradation due to any damages reported from routine infrastructure inspection is required to increase the resilience of such deteriorating transportation systems. Additionally, information about how the detected defects would impact overall infrastructure performance should be easily accessible for decision-makers and stakeholders to maintain and operate the transportation system properly. To readily check the location of significant damages, their effects on infrastructure hazard vulnerability and the projected economic and life losses from an expected hazard, an enhanced and interactive hazard risk management framework for transportation infrastructures is urgently needed. The objective of this project is to provide an integrated hazard vulnerability assessment and mitigation framework for transportation infrastructures with mixed reality (MR) and progressive vulnerability evaluation. Engineers will be able to monitor damage and degradation propagation over time, reduce hazard risk, predict the remaining lifetime of transportation infrastructure, and optimize maintenance time and cost with the help of the suggested framework. The analysis results from complex structural performance assessment will be more easily accessible and more understandable for decision-makers with the aid of MR technology.

Integrated Hazard Vulnerability Assessment and Mitigation Framework with Mixed Reality for Transportation Infrastructures

Executive Summary

The goal of this research is to develop and test an immersive and interactive mixed reality (MR) framework for hazard risk assessment and mitigation of transportation systems such as bridges. The MR technique is exercised with the HoloLens to visualize the target structure, to show analyzed fragility curves against a given hazard, and to further provide an interactive environment to explore how a certain damage would affect the overall structural performance. To achieve this goal, this study aims to (1) develop a virtual prototype model of a target bridge structure; (2) program different interactive actions with the elements in the MR model; (3) prepare progressive fragility curves with provided damage data and corresponding model updating; (4) test the efficiency of the MR model in decision making, hazard identification, and vulnerability assessment; and (5) enhance interactive experience in exploring and visualizing the complicated fragility analysis results. This study provides an interactive MR model where the vulnerability or fragility curve can be updated based on actual damage data reported from routine safety inspection in a real-time manner and the new fragility curve can reflect the aging effect on the structure and its tolerance to the expected hazard over time.

Unlink other studies which utilized non-immersive or semi-immersive MR, this research is based on fully immersive and interactive MR technology. A user can fully interact with the physical world with the aid of MR head-mounted displays, which is the latest technology in MR. With MR goggles and hand-held devices, the user can experience 3D environment of a model that virtually simulates a target site with the real one in the background. Control over interactive hand within the MR model is promptly reflected in the virtual environment along with corresponding reactions and responses to the model. This research promotes the use the MR technology in the fragility inspection and health monitoring of transportation system.

Introduction

The USDOT's primary objectives are to maintain stability of transportation infrastructures and increase their resilience. Every year, millions of dollars in maintenance costs are incurred due to the performance degradation caused by physical or chemical damages of transportation infrastructures (such as roads and bridges). The damaged pieces of civil infrastructure become more susceptible to natural disasters including earthquakes, tsunamis, floods, storms, and rising sea levels. The damage data from routine structural safety inspections do not immediately indicate how significant or crucial the observed damage would be to the entire system's ability to withstand natural disasters. For the best transportation management and risk reduction strategy, it is more important to know what kind of structural performance degradation the damage will cause. A simulation-based technique called Monte Carlo Simulation (MCS) is widely used to determine hazard vulnerability or fragility curves, which show how well a given structure would perform under an assumed hazard event. However, the MCS approach is often unsuitable due to convergence and computational cost issues [1]. As a result, a novel vulnerability assessment technique is required to handle computationally expensive structural models regularly updated with damage data and to estimate structural failure likelihood rapidly. Towards this end, a platform for integrated hazard risk assessment is required to conduct serious of vulnerability simulations, identify critical damages that have the potential to adversely affect the structure's overall performance, and estimate the resilience reduction caused by such critical damages. However, it would still be challenging for non-engineers to understand final results from advanced vulnerability analysis. Decision-makers will benefit immensely from using mixed reality techniques in presenting the assessment results

This project aims to provide an integrated hazard vulnerability assessment and mitigation system with mixed reality for transportation infrastructures to address the abovementioned problems. A practical approach to evaluate hazard risk vulnerability is introduced, and a progressive fragility evaluation technique is exercised with updated structural models based on damage data. Further, a decision-support system for transportation infrastructure that utilizes virtual reality is delivered. Cutting-edge methodologies such as integrated structural reliability analysis, model updating, and mixed reality are developed and applied. In transportation decision-making, it is crucial to optimize limited resources through a strategic management plan. This study will offer the best maintenance and risk reduction solutions based on the updated infrastructure health condition and progressive vulnerability evaluation.

Literature Review

Virtual reality has exploded in popularity in recent years even though construction sector uses this technology sparingly. Numerous academics have favored using cutting-edge technologies in construction safety training, such as immersive mixed reality (MR) [2]. However, a thorough literature study revealed that there is a shortage of convincing data supporting using the fully immersive MR technology to improve safety training in the sector; there is a wealth of literature on the tests of traditional training methods but not on immersive computer-aided technology [3]. As a result, there is a desire to continue testing this technology and offer insightful comments on how to use it in construction health monitoring, particularly in identifying fragility hazards rather than training for specific equipment.

Numerous sectors have made substantial use of MR technology. As an example, in the aviation sector, MR is used to teach safety procedures such as how to put on an airplane life preserver [4], to create realistic flying simulations [5], to train for aerial firefighting [6], and more. The provision of descriptive and useful information in the fields of medicine and therapy training [7], human health diagnostics, treatment, and care [8], as well as medical education, surgical simulation, and psychotherapy [9], has proven to have significant promise in the field of medicine. MR has been utilized in the automobile sector for manufacturing, testing, training, and design [10].

Although MR is mostly used for gaming, it is also increasingly used in education and industry [11]. Few studies in engineering have been utilize MR capabilities. For instance, MR models were employed to give architecture students enhanced visualization, allowing architects to spot design flaws [12]. It demonstrated that a thorough understanding of construction projects enables improved scheduling of construction sequences, site layouts, safety concerns, and design enhancements for constructability. On the other hand, MR-based field tours were created to let students study petroleum engineering access and see real-world petroleum facilities while still in traditional classroom settings [13]. Accordingly, it showed that the MR technology helped students overcome various obstacles, including harsh weather and limited accessibility, and enjoy a wide range of field regions at an economy cost. Similarly, a cutting-edge teaching strategy was implemented in the business school by incorporating MR into an experimental real estate course design [14]. The questionnaires' findings showed that technology helped pupils develop and improve their sense of place and worth. Moreover, the new strategy improved the effectiveness of trade process analysis and property research communication.

Many research projects have attempted to explore and test the effectiveness and efficacy of MR technology in performing health monitoring in the construction sector. According to a poll of 228 construction workers in Australia with various professional and trade backgrounds [2], typical training programs had little to no impact on workers' views. A more noticeable effect of this kind was cognitive and behavioral, where employees were left with a somewhat improved understanding of safety threats and safety habits. The results demonstrated that conventional programs could not emotionally engage the audience, leaving the unfavorable work attitudes unchanged after training sessions. This means that they do not directly address the affective component of safety attitudes. Due to the importance of safety and safety attitudes in construction sites, using immersive training sessions was advised as an interactive training method for construction workers [2].

The effectiveness of MR technology in boosting construction workers' capacity to recognize and evaluate construction safety issues was examined [15]. Safety training included concrete pouring, working from heights, operating tower cranes, and other general site safety operations. The findings demonstrated that MR improved trainees' focus and attentiveness during the training session. Significant advancements were also made in the cast-in-situ concrete construction and cladding activities. The research setup, however, did not offer a fully immersive environment; it was based on a power-wall system that used rear projectors, head tracking systems, XBOX controllers, and cameras mounted on top of screens rather than the fully immersive experience that is currently offered on the market. A framework that integrates safety with the education of building processes and materials has been established in response to the industry's recognition of the ineffectiveness of the existing pedagogical approaches and instruments for safety education [16]. The framework consists of three consecutive modules: a lecture on safety and hazards, a game for identifying hazards on a smartphone-based virtual building site, and a module for student evaluation. The findings show that MR technology can portray the intrinsically dynamic nature of university-level building projects, boosting students' educational experience and acquired skills and knowledge.

How MR technologies could be used to improve safety evaluations in connection to roof-fall hazards that are present during the development of underground mines and tunnels were examined [2]. The findings showed that MR training significantly improved participants' decision-making skills, enabling them to make safety-related judgments quickly to maintain a safe working environment throughout tunneling operations. These corrective actions were mostly based on the participants' improved risk identification and assessment skills. MR technology could train heavy equipment operators on construction sites and regular site-safety training for on-site activities. To improve user engagement, real-time visualization and analysis, and information retention capabilities, an MR-based safety training simulator was developed to instruct overhead crane operators [17]. The study involved 19 new and seasoned operators, and the findings showed that MR-based training was superior to desktop-based instruction. The ability of the operators to recognize hazards and dangerous factors as well as the proper initiative mechanisms improved as a result of the learning results. An MR prototype that helps trainees learn the necessary skills by exposing them to the principles of off-site production systems was developed [18] in response to the trend toward prefabrication and off-site production. The prototype not only exposes students to subpar work and unanticipated health and safety hazards but also enables them to experience the effects of their decisions and rate them according to the amount of time, money, and resources they used. The findings demonstrated the value of virtual reality as a supplement to theoretical research; these findings were supported by a wide range of stakeholders, including developers, manufacturers, and academics.

Regarding academic institutions, a framework to enhance construction students' safety instruction with MR technologies was developed [7]. The main goal was to give children the opportunity to engage in social interaction, dialogic learning, and role-playing while receiving health and safety instruction. Their methodology consisted of three key modules: Active Safety Game-based Learning (ASGL), Hazard Inspection and Safety Cognition (HISC), and Cooperative Distributed Safety Learning (CDSL). These modules focused on improving risk assessment and inspection abilities and comprehending the underlying sources of problems. Their findings showed that the technology could improve construction health and safety training.

Research Development

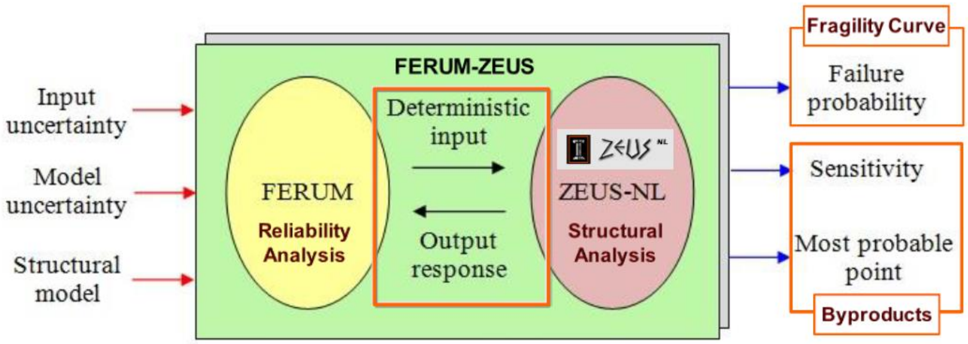
The research utilizes and integrates concepts from structure fragility analysis, simulation modeling, and interactive programming into one advanced monitoring framework. First, structural performance of a target 4-span concrete bridge was assessed with selected earthquake events. A detailed numerical model was adopted to represent realistic seismic behavior and its hazard resilience was evaluated under the computationally efficient fragility analysis framework. The hazard vulnerability information was presented by the fragility curve. Then, a 3D modeling of a prototype of a 4-span concrete bridge was modeled on Unity® software; this platform can be used to create an exact replica of a megastructure project, including all the required levels of details. Different interactive actions with the 3D model were programmed to suit the Microsoft® HoloLens' requirements, such as hovering over objects, clicking, presenting the fragility graphs, and making different sounds. The interactive model was installed on the first generation of the HoloLens and tested with a small sample of individuals. The model simulates a structure prototype, animates the different parts, allows the user to interact with them and presents the updated fragility curves with changes over time. One of the main contributions of this work is to save time and effort to present accurate health status and fragility of the structure over time. The interactive model can be used on-site, where the HoloLens may be used to get the computational data instantaneously. Future-wise, the developed framework will be used with more complicated detailed structures to validate its effectiveness in reflecting the desired results. A detailed description is provided in the following sections.

Integrated Hazard Vulnerability Assessment Framework

An integrated computing platform for hazard vulnerability assessment is established which can provide an effective way to perform a serious of hazard risk assessment. To handle the computational challenge in fragility analysis, this framework necessitates the integration of structural analysis and reliability analysis, as shown in Figure 1. For the reliability analysis and structural analysis, the computational tools FERUM (Finite Element Reliability Using MATLAB) and ZEUS-NL were used, respectively. FERUM [19] by the University of California, Berkeley is a reliability analysis software program providing different reliability analysis techniques, such as FORM and SORM; it has been used to address a range of structural reliability problems. ZEUS-

NL is an advanced earthquake simulation analysis program developed by the Mid-America Earthquake (MAE) Center [20,21]. It adopts a fiber-based element modeling approach so that it can represent how material inelasticity spreads inside the member's cross-section as well as along its length. Since source codes of both programs are available to public, any modification can be easily made required to create the integrated platform coupling FERUM and ZEUS-NL.

Figure 1. Integrated vulnerability analysis framework

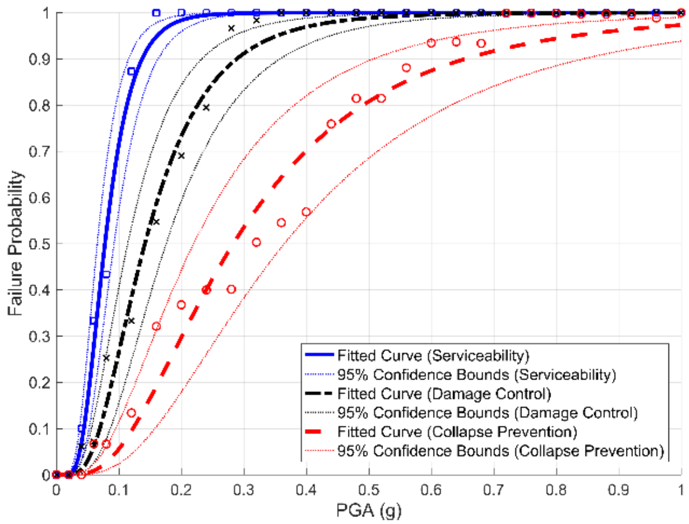


The suggested platform uses the linking interface known as FERUM-ZEUS established in MATAB [22] to enable automatic exchange of required data between two analysis programs. When assessing conditional failure probability, the first order reliability method (FORM) [23] is used to ensure accuracy and computational efficiency. A parallel computing algorithm that can further reduce simulation time is explored to support the adoption of realistic and advanced analytical models for transportation structures. Even with intricate 3D models, the fragility curve, which graphically depicts how well an infrastructure functions under a specific danger, can be rapidly generated using the established framework [24].

Progressive Vulnerability Analysis Method with Damage-based Model Updating

Progressive vulnerability analysis is conducted to account for the impact of gathered damage data or envisioned damage scenarios for transportation infrastructure. The most current numerical model is maintained using the damage data, and the updated model is examined under the integrated vulnerability analysis platform. By comparing fragility curves, it is possible to explore how various damage scenarios would affect the overall structural resilience of the selected bridge model. The functional form of each frailty curve is obtained for the general application after the fragility data have been fitted using the least square approximation, as shown in Figure 2. The results of such vulnerability analysis can be used to forecast the potential economic and human cost of damaged transportation facilities under the specified seismic hazard. Making decisions about which damage should be fixed first and what will be the best maintenance plan will be much easier with the help of this information.

Figure 2. Derived Seismic Fragility Curves



3D Graphical Modeling and Interactive Actions Programming

Developing the 3D modeling involves different prototype elements; this should be made in a Unity-friendly environment such as SketchUp or 3D viewer, as shown in figure 3. The elements should be modeled depending on the required level of details. The presented element in figure 3 is an interactive element in clicking, grabbing, highlighting and so on. If more details are needed, this element need to be broken down in more parts and each one will be modeled and collected inside Unity software.

Figure 3. 3D modeling of structural element

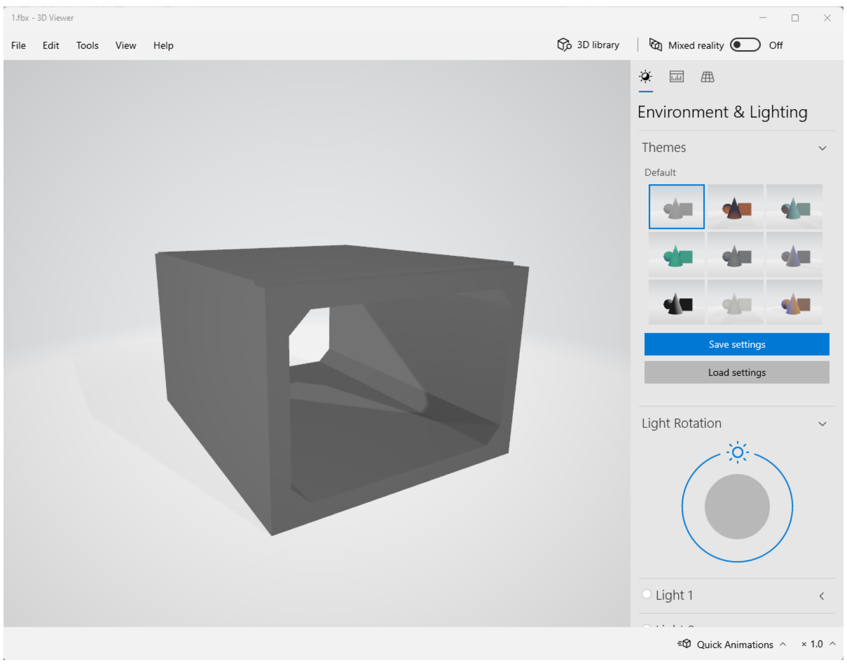


Figure 4 presents the prefab environment inside the Unity software, where elements' details, such as the element's size in the three directions, the position to grab the element and the rotation angle, can be modified. Also, the materials of the element can be changed for a more realistic presentation; for example, the concrete material can be used to show the realistic concrete structure. Rendering effects can also be added to the model elements for better presentation.

Figure 4. Element prefab details

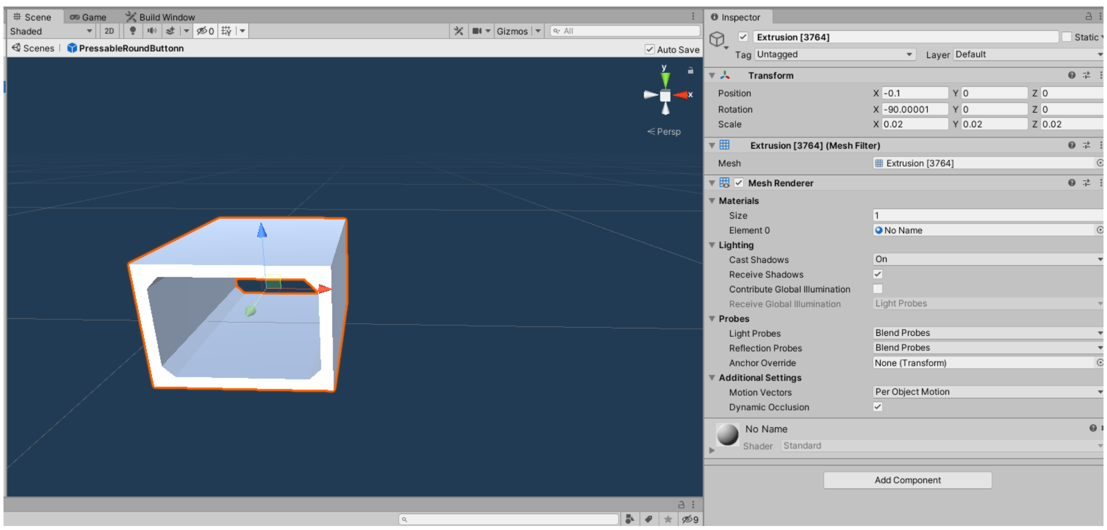


Figure 5 shows an example of the prototype's components. It shows elements needed to be modeled and programmed for interactive actions; buttons, texts, shapes, etc., are examples of these elements.

Figure 5. Element components of virtual model

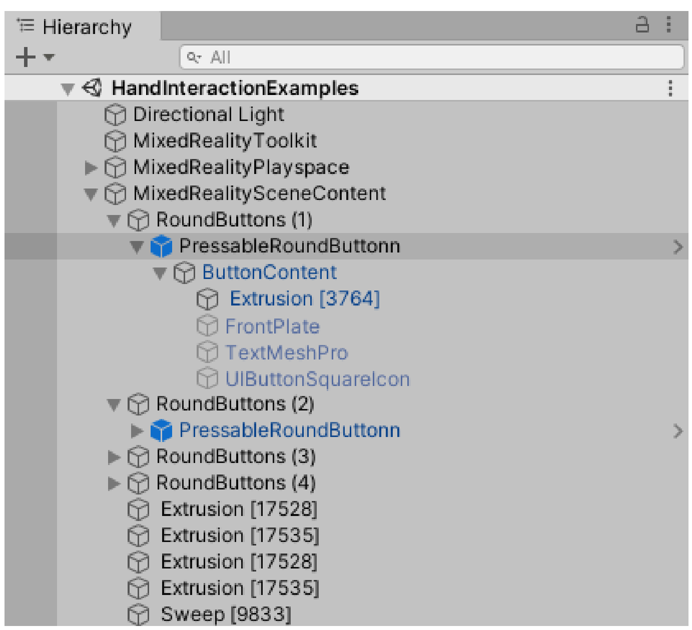
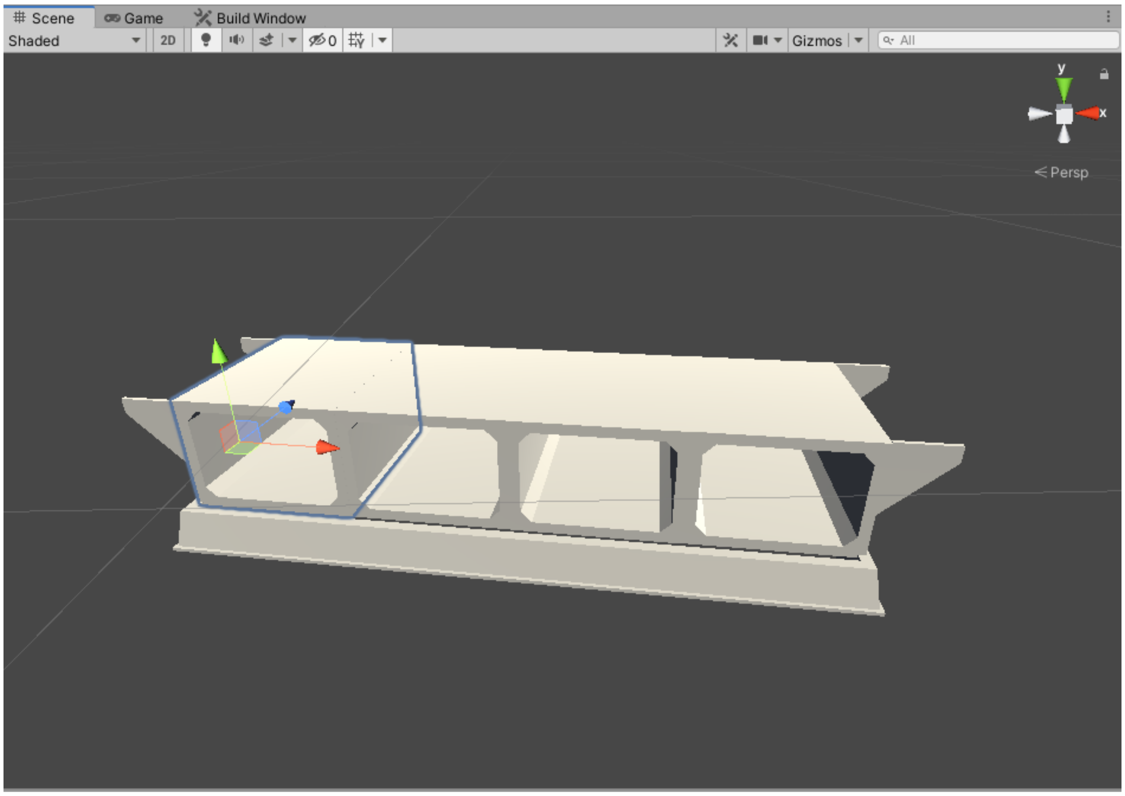


Figure 6 presents the complete prototype mixed reality (MR) model of the studied bridge that consists of 4 spans connected with a mesh foundation. The structural details are neglected in this stage as this prototype model is to present overall concept and the required results. Future implementation of this concept on a more detailed model will include all the sophisticated structure details.

Figure 6. Prototype MR bridge model



Interaction programming and coding are done in the inspector window as shown in figures 7-12. In figure 7, the size of the prototype inside the HoloLens can be changed depending on the rotation angle. The collider is an invisible cube surrounding each model element, defining the boundaries of the interaction; if the MR hand enters or touches this collider, it acts as a trigger to start the interactive and response actions. From the inspector window, the collider's material, size, and center can be modified. Also, the duration of the press, the response speed, release return and other properties can be modified. In figure 8, a sample of the interactive events is presented. Hovering and highlighting of the element are a sperate event. Also, the press, the sound, and the release are all different events. The connections between these events and responses in the MR prototype (appearance of fragility curves) are all written in C# scripts. Figures 9 and 10 show different properties and options inside the inspector windows; defining a global action for the MR model or an action connected with certain events can be determined. The user can choose if other actions will happen on press and release besides the main actions.

Figure 7. Interactive collider details

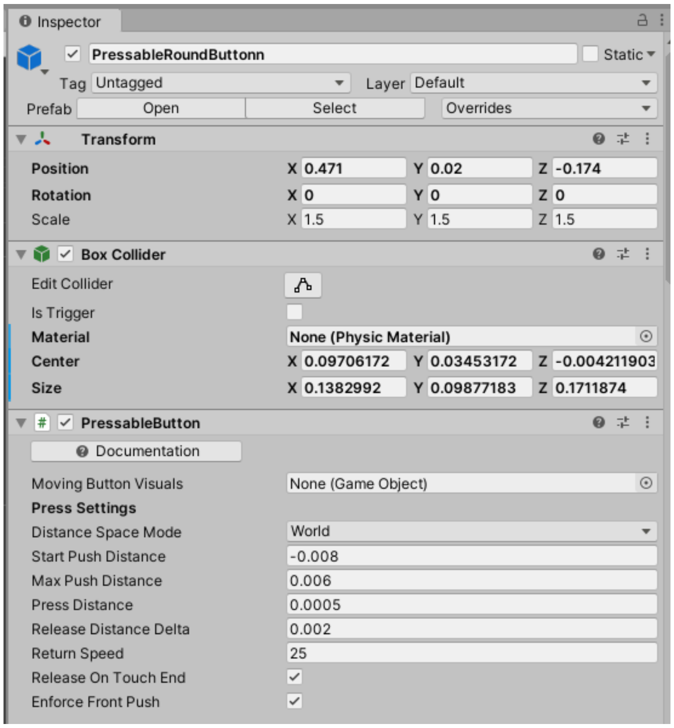


Figure 8. Consequent Events programming

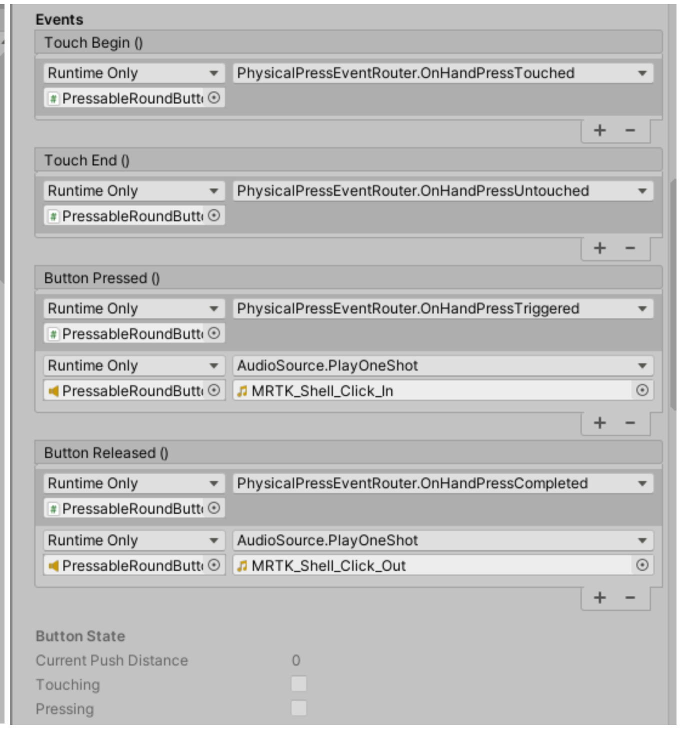


Figure 9. Interactive collider details

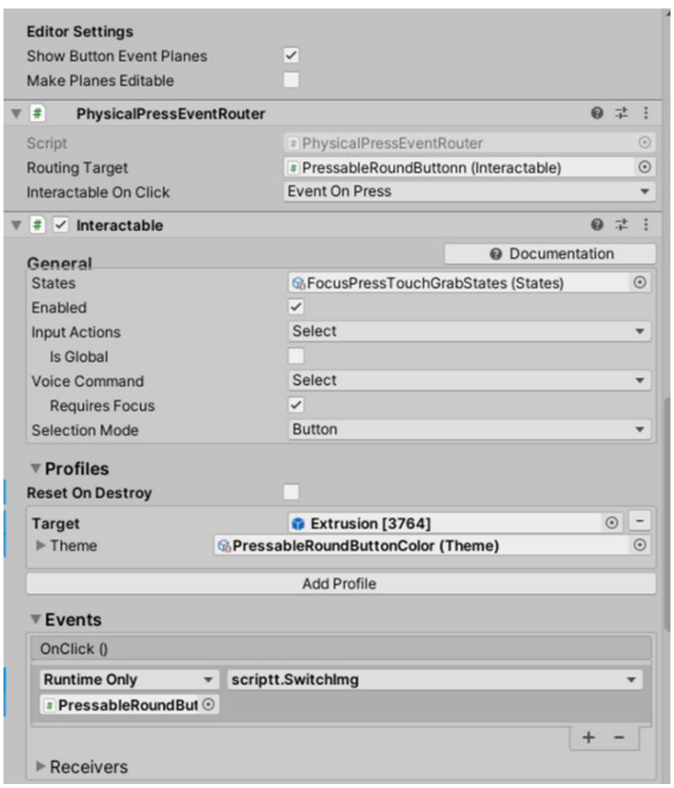
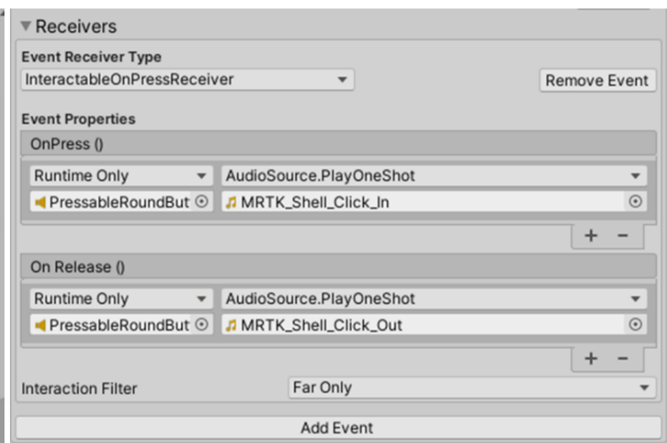


Figure 10. Consequent Events Programming



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The sounds associated with the model at different stages can also be modifed from the options presented in figure 11. For example, the user can choose the required audio clip, volume, duration and pitch with different presses, releases and idle periods. Figure 12 shows the near interaction touchable properties, such as the touchable collider, which define the main collider associated with each prototype element. The connection between the events and the responsive action (fragility curves appearance and disappearance) are coded using the C# scripting environment. Figure 13 shows the script used for switching the scenes between different figures. Figure 14 shows the script for loading the real-time fragility curves associated with each element and hidding them when the user presses them again.

Figure 11. Interactive Audio Setting

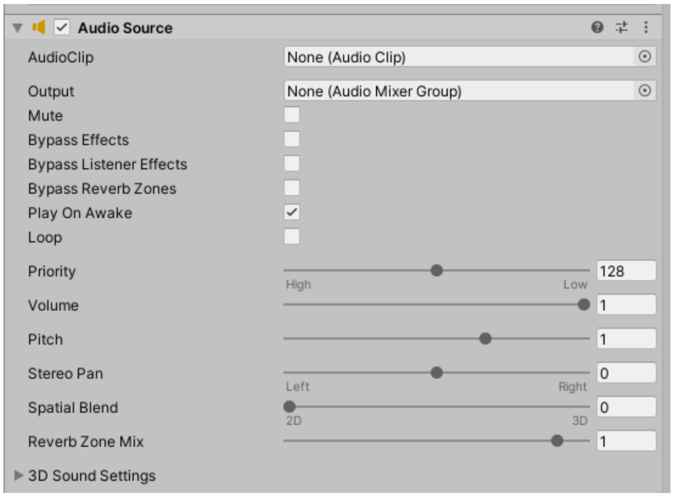


Figure 12. Elements Grabbing Center

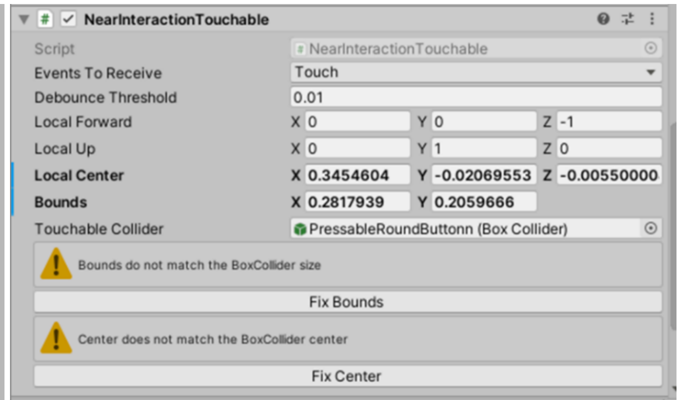


Figure 13. Sample Script for scene switching

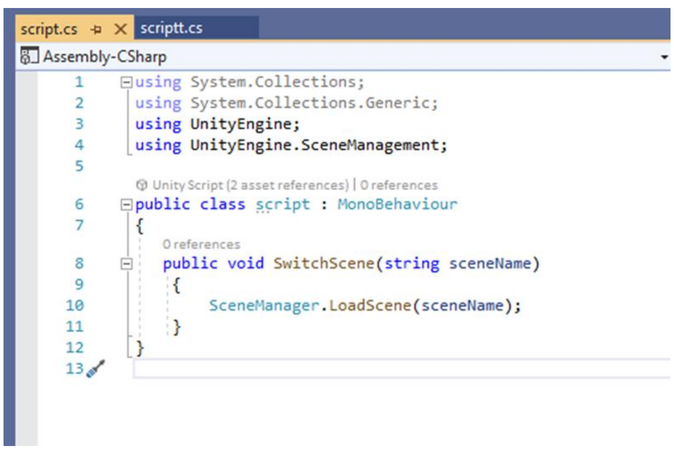
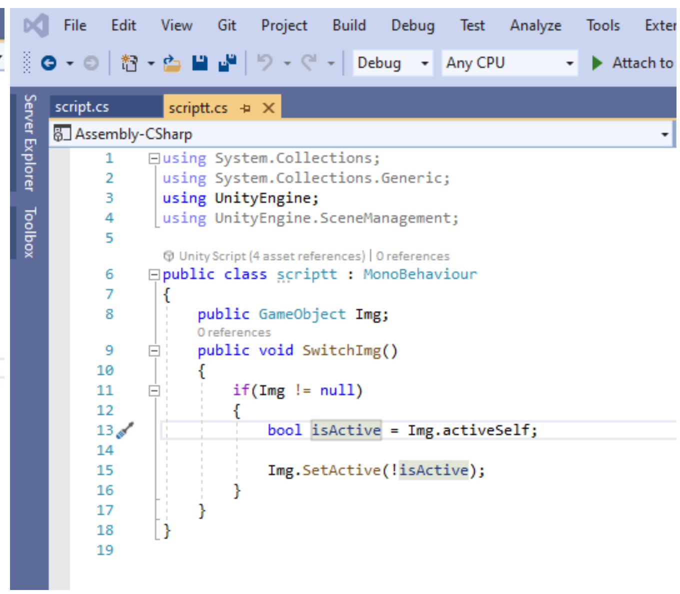


Figure 14. Sample script for image switching



Mixed Reality Model

The prototype shown in figure 15 is modeled on the Microsoft® HoloLens 1. The mixed reality toolkit® shown in figure 16 is used inside the unity software to build data.

Figure 15. Prototype Scene from HoloLens

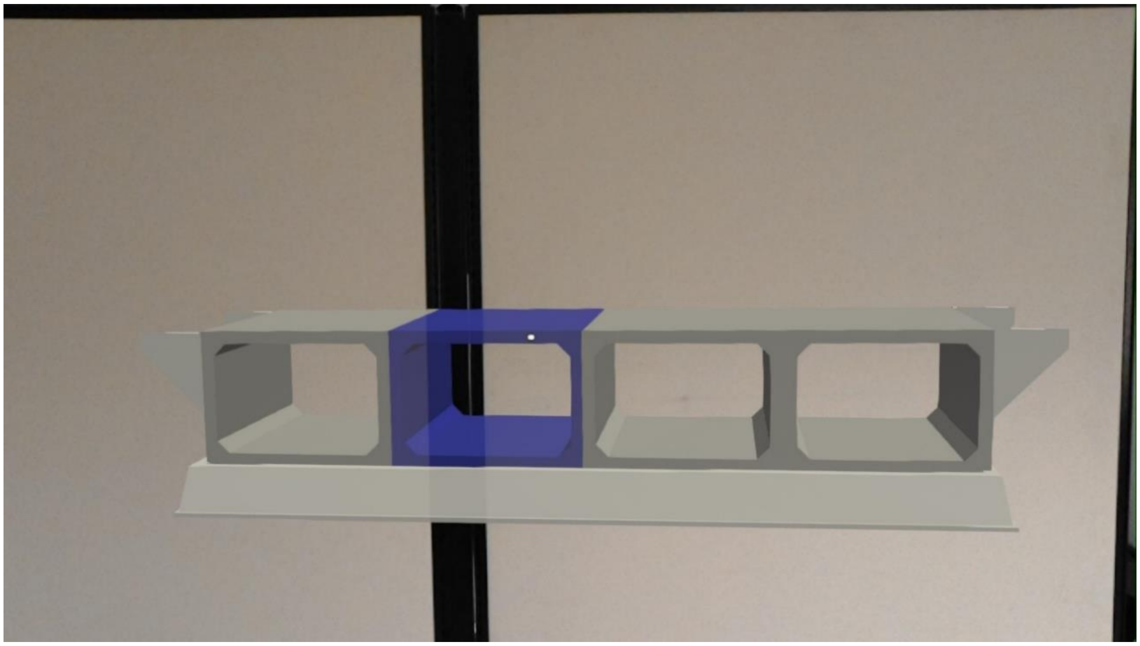
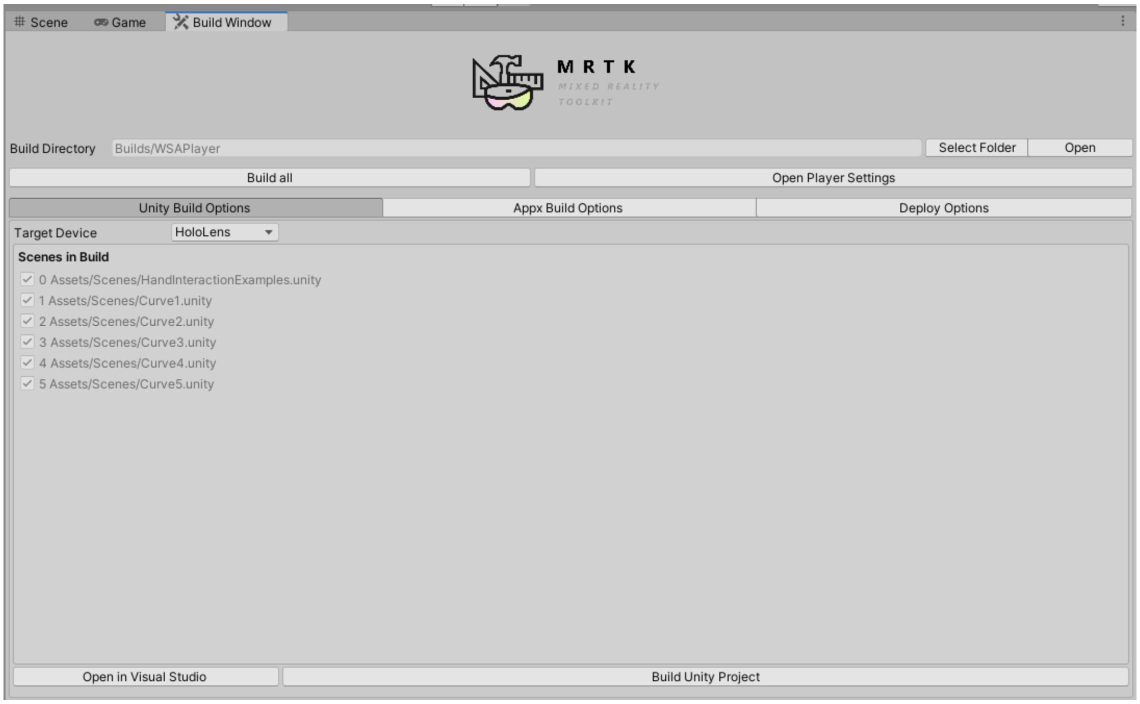


Figure 16. Mixed Reality Toolkit used to install prototype on the HoloLens



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Screenshots from the MR prototype model with the fragility curves are collected and presented in Figures 17-20. The user can hover and select any model element, click it for updated fragility curve to appear, click it again to hide the fragility curve, and hover to another element to check new fragility curve when the selected element is severally damaged. Note that the background and surroundings of the mixed reality model can be the real surrounding.

Figure 17. MR prototype screenshot -1

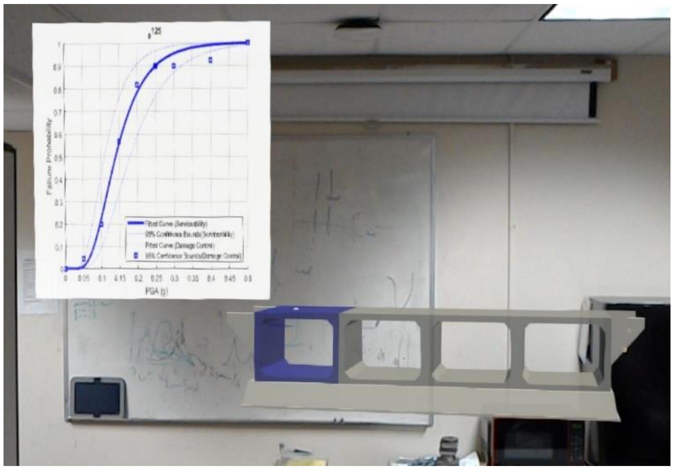


Figure 18. MR prototype screenshot -2

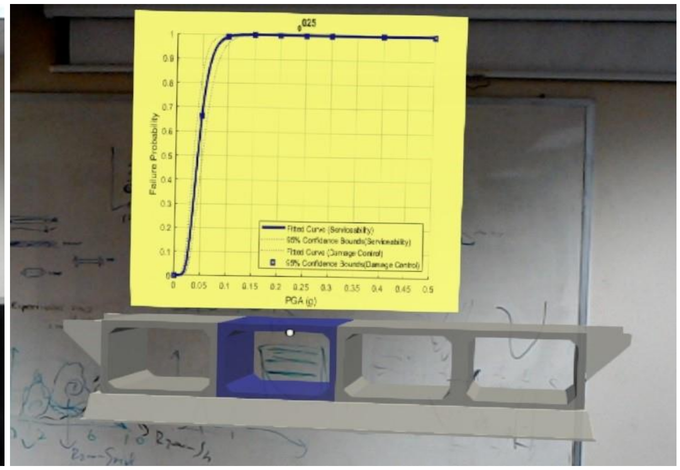


Figure 19. MR prototype screenshot -3

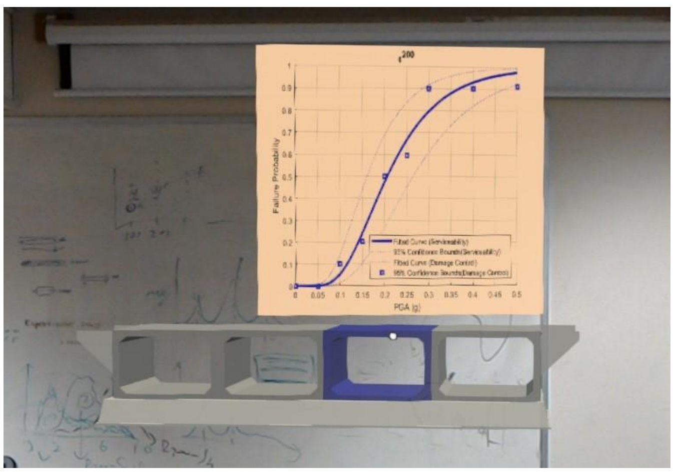
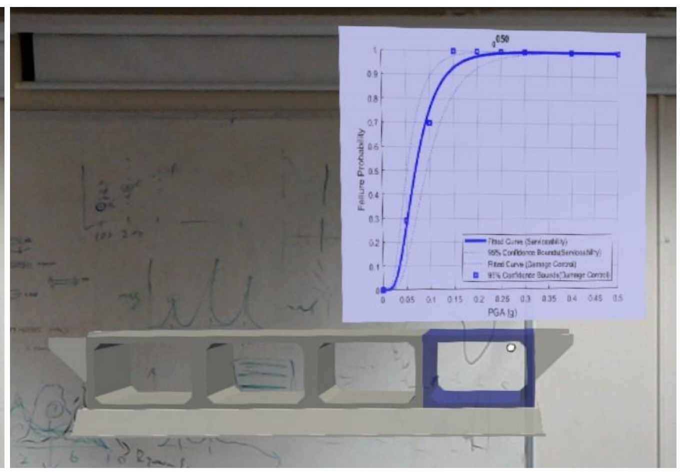


Figure 20. MR prototype screenshot -4



Results and Recommendations

The following are the primary findings from this project. A mixed reality-based hazard vulnerability assessment and mitigation system for transportation infrastructure was created, allowing users to explore any available date interactively with 3D visualization. Though the developed system how the damaged structural system will function against the selected natural hazard event is virtually presented; it would help city planners assess the transportation system's hazard exposure and create investment plans for infrastructure upkeep that would increase resilience. This research will benefit the engineers and practitioners working on the next generation of infrastructure management systems

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Data Management Plan

Data Format and Content

1) FE model and vulnerability analysis data (file format: dat, m, and jpg):
   A FE model is developed in ZEUS-NL software with a dat input file. Vulnerability analysis data is stored in a mat file. Fragility curves are saved in jpg files
2) Mixed reality model (file format: FBX):
   The virtual model is created and visualized in the Microsoft® HoloLens 1 in a FBX file.
3) Documentation (recording format: docx, pdf):
   Conference or journal (in the future) publications and one final report.

Data Access and Sharing

All participants in the project will publish the results of their work. Any publications including the final report are primary source of data sharing. The data will be available to the public except sensitive or confidential data. The PIs shared data through Google Drive. Anyone from the public domain will be able to register as a user of such a system to get access to selected project documentation for research and educational uses.

Reuse and Redistribution

All participants in the project published the results of their work. Any publications including the final report are primary source of data sharing. In addition, the data for structural responses and FEM models including ML code are available to the public except sensitive or confidential data. For sharing purpose, the PIs set up Google Drive as the link below.

https://drive.google.com/drive/folders/1fJN9WR52nxwGSj0iH9N0FM_eWeErVKx6?usp=sharing