The Pombaline Building in 3D: Didactic Models

Edifício Pombalino 3D: Modelos didáticos

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ABSTRACT

The “pombaline cage” is a seismic-resistant timber structure, thought and applied massively in buildings during the reconstruction of Lisbon, after the 1755 earthquake. Despite being a system that has been extensively studied in its structural and constructive essence, it appears that there is no global and accessible representation, as a whole, that facilitates its study and understanding.

This study explores the potential of 3D printing technology FFF (fused filament fabrication) to recreate physical models, at scale, of a pombaline building archetype: a typical building composed by three upper floors, ground floor and roof. The requirements of the models were essentially based on educational and training objectives.

The scales of the models considered the general description of the structure (scale 1:50) and the representation of details that allowed to deep its understanding such as the “Saint Andrew” cross (scale 1:10). The results obtained demonstrated the ability to describe the “pombaline cage” as a whole.

Keywords: Pombaline Cage 3D, Physical models, 3D printing, Teaching, Didactic models.

INTRODUCTION

There are countless works on “pombaline construction” in its multiple angles, eg, cultural and architectural, structural behavior under different input loads, innovative contribution to the evolution of construction (França, 1998; Lopes, 2012; Teixeira, 2010; Cardoso, 2002; Appleton, 2005; Appleton, 2011). As for the representation of this structure, there are several approaches based on drawings, diagrams and photographs (Langenbach, 2007; Nunes, 2017; Leitão, 1896). Regarding its physical representation, information is scarce, with the available one being quite incomplete. The existing models mainly focus on specific components, with a few showing details of connection, or connections with the other elements of the building. We can confirm that we have not found one that would allow us to understand the operation and global aspect of the pombaline building.

This study aims at to the fully understanding of the pombaline cage structure, since the existing physical models do not guarantee its global understanding in relation to all elements of the building. The main objective - to develop and make available didactic models - is directly related to the lack of models prepared for this purpose. The developed models aim to associate essential and relevant knowledge about the pombaline cage, resulting in an integrative representation.

We opted for the presentation of several physical models because they allow a more direct reading of the object under study and a more immediate and interactive knowledge sharing. The use of 3D printing, according to the FFF (Fused Filament Fabrication) method, uses the fusion and deposition of a thermoplastic material allowing the creation of pieces with different shapes, regular or organic, by successive layers deposited on a platform. The printed models have good finishes and support any type of detail. The low costs associated with the production process facilitate experimentation and reproduction of the model.

There are essentially three topics to consider: 1) the complete understanding of the pombaline construction, 2) the advantages of physical models for studying the represented objects, i.e, the didactic value of the models and, 3) the potential of 3D printing applied to the development of scale physical models.

I. History and representations of the pombaline cage and its antecedents

In Lisbon, on November 1, 1755, there was a strong earthquake that reached grade IX on the Mercalli Intensity scale (Ferreira, 2013). Without any kind of land use plan and with buildings that lacked the necessary structure to support the type of forces resulting from an earthquake, the city was completely destroyed. 10% of the buildings were destroyed, 60% were damaged and the remaining 30% did not suffer damage. The highest buildings were the ones that suffered the most damage (Ramos and Lourenço, 2000).

Taking charge of the reconstruction of Baixa de Lisboa, the Conde de Oeiras and future Marquis of Pombal, Sebastião José de Carvalho e Mello, brought together a group of professionals who took the first steps to stabilize and guarantee the safety of the population. Urban functioning was restored, after draining stagnant water, registering ruined buildings and removing debris with the work of prisoners (Mascarenhas, 2009).

Considering the possibility of a new earthquake, the Marquis of Pombal demanded that the buildings to be built should integrate an earthquake-resistant structure, in order to avoid further uncontrolled destruction of the city. In response, the pombaline cage was created. A latticed structure, in wood, resistant to the different directions of the seismic waves. For the first time in human history, a city has been (re) built using seismic-resistant techniques (Lopes, 2012).

The pombaline cage follows the development of several types of earthquake-resistant structures over time. The structure most comparable to the pombaline cage is, until today, the so-called Baraccata house (Figure 1). It is a building with one or two floors in height, regular and symmetrical. The wooden porches with sleepers, filled with clay or stone masonry, ensure resistance to earthquakes.

There are multiple theoretical studies on the subject of the pombaline cage, but in relation to physical models, there are only two known cases. The existing model at the Civil Engineering Museum of the Instituto Superior Técnico (IST), in Lisbon. This portrays only the wooden structure, from the crosses of Santo André, to the way the stairs develop (Figure 1). The model of the Sapadores

Firefighters Regiment of Lisbon is a simplified model of two floors, also in wood, which shows part of the pombaline structure, aiming at its study by the firefighters (Figure 2).

Figure 1. Photograph of the pombaline cage model from the IST Museum of Civil Engineering. Source: Wikimedia, 2008.

Figure 2. Pombaline building model in the Sapadores Firefighters Regiment of Lisbon. Credits: Manuel Levita, 2015. In: Facebook CML.

II. Constructive and structural description of the pombaline cage

The pombaline buildings have varied characteristics, depending on their location on the block. The height remains regular, the length is variable, and the number of spans can vary between two and six, the most common being the presentation of three or four spans.

The structure of the pombaline building on alluvial soil, in the embankment of an old shipyard, required a particular type of foundation, in which two of the solutions stand out (Mascarenhas, 2009). The first solution consists of a set of piles that are in direct contact with the ground. These support masonry arches strategically located under the gap between the walls and the ground floor pillars. The second solution differs from the first one in that it does not have arches, but a masonry slab that rests directly on the wood railing. Throughout the building's implantation area there is a structure of piles and logs. Thus, master walls and pillars share the same foundation, contrary to what happens in the previous system.

The ground floor develops essentially on pillars and master walls corresponding to the exterior walls, creating a free space used in a multipurpose manner. These pillars are built by rigging large stones, carefully cut. The walls, on the other hand, are formed with large irregular shaped stones garnished with smaller stones. This floor reveals a structure completely different from that of the upper floors, secured in two different ways: the first by masonry pillars, as described above, topped by brick arches; the second, through pillars connected by arches and also brick vaults, therefore, there is no reinforcement of wooden structure.

The pombaline cage, developed on the upper floors, consists of a kind of matrix, in which the fit between different pieces is done strategically. The vertical, *prumos*, continuous along their length, equivalent to the dimension of the right foot of the floor, are distributed equally. Its ends fit into horizontal elements, *travessanhos*. These pieces are present only on the horizontal perimeter of each wall. Other horizontal elements, *frechais*, fit into the *prumos* and prevent their lateral movements. In this way a grid is created, in which the lateral movements are hindered, but it is necessary to introduce diagonal elements, *escoras*, which form the crosses of *Santo André*, to resist the horizontal forces, the most typical during an earthquake.

Different types of wall can be highlighted (Figure 3): 1) main walls, located on the façades, present a simplified structure, without diagonal elements; 2) structural or frontal walls, interior walls formed by the most recognized structure of the pombaline cage - they have vertical, horizontal and diagonal elements, forming the crosses of *Santo André* and; 3) non-structural walls, partition walls. In each case, the cage works differently and its parts are distributed differently.

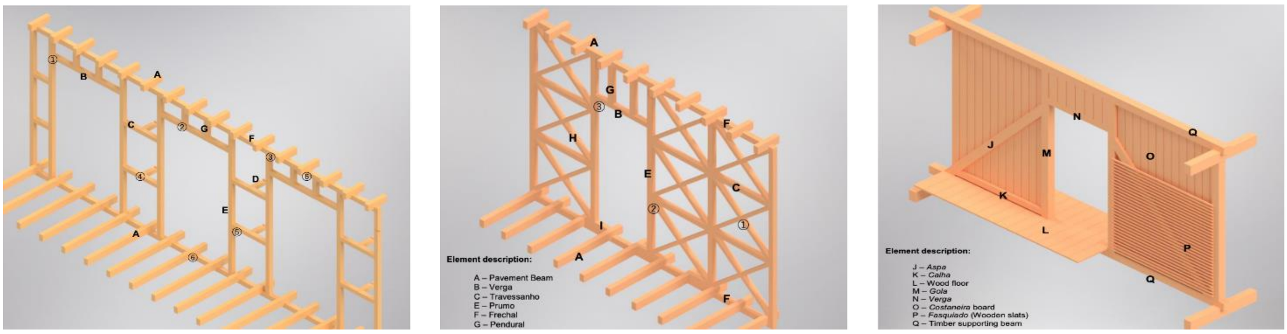

Figure 3. Representation of main walls, frontal walls and partition walls, respectively (Nunes, 2017).

Floors and ceilings vary from floor to floor. The type of floor on the ground floor varies depending on the use of this space. If intended for commerce, the floor consisted of a large irregular stone slab. If intended for stables, the case of most secondary street buildings, the floor was cover with graded pavement or even dirt (Santos, 1989).

The ceilings on the ground floor are also very different from the ceilings on the upper floors. They are made in stone or brick masonry, composed of arches or vaults, covered with a plaster of sand and lime.

From the first floor, in perfect harmony with the rest of the pombaline cage structure, wooden floors are developed, the element that interconnects all the other elements of the structure. The beams rest on the *frechais*, through a half-wood samblage, with a top to bottom nail. To guarantee the horizontality of the floors, beams and frames, they should be perfectly levelled with each other.

In addition to laying on the façades of the façades and delivery to the masonry walls, the beams also rested on the façades of the front walls, which ensured the connection of the floor to all the walls and also helped to keep the beam completely straight.

The cladding on the upper part of the beams was normally made of wood, with planks of timber. These boards were nailed perpendicular to the framework, from top to bottom.

Regarding the floor coverings, different techniques could be applied. One of the most used was similar to the paving of the floor, where, at the bottom of the framework and perpendicular to it, wooden planks were nailed.

The stairs of the pombaline buildings, for the sake of lighting, are built close to the main façade, or the back façade. The staircase develops differently on the ground floor. On this floor, the first and / or second flight of stairs is made of stone masonry, limited by resistant masonry walls.

From the first floor, the development of the stairs is made of wood. The stairwell consists of three front walls, one of which divides the two flights of stairs between floors. The legs, diagonal elements on which the steps rested, were locked to a stone block, which served not only as a starting point, but also as a guarantee of locking them.

The roof has a simple shape, with *asnas*, *madres*, *fileira*, *ripas* and *frechais*, which support the straw tiles. This gabled structure is supported by the structure of the walls of the main and back façades. Although the roofs are very similar from building to building, in the pombaline system there are two types of roof: mansard and triangular.

III. Educational models, 3D printing, teaching and heritage - for a synthesis

The way of thinking about Architecture was until recently directly related to the production of drawings by hand, a common means of communication between the architect, the engineer and the client.

With the advancement of technology, three-dimensional, digital and physical representation, allows more effective communication of the proportions, perspectives and functionalities inherent to the project (Pupo, 2009). 3D modeling deals with the digital three-dimensional representation of an object, using software. Its use paves the way for workflows that allow the incorporation of rapid prototyping technologies, such as 3D printing, and CNC (computer numerical control) for the production of physical models.

There are several 3D printing techniques and materials, but the one used in the production of the Pombaline cage models developed was the fused filament fabrication (FFF). FFF technology works by melting and depositing a thermoplastic material, such as PLA (lactic polyacid), to create pieces of specific design. Among the several advantages of 3D printing are the high precision and the detail of the pieces, even in the scales of greater reduction, unlimited production of pieces with the same shape and size, good finishes and little waste of material (Celani and Bertho, 2007).

With the evolution of technology and its increasingly frequent application in several areas such as industry and construction, the lack of preparation in this area of future professionals has become a concern. The introduction in teaching of themes related to 3D printing has been introduced, mainly at international level, in schools, universities and libraries (Ford and Minshall, 2018). The use of 3D printing to support the development of projects in several disciplinary areas (e.g. mechanical engineering, chemistry, materials) and the creation of didactic models to support teaching (e.g. biology, anatomy, astronomy) is an increasingly common practice.

Didactic models are physical models that aim to assist the practice of teaching. These models appear as a complement, both in practical and theoretical disciplines, offering a more direct transmission of information, through touch and the observation of various perspectives.

In teaching architecture, although it is common to use prototypes, or models, as a method of simulating the design process, the use of didactic models in the teaching-learning process is not, however, a common practice. Disciplines based on theory such as History, structural construction, building rehabilitation, etc., do not, as a rule, use didactic models to demonstrate fundamental concepts and notions. Nor does this occur in disciplines of a more theoretical-practical nature such as architectural design or in laboratory-based disciplines such as Strength of Materials, Conservation and Restoration Theory, Geotechnics and Foundations, among others.

Due to the existence of buildings with historical and cultural value, it is a common practice to store and share information about the past, present and possible future that the building may have. To this end, and with the evolution of technology, methods of massive data acquisition (e.g. laser scanning) have become increasingly complete and accurate, allowing to strengthen digital workflows. In this context, three-dimensional modeling and exploration of model production methods are not only used to understand the intention and complexity of existing projects, but also to understand what developments can occur in the cases under study (Almerbati, 2016) .

Unfortunately, in the area of architecture there are not many examples of didactic models dedicated to the study of the built heritage. However, in other areas, e.g., archeology, 3D printing models are more and more frequent, with studies of reconstruction of ruins using this technology.

IV. Development of physical models of the pombaline cage

The realization and production of the physical models was a phased task, defining, first, its requirements considering its usefulness and final objective, and later carrying out the modeling, planning and preparation for printing, and finally its printing and assembly.

Considering the didactic purposes of the models, the main requirements considered were size, weight, transportability and level of detail. The scale of the models was a key factor in responding to all requirements. A 1:50 scale model was chosen - as a representation of the whole - complemented by a 1:10 scale for detailed models.

After the in-depth study of the parts belonging to the pombaline cage, described earlier, the virtual construction of the models began. All virtual development was carried out in an Autodesk AutoCAD® environment. The initial phase went through the exploration of the modeling strategies most appropriate to the objectives of the work. All parts developed are the result of a similar modeling process. The profile of the parts was designed in two dimensions and subsequently extruded, resulting in a solid element. The grooves and voids present in each element resulted from the application of Boolean operations, such as subtraction, union and intersection between the different volumes.

The 1:50 scale model was developed thinking initially about its plan and later developing and modeling its parts, from the vaults of the ground floor, through the structure of the pombaline cage on the upper floors, as well as the representation of the building, ending at production of the roof elements, their structure and coating.

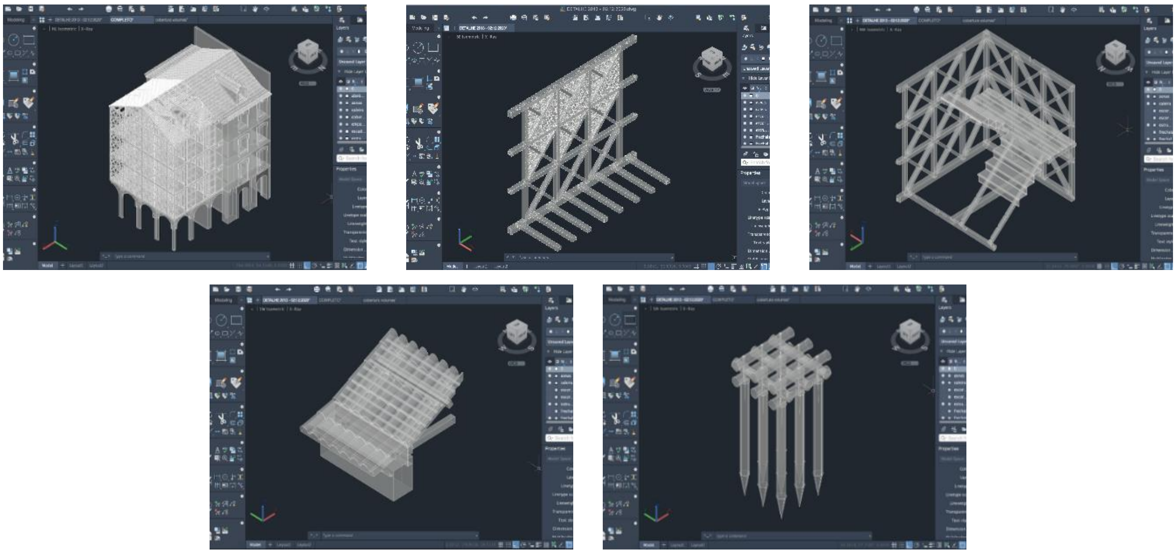

Figure 4. Complete modeling of the 1:50 scale model (upper left corner) and of the 1:10 scale models: *frontal*, stairs, eaves and foundation piles, respectively.

The 1:10 scale models were created as a complement to the 1:50 scale model, i.e., they contain important details whose representation is not feasible in the model with the greatest reduction. The analysis of this set of models is what allows the global and complete understanding of the structure of the pombaline cage and its relationship with the remaining elements of the pombaline building.

The planning of the physical models was thought during the three-dimensional modeling of the models and carried out immediately after the end of the modeling, so that it became possible to move to the final phase, the printing. This process is very important because the success of printing the parts depends on it. Little thought can lead to difficulties in printing, that is, errors and unnecessary expenditure of time. For the planning of the parts it was necessary to understand how the printer works and what are the best methods so that the printing of the parts is optimized to lead to the shortest possible time.

After planning, printing of parts started. Although, normally, without any hitch, failures sometimes occur (e.g., chain break, poor adhesion of parts to the printing platform, filament failure). When these errors do not occur, the part is usually printed without imperfections and with an excellent finish. The printing time of the parts can take several hours, depending on their size and the print settings adopted. The assembly of the models was done very quickly, since the parts at the end of their printing, present good finishings.

V. Discussion of results and future developments

The result of the models is, in general, very satisfactory. Reading the models as a set allows a very complete understanding of what pombaline buildings are, as well as the structure of the pombaline cage.

The 1:50 scale model represents a well executed replica of how a pombaline type building is structured, allowing an understanding of how the structure connects with the rest of the building. The detail and completeness of this model, from the ground floor structure to the development of the roof structure, is the result of a thorough study of all elements of the structure. The 1:10 scale models faithfully represent each component part and how each one fits into the others, gradually showing, through a puzzle-like assembly, how each detail is obtained in a step-by-step mannor.

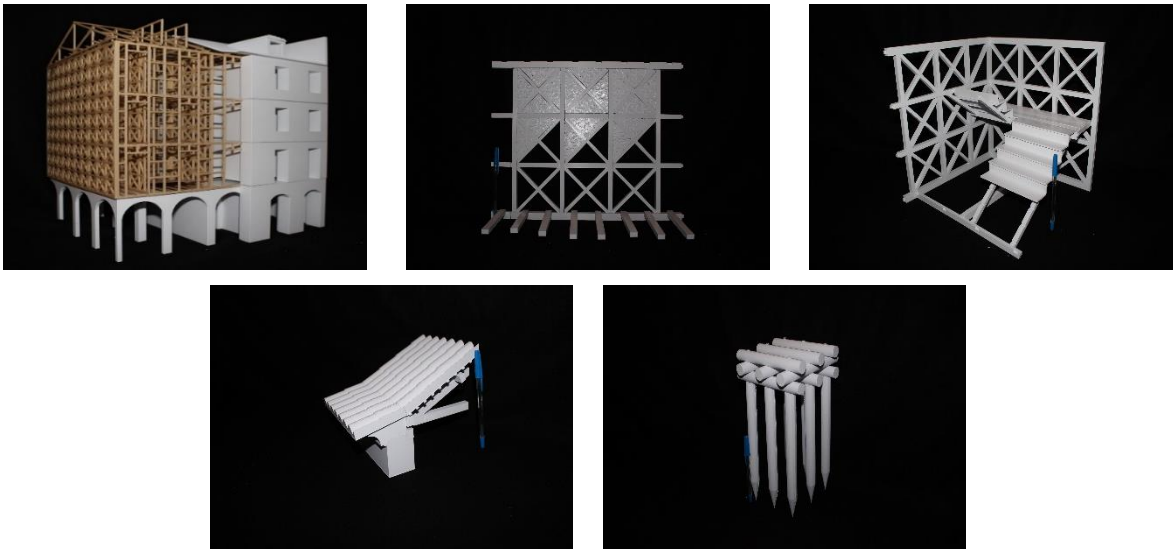

Figure 5. Final result of the 1:50 scale model (top left corner) and the 1:10 scale detail models, frontal, stairs, eaves and foundation piles, respectively.

The real difference between this model and the existing ones is the fact that details are attached to a scale with less reduction, which, being dismountable, make the experience of understanding the structure much more personal, as each person can, in a simplified but realistic way, simulate the construction and the necessary steps needed towards the production of certain parts of the building.

The models present aspects that can be improved, for example, in the 1:50 scale model, make the building's representative part more realistic, by applying more details, such as balconies and their railings, applying typical stonework details of the pombaline buildings, or even use a different color that is more common outside the pombaline buildings. In relation to the 1:10 scale models, the use of more fitting points only for model purposes, which would allow the stability of certain parts without the use of glue, since their purpose is to be dismountable. Still, if you feel the need, later you can create more details that are considered relevant or even make a complete model, all dismountable, on a scale of less reduction, which allows to show exactly the whole process and elements used for the construction of a pombaline building. It is expected that the simulation of the “construction” allowed by the models will be accompanied by technical guidelines for the assembly, to be developed in the future. These guidelines would provide a brief theoretical framework on the structure of the pombaline cage, explanations of the construction procedures and technical designations of the elements, which would complement the didactic (and, why not to say it, playful) potential of these models.

CONCLUSION

The structure of the pombaline cage is a true example of the evolution of construction. Its historical and cultural importance is indisputable. The fact that it is such an innovative structure, taking into account the time and situation in which the city of Lisbon was in, and since an earthquake of the same dimensions has not been repeated (despite the predictions in this regard), it is vital to preserve integrity of this structure, because a large part of the buildings in the older pombaline quarter of the city were built based on it. The rehabilitation of these types of buildings must be considered and respect the stability of the structure, so that it can ensure the appropriate level of seismic safety, if and when necessary.

Technological evolution, associated with the study of heritage, guided the fulfilment of this dissertation, which, despite having been a lengthy process, it is very advantageous, when compared to traditional methods of model production, its time of realization, as well as its quality and strength. The digital workflow considered and the use of 3D printing technology allowed the development of relatively easy physical models, with moderate costs. Due to these advantages, the models can be easily reprinted - an important factor for their sharing and dissemination of the knowledge that they represent.

The models obtained meet the targeted objective, as they reliably represent the seismic resistance system of the cage. It is possible to analyze the development of the structure over the four floors from various angles. Through its observation it is possible to describe, in general, how this structure evolves, providing a global understanding of it, contrary to what happens with pre-existing models.

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