Between Manual and Robotic Approaches to Brick Construction in Architecture

Expanding the Craft of Manual Bricklaying with the Help of Video Projection Techniques

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Brick construction has a long and rich structural and aesthetic traditions in architecture, which can be traced back to the origins of our civilization. However, despite the remarkable works of Frank Lloyd Wright, Louis Kahn, Eladio Dieste or Alvar Aalto in the 20th century, the application of this construction process to address more irregular geometries is very difficult to be achieved by conventional manual means. In this context, the last decade assisted to emergence of robotic applications in architecture. While Gramazio & Kohler looked for solving non-standard brick structures, others, like the S.A.M. robot initiative, are interested in improving the productivity in the fabrication of regular brick structures. By surveying the recent advances on bricklaying automation, this paper is interested in reflecting on the actual role of manual brickwork. In doing so, the authors present the Brick Tower experiment developed at the DFL/CEAU/FAUP, where two different fabrications processes are critically compared: a robotic and a manual one, which is aided by a video projection technique. By describing and illustrating this experiment, the authors argue that it is possible to expand the traditional craft of bricklaying by devising simple strategies to increase the human capacity to understand and materialize more elaborated geometries. This research avenue can be relevant if one considers that manual work should remain the most common form of brickwork practice in the next decades.

Keywords: *Brick Construction, Digital Fabrication, Robotics, Video-Projection, Non-Standard Structures*

INTRODUCTION
Brick construction counts with a long and rich tradition in architecture, which can be traced back to the origins of our civilization. As noticed by Campbell (2005: 13), its evolution overtime has been grounded in two major areas: brickmaking technologies and brickwork techniques. While the first one sets the physical properties of the material (i.e. weight, dimensions, resistance, appearance...), the second one defines the space for design creativity and efficiency of masonry constructions.

The developments in brickwork techniques tend to be driven by structural and aesthetic goals, supporting the materialization of magnificent brick walls, arches or vaults, and also ornamental surface effects. However, with the industrialization in the XIX century, the dominance of standard bricks over the variability of the manually produced ones, introduced some design constraints in their application in architecture. As a result, those interested in achieving customized structures and aesthetic effects had progressively to rely more and more in exploring bricklaying strategies of identical units rather than in designing and producing variable ones.

BRICK CONSTRUCTION
The Manual Approach
In the last century, many renowned architects dedicated a special attention to brickwork in many of their built works. The horizontal effects in Frank Lloyd Wright's prairie houses or the beautiful arches in Louis Kahn's buildings for Dacca are clear examples of such interest. But looking into the attempt of solving more difficult geometries, the work of Eladio Dieste must be highlighted. His Church of Christ the Worker in Atlântida (1958-60) is a masterpiece of brick construction where, as highlighted by Anderson (2004: 42), the structural and the aesthetic concerns are seamlessly fused. For instance, Dieste improved the structural stability of the lateral facades by designing a ruled surface geometry, which, at the same time, creates a dynamic appearance enhanced by the light and shadows effects cast on their surfaces. On a more aesthetic level, the Muuratsalo experimental house (1953), designed by Alvar Aalto, is exemplar in the way different bricks and brickwork patterns are explored to achieve different surface effects (Jetsonen and Jetsonen 2008: 80). In both cases, besides their design principles, building such curved and ornamental constructions required the architect's carefully guidance of the on-site construction process and, as well, the talented skills of the manual labor.

Despite the success of such interventions, the exploration of more irregular geometries is hard to be imagined, represented and built. For instance, in Frank Gehry's MARTa Herford museum (2005), the curved brick facade was laid by following and covering a previously built undulated concrete structure (Brinkmann 2005). In SHoP architects' Mulberry House in New York (2013), the faceted effect of the brick facade is actually made out of a set of standard prefabricated concrete panels containing an integrated set of bricks [1].

The Robotic Approach
Looking for overcoming the geometric constrains imposed by standardization, Gramazio and Kohler introduced in 2006 the use of robotic technologies to bridge design and construction in architecture (Gramazio and Kohler 2007). In their pioneering work, bricks were one of the first materials to test this technology. In the "Programmed Wall" experiment, they used an industrial robot to construct variable wall parts out of identical bricks. The overall geometry of the design was difficult to be conceived, represented and materialized without the help of digital technologies. Indeed, when attempting to build an irregular brick structure, it is very difficult for man to understand and translate it from 2D drawings and 3D models into a precise physical construction. On the contrary, the robot can naturally read all the different spatial coordinates describing each brick's position and orientation and, then, pick and place them correctly in space. This robotic approach to masonry construction was translated into real applications,

like in the facade of the Gantenbein Winery (2006) or the recent Manchester City's Stadium wall, both developed with the support of R-O-B Technologies, the spin-off company from the ETHZ.

However, aside with this non-standard architecture trend, robotic technologies have started to make an impact at different level. Since brick construction is based on the repetitive assembly of numerous small and identical physical units, it presents a strong potential to be automated. Therefore, some companies have started to use robots in the production of regular and flat brick walls in a faster way than humans do. The robotic bricklayer S.A.M. (i.e. Semi-Automated Mason) has been developed and tested by Construction Robotics since 2011, in both prefabrication and on-site applications (Peters 2014).

Critical Overview

Regarding craftsman work, the advantages of automation are clear and related with increasing the speed and precision of manufacturing, while sustaining longer working periods without compromising human safety. However, the Gramazio & Kohler's approach also revealed the limitations of human capabilities to deal with geometric complexity. Thus, with the advancements in robotic fabrication, both repetitive and differentiated brickwork strategies can be now potentially automated.

Despite these possibilities, robotic laying processes also present some limitations. On the one hand, in on-site construction, the setup and manipulation of robots is a difficult task. For instance, the execution of non-vertical walls or spatial structures (e.g., arches or vaults) is difficult to be achieved by the limited range of action of industrial robots. Therefore, the advantages of automation are clearer in the context of prefabrication scenarios. On the other hand, robots are still an expensive and uncommon technology in building construction, which, furthermore, require several other automation devices to assure a flexible and autonomous functioning (e.g., a system for feeding the bricks to the robot, a tool for laying the mortar or glue on the bricks, or sensors to monitor the correct geometric evolution of the built structure).

Facing the emergence of robotic automation, with its productive advantages but also jobs threat, it is important to reflect about the actual role of manual brickwork. The historical and worldwide dissemination of this craft, the higher flexibility to work in on-site conditions, and the easier capacity to accommodate changes during the construction process, are some of the positive qualities of craftsman. In this context, the Digital Fabrication Lab (DFL / CEAU) of the Faculty of Architecture of the University of Porto (FAUP), has developed a research line dedicated to rethink the pros and cons of robotic and manual approaches in brick construction, and investigate the interest and possibility to envision alternative strategies that may point towards the cooperation between the two. In this paper, the authors present a first practical experiment -The Brick Tower-, which tries to combine some of the advantages of both worlds.

THE BRICK TOWER EXPERIMENT

The Brick Tower experiment intends to investigate the potentials of manual and robotic approaches in brick construction. With this goal, the team designed a brick structure model with a geometry that challenged the conventional modes of representation and construction. This model served as the common source to test the potential for materializing non-standard structures through:

- A robotic assembly process;
- A manual assembly process aided by a video-projection technique.

The geometry of this model was also conceived to create the form of a Brick Tower by overlapping two copies of the model, with one of them turned up side down. Since the experiment produces 2 physical constructions, it seemed interesting to create a single final installation -The Brick Tower- instead of getting two isolated pieces in the end (Figure 1).

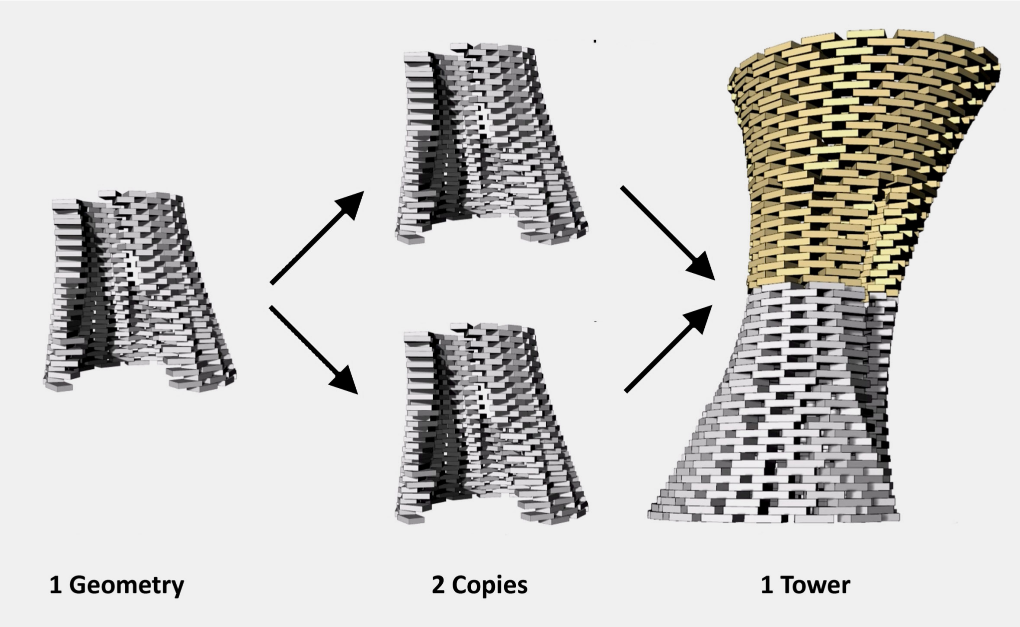

Figure 1
Diagram explaining the Brick Tower experiment and the design of the structure.

The Design Description

The design geometry is based on a truncated cone with an opening, and it was modeled in Rhinoceros ((C)McNeel). With the parametric design plugin Grasshopper ((C)David Rutten/McNeel), its surface was converted into a series of stacked EPS bricks with 250x100x50mm, which is one of the standard dimensions of commercial bricks. In total, the model comprises 414 bricks distributed along 36 levels.

The algorithm for the distribution of the bricks in the surface was one of the main design challenges. The parametric exploration of variable spacing and number of units to describe each level of bricks resulted in confused brickwork patterns, frequently lacking supports in some points of the structure. To avoid this, a different strategy was developed. By considering the same number of bricks in all levels, the final algorithm assigned a specific rotational value for each brick in order to fit all of them on each level. The resulting aesthetic effect is more logic, displaying incremental variation effects, and, from the structural point of view, the masonry solution is much more stable.

To support the design development, a series of 3D models were printed along the process using a MAKERBOT Replicator 2x printer, based on FDM technology. Without this additive fabrication process, it would have been very difficult to evaluate and refine the variable geometry of the brick structure (Figure 2). Thus, it became clear the critical interest of the geometry to conduct the experiment. With this design model description, the two fabrication tests could take place.

The Robotic Fabrication Test

The robotic fabrication of the brick structure was done with the industrial robot at the DFL, a KUKA KR120 R2700, equipped with a vacuum gripper from Schmalz. The setup for running the test included the working table in front of the robot (i.e. with

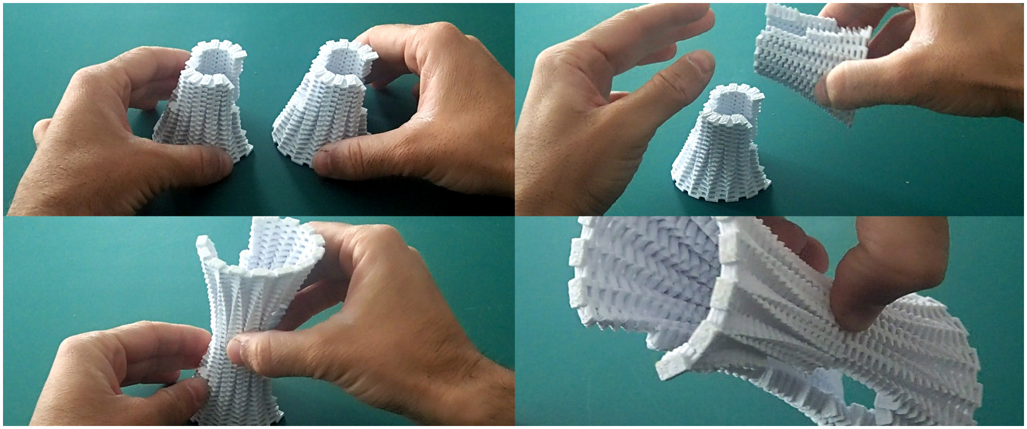

Figure 2
The two identical 3D printed models of the brick structure and the confirmation of the possibility to assemble them to create the brick tower geometry.

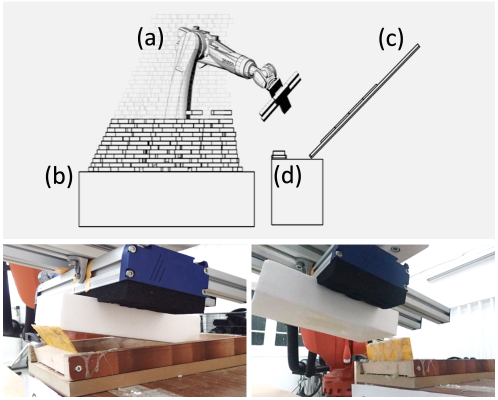

Figure 3
On the top, the scheme of the fabrication setup: (a) the robot; (b) the working table); (c) the brick dispenser; (d) the glue basin, which was discarded later. In the bottom, testing the automation of the gluing process.

2400x2400mm area) and a wooden ramp next to it to work as the bricks dispenser. The robot was programmed with the software KUKA|Prc ((C)Association for Robots in Architecture). With this Grasshopper plugin, the complete cycle of fabrication instructions was sequenced: starting the vacuum, picking the brick from the dispenser, placing it in the right position over the table and, finally, stopping the vacuum before moving again to pick another brick. To prevent falling down some bricks in cantilever located in the edges of the structure, a set of extra supporting bricks was modeled underneath to support them during construction. Although the robot would automatically position these new bricks, they would be manually removed from the structure in the end.

Due to the height of the brick structure (i.e., 160cm), the design model has to be divided in two parts to fit the robot's maximum range of motion. In a first trial, the team installed a small basin with contact glue to dip the bricks before being laid in the structure. This idea aimed at setting up a fully brick laying automated process, but the system turned out to be very slow while it consumed and wasted a lot of glue. Without having the means and time to setup a more advanced system, the experiment move forward comprising the manual deposition of glue after the robotic assembly of each layer of bricks. (Fig. 3)

The robotic fabrication process occurred with no surprises. Overtime, the pick and place PTP movements were tuned to around 70% - 80% of the maximum speed, without compromising the great precision of the whole process (Figure 4). As an average, each level of bricks took around 4 minutes to be completely laid, including 1 minute for putting the glue. At this point, the robotic motion definitely surpassed the speed that could be attainable by manual brick layering. In the end, the two fabricated parts were glued together to form the first half of the Brick Tower.

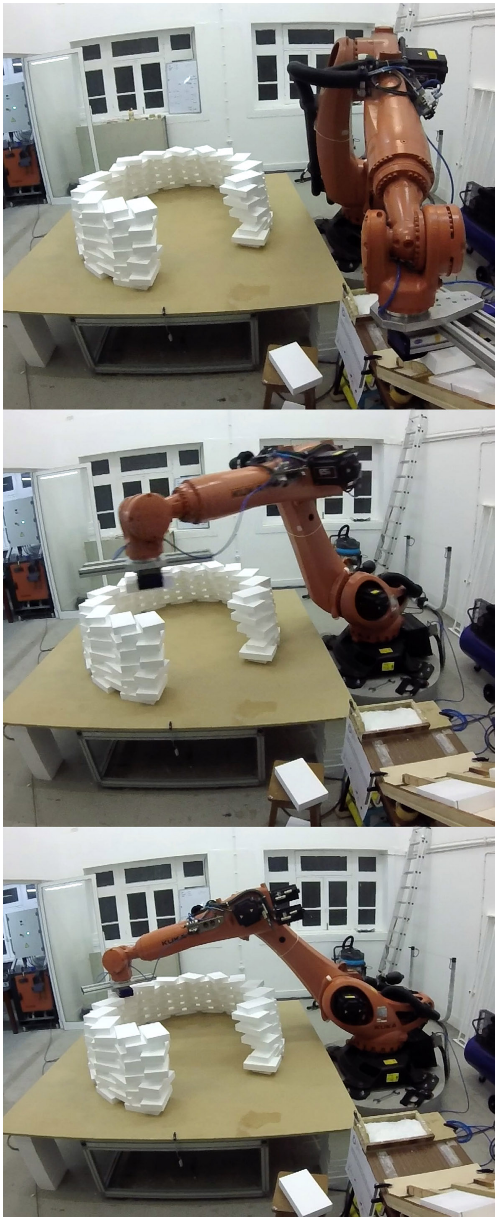

Figure 4
Sequence of the robotic fabrication process of the brick structure.

The Manual Fabrication Test (aided by video-projection techniques)

Given the human trouble in dealing with the irregular geometry of the brick structure, an alternative method was devised to expand the possibilities of manual assembly. The idea was based on using a video projection technique to orient the construction of the structure by hand. The setup of this test simply required to mount, over the working table, a video projector connected to a laptop. In the computer, the 3D model of the structure was sectioned every 5cm in height, to generate the plan drawings of each one of the 36 layers of bricks. These 2D representations would be then projected over the table, level by level, to guide the manual positioning of the bricks.

The crucial part of this strategy is focused in fixing the geometry of the projected image according to two factors. The first one is concerned with the fact that the projection axis is not perpendicular to the video projector, which deforms the projected image into a trapezoid. This problem is even clearer, if the position of the video projector is not aligned with the vertical of the table center. To solve this, the 2D drawings of the brick plans have to be carefully distorted in the computer screen to guarantee the projection of non-distorted rectangular images over the working table. The second factor consists in controlling the scale of the projection for each layer of bricks. While the first layer is projected over the table, the other ones are projected over the top surface of the bricks underneath. As one moves vertically, the images become smaller due to the perspective cone of the video projection. Therefore, besides the distortion, the 2D drawings of each layer of bricks have to be conveniently scaled up in the computer to compensate this immediate reduction. The twofold calibration was achieved with Grasshopper, by making a parametric system to generate the 2D drawings (Figure 5).

If the projector was mounted in the robot, it would have been possible to make this calibration by controlling and synchronizing its movement. However, the limited motion range in height of the in-

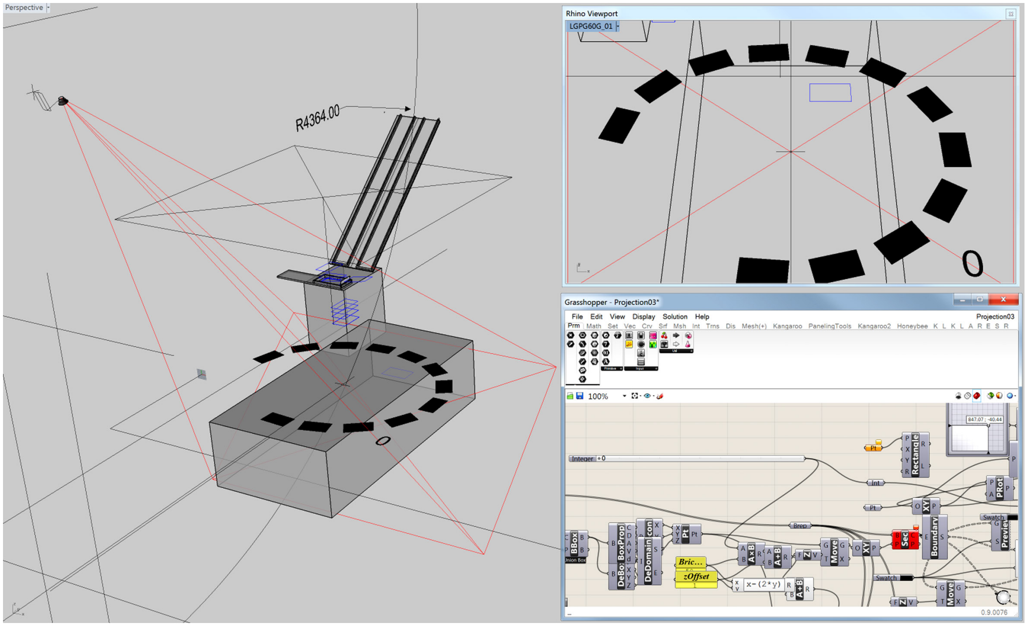

Figure 5
The digital parametric process to generate and adjust the perspective deformation of the 2D drawing images to be project.

dustrial robot at the DFL wouldn't create a projection large enough to allow building big parts. For the current test, the video projection was mounted on the top of a taller ladder. Given the narrow lens of the projector, the design model had to be divided in 5 parts, which were assembled separately.

To confirm the effective calibration of the system, a few projection tests were carried out in the beginning, by using objects with different heights and orientations in space. With everything set, the experiment started with two persons picking and placing the bricks, following the projected images of 2D plan drawings. Like in the robotic experiment, the glue was manually introduced after laying each level of bricks. To improve the control and precision of the assembly, the projected image consists in two overlapped crossed rectangles. While the dark one represents the bottom surface of the brick (i.e., the reference for its placement), the brighter one describes the contour of its upper surface. Due to the conic projection, both rectangles are not aligned in the same plane. So, if the system is calibrated, once the brick is placed on its real position, the bright rectangle has to coincide with its top surface. The worker thus gets two complementary information: to know where to place the brick and to confirm its right positioning. Furthermore, by overlapping the image projection of the next level over the bricks laid in the table, the intersection space indicates where to put the glue. In average, the positioning and bonding of each layer of bricks took around 5 minutes to be completed. In the end, the fabricated parts were assembled together to form the second half of the Brick Tower (Figure 6).

The Result

The end of the experiment resulted in the production of 2 brick structures by employing 2 different fabrication processes, which departed from the same digital information (Figure 7). In resume, the comparative analysis of both experiences reveals that:

Figure 6
In the top row: (left) the dark crossed rectangle indicating the position to laid the brick; (center) the bright crossed rectangle matching the upper surface of bricks confirms that they were laid right; (right) the portion of the dark crossed rectangle (the position of the upper brick) over the laid brick indicates the area to put the glue. In the bottom: a sequence of the manual process of assembly the structure with the aid of the video projection technique.

- The robotic construction was around 20% faster than the manual one. If one automates the gluing process this difference will have a tendency to increase.
- The gluing process was more optimized in the manual approach, since the video projection system provided a visual reference about the area to place the glue;
- The robotically fabricated structured is very precise. Some of the deviations verified in a 3D scanning comparison with the digital model were caused by a minor structural deflection due to the material weight. The manually assembled structure present a little deviation regarding the digital model, due to some small brick slippage occurring with the manual gluing process, but also, due to the tiny structural deflection over the construction, which necessarily affects the precision of the projected image.

Figure 7
The two fabricated brick structures. On the left, the robotically assembled one. On the right, the manually assembled one.

Despite these differences, when the structures are put side by side, it is difficult to visually detect their differences. And when the two are assembled together to create the Brick Tower, the geometric continuity between them can be perceived (Figure 8). The imperfection of the manually assembled part is somehow distributed in a coherent way over the whole form. Although this is acceptable for the design effect of this experiment, this could be more problematic in other building circumstances, for instance, when the fabricated part has to match another one. To overcome such problem, the manual assembly process had to be slower to improve the precision level of the process.

CONCLUSION

The Brick Tower experiment was an opportunity to reflect about the impact of robotic automation in brick construction, and on the resilience of craftsman masonry practice. Without analyzing the jobs threat questions, which is beyond the scope the present paper, this investigation made clear the potential of robotic technologies to overcome several human limitations in construction, especially in prefabrication scenarios. Indeed, the robotic fabrication test demonstrated the great flexibility, precision and speed of such automated process. Nevertheless, it is not expectable to witness, in a short time period, these new technologies taking over the brick masonry industry at the global scale. In the next decades, manual brickwork should still prevail in conventional building construction scenarios, especially in those countries with less economic and technological capacities. The low cost and the connection with local traditions are still important factors in favor of this manual work.

In this context, the video-projection test may become significative. By requiring very simple means (i.e., a computer and a video projector) it aims at providing the means for more flexibility and precision in the manual approach to brick construction. With this first experience, the present paper intends to contribute to expand the manual brickwork possibilities to materialize structural and aesthetic design ideas within a feasible timeframe and without requiring cutting-edge technologies. It should be highlighted that despite the emergence of other building construction methods (e.g., concrete structures), masonry construction is a relevant additive construction process to address the contemporary challenges related with sustainability.

Figure 8
The Brick Tower structure made out of the 2 fabricated parts. On the right, detailed views from the interior (top) and the exterior (bottom).

ACKNOWLEDGMENTS

The authors would like to acknowledge the support to this experiment provided by the DFL team, the research partnership with INESC TEC on robotic fabrication technologies, and the industrial support of Cerâmica Vale da Gândara company in the study of brick construction.

This work was developed in the scope of the Research Project with the reference PTDC/ATP-AQI/5124/2012, funded by FEDER funds through the Operational Competitiveness Programme - COMPETE, and by national funds through the FCT - Foundation for the Science and Technology.

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