EUROGRAPHICS Workshop on Graphics and Cultural Heritage (2018)
R. Sablatnig and M. Wimmer (Editors)

Short Paper

Earthquake Simulation for Ancient Building Destruction

Josep Lluis Fita, Gonzalo Besuievsky and Gustavo Patow

ViRVIG, University of Girona, Spain

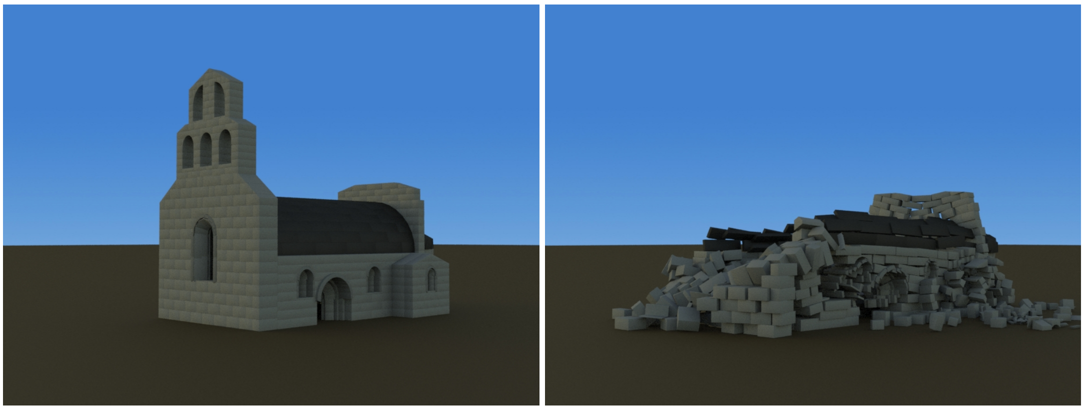

Figure 1: *A church affected by an earthquake. On the left, a Romanesque church of the 11th century. On the right, the same church after a large earthquake simulation.*

Abstract

Research on seismic simulations has been focused mainly on methodologies specially tailored for civil engineering. On the other hand, we have detected a certain lack of this kind of tools for interactive cultural heritage applications, where speed and plausibility are the main requirements to satisfy. We have designed a tool that allows to parameterize and recreate real earthquakes in an accurate, but simple way. Furthermore, we have focused our efforts on those users without much technical experience in geology or seismic simulation, such as historians, art historians, museum curators and other similar stakeholders. We have performed a series of tests over a set of ancient masonry buildings such as walls with their respective battlements, houses and a Romanesque church with structural simulation enabled, thus, allowing the coupling between the earthquake being simulated and the objects of interest. We show the feasibility of including earthquake simulations and structural stability into historical studies for helping the professionals to understand better those events of the past where an earthquake took place.

Keywords: Earthquake simulation, Historical masonry buildings, Structural analysis, Virtual heritage

1. Introduction

Over the past years, the new technologies have shown a large improvement, where the research of new techniques in Computer Graphics has benefited fields like video-games, film, urban studies and, especially, cultural heritage. In particular, research for the latter has focused on the digital preservation of artifacts and architectonic structures with the aim not only of preserving them from external damage, but also to share these human creations for their widespread knowledge and study. Most of the methodologies for ancient architectural structures are centered on the development of buildings as simple 3D textured objects.

However, only a few of these research efforts have studied the combination of 3D modeling with structural analysis for the simulation, specially those efforts focused on structural engineering research. On the other hand, research of simulation of natural phenomena, like earthquakes, in combination with 3D modeling of historical buildings for cultural heritage, is merely testimonial.

In this paper, we have focused our research on these two concepts, where 3D masonry buildings, such as a Romanesque church or a set of Medieval walls, have been tested together with seismic simulations, with the aim of achieving a realistic and accurate visual effect. Our main contribution is providing a methodology for his-

DOI: 10.2312/gch.20181351

torians and curators that helps them to better understand historical events where an earthquake took part, or to provide tools to assess the effects such an event might have on current cultural heritage structures. Our methodology is completely based on off-the-shelf tools and can be used on a single or on a set of masonry building for making cultural heritage studies, but that also can benefit video-games and film visual effects set in historical contexts.

2. Previous Work

Our work focuses mainly on two research lines: First, on recreating masonry historical buildings. Second, on the research of natural phenomena like earthquakes, applied to structural analysis for simulation.

Recreating historical masonry buildings: The virtual recreation of historical buildings implies knowing the architectural style of a period of time, what kind of buildings were built, how it evolved afterwards, and the techniques used for building them. For example, a description of building construction techniques for the Medieval period can be found in the literature [Fit61, HCSZ*01]. Among the available modeling techniques for buildings in Computer Graphics, the first method based on shape grammars was developed by Muller and colleagues [MWH*06]. Later, some works based on shape grammars were developed by different authors such as Patow [Pat12], Krecklau and Kobbelt [KK12b] and Musialski and co-workers [MWA*13]. Saldana [SJ13], recreated a building from GIS data. Capellini and co-workers [CSS*13], presented a modeling technique based on Roman construction techniques. However, all these techniques are based on the shape of buildings and do not combine it with structural analysis for simulation, that is the point of our interest.

Among those techniques that combine the two subjects, we could mention the work by Whiting and co-authors [WOD09], where a historical building is created and parameterized for a stable configuration through physical constraints. We must remark that this work describes a test where it was applied a shock on the ground with the aim of studying the building stability. Moreover, Whiting and colleagues [WSW*12], recreated buildings and their stability through constraints introduced by the users. The work by Panozzo and co-workers [PBSH13] automatically generates a 3D structure from an input shape surface. Lately, Deuss and colleagues [DPW*14], following the technique described before, extended it for all kinds of masonry shapes, and Fita and co-authors [FBP17a] developed a methodology for structural analysis in the cultural heritage field. But, in spite of having elements of structural analysis, none of these works described before have dealt with Earthquake simulations.

Structural analysis and earthquake simulation: The combination of structural analysis and earthquake simulation over masonry buildings research has not been completely addressed in Computer Graphics. However, in the context of civil engineering, Altunisik and co-workers [AAG*16], Castori and colleagues [CBM*17], Fortunato and co-authors [FFL17] and finally Souami and colleagues [SZAM16], presented methodologies based on the analysis of the seismic behavior of historical buildings. Bosiljkov and co-workers [BUZBB10], improved different test methodologies over different historical masonry buildings. Kouris and Kappos [KK12a], presented the results and conclusions of two model tests of non-linear static analysis for timber framed masonry buildings. Mosoarca and Gioncu [MG13] developed a method for predicting the masonry building behavior under a simulated earthquake. Also, a methodology of an historical city center rebuilding situated in seismic areas was developed by Ramos and Lourenco [RL04]. Uphoff and colleagues [URB*17], developed a work where the Sumatra earthquake of 2004 was simulated accurately with all their parameters such as non-linear frictional failure and detailed 3D topography.

3. Seismology

3.1. The seismic waves: Body waves

It is difficult to mathematically describe the propagation of seismic movements through the Earth [Low07, Raw08], mainly because of their heterogeneity. In general, seismic movement under the surface is known as *body waves*. Body waves travel through the medium in two ways. In the first one, longitudinal waves motion happens by compression, back and forth, of any particle that defines the affected area in the *x-axis*, parallel to the direction of propagation. In seismology, these waves are called *P-Waves*. The second type is known as transverse waves, whose motion happens only by vibrations in solid particles that define the medium through the *y-axis*, referred to as *SH-Waves*, and *z-axis*, referred to as *SV-Waves*, transversal with the direction of propagation, the *x-axis*.

When the body waves composed of *P-waves* and *S-waves* reach the surface, their combination and their interaction with the free surface transform these into surface waves that propagate along the surface of the Earth from the earthquake epicenter.

3.2. The seismic waves: Surface waves

Surface waves are slower than body waves and their amplitude decay with the depth of the medium. However, their effects are more destructive for human environments. The surface waves are distinguished by their motion, *Rayleigh waves* and *Love waves*.

Rayleigh waves: Their motion is a combination of *P-waves* and *SV-waves*, and have a mathematical description of motion given by the position equation for the *x-axis* and *z-axis* respectively at the free surface. These equations can be described as:

$$\theta_x(x,t) = a\left(\frac{\omega^2}{2k\beta^2}\right) cos\,(kx-\omega t)\,, \tag{1}$$

$$\theta_z(x,t) = a\left(\frac{2k\kappa_\alpha}{k^2+\kappa_\beta^2}\right)\left(\frac{\omega^2}{2k\beta^2}\right) sin\,(kx-\omega t)\,, \tag{2}$$

where $\kappa_\alpha^2 = k^2-(\omega/\alpha)^2$ and $\kappa_\beta^2 = k^2-(\omega/\beta)^2$. Equation 1 and Equation 2 describe the motion of the *Rayleigh waves* as retrograde and elliptical parallel to the direction of propagation.

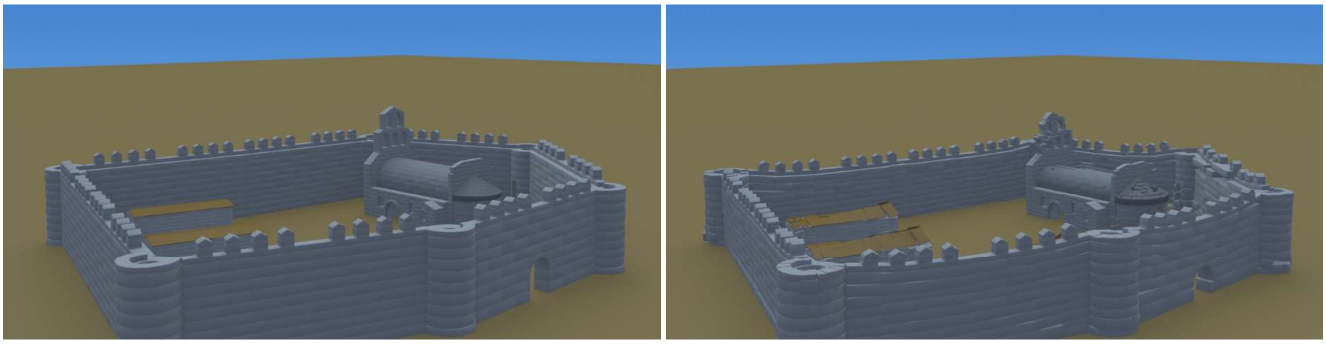

Figure 2: *A recreation of a little village with its respective houses and a Romanesque church (on the left top corner) and the village affected by an earthquake (right top corner).*

	Test 1	Test 2	Test 3	Test 4
Richter Magnitude	4.0	5.0	6.0	7.0
Frequency (Hz)	4.05	4.05	4.05	4.05
Phase (rad)	1	1	1	1
Amplitude (m)	0.002	0.02	0.2	0.5
Delay Time (s)	21	21	21	32

Table 1: *Main settings applied for each test and orientation over the two walls.*

Love waves: Their motion comes from the *SH-waves*, focused on the surface. These waves are dispersive and faster than *Rayleigh waves* and their propagation is along the surface. *Love waves* travel in groups of waves, carrier and envelope waves. Thus, the mathematical description of these can be expressed by the position equation as a sum of two harmonic waves that can be described as a product of two cosine functions, as:

$$\theta_y(x,t) = a2\cos(kx - \omega t)\cos(\delta kx - \delta\omega t). \qquad (3)$$

Equation 3 describes the *Love wave* position at a given time, where the carrier wave has an angular frequency ω and wavenumber k, and the envelope wave has a lower angular frequency $\delta\omega$ and wavenumber δk.

The Richter magnitude scale: A seismograph is a device designed for recording the vibration of the ground motion. Based on the Woods-Anderson seismograph, the seismologist Charles F. Richter developed a formula that measures the magnitude of an earthquake where the magnitude is based on the amplitude recorded in *mm* by a seismograph [Uni18, Raw08].

4. Methodology

Our method is based and developed on off-the-shelf tools such as *Houdini 3D* from SideFX [Sid12], Houdini's Python libraries and its plug-in *Bullet* [Bul16]. Our tool has been designed for reproducing wavefronts over a geometrical grid that conforms the soil in a period of time determined by the user, assuming the wavefronts originated at an epicenter located far away. For the wavefronts, we focused on the surface waves, *Love* and *Rayleigh* waves, because these waves are the main cause of the damage that takes place during a seismic movement.

Before starting the simulation, the user must connect the grid that conforms the ground to the input of our Houdini's Python method. Once done, the user can configure through the integrated interface the surface wave parameters such as *frequency*, *phase*, *amplitude*, *wave direction*, the *duration of the seismic simulation* and the *Magnitude* of the earthquake.

Earthquake simulation: To perform the simulation, our algorithm first reads all the wave parameters such as the *frequency*, *phase*, *amplitude* and *wave direction*, given by the user through the interface. The phase velocity of these waves has been modeled as $C_R = \beta\sqrt{0.8453}$ for *Rayleigh waves*, and $C_L < \beta$ for *Love waves*, where β is the *S-waves* speed for a granite ground. Also, it reads the time parameters, *earthquake duration*, and it does the respective calculations for *angular frequency*, among other parameters needed for the correct application of the different wave motion.

Once the algorithm has made the parameters calculation, and for each point of the grid that represents the ground, it computes the *velocity* for each axis (*x, y, z*). Through this calculation, our algorithm determines if the wavefront has arrived at a concrete point. If the velocity value on the x and z axis are not equal to *0*, then it applies the point position equations, Equations 1 and 2, respectively, which simulate the motion of the *Rayleigh waves*. The algorithm does the same for the y, where it applies the Equation 3, which simulates the *Love waves* motion.

Building dynamics: Our technique, which has been designed for applying the motion of the surface waves over the ground, allows the user to recreate all kinds of human structures and connect these with the earthquake through a dynamic network that uses the *Bullet* [Bul16] solver, a library for physics simulations. Through the dynamic network, the user can configure the physical features for the building geometries, such as *density*, *stiffness*, *bounce*, *friction coefficient* and *ambient temperature*.

The recreation of ancient masonry buildings has been implemented following a methodology described in [FBP17b]. This methodology takes an input geometry shape given by the user, creates the bricks and finally gives them physical features. This methodology

Richter Magnitude	**4.0**			**5.0**			**6.0**			**7.0**		
Wavefront	**N.**	**S.W.**	**E.**	**N.**	**S.W.**	**E.**	**N**	**S.W.**	**E.**	**N.**	**S.W.**	**E.**
Wall 1	0	0	0	0	0	0	10	69	69	29	69	69
Wall 2	0	0	0	0	0	0	40	58	69	37	69	69

Table 2: *Test results that shows the number of bricks moved for each wall and earthquake strength.*

has allowed us the creation of a set of ancient masonry structures such as walls, towers, churches and houses based on the medieval period style. Specifically, buildings built with stone and designed for supporting vertical loads, as shown in Figure 2.

The user interface: We have designed an interface oriented for non-expert users that allows the control of the earthquake strength based on the Richter magnitude scale. This interface allows reproducing earthquakes from minor magnitudes up to large earthquakes with a Richter magnitude value of 8.0. With this restriction, we avoid the saturation in the calculus of Richter magnitude that happens over values greater than 8.0. Our tool only allows the magnitude value adjustment before starting a simulation that depends of two configurable parameters, *delay time* and *amplitude*. The *delay time* given in *s*, refers to the time difference between the arrival of the *p-waves* and the *s-waves* registered on a seismograph; and *amplitude* given in *m*, refers to the amplitude of the waves.

Our tool also allows the configuration of other parameters through the interface, such as the *time duration* of the earthquake, the *frequency* (given in Hertz), the *phase* given in radians, and the *wave direction* given in degrees, where the values of this last parameter correspond to $0-180$ degrees in the North-South axis and $90-270$ degrees in the West-East direction.

5. Results

We have tested our methodology through a set of examples based on different magnitudes in the Richter scale, applied to a set of ancient masonry buildings. In the first test, we applied the earthquake simulation with different magnitude strengths over single walls. In the second test case, we observed how different wave frequencies have affected the given structures. Both tests have been performed on a CPU Intel-core i5-3210M and 12 Gbytes of RAM memory.

Test over two walls: The goal of this test is to analyze the behavior of our method when it applies the seismic surface wave on a ground and a basic masonry construction with different Richter magnitude scales. For this purpose, in this test we placed a ground with a size of 1500m x 1500m composed of 64 points, and physical features. Over this ground we placed two masonry walls composed of 74 bricks each, with their respective battlements and different orientations, North and East. Through the dynamic network, we have configured their physical features such as the *density* of the wall material set with a value of 2691 kg/m^3 for simulating granite stone, and the *friction coefficient* with a value of 0.7, which corresponds to the *friction coefficient* of the rock.

We have adjusted the parameters needed for each seismic simulation with the values shown at Table 1. We have made three tests with different wavefront orientations, such as North, South-West and East for each Richter magnitude. With the aim of quantifying the number of bricks affected in each seismic movement, our methodology has set a threshold of 15 *cm* for considering the minimum movement of a brick on the wall. With this test we can analyze how the different magnitudes and wavefronts affect a human structure. The results of these tests are given at Table 2.

Frequency test: The purpose of this test is to verify the affectation of single walls, described in the previous test, by earthquakes that have different wave frequencies. We configured each earthquake with a magnitude of 6.0 and a South-West wavefront direction. Then, for each test, we have increased the frequency with the same value for both surface waves and counted the number of bricks that were displaced, following the methodology already explained.

Discussion: Table 2 shows the number of bricks displaced during the simulations for the *two-wall test*. For a weak earthquake, with a Richter scale of *4.0*, the walls resist without problem the earthquake in any wavefront direction. We can see that the number of bricks displaced after the earthquake simulation increases with the magnitude of the earthquake, where, for strong and major earthquakes, there was a larger number of bricks displaced, and the walls have ended with several damages, or completely destroyed. Thus, from both tests we can observe that both the magnitude of an earthquake and the wavefront direction are important factors to be considered because the damage over the masonry structure is related to these two features. Also, the wave frequency is an important factor too, and it is tightly related to the increment of bricks displaced in each simulation.

6. Conclusions and Future Work

We have presented a methodology based on off-the-shelf-tools intended for users without experience in the simulation of earthquakes, such as historians, art historians and curators. Following our methodology, they can easily reproduce, at low cost, an ancient masonry building, and study the effects of seismic movements for recreating past events.

Our future work focuses on the improvement of our methodology, where we would like to include the possibility of reproducing the seismic secondary effects of the waves caused by the composition of the soil. Moreover, we would like to add more flexibility to the user interface, for which we have would like to perform an informal usability study involving heritage researchers and other stakeholders.

Acknowledgements

This work was partially funded by the TIN2017-88515-C2-2-R project from Ministerio de Ciencia, Innovación y Universidades, Spain.

References

[AAG*16] ALTUNIŞIK A. C., ADANUR S., GENÇ A. F., GŬNAYDIN M., OKUR F. Y.: Non-destructive testing of an ancient masonry bastion. *Journal of Cultural Heritage 22* (2016), 1049 – 1054. 2

[Bul16] BULLET PHYSICS LIBRARY: Bullet 2.83, 2016. http://bulletphysics.org. 3

[BUZBB10] BOSILJKOV V., URANJEK M., ZARNIĆ R., BOKAN-BOSILJKOV V.: An integrated diagnostic approach for the assessment of historic masonry structures. *Journal of Cultural Heritage 11*, 3 (2010), 239–249. 2

[CBM*17] CASTORI G., BORRI A., MARIA A. D., CORRADI M., SISTI R.: Seismic vulnerability assessment of a monumental masonry building. *Engineering Structures 136* (2017), 454 – 465. 2

[CSS*13] CAPPELLINI V., SALERI R., STEFANI C., NONY N., DE LUCA L.: a Procedural Solution to Model Roman Masonry Structures. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2 (July 2013), 149–153. 2

[DPW*14] DEUSS M., PANOZZO D., WHITING E., LIU Y., BLOCK P., SORKINE-HORNUNG O., PAULY M.: Assembling self-supporting structures. *ACM Trans. Graph. 33*, 6 (Nov. 2014), 214:1–214:10. 2

[FBP17a] FITA J., BESUIEVSKY G., PATOW G.: A perspective on procedural modeling based on structural analysis. *Virtual Archaeology Review 8*, 16 (2017), 44–50. 2

[FBP17b] FITA J. L., BESUIEVSKY G., PATOW G.: An interactive tool for modeling ancient masonry buildings. In *Spanish Computer Graphics Conference (CEIG)* (2017), Melero F. J., Pelechano N., (Eds.), The Eurographics Association. 3

[FFL17] FORTUNATO G., FUNARI M. F., LONETTI P.: Survey and seismic vulnerability assessment of the baptistery of san giovanni in tumba (italy). *Journal of Cultural Heritage 26* (2017), 64 – 78. 2

[Fit61] FITCHEN J.: *The construction of Gothic cathedrals : a study of medieval vault erection /by John Fitchen*. Clarendon Press Oxford, 1961. 2

[HCSZ*01] HENRY-CLAUDE M., STEFANON L., ZABALLOS Y., FOURNIER S., REGO A.: *Principles and Elements of Medieval Church Architecture in Western Europe*. Livre ouvert: Architecture. Les éditions Fragile, 2001. 2

[KK12a] KOURIS L. A. S., KAPPOS A. J.: Detailed and simplified nonlinear models for timber-framed masonry structures. *Journal of Cultural Heritage 13*, 1 (2012), 47 – 58. 2

[KK12b] KRECKLAU L., KOBBELT L.: Smi 2012: Full interactive modeling by procedural high-level primitives. *Comput. Graph. 36*, 5 (Aug. 2012), 376–386. 2

[Low07] LOWRIE W.: *Fundamentals of Geophysics*, 2 ed. Cambridge University Press, 2007. 2

[MG13] MOSOARCA M., GIONCU V.: Failure mechanisms for historical religious buildings in romanian seismic areas. *Journal of Cultural Heritage 14*, 3, Supplement (2013), e65 – e72. Science and Technology for the Safeguard of Cultural Heritage in the Mediterranean Basin. 2

[MWA*13] MUSIALSKI P., WONKA P., ALIAGA D. G., WIMMER M., VAN GOOL L., PURGATHOFER W.: A Survey of Urban Reconstruction. *Computer Graphics Forum* (2013). 2

[MWH*06] MÜLLER P., WONKA P., HAEGLER S., ULMER A., VAN GOOL L.: Procedural modeling of buildings. *ACM Trans. Graph. 25*, 3 (July 2006), 614–623. 2

[Pat12] PATOW G.: User-friendly graph editing for procedural modeling of buildings. *IEEE Computer Graphics and Applications 32*, 2 (March 2012), 66–75. 2

[PBSH13] PANOZZO D., BLOCK P., SORKINE-HORNUNG O.: Designing unreinforced masonry models. *ACM Trans. Graph. 32*, 4 (July 2013), 91:1–91:12. 2

[Raw08] RAWLINSON N.: Seismology lectures, 2008. http://http://rses.anu.edu.au/ nick/teaching.html. 2, 3

[RL04] RAMOS L. F., LOURENÇO P. B.: Modeling and vulnerability of historical city centers in seismic areas: a case study in lisbon. *Engineering Structures 26*, 9 (2004), 1295 – 1310. 2

[Sid12] SIDEFX: Houdini 16, 2012. http://www.sidefx.com. 3

[SJ13] SALDANA M., JOHANSON C.: Procedural modeling for rapid-prototyping of multiple building phases. 205–210. 2

[SZAM16] SOUAMI M. A., ZEROUALA M. S., AIT-MEZIANE Y.: The impact of building proportions in the preservation of algiers architectural heritage against the seismic hazards. *Journal of Cultural Heritage 20* (2016), 686 – 693. Cultural HELP 2014 Special Issue. 2

[Uni18] UNITED STATES GEOLOGICAL SURVEY: Measuring the size of an earthquake, march 2018. https://earthquake.usgs.gov. 3

[URB*17] UPHOFF C., RETTENBERGER S., BADER M., MADDEN E. H., ULRICH T., WOLLHERR S., GABRIEL A.-A.: Extreme scale multi-physics simulations of the tsunamigenic 2004 sumatra megathrust earthquake. In *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis* (New York, NY, USA, 2017), SC '17, ACM, pp. 21:1–21:16. 2

[WOD09] WHITING E., OCHSENDORF J., DURAND F.: Procedural modeling of structurally-sound masonry buildings. *ACM Trans. Graph. 28*, 5 (Dec. 2009), 112:1–112:9. 2

[WSW*12] WHITING E., SHIN H., WANG R., OCHSENDORF J., DURAND F.: Structural optimization of 3d masonry buildings. *ACM Trans. Graph. 31*, 6 (Nov. 2012), 159:1–159:11. 2