archi|DOCT

The e-journal for the dissemination of doctoral research in architecture

July 2019

www.archidoct.net

ISSN 2309-0103

13

FORCES

Listed in:

Scopus®

ISSN 2309-0103
www.archidoct.net
Vol. 7 (1) / July 2019

Static performance-oriented design of variable modular bricks for automated fabrication using an adaptive formwork

Panagiota Konatzii // Department of Architecture, University of Cyprus

Abstract

This ongoing research work aims to develop an automated fabrication process for the production of multi-modular bricks by using a custom-made end-effector tool as adaptive formwork and by integrating different design criteria that are associated with static and environmental impact analysis based on different building materials. In the current paper, the investigation undertaken based on criteria related to the morphology of modular bricks and their static adequacy in the digital environment are demonstrated, together with an overview of the proposed robotic fabrication process. In order to achieve this, three different building materials are proposed; adobe, concrete and clay mixture based on soil and cement. The aim is to compare the compressive strength of modules between different materials and to evaluate the amount of material used in alternative typologies. The integration of digital investigation and robotic fabrication processes using as design objective a brick configuration upgrades and complements conventional approaches that are currently followed in this field of study.

Keywords

Static performance-oriented design; Modular bricks; Variable design; Robotic fabrication; Adaptive formwork

ISSN 2309-0103
www.archidoct.nett
Vol. 7 (1) / July 2019

1. Introduction

Latest developments in the area of computational design and fabrication open up possibilities for a more robust and effective integration of workflows from design and then to construction using as case studies whole structures or building elements in actual scale. Advantages of this new paradigm shift towards more seamless processes might include minimization of failures and misfits during different design to fabrication stages, which are found to be fragmented in case of conventional implementations (Kontovourkis and Konatzii, 2016). In the literature, this direction and especially the involvement of automation and robotics in construction is in continues development (Bock, 2008; Bock and Linner, 2015) with different scenarios of such integrations to be included, for instance robotic pick-and-place of bricks, achieving the development of complex wall structures (Giftthaler et al, 2017; Dörfler et al, 2016), robotic cut-and-place of timber for the development of wooden structures (Willmann et al, 2012) and flexible formworks for concrete casting of free-form building components (Kristensen et al., 2013).

Towards this direction, automation and robotic mechanisms that are responsible to accomplish the given tasks are of great importance, mainly due to their ability to be flexible, accurate and numerically controllable allowing transferring of design data from the design platforms to the mechanism for construction execution. In most of the cases, construction tasks require custom-made end-effector tools, such as flexible or kinetic formworks (Kontovourkis and Konatzii, 2018) and 3D additive mechanisms (Kontovourkis and Tryfonos, 2016; Keating and Oxman, 2013), considering minimization of time (Ena et al., 2013) and maximization of accuracy as important factors to be taken into account. In the area of building components and overall wall construction, examples like the work by (Hack et al, 2013) achieves to minimize wall thickness and improve the environmental performance of conventional walls through the development of a custom-made end-effector tool that produces the rebar and coffin before concrete pouring. In another case, the work by (Oesterle, 2012) aims to reduce waste material by developing a flexible mold using hot wax that is casted and then solidified in order to be used as temporary concrete formwork. In addition to casting kinetic formworks, the 3D printing method is currently expanded in the construction sector and is studied in terms of application scale, process cost, construction time, material type and other criteria (Wu et al, 2016).

In both cases, casting kinetic formworks and 3D printing, aim is to search for practicality and precision in solutions of non-conventional formatting. On the one hand, 3D printing enables the construction of any form to a great extend due to the versatility of the process, provided that the printing size is within the boundaries of the machine (Kontovourkis and Tryfonos, 2018; Holt et al, 2019). On the other hand, in case of kinetic formwork casting, the process can be speed up by using the same mechanism, however this can be done within a certain range of geometrical limits according to the mechanism applied. In general, although bricks have been widely used in construction as an inexpensive material, practicality and precision in case of customized design and non-start morphologies development have not been examined in full extend yet. The use of flexible molds and robotic machines can automate the process of manufacturing and positioning of such unit elements (Dörfler et al, 2016).

Inevitably, such attempts are directly associated with investigations conducted in design and analysis stages. For instance, in several cases, automated fabrication processes take into account static behavior assessment of structural elements to be constructed. In this context, examples can be found where integration with static analysis processes is made as part of brick design and fabrication

ISSN 2309-0103
www.archidoct.net
Vol. 7 (1) / July 2019

investigation. In particular, digital model simulation through loads exercising aims to investigate their static behavior (del Coz Diaz et al, 2011). The process of calculating the behavior of masonry in the physical environment is a complex process and this is why simulation under different loading conditions through modeling in digital environment for different morphologies is required (Viswanathan et al, 2014). Through calculation, the maximum strength of the specimen can be determined and thus its compressive strength can be derived (Karadoni, 2012; Illampas et al, 2011). For investigation of wall structures at the design and construction level, static analysis confirms the adequacy of the proposed outcome, especially when developed on the basis of different typologies.

2. Methodology

Within the framework of this ongoing research work, a methodology is developed, which aims towards an automated fabrication through the development of a flexible kinetic formwork that is capable of adapting its configuration according to a variety of brick morphologies. This is used as a custom-made end-effector tool that can be mounted at the edge of an industrial robotic arm, achieving the gradual production and placement of custom bricks and masonry systems according to their predefined design.

The suggested methodology lies within two equally important pillars of investigation, on the one hand static and shading performance – oriented design with the aim to find appropriate typologies that minimize volume and hence material of brick modules, and on the other hand, Life Cycle Analysis that include material selection, CO_2 emission and energy consumption evaluation during the whole fabrication cycle (Figure 1). Static and shading performance are in the same pillar of investigation, influencing design decisions regarding the morphological investigation of variable modular bricks. Both performance analyses are integrated with objectives related to minimum ecological footprint throughout the fabrication life cycle, a part of study that has been presented in (Kontovourkis and Konatzii, 2018).

This paper focuses on static performance-oriented design, which allows design-decisions to be made regarding the morphology of the modular brick results in the digital environment. These decisions are associated with various design parameters, formulating the type and dimensions of the overall shape and openings of a folding-porous wall consisting of modular bricks. Design results are analyzed to find desirable solutions that meet the objectives of maximum compressive strength and minimum material use. Analyses are conducted for three different materials; adobe, concrete and clay with cement, so that a comparison between derived results will allow decision to be made regarding the best environmental friendly material to be implemented.

Static performance-oriented design of variable modular bricks for automated fabrication using an adaptive formwork

ISSN 2309-0103
www.archidoct.net
Vol. 7 (1) / July 2019

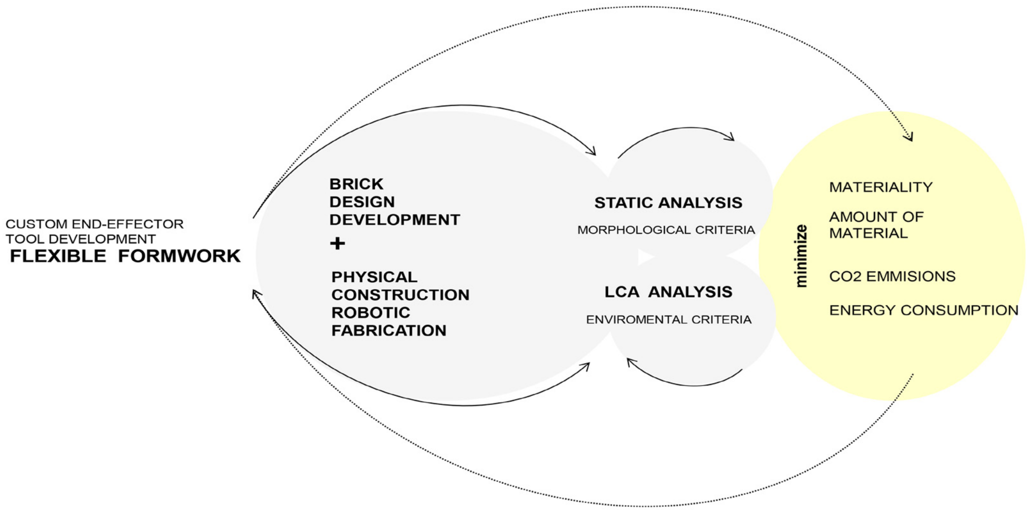


Figure 1.
Research methodology diagram

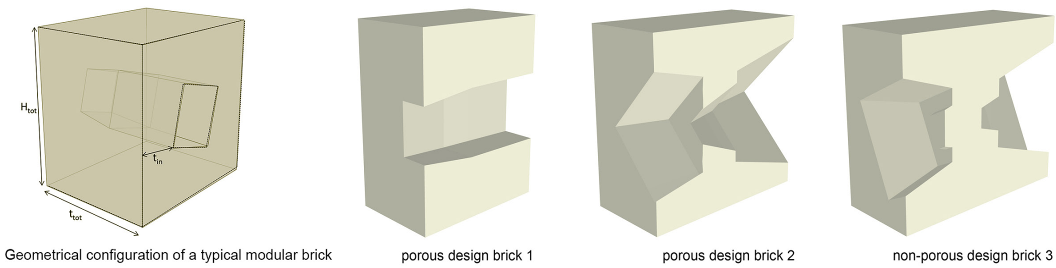


Figure 2.
Brick typologies and geometrical parameters /constraints

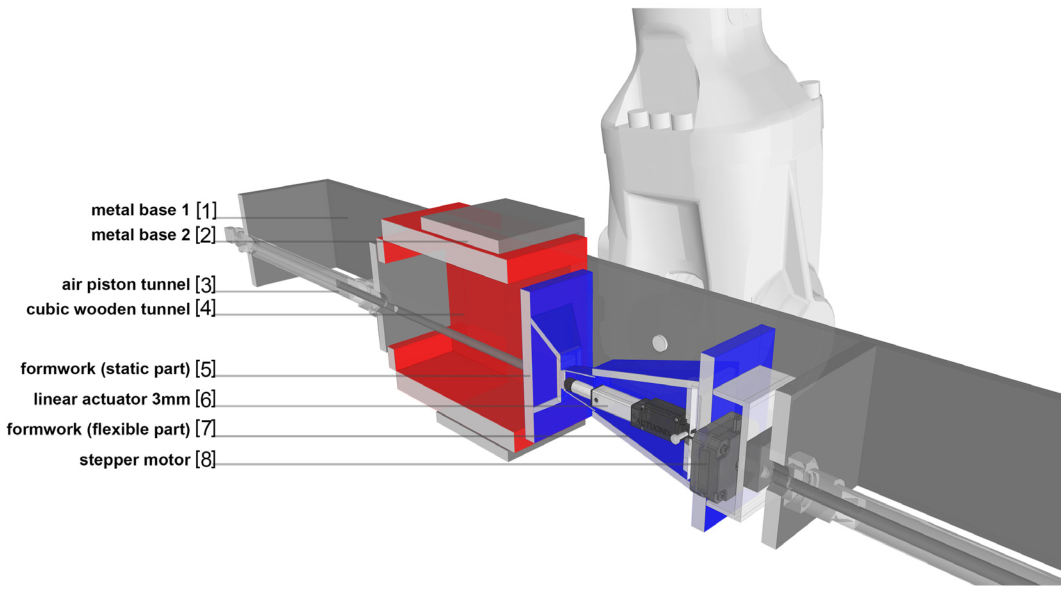


Figure 3.
Custom end-effector tool development

ISSN 2309-0103
www.archidoct.net
Vol. 7 (1) / July 2019

3. Digital to physical development of variable modular bricks

3.1. Geometrical and static parameters/constrains

The investigation starts by examining the geometrical configuration of modular bricks that can be used in the construction of walls allocated in semi-open spaces in order to protect and act as filters for shading and natural ventilation purposes.

The selected geometry of modular brick is a cuboid, either with a central opening or without or a combination of the two. In typologies that consist of openings, their inner edges are formulated by folding faces. The folding faces together with the size and rotation angle of openings, in addition to their contribution towards an improved shading performance of modules, help towards material minimization, keeping structural adequacy but at the same time following limitation and possibilities offered by the automated regarding its ability to produce the desired morphologies. Thus, their design takes into account the parameters and constraints that arise from the adaptive formwork mechanism, which enables the production of variable morphologies with flexible opening size and angle as well as inclination of edges folds.

Three main types of bricks are investigated (Figure 2), approaching the adaptation logic of the flexible mold. In the first category, large material removal formulates a central opening, in the second category, small removal of material formulates a smaller opening and in the third category, material subtraction creates recess with folded faces. In addition, another parameter influencing geometry is the rotation of opening or recess in each typology of brick units. This is defined at specific angles of 0^0, 15^0, 25^0 and 45^0 with axis of rotation perpendicular to the elevation of module.

The boundaries of geometry are defined by taking into account the criteria governing holes/openings based on the European Eurocode, the orientation of the masonry and the design of the end-effector tool, and more specifically, the limitations imposed by the flexible mold mechanisms. Based on the geometric requirements of the masonry walls in Eurocode 6 (EN: 1996-1-1, 2005) and the Seismic Regulation (Eurocode 8), which determines the volume of a single hole/opening, the minimum thickness in and around the holes, the effective thickness (t_{tot}) of the masonry and the total height (H_{tot}) (Figure 2) of the masonry, the proposed geometry of the modular brick is defined with external dimension of 120 × 120 × 80mm and with maximum dimension for the rectangular opening of 70 × 70mm.

The parameters and limitations regarding the design of the flexible formwork influence the dimensions of the total brick thickness, but also the size of the compressed surface of the material or the size of the hole/opening. The automated mechanism can be activated at specific power values, also the linear actuator, which is responsible for controlling the thickness of the wall, and has a maximum elongation of 30mm. Based on the design of the flexible formwork, the thickness of the modular brick ranges from 40-80mm.

ISSN 2309-0103
www.archidoct.net
Vol. 7 (1) / July 2019

Figure 4.
Robotic procedure in physical environment

Material	Mass Density(ρ)	Poisson ratio	Young's modulus	Yield stress	Inelastic strain	Yield stress	Cracking strain
Adobe	1400	0.3	$300e^6$	$20\ e^6$	0.0035	$2\ e^6$	0.0001
Concrete C20/25	2565	0.175	$208e^8$	$30\ e^6$	0.0035	$2\ e^6$	0.0001
Clay with cement	1520	0.4	$122e^6$	$20\ e^6$	0.0035	$2\ e^6$	0.0001

Table 1.
Materials' characteristics.

Typology cases	1a 0	1a 15	1a 25	1a 45	1d 0	1d 15	1d 25	1d 45
Fbc(MPa) adobe	0.221145	0.214687	0.206562	0.196345	0.175486	0.165208	0.152251	0.140023
Fbc(MPa) clay	0.183731	0.196927	0.189645	0.180355	0.142619	0.131585	0.126984	0.116928
Fbc(MPa) concrete	22.67835	21.12014	22.67835	16.38183	18.13673	14.69469	12.05922	10.24148

Typology cases	2a 0	2a 15	2a 25	2a 45	2d 0	2d 15	2d 25	2d 45
Fbc(MPa) adobe	0.311979	0.338096	0.298958	0.319543	0.29438	0.285611	0.274389	0.235937
Fbc(MPa) clay	0.260349	0.255585	0.249375	0.241666	0.222205	0.215755	0.207411	0.194019
Fbc(MPa) concrete	33.63774	32.59106	29.55561	27.61348	29.3588	23.90717	20.72138	13.53386

Typology cases	3a 0	3a 15	3a 25	3a 45	3d 0	3d 15	3d 25	3d 45
Fbc(MPa) adobe	0.401764	0.396171	0.388932	0.379266	0.352348	0.344533	0.334373	0.321152
Fbc(MPa) clay	0.30419	0.299802	0.294163	0.28668	0.266634	0.260622	0.252818	0.242694
Fbc(MPa) concrete	24.48159	34.5376	32.46788	30.40821	16.3296	16.45944	14.43382	13.10095

Table 2.
Characteristic values of compressive strength of the three materials under investigation

ISSN 2309-0103
www.archidoct.net
Vol. 7 (1) / July 2019

3.2 Material mixtures investigation (adobe, concrete, clay)

As it has been mentioned, the three materials selected for analysis are adobe, C20/25 concrete and clay with the addition of cement. In particular, for the composition of the adobe samples, this study uses ground clay and calcium sand mixed in 1:1 w/w ratio based on the work of (Houben and Guillard, 1994; Illampas et al, 2017). The resulting mixture consists of 13% clay (d <0.002 mm), 44% silt (0.002 mm <d <0.075 mm) and 43% sand (0.075 <d <2.36 mm). Also, 4% fiber content, 29% water content and 18% homogeneity of fresh mixture.

In the case of concrete, ready-made mix concrete C20/25 is used. This consists of 10% recycled binders in cement (300kg/m^3). The composition of materials in this type of concrete is defined according to BS 8500-1: 2006, where the water/cement ratio=0.6, 300kg/m^3 in which Portland cement and binders are used. In the case of ground clay as the building material, its composition consists of ground clay, water and soil stabilizer. In the present study, a blend of clay is used, which is combined with a maximum percentage of cement at 8% according to (Minke, 2006). Generally, this is a hybrid mix that contains cement and clay.

3.3 Custom-made kinetic formwork design and physical development

The brick production scenario is conducted in the workshop and includes three phases: pressure, demolding and positioning of bricks on a flat surface, remaining there until they reach a maturity stage. Then, the bricks are transferred to the building site for construction.

In order to achieve the automated brick production, the design and physical development of the custom-made kinetic formwork is influenced by the geometric and static parameters/constraints that are explained in previous sections. Briefly described, the custom tool consists of two parts, the press and the pressing container, which are supported by an aluminum base (1,2) mounted at the edge of the industrial robot. The press system is designed to be adaptable to the different typologies of modular bricks. In particular, the press part is responsible to compress the material after being placed in the pressing container and consists of two pneumatic pistons (3). In each end of the pistons, the two parts of formwork are adjusted, one static (5) and one flexible (7), which are responsible to press material and formulate the two surfaces of the brick. The flexible mechanism is responsible to adapt its shape according to the different typologies of bricks based on their hole/opening size and rotation as well as their thickness dimensions. In order to achieve this, a linear actuator and a stepper motor are placed on the flexible part (7), controlling different behaviors like expansion and rotation (Figure 3).

Apart from the production of a single brick, the robotic procedure includes repetition of physical development and placing of bricks on a flat surface for a certain time period (Figure 4), a workflow that is programmed in HAL [1], a plug-in for Grasshopper [2] and executed through Robot Studio 6.0 [3]. The automated and robotic programming incudes the actuation and deactivation of kinetic formwork and particularly the control of the formwork mechanisms, the task programming of robotic motion behavior together with the calculation of the time duration of the press mechanism.

4. Numerical static analysis and results

As it has been mentioned, the brick element is distinguished in two types: brick with hole/opening and brick with recess. In the first case, the holes/openings vary in size from 2x2cm to 7x7cm. In

ISSN 2309-0103
www.archidoct.net
Vol. 7 (1) / July 2019

the second case, recesses are formulated by simply removal of material with the assistance of the flexible mold. In all brick types, the openings or recesses are able to be rotated.

In the first stage of numerical static analysis, the static behavior of brick typologies is examined under vertical loading. Then, the strength of the structural element is calculated based on additional loads from beams and slabs, i.e. when elements are part of load-bearing walls. The numerical static analysis explained in this paper is followed by physical tests in a future stage of experimentation.

In the following investigation, the characteristic compressive strength of adobe, concrete and clay is calculated to confirm the sufficient static behavior of the brick typologies. In the current stage, a method for calculating the compressive strength of the bricks produced in conjunction with the simulation of their static behavior in the ABAQUS CAE software [4] is conducted. First, linear analysis and second, non-linear analysis is performed for each brick typology. The investigation examines the strength of the bricks against the three different materials and the geometrical limitations of brick typologies according to the size of hole/opening.

4.1 Linear static analysis

In case of linear static analysis, calculation of the load is based on the equation P = F / A, where P is the total load (N) that exert force F on brick elements above support base on typical masonry with 3m height, and A is the surface area on which the loads are applied (Equation 1).

$$P(1\ brick) = \frac{F}{A} = \frac{m \times g}{A} = \frac{1.5kg \times 9.8m/s^2}{0.0087m^2} = \frac{14.7\ N}{0.0087m^2}$$

$$P(25\ brick) = 25 \times \frac{14.7\ N}{0.0087m^2} = \frac{367.5\ N}{0.0087m^2} = 42241.37\ Pa \qquad (1)$$

The pressure load for brick masonry is calculated at 42,241.13 Pa in case of adobe, at 84,482.7 Pa in case of concrete and at 63,361.695 Pa in case of clay with cement addition. The results show that concrete has the largest pressure exerted compared to the three materials examined in this research. For the analysis, a brick was used as a finite element model (FE), having three elements (C3D8) and 8 nodes. The FE grid consists of 5093 elements and is considered as a simple isotropic model of elastic material component. This is based on the plasticity theory of metallic elements and uses the typical von Mises yield surface.

Numerical simulation of adobe bricks

For the simulation of adobe bricks, parameters defined in the FE model takes into account the results of the work in (Illambas R. et al, 2017). In particular, Mass density is defined as $\rho\alpha$ = 1400 kg / $m^{3.}$ Poisson ratio as $v\alpha$= 0.3 and Young coefficient as $300e^6$ (Table 1).

Numerical simulation of concrete bricks

For the simulating of concrete bricks, the parameters defined in the FE model are in line with Eurocode 6 for concrete (EN: 1996-1-1, 2005). In particular, mass density is set to $\rho\alpha$ = 2565 kg/m^3 and Poisson ratio is set to $v\alpha$ = 0.175. Also, Young coefficient is set to $208e^8$, tensile stress is set to $30e^6$ and maximum value of inelastic area is set to 0.0035. Finally, maximum compressive stress is set to $2e^2$ and breaking point at 0.0001 (Table 1).

ISSN 2309-0103
www.archidoct.net
Vol. 7 (1) / July 2019

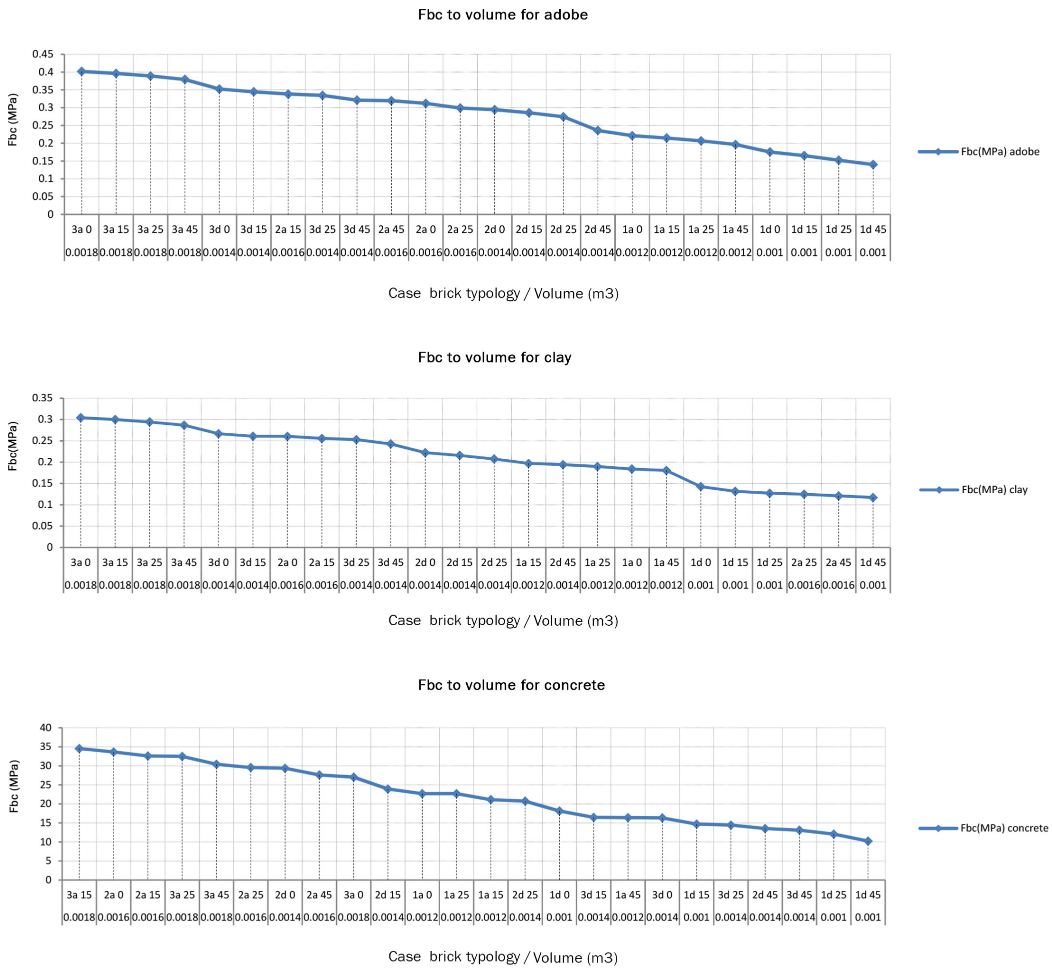


Figure 5.
Graphs showing compressive strength to brick volume for the three investigated materials

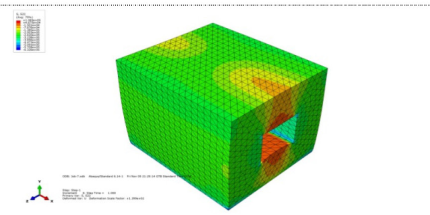
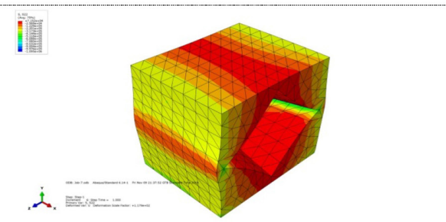
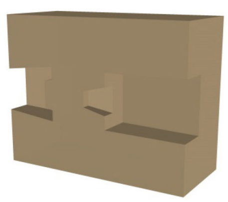
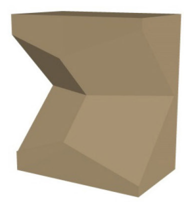
Adobe S-S_{22} diagram	 Maximum value compressive strength: 3a0	 Minimum value compressive strength:1d45
Model section	 Case 3a0	 Case 1d45

Figure 6.
Case of maximum and minimum compressive strength of brick types in case of adobe material

ISSN 2309-0103
www.archidoct.net
Vol. 7 (1) / July 2019

Numerical simulation of clay and cement bricks

For the simulation of bricks with clay and cement, the parameters defined in the FE model are derived by the research work conducted in (Lorenzo and Bergado, 2006), and particularly Mass density is set to ρa = 1520 kg/m^3, Poisson ratio at να = 0.4, and Young coefficient at $122e^6$ (Table 1).

4.2 *Results of linear static analysis of brick typologies*

The linear static analysis provides a number of results associated with von Mises, U22 and S22 maximum values. Analytically, U22 is defined as the maximum permissible displacement value according to the brick strength and it is measured in mm. This is caused on z-axis, perpendicular to the brick opening, after the uniformly distributed load is applied to the top surface area of the brick. S22 is defined as the compressive stress, it is differentiated on the basis of the materiality, the type and the maximum permissible value of the percentage of the brick's openings, and it is measured in Pa. This is caused on the z-axis and perpendicularly to the opening of the brick, after the evenly distributed load is applied on the top surface area of the brick. The displacement and the stress on the z-axis, due to their parallel action to the load pressure, define the elastic-tension limits of the brick geometry and hence are considered as the most critical values.

The results of analysis show that higher values occur in the case of concrete compared to the adobe material. Also, in both cases, maximum compressive stress in z-axis can be observed in the cases where holes/openings are rotated in 150 degrees. Moreover, displacement is decreased in cases of minimum dimensions of holes/openings and increased in cases of their rotation. Finally, in most of the cases, maximum values of compressive stress are observed when the holes/openings are rotated 150 degrees. In the case where clay mixture consisting of soil and cement is examined, an intermediate situation of static behavior is observed if this is compared with the behavior of adobe and concrete materials. The results of linear static analysis in the case of clay mixture and particularly the von Mises, U22, S22 maximum values of all brick typologies show similar static behavior as the one derived in the analysis of adobe material but with more resistance.

4.3 *Results of non-linear static analysis related to brick-force compression*

In order to investigate the strength of bricks, a displacement force is evenly distributed over the upper surface of the brick. In this way, the value of maximum force that can be applied to each brick until it is cracked and crushed is exposed. Respectively, by having a physical prototype of the brick, its resistance under compression can be tested in the laboratory.

During the digital process, the model is gradually loaded with 50000N/m^2 in all cases, causing a 0.001-0.0009mm maximum displacement in its overall height. The results are presented in a force-displacement graph from which the maximum force that can be exerted in each model is derived. The characteristic compressive strength is the result of the maximum force divided by the area on which the force is exercised (Equation 2). Calculation of the compressive strength of a modular brick follows:

$$F_{\mathrm{bc}} = \frac{Fmax(N)}{A_{sum}(m^2)} \qquad (2)$$

ISSN 2309-0103
www.archidoct.net
Vol. 7 (1) / July 2019

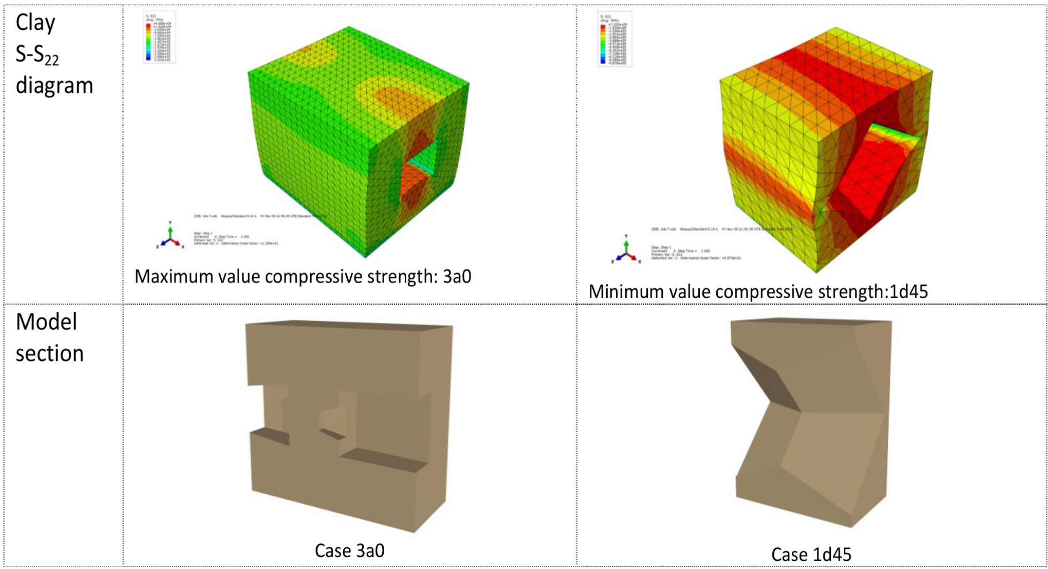


Figure 7.
Case of maximum and minimum compressive strength for ground clay with cement

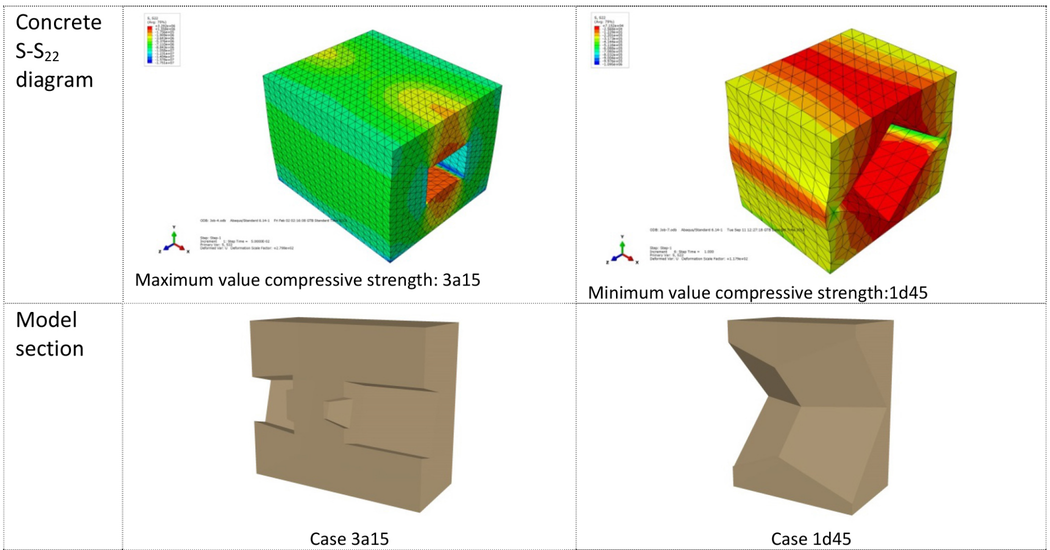


Figure 8.
Case of maximum and minimum compressive strength of brick types in case of concrete

ISSN 2309-0103
www.archidoct.net
Vol. 7 (1) / July 2019

The force-displacement graph is derived by calculating the sum of forces that are uniformly applied to the nodes of the mesh geometry on the bottom surface area of the brick, divided by the displacement value occurred at a central node of the top surface.

$$\frac{F}{U} = \frac{SumF(N)}{U_{centre}(m)} = \frac{F_1+F_2+F_3+F_n}{U_C} \qquad (3)$$

In case of concrete material, the compressive strength of the brick has its lowest value at 10,241 MPa and its maximum value at 34,537 MPa. Values up to 30 MPa are within the allowable limits, so models that exceed these limits are under investigation, in terms of their morphology and their total volume. In case of adobe material, the minimum compressive strength is 0.14 MPa and the maximum is 0.4 MPa. Based on Eurocode 6, cases that exceed 1 MPa are not within acceptable limits.
In case of clay mixture with the addition of cement, the range of compressive strength values is from 0.11 MPa to 0.30 MPa. Based on Eurocode 6 for adobe materials, compressive strength of up to 1 MPa is allowed (Table 2).

4.4 Comparative analysis and discussion of result

The graph of compressive strength-volume demonstrated in Figure 5 represents the strength values for all three material mixtures in relation to the volume of all modular brick typologies. The values are presented based on the highest strength of the bricks in compression. As it can be observed, most brick typologies in all three materials (adobe, concrete and clay with cement) with greatest material volumes are most resistant. Correspondingly, brick types with small material volumes have lowest strength values.

Analytically, with respect to the results of the static analysis compared to the volume of each brick unit type, maximum compressive strengths are observed in all case of materials where there is little material removal, that is, brick typologies with small holes/openings. The graphs in Figure 5 show that the strength of bricks is increased as the volume of material is increased non-linearly.

In case of adobe material, in all brick with volume 0.0018m^3, maximum compressive strength is observed (Figure 6). These brick types have no holes/openings but recess with minimum material removal. In brick types with volume 0.001m^3, which have large and rotated holes/openings, minimum compressive strength is observed.

In case of clay mixtures, maximum compressive strength is observed mainly in bricks with maximum volume of 0.0018m^3. Minimum compressive strengths are detected in brick types with volume 0.001m^3. In the first category cases where brick types with recess and minimum material removal are observed, while in the second category cases where brick types with large and small holes/openings that are rotated are observed (Figure 7).

In case of concrete, maximum compressive strength is observed in bricks with volumes of 0.0018m^3 and 0.0016m^3, and minimum compressive strength in bricks with volumes 0.001m^3 and 0.0014m^3. In the first case, the brick types are the ones with minimum hole/opening and with/without rotation, as well as types with recess and minimum removal of material. In the second case, brick types with holes/openings and large material removal are observed (Figure 8).

ISSN 2309-0103
www.archidoct.net
Vol. 7 (1) / July 2019

5. Conclusion and future works

This ongoing research works considers a series of investigations including static performance-oriented design in order to find desirable modular brick typologies with and without hole/opening based on three types of materials. Aim is to integrate performance-oriented design investigation with an automated fabrication process and particularly a kinetic and flexible formwork mechanism in order to allow the production of variable modular bricks accurately and in less construction time. Purpose is to examine the potential of different tools and analysis mechanisms incorporated in the early stage of design in order to achieve minimum material and static adequacy of design under investigation.

In this paper, the static performance-oriented design process is presented, aiming to assess the results in accordance to the suggested design under investigation. Static analysis is essential in order to avoid errors and failures of the construction of the modular bricks. Currently, this is possible through digital platforms, which allow an easy and quick evaluation of design attempts and imitate extraction of quantitative results that can be used in the next stages of design investigation and construction. Finding related to the compressive strength of brick type solutions through digital computation in the first stage of design experimentation helps to distinguish solutions with sufficient and effective static performance and therefore helps to determine the solutions that can be produced based on the suggested materials.

Further research work, in addition to the study of adaptive formwork mechanism and static adequacy of the modular brick units, will aim towards the development of an integrated methodology where environmental criteria will be examined in the early stage of design process. More specifically, work towards the quantitative analysis and evaluation of solutions based on the performance of process and the products in terms of carbon dioxide emissions, energy, costs and time will be conducted. At the same time, the possibility of implementing the adaptive formwork in construction scale scenarios for physical prototyping will be investigated.

Acknowledgements

I would like to express my gratitude to my first advisor, Dr. Odysseas Kontovourkis, Assistant Professor and Director of the research laboratory for Digital Developments in Architecture and Prototyping – d2AP in the Department of Architecture, University of Cyprus for his support, patience, and encouragement throughout my ongoing PhD research.

Notes

(1) http://www.hal-robotics.com/

(2) https://www.grasshopper3d.com/group/fireflyplugin

(3) http://new.abb.com/products/robotics/robotstudio/

(4) https://www.3ds.com/products-services/simulia/products/abaqus/

ISSN 2309-0103
www.archidoct.net
Vol. 7 (1) / July 2019

References

Bock, T. 2008. Construction Automation and Robotics, *Robotics and Automation in Construction*, Carlos Balaguer and Mohamed Abderrahim (Ed.), ISBN: 978-953-7619-13-8.

Bock, T. and Linner, T. 2015. *Robotic Industrialization,* Cambridge University Press.

Del Coz Díaz J.J, García Nieto P.J, Álvarez Rabanal F.P, Lozano Martínez-Luengas A. 2011. 'Design and shape optimization of a new type of hollow concrete masonry block using the finite element method', *Engineering Structures*,33(1), pp. 1-9.

Dörfler, K., Sandy, T., Giftthaler, M., Gramazio, F., Kohler, M., Buchli, J., 2016. 'Mobile Robotic Brickwork.' In Robotic Fabrication in Architecture, Art and Design 2016, Dagmar Reinhardt, Rob Saunders, Jane Burry(Eds), *Springer International Publishing*, pp.204-217.

Ena, L., Shahab, A. R., Linus, M., Flatt, R.J., Gramazio, F., Kohler, M., Langenberg, S., 2014. 'Complex concrete structures: Merging existing techniques with digital fabrication.' *Computer-Aided Design,* 60, pp.40–49.

EN:1996-1-1, Eurocode 6. Design of masonry structures. Part 1-1, General rules for buildings: rules for reinforced and unreinforced masonry, 2005.

Giftthaler, M., Sandy, T., Dorfler, K., Brooks, I., Buckingham, M., Rey, G., Kohler, M., Gramazio, F., Buchli, J., 2017. Mobile Robotic Fabrication at 1:1 scale: the In situ Fabricator-System, Experiences and Current Developments. *Construction Robotics,* 1(1–4), pp 3–14.

Hack, N., Lauer, W., Langenberg, S., Gramazio, F., Kohler, M., 2013. 'Overcoming Repetition: Robotic fabrication processes at a large scale.' *International journal of architectural computing,* 3(11),pp.285-99.

Holt, C., Edwards, L., Keyte, L., Moghaddam, F., Townsend, B. 2019. *3D Concrete Printing Technology*, Butterworth-Heinemann.

Houben, H. and Guillaud, H. 1994, *Earth Construction – A Comprehensive Guide*. ITDG Publishing, London, UK.

Illampas, R., Ioannou, I. and Charmpis, D. C., 2011. 'A study of the mechanical behaviour of adobe masonry'. WIT Transactions on The Built Environment, 118, pp.485 – 496.

Illampas, R., Loizou, V. G. and Ioannou, I., 2017. 'Effect of straw fiber reinforcement on the mechanical properties of adobe bricks', *Sixth Biot Conference on Poromechanics July 9–13,* Paris, France.

Lorenzo G. A. and Bergado D. T., 2006. 'Fundamental Characteristics of Cement-Admixed Clay in Deep Mixing', *Journal of Materials in Civil Engineering,* 18(2) (April 2006), pp.161-174.

Keating, S. and Oxman, N., 2013. Compound fabrication: A multi-functional robotic platform for digital design and fabrication. *Robotics and Computer-Integrated Manufacturing*, 29(6), pp. 439-448.

ISSN 2309-0103
www.archidoct.net
Vol. 7 (1) / July 2019

Kontovourkis, O. and Konatzii, P., 2016. 'Optimization Process Towards Robotic Manufacturing in Actual Scale - The Implementation of Genetic Algorithms in the Robotic Construction of Modular Formwork Systems', *Proceedings of the 34th Conference on Education in Computer Aided Architectural Design in Europe: Complexity & Simplicity (Volume 1)*, University of Oulu, pp. 169-178.

Kontovourkis, O. and Konatzii, P., 2018. 'Design-static analysis and environmental assessment investigation based on a kinetic formwork driven by digital fabrication principles', In O. Kontovourkis ed. *Proceedings of the 6th eCAADe Regional International Symposium: Sustainable Computational Workflows*. Nicosia: University of Cyprus, pp. 131-140.

Kontovourkis, O. and Tryfonos, G., 2016. Design optimization and robotic fabrication of tensile mesh structures: The development and simulation of a custom-made end-effector tool. *International Journal of Architectural Computing, SAGE*, 14(4), pp. 333-348.

Kontovourkis, O. and Tryfonos, G., 2018. Integrating parametric design with robotic additive manufacturing for 3D clay printing: An experimental study. *Proceedings of the 35th International Symposium on Automation and Robotics in Construction.* Berlin, pp. 909-916.

Kristensen, E.L., Gramazio, F., Kohler, M. and Langenberg, S., 2013. 'Complex Concrete Constructions: Merging existing casting techniques with digital fabrication', Open Systems: *Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research (CAADRIA 2013),* Asia, pp. 613–622.

Minke, G. 2006. *Building with Earth,* Design and Technology of a Sustainable Architecture.

Oesterle, S, Vansteenkiste, A, and Mirjan, A 2012. 'Zero Waste Free-Form Formwork', *Proceedings of the Second International Conference on Flexible Formwork, BRE CICM,* University of Bath, pp.258-267.

Willmann, J., Gramazio, F., Kohler, M. and Langenberg, S., 2012. Envisioning an extended performative materiality in the digital age of architecture, in *Robotic Fabrication in Architecture, Art and Design.* Springer Wien New York, Austria, pp. 12-27.

Wu, P., Wang, J., Wang, X., 2016. A critical review of the use of 3-D printing in the construction industry. *Automation in construction*, (68), pp.21-31.

Viswanathan, S., Ravi, S., Nagarajan, T., Srinivas, V. and Narayanan, P., 2014. 'Numerical Simulation of Compression and Shear Behaviour of Unreinforced Brick Masonry', *International Conference on Biological, Civil and Environmental Engineering* (BCEE-2014) March 17-18, 2014 Dubai (UAE).

Καραντώνη, Φ. Β., 2012. *Κατασκευές από τοιχοποιία*, Εκδόσεις Παπασωτηρίου.