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Destroying Cultural Heritage: Technical, Emotional and Exhibition Aspects in Simulating Earthquake Effects on a Gothic Cathedral

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Abstract

While a significant research effort has been devoted to produce virtual reconstructions of cultural heritage, the issue of reproducing the effects of natural or man-provoked disasters (e.g., earthquakes, floods, wars) on cultural heritage has received much less attention. Moreover, presenting these events with multimedia installations on museums requires to consider how to properly convey the dramatic aspects of the experience besides the faithful simulation of the damage caused. In this paper, we focus specifically on earthquakes and their effects on historical buildings. We present the methodology we have followed to produce a museum experience of a real earthquake that struck a gothic cathedral. We discuss technical (e.g., building a 3D model that is suitable to the considered purpose), emotional (e.g., testing the exhibit with pilot studies on users), and exhibition aspects (e.g., using infrasound to increase the realism of the experience and the dramatic feelings it evokes).

1. Introduction

While a significant research effort has been devoted to produce virtual reconstructions of cultural heritage (e.g., [GCR01, MVSL05, STY*03, dHCUCT04]), reproducing the effects of natural or man-provoked disasters (e.g., earthquakes, floods, wars) on cultural heritage has received much less attention. In the latter case, there are new technical, exhibition and methodological issues that need to be considered.

From a technical point of view, cultural heritage objects need to be modeled and rendered in such a way that the effects of disasters can be properly visualized. In the case of buildings, for example, 3D modeling and rendering must take into account damages to structural elements (e.g., broken walls). When one wants to realistically simulate the effects of past disasters, an additional issue concerns how to effectively combine and exploit the available sources of information (e.g., photographs of the objects after the disaster) or to compensate for the lack of data (e.g., sufficiently detailed structural and construction data are unlikely to be available for old buildings).

In presenting the results of modeling and (possibly) simulation in the context of multimedia experiences, e.g., installations in museums, emotional and exhibition aspects play a major role. For example, how can we properly convey the dramatic feelings of the experience besides the faithful visualization of the damage caused?

Finally, there is also the problem of finding a proper design methodology and identifying necessary sources of information and technical skills needed in producing this kind of virtual experiences.

In this paper, we focus on earthquakes and their effects on historical buildings, and present a case study involving the production of a museum experience concerning a 6.4 Richter magnitude earthquake that on 1976 hit the Friuli region in Italy causing about 1000 casualties and severe damage to the historical and cultural heritage of the region. The museum experience concentrates on what happened to a symbol of the Friuli region, i.e. the gothic cathedral in the town of Venzone (which now has been fully rebuilt). The project has two main goals:

- to obtain a realistic physically-based animation (through simulation) of the effects of the earthquake on a 3D model the cathedral;

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- to present the rendered animation in a museum multimedia experience able to convey emotions and feelings related to the event.

Although our case study refers to a specific kind of disaster and cultural heritage object, we identify in the paper a number of general issues and possible solutions that can be applied in related projects. Moreover, we mostly use off-the-shelf and relatively affordable hardware and software, so that the ideas in the paper can be easily adopted by teams that want to develop computer-generated experiences of the effects of disasters on cultural heritage.

The paper is structured as follows. In section 2, we outline the general design process that has been followed. Section 3 provides more detail on the technical aspects of the 3D modeling and simulation of the earthquake effects on the cathedral. In Section 4, we describe how the museum experience was designed, including details on how to increase the realism of the experience and the dramatic feelings it evokes using infrasound. Section 5 concludes the paper and outlines future work.

2. Methodology

In the first weeks of the project, we interviewed domain experts (i.e., seismic engineers, civil engineers and experts in the analysis of earthquake effects on churches) and witnesses. By witnesses, we mean people who personally experienced the considered earthquake in Venzone, since there were no witnesses of the cathedral collapse. Moreover, we collected relevant sources of information: photographs and drawings of the cathedral before and after the earthquake, relevant newspaper articles, books, and film footage.

The goal of interviewing domain experts was to identify an effective way of simulating the effects of the earthquake on the cathedral. Ideally, with detailed data about the structural and mechanical features of the building, as well as about the forces applied by the disaster, reproducing the effects is mainly a matter of finding an effective simulation technique. In practice, we found that available data were insufficient for this approach, and we believe that this issue is not peculiar to our project: it is often hard to collect detailed structural information about cultural heritage objects, and it can be even more difficult to have accurate data about the physics of a disaster in the precise location of the cultural heritage object. On the other hand, it is easier to get information about the state of the cultural object after the disaster (in our case, photographs of the cathedral taken after the earthquake). However, these sources of information cannot be directly used as inputs to simulation, but they rather can be used to evaluate how realistic it is.

After interviewing the experts, we chose to follow a methodology based on starting with a coarse visual simulation (using parameters given by seismic engineers), and successively refining it by having different kind of domain experts evaluating the results (also matching them with the photographs of the cathedral after the earthquake). The main advantage of this approach is that it was much easier for the experts, by visually evaluating the simulation result, to elicit and refine their knowledge and hypotheses about the earthquake effects on the cathedral (and then suggest refinements to the simulation). This allowed us to properly take into account structural modifications or consolidation works that were known to have been performed on the cathedral in the past, but about which the experts could initially only make vague hypotheses with respect to simulation. As we will see in Section 3, special 3D modeling operations were performed to ease the work of the experts in evaluating the accuracy of the simulation and suggesting improvements.

In a second phase, we identified a group of pilot users to test prototypes of the museum experience. The user group was composed by witnesses (to test the fidelity of the experience from a perceptual and emotional point of view) and people that had no previous experience of major earthquakes (to check if the lack of episodic memory could play a role and make the experience less intense).

In the interviews with witnesses, the main purpose was to identify important aspects in their emotional and sensorial experience of the earthquake, such as sounds, images, events and feelings that they felt to characterize their experience. Two main topics recurred in most interviews. First, sound played a very important role. Therefore, we decided to focus part of the museum experience on this aspect, and to investigate how to effectively render a proper earthquake aural experience (see Section 4.2). Second, many witnesses' memories highlighted that clouds of dust made it difficult to see a few seconds after the earthquake start. Faithfully reproducing the latter aspect in the simulation would have contrasted with the goal of visualizing how the cathedral collapsed, so we decided to limit visual occlusion caused by clouds of dust.

The work was then divided into three main parts: 3D modeling and simulation, sound production, and museum experience design. In each part, we used an iterative design process, with prototypes (simulation renderings, sounds, storyboards) evaluated by the whole team, by experts, and with pilot users.

3. Modeling and Simulation

In modeling cultural heritage objects for simulating and visualizing the effects of disasters, we followed an iterative process that can be decomposed into the following main steps:

- first, build a 3D model where all parts that have a role in the simulation (e.g., structural elements of the cathedral) are modeled as separate objects. In this step, the 3D model can be composed by just geometries, without any shading information. When objects break into parts because of the

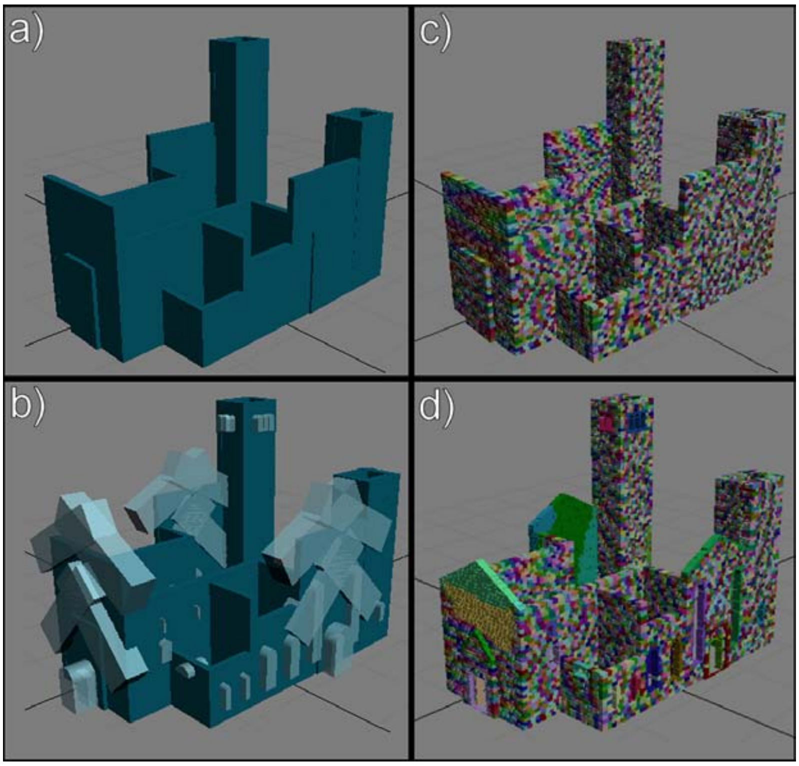

Figure 1: *(a) coarse 3D model of the cathedral using just bounding boxes of the cathedral walls; (b) the same model with geometries to be subtracted visualized with semi-transparent color; (c) detailed model with single stones ; (d) detailed model with single stones after the volume subtraction operations.*

disaster, we model those parts as separate objects, exploiting information about the object after the disaster (in particular, photographs of the cathedral after the earthquake) to infer which parts needed to be modeled;

- second, enter physics-related information about the various modeled parts into the simulation, together with the available data about the disaster (forces applied to the building by an earthquake shock) and run the simulation;
- third, apply the results of the simulation to the 3D model (deriving an animation), and test it with domain experts and against the available sources of information (in particular, photographs taken after the disaster). When the result is not satisfying, either the 3D model needs to be improved (e.g., by modeling new parts), or the simulation parameters need to be refined;
- fourth, model additional objects that have no role in the simulation, add effects like dust clouds and fragments, as well as lights and shading information. The final result is then rendered to a movie or possibly converted into a format suitable for real-time interaction.

An interesting alternative that has the potential to greatly simplify the modeling step is to employ techniques that are able to automatically (and in a visually convincing way) compute breaks, cracks or tears [OH00, OH99, PKA*05]. However, some of these methods are mostly intended to ease the work of the animator by generating physically plausible animations, but have not been demonstrated to be able to produce physically faithful animations [OH00] (and this is a requirement in our case study). Other methods [PKA*05] are too complex for simulating an entire building. Finally, none of these methods is, to the best of our knowledge, integrated into tools that can be readily used for production.

In the following, we explain how these steps have been carried out in our case study, particularly focusing on the first three ones.

3.1. Modeling

The entire modeling and simulation steps have been carried out using 3DS Max 6 and the Reactor plug-in for physics-based simulation.

First, we created a coarse model of the cathedral by using bounding boxes of the cathedral walls (see Figure 1a), and a number of volumes (to be subtracted from the walls) to model holes (doors, windows), archways and the roof profile (see Figure 1b).

Single stones in walls were then automatically created by scripts we wrote to the purpose (the scripts allow one to fill a bounding box with stones with different patterns, randomly determine the size of each stone inside a given interval). Figure 1c shows the application of the scripts to the initial boxes model, while Figure 1d shows the final result after the subtraction operations that carve holes and modify the upper contour of the walls. At the end, the fully detailed cathedral model contained about 15000 stones.

The last step before simulation consisted in coloring the stones on the basis of their movements caused by the shock, to help the experts in evaluating the outcome of the simulation. Starting from photographs of damages to the cathedral taken after the earthquake, experts drew lines over them to highlight so-called macro-elements, i.e., portions of walls (divided by so-called fracture lines) that "stayed together" at least in the initial instants of the earthquake. For example, Figure 2 shows one of the photographs with the superimposed lines drawn by the experts, and the resulting colors that were applied to the 3D model of that part of the cathedral.

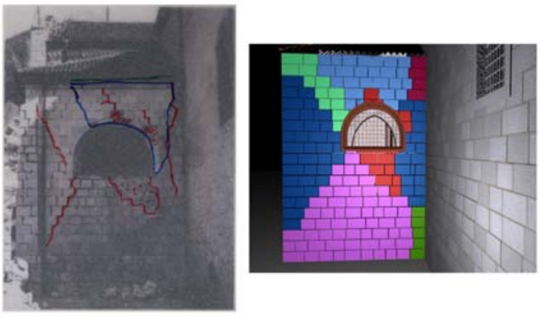

Figure 2: *(left) photograph of part of the cathedral after the earthquake with lines highlighting relevant macro-elements; (right) resulting coloring of cathedral stones (red indicates stones that fell down after the shock, color changes highlight fracture lines).*

At this point, the boxes and the colored-stones model were fed into the simulation. The 3D model was successively refined by adding detailed models of architectural elements, such as windows, portals, and statues, and shading information (lights, materials, textures). The final 3D model of the cathedral can be seen in Figure 3.

Figure 3: *The final 3D model of the cathedral.*

3.2. Simulation

As mentioned previously, accurate simulation of the effects of the earthquake on the cathedral would require:

- to know how the terrain under the cathedral moved because of the shock. This would in turn require both to have sensors (e.g., accelerometer) recordings of the movement under the cathedral, as well as to model the mechanical features of the terrain below it. Neither of the two information was available.
- to have an accurate structural and mechanical model of the cathedral. This is problematic for old buildings, since they typically do not have construction plans available and, furthermore, several modifications or consolidation operations may have been done on them over centuries (and this was the case for the building under consideration), thus making it very difficult to predict mechanical behavior.

As explained in Section 2, the strategy we used to compensate for the lack of sufficiently detailed data was to start with a coarse simulation, and then progressively refine it together with domain experts. In the following, we explain in detail the adopted simulation procedure.

The initial coarse simulation was done on the bounding box model of the cathedral, using as input the 3D movements derived by a sensor recording of the 1976 earthquake measured by accelerometers at a nearby dam. As shown in the plot in Figure 4, the recording describes terrain movements in time along the North-South, East-West and vertical axes. Domain experts suggested values of parameters such as wall mass, elasticity and strength of structural linkages between walls, and corrections to be done on the movement recording (to take into account the distance between the cathedral and the dam) and terrain differences (the dam accelerometers were mounted on harder, rocky terrain). The goal of this initial step was to obtain, taking into account the whole architectural structure of the cathedral, the movements in time of each wall determined by the shock.

After that, the simulation was divided into parts, with each part dedicated to an independent zone of the cathedral. Nine

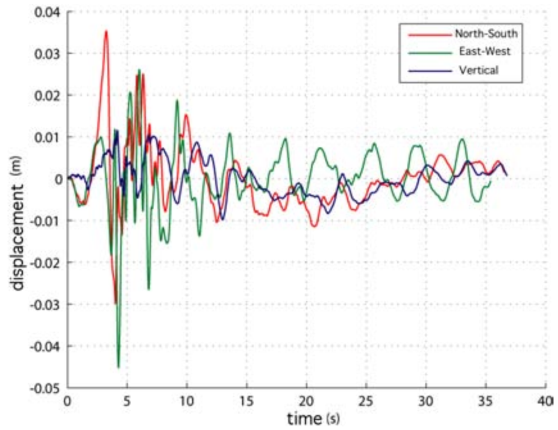

Figure 4: *Plot of the earthquake shock as measured by accelerometers in a dam a few kilometers from the cathedral.*

different zones were determined by the experts, considering the photographs taken after the earthquake (such the one in the left of figure 2). Each zone presented damages that had no causal relations (e.g., due to collisions between stones) with damages in other zones. Each zone simulation used only the relevant part of the 3D colored-stones model, with mechanical parameters (mass, elasticity, friction) defined for each stone, and mechanical links (such as springs) to model physical linkages between stones. Moreover, each simulation used as input the wall movements computed in the initial global simulation. This allows to take into account the whole structure of the building while we are computing simulation on just a part of it. Moreover, by dividing the simulation into local zones, we were able to reduce the time to compute each simulation, thus making the refinement process easier (each zone simulation took from a few minutes to a few hours, depending on the number of structural elements that were part of the zone). Each local simulation was iteratively refined by examining the results with the domain experts, who then suggested modifications on the basis of their knowledge about the cathedral and their hypotheses about its structural properties. For example, Figure 5 shows some frames from one of the computed local simulations which refers to the south facade of the cathedral. Blue-colored brick stones stayed in place after the shock, while purple stones are a fracture zone that fell down to the ground, successively breaking into pieces because of the reached speed.

Additional structural constraints were often introduced to model known structural modifications (e.g., consolidation operations) that in the past were carried out on the cathedral. In particular, this was done by introducing more or less rigid links in locations suggested by the experts. For example, the left part of Figure 6 shows the west facade of the cathedral; note that the upper part of the facade falls to the ground but does not break into single pieces: in the real cathedral, this was due to injections of concrete that were performed some years before the earthquake.

Once experts thought the simulation had reached a satisfactory level of realism, we integrated the local animations together, deriving a full animation of the effects of the earthquake on the cathedral. Dust clouds and stone fragments were then added by using particle systems, as can be seen in the right part of Figure 6.

4. Museum Experience

In this Section, we describe how the museum experience has been designed and developed. The experience is based on a short movie †, which is shown to museum visitors inside a properly equipped projection room. In the following, we briefly describe what the movie shows, provide more details the work done on sounds, and on the projection room.

4.1. The Movie

The movie combines the computer-generated animation with existing film footage to recreate the experience of the earthquake. It is structured in three parts.

The first part, using pre-earthquake film footage, shows the town surrounding the cathedral. Its purpose is to introduce the viewer to the experience and provide an historical context.

The second part is rendered from the simulation described in the previous Section. The transition from the first to the second part uses a wireframe model of the cathedral (which is then shaded after a few seconds) to convey the idea that the viewer is going to see a computer-generated simulation. After a flyby showing the cathedral from various points of view, the earthquake begins. The simulation part lasts about one minute (as the 1976 earthquake did) and exploits camera movement techniques that are inspired by disaster movie scenes to increase the emotional involvement of the viewer.

The third part exploits film footage to show the enormous reconstruction effort that took place in the area (the earthquake killed about one thousand people and destroyed or damaged thousands of buildings). The movie ends with ordinary scenes from today's life, to relax the viewer and show the successful result of the reconstruction of both the cathedral and its surrounding area.

4.2. Modeling Sounds

There are multiple sound sources that combine to create an earthquake aural experience: the typical rumble of the

† the movie can be watched on the Web site dedicated to the project: http://hcilab.uniud.it/earthquake/

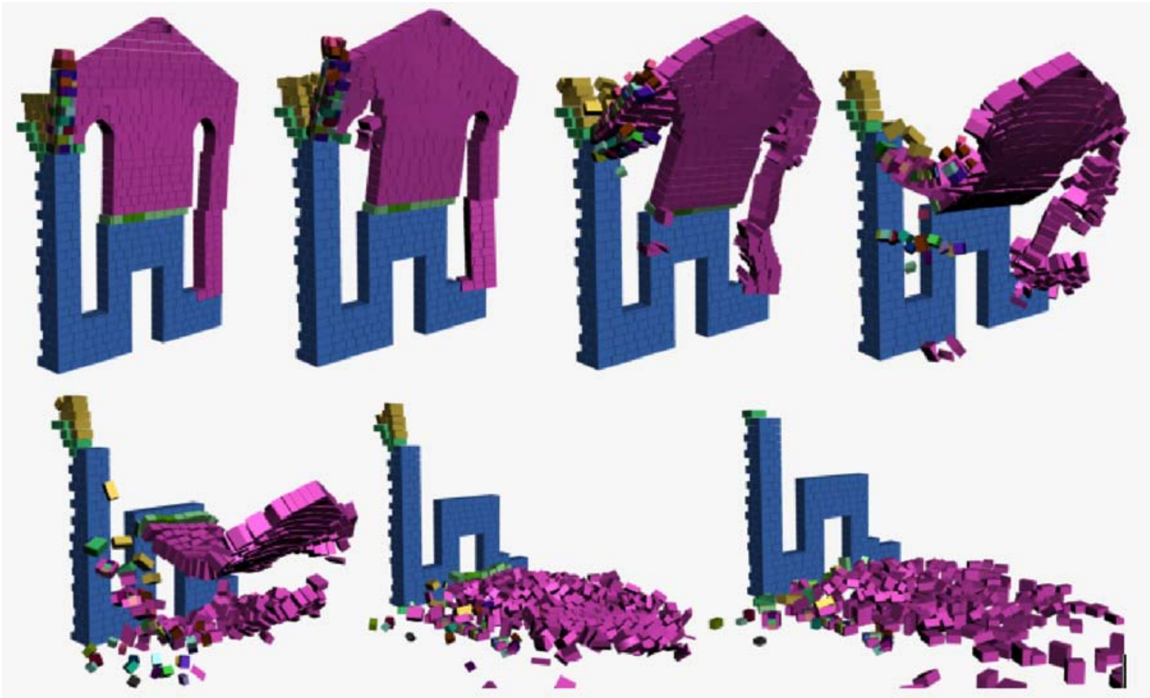

Figure 5: *Some frames from the (local) simulation of the south facade of the cathedral .*

earthquake, nearby buildings falling down, glasses breaking, landslides on close mountains, etc. These sound sources have different spatial locations, generally fill the auditory channel of the listener, and have a primary role in generating emotions of fear. Moreover, an earthquake produces infrasonic frequencies (i.e., below 20 Hz) that cannot be heard, but that are perceived through the body and have a role in producing feelings of panic, fear and sense of disorientation [OCA04].

Since we did not have any accurate audio recordings from the 1976 earthquake, the work on sounds was divided into two main activities: producing and combining the above mentioned different sound sources and finding effective ways to use infrasound and deliver it to visitors.

With respect to the first activity, we started by plotting in the frequency domain (see Figure 7) the movements produced by the 1976 earthquake as measured by the available sensors (plotted in Figure 4). The idea was to use the result to shape the earthquake typical rumble.

Most sound sources in the movie were derived from recordings of seismic events (earthquakes and tsunamis), or of related events (such as stones falling to the ground, landslides). These sounds were then filtered and assembled together to recreate a plausible aural experience, also according to the corresponding events shown in the movie, and by using positional audio for some of them (e.g., for stones that roll towards the viewer).

With respect to the second activity, we used two kind of infrasound. In the movie, before the earthquake starts, we use a continuous infrasound (with a frequency of 12 Hz), produced by using a software low-frequency generator, to induce changes in the emotional state of viewers [OCA04]. During the earthquake sequences, infrasound taken from recordings of real earthquakes and tsunamis are used.

The audio part was encoded according to the Dolby Digital 5.1 standard, which is the de-facto solution in the movie industry [‡].

4.3. The Museum Room

The museum room dedicated to the earthquake experience is based on the following components:

- DVD player with optical outs;
- DLP projector;
- Audio decoder able to reproduce infrasound. Typical consumer audio decoders cut very low audio frequencies (below 20 Hz), and as a result do not allow the reproduc-

‡ the movie available on the Web site uses stereo sound and does not contain infrasound for ease of playback on standard equipment

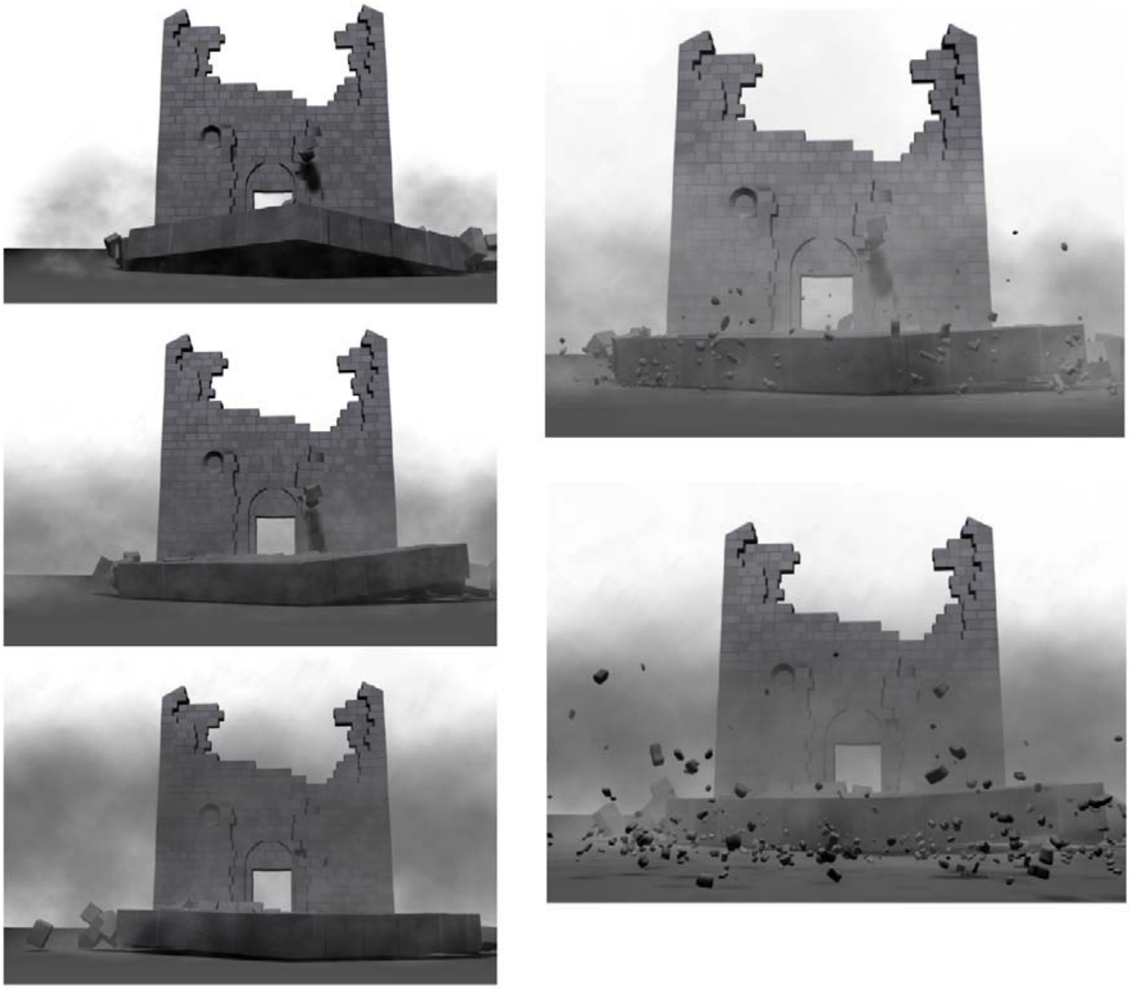

Figure 6: *(left) Some frames from the simulation of the west facade (with textures and dust clouds); (right) some frames from the simulation of the west facade (with textures, dust clouds and fragments)*

tion of infrasound. Therefore, we had to resort to a professional decoder (Lexicon MC-8) that allows for the reproduction of frequencies between 10 and 30 Hz;

- a system for reproducing infrasound. We evaluated existing solutions on the market, from mechanical shakers (i.e., devices able to produce mechanical vibrations, which are usually tied to users' seats and mostly used in theme parks) to more common sub-woofers used in theaters. Mechanical shakers were ruled out due to convenience, complexity and maintenance considerations. We finally considered hi-end hi-fi subwoofers, and chose a VeloDyne DD-18 subwoofer, because it is able to reproduce audio frequencies as low as 10 Hz with the needed acoustic pressure;
- five speakers for medium and high audio frequencies (specifically, TRUTH B2031A).

5. Conclusions

Simulating disasters on cultural heritage objects and building museum experiences about those disasters is an interdisciplinary activity that requires various kind of skills (such as disaster experts, sound technicians, 3D modelers) as well as methods to effectively combine the available sources of information.

In this paper, we have considered the reproduction of earthquakes on cultural heritage buildings, describing the issues we have encountered and the processes we have followed in our project, with the goal of suggesting possible

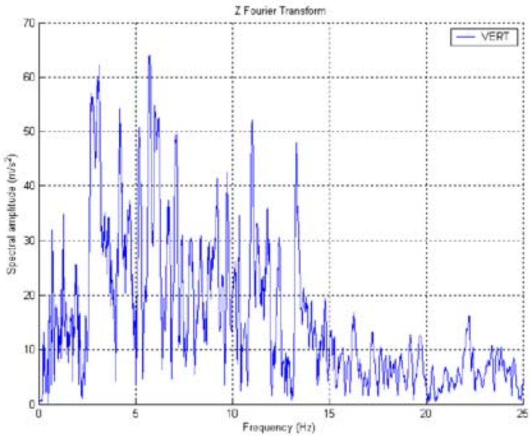

Figure 7: *Graphic plot of the vertical movements produced by the earthquake in the frequency domain.*

methods and solutions for similar projects. While we are aware that simulating completely different kinds of disasters or simulating the effects of earthquakes on much larger scale (e.g., on a city) may require different techniques and approaches, we also believe that this kind of problems are worth being investigated for their different applications (architecture, history, didactic tools for schools and museums, ...).

With respect to future work, we are working on producing a (simpler) version of the simulation that can be rendered in real-time, both as a complement to the museum experience (e.g., to be interacted with after the visitor has seen the movie) and as a multimedia experience that can be downloaded from the internet. Moreover, a 3D stereoscopic version of the movie is being produced, and its introduction into the museum experience will be evaluated in the next months.

6. Acknowledgments

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