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A PERSPECTIVE ON PROCEDURAL MODELING BASED ON STRUCTURAL ANALYSIS

UNA PERSPECTIVA SOBRE EL MODELADO PROCEDURAL BASADO EN ANÁLISIS ESTRUCTURALES

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Abstract:

With the rise of available computing capabilities, structural analysis has recently become a key tool for building assessment usually managed by art historians, curators, and other specialist related to the study and preservation of ancient buildings. On the other hand, the flourishing field of procedural modeling has provided some exciting breakthroughs for the recreation of lost buildings and urban structures. However, there is a surprising lack of literature to enable the production of procedural-based buildings taking into account structural analysis, which has proven to be a crucial element for the recreation of faithful masonry structures. In order to perform an in-depth study of the advances in this type of analysis for cultural heritage buildings, we performed a study focused on procedural modeling that make use of structural analysis methods, especially in its application to historic masonry buildings such as churches and cathedrals. Moreover, with the aim of improving the knowledge about structural analysis of procedurally-recreated historical buildings, we have taken a geometric structure, added a set of procedural walls structured in masonry bricks, and studied its behavior in a generic, freely-available simulation tool, thus showing the feasibility of its analysis with non-specialized tools. This not only has allowed us to understand and learn how the different parameter values of a masonry structure can affect the results of the simulation, but also has proven that this kind of simulations can be easily integrated in an off-the-shelf procedural modeling tool, enabling this kind of analysis for a wide variety of historical studies, or restoration and preservation actions.

Key words: procedural modeling, virtual historical buildings, masonry structures, stable structures

Resumen:

Con el creciente aumento de las capacidades computacionales, el análisis estructural se ha convertido en una herramienta clave para la evaluación del estudio y conservación de edificios antiguos por parte de los historiadores del arte, curadores y otros especialistas. Por otro lado, el floreciente campo del modelado procedural ha proporcionado avances interesantes para la reconstrucción de edificios y estructuras urbanas no accesibles. Sin embargo, hay una sorprendente falta de métodos que permiten la generación de edificios procedurales, teniendo en cuenta el análisis estructural, los cuales han demostrado ser un elemento crucial para la concepción de estructuras de mampostería. Con el fin de realizar un estudio en profundidad de los avances en este tipo de análisis para edificios del patrimonio cultural, se realizó un estudio centrado en el rol del modelado procedural que realizan métodos de análisis estructural, especialmente en su aplicación a los edificios históricos de albañilería, tales como iglesias y catedrales. Por otra parte, con el objetivo de mejorar el conocimiento sobre el análisis estructural de los edificios históricos concebidos proceduralmente, hemos tomado una estructura geométrica de un atrículo, añadido un conjunto de paredes procedurales estructuradas en ladrillos, y estudiado su comportamiento con una herramienta de simulación de pública disponibilidad. Con esto se demuestra la viabilidad de su análisis con herramientas no especializadas. Esto no sólo nos ha permitido entender y aprender cómo los diferentes valores de los parámetros de una estructura de mampostería pueden afectar los resultados de la simulación, sino también que este tipo de simulaciones se puede integrar fácilmente en una herramienta de modelado procedural al alcance de todo público, lo que permite acercar este tipo de análisis a una amplia variedad de estudios históricos o acciones de restauración y conservación.

Palabras clave: modelado procedural, edificios históricos virtuales, estructuras de ladrillos, estructuras estables

1. Introduction

Modeling of urban environments is becoming increasingly popular in Computer Graphics research for applications such as urban planning, videogames and GPS-based navigation tools, just to name a few. However, generating a convincing urban environment requires considerable manual work, unless more advanced techniques are used. At first, one of the geometric modeling techniques that was used by designers when they would like to recreate a historical building is constructive solid geometry, which combines quadric surfaces and Boolean operations; through modeling softwares such as Blender, Autodesk Maya or Autodesk 3Dstudio, that allow them to work with some surfaces such as polygons and NURBS curves. This kind of software has the disadvantage that generates large files when a building shape is designed and physics is not considered to create feasible structures. Also, we should add to the mentioned, the software

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based on Computer-Aided-Design (CAD), such as Autodesk AutoCAD. We can see in Figure 1 a church modeled with the techniques of solid modeling. The designer has built this historical building through the usage of polygonal primitives such as cones, boxes, cylinders and spheres combined with Boolean operations, among others. The result is a functional building without any structural constraints that probably will be unfeasible on real environments. Application examples, such a recreation of an Egyptian temple, were introduced in the work of Sundstedt, Chalmers, & Martinez (2004). It is important to make the distinction between the use of structural analysis for existing structures (by using digitized 3D models) and the use of structural analysis as a tool for virtual reconstruction. In this perspective paper we focus mainly on the latter, leaving the study of structural analysis for other, more specialized engineering venues.

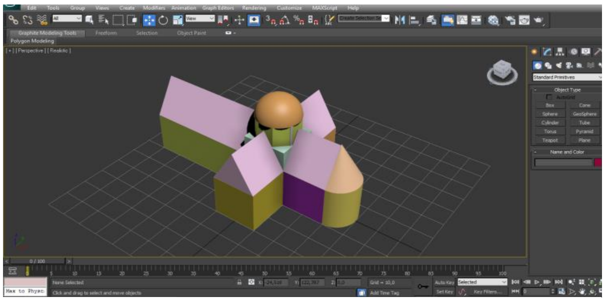


Figure 1: A church modeled through solid modeling.

Modern state of the art techniques are based on the procedural techniques developed in the seminal papers by Wonka, Wimmer, Sillion, & Ribarsky (2003) and Müller, Wonka, Haegler, Ulmer, & Van Gool (2006a). Procedural modeling refers to 3D models created algorithmically through a set of rules, as we can see in the example of Figure 2. Although procedural modeling was originally conceived for the recreation of not well defined geometry objects such as mountains, clouds, plants, fire, clothes and particles methods, it has proven to be useful also for architectural models. The designers can use a methodology based on grammar models that allow them to recreate well detailed ancient buildings. Procedure-based content creation tools, such as (CityEngine, 2016) or UDK (Epic, 2016), include a visual language to somewhat alleviate the creation process.

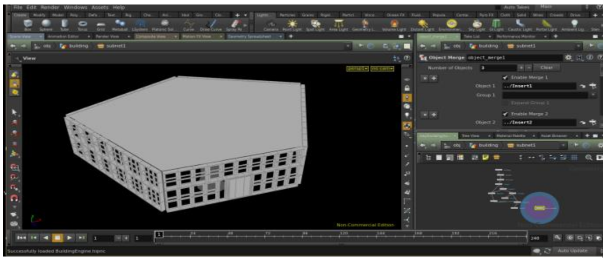


Figure 2: A building generated procedurally from a set of rules.

However, all these mainstream tools lack one important feature for the descriptions of buildings in general, and ancient masonry structures in particular: their lack of any structural analysis, which is a crucial component for the understanding of such architectonic structures, the way they were built, their evolution and any possible preservation or maintenance actions. Only up to recent years some researchers have found ways to explore methodologies that combine visual results with structural stability analysis, especially on masonry structures. This is the reason why we have focused our perspective analysis on this kind of methodologies, where the aim is to know how these techniques influence the creation of a consistent, realistic virtual environment. In this paper we describe the open perspectives with the most suitable techniques for research about procedural modeling based on the structural stability studies, masonry structures and ancient buildings, especially in those buildings built on the Romanesque and Gothic periods such as churches and cathedrals. Finally, we decided to run a structural analysis of the feasibility, through an off-the-shelf physical simulator provided from freely available tools, of a geometrical structure provided by the work of Panozzo, Block, & Sorkine-Hornung (2013), which was obtained after a sound procedural methodology.

2. Perspective on procedural modeling

This section discusses about procedural modeling techniques that are suitable for modeling ancient buildings of archaeological value, as previously commented. We start an analysis of the previous work of the topic based on the concept of shape grammars, and we continue with the methodologies based on structural masonry buildings, reviewing the most popular tools used for content creation.

2.1. Procedural modeling

Müller, Vereenooghe, Wonka, Paap, & Van Gool (2006b) presented a methodology based on the concept of a shape grammar, which is based on a base rule called seed; followed with an iterative application of transforming rules. Each rule starts with the specification of a label, called predecessor, where an input shape (a part of a building) is selected, and then the rules themselves, called successors, change the geometry and, consequently, the shape of the building.

Seed Rule → Successor Rule 1 →Successor Rule 2 → …

Indeed, when we add a new rule successor to a given predecessor, we are actually creating a graph of rules (Patow, 2012), as we can see in Figure 3. As possible commands, Müller et al. (2006a) introduced commands such as <Split>, <Repeat>, <Component Split> and <Insert>, which have become commonplace in current procedural modeling systems.

Recently, Kelly & Wonka (2011), introduced a methodology where the concept of a generalized extrusion is applied on a building through a set of profiles. Once the extrusion has been applied, the result is a complete mass model for a new building, which can be enhanced with elements such as windows and doors. See the sequence in Figure 4.

Talton et al. (2011) describe a methodology where a Markov Chain Monte Carlo system is used to create variations on a given rule set, and apply their technique to complex structures such as vegetation and buildings. Later, Hou, Qi, & Qine (2012) presented a methodology where a set of rules are extracted from a drawing elevation with the aim of reproducing 3D buildings of Chinese architecture. In the same year, Musialski, Wimmer, & Wonka (2012) based their work on an

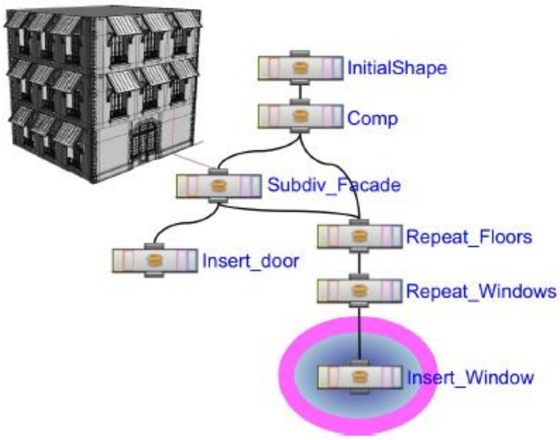


Figure 3: A set of procedural modeling rules representing a procedural model that generates a graph (from Barroso & Patow, 2012).

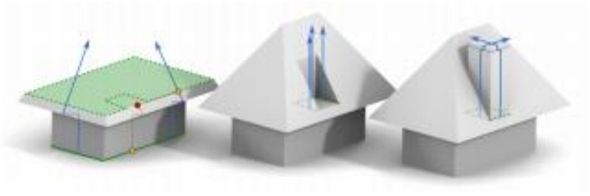

(a) (b) (c)

Figure 4: An *extrusion* building sequence (from Kelly & Wonka, 2011): a) Definition of the shape of the structure; b) The finished 3D geometry; c) An additional rectangle into the plan to specify a chimney.

interactive framework that use images for the building facade modeling.

Following a similar approach, Krecklau & Kobbelt (2012) created a tool designed for ordinary users without any programming knowledge that manipulates the procedural grammars in a transparent way when a building is created or modified. Finally, we must mention the methodology designed by Besuievsky & Patow (2013), through a set of tools allows users the generation of ancient buildings for serious games platforms. Although, the methodologies presented represent a great advance, they still pose some problems for the non-expert designer. In that line, some researchers presented visual editing systems, such as the one described by Patow (2012) (see Fig. 3), and the one simultaneously developed by Procedural, now part of Esri, for their CityEngine system (2016).

Editing systems have allowed some researchers to develope their respective methods such as Müller et al. (2006b), who introduce a method for the reconstruction of Puuc buildings based on the pre-Colombian Mayan architecture. Dylla, Frischer, Mueller, Ulmer, & Haegler (2010) introduced the reconstruction of the ancient Rome in the year 324 AD. Barroso & Patow (2013) introduced a method for the recreation of architectural structures such as Roman bridges and Gothic churches such as *La Sainte Chapelle* of Paris based on volumes. Koehl & Roussel (2015) based their work on the reconstruction of a French chapel from the 12th century. Finally, we must mention that these works described have been designed only with the visual presentation aspects in mind, neglecting completely any sort of structural problems. However, this is a crucial element for ancient buildings such as masonry churches and cathedrals, where we need a new paradigm focusing on structural-based analysis tools.

2.2. Structural masonry buildings

Whiting, Ochsendorf, & Durand (2009) introduced one of the first works to describe a procedural modeling method based on masonry structures such as cathedrals, stone bridges and churches. Their method allows the user or designer to create a set of rules for the creation of the building, through the introduction of user-defined parameters. Once the user has created the set of rules, the method automatically searches for a stable configuration for the building shape according to physical constraints with the resolution of inverse static problems through quadratic equations of equilibrium. As a result, this method is suitable for historical education and architectural design, and allows the user to analyze ancient buildings. We can see an example in Figure 5.

Figure 5: Cluny Abbey in France (from Whiting et al., 2009).

Later on, Whiting (2011) presented an extension of their previous work (Whiting et al. 2009), introducing a new set of methods that integrate the study of a building soundness through the integration of architecture design and structural analysis. Furthermore, to achieve this, they developed two methods focused on geometry and guaranteeing the equilibrium of masonry structures with the aim to obtain the most feasible building.

More recently, Whiting, Shin, Wang, Ochsendorf, & Durand (2012) introduced a method to analyze a given masonry building geometry through their vertex coordinates. Once the geometry is loaded, the aim of the method is to create a new stable structure through the analysis of the stability gradient, according to constraints previously introduced by the user, such as horizontal direction, vertical direction and block thickness. Indeed, we should mention that this method allows the user to load cable-stayed structures and do the corresponding analysis. This method is suitable for those designers who want to improve the feasibility of their design by changing the geometry through constraints on the gradient. We can see an example in Figure 6.

Panozzo et al. (2013) introduced an algorithm that does not require any structural knowledge from users because it automatically generates a 3D masonry structure from an input shape (an input patch, such a NURBS surface)

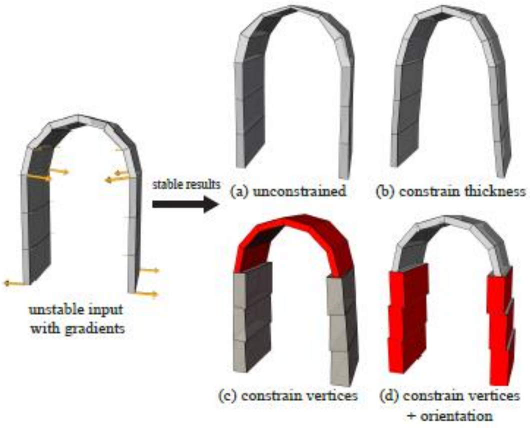
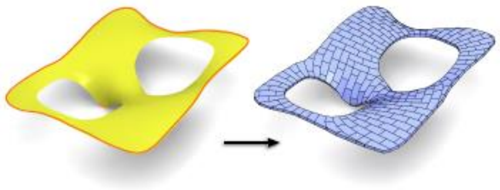


Figure 6: Changing the design of a building through constraints on the gradient (from Whiting et al., 2012).

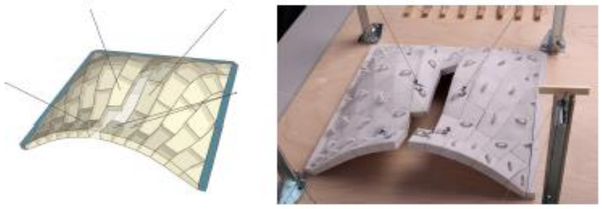
and a given height. Moreover, the new structure is generated and designed to be a self-supporting structure without mortar, in such a way that its shape is as close as possible to the one given as input, but suitable for building with masonry blocks. The authors validated this new algorithm by printing 3D models of the blocks and assembling the resulting model. For this reason, we choose their freely available models as a testbench to check their feasibility for sound analysis with standard, off-the-shelf simulation tools, and thus check their suitability for virtual environments. We can see an example of such a masonry structure in Figure 7.



(a) (b)

Figure 7: An illustration of how the algorithm works and its results (from Panozzo et al., 2013). From an input surface (a), the algorithm automatically transform the surface into a masonry 3D model (b).

Deuss et al. (2014) introduced a new algorithm that processes all kind of generated masonry models, from historical buildings to freeform ones. Initially, the algorithm takes a masonry structure built with rigid blocks and transforms it into an ordered sequence, where each block can be added to the construction process by the use and placement of series of chains and hooks. Its method is based on the detection of structures called quasi-arches, which represent subsets of the original input masonry structure that can be built independently of any other part of the same roof. Once the roof is partitioned in these subsets, the algorithm provides detailed instructions to build each subset, holding them with hooks and chains, as already mentioned. When this step ends, the next one is to fill the empty regions among the quasi-arches with blocks, completing the process described before for roof construction. They tested their model with a self-supporting surface, again taken from the previous work of Panozzo et al. (2013), based on the previously mentioned validation at small-scale with 3D printed models. As a practical application, this algorithm can help curators in building restoration (Fig. 8).



(a) (b)

Figure 8: Testing the algorithm with the Panozzo et al. (2013) vault (from Deuss et al., 2014). The algorithm finds a sparse set of chains (a) that guarantee stability even after the removal of a subset of the blocks (b).

Given the above mentioned arguments, we have decided to take one masonry structure generated by Panozzo et al. (2013), and test it on a virtual environment using an off-the-shelf numerical physics simulator, with the aim of improving the knowledge about this type of virtual shapes and their performance in a simulation with standard, freely available tools.

3. Static study of a masonry structure

In the middle ages, when a church was built by masons, especially when they were finishing its last stages, there was one particularly critical key stage that had to be carefully planned and executed. We refer to the construction of the vault, where the habit of the sculptors of making each block of stone with the proper size that fitted in the final placement of the vault resulted in complex production procedures, generally based on trial and error. This action allowed them to build the vaults without mortar because the vault self-supported its weight through friction. Following a similar reasoning, we have taken as a model for our structural tests the vault model from the work of Panozzo et al. (2013), because each piece of this vault was designed with the most suitable size for its corresponding place, like was done in ancient buildings such as churches or cathedrals.

To perform our tests of the statics of this vault, we have chosen a freely available commercial software such as Houdini 3D, using the standard Apprentice licence (SideFX, 2016), and the open source Bullet solver that it incorporates by default. Other solvers are also possible within the software, but we recommend avoiding the so called “naive” simulator as its simple implementation precludes its usage for our purposes.

3.1. Testing the vault

To perform the structural test, we must first build the geometry that supports the masonry vault. In our first experiment, we built three supporting walls of voussoirs (blocks), each with a density of 2691 kg/m^3 that corresponds to the one of granite stone. Then, we gave a width of 2 m to the walls with the aim of building a structure resembling a Romanesque church. Furthermore, we have added a bit of “glue”, as it is called this internal simulation parameter that simulates the little ancient mortar used between the blocks of stone. Although rarely necessary, a very fine, almost inexistent, layer of mortar was usually added simply as a security measure to add to the final stability of the building. Given this basic structure, we placed the imported vault geometry (Panozzo et al., 2013) on top of it and we gave it a density value of 2651 kg/m^3 that simulates a slightly different variant of stone granite. In this case, the voussoirs were added without mortar among them, following Panozzo et al.'s specifications (see Fig. 9).

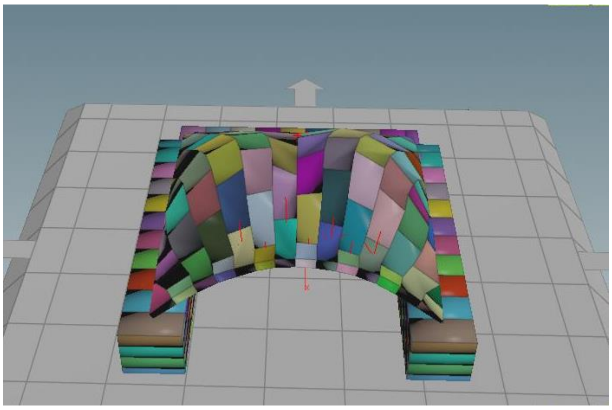


Figure 9: Our vault over the walls that simulate a Romanesque church.

Once we run the simulation with this basic set of parameters, we can observe that the vault collapses, as it is shown in Figure 10. In order to improve stability, we adjusted (increased) the value of the so called "rotational stiffness" for the vault until it worked in the simulation. A higher value for this parameter would make the objects less liable to spinning; a lower value will make them more ready to spin. Basically, it is a scaling factor applied to the inertia tensor, lowering its rotational freedom.

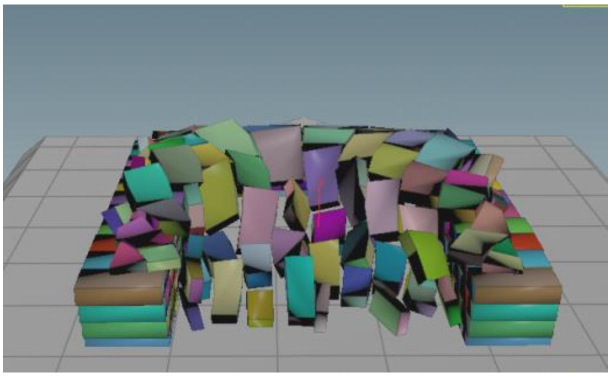


Figure 10: Our vault has fallen down during the first test with the basic set of parameters.

At this point, we begin reducing the width of the walls until 1.5 m in an iterative way. We found out that the vault supports its weight with the new wall parameters, but we must add that we observed a few cracks (in our case, represented by some loose stones) on the walls. With these results, we continued decreasing the wall width with the aim of finding the minimum width that supports the entire structure. In this case, a value of 1.2 m was found where the number of the cracks on the walls increased, as expected. Beyond this point, if we continued with the reduction of the width value for the walls, the whole structure would fall into pieces. For this reason, we have decided to add six buttresses to the entire structure, as shown in Fig. 11.

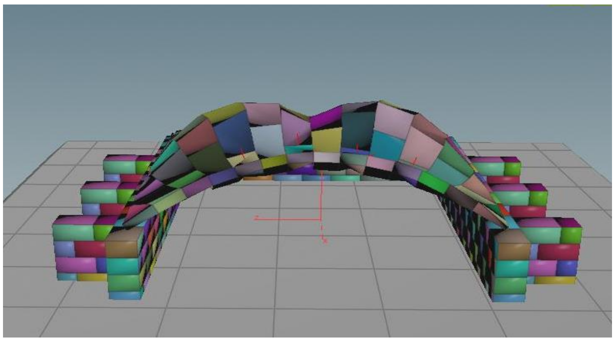


Figure 11: Our structure with buttresses.

When we had added the buttresses, we obtained better results: the vault now supported its own weight and the walls did not show any damage in their structure. At this point, we decided to reduce the width of our walls again, until 0.5 m. With these wall parameters, we still obtained good results for the structure (i.e., the vault and the walls).

At this point, we have a good perspective on how the whole simulation works, especially for the selected case of a vault over some walls. Then, we designed a new static test with the aim of improving the minimum number of buttresses per wall. At the same time, we incremented the wall buttress width to 1 m. Again, we observed severe instability and finally, the total collapse of the structure. Finally, during our last test, we added some glue (i.e. mortar) to our vault structure, in spite of the fact that this kind of vault had been designed to work without any mortar. We ran the simulation again and the obtained results were similar to what happened to the last test, a building collapse. The reason is, probably, that the rotational stiffness plays a more important role than any mortar, as it prevents the voussoirs from rotating around their gravitational center of mass.

4. Discussion

As we have seen, the state-of-the-art literature that successfully merges procedural modeling and structural analysis on masonry buildings is, at most, scarce. Also, it can be seen that all of the presented techniques (i.e., Whiting et al., 2009; Whiting, 2011; Whiting et al., 2012; Panozzo et al., 2013; Deuss et al., 2014) rely on custom, specifically tailored solutions that involve expensive development efforts to produce the required code. On the contrary, our implementation relies on standard, off-the-shelf tools that are freely available and, quite probably, already part of the modeler toolbox. In spite of the lack of detailed studies, we consider that structural studies are a key element for achieving realistic masonry structures, in particular for both churches and cathedrals, and that their importance and usefulness cannot be denied in this context. Thus, we analyzed currently available, off-the-shelf procedural modeling tools and proposed, using one of these tools (SideFX's Houdini), a platform where to integrate modern procedural modeling techniques with freely available simulation tools (i.e. the Bullet solver). Both tools are either free or have freely available apprentice licenses which eliminate monetary costs for the development, and their integration is almost trivial, also avoiding costly development costs. All this enabled us to build a practical soundness analysis tool that can be easily used by any stakeholder interested in masonry buildings, including, but not limited to, curators, architects, engineers, urban planers and even movie filmmakers and videogame designers. With all this, we can state that there is no reason, technical or whatsoever, to avoid the use of these tools that should become part of any modeler toolbox.

Our tests show that studies such as the ones carried out by Whiting et al. (2009) are feasible on a low implementation cost budget, without relying on expensive, custom implementations, a sour study shows. Also, structural studies such as the one presented by Deuss et al. (2014) are feasible also on a low cost budget, but they still require the use of some clustering and optimization process that cannot be modelled without the introduction of an optimization library (e.g. MOSEK library), which is commonplace but still requires an expert's intervention.

5. Perspective Work

With the previous analysis, we have obtained a basis for following the research about procedural modelling in the context of sound masonry structures. We plan to focus on the construction, structure, form and general evolution of masonry buildings, such as cathedrals and medieval churches. For this purpose, we plan to use concepts borrowed from structural engineering and architecture, together with the knowledge gathered by art historians to generate plausible models of the building process of these structures.

Another future interesting line of research could be the accurate simulation of the construction process itself, by providing an ordering to the way the different stones were placed, with the support of the scaffolding structures used during the time of construction. As art historians sometimes do not agree on the exact ordering of the construction of the different elements (atrium, basilica, transept, etc.), we plan to design a model, based again on procedural modeling principles, that will allow the easy change in the construction ordering, which will allow not only to reflect the different views on the construction process, but also to serve as a workbench for testing working hypothesis, validating or ruling them out.

The last line of research we would like to pursue is the study of the building maintenance, refurbishing and, in some cases, degradation. Masonry buildings, as sound as they might seem, are part of a lively environment, being affected by external factors, both natural and human-made. Among the first ones, storms, earthquakes and landslides are known to have broken important parts of ancient buildings, such as the case of ChristChurch Cathedral, in the city of Christchurch, New Zealand, which was collapsed by several earthquakes in 2011. Among the latter ones, one can mention destructive effects (e.g. wars), but also more peaceful changes for refurbishing, rehabilitation or expansion changes introduced to improve the building for societal requirements. Starting from the sound architectural structures obtained in the previous two stages, this one has as its objective the introduction of tools that will simulate these processes, probably becoming tools that would help urban planners, architects and curators to plan prevention and maintenance tasks, at the same time being a practical tool for refurbishing proposals.

6. Conclusions

We have reviewed the state-of-the-art literature on techniques involving procedural modeling tools that incorporate soundness analysis. From this analysis we found that only a handful of papers deal with this complex, but crucial, aspect of modeling. This is important not only for entertainment purposes, but also for art historians, curators, conservators and other specialists related to ancient masonry buildings who would benefit from the possibility of simulating, in an early study stage, the structural soundness, the future evolution, and the results of any possible intervention using simple, low-cost, off-the-shelf tools. Of course, if any concrete measure must be taken, these studies should be followed by a careful engineering study, but this first analysis could prove as an invaluable assessment and estimation tool.

As part of an ongoing experimental study, we have tested the statics of a structure that combines the geometry of the walls and the geometry of an imported vault. We have learnt how this kind of building that simulates an ancient vault structure, simulating a Romanesque church, works. Also, we have learnt about the complex interplay of the different parameters affecting the simulation, in particular through the relationship between wall thickness and the number of buttresses. This allowed us to go a step forward and simulate the process in masonry building construction.

Finally, we have tested and validated the methodology proposed by Panozzo et al. (2013), and performed an in-depth structural analysis on a model resulting from their simulation, being able to validate their results under different simulation conditions, and determine the validity of their results in a generic, configurable environment.

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