Exploring Architectural Language evolution as a consequence of 3D-Printed Concrete Technology

Exploración de la evolución del lenguaje arquitectónico como consecuencia de la tecnología de concreto impreso en 3D

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Abstract:

The convergence of innovative 3D printing technology and high-performance concrete mixes introduces a potential paradigm shift in architectural design and the entire Architecture Engineering Construction (AEC) industry, addressing important issues like the implementation of Construction 4.0 (the equivalent of Industry 4.0 for construction) and Sustainability The ongoing research project forms part of an articulated interdisciplinary and international endeavour at the intersection of Architecture and Civil Engineering, with three funded projects aiming to define firstly a rationale for the industrial applications of 3D-printed concrete (3DPC) and secondly the architectural value of this relatively new technology. The research is conducted in collaboration with an industrial partner specializing in large-scale concrete 3D printing, making it possible to assess the feasibility of the research outcomes at the industrial scale. This article reports on the first phases of the research, consisting in the production and testing of 3DPC specimens with different types of concrete mix, and explores the transformative impact of 3DPC on the architectural language, considering its aesthetic, functional, and cultural dimensions. Through a literature review, examining case studies, theoretical frameworks, and prototyping, this paper opens a reflection on the implications of applying this innovative technology to architectural expression and spatial configurations.

Keywords: 3D-printed concrete; robotic fabrication; architectural language, materiality, 3d texture.

Resumen:

La convergencia de la innovadora tecnología de impresión 3D y las mezclas de concreto de alto rendimiento, introducen un posible cambio de paradigma en el diseño arquitectónico y en toda la industria de arquitectura, ingeniería y construcción (AEC), y abordan cuestiones importantes como la implementación de la Construcción 4.0 (equivalente a la Industria 4.0 para la construcción) y la sostenibilidad. El proyecto de investigación en curso forma parte de un esfuerzo interdisciplinario e internacional, articulado en la intersección de la Arquitectura y la Ingeniería Civil, con tres proyectos financiados que buscan definir, en primer lugar, una justificación para las aplicaciones industriales del concreto impreso en 3D (3DPC); y, en segundo lugar, el valor arquitectónico de esta tecnología relativamente nueva. La investigación se lleva a cabo en colaboración con un empresario industrial especializado en la impresión de concreto en 3D a gran escala, lo cual permite evaluar la viabilidad de los resultados de la investigación a escala industrial. Este artículo informa sobre las primeras fases de la investigación, que consisten en la producción y prueba de especímenes de 3DPC, con diferentes tipos de mezcla de concreto, y explora el impacto transformador de 3DPC en el lenguaje arquitectónico, considerando sus dimensiones estéticas, funcionales y culturales. A través de una revisión de la literatura, y al examinar los estudios de caso, marcos teóricos y prototipos, este artículo abre una reflexión sobre las implicaciones de aplicar esta tecnología innovadora a la expresión arquitectónica y a las configuraciones espaciales.

Palabras clave: concreto impreso en 3D; fabricación robótica; lenguaje arquitectónico, materialidad, textura en 3D.

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1. INTRODUCTION

By aiming to the integration of aesthetic values with the structural performance of 3DPC elements, this project plants a more holistic approach to architectural and structural design, bridging the gap between construction disciplines and aiming towards a unified design-to-build approach that includes construction site management.

3DPC is a relatively new technology that allows the creation of complex structures by deposition of layers (Xiao et al. 2021). The behaviour of 3DPC is different from traditional casted concrete: the layered and non-orthotropic structure of the built element, together with the material deposition process, make combining concrete with other materials capable of resisting tensional forces a challenging task. Attempts have been made to create concrete mixes that transmit tensional stresses between the layers, usually through small pieces of shear-resisting materials such as carbon fibre (Melenka et al. 2016). However, this method only partially addresses the issue of non-homogeneity of the material, thus resulting in an unforeseeable diffused weakness of the 3D-printed element.

Therefore, at least at present, 3DPC structures rely primarily on the material's compression-only resistance, limiting the design possibility to a relatively small range of non-load-bearing elements (Quan et al., 2022) or to emulating traditional structural elements (Di Marco et al., 2023).

From a structural point of view, considering 3DPC as a potentially free-form stone, it is possible to imagine complex compression-only structural elements obeying the same principles adopted in the Romanic and Gothic styles and, more recently, in Antoni Gaudi's work (Figure 1).

Lastly, it is interesting to recognise the aesthetic value of 3DPC and its layered texture, witnessing and resembling a production process that stays visible once the concrete element is finished, but also the infinite possibilities and spatial configurations deriving from the absence of formworks and the direct creation of the desired shape.

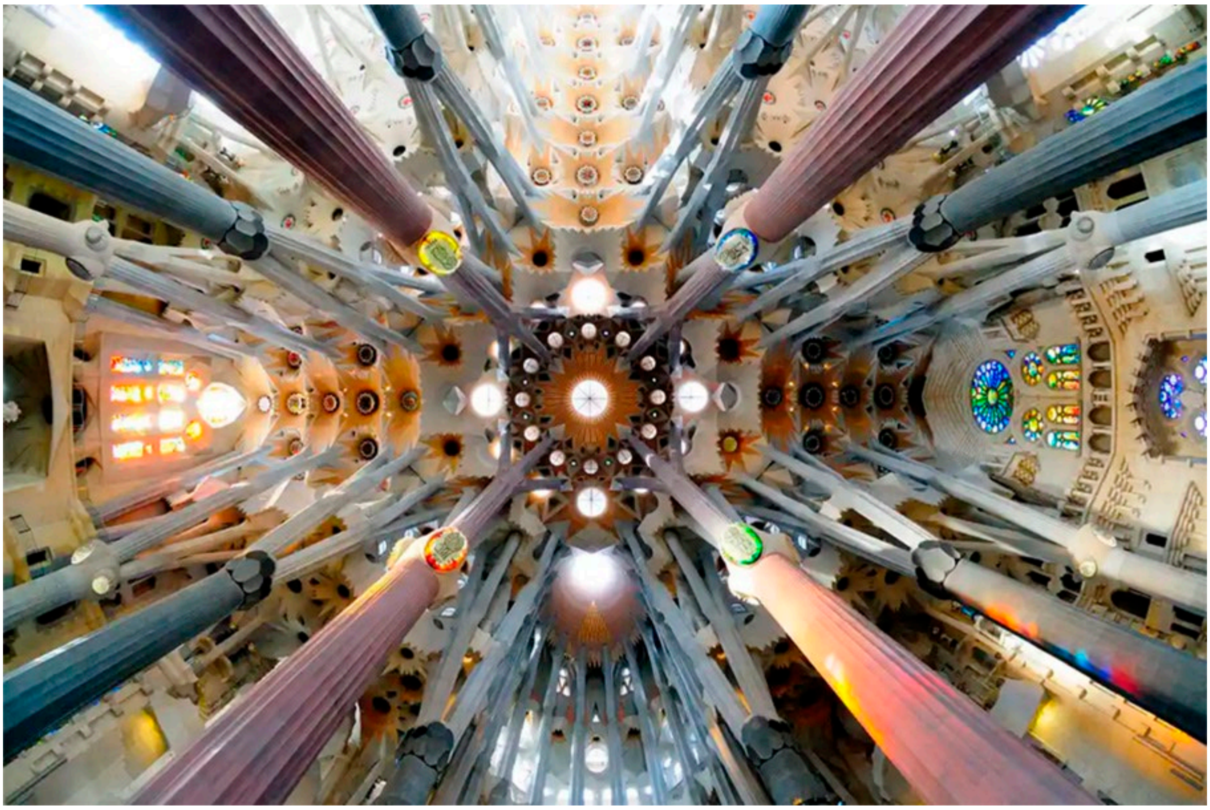

Figure 1 Antoni Gaudi, columns in the Sagrada Familia
https://www.theguardian.com/artanddesign/2020/apr/03/antoni-gaudi-sagrada-familia

2. RESEARCH METHODOLOGY

This research project lies at the intersection between structural performance and aesthetics: one is essential for the other. That is why the first part of the research focuses on assessing the performance of 3DPC. Once the performance has been assessed and benchmarked then it will be possible to explore the architectural value of 3DPC as a construction material.

We can identify three different phases, each one characterised by specific research questions.

Phase 1 – Materials benchmarking

- What is the actual performance of 3D-printed concrete compared with traditional casted concrete?

- What is the strength of the steel/concrete bond in steel-reinforced 3D-printed concrete elements?

With two different types of concrete mix, robotic fabrication, large-format 3D printers and a bespoke 500-ton hydraulic press, this research project aims to cover the entire design, production and testing cycle of 3DPC structural elements, starting with the study of an optimised beam.

The first step is the benchmarking of the materials involved.

Some tests had already been conducted on one of the two concrete mixes. Unfortunately, it turned out that the specimens used during the tests were casted and not 3D-printed: this alters completely the nature of the specimen (continuous and orthotropic instead of discontinuous and non-orthotropic) and its structural performance.

Each concrete mix has been used to create 20 fully 3D-printed specimens (20x20x20cm) (Figure 4) to evaluate their compression resistance and 10 fully 3D-printed specimens (20x20x20cm) with one 40cm rebar installed for 20cm inside the specimen to test the rebar/concrete bond.

Figure 2 3DPC specimen used for compression tests. Photo by the authors.

The first batch of tests has shown that the compressive strength is higher in absolute value when the load is applied perpendicularly to the deposition layers of the specimen. Although this result was predictable, it’s important to observe how the number of specimens qualifying as M20 (grade 20, suitable for reinforced concrete applications) were 10, 5 of which were subject to load applied perpendicularly to the layers and 5 to load coplanar with the layers. This circumstance makes it necessary to conduct additional extensive compression tests.

Phase 2 – Computational Design of 3DPC elements

- Is it possible to improve the structural performance of 3DPC elements through computational design strategies?

Computational methods allow for designing structural elements and simulating their physical and structural behaviour under specific load configurations, thus evaluating their performance.

This phase will consist of the design and topological optimisation of a structural element created in Rhinoceros and Grasshopper with additional tools such as Karamba3D for structural analysis.

Topological optimization allows reducing the quantity of compression-resistant material inside the structural element, removing it from those areas in which compression stress is not present or is reasonably negligible. The criteria for defining the threshold of compression resistance for the optimised volume come from the benchmarking of concrete mixes.

The computational model will consider the mechanical properties of the concrete mixes used in the research project.

When the computational model will be ready, we finally aim to explore computational design methods to integrate architectural value into the structural elements in three different ways:

- The creation of informed patterns and textures on the elements' surfaces.
- Playing with continuity to create seamless structural elements merging the vertical and horizontal ones.
- Playing with spatial configurations of non-load-bearing lightweight elements – the same topological optimisation can help define the voids ratio in non-load-bearing elements.

Together with the industrial partner, some tests have been conducted using large-format concrete 3D printers to create different types of complex shapes. Counting on the availability of a known concrete mix with specific rheology, and pushing the cartesian 3D printers beyond their conventional use for 3DPC (horizontal layering), we have achieved the results shown in the following images.

The most promising result for this phase of the experimentation on 3DPC aesthetic is shown in the following image (Figure 6), where non-planar 3DPC layers where deposited by operating the 3D printer simultaneously in the X, Y, and Z directions (3 axes instead of 2½) and constantly adjusting the speed and material flow to obtain every time a continuous deposited layer.

The methodology employed to investigate the relationship between technological evolution and the evolution of architectural language, specifically focusing on the impact of 3DPC technology is structured around several key components, in-

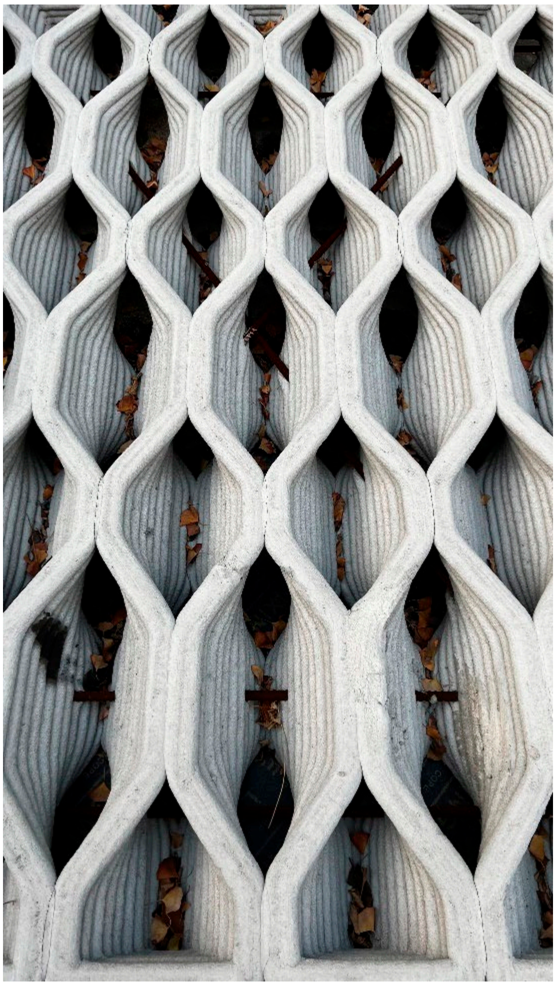

Figure 3 3DPC three-dimensional pattern
Photo by the authors.

Figure 4 Non-planar concrete 3D printing
Photo by the authors.

cluding data collection, data analysis, and theoretical frameworks.

Data collection includes:

- Literature Review to establish a comprehensive foundation for our research, we conducted an extensive literature review. This involved the examination of peer-reviewed articles, books, conference papers, and reports related to architectural evolution, technological advancements, and 3DPC.

- Case Studies to gain empirical insights into the impact of 3DPC on architectural language, we selected a series of relevant case studies. These case studies encompassed a range of architectural projects and applications of 3DPC; the selection criteria included diversity in design approaches, technological integration, and geographic location.

- Qualitative Data Analysis to scrutinize the collected data from the case studies. We utilized thematic analysis to identify recurring patterns, themes, and concepts within the architectural projects. This process involved coding and categorizing data to extract meaningful insights into how 3DPC has influenced architectural language, including changes in form, materiality, and design processes.

- Comparative Analysis to discern commonalities and distinctions among the selected case studies. This approach enabled us to draw parallels between different architectural contexts, identifying overarching trends and variations in the impact of 3DPC on architectural language.

3. 3D-PRINTED CONCRETE TECHNOLOGY

The first concrete 3D printer dates back to 2007 when the Italian engineer Enrico Dini created the D-Shape, a cartesian large-format 3D printer with a work area of 6x6m.

3DPC is commonly achieved by deposition of layers, and it is made by moving an extruder in the X, Y and Z directions while pumping a concrete mix through the nozzle (Figure 2).

Figure 5 Robotic 3D printing
Photo by the authors.

Apart from technicalities, the process relies on gravity, so the extruded concrete mix falls on the building platform. Then, subsequent layers are stacked on top of the previous ones for the same natural principle. For this reason, voids cannot be created directly, and some support material or device is needed to hold the concrete layers on top of the void. In standard Fused Deposition Modeling (FDM) 3D printing, the use of Polyethylene Terephthalate (PET) filament makes it possible to bridge relatively long spans without any support because the thin plastic extrusion solidifies immediately. Concrete mix, on the contrary, remains wet and fluid for a relatively long time, making it only possible to extrude on existing and stable supports.

From the material perspective, using a 3-5cm nozzle demands particular attention. Concrete mix must flow through the nozzle, which makes using standard mixes impossible due to the size of the aggregate. The use of smaller aggregates makes the concrete mix even more fluid, thus affecting rheology (critical for the 3D printing process) as well as the final performance of the architectural element.

The research on materials for 3D printing has already produced some results in the form of high-performance concrete mixes. Nevertheless, performance-wise, concrete is compression-resistant and it is challenging to combine it with other materials that would provide the necessary strength to resist tensional forces.

Fibres are the most promising solution to address the tensional stress. However:

- fibres do not create continuity between the deposited layers;
- the homogeneous concrete mix with embedded fibres cannot provide the necessary differentiated behaviour required by the non-uniform distribution of stresses within a structural element.

Parallel to the production technology background, another important contribution to the research on 3DPC comes from the development of computational technologies and methods.

The increased computational power makes it possible to conduct digital experiments and simulations with a good level of precision in terms of correspondence to real physical behaviors and system dynamics (Di Marco, 2018; Tedeschi & Lombardi, 2018).

The benefits deriving from digital simulation regard the possibility to reduce the quantity of prototypes, physical models and laboratory tests, as well as the possibility to run optimisation iterations exploring new possibilities for materials distribution within the structural elements and a general better performance.

This project aims to analyse and optimise the production processes of steel-reinforced 3D-printed high-performance concrete elements to push the limits of concrete 3D printing applications. By using computational design methods for optimising the layout of concrete and rebars, longer spans, higher structural performance, and a better architectural design can be achieved while lowering the time and costs of building complex architectural shapes.

Special consideration will be given to adding architectural value to the structural elements.

As with every new technology, 3DPC is still evolving and is now emulating the traditional construction language: columns, walls (Figure 3).

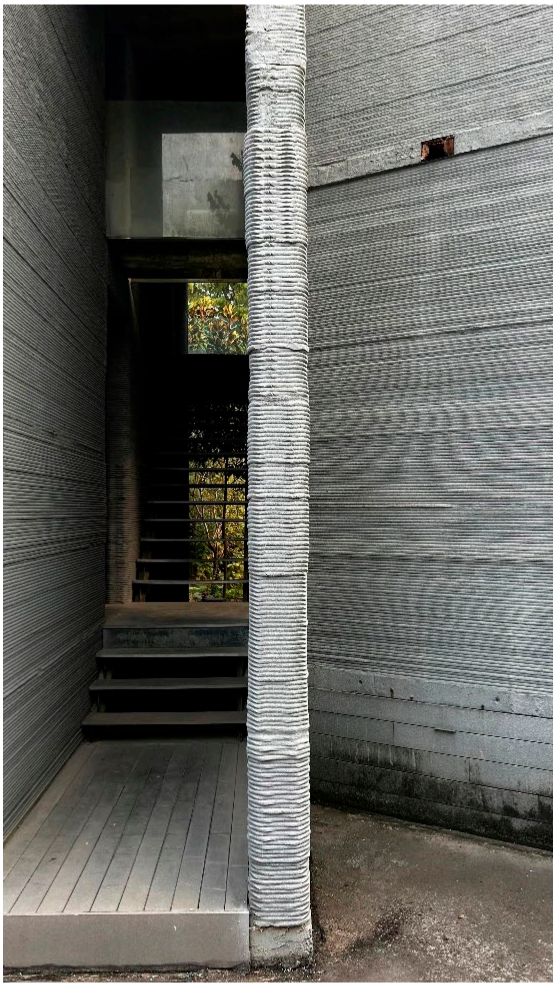

Figure 6 3D-printed walls
Photo by the authors.

The technical feasibility of compression and shear-resisting 3DPC structural elements opens up new, challenging applications for the construction industry, creates a new path for architectural and structural design and opens the gates of specialisation and experimentation (Sabate et al., 2003) to concrete 3D printing, at the same time addressing the actual financial and sustainability issues deriving from the use of concrete.

4. EVOLUTION OF ARCHITECTURAL LANGUAGE AND TECHNOLOGY

The symbiotic and fascinating relationship between architectural language and technological progress has been a defining characteristic of the built environment's evolution, a narrative able to represent human evolution. This research focuses on the trajectory of architectural language, highlighting key moments where technological advancements catalysed transformative shifts in design paradigms.

Throughout history, architectural language has been closely in dialogue with the technological capabilities of its time; from the very beginning, human beings, as constructors of the built environment, explored how their primordial achievements laid the foundation for the fusion of form and function, setting a precedent for future technological influences. The advent of the Industrial Revolution in the 18th century heralded a new era of architectural possibilities. With the proliferation of iron and steel, architects created daring structural designs that defied gravity; the rise of skyscrapers, bridges, and other monumental structures that demonstrated the marriage of technological innovation and architectural expression witnessed the fascinating relationship between technology and language as a representation of incalculable culture. Architecture becomes a revelation of what humanity is able to achieve through the transformation of the built environment.

The 20th century expresses a moment of discontinuity from historical architectural styles, driven by technological breakthroughs and shifting societal values. The Bauhaus movement, emphasising functionalism and efficiency, exemplified how technological advancements in materials and construction techniques influenced architectural aesthetics and gave birth to Modernism's minimalist language.

Digital Revolution and Computational Design, from the early 21st century, marked the emergence of the digital revolution, introducing computational design tools that transformed the architectural landscape. Pioneers like Frank Gehry demonstrated to the world the power of digital modelling and parametric design to conceive complex geometries that were previously unreachable, shifting the focus towards algorithmically generated forms that seamlessly integrate with technological advancements. Today, the integration of cutting-edge technologies, such as 3DPC, continues to redefine architectural language. Architects and designers are influenced by technology and use it as a canvas to explore novel design paradigms, incorporating technology into their designs to express cultural narratives and push boundaries.

The relationship between architectural language and technological evolution is a dynamic and cyclical process, often characterised by three recurring phases: emulation, specialisation, and experimentation. Concrete, as a versatile building material, provides an excellent case study of how these phases are continually revisited. (Di Marco et al., 2023).

The emulation of established architectural forms and practices is a constant thread in the history of concrete in architecture. Technological emulation can be found in early concrete structures; we can refer for example, to the Roman Pantheon, where were emulated traditional architectural elements like the dome. The Pantheon's concrete dome replicated the significance of classical temples while understanding the material's unique capabilities. This phase represents the ongoing inspiration drawn from historical and cultural contexts.

Innovations in concrete technologies came through the specialisation phase as its technology evolved. Architects approached the specialisation phase, focusing on comprehending the unique properties of the material. The late 19th and early 20th centuries saw specialisation in concrete construction, with the development of reinforced concrete. Architects like Auguste Perret and Le Corbusier specialised in using reinforced concrete to create structures with thin, expressive shells and innovative spatial configurations. This specialisation phase signifies architects' increasing expertise in manipulating concrete's structural potential.

Pushing boundaries has always been an obsession of creatives; the experimentation phase has been a mirage of concrete's architectural journey. Architects continually push the boundaries of what is achievable with concrete. Around eight decades ago, architects like Oscar Niemeyer experimented with expressive, sculptural forms made possible by reinforced concrete. His design for the National Congress in Brasilia exemplifies how concrete's plasticity and structural versatility encourage architectural experimentation. Experimentation is an ongoing cycle as architects continually challenge conventions with concrete's evolving technological capabilities. The masterpieces by Felix Candela represent a milestone of this phase.

This article approaches concrete's evolution as an illustrative case study of these recurrent phases. Initially, architects emulated traditional architectural elements with concrete, reproducing familiar forms but with a newfound material. For example, early roman's concrete structures emulated the monumental arches and columns of classical architecture.

The specialisation phase saw architects developing their understanding of concrete's properties. Reinforced concrete became the focus, allowing specialised designs showcasing the material's strength and flexibility. New languages developed as a consequence of technological evolution. Innovations in formwork and casting techniques enabled the construction of structures by moderns, where concrete was used to create smooth, functional, geometrically and aesthetically precise forms.

Experimentation with concrete continues and sees a new chapter with the introduction of 3DPC technology. Contemporary architects use advanced computational tools and formwork technologies to create structures that challenge conventional norms. Even after eight decades from Neimayer's work, projects like the Heydar Aliyev Center in Baku, designed by Zaha Hadid Architects, showcase how concrete's potential for experimentation remains boundless, enabling the creation of fluid, sculptural forms that redefine architectural aesthetics.

Concrete's evolution in architecture exemplifies the recurring phases of emulation, specialisation, and experimentation in the relationship between architectural language and technological evolution. Concrete's malleability and adaptability inspire architects to revisit and push the boundaries of architectural expression, making it a perpetual case study in the dynamic dialogue between technology and architectural language.

The evolution of architectural language has been intricately part of technological progress. From ancient engineering wonders to the digital age of computational design, technology has consistently shaped the way architects conceptualise and create. The historical continuum between architectural expression and technological innovation serves as evidence of the dynamic relationship between human creativity and the tools that enable it. 3DPC is a new chapter of this fascinating story.

5. TRANSFORMING ARCHITECTURAL AESTHETICS AND FORMS

Integrating 3DPC technology into the architectural world marks a significant moment in design innovation, offering architects opportunities that challenge the boundaries of conventional aesthetics and forms.

3DPC technology liberates architects from the constraints of traditional construction methodologies, conducting in an era of unprecedented design freedom. By enabling a specific process where concrete is deposed layer-by-layer, architects can imagine and conceive complex, organic, and intricately detailed structures that challenge the limitations of conventional formwork. In a few words, it is a revolution in the relationship between aesthetics and form. The pioneers and visionary "Bespoke Vase Series" by Zaha Hadid Architects exemplifies this liberation, showcasing the fusion of algorithmic precision with fluid, avant-garde forms (Hadid, 2019). From another perspective, considering the controversial relationship in architecture between ornament and structure, historically, architectural ornamentation has been interlaced with craft, requiring extensive manual labour (Loos, 2014). 3DPC redefines ornamentation by integrating it into the structure itself, one of the milestones of modern discussion all across the twentieth century. In the MIT Medialab, the work of Neri Oxman and the Mediated Matter Group demonstrates this synergy in works like the "Silk Pavilion II" project. Through these cutting-edge experimentations, it is possible to showcase the intricate interplay of form, structure, and ornament, realized through 3D printed technology inspiration (Oxman et al., 2016).

Parametric Exploration and Variability are further factors that represent the innovative shift in design by 3DPC. The introduction of this new technology converges with parametric design methodologies, enabling architects to drive computational algorithms to generate a collection of design iterations. This variability amplifies in projects like the "Digital Grotesque" by Benjamin Dillenburger and Michael Hansmeyer (Figure 7), where intricate, algorithmically generated geometries are translated into tangible architectural forms through 3DPC. (Dillenburger & Hansmeyer, 2017).

Variability then is at the base of another design opportunity, that is, potential customization of 3DPC extends to site-specific adaptations that harmonize architecture with its environment. This specific opportunity is relevant for designers who consider engagement with the cultural environment as the foundation of the design process of determining shape and language. The "Curve Appeal" project by Gregory Quinn exemplifies this potential, where 3D-printed concrete facades respond to solar exposure, ventilation needs, and spatial adjacencies, reflecting an era of adaptive architecture that 3D printing technology facilitates (Quinn, 2018).

Variability could be further explored in terms of mineral pigments and chemical pigments which could be used in 3DPC to add colour and aesthetics to the finished product. Mineral pigments, including iron oxide pigments, titanium dioxide and chromium oxide are preferred usually prefered for their durability and resistance to fading, making them appropriate for outdoor applications where exposure to sunlight and weather is a concern.

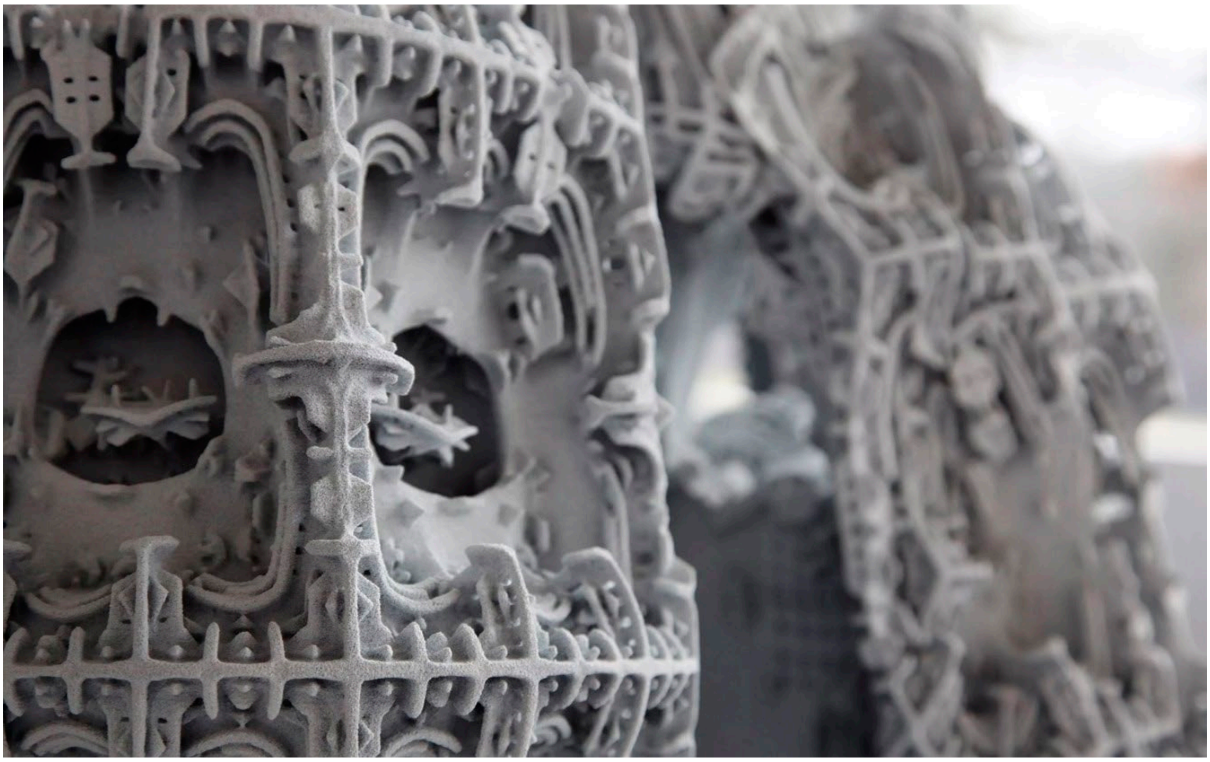

Figure 7. Digital Grotesque experimentation by Benjamin Dillenburger and Michael Hansmeyer
https://www.michael-hansmeyer.com/digital-grotesque-II

In addition to the form, the tactile qualities of architecture play a key role in human experience within the built environment. 3DPC presents a novel material expression that combines visual aesthetics with tactile expressiveness. The “Voxel Chair” by François Brument and Sonia Laugier demonstrates this synthesis, as the layering process of 3DPC creates a textural richness that redefines materiality in architectural design (Brument & Laugier, 2012).

The progress of 3DPC introduces a sensory dimension to architectural experiences, prompting emotional responses that resonate with inhabitants and observers alike. , materiality through its singular density and mood sensory, generates a dimension which transcends to the feeling of existence, harmony, beauty, and wellness. (Zumthor, 2006).

The integration of 3DPC technology indicates a renaissance in architectural aesthetics and forms, transcending the visual realm to engage the senses and emotions of inhabitants and observers. By transcending traditional construction methodologies, architects can explore the technology to sculpt intricate geometries, blur the boundaries between ornament and structure, and foster a symbiotic relationship between digital design and material realization. The transformative nature of 3DPC is not only confined to the technical realm but extends to the very essence of architectural expression.

6. MATERIAL INNOVATION AND ENVIRONMENTAL IMPLICATIONS

3DPC is a relatively new technology that allows the creation of complex structures by deposition of concrete layers (Xiao et al. 2021). This process requires a unique concrete mix capable of extruding through a relatively thin nozzle while maintaining the same performance as traditional cast concrete.

The usual maximum aggregate size in traditional concrete is too big for 3DPC since the regular ratio aggregate size/nozzle’s diameter does not allow a proper application. The use of smaller aggregate sizes changes the performance of concrete, reducing the structural performance (Monteiro and Mehta 2006). Therefore, 3DPC uses high-performance binders to increase strength, typically high-performance cement, high-resistance fine aggregates, quartz flour, reactive powders, metal chips, and fibres (Alkadhim et al. 2022).

On the other hand, addressing tensional stress within 3D-printed elements remains the main issue (Xiao et al. 2021).

Many studies are conducted on alternative types of formworks intended to optimise concrete distribution, such as ribbed slabs (Aghaei Meibodi et al. 2018).

3DPC allows discrete material deposition instead of uniform casting inside a formwork, making it possible to concentrate the materials only in areas where compression stresses will be present.

The discrete material deposition will mark a significant breakthrough from the sustainability point of view, as the amount of material used in a structural element will be considerably less than the actual. Another critical consequence deriving from the extensive use of 3DPC in the Architecture Engineering Construction (AEC) industry would be, in fact, the implementation of a more sustainable practice. Let’s remember that the construction industry uses almost 50% of natural resources and accounts for almost 15% of global CO2 emissions, with a progressively widening gap from the 2050 decarbonisation target (UN Environment Programme, 2022).

7. DESIGN PROCESS IMPLICATIONS

The introduction of 3DPC concrete technology brings a significant shift in architectural practice, redefining the design process and enhancing collaboration among various stakeholders. It’s essential to consider the transformative impact of this technology on the collaborative nature of architecture and the evolution of the design process.

We can consider collaborative synergy as one of the main opportunities rather than necessities incoming from this specific technological evolution. The complexity of 3DPC projects needs a multidisciplinary approach, catalyzing collaboration between architects, engineers, material scientists, and digital fabrication experts. Collaborative synergy goes beyond conventional workflows, necessitating that experts share their knowledge and skills to increase the potential of 3DPC. As a paradigmatical case, the collaboration between Foster + Partners and the European Space Agency on the “Lunar Habitation” project exemplifies how architects and engineers collaborate to design habitable structures using 3DPC for extraterrestrial environments (Foster + Partners, 2021).

The iterative nature of 3DPC technology encourages architects to embrace a process of exploration and experimentation. Projects like the “Urban Cabin” by DUS Architects showcase the iterative design process facilitated by 3DPC, as architects experiment with form, scale, and texture, resulting in an architecture that evolves in tandem with technology (DUS Architects, 2015).

A relevant innovation in the process workflow is the direct connection from virtual to physical; the transition from digital models to physical structures becomes seamless with 3DPC. Designers can directly translate digital designs into tangible forms, minimizing the gap between conceptualization and realization, which very often affects the design outcome. This simplified transition empowers architects to understand the spatial implications of their designs better and refine them in response to real-world requirements. The “Casa de los Dioses” project by XtreeE exemplifies this fluid transition, as architects seamlessly materialize their digital concepts into habitable spaces (XtreeE, 2019).

3DPC technology is a dynamic platform for architects to experiment with new materials, compositions, and finishes. Prototyping and material possibilities exploration lead to innovative surface treatments and novel material applications. The “C-FAB” project by Emerging Objects showcases the experimental opportunity as architects manipulate material compositions through 3D printing, resulting in a tactile and visually engaging facade.

The well-known malleability and adaptability of 3DPC transforms the design process and encourages architects to embrace adaptive design strategies. Real-time feedback from the technology iteratively adapts designs to optimize structural performance, thermal efficiency, and linguistic aesthetical qualities.

The integration of 3DPC technology guides a new era of collaborative design and iterative exploration. Architects, engineers, and construction professionals converge to control the full potential of this technology, resulting in a different understanding of the design process that is characterized by innovation, fluidity, and a closer alignment between digital ideation and physical realization.

8. CHALLENGES AND FUTURE DIRECTIONS

Throughout our exploration of the dynamic relationship between technological evolution and architectural language, with a keen focus on the influence of 3DPC, it has become evident that while this innovation holds remarkable promise, it is not without its challenges and limitations.

The technical issues characterising 3DPC as described in this article and the absence of an existing framework for materials and processes are the main challenge for the ongoing research.

Solving the problem of the insertion of rebars within the layers of 3DPC structural elements remains one of the most difficult tasks. Understanding if the use of shear-resistant fibers embedded in the concrete mix can have the same performance as the actual rebars is a priority. Doubts arise on the effectiveness of having diffused shear-resistance within the 3DPC parts instead of concentrated high resistance in those areas in which tensional stresses are present. Nevertheless, if fibers-reinforced concrete proves to be resistant to shear it would be a giant step towards the application of 3DPC in the construction industry.

One of the concrete mixes used in this research project contains metallic chips, one of the components used to obtain some shear-resistance. Additional tests will be conducted on this concrete mix.

The rheology of concrete mixes together with the geometric limitations deriving from the absence of formworks and supports mark the complexity of designing new spatial configurations for structural elements and non-load-bearing architectural elements.

As part of a more articulated research endeavor, the benchmarking of concrete mixes and rebars is a fundamental part of the project and needs to be further developed. Only after reaching a clear understanding of the performance and rheology of materials it will be possible to create a computational design model capable of determining new shapes.

The geometry of 3DPC is itself extremely challenging: the absence of formworks and supports means that the presence of undercuts in the section of the printed element must be carefully considered in order to avoid the collapsing of the element (Di Marco, 2018).

Geometrical issues arise in relation with rheology and the dimensions of the 3D-printed element: smaller elements require less time to complete one layer, therefore the deposition of the second layer falls on non-set concrete causing a considerable deformation that can compromise the final performance.

On the other hand, the 3D printing of large-scale elements suffers from the opposite problem: concrete mix will tend to set during the printing job, causing the clogging of the extrusion system.

All of these considerations suggest that a key aspect of the next phases will be finding the balance between the material rheology and its preparation, the 3D printing speed, and the geometry of the element.

Sustainability, a major concern in contemporary architecture, opens questions regarding the environmental impact of concrete production and the energy consumption inherent in 3DPC processes need to be addressed.

Looking ahead, there are exciting prospects and directions for future research and advancement in architectural language and 3DPC; one evidently involves the development of advanced materials explicitly tailored for 3D printing. These materials should not only prioritize structural integrity but also emphasize durability and sustainability, offering architects a broader palette for creative expression.

Beyond the technical aspects, there is a profound need for research that focuses on the human experience of architectural spaces created with 3DPC. Understanding how inhabitants interact with and respond to these structures can guide architects in designing spaces that prioritize comfort, well-being, and aesthetics.

The interplay of technological evolution, architectural language, and 3DPC technology has revealed not only the remarkable advancements but also the challenges that lie ahead. It is in addressing these challenges and embracing future directions that architects, researchers, and industry leaders will continue to redefine the landscape of architectural innovation, opening a new era of design possibilities.

9. CONCLUSION

Our exploration of the impact of 3DPC on architectural language reveals enormous transformative possibilities. It frees creatives, including architects, from traditional constraints, allowing for intricate, explorative and tailored complex designs.

From a structural point of view, the first results of the compression tests conducted on concrete mixes demonstrate how the discontinuous and non-orthotropic structure of the specimen heavily affects its performance (Table 1).

The extreme variation of the compression strength indicates that a 3DPC element seems to not have a precise foreseeable resistance. We consider repeating the compression tests several times throughout the research project duration (2 years) aiming at a sample of 100 tests.

Table 1. Compression strength

Sample No.	Force value (KN)
20230713-3.1	597.17
20230713-3.2	747.57
20230713-3.3	632.14
20230713-3.4	578.52

From an engineering perspective, even if an average value will be calculated, it would be irresponsible to take it as representative given the relevant deviations.

We predict that a more rational approach would be to use the lowest value as compression strength, eventually adding a safety coefficient in the computational model to remain far from critical stresses.

From an aesthetical perspective, architectural ornamentation is redefined, and parametric design and 3DPC merge, enabling architects to generate diverse design iterations while delivering a new language.

Customization extends to site-specific adaptations, creating an era of adaptive architecture and rediscovery of the myth of Genius Loci in design processes. (Norberg Schulz, 2011)

Material expression and texture gain prominence, illustrating how 3DPC enriches architectural aesthetics; this integration introduces a sensory dimension to architecture, evoking emotional connections. Challenges lie in technology maturation, cultural/regulatory adaptation, and sustainability.

The future holds promise in advanced materials, robotics, human-centric design, and interdisciplinary collaboration, offering professionals new frontiers for innovation, inviting designers to transcend boundaries and create a dynamic, vibrant built environment.

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