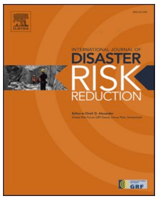
International Journal of Disaster Risk Reduction 115 (2024) 104979

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr



Simulating and visualising indoor seismic damage: A systematic literature review

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ARTICLE INFO

Keywords:
Simulation
Visualisation
Indoor seismic damage
Digital technologies
Virtual reality

ABSTRACT

Earthquakes pose a significant risk to human lives because they can cause severe damage to structural and non-structural components of buildings, thereby harming building occupants. Accordingly, reducing earthquakes' social, economic and environmental losses requires significant effort. Indoor seismic damage, which refers to damage caused by earthquakes inside buildings, such as falling objects, broken furniture and collapsed walls, is especially important for assessment and mitigation because it directly affects building occupants. Therefore, understanding and mitigating indoor seismic damage have become necessary. Many damage assessment tools have been introduced and adopted to assess the impact of earthquakes on buildings. Digital technologies can be essential in simulating and visualising earthquake damage, providing realistic, interactive and immersive experiences for different purposes and stakeholders. This systematic literature review critically aims to investigate existing approaches and methods for simulating and visualising indoor seismic damage to provide a comprehensive overview of the current state of research, identify knowledge gaps and offer insights into the future. Thus, a conceptual framework was developed, which integrates essential aspects, including methods and tools, to develop seismic damage simulation and visualisation. This objective was achieved by systematically reviewing 20 articles published between 2017 and 2023 to answer several research questions on the type of application, software, interoperability challenges and hardware adopted to visualise the damages.

1. Introduction

Building damages caused by earthquakes generate huge losses and disrupt society. Accordingly, understanding and assessing the damage caused by earthquakes is essential for developing effective mitigation strategies. Structural collapse in earthquakes frequently results in high casualties, as evidenced by the February 6, 2023, Turkey earthquake [1,2]. However, research indicates that in several seismic events, buildings remain structurally intact, while non-structural elements, such as furniture, ceilings, and partitions, can cause significant injuries and fatalities [3–8]. For example, during the Jiuzhaigou earthquake in China in 2017, with a magnitude of Ms 7.0, most buildings did not suffer severe damage or collapse. However, However, the interior environments were significantly affected,

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https://doi.org/10.1016/j.ijdrr.2024.104979
Received 31 July 2024; Received in revised form 10 November 2024; Accepted 13 November 2024

with notable occurrences such as the collapse of ceilings and the displacement of furniture [9,10]. This earthquake caused damage to over 73,000 buildings, with 25 fatalities, 525 injuries and six missing people [11] Another real-life example is the 2010 Darfield earthquake (Mw 7. 1) and 2016 Kaikoura earthquake in New Zealand (Mw 7.8), where extensive non-structural damages were reported in the affected buildings with minor structural damages [12,13]. Thus, non-structural components are important in losses during earthquakes [13].

Additionally, there is a severe need to evaluate building damage to avoid exposing hazards and risks to building occupants [14]. In recent years, significant progress has been made in effectively managing and preventing earthquake-induced building structure collapse. However, indoor non-structural damage to buildings remains a critical issue for occupant safety [3–7,15]. Hence, knowing the seismic response and vulnerability of non-structural elements within an indoor environment is important.

Earthquake simulation is necessary for understanding and mitigating indoor damage in buildings. It provides the possibility of damage prediction to structural and non-structural components in case of potential hazards by using technologies, such as building information models (BIM) combined with virtual reality (VR) and high-fidelity structural models, thereby enhancing preparedness and safety measures [16]. Furthermore, through such simulations, apart from the following markedly realistic descriptions of the potential losses in case of disasters, superior response plans can be provided [15]. Therefore, earthquake simulations are essential tools for minimising disaster risks [17].

Earthquake simulations focus on earthquakes' seismic activities and show how they can affect buildings [18]. Ground shaking is caused by seismic waves originating from the earthquake epicentre, resulting in the building structure vibrating [19]. Vibrations affect non-structural components, such as partitions, ceilings and furniture [20].

The relationship between these seismic forces and the response of buildings and other structures can be studied through the use of either shake tables or computational models to assess the structural and component-level behaviour [21].

Different strategies are focused on finding the best ways to minimise structural vibrations, but despite the presence of several ways to minimise the transferred vibrations to structures, the need for advancements in damage visualisation is still significant [22–25].

Seismic activities and their consequential impact on structural and non-structural components are subjects of extensive simulation studies. These simulations are based on physical and computational models. For example, simulations of ground shaking often incorporate ground motion records and geological data to generate reliable ground motion scenarios [26]. Moreover, visualising earthquake damage provides a comprehensive and clear view [27]. This technique enables rapid assessment and detailed analysis, helping emergency responders make immediate, informed decisions [28]. Visual data enhance communication with policy-makers and aid organisations by clearly illustrating the extent of damage [29]. Additionally, visual data provide real training situations that enhance preparedness and education [16]. Different methods exist to simulate and visualise building damage using digital technologies. A common and traditional method for simulating is to conduct physical experiments on materials and components and, through the results, determine their durability by the possibility that they can bear external forces [30]. This method simulates earthquake motion on a shaking table test for scaled models of buildings and structures. Moreover, this method can determine structures' realistic behaviour and failure modes; however, it is also costly, time-consuming and limited by scaling and experimental factors [31]. Another method uses computer simulation to simulate a structure's behaviour during ground motions. These simulations consider materials, how much load they can bear and how the different parts react to stress and strain. Four categories are commonly used for simulating damage from earthquakes on buildings. These categories are fragile analysis, capacity spectrum method (CSM), nonlinear time-history analysis based on multiple-degree-of-freedom and using refined finite element models [32]. Digital technologies have the potential to improve future forecasting and contribute to life-saving effort [33].

Despite the new digital technologies that can simulate and visualise earthquake damage, there is still a gap in the literature on the need for a systematic review of this solution. This study is the first literature review on simulation and visualisation methodologies of earthquake damage. This review investigates the existing simulation and visualisation solutions used to visualise earthquake damage. To achieve this goal, we conducted a systematic literature review to identify and assess the most used simulation and visualisation techniques (e.g., software and tools) for indoor seismic damage to provide a comprehensive overview of the existing knowledge on the subject matter.

Our study examined 20 papers from 2017 to 2023. We aimed to identify the different types of applications they covered and their development and testing methods. Our analysis answered the eight research questions to explore literature gaps and suggest areas for future research direction.

2. Background

This section briefly explains the simulation and visualisation of indoor seismic damage to highlight the significance and ways of mitigating it.

2.1. Simulation of indoor seismic damage

For indoor seismic damage, the simulation concept involves making a model to analyse how a building and its contents respond to an earthquake. Whether the model is making predictions for the structure (e.g. walls and floors) or non-structural components (e.g. furniture and partitions), it predicts the expected behaviour of the natural phenomenon [34]. For example, a simulation could indicate that a specific type of furniture will probably tip over during an earthquake, which may pose a risk to occupants. This information could be used to secure or design safe furniture [35]. Physics-based models are excellent for predicting the effects of earthquakes on non-structural components and furniture [36]. These simulations are important for identifying hazards in indoor spaces during seismic events and contribute to developing damage mitigation strategies [37].

Numerous studies have been conducted on seismic scenario simulations [38]. found the range of two-dimensional (2D) non-structural components (NSCs) that fall to the ground [39]. used the physics engine to qualitatively simulate the movement of NSCs in three dimensions (3D), providing a markedly realistic experience for VR emergency drills. When discussing how NSCs change during earthquakes, existing studies have often made qualitative predictions on the change result and need additional consideration of how NSCs change dynamically during earthquakes. Consequently, the simulation's rationality and realism are insufficient [40], and the dynamic motion of NSCs should be considered during an earthquake to obtain considerably realistic and credible simulation results. However, it can be determined which NSCs mainly change and how they move [40]. Accordingly, ground shaking, structural shake, non-structural component behaviour, and furniture movement must be integrated for a comprehensive and realistic understanding of earthquake impact on indoor spaces [36,37].

Simulation of non-structural components and building contents has gained considerable attention as these elements can pose significant risks during seismic events. The FEMA-P58 guideline provides a framework for evaluating non-structural damage, focusing on the impact of falling or shifting objects within buildings. This guideline highlights the importance of simulating non-structural components to improve safety and preparedness in seismic-prone buildings [41]. Several studies have focused on simulating non-structural components and building contents to understand their behaviour during earthquakes. Researchers have utilised only FEMA P-58 guidelines [28,34,42] or a combination of time-history analysis (THA) and fragility curves from the FEMA P-58 guidelines [36,37] for simulation. One study developed fragility models for freestanding items like furniture, highlighting their susceptibility to seismic forces [43]. Another applied performance-based design method to simulate non-structural components, aiming to enhance their resilience [44]. A separate analysis of non-structural damage during the 2010 Chile earthquake used FEMA to address issues with ceilings, partitions, and other components. Together, these studies underscore the importance of evaluating and securing non-structural elements to enhance indoor safety and resilience during seismic events [45].

2.2. Visualisation of indoor seismic damage

Visualisation is representing data or information graphically to understand and simplify complex concepts. Visualisation techniques range from simple charts and graphs to complex 3D models and virtual reality environments [46]. Immersive systems, including VR, augmented reality (AR) and mixed reality (MR), offer the capability to obtain new data, create new experiences and provide new insights by creating virtual elements of physical and imagined worlds. These systems are widely used in various fields and can also visualise indoor seismic damage. This aspect is essential because building damage is one of the leading causes of death and injury during earthquakes [47]. Immersive Virtual Reality (IVR) provides a fully immersive experience, enabling users to interact with 3D seismic data in a virtual environment. IVR and serious games (SGs) are used to study various training systems in emergency conditions to rescue people, as well as used in training systems [48]. IVR offers users a fully immersive experience where they are placed in a virtual environment that replicates real-world scenarios, often through headsets like Oculus Rift or HTC Vive. This technology is essential in earthquake training and preparedness, as users can virtually experience seismic events, interacting with 3D damage models in real-time. Studies have shown that IVR can significantly enhance earthquake preparedness by providing realistic and dynamic environments for users to practice safety measures during simulated earthquakes [17,49]. Non-immersive VR means users are not immersed in a virtual environment. It features a desktop monitor showing a 3D environment and a person operating it using familiar input devices. Non-immersive VR offers a more desktop-based experience where users interact with a 3D virtual environment through a standard computer interface and has been used effectively in simulating earthquake scenarios for training purposes and building assessments, allowing users to visualise the effects of seismic damage in a more accessible format. This method is often paired with Building Information Models (BIM) to provide detailed structural analysis without requiring fully immersive equipment [50].

AR is the way virtual objects are attached to the real environment [51]**.** AR integrates virtual elements into the real world by overlaying digital information onto physical spaces. AR can be used on smartphones, tablets, or AR glasses. In the context of earthquake damage simulation, AR can offer real-time data about a building's structural health and guide users through post-earthquake evacuation procedures. It helps visualise non-structural damage, such as furniture displacement and falling objects while interacting with the real environment [52]. MR technology enables participants to move freely in the real world whilst experiencing realistic earthquake scenes to improve the earthquake safety abilities of occupants [34]. Visualisation of indoor seismic damage has developed significantly with the technology, ranging from simple photographic documentation to advanced VR simulations. Meanwhile, 2D visualisation techniques, such as screenshots and graphs, are commonly used in seismic damage analysis. They provide a simple and effective way to represent and interpret data [46].

Several studies have investigated visualisation methods for the assessment of indoor seismic damage. Some of these studies have used qualitative data to visualise indoor damage and to show the extent of structural deformations, non-structural component failures and furniture movement. These studies have focused on the visualisation of damages to buildings for training and evacuation procedures without using actual accurate simulation or physical models for their analyses [39,49,53,54]. Different simulation methods can cause uncertainties in visualisation outcomes. Some studies have relied on more than qualitative data or simplified simulation methods, which may not accurately represent the complexity of indoor seismic damage. For example, some studies have created indoor earthquake scenarios without considering a building's valid dynamic seismic responses [40,50]. Most studies have used the scope of the research as a basis for utilising IVR on indoor seismic damage. However, some studies have also utilised 2D [42] or non-immersive VR [16,17,55] and AR [34,52] to visualise indoor damage.

Significant progress has been made in representing indoor seismic damage, but gaps and challenges still need to be addressed. Consequently, future studies should focus on improving the consideration and integration of all aspects (e.g. ground shake, structure shake, non-structure shake and furniture movement) of indoor damage, minimising uncertainty in visualisation results, developing comprehensive systematic simulation models and implementing verification processes [36].

Several novel techniques are used to detect the visualisation of damages through non-immersive, immersive virtual and augmented reality solutions. VR technology uses the power of software and hardware to generate a virtual environment for its users [56]. In VR technology, computer-generated display enables users to feel as if they are present in a space and interact with the environment with immersive or non-immersive experiences [57]. IVR is a visual display device that provides high-level immersion and visual realism, which is considerably like a real experience. In contrast, non-immersive VR is often used on standard computers [58].

Building Information Modelling (BIM)-based visualisation has become valuable for assessing and managing seismic risks, especially in high-risk environments like hospitals and urban infrastructure. For example, one study introduced a BIM-based approach designed for hospitals, which visualises the probability of functional failure in critical departments after an earthquake. This visualisation technique aids decision-makers by illustrating how structural damage impacts operational functionality, allowing them to prioritize emergency response and retrofitting efforts in critical areas [59].

BIM's adaptability also extends to non-structural elements essential for maintaining functionality. Another study demonstrated BIM's capability to simulate the vulnerability of non-structural components, such as freestanding equipment and partitions, during seismic events, providing insights into planning the placement and securing of these elements to minimise disruption and enhance occupant safety [43].

3. Methods

This study conducts a systematic literature review involving a comprehensive process of identifying, assessing and integrating existing literature in line with a research question or focus area.

The current research identifies experiments currently available, searches for experiments and analyses the experiments to obtain the most updated and accurate data [60].

This study follows the method called "Five steps for conducting a systematic review" [61]: (i) defining research questions, (ii) identifying relevant works, (iii) assessing the quality of the studies, (iv) summarising the evidence and (v) interpreting the findings.

This section explains the details of the first and second steps. Given that only a few articles have been found for review in the second step, it has been decided not to make the third step to evaluate the selected articles' quality and relevance. The fourth procedure is discussed in the Results section, whilst the fifth is presented in the Discussion and Conclusion section.

3.1. *Defining research questions*

This research aims to comprehensively analyse and categorise existing methods and tools for simulating and visualising earthquake damage, explicitly focusing on indoor seismic risks. This systematic review identifies and addresses knowledge gaps, establishes the current capabilities and limitations of available technologies, and offers guidance for future research and development. Multiple research questions are used to classify and gather detailed information from various studies. By using specific questions, this review explores each study's contributions. It ultimately brings them together under a main question: How can current simulation and visualisation technologies be effectively used to improve the assessment and reduction of indoor seismic damage, and what are their limitations? The following research questions were utilised to guide this review:

1. What type of built environment and location did the study focus on?
2. Which specific aspect of the seismic simulation was the focus of the study?
3. What software and data were utilised for earthquake simulations in the study?
4. Which type of visualisation technology was used?
5. What software and hardware were utilised in the study to visualise the earthquake results?
6. What was the primary goal or purpose of the tested application?
7. Who was the target audience of the tested application?
8. What were the challenges associated with the tested application?

3.2. *Identifying the relevant works*

This study followed the PRISMA statement to ensure maximum methodological clarity and transparency [62]. Eligible papers must include the significant simulation concept and visualising indoor earthquake damage. Additionally, eligible papers included in the systematic literature review were collected from journals and conference proceedings. To obtain the maximum coverage of publications and to address the research questions within the academic literature, the following comprehensive keyword search string was developed: 'seismic damage' OR 'earthquake damage' AND 'simulation' OR 'visualisation' AND 'digital technology*' OR '3D' OR '2D' OR 'virtual reality' OR 'augmented reality' OR 'mixed reality'. Searches were conducted on 15 January 2024 and yielded 344 results (including duplicates). The papers were retrieved from the Google Scholar (n = 100), Web of Science (n = 88) and Scopus (n = 156) databases. Google Scholar is a powerful database of scholarly literature [63]. Web of Science is the most widely used and authoritative database of research publications and citations [64]. Scopus is the most significant scientific literature database [65]. The following steps filtered the papers: before, initial and full-text screenings. Table 1 presents the inclusion criteria for eligible articles.

To cover any missing papers, a backward and forward snowballing approach was adopted to find additional relevant papers based on the target papers' references list or paper citation [66]. Snowballing was based on the previous filtered results after PRISMA. Four additional papers were identified as relevant to this systematic literature review through snowballing. Hence, 20 papers were identified as relevant to this systematic literature review [16,17,28,34,36,37,39,40,42,49,50,52-55,67-71]. The criteria and approach used for selecting papers are outlined in Fig. 1.

4. Results

This systematic literature review identified 20 papers published between 2017 and 2023. A summary of all eligible papers is provided in Appendix A (Summary of eligible papers).

4.1. Built environment characteristics and location

The studies identified three types of built environments: commercial, residential and institutional buildings. Most studies focused on institutional buildings (n = 9), including hospitals [16,39,49,53,69], universities [42,67] and schools [54,68]. Five studies investigated commercial buildings, including supermarkets [17,40] and office buildings [28,34,71]. Only a few studies focused on residential buildings (n = 2). In the residential category, the studies focused on living spaces such as apartments [70] and a five-story masonry house [52]. Additionally, there were entries where the type of built environment was not mentioned but typically involved reinforced concrete structures [37] or buildings with mixed-use spaces, such as dining rooms, living rooms and offices [36, 37, 50]. Geographically, most papers focused on buildings in China (n = 9) [16,28,34,36,37,40,52,55,70]. Another critical focus area was New Zealand (n = 7) [39,42,49,53,54,67,69], and one study was in Australia [68], with the rest not specifying a particular location (n = 3) [17,50,71]. From the material perspective, most commercial buildings mentioned were reinforced concrete frames (n = 5) [28,34,36,37,55], and one of the residential buildings was masonry (n = 1) [52]. Moreover, other papers were unclear about their targeted material (n = 14). Fig. 2 categorises the related publications based on the type of built environment.

4.2. Specific aspects of the seismic simulation

The eligible papers used different aspects for simulation and visualisation damage, including ground shake, structural shake, non-structural shake and furniture responses. The majority of the studies focused on furniture movement and non-structural component shake (n = 8) [39,42,49,53,54,67–69]. Two studies considered all aspects of ground shake, structure shake, non-structural shake and furniture for a comprehensive approach [36,37]. Two studies evaluated ground shake and furniture movement [40,50]. Two studies concentrated on ground, non-structural and furniture, leaving out structural shake [17,34]. Two studies investigated ground and structure shake but did not include non-structural shake or furniture [28,55]. One of the studies explored ground shake, structure shake and non-structural shake without addressing furniture [16]. One study only focused on structural shake [52]. Meanwhile, two studies concentrated solely on the stability and response of furniture [49,70,71].

Some studies were highlighted using actual physical models [16,17,28,34,36,37,40,42,50,55], whilst others utilised a qualitative approach to simulate and visualise earthquake damage without using any actual physical model [39,49,52-54,67-71]. Fig. 3 shows the classification of studies based on the physical models, qualitative approaches and different aspects used in each study.

4.3. Simulation software and data

Based on eligible papers, various software, such as Unity, Revit, 3D Max and Unreal Engine 5, were utilised to model and simulate the potential damage resulting from seismic events. Unity is a popular game engine for creating IVR. Unity has integrated a physics engine, PhysX, which can be used to simulate the movement of damaged non-structural components. Revit is a widely used building information modelling (BIM) program to generate detailed 3D information models of buildings [36]. Unity and Revit were the most common software choices for simulating earthquake damage. Some studies exclusively used Unity as the sole software tool for simulating damage scenes [17,40,50,55,71], whilst many studies combined Unity with Revit in their research [49,54,67,68]. In a few studies, Unity and Revit were combined with other specialised software tools, such as Yingjianke (YJK) [36,37], 3DS Max [39], Netlogo and Excel [42], Protégé [28] and PyroSim [16], for specific tasks.

YJK is a structural analysis software that has developed numerous predefined sub-models for the joints and sections in Revit [36].

Table 1
Eligibility inclusion steps for the study selection.

Eligibility Criteria	Stages	Decisions
Any of the search strings were in the title, abstract or keywords of the studies	Pre-screening	Inclusion
Duplicated papers	Pre-screening	Exclusion
Peer-reviewed journal articles, conference papers	Pre-screening	Inclusion
Review papers	Pre-screening	Exclusion
The full text of the studies was in English	Pre-screening	Inclusion
No simulation and visualisation for indoor damage in titles, abstracts and keywords	Initial Screening	Exclusion
Data analysis of the outcome was conducted to evaluate and validate the prototype	Full-text screening	Inclusion
Theories, concepts, frameworks or proposals were discussed with actual prototypes or applications	Full-text screening	Inclusion

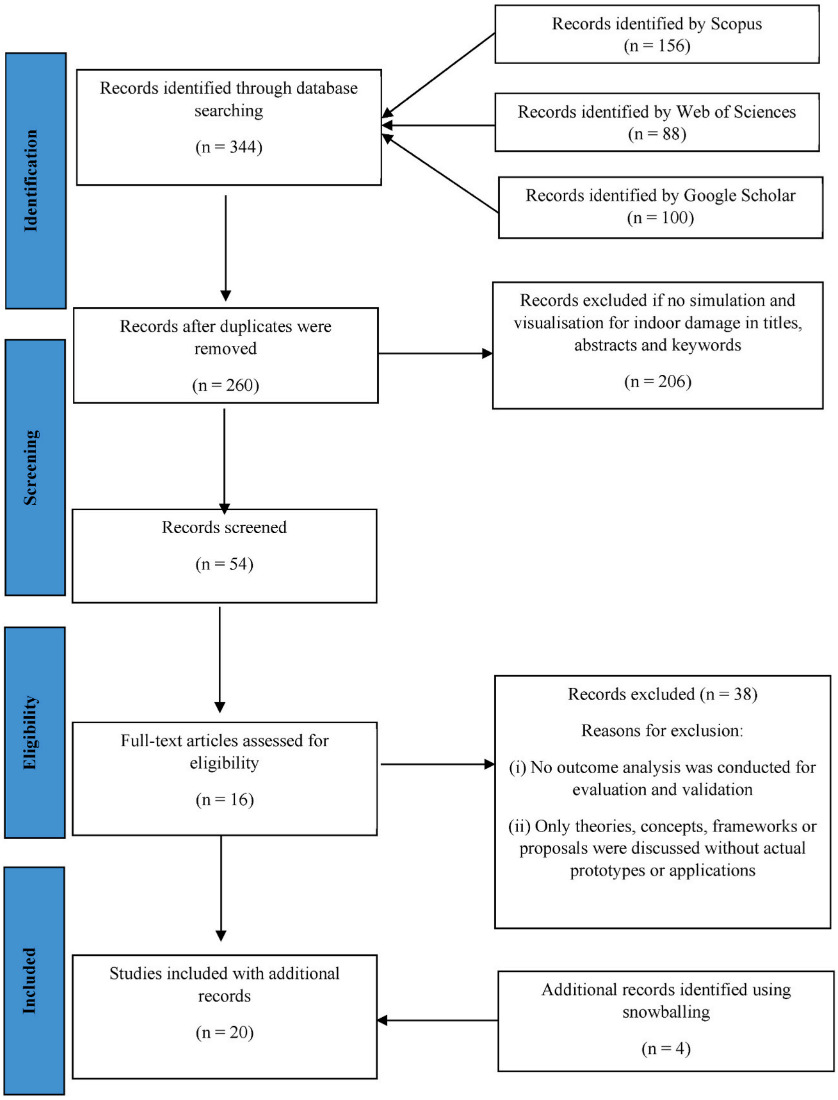


Fig. 1. PRISMA diagram and the process of identifying the relevant research papers.

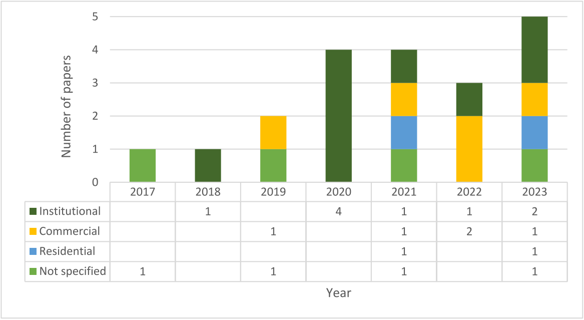


Fig. 2. Types of built environment.

3DS Max is a professional 3D modelling, rendering and animation software developed by Autodesk [39]. NetLogo is a software platform designed explicitly for agent-based modelling that is a free programmable environment in multi-agent modelling [42]. Protege is the most widely used software tool for working with Web Ontology Language (OWL). It provides an interface for creating,

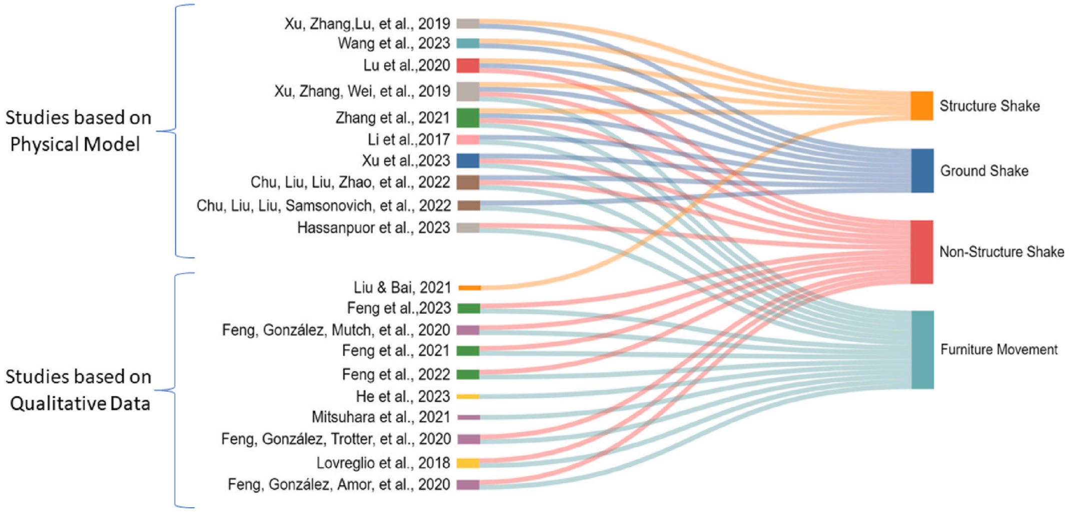


Fig. 3. Classification studies based on physical models and qualitative approaches.

editing and visualising OWL ontologies [28]. PyroSim is a software tool that simulates fire and smoking behaviours in structures [16]. Unreal Engine 5 was used in one study as a way to simulate earthquake damage; this software is a high-performance framework for real-time 3D rendering [70]. One study exclusively used Revit for earthquake damage simulation study [52].

Different types of data were used based on the study's modelling approaches. Studies using qualitative data sources utilised a combination of pre-existing BIM models, 2D building plans and site photos [39], building data (structural and non-structural data), videos and images of building [49], original building drawings and models, post-earthquake site media information [52], 3D scene model [70] and real-world earthquake scenarios [71].

In studies involving physical models, the choice of data sources varied based on specific aspects of analysis. The ground motion database was used for studies focused on ground shake. Ground motion data refer to records of the movement of the earth's surface caused by seismic waves generated by earthquakes [16,28,36,37,40,50,55].

Researchers have utilised time-history analysis (THA) and fragility curves from the FEMA P-58 guidelines [36,37] or only FEMA P-58 guidelines [28,34,42]. A building structure's THA can provide a detailed structural seismic response. FEMA P-58 guidelines are state-of-the-art seismic performance assessment methods for structural and non-structural components. Table 2 shows the details of the simulation software and data that studies used to simulate indoor seismic damage of buildings [36].

4.4. *Visualisation technologies*

Studies applied different visualisation technologies to address seismic damage analysis, highlighting IVR, non-immersive virtual reality, AR, MR, 2D/3D colour-coded plans, screenshots and graphs 2D/3D colour-coded plans are visual representations of a layout or design using different colours to distinguish between various elements or areas [42]. One study used screenshots and graphs as visual tools to enhance indoor earthquake damage scene [40]. Most of the studies mainly utilised IVR as their visualisation technology. Meanwhile, some studies used non-immersive virtual reality [16,17,55].

The use of mixed VR and AR in one of the studies marks a notable integration [34]. By contrast, another study only used AR to overlay digital seismic information onto the real-world environment [52]. Fig. 4 shows several studies based on visualisation technologies done each year.

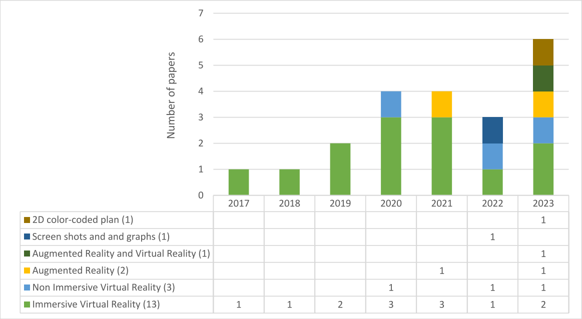
4.5. *Visualisation software and hardware*

The eligible papers indicated that a range of software and hardware is used to visualise damage. Unity was the predominant software utilised for visualisation. This software was often paired with head-mounted display VR headsets, particularly HTC Vive [36,37,39,50,70] and Oculus Rift [49,53,54,67–69,71], to immerse users in virtual environments. In some studies, computers were commonly used as visualisation hardware by rendering images and videos to visualise damaged scenes [16,17,28,40,42,55]. Particularly, Unreal Engine 5 was chosen to build the simulated environment for this investigation in one of the studies. Unreal Engine 5 is extensively utilised in the video game, advertising and film industries [70].

One study used Augin on iPhones for visualisation purposes. Augin is a mobile AR application designed for iPhone mobile devices for visualisation needs [52]. Smoke View is a specialised visualisation software used for analysing fire and smoke behaviour in fire protection engineering and research; this software was used, besides Unity, in one of the studies to visualise the movement and dispersion of smoke within indoor environments [16]. The combinations of software and hardware used for visualisation are presented in Table 3.

Table 2
Simulation software and data.

No.	References	Simulation software	Simulation Data and Input
1	[36]	Revit Unity YJK	Building data Time-history analysis (THA) FEMA P-58 guidelines Ground motion data
2	[37]	Revit Unity YJK	Building data THA FEMA P-58 guidelines Ground motion data
3	[39]	Revit Unity 3DS MAX	Pre-existing BIM-based 3D models 2D building plans Site photos
4	[49]	Revit Unity	Building data Existing videos and images of building earthquake damage
5	[50]	Unity	Ground motion data
6	[40]	Unity	Ground motion data
7	[42]	NetLogo Revit Microsoft Excel	Building data FEMA P-58 guidelines
8	[34]	Revit Unity	Ground motion data FEMA P-58 guidelines
9	[17]	Unity	Ground motion data
10	[28]	Revit YJK Protege	FEMA P-58 guidelines Building data
11	[52]	Revit	Original building drawings and models Post-earthquake site media information Building data
12	[16]	Revit PyroSim Unity	Ground motion data Building data
13	[55]	Unity	Ground motion data Building data
14	[67]	Revit Unity	Building data
15	[54]	Revit Unity	Building data
16	[68]	Revit Unity	Plan drawings and on-site 360° panoramas Building data
17	[69]	Revit Unity	Building data
18	[70]	Unreal Engine 5	3D scene model
19	[71]	Unity	Real-world earthquake scenarios Building structure data
20	[53]	Revit Unity	Building data



	2017	2018	2019	2020	2021	2022	2023
🟫 2D color-coded plan (1)							1
🟦 Screen shots and and graphs (1)						1	
🟩 Augmented Reality and Virtual Reality (1)							1
🟨 Augmented Reality (2)					1		1
🟦 Non Immersive Virtual Reality (3)				1		1	1
🟩 Immersive Virtual Reality (13)	1	1	2	3	3	1	2

Fig. 4. Visualisation technologies.

Table 3
Visualisation software and hardware.

References	Visualisation Software	Visualisation Hardware
[36,37,39,50]	Unity	Head-mounted display VR headset (HTC Vive)
[49,53,54,67–69]	Unity	Head-mounted display VR headset (Oculus Rift)
[16,40,55]	Unity	Computer
[17,28,42]	Revit	Computer
[34]	Unity	Head-mounted display VR headset
[52]	Augin	iPhone
[16]	Unity/Smoke View	Computer
[70]	Unreal Engine 5	Head-mounted display VR headset (HTC Vive)
[71]	Unity	Head-mounted display VR headset (Oculus Quest)

4.6. Primary goals and purposes

The primary goals focus on two aspects: training and non-training. Training studies were designed to educate and prepare occupants for earthquakes. These studies aimed to teach survival strategies and enhance occupants' awareness, knowledge, skills and confidence in dealing with earthquake emergencies by focusing on the following aspects: (1) providing well-founded scenes for virtual earthquake safety drills to reduce casualties by teaching occupants how to survive earthquakes [36], (2) providing guidance and support for occupant safety decision-making [37], (3) proposing a possible VR and SG training tool to enhance earthquake preparedness in public buildings [39], (4) presenting an IVR- and SG-based training system to improve earthquake behavioural responses and post-earthquake evacuation preparedness [49], (5) providing an immersive and novel VR training approach designed to teach individuals how to survive earthquakes in a typical indoor environment [50], (6) enabling participants to experience realistic earthquake scenes and learn proper earthquake safety strategies through MR visualisation and guidance [34], (7) providing the necessary and reliable training system for evacuation and rescue [16], (8) allowing participants to improve their responses during earthquake simulations and enhancing their adaptability for real-life emergencies [67], (9) presenting a customisation framework for IVR and SGs suited to earthquake emergency training [54], (10) studying the behavioural responses and sequences occurring in earthquakes and post-earthquake evacuation [69], (11) examining the effectiveness of early earthquake warning (EEW) [70], (12) developing a VR-based evacuation training [71] and investigating the decision-making of building occupants during earthquakes and post-earthquake evacuation [53], **(**13) Designing instructional mechanisms in immersive virtual reality (IVR) serious games tailored for earthquake emergency training for children [68].

Meanwhile, non-training studies were developed to provide a scientific foundation for creating realistic indoor earthquake scenarios. These scenarios can be used for future crowd evacuation models and VR evacuation drills [40], to evaluate the impact of indoor non-structural damage on the post-earthquake evacuation process and to assess different building design geometries to increase the chances of a suitable evacuation process [42]. These studies also investigated the indoor seismic evacuation process and proposed a simulation model [17], evaluated the post-earthquake economic resilience of different buildings [28], developed a visualisation method and framework for the post-earthquake retrofitting of buildings [52] and proposed a rapid visual simulation method [55]. Fig. 5 shows the primary goal and scope of studies categorised in training and non-training purposes based on the year. A more detailed description of each research paper's achievements is described in Table 4.

4.7. Target audience

The target audience for the tested applications varied across the studies. The studies' target audience was participants with different involvements and interests in the subject matter. For training purposes, building occupants were a primary focus as participants, including office occupants [36,37], volunteers in a teaching building [34], university students [50,67,70,71], school students

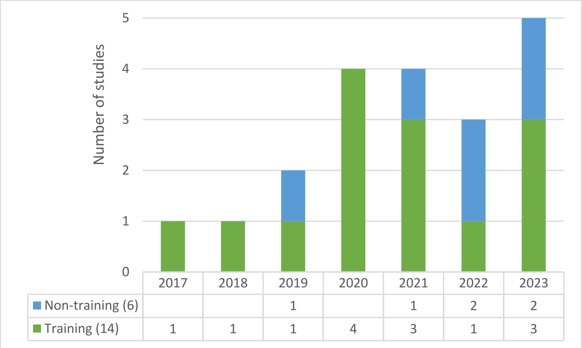


Fig. 5. The primary goal of the scope.

Table 4
Summary of main achievements from different studies.

Reference	Main Achievement
[16]	They created a BIM-integrated VR simulation framework that enhances training and preparedness for post-earthquake fire rescue operations. By combining detailed structural data from BIM with immersive VR environments, the framework accurately simulates building damage, blocked paths, and fire spread after an earthquake. This realistic, scenario-based training tool enables emergency responders to practice navigating complex rescue scenarios, assess potential hazards, and refine response strategies, ultimately supporting safer and more effective rescue operations in real-world emergencies.
[34]	They developed MR drills that integrate real-time visualisation of non-structural damage, such as ceiling tiles and lighting fixtures, allowing participants to practice in a realistic environment. These drills give immediate feedback, enabling users to adapt their behaviour and better prepare for actual earthquakes by familiarising themselves with potential hazards.
[36]	They created a VR environment to simulate seismic impacts on ceilings and furniture. This virtual model allows occupants to practice earthquake safety drills in a controlled but realistic setting, where they can rehearse responses to falling objects and debris, ultimately helping to reduce injuries and enhance survival skills.
[37]	They developed VR scenarios to evaluate and improve occupants' reactions to earthquake conditions. This system enables participants to experience an earthquake in a safe, virtual setting, where they can practice appropriate responses, such as identifying safe zones and making quick, informed decisions on evacuation.
[39]	They designed a VR serious game tailored for hospital environments, allowing healthcare staff and patients to practice earthquake safety protocols in a realistic yet safe space. This study emphasises the need for specialised earthquake training in high-risk settings like hospitals, where quick and efficient responses are crucial for patient and staff safety.
[49]	They created a VR serious game that immerses users in earthquake scenarios to practice behavioural responses, such as moving to safe zones or finding escape routes. The game focuses on post-earthquake evacuation, helping occupants rehearse evacuation procedures realistically, which builds their confidence and readiness.
[50]	They developed VR-based earthquake drills that teach essential survival strategies, allowing occupants to learn how to protect themselves during earthquakes. These drills simulate realistic scenarios to help users understand the importance of quick responses and reinforce safety behaviours in earthquake-prone areas.
[67]	They introduced spiral narrative structures and immediate feedback in VR training, which helps participants learn incrementally. Users receive real-time feedback on their actions, enabling them to correct mistakes and improve their responses for future earthquake scenarios, increasing retention and adaptability.
[54]	They developed a customisable VR game adaptable to various building layouts and scenarios, providing tailored earthquake emergency training. This adaptability allows the tool to be used across different types of buildings, such as schools, offices, and public spaces, ensuring relevant and practical training for diverse environments.
[68]	They created VR serious games specifically for children, incorporating age-appropriate instructional mechanisms. This training is designed to engage children in learning earthquake safety in a way that is memorable and easy to understand, thus increasing their awareness and ability to respond appropriately in real events.
[70]	They examined the impact of early earthquake warning messages in VR, analysing how effectively different messages prompt immediate responses from occupants. This study provides insights into optimizing early warning systems to ensure that people understand and respond swiftly when an earthquake warning is issued.
[71]	They investigated how individuals react to unexpected earthquakes in VR, providing valuable insights into natural evacuation behaviours under surprise conditions. These findings help refine evacuation training by accounting for realistic, instinctive responses, making emergency drills more effective.
[53]	They provided a detailed analysis of human decision-making processes during earthquakes and post-earthquake evacuations by utilising verbal protocol analysis in an immersive virtual reality (IVR) environment. It identifies key behavioural patterns, such as how individuals choose safe zones, prioritize actions, and navigate evacuation routes under stress. These insights enhance the understanding of occupant behaviour during emergencies, enabling the development of more effective evacuation strategies and improving training systems for earthquake preparedness.
[69]	They conducted a sequence analysis of occupant behaviours during indoor earthquakes and post-earthquake evacuation using immersive virtual reality (IVR). It identifies patterns in evacuation actions, decision-making sequences, and behavioural responses under stress. These findings provide valuable insights into optimizing evacuation procedures and designing safer indoor environments by tailoring strategies to actual behavioural tendencies during emergencies.
[40]	They improved the realism of earthquake evacuation models. The study introduces a physics-based model that simulates the movement of non-structural components (like furniture and ceiling fixtures) during an earthquake. By simulating both the oscillation of flexible components (e.g., shelves) and the movement of movable components, this model accurately depicts how objects behave under seismic forces, enhancing the predictive accuracy of crowd evacuation and virtual emergency simulations. This work provides a scientific basis for creating highly realistic indoor earthquake environments, helping researchers understand potential obstructions and safety risks.
[28]	They have developed a predictive model using BIM combined with FEMA P-58 standards to assess potential seismic loss. This model aids in resilience planning by helping building owners and policymakers anticipate financial losses, structural damage, and occupant safety risks, enabling proactive mitigation strategies.
[17]	They created dynamic simulations for indoor evacuation during seismic events, allowing planners to evaluate and optimise escape routes under earthquake conditions. This tool helps to design safer building layouts and prepare evacuation plans that account for the unpredictable nature of seismic events.
[42]	They integrated BIM with agent-based modelling to assess the impact of non-structural damage on evacuation processes. This approach enables the simulation of various damage scenarios, such as blocked exits due to falling debris, which is essential for developing emergency planning and evacuation strategies.
[55]	They created a machine learning-based simulation to predict the progressive collapse of reinforced concrete structures during earthquakes. This tool provides policymakers and engineers with rapid structural integrity assessments, enabling quick decisions about building safety and retrofitting needs.
[52]	They combined AR with BIM to create a visual framework for post-earthquake damage assessment. This approach allows engineers and planners to visualise the extent of damage and plan retrofitting actions effectively, ensuring that repair strategies are data-driven and accurately address structural vulnerabilities.

[54,68] and hospital staff and visitors [39,49,53]. Furthermore, planners, designers, engineers, architects and building occupants were identified as essential target audiences, highlighting the importance of integrating seismic resilience into building design and construction practices [42]. Some studies targeted safety engineers and architectural designers [17,40]. Additionally, there were several instances when no specific audience was applicable [16,28,52,55,69].

4.8. Reported challenges

This research identified several technological and interoperability challenges related to the study objectives. The challenges outlined in this review are reported directly by the study authors. A comprehensive overview of the prevalent issues encountered in the field is presented by systematically organising and categorising these reported challenges. This approach ensures that the findings reflect a broad consensus within the literature rather than individual interpretations or assumptions, providing a foundational understanding of the primary obstacles currently facing research and practice in this area. Uncertainty was notable in the simulation processes, which could affect the reliability of the results. Additionally, there were limitations in considering only specific components, such as suspended ceilings, but disregarding other important nonstructural components, such as partitions, cladding or piping, potentially undermines the comprehensiveness of the findings [36,37]. One of the challenges was evaluating the safety of different earthquake actions based on determining the actions of a single occupant. However, it was recognised that in real-life scenarios, multiple occupants may interact and influence each other's decisions during an earthquake [37]. Moreover, the transition of BIM data into gaming engines raised concerns about data loss and the need to optimise virtual environments. Reliance on simplified physics simulations rather than highly realistic ones in the Unity game engine was acknowledged as a constraint [39]. Using video and image datasets showcasing earthquake-induced building damage could not accurately simulate the structural responses of building elements during and after earthquakes [49]. Furthermore, challenges related to human behaviour modelling and the lack of earthquake videos for validation purposes were recognised as difficulties to some of the studies' accuracy and reliability [17].

A gap exists between IVR and reality for IVR SG training research. IVR training for earthquake preparedness has several limitations that create a gap between simulated and real-life scenarios. IVR lacks key sensory elements such as ground vibrations and structural shaking, which are critical for conveying the urgency of an earthquake. Without these physical factors, participants may not fully perceive the event's intensity, leading to less realistic responses [36,40]. Additionally, IVR does not expose participants to real physical risks or genuine stress, which is essential for quick decision-making. In actual earthquakes, the threat of harm drives rapid reactions, while IVR's absence of true danger can lead to slower responses and a false sense of readiness. Simplified decision-making and calmer emotional responses in IVR mean participants might not develop the adaptive skills needed for real emergencies [72]. Furthermore, IVR often lacks physical models of non-structural components, like furniture, which move dynamically during earthquakes, limiting its ability to simulate real hazards from falling objects [36,40].

Another issue is the fidelity of IVR. Although IVR has been reported with a high level of realism, which was identified as the main contributor to the sense of presence, there is still room for improvement [53]. Moreover, retention measurements were notably limited in these studies, highlighting the need for a markedly comprehensive investigation of long-term training effects and the narrow scope of comparison against all traditional earthquake training methods. For studies that used qualitative data, the types of damage scenes are possibly limited by existing data [37]. In some studies, ground motion was directly used to calculate the damage to nonstructural components. Additionally, the dynamic seismic response of the building structure was not considered, leading to a significant error in determining the damage to nonstructural components [50]. All human behaviours, such as collision, which can directly affect another agent's injury or fear level, were not considered [42]. Quantitatively verifying the model using real videos was challenging due to the lack of global earthquake videos of public places and the lack of corresponding location and seismic data. Therefore, models have verified rationality by comparing them to other models [17].

5. Discussion and Conclusions

This study provides a systematic literature review of existing approaches and methods to simulate and visualise indoor seismic damage. This undertaking was done by analysing 20 papers published between 2013 and 2023 that provide insights into simulation and visualising indoor earthquake damage (see the selection criteria in Section 3.2). Analysis of the selected papers was guided by the eight questions to assess the type of applications and design solutions (i.e., hardware and software) proposed to simulate and visualise earthquake damage, as presented in Section 3.1. As such, data extracted from the 20 papers provide a comprehensive overview of the research from 2017 to 2023. This review shows a significant increase in publications from 2017 onwards, indicating an increasing interest in this field. The development of numerous sophisticated computational tools and visualisation software has facilitated detailed and accurate simulations of earthquake impact in recent years [73].

The studies showed that most existing literature focuses primarily on institutional buildings, including hospitals, universities and schools. This finding could be attributed to these buildings' high occupancy and significant functions, prioritising their safety and resilience. When assessing the case study geographically, the findings show that most studies are in China, with some focusing on New Zealand and Australia (Section 4.1). This finding could reflect these regions' seismic risk profiles or the academic communities' research priorities. New Zealand and China are located in seismically active areas, making researchers particularly interested in developing technologies to mitigate the effects of earthquakes. Other seismically active areas could significantly benefit from similar studies in the future. These studies followed significant earthquakes in both countries, raising awareness of the need for additional research.

Most studies prioritised investigating furniture movement and non-structural component shake, highlighting these factors' impact on the overall seismic damage. Only two studies (10 %) adopted a comprehensive approach that considers all aspects of seismic damage, including ground shake, structural shake, non-structural shake and furniture response. This case could result from the technical and interoperability challenges in integrating the different damage simulation parts. The findings suggest that future studies should aim for a substantially balanced investigation encompassing all aspects of seismic damage to provide a comprehensive risk assessment and to enhance mitigation strategies.

This research also shows that studies simulate earthquake damage based on physical models or qualitative data. Each approach has advantages and can contribute valuable insights into earthquake simulation and visualisation. Meanwhile, physical models can receive reliable simulations, and qualitative data can offer a considerably extensive perspective and context. Advanced calculation and information required to process the physical model are complicated, and several detailed pieces of information, such as the structural and non-structural building components, earthquake location and magnitude and ground motion conditions, are necessary for assessments. However, the number of assumptions involved in qualitative data assessments can decrease the damage representation's reliability significantly; however, they may not provide the detailed information needed for precise engineering analysis and decision-making purposes and are suitable for training purposes [39]. However, complementing qualitative approaches with physical models to achieve the best results in real-world applications is often advantageous because they offer a considerably accurate representation of seismic effects and structural responses. In seismic damage simulation, the surveyed literature indicates a preference for utilising advanced software tools to model and visualise the potential impact. According to the survey, Unity and Revit were the most popular choices for software; they combined different sets of features and were, therefore, the most effective for simulating structural and non-structural damages. The simulation was made possible through Unity's integration of the PhysX physics engine, enabling substantially accurate simulations of non-structural movements without compromising physical accuracy. Moreover, Revit's detailed 3D modelling capabilities were utilised to represent building structures accurately. Data sources played an essential role in informing these simulations, with qualitative data derived from BIM models, building plans and post-event media providing a solid foundation for realistic modelling. Ground motion database and FEMA P-58 guidelines were instrumental in analysing ground and structure shakes, offering a data-driven approach to understanding seismic responses. The selection of software and hardware plays an important role in determining the effectiveness and realism of visualisation. The utilisation of Unity has been particularly prominent. Its pairing with head-mounted display VR headsets, such as HTC Vive and Oculus Rift, has enabled meaningful immersive experiences for understanding and analysing damage scenarios in virtual environments. Most studies used unity pairing with head-mounted display VR headsets for visualisation, whilst a few used other visualisation software, such as Unreal 5 or Augin, for phones. Based on the data analysed, the various aspects of simulation and visualisation of earthquake damage are summarised into a conceptual framework, as shown in Fig. 6.

One of the notable challenges highlighted is the uncertainty of the simulation processes, which impacts the reliability and accuracy of the results. Reliance on simplified physics simulations rather than highly realistic ones in specific gaming engines underscores a constraint that could compromise the simulations' reliability. Furthermore, limitations in considering only particular components, such as suspended ceilings, whilst disregarding other critical non-structural components, such as partitions, cladding or piping, pose a significant risk to the comprehensiveness of the findings. Another important challenge is the modelling of human behaviour during earthquakes. The absence of comprehensive human behaviour modelling, including such factors as collision dynamics and their impact on injury or fear levels, represents a notable research gap. Moreover, the lack of earthquake videos for validation purposes presents a challenging problem in quantitatively verifying the models. Without access to real-world data for comparison, researchers must rely on alternative methods, such as model-to-model comparisons, to validate the rationality of their simulations. Furthermore, considering ground motion directly to assess non-structural damage instead of the dynamic seismic response of the building is another challenge that may cause significant errors.

This study conducted a systematic literature review highlighting the need for advanced simulation and visualisation technologies in understanding and mitigating indoor seismic damage. The review highlights the importance of integrated approaches that merge ground shaking, structural response, and non-structural component behaviour to achieve a higher level of reality in damage prediction. Future research should focus on enhancing the realism and accuracy of simulations and improving interoperability between various digital tools. Advancing these technologies is essential for developing more effective earthquake preparedness and response strategies, ultimately reducing the social, economic, and environmental impacts of seismic events. This research identified gaps and opportunities that outline a clear roadmap for advancing the field. This review offers insights into how researchers can enhance the accuracy and integration of simulations, paving the way for realistic applications in disaster preparedness. Specifically, VR and AR-enhanced simulations can serve as immersive training tools for building occupants and emergency responders, improving readiness and minimising casualties and economic losses during real earthquakes. For industry stakeholders, these findings highlight the capabilities and limitations of current technology, promoting innovation in building design, safety protocols, and disaster response.

Funding

This research was supported by the Massey University Doctoral Scholarship, which is gratefully acknowledged.

CRediT authorship contribution statement

Noushin Naraghi: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Zhenan Feng:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Ruggiero Lovreglio:** Writing – review & editing, Supervision, Methodology, Conceptualization. **V. Vishnupriya:** Writing – review & editing, Supervision, Conceptualization. **Suzanne Wilkinson:**

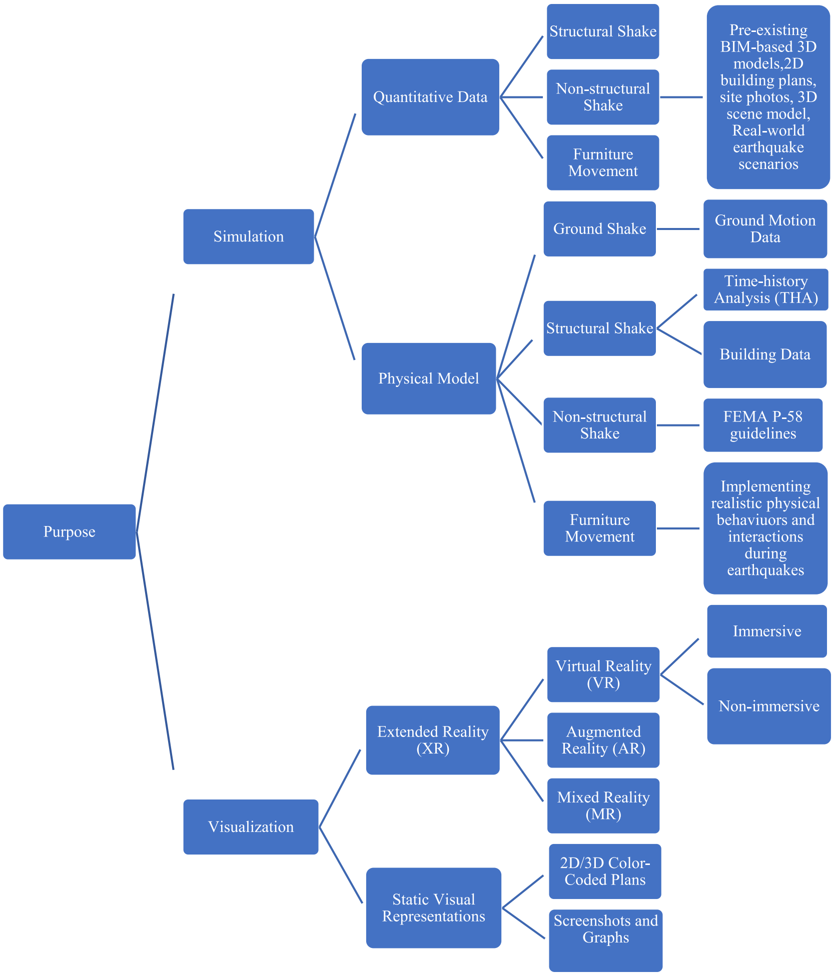


Fig. 6. Conceptual framework for the simulation and visualisation of seismic damage.

Supervision, Conceptualization. **Abdollah Baghaei Daemei:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendices.

Appendix A. Summary of the eligible papers (Attached during the submission as an Excel file).

Data availability

No data was used for the research described in the article.

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