Digital Fabrication Technology in Concrete Architecture

Pedro Filipe Martins[1]*, José Pedro Sousa*[2]
[1,2]*Faculdade de Arquitectura da Universidade do Porto*
[1]*www.faup.up.pt*
[1,2]*{pcarvalho|jsousa}@arq.up.pt*

Technological innovation has been an important driving force in architecture, enabling and inspiring architects and engineers by giving them new tools for solving existing problems. In the last two decades, the exploration of digital design and fabrication technologies has stimulated the development of a variety of interests and strategies to materialize increasingly complex and customized solutions in architecture, with traditional building materials.Reinforced concrete is the most widely used material in the building industry today and throughout its history has been the subject of vast research into its performance as a construction material and its tectonic potential in architecture. As such, the introduction of digital fabrication processes in concrete construction represents the biggest prospect for renovation of our built environment and at the same time, presents particular difficulties and opportunities, which are now being addressed. In an effort to investigate the alternative design and material possibilities in concrete emerging from the use of digital fabrication technologies in architecture, this paper proposes a focused view of digital fabrication applied to concrete construction with two areas of research. By framing the research in the context of reference works in concrete architecture of the 20th century, this paper describes and illustrates taxonomy of existing and possible types of integration of digital fabrication technologies in concrete architecture in the realms of Practice and Research.This characterization allows the authors to frame the relation between material, technology and architecture in different environments regarding the same material, extracting a clear image of existing processes, their potential and shortcomings, as well as expectations for future developments.

Keywords: *Digital Fabrication, Concrete, CAM, Robotics, Sustainability*

INTRODUCTION

Since the rediscovery of roman concrete and the invention of reinforced concrete in the nineteenth century, concrete has been the focus of continuous technological advances, driving with it an expectation for new architectural possibilities.

Reinforced concrete is a compound material composed of two elements: the cementitious matrix and the reinforcement. It can thus be considered a hybrid material, which combines the properties of its constituents to achieve a different set of characteristics. This hybrid nature, which is further characterized by a duality of states (i.e. evolving from liquid to solid) through a mould, has been at the core of contemporary discussion about the intrinsic plasticity of this material in architecture. For instance, Forty (2006) suggests the idea of understanding concrete as a process rather than solely as a material. Indeed, its rich and diverse history of technological innovations through research and practice has prevented concrete to have a fixed underlying traditional and accepted aesthetics.

This multi-faceted background of a material has provided a fertile ground for exploration for new materialities. This has become increasingly relevant in the last decades, with the dissemination of the emerging digital design and manufacturing technologies (CAD/CAM). Together, they have inspired a growing interest in rethinking concrete, while helping and builders to bridge the gap between design and construction. In this context, the subject of this paper is to investigate and outline the emergent opportunities for concrete architecture that have been supported by the use of digital fabrication processes.

HISTORICAL PERSPECTIVE

As a starting point it is important to contextualize this subject by examining some innovative examples in the history of concrete architecture. Past architects and engineers have produced relevant works in concrete, which have been a source of inspiration for those who are trying to innovate the application of this material in architecture.

Thus, the following themes were selected to set a framework to analyse the reference works of concrete architecture:

1. Complex Forms
2. Surface Textures
3. Material Composition

While form and surface are the basis of the majority of the examples surveyed, changes in the material composition of concrete have been used to improve its functional properties and to renew its aesthetic qualities.

In this context, this research contextualizes these traditional recurring themes to use them as a basis to analyse and characterize the recent 'digital' works.

Complex Forms. The first reinforced concrete prototypes, the concrete boat and conical vases of Lambot and Monier in 1848-50, exposed at an early age the opportunity of materializing complex forms in this material. Decades later, several geometrically appealing images of American silos and industrial buildings in concrete, were published by Walter Gropius in 1913 and re-used in Le Corbusier's manifesto of 1925, illustrating this early link between concrete and expressive forms in architecture.

Reinforced concrete made its way into architecture through the development of innovative construction systems (e.g. Hennebique system), which opened new spatial possibilities. However, it was its plastic properties of conforming to any shape that made it a prime material for exciting formal explorations, which were subsequently adopted by modernist architects as the medium for a new architecture.

In the first decades of the 20th century, architects and engineers seek to control the process of materializing concrete, testing the limits of its material, formal and aesthetic possibilities. Among the different types of buildings, the exploration of concrete forms was particularly relevant in the thin shell constructions. Pioneered in early 30s by architects and engineers like Eduardo Torroja, Felix Candela and Miguel Fisac, this type of constructions showcased the plasticity of concrete in assuming self-supporting and continuous curved surfaces of reduced thickness. The Zarzuela Hippodrome (1935), the Palmira Chapel (1959) or the Jorba Laboratories (1965) are some clear examples of that. In most cases, the complex geometries exhibited in these works were based on exploring and combining ruled surface geometries. One of the most notable cases is Felix Candela who spent most of his career working with hyperbolic paraboloid surfaces, which were carefully combined and adapted to a large set of architectural programmes (Garlock 2008). One particular aspect of these constructions was the fact that their formwork was built with rigid wooden planks following the same geometrical creation rules. This defined a direct relation between material behaviour, form and construction technology, which has become increasingly relevant in the contemporary concept of digital materiality (Gramazio and Kohler 2008).

Surface Texture. Although the previous works had implicit qualities regarding the expression of their skin, they were mainly concerned with the formal expression of concrete. In the second half of the 20th century, architects started to insist more with the surface finishing of their concrete constructions. Le Corbusier's "béton brut" experiments, in which concrete cast with rough wood boards was left bare, prompted an exploration into the possible aesthetic properties of exposed concrete. American architects, like Louis Khan Paul Rudolph or I.M. Pei, developed throughout the 60s numerous works where the exposed concrete skin was treated to achieve expressive qualities. In works such as the Yale Art Gallery (1953), the Art and Architecture Building (1963), the Everson Museum (1968) and the Jonas Salk Institute (1965) surfaces textures ranged from rough to smooth features. In these cases, texture resulted from the formwork design or by mechanical or manual post processing techniques (Legault 2005), achieving varying visual and tactile sensations with the same material by manipulating the properties of its finished surface. Another relevant example consisted in the experiments of Miguel Fisac with flexible formwork, where the integration of new technologies within the process of concrete creation introduced deep changes in the textural and visual properties.

From this scenario, one can extract the relevance of controlling the production process of concrete as a medium for achieving expressive surface textures and infer that changes to this process can impart new material qualities.

Composition. Although, when referring to the works discussed before, traditional literature focuses mostly on shape and surface texture, much of those defining features were dependant on a careful attention to its mixture composition. Going back to the notion of reinforced concrete as a hybrid material, where steel was incorporated into a matrix of cement, sand and gravel, it is possible to understand the opportunity and potential of changing the composition of concrete. For instance, most of the works of Pier Luigi Nervi, like the Sports Palace in Rome (1958), featured a structural and formal complexity that was made possible by his research into the composition (i.e. reinforcement) of concrete and the subsequent development of ferroconcrete (Iori and Poretti 2005). Moving from the structural to the aesthetic properties, the composition of concrete has also been explored to achieve different visual expressions. Forty (2012) mentions Perret's careful selection of aggregates by their colour to feature in exposed concrete, while Legault (2006) mentions the case of Pei's use of selected mineral additives to achieve white or earth coloured surfaces in his projects.

The works described in this survey, suggest relevant clues to understand the possibilities that concrete construction can follow through digital fabrication. Nevertheless, they also reveal some of the greatest problems of materializing expressive works in concrete. As it was already discussed, formwork played a major role in the characteristics of the material and in the building process. Formwork construction conveyed a large part of expenditures in materials, labour and assembly time. Moreover, the particular types of formwork traditionally available (timber and, later, steel) introduce significant geometrical constraints on possible forms and undifferentiated repetition in most concrete constructions, which can only be partly overcome with additional building time and costs. Also, relevant efforts were put into achieving desired surface finishes through the careful control of the formwork materials and building processes, as well as by means of controlling the mixture of its components. However, these interventions were still tied to the standardization constraints of the industry.

In this context, the recent use of digital fabrication technologies have started to tackle some of these constraints, proposing new ways of materializing concrete and revisiting and further exploring traditional concepts of form, texture and composition in concrete architecture.

THE INTEGRATION OF DIGITAL FABRICATION IN CONCRETE ARCHITECTURE

To examine the integration of digital fabrication technologies in the production of concrete architecture this paper considers the realms of practice and research. While the first side testifies the real impact in the built environment of using such technologies, the second one indicates the tendencies that can shape the next innovative applications of concrete in architecture.

Analysis methodology. The first step of the analysis consisted in surveying existing literature on relevant built works in which digital fabrication played a key role in the materialization of concrete elements. A set of key examples was then selected to illustrate the spectrum of similar and diverse approaches that could sustain the proposal of a taxonomy of the digital fabrication strategies.

To construct this analysis, a structure based on three consecutive categories was defined to organize the studied works:

1. Intervention mode
2. Digital Fabrication Technology
3. Theme

Facing the existing landscape of digital fabrication technologies and the dual state of the material (i.e. liquid and solid), the (1) Intervention Mode topic comprises two possibilities - direct and indirect. This division separates the cases where digital fabrication technologies are directly employed over the building components in concrete, from those where they are applied to other elements, which will then, indirectly, affect the production of concrete elements. In the latter case, a further distinction is considered by considering the possibility of intervening in the formwork or in the reinforcement. Furthermore, because the production of formwork is the focus of the majority of the surveyed works, this topic had to be subdivided taking into account different strategies based on their materiality: rigid, flexible or dynamic.

The (2) Digital Fabrication topic was divided into subtractive (Table 1), additive and formative categories, as proposed by Branko Kolarevic (2003). These topics were then subdivided into the specific fabrication technologies in order to illustrate the differences within the same family of fabrication processes.

Finally, specific (3) Themes were identified to each example according to three key concepts in the materiality of concrete architecture: Form, Surface and Composition. Given that these three goals, or interests, can be found in the relevant historical examples, critical comparisons between past and current works can be developed.

Examining the developments in Practice

The use of digital fabrication technologies became, in the mid 1990's, a indirect solution to the problem of building complex geometry in concrete, by enabling the production of custom moulds. The ca-

INTERVENTION			DIGITAL FABRICATION		THEME	EXAMPLE	
Mode	*Object*	*Type*	*Process*	*Technology*		*Work*	*Author*
INDIRECT	FORMWORK	RIGID	SUBTRACTIVE	CNC MILLING	FORM	Big Belt House	William Massie
			SUBTRACTIVE	CNC MILLING	FORM	Der Neue Zollhof	Frank Gehry
			SUBTRACTIVE	CNC MILLING	FORM	Phaeno Science Center	Zaha Hadid
			SUBTRACTIVE	CNC MILLING	FORM	Spencer Dock Bridge	Amanda Levete
			SUBTRACTIVE	CNC CUTTING	FORM	EPFL Rolex Learning Center	SANAA
			SUBTRACTIVE	CNC CUTTING	FORM	Mercedes Benz Museum	UNStudio
			SUBTRACTIVE	CNC MILLING	FORM	0-14 Tower	Reiser+Umemoto

Table 1
Digital Fabrication in Concrete Architecture – Developments in Practice

pabilities of CNC (Computer Numerical Control) subtractive processes were employed in the production of complex formwork in EPS (Expanded Polystyrene Foam). This material proved to be capable of withstanding the forces of the casting process and at the same time, was sufficiently soft to be quickly and accurately milled into a complex surface, reducing fabrication costs. The Table 1 summarizes the analysis about the use of digital fabrication technologies in the production of concrete elements in architectural practice.

Early examples of this production strategy can be found in the Neue Zolhoff project in Dusseldorf, Germany (Gehry Partners, 2000) and the Big Belt House in Montana, USA (William Massie, 2000). In both cases, digital fabrication technologies were used in the production of precast structural components (beams and walls) with geometrical features difficult to achieve with traditional formwork systems. This condition allowed the architects to further explore the formal plasticity of concrete.

As seen in the Table, CNC milling of homogeneous materials dominates the production in practice of complex geometries in concrete. Recently, these processes were developed and scaled up to the construction site, overcoming the need for prefabrication. The Science Center in Wolfsburg, Germany (Zaha Hadid Architects, 2005) and The Spencer Dock Bridge in Dublin, Ireland (Future Systems / Amanda Levete, 2008) are exemplar in showing the intrinsic relation between the design geometry and the fabrication possibilities. In the Phaeno Science Center, a careful analysis and subdivision of the designed form into single-curved and doubly-curved parts was developed in order to be, respectively, constructed with standard wooden formwork and with milled EPS formwork (Kara 2008). This feature had an immediate impact on the surface finishing qualities, given that one can clearly identify the wooden textures for the ruled sections of the cones and the smooth surface in the doubly curved transition areas. The Spencer Dock Bridge goes further with the materialization of doubly curved surfaces. Using milled formwork in high-density EPS, the building was built in a continuous way by pouring concrete onsite.

Another application of CNC milling of EPS has been for the production of sculptural voids in concrete surfaces, as was the case of the O-14 Tower (Reiser+Umemoto 2007). At the same time, other recent built projects employed the same technologies for the production of non-standard formwork in wood. The Mercedes Benz Museum (UNStudio, 2006) and the Rolex Learning Center (SANAA, 2010), both featured curved surfaces in concrete that were achieved through the precise CNC cutting of planar plywood panels to compose the desired double-curved geometries.

Although in the mentioned works it is clear that the application of digital fabrication in the production of formwork has enabled exciting formal explorations in concrete, it is also revealing that new problems emerge from this condition.

One issue regards the surface smoothness. When comparing these processes to traditional wood or steel formwork in standard construction, smooth surfaces are much harder to achieve through the materials commonly used in milling than with the traditional standard sheet materials. Moreover, in terms of formal freedom, the CNC milling process has its own geometrical constraints, depending on the number of available movement axis and the size of formwork stock material.

Problems with sustainability are also inherent to subtractive processes. The gradual removal of material layers produces large amounts of waste material that are not easily reusable. For instance, in the specific case of milled EPS, the need to apply non-recyclable coating agents to achieve satisfactory surface finishes makes the recyclable process necessary quite unviable. Facing the scale and complexity of architectural construction, research in digital fabrication technologies and materials engineering is required to overcome these problems (Table 2).

INTERVENTION			DIGITAL FABRICATION			EXAMPLE	
Mode	*Object*	*Type*	*Process*	*Technology*	*Theme*	Work	Lead researcher
INDIRECT	FORMWORK	RIGID	SUBTRACTIVE	ROBOTIC HOTWIRE	FORM	Fisac Variations	Felix Raspall
				CNC MILLING	FORM/TEXTURE	Tailorcrete	Silvan Oesterle
				CNC CUTTING	FORM	Pre: Vault	Dave Pigram
		FLEXIBLE			FORM	Fatty Shell: Fabric Formwork	Dave Pigram
		DYNAMIC	ADDITIVE	3D PRINTING	FORM	Smart Dynamic Casting	Ena Lloret Kristensen
	REINFORCEMENT				COMPOSITION	Mesh-Mould	Norman Hack
			FORMATIVE	ROBOTIC BENDING	COMPOSITION	Tailorcrete	Jens Cortsen
DIRECT	BUILDING COMPONENT		SUBTRACTIVE	CNC CUTTING	FORM	[c]shape pavilion	Alan Dempsey
				ROBOTIC DIAMOND WIRE	FORM	Diamond-wire Cut Concrete	Wes Mcgee
			ADDITIVE	3D PRINTING	FORM	Freeform Construction	Richard Buswell
					FORM	Contour Crafting	Behrokh Khoshnevis
					COMPOSITION	Variable Density Concrete	Neri Oxman

Table 2
Digital Fabrication in Concrete Architecture – Developments in Research

Examining the Developments in Research

The academia has been increasingly active in investigating the use of digital fabrication technologies in the production of concrete elements. On the one hand, research groups have tried to address solutions to some of the problems identified in the practice. On the other hand, they have tried to suggest new avenues that eventually can inspire new developments in practice. The Table 2 resumes the current tendencies in the realm of Research, which are then described and analysed.

Indirect intervention / Rigid Formwork / Subtraction. The fabrication of formwork noticeably continues to be a core issue in research, as it is reflected by most of the examples considered. However, there is an interest in exploring different strategies for its production with the aid of digital fabrication. To surpass the limitations of using standard EPS milled formwork, the TailorCrete project (Gramazio and Kohler 2011) [1] recently developed a wax-based formwork for complex geometries with the aid of robotic pin actuators (Figure 1). This strategy showed comparable efficiency to EPS systems but performed better in terms of the economy and ecology of the process, and of the surface finishing qualities of the fabricated pieces. At the same time, a greater level of geometrical freedom and texture expressions were made possible with EPS formwork by the adoption of 6 and 7-axis robotic arms instead of the standard 3-axis CNC routers commonly used for milling [4].

Figure 1
TailorCrete Project - Wax Formwork

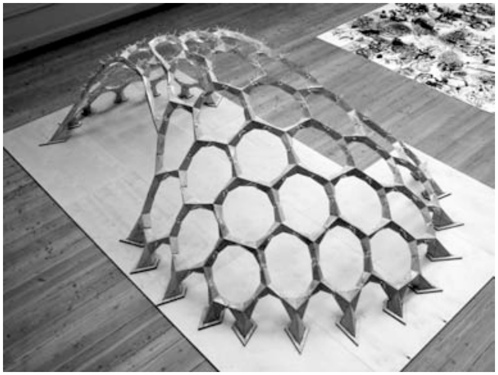

Figure 2
Pre:Vault Pavilion

Despite the traditional relation of concrete with continuous surfaces, the integration of digital fabrication technologies in the production of rigid formwork has been studied for the prefabrication of customized discrete components as illustrated by the

Figure 3
Robotic Slipform
research prototype

Figure 4
MeshMould
research prototype

Pre:Vault research pavilion (Figure 2) (Larsen et al. 2012). In this case, laser cutting enabled the mass-customized production of digitally scripted sets of unrolled geometric surfaces that were subsequently folded into moulds for unique building components. This digital process points towards the emerging design possibilities for building complex and highly customized structural components in concrete. A similar approach was featured in the research project "Fisac Variations" for the reinterpretation of Miguel Fisac's bones system, using a robotic hotwire to produce EPS moulds for customized concrete elements (Raspall 2013).

Indirect intervention / Flexible Formwork / Subtractive. Non-rigid and non-static formwork systems have been less used in the history of concrete production; However, they are also starting to integrate digital fabrication technologies in their specific processes. Although various researchers are currently exploring the tectonic, formal and textural potential of flexible textile formwork, built prototypes and literature suggest the use of craft-based approaches for building components such as columns, beams and walls (West 2009) [2] (Manelius 2012). Digitally driven processes, such as the case of the Fatty Shell exercise (Mcgee and Pigram 2012) [3] show the relevance of integrating CNC technologies to cut unfolded complex patterns in fabric formwork solutions.

Indirect intervention / Dynamic Formwork / Additive. Dynamic formwork systems consist in those strategies that consider the displacement in space (e.g. translation) of rigid moulds to produce forms. Approaches that fall in this topic join some of the benefits of rigid formwork (e.g. the reduced difficulty of achieving smooth surfaces) with a higher degree of formal freedom through spatial movement. In the case of the Robotic SlipForm (Figure 3) process developed at the ETH in Zurich, the integration of a multi-axis robotic arm to control the vertical and rotational movement of the formwork in space, calibrating the deposition speed of the wet concrete, greatly increases the formal capabilities of an otherwise geometrically limited strategy. (Kristensen 2013)

Indirect intervention / reinforcement / formative and additive. To overcome the complex and manual labour process of creating steel reinforcement cages, the "Tailorcrete" research project has explored the automation of this process through the formative process of robotic bending[4].

Establishing some similarities to the ferroconcrete production system used extensively by Nervi, the problem of reinforcement and, simultaneously, of the formwork production is being addressed in the on-going research by Fabio Gramazio & Matthias Kohler "Mesh-mould" (Figure 4). This work investigates the use of a robot to 3D print the 3D mesh component that serves as reinforcement and guides the creation of the concrete element. With this fabrication system, the design of the 3D mesh can be customized to address variation, for instance, in size, geometry or density. (Hack 2013)

Direct intervention / Additive fabrication. A more recent trend in the field consists in using additive fabrication processes to directly produce concrete elements. 3D printing technologies, in which materials are sequentially solidified layer by layer to produce customized objects, have been translated to the construction scale and used concrete as a base material for printing building components. The use of these processes introduces a higher degree of geometric freedom in the production while avoiding the need of formwork. Currently, two of the most consolidated examples of this strategy are Contour Crafting (Figure 5) (Koshnevis 2006) and "Freeform Construction" (Figure 6) (Lim et al. 2012), which already proved the feasibility of 3D printing functional concrete elements. In the first case, mainly wall segments were produced, optimized to speed-up the production and obtain smooth surface finishes. In the second case, the built prototypes proposed a larger emphasis on formal freedom. (Lim et al. 2012)

Facing the inherent promises, this technological trend still reveals some limitations. For instance, attaining formal freedom is mostly dependent on two key issues: printing resolution, which is mainly defined by the height of concrete layers and the diameter of the printing head, and the need for secondary structures to support the hanging parts. These constraints contribute to design lower curvatures in height, when compared with concrete elements made with milled formwork, and feature additional difficulties in creating voids in planes orthogonal to the base printing plane. Also, in terms of surface finishing, both technologies still leave distinctive marks in produced elements, which are not fully desired. This feature must be improved towards its implementation in practice.

An alternative approach using the same tech-

Figure 5
Contour Crafting wall prototype

Figure 6
Free Form Construction panel prototype

nology was presented by Neri Oxman (2011), entitled "Variable-Density Graded Fabrication of Concrete". Instead of the design geometry of a product, this research is focused instead in its material composition. Using additive fabrication in a robotic printing platform, it looks for controlling the material properties and cellular structure of concrete, following the inspiration from the gradient structures presented in natural systems. This approach enables decoupling form from expected structural behaviour in concrete structural elements, as well as allowing the modulation of some properties (e.g. colour, texture) in concrete surfaces.

Direct intervention / Subtractive fabrication. All previous applications of digital fabrication technologies occur in different moments prior to or during the casting of concrete. However, a few were found that directly transform the produced concrete element in other forms or textures.

For instance, and considering the use of a concrete composite, the [c]shape Pavillion built at the Architecture Association in 2008 employed over 850 glassfibre-reinforced concrete panels, which were cut with CNC technology. Also, there are some experiments of cutting prefabricated concrete blocks using a diamond wire attached to a robotic arm in the construction of self-supporting assemblies (McGee et al. 2012). Both situations point out to the possibility of CNC post-processing operations directly over the concrete elements for the materialization of geometrically complex assemblies.

CONCLUSION

Recognizing the current dissemination of using digital fabrication technologies in architecture this paper investigate the state of the art of their application in the production of building elements in concrete. From the presented survey, its seems that the use of these processes has served more to fulfil the desire of materialising expressive forms rather than that of achieving customized surface effects.

In pursuing an increasing level of formal complexity in the built works, this study reveals the natural predominance of recurring to the use of subtractive processes to produce customized formwork. This general tendency in practice, raises an important concern with sustainability, which makes the research efforts on additive processes a promising technological alternative.

Although the surveyed works in practice and research are concerned with surface smoothness, few examples have been found trying to exhibit new texture effects from digital fabrication means. In most cases, the surface texture of exposed concrete is mainly regarded as technical concern to be addressed rather than as a topic of design exploration. Nonetheless, the existing technologies and examples shown, in direct and indirect subtractive fabrication, suggest the possibility for the expansion of textural effects. One possible path lies in acknowledging the inherent properties of specific technologies and integrating them into the design stage, as was found in some of the historical examples mentioned in the second chapter of this paper.

Finally, although it has been a recurrent research topic in contemporary architecture, the exploration of the material composition is still underdeveloped in relation with other digital fabrication trends. The concept of its controlled variability is therefore an exciting new theme that can yield interesting aesthetic, formal and structural results.

The wide set of technologies mentioned throughout the analysis establishes different relations with the materiality of concrete, depending on the specific role each plays. Whether working directly on concrete elements or, indirectly, in the formwork production, it is interesting to notice how technology options can be intrinsically linked with the design languages. The works presented in this paper thus show the exploration of a variety of geometries such as free-forms, ruled surfaces, single-curved shapes or extruded forms.

Because no identifiable process can be used to achieve all desirable outcomes in construction, it is foreseeable that several research works will make their way into the architectural practice. It is our understanding that the these particular languages as well as other material imprints emerging from specific technological processes can become relevant sources for new effects and material expressions in concrete and should be further developed in the future.

ACKNOWLEDGMENTS

This work is part of a PhD research developed with the support of the FCT - Foundation for Science and Technology (ref. SFRH / BD / 79227 / 2011). It is also integrated in a Research Project that is financially supported by FEDER funds through the Operational Competitiveness Program - COMPETE and by National Funds through FCT - Foundation for Science and Technology, in the scope of the project "PTDC/ATP-AQI/5124/2012".

The authors would like to thank Professors Fabio Gramazio & Matthias Kohler, Dr. Berkoh koshnevis, Dr. Richard Buswel and Dr. Ole Egholm Perdersen for their help in illustrating some of the works surveyed in this paper.

REFERENCES

Forty, A 2012, *Concrete and Culture: A Material History*, Reaktion Books

Forty, A 2006, 'A Material Without a History', in Cohen, JL and Moeller, GM (eds) 2006, *Liquid Stone. New Architecture in Concrete.*, Birkhauser Architecture, pp. 34-45

Garlock, MEM and Billington, DP 2008, *Félix Candela: Engineer, Builder, Structural Artist*, Yale University Press

Gramazio, F and Kohler, M 2008, *Digital Materiality in Architecture*, Lars Muller

Hack, N, Lauer, W, Langenberg, S, Gramazio, F and Kohler, M 2013, 'Overcoming Repetition: Robotic fabrication processes at a large scale', *International Journal of Architectural Computing*, 11, pp. 285-299

Iori, T and Poretti, S 2005 'Pier Luigi Nervi's Works for the 1960 Rome Olympics', *Actas del Cuarto Congreso Nacional de Historia de la Construcción*, Cádiz

Kara, H (eds) 2008, *Design Engineering: Adams Kara Taylor*, Actar

Khoshnevis, B, Hwang, DP, Yao, K and Yeh, Z 2006, 'Megascale fabrication by contour crafting', *International journal of Industrial and System Engineering*, 1, pp. 301-320

Kolarevic, B 2003, *Architecture in the Digital Age: Design and Manufacturing*, Taylor & Francis

Kristensen, EL, Gramazio, F and Kohler, M 2013 'COMPLEX CONCRETE CONSTRUCTIONS: Merging existing casting techniques with digital fabrication', *Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, pp. 613-622

Larsen, NM, Pedersen, OE and Pigram, D 2012 'Realisation of complex precast concrete structures through the integration of algorithmic design and novel fabrication techniques', *Advances in Architectural Geometry 2012*

Legault, R 2006, 'The Semantics of Exposed Concrete', in Cohen, JL and Moeller, GM (eds) 2006, *Liquid Stone. New Architecture in Concrete.*, Birkhäuser Architecture, pp. 46-56

Lim, S, Buswell, RA, Le, TT, Austin, SA, Gibb, AGF and Thorpe, A 2012, 'Development in construction-scale additive manufacturing processes', *Automation In Construction*, 21, pp. 262-268

Manelius, AM 2012, *FABRIC FORMWORK: Investigations into Formwork Tectonics and Stereogeneity in Architectural Constructions*, Ph.D. Thesis, Royal Danish Academy of Fine Arts Schools of Architecture, Design and Conservation, School of Architecture

McGee, W, Feringa, J and Søndergaard, A 2012, 'Processes for an Architecture of Volume: Robotic Wire Cutting', in Brell-Çokcan, S and Braumann, J (eds) 2012, *Rob|Arch 2012: Robotic Fabrication in Architecture, Art, and Design*, Springer, pp. 62-71

Oxman, N, Keating, S and Tsai, E 2011 'Functionally Graded Rapid Prototyping', *Proceedings of VRAP: Advanced Research in Virtual and Rapid Prototyping*

Raspall, F, Imbern, M and Choi, W 2013 'Fisac variations: an integrated design and fabrication strategy for adaptable building systems', *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, pp. 55-64

[1] http://www.dfab.arch.ethz.ch/web/e/forschung/164.html

[2] http://www.umanitoba.ca/cast_building/assets/-downloads/PDFS/Fabric_Formwork/Thin-Shell_Concrete_From_Fabric_Forms_SCREEN.pdf

[3] http://cargocollective.com/fabroboticsnet/Fatty-Shell-Flexible-Formwork

[4] www.tailorcrete.com