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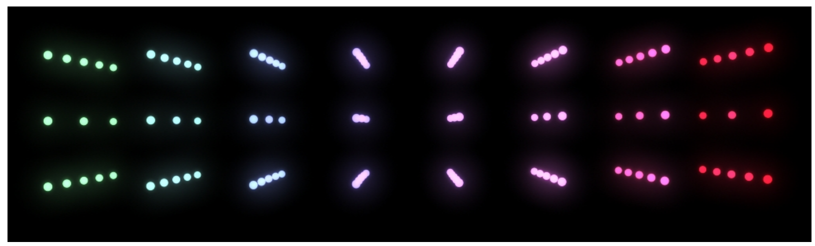
Digital Re-creation of a Seven-Story Building Shake during an Earthquake

by ***Amit Chourasia***



Introduction

It is often desirable to recreate environments and events based on observed data. Uses of such reconstructions are varied, ranging from documentary use to a specific scientific analysis. Computer graphics has become a mature discipline used to recreate past events in accurate and realistic detail. In this article, we explore the re-creation of a seismic response of a seven-story building based on recorded data of a full scale shake table test. This re-creation can potentially be used by structural engineers to study and analyze the data, and to understand the structural nuances from a 360-degree viewpoint.

Motivation

Earthquakes are a major threat in seismically active parts of the world. These seismic zones are mainly located near tectonic plate boundaries around the globe (**Figure 1**). Engineers are trying to design structures which can handle onslaughts of earthquakes. To analyze the impacts of an earthquake on a building, engineers study the building's structural performance in controlled test environments. Earthquakes are created by using Shake Tables. These tests yield a wide range of structural data including temporal recordings of stress, strain, displacement, accelerations, etc. In the present case, footage was recorded for each experiment by multiple video cameras and sensors recorded the impacts of the shake.

Such data is typically analyzed by creating tables and plots. There exists no clear way to combine textual data with video footage. An intuitive way to tie this data together is to create a visual representation. Thus, we set out to create a high quality visualization based on observed and recorded data. This visualization can make the results and conclusions of the experiment accessible to people beyond the domain experts, thus aiding the dissemination of the knowledge gathered. Our goal was three fold: 1) to create an intuitive and useful visualization, 2) to determine the requirements and features of an integrated visualization system for use by the engineers and scientists that can be used by the structural engineering community in general, and 3) to show that existing animation packages could be leveraged for scientific visualization. Before going into further detail on the digital re-creation, a brief overview of the seven-story shake experiment and its components is provided.

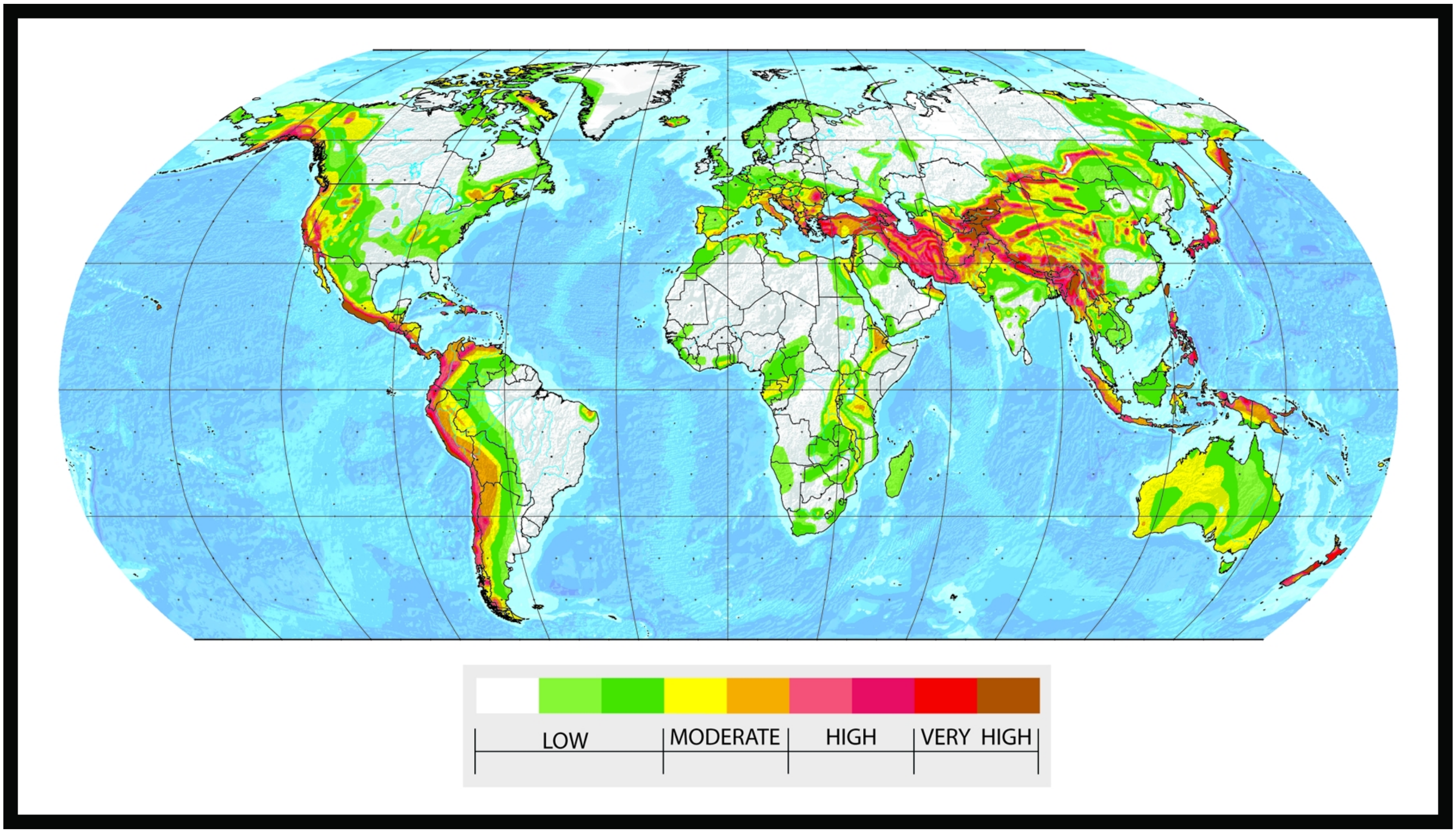


Figure 1: Global Seismic Hazard Map. The different colors indicate the level of seismic risk in a region. Source: Global Seismic Hazard Assessment Program

Shake Table

The Network for Earthquake Engineering Simulation (NEES)/Large High Performance Outdoor Shake Table (**Figure 2**) is a 7.6 meter by 12.2 meter long single degree of freedom (DOF) system with the capability of upgrading to 6-DOF. The specifications for the first phase of the facility are a stroke of ±0.75meters, a peak horizontal velocity of 1.8 meters per second, a horizontal force capacity of 6.8MegaNewton, an overturning moment capacity of 50MegaNewton-meter for a 400 ton specimen, and a vertical payload capacity of 20MegaNewton. The testing frequency range will be 0-20 Hz. Although this table is not the largest of its kind in terms of size, the velocity, frequency range, and stroke capabilities make it the largest table outside Japan and the world's first outdoor Shake Table. The facility [4] will add a significant new dimension and capabilities to existing United States testing facilities with no overhead space and lifting constraints.

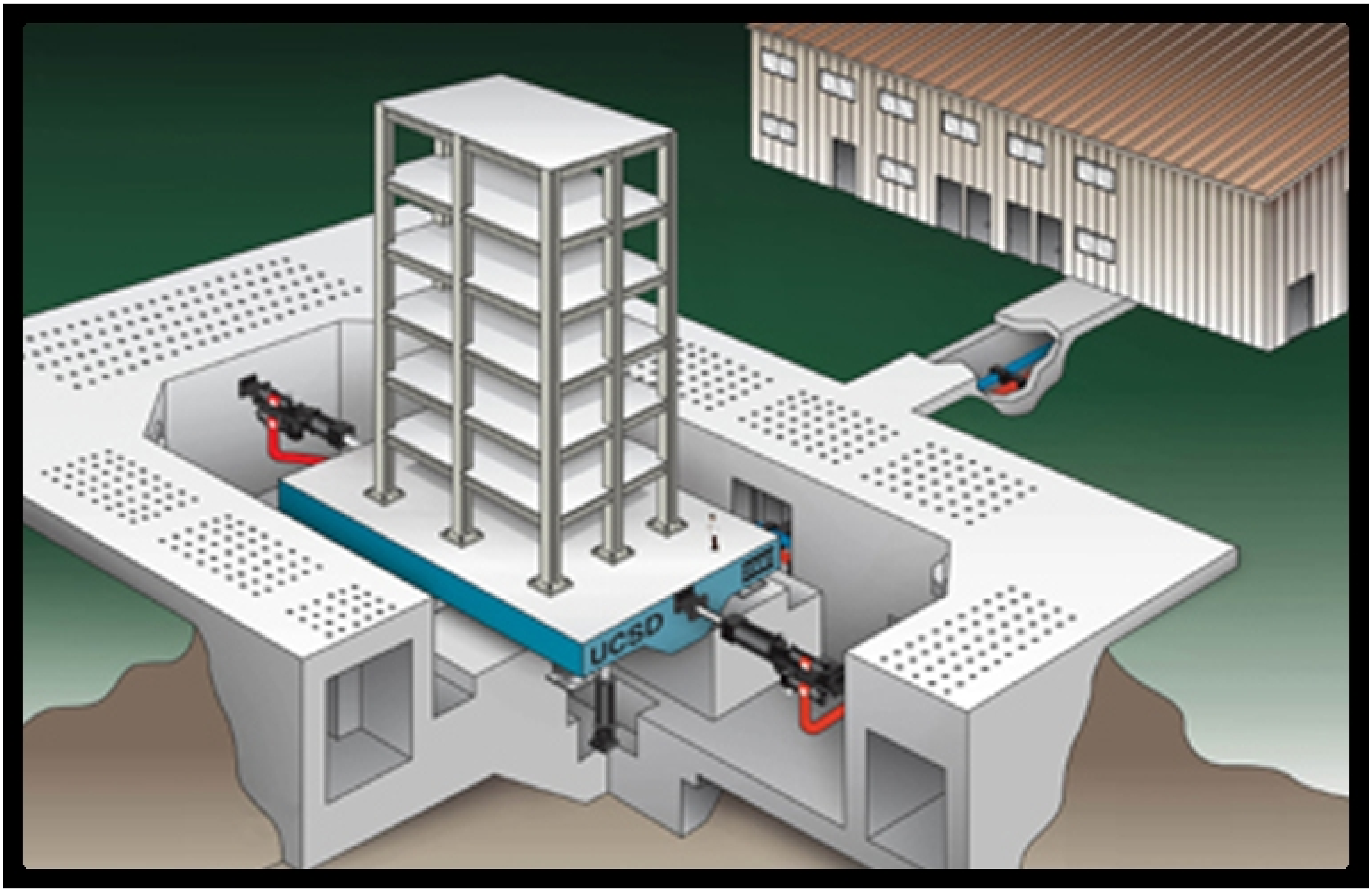


Figure 2: An isometric section of the Shake Table. The Shake Table is a flat platform shaken by hydraulic shafts as shown.
An animation of Shake Table operation is availble at the project website [1]. Source: NEES at UCSD

Seven-Story Building

The test structure is a slice of a seven-story residential building, 65-foot tall and 275 tons in weight. The building has structural walls as the lateral force-resisting system. A full scale replica of the building was created (**Figure 3**). The building consists of a main 12-foot long rectangular wall and two transverse walls which provides lateral and torsion stability during the test. The building is a cast in place reinforced concrete structure built on the Shake Table. An extensive network of sensors with more than 600 channels is used to measure the dynamic response of the building and its surroundings. For our re-creation, we were restricted to 108 channels of displacement data.

Figure 3: Photograph of the site showing the Seven-Story building built on the Shake Table.

Northridge Earthquake

On January 17, 1994, one-mile south-southwest of Northridge California an earthquake of magnitude 6.7 resulted in 60 deaths, more than 7,000 people were injured, 20,000 left homeless, and more than 40,000 damaged buildings in Los Angeles, Ventura, Orange, and San Bernardino Counties. The death toll and roughly $40 billion in property damage prompted professional structural engineers to call for more scientific testing of mid-rise residential buildings. The recorded seismograms from this earthquake were used for this experiment.

The Experiment

Ground motions associated with the Northridge earthquake were recorded at a hotel in Van Nuys, farther away from the epicenter of the earthquake. Since empirical data was available for a seven-story building, the proponents of the experiment chose to reconstruct the impacts of the earthquake on a slice of the seven-story building. The ground forces recorded at the Van Nuys location were recreated on the Shake Table. The shake tests were done in different phases with varying forces on the Shake Table. Panagiotou et al. [6, 7] describe the details and findings of this experiment. Here we concern ourselves with visualization of phase 1 data.

Related Work

Limited work has been done in the scientific domain for creating high quality visualizations. Light Detection and Ranging (LIDAR) based methods scan around the globe to create 3 dimensional (3D) terrains from the measured data. Image based reconstruction of geometry is a well studied area. Scientific visualization of MRI and CT scan data is a routine application in the field of medicine. Digital reconstruction is becoming a mainstream commodity with motion capture solutions leading the forefront of the gaming and film industry. Scenario simulations and their visualizations are gaining popularity as well. Popescu et al. [9, 10] and Meador [3] have demonstrated the use of animation tools to create visualization of September 11th terrorist attack on the Pentagon. Olsen et al. [5] have simulated and visualized a large earthquake on the Southern San Andreas Fault. Toolkits like VTK offer a framework for visualization but they lack realism. Off-the-shelf software solutions for 3D animation and modeling are becoming lucrative for scientific visualization. Our own efforts of recreating of 1906 San Francisco earthquake [11] based on simulated data with animation packages was very successful. The present study required the capability of Free Form Deformation (FFD) of a seven-story building. Most scientific visualization tools lack this capability. Further, implementing FFD of arbitrary geometric objects is a quite challenging task, typically consuming substantial resources. In this study we utilize an existing off-the-shelf animation tools and show how these tools can be applied to the structural engineering domain. Significant benefits can result from the use of animation tools that offer state of the art FFD techniques and high quality rendering. They can also provide an added advantage of reduced turn around time for visualization.

Visualization Challenges

Our goal was to recreate the Shake Table experiment. Therefore, the visualization was required to have fidelity not just in rendering quality but also in visual realism. It was necessary that the visual representation be recognizable when compared to the real world counterpart. This necessitated the integration of surrounding elements for providing a rich visual context. The resulting visualization can potentially lead to improved communication among interdisciplinary teams and help in dissemination of results to non-specialists. Additionally, the visualization had to be capable of presenting the information in an intuitive manner with a high degree of accuracy. This would require depiction of sensors in a visually non obstructing manner. Lastly the visualization system had to be capable of scene file management, material editors, light utilities, camera setup and able to show results in real-time through a user interface (UI). Some of these issues have been mentioned earlier [10]. Though some progress has been made, but largely these challenges remain.

Digital Re-creation

Several commercially available packages can be used to recreate this experiment. We chose Autodesk's Maya [2] as the platform for digital re-creation. Maya provides a rich set of built-in functionality for 3D modeling, animation, FFD, lighting and rendering. In addition, it provides an easy to use interface and flexible framework to lend itself for different programmable customizations. We provide a brief overview of our visualization pipeline.

3D Modeling

The very first step to re-creation is to create the site. We used digital drawings of the test site to create a detailed 3D model (**Figure 4**). The building is simple as it contains only the structural elements with no ornamentation. Creating the 3D model was a straightforward process. We also created a few key surrounding elements around the building to provide contextual information. The polygon count for the 3D model was about 20,000 triangles. To make the test site look real we textured our 3D model using photographs of the actual site processed in an image editing software.

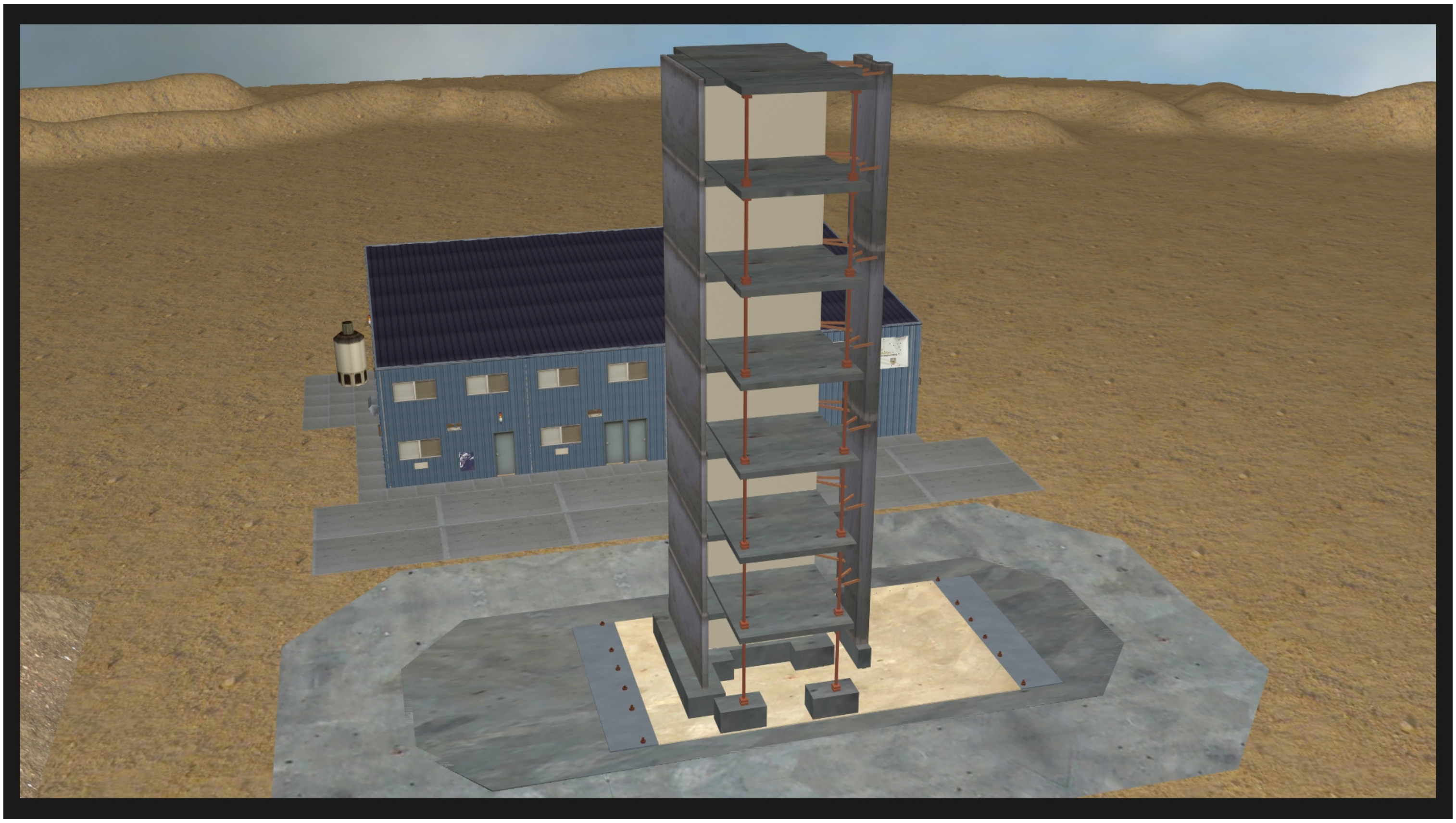


Figure 4: A 3D model of the experiment site. The seven-story building is built on the Shake Table. The machine room and monitoring facility is located in the rear building.

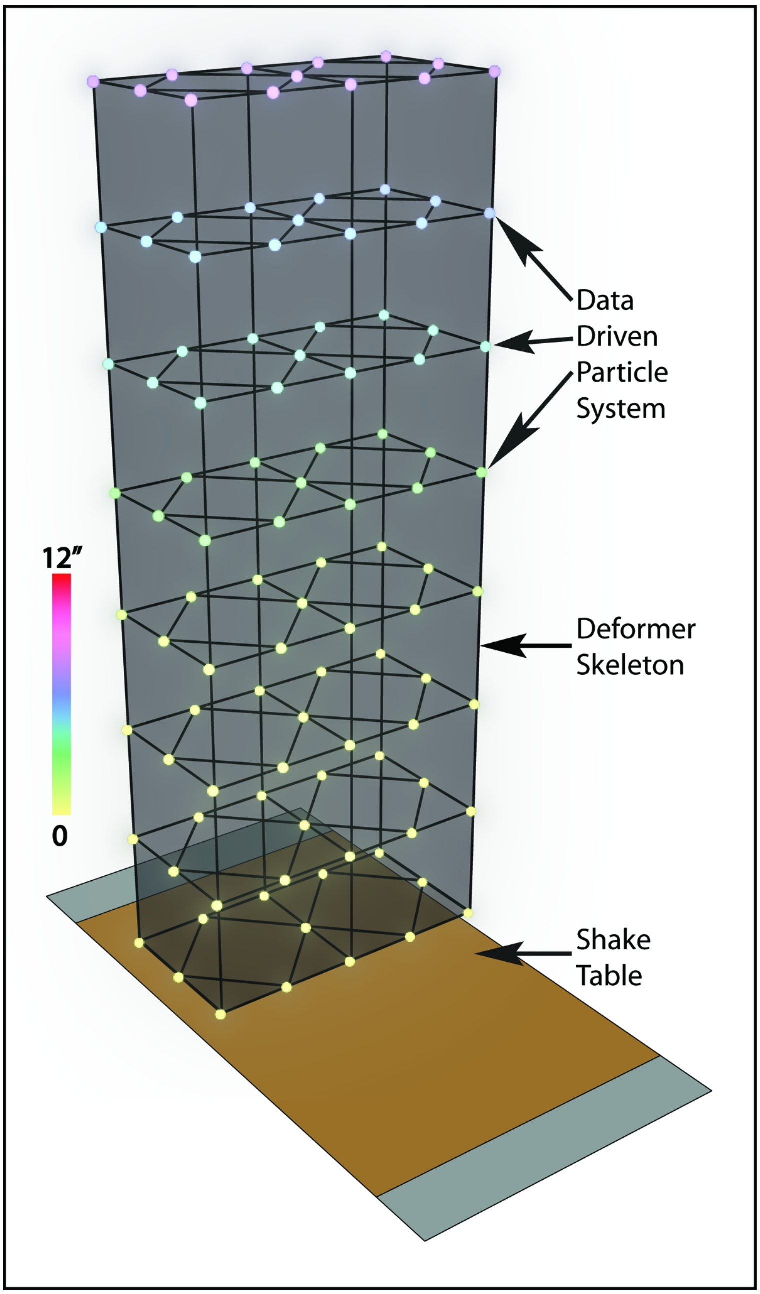
Data Translation

The experimental data was provided as an ASCII text table. This needed to be transformed into a format that Maya can interpret. We have developed a custom C++ library [8] that transforms this data into particle disk cache (PDC) format. This format is internally used by Maya's particle system to drive animation of each particle with various properties including position, color, mass, velocity and lifespan. The PDC format stores real numbers in double precision which ensures that the accuracy of data is maintained during translation. There exists a simpler method to achieve a similar result with Maya Embedded Language (MEL); however, from our experience we have found the MEL implementation to be non-scalable, resource hungry (memory and CPU intensive) and unsuitable for real time feedback.

Animation and Deformation

The key aspect of the visualization was the deformation of the building based on observed data. Maya provides built-in tools to perform artistic deformations interactively through the UI. Usually, it is an iterative process to achieve the desired look and feel. However, our goal was to drive the deformation and animation based on observed data from real world tests in an accurate and automated way. Thus, we created a custom pipeline to adapt Maya's deformation capabilities for our use.

FFD is driven by a skeleton around an object. The skeleton is created in such a way that its geometric shape nodes correspond to the (108) sensor locations. This skeleton can then be used to deform the building accurately by push or pull of different nodes (**Figure 5**). For driving the skeleton that in turn deforms the building, we employ a particle system with each particle representing a sensor location. The particle system has a disk cache of each particle's position and color for 5,250 time steps based on the data (as described in data translation). We fetch position attributes of the particle system in real time by custom Maya expression and drive the deformer skeleton with it (An animation of skeleton deformation could be viewed at [1]). A color mapping was applied to each particle based on its relative displacement from its original position. This coloring helps to visually identify the displacement at each sensor location. This system allowed us to view the animation in real time with textures inside Maya's UI and with interactive frame rates on a desktop computer.



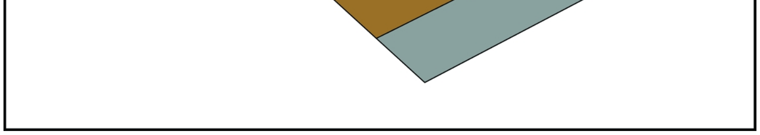


Figure 5: An illustration showing the particle system and a deformer skeleton. Each particle (sphere) corresponds to a node location on the deformation skeleton. The particle system is driven by PDC files translated from observed data. Each particle's color depicts the displacement at their location as shown in the color map. The position and color of the particles change with time based on observed data. An animation of skeleton deformation could be viewed at [1]

Camera Matching and Light setup

The next step was to match the real world camera with the virtual camera and add lighting. Both of these tasks proved to be difficult. We found no record of Metadata about the camera like focal length, device aspect ratio, zoom factor, etc. The positional information of the camera was also not known. We used actual photographs from the video footage to approximately match a virtual camera to the real camera. We also positioned cameras at other locations to capture the essence of the experiment.

Lighting the scene remains a concern. The video footage revealed that the experiment was done on a cloudy day and light conditions varied substantially over short time periods. At one moment, the sun shone brightly casting sharp shadows and next moment it would be overcast. We present our result with a simple diffuse lighting setup.

Rendering and Compositing

Once the 3D scene was lit we created rendered sequences with different camera viewpoints. For rendering we utilized a cluster of 20 desktop machines. Each machine is given a different set of frames for rendering in a distributed manner. The resulting images are stored on a shared file system for retrieval. On completion of rendering the image sequences were annotated and encoded into an animations using compositing software.

We wanted to utilize the actual video footage for compositing, which would provide a real context and allow us to verify and validate our reconstruction visually. We found that the instruments sampled the data at 50 Hz but the video was recorded at 29.97 Hz. Further there was no temporal synchronization between the measuring instruments and camera. This posed to be a serious hurdle for compositing. After viewing the video footage we found that the recording contained audio data as well. When the building and Shake Table move rapidly they create a noise due to increased friction with the building's foundation, this proved to be the key and by analyzing the audio spectrum and sensor plots we were able to approximate the temporal synchronization of the video and instrument data. Further, by trial and error, we found a workable temporal match. Synchronized composite of video footage with 3D model's deformation and its visual check can be viewed at the project website [1].

Results and Conclusions

We were able to successfully recreate the shaking of a seven-story building (**Figure 6**) with a high degree of accuracy (see camera match check animation at [1]). Our results were found to be plausible by the structural engineers and scientists. The animations of our digital re-creation can be viewed at the project website [1]. The conclusions of the study are summarized below

- We were able to identify basic requirements of a visual system that can enable integration of disparate test data and help in analyses. The visual system should include the capability of real-time interaction with deformation of a textured 3D model. The system should incorporate contextual elements when possible. A visual representation of sensor locations and properties of the sensors is also desirable.
- Animation packages can be successfully utilized for scientific visualization. They offer state of the art 3D modeling, animation, FFD, lighting and rendering capabilities. These packages can be used for experimentation with visual representation. They are flexible and extensible for quick prototyping. The visual results are highly realistic with high fidelity.
- Proper registration of data and metadata is important. Without registration, features like camera matching and compositing can be guesswork at best.
- Matching environmental light is still a challenge. The lighting conditions during the tests changed drastically making the conditions harder to reproduce synthetically. A potential solution [12] to this problem is to actually measure the light during testing and use the resulting measurements for light setup in the model; however, this was beyond the scope of this project.
- The visualized results are valuable tools for dissemination of information and suitable for both a broader scientific and non-scientific community.

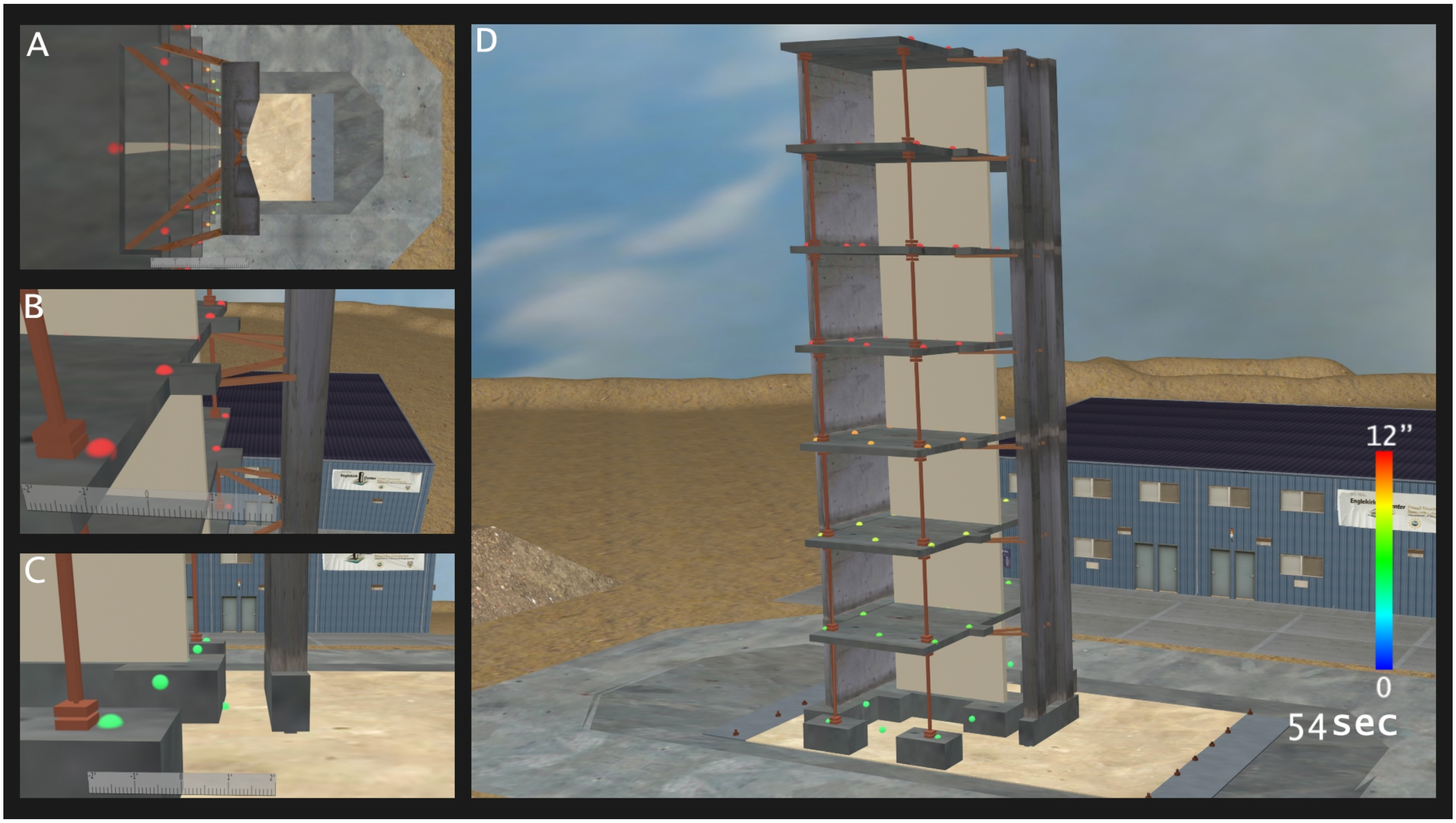


Figure 6: A snapshot of the building at 54 seconds into the test. Frame A shows a view from the top, Frame B shows a close up view of the seventh floor and Frame C shows a view of the building's foundation on the Shake Table. In Frame D the entire building can be seen tilted towards the left. The different colors on the particles (spheres) depicting the displacement as shown in the color map. Animation results can be viewed at the project website [1].

Future Directions

In the future, we would like to find workable lighting models for more realistic rendering. In addition, we will need to find automated ways to match cameras in space and time. We intend to use the lessons learned from this study to formulate desirable requirements for a visualization system and then embark on building such a system that will serve as a workbench for analysis of heterogeneous data from structural and seismic experiments.

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