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EDUCATION OF EXPERTS FOR DAMAGE ASSESSMENT OF BUILDINGS IMMEDIATELY AFTER AN EARTHQUAKE USING XR – PROJECT PROGRESS

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Abstract

Post-earthquake damage assessment is a critical process carried out by engineers and emergency responders to evaluate structural safety and guide decision-making in the aftermath of seismic events. Traditional training methods face limitations such as restricted access to real damaged structures, safety risks, and high logistical costs. This paper presents the progress of an ongoing project that leverages Extended Reality (XR) technologies to enhance the training of experts in post-earthquake damage assessment. Conducted in collaboration with the University of Zagreb's Faculty of Civil Engineering, the Croatian Centre for Earthquake Engineering (CCEE), and the LINKS Foundation, the project integrates immersive virtual reality (VR) simulations to provide realistic training environments. The development includes high-fidelity 3D models of earthquake-damaged structures, a virtual learning platform, and scenario-based training modules to improve knowledge retention, safety, and decision-making skills. The paper discusses the methodological approach, implementation phases, and preliminary results of the VR-based training pilot, emphasizing its potential to standardize and enhance post-earthquake assessment procedures.

Keywords: XR training, earthquake engineering, damage assessment, virtual reality, expert education.

1. Introduction

Figure 1. Damage to heritage buildings in Petrinja region

Post-earthquake damage assessment is a vital and systematic process conducted by first responders and engineers to evaluate the extent of destruction caused by seismic events on infrastructure and communities. This process is essential not only for ensuring immediate safety and coordination of rescue efforts but also for informing long-term recovery and rebuilding strategies. The assessments typically unfold in multiple phases, starting with rapid initial evaluations that identify visibly damaged structures, followed by more detailed analyses as conditions stabilize and more information becomes available. These activities play a critical role in mobilizing resources and securing federal assistance for affected areas, underscoring their significance in disaster management and recovery efforts.[1][2]. The involvement of diverse teams, including local emergency management agencies, structural engineers, and non-governmental organizations, is crucial for comprehensive damage assessments. First

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responders are typically the first to arrive on the scene, performing rapid inspections to determine the safety of buildings and prioritizing life-saving operations.[3] Engineers complement these efforts by conducting evaluations of structural integrity and advising on safety protocols. Effective communication and collaboration among these groups are essential for overcoming the challenges posed by chaotic post-disaster environments, such as difficulties in documentation and coordination of efforts across different agencies.[4][5]. Despite advancements in technology, including the use of drones and machine learning for real-time data analysis, damage assessment activities still face significant challenges. [6][7].

Traditional training methods for post-earthquake damage assessment have limitations, including restricted access to real damaged structures, safety risks, and logistical challenges. The integration of XR (Extended Reality) technologies offers an innovative approach to overcoming these constraints. By providing immersive and interactive simulations, XR enables experts to experience various earthquake scenarios in a safe, repeatable, and scalable manner.

This paper presents the progress of an ongoing project aimed at utilizing XR for training experts in rapid damage assessment. Conducted in collaboration with CCEE (University of Zagreb, Faculty of Civil Engineering, Croatian Centre for Earthquake Engineering) and the LINKS Foundation, the project involves developing XR-based training modules, creating 3D models of earthquake-damaged structures, and deploying a virtual learning platform to enhance the preparedness and effectiveness of engineers and emergency responders in post-earthquake scenarios.

1.1. Motivation

Engineers play a crucial role in post-disaster response activities, supporting first responders, assessing damage, and assisting in post-earthquake recovery. The immediate post-disaster response phase involves tasks such as rapid structural evaluations to ensure public safety, while the recovery phase includes developing regulatory frameworks to guide reconstruction. In the aftermath of the 2020 earthquakes in Croatia, engineers were deeply engaged in assessing damage to thousands of buildings, establishing vulnerability classifications, and contributing to governmental decision-making regarding financial aid and reconstruction strategies [8].

One of the major challenges encountered during the response to the 2020 Petrinja earthquake was the lack of systematic training for engineers involved in rapid damage assessments. Many engineers had limited prior experience in post-disaster environments, leading to inconsistencies in damage classification and decision-making. Additionally, the high-risk environment of collapsed and unstable structures posed significant safety concerns for assessment teams [9].

To address these challenges, leveraging technological advancements such as Extended Reality (XR) can enhance training programs by providing a safe, immersive, and standardized learning experience. XR allows engineers and emergency responders to engage in realistic simulations of post-earthquake scenarios, enabling them to develop critical decision-making skills and familiarize themselves with damage assessment protocols before working in real disaster zones. Furthermore, digital reconstruction techniques, such as Structure-from-Motion Multi-View Stereo (SfM-MVS) photogrammetry, can create high-fidelity 3D models of damaged structures, offering a valuable resource for training and post-disaster analysis [10].

The integration of XR in expert training is expected to mitigate the limitations of traditional training methods by improving knowledge retention, reducing safety risks, and allowing for repeatable and scalable training exercises. By using XR-based approaches, future engineers and first responders will be better equipped to assess structural damage efficiently, contribute to disaster response efforts, and support the long-term resilience of affected communities.

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2. Why XR/VR for Expert Education

2.1. Limitations of Traditional Training Methods

Traditional training for post-earthquake damage assessment is often conducted in classrooms or through limited hands-on field exercises. These approaches present several challenges:

Earthquake damaged buildings "in use": Conducting field training in real damaged buildings presents numerous dangers, primarily due to the limited controllability of the behaviour both of trainees as well as the limited capability to control the safety of the surroundings in damaged buildings. In addition, most of these damaged buildings do not remain available in the long-term due to their market value or the value of the land on which they are built upon. Thus, they tend to be either demolished or repaired and improved for further use. Additionally, these environments often contain hazardous materials such as asbestos, lead-based paints, and exposed electrical wiring, which pose severe health risks. These risks and limitations make it crucial to develop alternative training methods that provide realistic experiences without endangering the safety of participants.

Cost Related Issues: Implementing in-person training programs often entails significant financial burdens, including travel expenses, accommodation, and equipment procurement. Additionally, securing access to earthquake-damaged structures for training purposes involves high insurance costs and legal considerations. These financial constraints can limit the feasibility of large-scale training initiatives, making it imperative to explore cost-effective alternatives such as XR-based simulations.

Limited Exposure to Scenarios: Traditional theoretical, teacher-led learning methods often fall short in preparing engineers and responders for the unpredictable nature of post-earthquake damage assessment. In such conventional settings, trainees are typically exposed to a limited range of hypothetical case studies, diagrams, and lectures, which may not adequately reflect the complexity and variability of real-world disaster scenarios. As a result, learners may struggle to apply their theoretical knowledge in practical field conditions where unexpected structural failures and diverse damage patterns demand quick, informed decision-making. Without hands-on exposure to a broad range of damage scenarios, professionals may find it challenging to adapt effectively when confronted with unfamiliar or extreme situations in the field.

2.2. Advantages of XR/VR for Training

The integration of Virtual Reality (VR) and Extended Reality (XR) technologies into training for post-disaster damage assessment offers numerous advantages that enhance both the learning experience and the effectiveness of training programs.

Enhanced Learning Experience: One of the primary benefits of VR-based training is its ability to facilitate individualized learning. Trainees can progress at their own pace, allowing for a more thorough understanding of complex disaster-related concepts through asynchronous learning methods [11]. Furthermore, VR applications enable participants to interact with various components of a virtual environment, such as medical interventions and disaster response features, which can mimic real-life scenarios more accurately than traditional methods [11].

Realistic Simulations: VR training provides immersive and realistic scenarios that increase engagement and retention. Participants can experience auditory cues and visual stimuli, which help to recreate the pressure of actual emergency situations, thereby enhancing the learning experience [12] [13]. The realism of these scenarios not only makes training enjoyable but also prepares trainees for the unpredictability and stress of real-world emergencies [12].

Immediate Feedback and Performance Analysis: Another significant advantage is the capability of VR systems to offer immediate feedback and performance analysis. Trainers can observe trainees in real-time, providing corrections and guidance as needed, which fosters a more effective learning environment [14]. Additionally, VR systems can track various metrics, such as response times and

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decision-making processes, allowing for tailored feedback that addresses specific weaknesses in a trainee's performance [14].

Cost-Effectiveness and Logistical Advantages: VR training also presents a cost-effective alternative to traditional training methods. Although the initial investment in VR technology can be substantial, it ultimately leads to long-term savings by reducing the need for expensive physical props and facilities required in live training exercises [14]. Moreover, VR training can be conducted more frequently and with less logistical overhead, enabling regular reinforcement of skills [14].

Long-Term Retention and Skill Development: Long-term retention studies indicate that VR training can significantly enhance knowledge and skill retention over time. This aspect is particularly vital for emergency responders, who must recall critical information and procedures under pressure [14]. The ability to practice in a variety of scenarios also helps to build confidence and improve self-perception among trainees, ultimately contributing to better preparedness in real-life situations [8].

Collaboration and Team Dynamics: Moreover, VR and XR technologies facilitate collaborative training experiences, allowing multiple trainees to engage in discussions and analyses within a shared virtual environment. This capability is essential for training teams on collective decision-making and communication during disaster response scenarios [11] [9].

3. Project Methodology and Progress

A key component of the project is the collaboration with international institutions that specialize in XR-based learning and structural engineering:

- LINKS Foundation (Italy): Provides expertise in XR development, hosting training sessions for engineers, and developing immersive learning environments.
- HCPI (Croatian Centre for Earthquake Engineering): Facilitates data collection of real-world earthquake damage, integrates engineering assessment methodologies into XR training, and ensures alignment with emergency response procedures.
- University of Zagreb Faculty of Civil Engineering: Manages the academic and research aspects of the project, ensuring the integration of XR training into engineering curricula and professional education programs.

The methodology for this project is structured around the development and implementation of XR-based training modules that will be designed to enhance the expertise of engineers and emergency first-responders in post-earthquake damage assessment. The education will be structured to adhere to at least 3 different goals:

- **Education of engineers on assessment of damaged buildings** – so far, the experiences have shown that the so far provided education of engineers usually results with dichotomous results of assessment on site. The assessment methodologies are usually relying on personal live experience of assessors and their subjective explanation of damages.
- **Education of first-responders on initial usability assessment of damaged buildings** – In the immediate post-disaster activities it is relevant to give reliable but safe information to building users on the usability of a building while at the same time not endangering the lives of assessors.
- **Education of first-responders on safe behaviour inside and around the damaged buildings** – this training is most essential for the safety of SAR (Search and Rescue) teams, where a good transfer of relevant and vital information of engineers to rescuers is essential.

The project started in the late 2022 and was structured in 4 phases:

1. Data collection
2. Basic education on VR/XR
3. Creation of the first functional VR environment
4. Cration of the educational platform for engineers and first-responders

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3.1. Data collection

At the outset of the project, the team conducted extensive field surveys to document real-world earthquake damage. This process involved capturing photographic evidence, performing structural assessments, and engaging with local authorities and residents to better understand both the extent of the damage and the challenges faced during emergency response efforts. A crucial element of this phase was the firsthand experience of the project lead and partners, who had been actively involved in post-earthquake activities following the 2020 Petrinja earthquake series.

To enhance data collection, the team employed advanced 3D scanning technology, ensuring a highly detailed and accurate representation of damaged structures. Unmanned Aerial Systems (UAS), including the DJI Matrice 300 and DJI Air 2s, were used for aerial surveys, providing a comprehensive overview of affected areas. For high-precision structural mapping, the FARO Focus M LiDAR scanner was deployed, enabling the capture of intricate building details. Additionally, 360-degree cameras such as the Insta360 X3 were utilized to create immersive visual records, offering a realistic and interactive perspective on the damage conditions.

Through this combination of field expertise and cutting-edge technology, the project established a robust foundation for developing improved post-earthquake damage assessment methods. Utilized 3D scanning technology to capture detailed images of damaged buildings, employing Unmanned Aerial Systems (UAS) such as DJI Matrice 300 and DJI Air 2s for aerial surveys. Additionally, FARO Focus M LIDAR scanner was used for high-precision structural mapping, while 360-degree cameras like Insta360 X3 were deployed to capture immersive visual records of damage conditions.

Figure 2. Damage to a building in Sisak that is about to be demolished

3.2.Basic education on VR/XR

A series of structured training sessions were conducted to educate participants on XR technologies, design thinking, 3D modelling, and XR application development.

Introduction to XR: Participants were introduced to Extended Reality (XR), including Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) (figure 2). The session covered the evolution of XR from early innovations to modern devices like Oculus Quest and Apple Vision Pro. Applications in education, healthcare, and emergency response were highlighted, alongside interactive demonstrations using AR/VR devices.

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Design Thinking for XR: The focus was on user-centred design and research methods, incorporating qualitative and quantitative techniques such as surveys, focus groups, and SWOT analyses. Participants learned to develop user personas and apply brainstorming methods to refine XR project concepts.

UI/UX Design and Prototyping: This session covered the fundamentals of user interface (UI) and user experience (UX) for XR applications. Key topics included ergonomic design, visual contrast, and interaction elements for VR environments. Participants practiced wireframing, storyboarding, and prototyping to create effective user interactions.

Figure 3. Introduction to XR technology

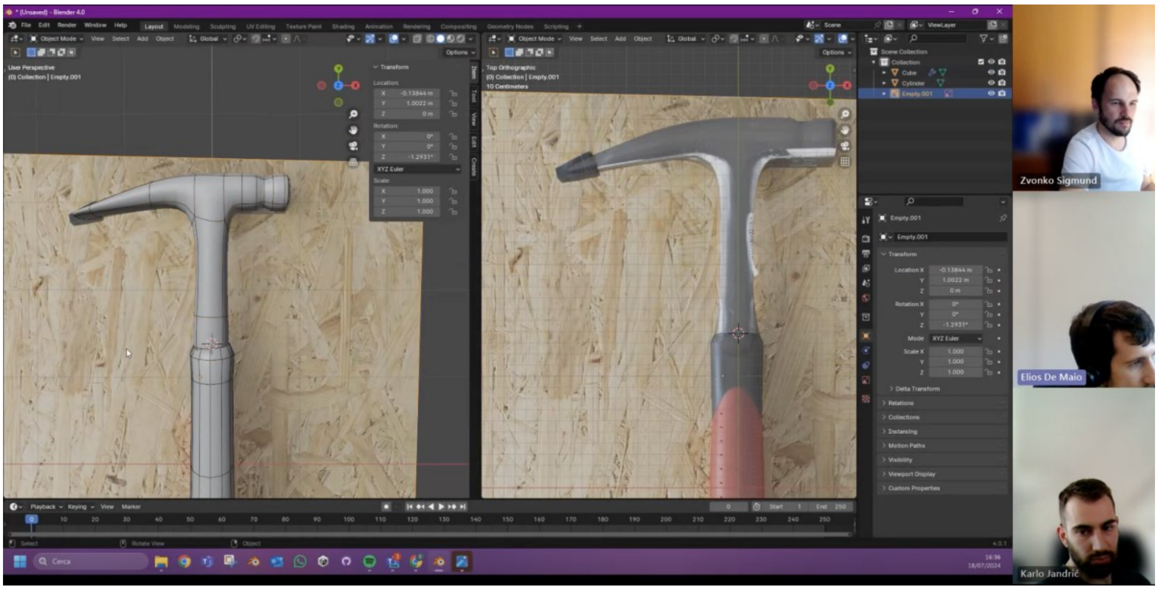

Figure 4. Blender modeling of a hammer

3D Modelling for XR Environments: Participants developed skills in 3D asset creation, including mesh modelling, shading, and texturing (figure 3). UV unwrapping and Physically Based Rendering (PBR) techniques were explored to enhance model realism. The session also introduced animation fundamentals, covering rigging and motion principles for interactive XR applications.

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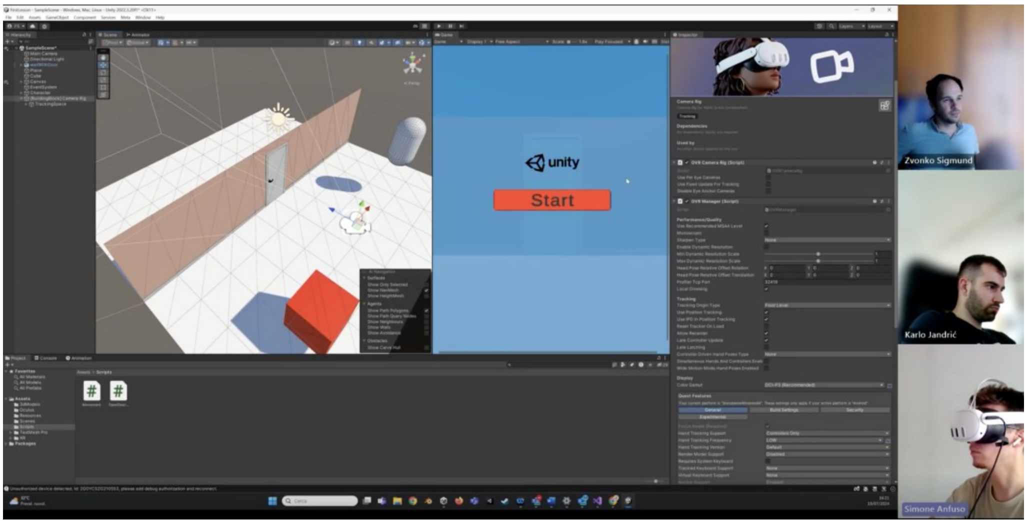

Figure 5. Configure Unity for VR development

Introduction to Unity for XR Development: Participants learned the basics of Unity, a game engine widely used for XR development (figure 4). The session covered Unity's interface, GameObjects, scene management, and animation. Basic scripting in C++ was introduced to enable interactive elements within XR environments. Participants also configured Unity for VR development, integrating the MetaXR SDK and testing their projects with Oculus devices.

3.3. Creation of the first functional VR environment

As part of the collaboration between Fondazione LINKS and HCPI, the project has advanced to the phase of designing and implementing a VR Pilot Demonstrator. This phase is crucial for developing an interactive and immersive training environment for experts in post-earthquake damage assessment. The implementation of the VR demonstrator consists of three key activities:

Storyboard Creation: The first step in the development of the VR Pilot Demonstrator involves transforming the established training concept into a structured storyboard. This storyboard defines the narrative sequences, user interactions, and key visual elements that will guide the virtual experience. By establishing a clear sequence of events and user engagement points, the storyboard ensures that the training module is both pedagogically effective and technically feasible.

3D Modelling: Following the storyboard development, the next phase focuses on creating optimized 3D models of the environments and objects that will be integrated into the VR application. These models replicate real-world earthquake-damaged structures, offering a realistic and interactive setting for training. The modelling process employs state-of-the-art photogrammetry and 3D scanning techniques to enhance the accuracy and fidelity of the virtual environment.

Demonstrator Creation in Unity: Once the 3D assets are developed, they are imported into Unity, a leading game engine used for VR applications. This phase involves programming interactivity, navigation, and user engagement in accordance with the predefined storyboard. The integration of physics-based simulations and user feedback mechanisms ensures that the VR demonstrator provides a dynamic and responsive training experience.

These activities represent a significant milestone in the project's progress, laying the foundation for the implementation and evaluation of the VR-based training program for post-earthquake damage assessment experts.

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4. Conclusions

The integration of Extended Reality (XR) into the training of experts for post-earthquake damage assessment represents a significant advancement in disaster response preparedness. Traditional training methods, which rely on theoretical knowledge and limited field exercises, often fail to provide engineers and first responders with sufficient experience in high-risk, real-world scenarios. By leveraging XR technologies, this project has developed immersive and interactive training environments that enhance skill development, improve knowledge retention, and ensure a safer, more effective learning process.

The project, conducted in collaboration with the University of Zagreb's Faculty of Civil Engineering, the Croatian Centre for Earthquake Engineering (CCEE), and the LINKS Foundation, has successfully progressed through several key phases: data collection from real earthquake-damaged structures, XR training methodology development, creation of high-fidelity 3D models, and implementation of a VR-based learning platform. The use of advanced 3D scanning techniques, drone imagery, and digital reconstruction has enabled the creation of realistic training environments that accurately reflect post-earthquake conditions.

Preliminary findings suggest that XR-based training offers multiple advantages over conventional approaches, including:

- Enhanced safety: Reducing exposure to hazardous conditions while allowing for repeated practice in a risk-free virtual environment.
- Improved decision-making skills: Enabling trainees to experience a variety of structural damage scenarios, reinforcing their ability to assess risks and make critical decisions under pressure.
- Standardization of assessment procedures: Providing a consistent and repeatable learning experience that ensures uniformity in damage classification and usability evaluations.
- Cost-effectiveness and accessibility: Eliminating the need for expensive on-site training and allowing a broader range of professionals to engage in high-quality education.

Despite these benefits, challenges remain, including the need for further validation of XR-based training effectiveness in real emergency conditions and the development of standardized assessment metrics for evaluating trainee performance. Future research will focus on refining the VR training modules, integrating real-time AI-driven assessment tools, and expanding the program to a larger pool of engineers and emergency responders.

Ultimately, the successful implementation of XR in post-earthquake expert education has the potential to revolutionize disaster response training, equipping professionals with the necessary skills to rapidly and accurately assess structural damage. This initiative not only enhances the effectiveness of emergency response efforts but also contributes to the long-term resilience of communities affected by seismic events.

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