

Earthquake Disaster Simulation in Immersive 3D Environment

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SUMMARY:

Human response to any adverse situation can be greatly enhanced through training and mind-body experience. Earthquake is one such phenomenon where human response to minimise injuries/deaths is constrained due to disorientation of the victims. People in regions with frequent earthquakes often exhibit better response due to past experience. Training of the mind and body can also be achieved in a virtual environment where the risks associated with a real earthquake shaking can be eliminated. This is feasible by using an immersive 3D environment for earthquake disaster simulation. This paper presents a new method for earthquake simulation for disaster management purposes, which combines knowledge in the field of structural engineering, cinematography and immersive 3D technology. In this technique, nonlinear time history analysis of a building and/or its internal content are performed and earthquake response of building along with its content recorded for duration of motion. These time history results of building and/or its contents are then used to realistically represent the consequences of the earthquake in a virtual 3D environment after converting the mathematical model to physical model. This method brings three very different fields, namely structural engineering, cinematography and immersive technology together and put it to a novel use as an earthquake simulation system. This paper describes the process of creating the final product in the form of 3D immersive virtual reality simulation of an earthquake.

Keywords: earthquake simulation, immersive environment, virtual reality, disaster management.

1. INTRODUCTION

The human response during disasters such as an earthquake is often observed to violate scientifically-recommended safety measures (Fritz and Williams, 1957). It is common knowledge that the response is most appropriate in regions with frequent earthquakes, while the response may be highly inappropriate resulting in avoidable casualties in regions with infrequent earthquakes. This is due to better training of the human mind to recognise an earthquake and determine safety actions during an earthquake in regions with frequent earthquakes. In regions with less frequent earthquakes, the mind's lack of experience in recognising the situation and its consequences constraints suitable actions. It is also recognized that response to infrequent events can be better remembered through experience than through other techniques such as reading about it. Since a real earthquake often has associated risk of injury or death, the training of mind can be safely enhanced only through the use of an environment similar to that due to a real earthquake, but without the associated dangers. In a limited way it is possible to create such an environment on large-size shake tables, but their applicability is very limited (only small area of room without the surrounding environment), expensive and non-repeatable (since the setup is likely to be damaged after one use).

This limitation of simulations on a shake table can be overcome by using immersive virtual reality solutions. Technological advancements in this field allow creating a real-looking situation of the buildings, their internal content and environment surrounding the building. By combining this facility with advanced nonlinear structural dynamics creates a powerful system which will help in creating seismic scenario. The simulations can be repetitive, cost effective, hazard-free and able to create as many audio and visual details as desired.

2. RELATED IMMERSIVE VIRTUAL ENVIRONMENTS AND DISASTER SIMULATIONS

Virtual environment has been used developed and used for various applications in other fields. US Patent No. 6,154,723 (Cox et al., 2000) describes a virtual reality 3D interface system for data creation, viewing and editing. The patent describes the hardware of 3D virtual reality creation, manipulation and editing system including a voice and 3D gesture input interface, wherein a group of people can experience virtual reality at the same time. Such a system can be utilized as a virtual reality platform on which the required earthquake simulations can be created.

US Patent No. US 6,563,489 B1 (Latypov and Latypov, 2003) describes system for placing a person into virtual reality. The system comprises a closed sphere shaped capsule defining a real environment. Any virtual environment can be created by virtual environment generating means and means for displaying the virtual environment to the user. Limitation of the system is that only one user at a time can use the system. This system too can be utilized as a virtual reality platform on which the proposed method can create the required earthquake simulation.

US Patent No. US 6,774,885 B1 (Even-Zohar, 2004) describes a system for dynamic registration, evaluation, and correction of functional human behaviour. The patent describes a real-time motion tracking and feedback technology using virtual reality and physical motions. Motion capture technology and a motion platform with runtime interaction in a real time feedback loop to provide a physical and virtual environment. Such interactive systems can be used in the present invention for registering interaction between the users and the objects under simulation.

It is seen that while technology platforms suitable for disaster simulation may exist, they have not been utilized to simulate realistic disaster scenarios. Developing a disaster scenario further requires mathematical simulations of structures and their content based on rigorous engineering principles, interfacing of effects such as light and sound, etc.

3. EARTHQUAKE DISASTER SIMULATION

The process of creating virtual earthquake disaster scenario can be split into four main components: (1) designing the scenario, (2) carrying out nonlinear dynamic analysis of buildings and their content, (3) interfacing light and sound simulations based on dynamic analysis results, and (4) creating a virtual environment based on the above. First part deals with the details of the visual scene. It deals with the questions like what to show, degree of complexity, details of scene, etc. The scene should be designed to meet the objectives of the simulation. The second part can be subdivided into: (a) planning of the earthquake scenario based on the insightful knowledge of disaster management training and earthquake engineering, (b) selection of a set of time-history excitations on the basis of the simulation objectives, (c) creation of structural models capable of linear and nonlinear analysis based on the knowledge of earthquake engineering and visualization objectives, and (d) nonlinear dynamic analyses of the structure and/or contents to generate response time history. The fourth part of creating virtual environment can be subdivided into: (a) creating 3D computer graphics models of the scenario objects and mapping the estimated time history responses onto these models thereby generating 3D animations depicting the exact things happening around in the scenario during the course of the earthquake, and (b) rendering the said animations for the virtual reality platform of interest.

3.1 Scene setup

The most important task is to decide the setup that is to be presented to the viewers. The setup depends on various factors such as the objectives of the disaster scenario, details of the target group, intended level of complexity and maximum number of people intended for simultaneous viewing.

A scenario can be developed for various purposes. It can be used to emphasize the need of earthquake resistance design to architectural/engineering students/teachers/professionals involved in building construction. For such a case scene should be able to capture behaviour of overall building, structural members such as beam-column joints, shear wall, etc. If the objective is to spread awareness among school children, a classroom setup can be created where importance of safety measures such as “drop, cover and hold” can be emphasized. A general purpose setup of a typical household room and/or office room can be created to spread earthquake awareness among general public. A very special target group can be rescue workers who are involved in search and rescue operations in the aftermath of an earthquake. This group needs special scenario setup because an already damaged building behaves very differently in case of aftershocks. Hence setup for this group will be entirely different from any other groups. Similarly, this group can be provided with simulation training to support their activities such as collapsed structure search and rescue, confined-space movement, etc.

In accordance with the scenario requirements, structural properties of the building are finalized such as material (masonry, steel, RCC etc), dimensions (height, length and width), plan (rectangular, circular, T-shaped, L-shaped or irregular) and elevation. Once a scenario is fixed it is very important to decide up the level of complexity. Careful selection of internal elements is equally important as too many elements may clutter the internal space during the earthquake excitation and may thereby create trauma among the viewers. On the other hand too few elements may not create strong enough impression for long-lasting memory. Hence a balanced should be struck between these two extremes and a realistic looking scenario should be presented to viewers. In addition to the contents of room, the scenario outside the room, if visible, can also be suitably displayed.

3.2 Dynamic Analysis

Dynamic analysis tools have improved much in last couple of decades. Now it is possible to perform dynamic analysis and contact analysis with relative ease and faster than ever before. This helps in generating time history results of buildings and its internal contents. Modeling setup for a dynamic analysis is a multistep procedure, which is discussed in the following subsections.

3.2.1 Selection of base-excitation time-history

Selection of suitable base-excitation time-history is the first step towards creation of earthquake scenario. A careful selection of scenario will provide realistic results as per target group needs. A simple educative/awareness scenario should not be having very strong or very long earthquake motions to create panic among the viewers. The earthquake scenario for target group with engineering background may have shaking strong enough to stress upon the need of earthquake resistance design. If the scenario is being developed for a particular region, the time history should be selected based considering site-specific parameters.

The ground motion data is available in the form of displacement/acceleration recorded at time interval of fraction of second to several seconds. Each earthquake has its own peculiar characteristic, such as duration, intensity, frequency and the like. Hence, it is extremely important to choose earthquake records that suit the requirement. This is a highly specialized skill because inappropriately chosen earthquake data cannot create the desired structural response to meet the simulation objective. This earthquake data could be a scaled/modified version of one of the pre-recorded historic earthquakes or could be a synthetic ground motion data appropriately complementing the simulation objective.

The selection of appropriate earthquake candidate is governed by many factors. For example the chosen building plan can be analyzed for its modal frequencies and a candidate earthquake data is then selected from the pool which does not adversely affect the simulation objective by exaggerating the building response due to tuning, or making the displacement response unstable for building components. The ground motion data may also be selected on the basis of site location of the building, for example if the building plan is imitating a real life structure, the historic earthquakes occurred in the surrounding geographical location could be used for the purpose of creating the simulation. Earthquake data selection could also be affected by target audience. For example if target audience is

school children and simulation objective is for just a mild sensitization and trauma-free experience, a low intensity earthquake might be selected for the simulation. On similar lines target audience could be professionals related to construction industry, search-and-rescue professionals, engineering/architecture faculty and students, government officials or other specific target groups, with each group influencing the simulation details. The selection is also affected by exact training purpose, which could be for example awareness or emergency management. It should be noted that these factors influence the formation of a pool of simulation candidates but ultimately the further steps in the process may reject any simulation candidate based on the unsuitability considering other factors.

3.2.2 Selection of buildings and their internal contents

In creation of a seismic scenario it is extremely important to select appropriate building/room dimensions. This selection depends upon immersive 3D system capabilities. A system which has projection system all around can very effectively produce the room effect. On the other hand if system is not fully immersive and is to be viewed by many people at the same time, it is more useful to show outside view of the building. This will again have many options to choose from, i.e. low-rise, mid-rise or high-rise buildings. The building selection also depends upon the structural software capabilities. For example a steel or RCC building is easy to model using FEM and produces reliable results for time history analysis. The structure models can be designed to simulate both linear as well as nonlinear behaviour to accurately replicate the response. On the other hand a random rubble masonry building or mixed construction type (e.g. wood and masonry) is not possible to solve realistically and efficiently using FEM analysis, and suitable approximations need to be made in order not to compromise the realism in the simulation.

In case the building interior is shown it is required to show internal artifacts which could convey realistic situation in the event of earthquake. A school room should have classroom furniture besides wall fixtures, electrical fittings, etc. The setup of an office room or living room should portray furniture, flowerpots/showpieces, wall hangings, chandeliers etc. Appropriate mathematical models of these should be created for their time history analysis.

3.2.3 Analysis of the model

Once the building exterior/interior is finalised an earthquake time history is chosen, the linear or nonlinear dynamic analyses can be performed using general-purpose or specialised software. The analysis results are required in the form of displacement time history of nodes.

Based on the simulation objectives, it can be decided whether nonlinear modelling and analysis is required for a particular object. Material nonlinear modelling depicts behaviour of the material, which is commonly observed in the case of strong earthquakes. Such modelling enables accurate prediction of cracking in masonry or concrete, dents in metallic objects and other such behaviour which is not possible to model through linear modelling. While designing linear models, a suitable element mesh configuration is estimated taking into the consideration the requirements and limitations of the visualization objective.

RCC or steel buildings are generally adequately analyzed as their wireframe model. Final time history response of the building can contain motion profiles, stress/strain profiles or any other desired physical quantity which can be helpful in creating the visualization. This is passed to the virtual environment creation software which generates earthquake response motion of the building using the nodal displacement history.

Once the displacement time history analysis of entire building has been completed, the results can be used to also model a part of building with internal components. This often requires geometrically nonlinear analysis including contact analysis as internal contents will slide/topple on floor, bounce of walls/floors, collide with adjacent objects, etc.

Apart from creating motion time history of the structure, it is equally important to simulate crack, damage and/or collapse in the structure for creating realistic visuals and lasting impression. Cracks

formed during the course of an earthquake are highly non-linear and their propagation geometry is a chaotic phenomenon. To model such behaviour, first a non-linear time history analysis is performed on the structure of interest. On the basis of the result strategic locations are identified on the structure where such cracks might appear with high probability. Characteristic parameters that may aid in the correct visualization of such behaviour are identified. For example in the case of cracks, these parameters are maximum depth, maximum width and evolution with time. Physical attributes such as force and moment time history which may affect these characteristic parameters are collected from the location of interest. Physical properties of the element or a group of elements on which crack/damage will appear at the location of interest are collected as well. Once this data is in place, it is fed into complex and heuristic based non-linear empirical equations in order to estimate the required characteristic parameters.

3.3 3D Virtual Environment Creation

Once the earthquake time history responses are ready the next steps are to visualize this simulation data in a way that can maximize the impact of sensitization. The best way to do this is to have the visualization as close to realty as possible. Creation of 3D virtual environment is a task which is both technical in nature as well as an artwork. It relies upon simulation results and adds various effects on it to make it more realistic. These effect include colour and texture of building/internal contents/outer scenario, sound effects, light effect, etc. which can be jointly called as cinematographic effects. This process can be divided into two main components: mapping of analytical results in virtual environment and creation of realistic scenario using cinematography.

3.3.1 Mapping of analytical results

In order to create these realistic visualizations advanced knowledge of computer graphics and cinematography is required. The visualization process starts with the creation of 3D computer models. On the basis of structural model of the object its corresponding 3D model is created (Figs. 3.1 and 3.2). While creating these 3D models particular attention is given to surface details, lighting conditions and texturing so as to mimic the real world as close as possible during the experience. Structural models act as a kind of skeletons for the creation of 3D visual models. The 3D modelling process can be carried out using numerous 3D software platforms such as Autodesk Maya, Autodesk 3D Studio Max, Blender to name a few. The process can itself be guided with the help of real life photographs of textures, lighting conditions etc.

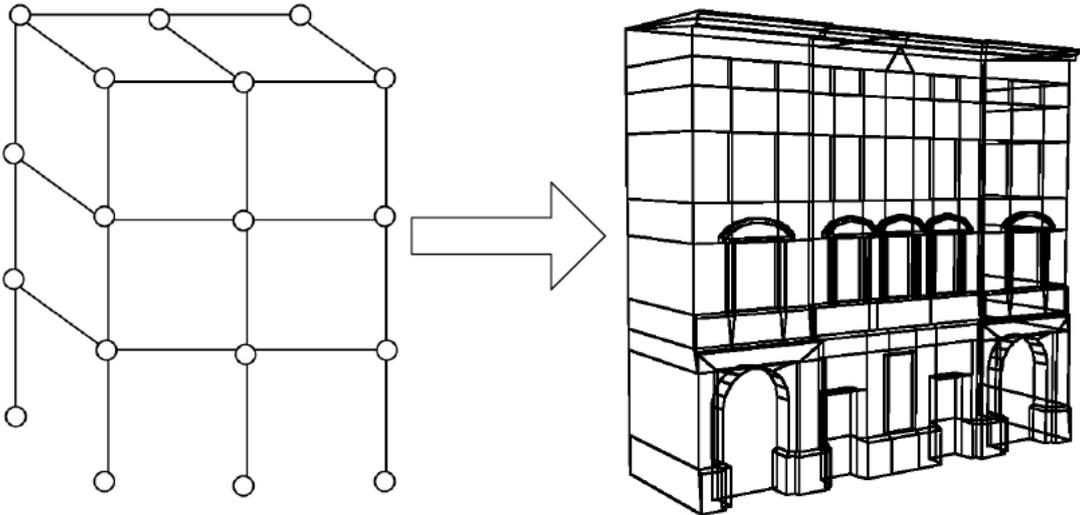


Figure 3.1. Conversion of FEM building model to virtual reality model

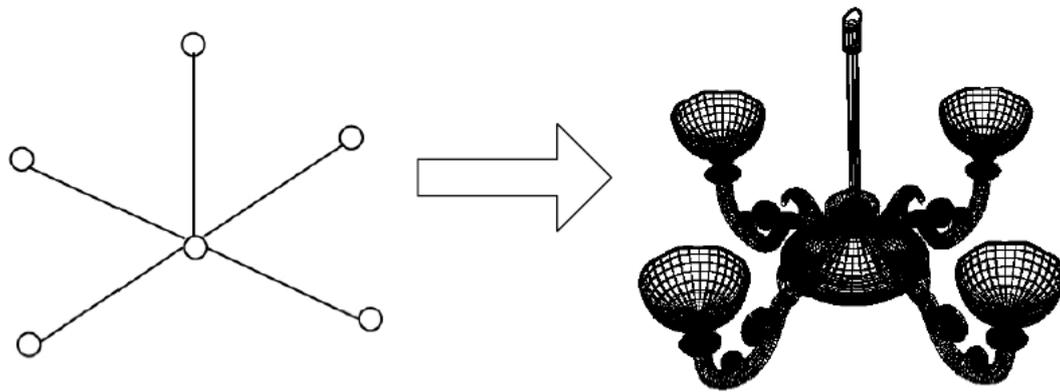


Figure 3.2 Conversion of FEM chandelier model to virtual reality model

The next step in visualization is to map the earthquake time history response estimated earlier to the corresponding 3D model. The result of this mapping is a dynamic animation showing the things happening in the scenario during the course of the earthquake. Earthquake response is not limited to simply the displacement profiles of the object during the course of the simulation but can also include things like crack formation, dust-debris and puff cloud formation etc. The visualization aspects of these responses can be governed directly by the numerical results as in the case of motion profiles (e.g. full building motion) and can also be mapped qualitatively (e.g. dust from cracks, light fluctuations) or a combination of both qualitative and quantitative approach (e.g. crack location, size and shape). While doing a qualitative mapping of the earthquake response onto the 3D object, earthquake engineering expertise play a major role in mimicking the effect of earthquake as closely as possible.

Earthquake motion response of the objects structure depends on many factors and can be highly complex and erratic during the earthquake. To map the motion profile of a particular object onto the corresponding 3D model, first it needs to be classified into appropriate category namely rigid, piecewise rigid or non-rigid. If the object structure does not significantly distort during the earthquake it can be classified as following approximately rigid body motion, for example a hard wooden photo-frame might behave like a rigid body during the course of the simulation. If object is an extended assembly such as a building structure, parts of facade can be classified to follow piecewise rigid motion, i.e. there is some amount of distortion across nodes and elements, but the general structure more or less remains same. If the major portion of an object is going under large distortions the motion is classified as non-rigid, an example of such a distortion will be the plates of an elevator colliding with enclosing slabs producing erratic deformations in the plate body. However it should be noted that this is done to simplify mapping process, in principle any parametric function can be used for mapping if it fulfils simulation objective.

For mapping the rigid motion profiles, the displacements of various nodes are taken and a least square solution is calculated which best approximates the required rotation-translation matrix for the displacement. These matrices can then be key-framed to create the animation of the 3D object. For mapping the piecewise motion profiles, lattice based animation techniques are used. Strategic lattice points are defined on the object facade, and node displacements are mapped onto these points. These lattice point movements then can be key-framed to create the animation of the 3D object. For mapping non-rigid motion onto 3D models, first a smooth subdivision surface representation of the 3D object is created, thereafter lattice points are defined at strategic locations which control the movement of the subdivision surface in a smooth manner. Once lattice points are in place, individual node

displacements are mapped parametrically on these lattice points. The distribution or density of nodes and elements created for the structural model play an important role in deciding the fidelity of such non-rigid animations. Further these lattice point movements are key-framed to generate non-rigid deformation animation for the 3D object.

3.3.2 Cinematographic effects based on earthquake experiences

Apart from motion profiles of the objects in the earthquake response, secondary effects do occur during the course of such an event. Formation of cracks on the walls or at beam column junction is very common during earthquakes. To map such effects with high fidelity a combination of numerical and qualitative methodology is used. Stress/strain profiles calculated during the numerical analysis can be used to arrive at strategic locations where possible cracks might appear; moreover these parameters can be used to arrive at approximate maximum depth and width of a crack at the point of interest. Qualitative approach comes into picture when determining the shape of a crack that might form at the point of interest, for example by studying the real world photographs of crack patterns during real earthquakes. A library of crack shape patterns in vector form can be created. Once such a library is there, an area of interest on the 3D object is chosen where these cracks can appear with high probability. An appropriate shape vector is chosen from the library which governs the shape of the crack that will appear in the animation. Maximum width and depth, estimated earlier at the point of interest governs the extent of the crack that will appear during the course of animation. Once location, shape and extent of a crack are decided, the frequency analysis of the earthquake can be used to derive the propagation and evolution of the crack with time. All of these can be key-framed to generate a displacement map textured onto the area of interest creating an effective 3D animation for crack formation. Figure 3.3 shows the motion of objects in a building corridor during a typical simulation after incorporation of cinematographic effects.



Fig. 3.3. Time-snaps of motion of objects in a building corridor showing the results of material and geometric nonlinear analysis after incorporation of cinematographic effects

Apart from motion and crack profiles there are other effects occurring during the course of an earthquake such as formation of dust and debris, puffs, smoke, and light fluctuations to name a few. A qualitative approach based on the knowledge of earthquake engineering and cinematography can be used to simulate these effects. The earthquake time history response can be used to identify possible strategic points at which such effects are to appear with high probability. Computer graphics methods such as particle systems or fractals can be used to simulate these effects. Light fluctuation occurring during the real earthquakes can be studied and artistically modelled in the simulation to mimic the real life effect. Although these effects are not necessary to be included in the simulation but they serve a purpose of increasing the realism and fidelity of experience. They can also substantially add value to the simulation objective.

The results of simulations where the motion of typical office furniture during an earthquake are shown in Fig. 3.4. Visual animations on immersive virtual reality platforms provide a sense of being present there in the simulation. The results thus are likely to remain in memory for a long time, and also assist to train the mind to behave appropriately during an earthquake. The sense of being present at site can

be further enhanced with the help of audio cues. Sounds produced during pre-recorded earthquakes can be used as a source or as guidance for creating simulation sounds. Various sounds occurring during the earthquake may include sounds arising out of collisions or collapse of scenario objects, ambient sounds, human voices/screams etc. For the purpose of realistically incorporating these sounds into the simulation, the location of sound sources and their propagation with time is modelled. Computer assisted methods for mixing sounds, as practiced in cinematography are used to produce multichannel spatial sounds which correctly replicate effects like Doppler, echo and decay.

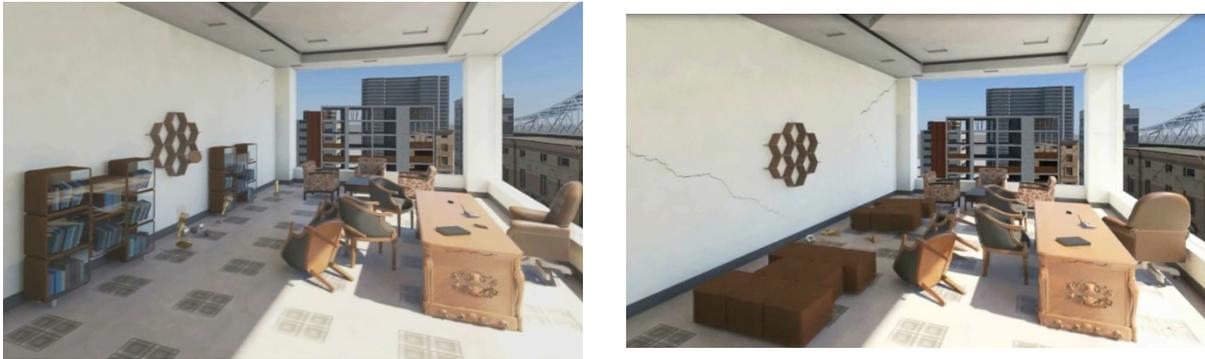


Fig. 3.4. Time-snaps of motion of office furniture that provides a realistic experience without the associated safety issues during a real earthquake

3.3.3 Selection of virtual reality platform

Once the visual and audio animation is ready, the next steps are to present this animation on the virtual reality platform of interest. Depending on the configuration of intended platform, required rendering output may differ. For example a 4 walled stereoscopic CAVE (Cruz-Neira et al., 1992) require 8 separate visual frames (left eye x 4, right eye x4) for each individual animation time step and can require as many audio channels as supported by the platform. On the other hand a simple one screen projection platform may require only 2 separate (one for left and one for right eye) visual frames per animation time step. Not only the number of frames but also the camera parameters for rendering an individual frame may differ across platforms, for example a cubical CAVE (Cruz-Neira et al., 1993) might require different camera parameters for rendering then a curved screen cylindrical system. On the similar lines placement of audio equipments can affect the rendering parameters for audio tracks. Depending on the virtual reality platform of interest rendering camera parameters are defined.

The path of an observer (camera assembly) in the earthquake scenario is decided based on simulation objective and cinematographic aspects. For example for the purpose of rescue training mission the camera path aligns with the training path which will be taken during the rescue mission. If the simulation objective is sensitization of school children, a less catastrophic camera path might be chosen to complement the simulation objective. Similarly if real-time rendering is being performed when simulation is playing on the platform, path of the camera can even be decided freely and interactively by the observer during the course of the simulation. The observer/camera motion is affected by the earthquake itself, which is accounted by adjusting the camera assembly displacement with the numerical time history response at the point of interest on the path. To illustrate this with an example, an observer at first floor of a building will feel different earthquake motion then an observer at 7th floor of the same building due to different locations having their own time history responses.

Frames can finally be rendered with the camera assembly. Rendering process itself can be performed in real time with the help of computers or it can be done as an offline batch process to generate video and audio sequences later playable on the virtual reality platform of interest. Offline visual rendering is performed in photo-realistic manner with the help of computer software such as Mental Ray or POV Ray to produce image sequences of exceptional quality and high realism. Advanced computer graphics rendering techniques for performing ray-tracing and global illumination are used by the software to arrive at the resulting photographic images. On the similar lines high quality audio rendering can be performed in real-time or offline. These rendered sequences can be played back on the virtual reality

platform in sync, to impart a wonderful immersive earthquake experience fulfilling the entire simulation objective for the participant.

4. CONCLUSION

Traditionally awareness about earthquake disaster has been spread through text and pictorial messages. Very limited live demonstrations with the help of shake tables or similar setups are possible due to safety, expenses and non-reusability issues. At the same time, it is well known that the human mind's ability to manage extreme events is greatly enhanced by past experience of similar events. In this paper, an immersive virtual reality system for earthquake disaster simulation has been described. This system uses the advances in nonlinear dynamic analysis, virtual reality technology and cinematography. The system can be used for various purposes such as sensitization of policy-makers, training and education of engineers and architects, sensitization of school children, and training of emergency managers. The "live" experience creates lasting impact on the viewers' mind. Hence the potential of this product is immense as a force-multiplier to enhance the impact traditional training and awareness campaigns.

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