SWINBURNE UNIVERSITY OF TECHNOLOGY

INSTITUTE FOR ADVANCED ARCHITECTURE OF CATALONIA

Department of Architecture - PhD by Artefact and Exegesis

High-Performance Freeform Spatial 3D Printing

Towards A Material Structurally Optimized Architecture

Confirmation of Candidature Submission

Swinburne Supervisor: Prof Mark Burry AO
Co-Supervisor (IaaC): Dr. Mathilde Marengo

TABLE OF CONTENTS

Design investigation of innovative additive manufacturing techniques as CFM, CLF, FRP for composite materials in the post of cost-effective structurally HIGH-PERFORMANCE design techniques applicable to the construction industry.

Overview and proposed structure of the thesis/exegesis

The main structure of the thesis follows a sequence of chapters, which composes its main structure The research can be read in a standard, linear chapter by chapter approach, which follows a sequential knowledge building process or can also be read in individual chapters, as isolated content, following to the interest of the reader. Each chapter incorporates the necessary background information, analysis and conclusions on the topic of investigation to allow its comprehension.

Chapter 1 - State of the art
This initial chapter of the thesis “High-Performance Freeform Spatial 3D Printing - Towards A Material Structurally Optimized Architecture” with an introduction to the current state of the art composites material and additive processes in architecture, which includes an account of my motivation to undertake this particular research. Digital fabrication methods, materials and architectural demonstrators currently in existence. It sets the basis of additive manufacturing at different levels, later focusing on the composite in the construction ecosystem.

Chapter 2 - High performance in constructions, frame of reference
I will follow this with chapter 2: a necessary outline of the discipline-specific definition of high performance as background information focusing on its relationship to architectural elements. General considerations towards the construction industry and sector comparisons, on materials and technique implementations. High performance in building technologies is stated and contextualized by specific case studies among research academia and practice.

Chapter 3 - Composite additive manufacturing materiality in architecture
This third chapter establishes a summary of my theoretical underpinning and conceptual framework. Focuses on the definition of composite additive manufacturing architecture. This includes a transversal structure of both material implications and methodologies to be used as materials within the construction sector with the focus on additive manufacturing techniques and industry adequation.

Chapter 4 - Fabrication
I have been compiling a critical review of other researchers’ work definition and development of a robotic end-effector series for tools for additive composite manufacturing and conclusions for Chapter 4, principally through a literature search and an examination of key exhibited research outcomes.

Chapter 5 - A computational geometric approach based on fabrication and material constraints
The next section outlines my thesis research approach and methods. I will present my evidence and findings principally as a design methodology based on structural composite additive manufacturing, adapted for the selected fabrication key outcomes among prior chapter 4. This will be composed of an integrated structural computational design workflow for continuous fibre integration through a series of demonstrators.

Chapter 6 - Design protocols
In Chapter 6 I analyse my findings of methods and workflows for hardware-software integration from the previous design workflows implemented in chapter 5 in terms of the specific hardware findings of chapter 4. Analysis of the outcoming probes, as case studies scenarios resulting from the methods and algorithms, developed.

Chapter 7 - Design workflow analysis
I analyse my findings from the previous chapter 6. In terms of my adopted approach and methods outlined in Chapter 5. Analysis on the results of the case studies proposed.

Chapter 8 - Contextualized findings
This chapter will address the findings of the presented research that come from the development and completion of the artefact production as a critical analysis of implementation viability, construction cost; assessing the quantitative outcomes of the design protocols methods used as part of the conceptual framework of AM applicability for structural architecture applications of composites. As well as a critical review of the state of the art of both historical and contemporary literature on the implication of composite AM among construction sites (chapter 3), operation and fabrication models(chapter 4), including comprehensive justification of the possible advancements in the field due to this thesis development and publication, as well as possible future lines of development.

Chapter 9 - Conclusions and outlooks
I summarise my conclusions in Chapter 9 of my thesis/exegesis “High-Performance Freeform Spatial 3D Printing - Towards A Material Structurally Optimized Architecture” and will offer a comprehensive set of recommendations of the accounted topics discussed emerged through the development of the thesis.

Chapter 10 - Research overview
This final chapter completes the document as a reflection on how the research process qualifies the conclusions I reached in chapter 9 given my approach and the applied methodology processes explained among the 5th chapter.

I. Thesis introduction

This introduction explains briefly the overall thesis and its development. Establishing context, focus and short description of the content and structure of the document.

This research explores the potential of embedding innovative material research directly into the architectural discipline through the development and refinement of accessible tools and design for manufacturing workflows, towards the distribution of high-performance structures as viable solutions for spatial design. In particular, the research focuses on how 3D printing can be incorporated in architecture and can assist in the fabrication of high-performance structures by adapting fabrication processes and techniques from the composite aerospace industry, to establish design workflows informed by materiality and structural performance.

The research experiments with and exposes the viability of continuous composite-based additive manufacturing processes in the construction industry and the potential of their usage for high-end customized architectural elements.

The present research finds its place centred in the discipline of architecture, applying interdisciplinary notions from the fields of engineering and material sciences, to unveil the potential and design opportunities offered by the geometrical freedom of newer additive manufacturing processes that could allow the fabrication of high complexity architecture. As the one usually generated by structural generative algorithms and optimization tools, but which has large difficulties to overcome the computational simulation.

Focusing this investigation on the adoption of continuous fibre additive manufacturing techniques not currently used among architecture and construction industry, but widely explored in the academic realm. For the development of novel manufacturing routes and systemic analysis of 3D printing for design-driven performance processes. The previously mentioned processes being: continuous fibre manufacturing(CFM), continuous fibre reinforced plastic (CFRP), continuous lattice fabrication (CLF), among other composite materials for continuous additive manufacturing composite based techniques.

This multidisciplinary focus introduces a challenge on how the investigation is approached in the quest of developing a design-based material driven system. The response at the core of the research is the use of practical experimentation as a key methodology to validate the exploration of load-tailored design systems. Accounted key probes validate the performance-driven design protocols, and will be presented as part of a series of artefacts of the strategies discussed in the thesis as findings of the fabrication processes.

Undertaking this research, as a PhD by Artefact and Exegesis, in which a written manuscript comprehending around 40.000 words and the aforementioned artefacts will be submitted, due to the high implication of a practice based approach for the methodological finding process.

To a certain extent, this load-bearing 3D printed architectural elements research emerges from the continuous investigation by the author of the latest techniques on additive manufacturing and materials technologies as novel design opportunities. Focusing on the application of these at the construction and architecture level, the understanding that there is a need for a methodological process, which in turn emerges from the multidisciplinarity of the processes, adapted through geometry and computational design.

II. Hypothesis & research questions

Traditional manufacturing processes involved in the fabrication of composite parts at an architectural scale implies a large material demand for producing lightweight parts and time-intensive fabrication procedures. Temporal base frames are strictly required by the material characteristics and fabrication strategies for this composites material usage, being those a slow curing process, pot life and layer by layer application.

Additive fabrication strategies utilizing fabrication informed, material-driven, computational design integrated processes can result in optimized structural models that can handle the manufacturing complexity and cost of these high-performance materials.Optimized design workflow with feedback from the 3D deposition, design and fabrication materials can help to optimize additive and multi-material production processes, resulting in more complex structures with improved self-weight to load-bearing performance as well as lower manufacturing costs.

By improving design workflows associated with the materiality of this process, it will likely be able to perform an additive based design wordflow that focuses in this specific manufacturing methodology, which is free from the use of a base frame or mold, making it possible to create spatial wireframes also called spatial lattices on any given working surface.

Fabrication technology of these characteristics will help manufacture large structures whilst keeping the geometrical complexity yielding to new architectural opportunities.

Research questions

- Are composite materials through additive manufacturing techniques encoded with computational design tools able to be cost-benefit applicable in the construction industry?
- How can high-performance materials be used in architectural models across scales, from single modules to full-size elements?
- How does architectural design practice change with the possibility of this geometrical freedom?
- How does the newel manufacturing methods used in this research transfer help in the application of these high-end materials in the construction industry?
- Is the current development state of additive manufacturing with continuous fibre, able to produce full architectural elements with embodied structural performance?

III. Framework

The construction industry is among the least digitised sectors in the world and has had the lowest productivity gains of any industry over the past two decades. One of the key aspects to deal with these challenges, increasing the speed, accuracy and safety whilst reducing cost and waste in the construction industry, is the integration of new and alternative construction methods (CECE, 2019).

The utilisation of additive manufacturing, in post of automatization of the construction processes, reduces the cost of high complexity structure implementation among the industry. This helps expand the geometric complexity, functional integration, and smart assembly logic to develop new methodologies and processes that evolve and reinterpret the use of materials to produce new architectural models.

This change of paradigm in architecture has already proven feasible at the academic and research level where multiple institutions have not only demonstrated the theoretical benefits of digitizing the industry but also built several demonstrators and state of the art pavilions to showcase the potentials of these new technologies.

Nowadays the major constraint for the integration of high-performance materials and additive manufacturing (AM) techniques in construction, is the cost of the material supplied, which is typically US $100 per kilogram, outweighing the cost of the machine itself. Therefore to allow these materials to be integrated into the construction industry they must come in at US $100 per tonne (Soar, R. and Andreen 2012). Several new material and fabrication technique investigations remain at exhibition scale as they cannot outperform already existing ones in relation to the combination of cost, on-site execution and construction.

3D printing should be used for what it does best (M.Tonizzo 2013), which includes optimizing workflows. Conventional methods of additive manufacturing have been affected both by gravity and the printing environment: the creation of 3D objects on irregular, or non-horizontal surfaces has so far been treated as impossible. As well, layer-by-layer AM is either constrained by that same need or limited geometrically by the inherent overhang capabilities of the material in deposition. For AM to be able to reach ‘volume’ construction on the construction market, it must form part of an integrated, digital continuum of which the performative impact performance-wise on deployment cost and structural improvement/proficiency- outweighs aesthetics alone.

There is a niche for exploration of the architectural possibilities of different composites AM techniques other than the layer-by-layer deposition as CFM, CLF, CFRP that research in the material usage on material-load capabilities through advanced fabrication techniques.

The research proposes an update of the previously done research of material-fabrication informed composites structures, structurally informed geometry systems and its application for architectural construction techniques with the existing state of the art additive manufacturing techniques on composite continuous manufacturing. Identifying the existing and future progress on the AM of continuous fiber reinforced composites research over time and therefore establishing a foundation on which the current research can propose the technique integration.

The discussion raises the question of the influence of material centred systems and manufacturing processes embedded as part of the design process in what is considered design for manufacturing practice. Which set the importance of building previous know-how on material behaviour and engineering techniques as the foundational base of the present research. Settling foundational literature over these fields as the initial point of the investigation as a focus in order to control the technical aspect of it.

IV. Aims and objectives

A Material Structurally Optimized Architecture (MSOA) is a term coined by the author to describe a comprehensive design framework informed equally by the material, the fabrication methods and geometrical capabilities of the previous, which is structurally optimized for an architectural application. The research addresses this outlook by exploring the possibility of a spatial extrusion for complex space mesh high-performance structures.

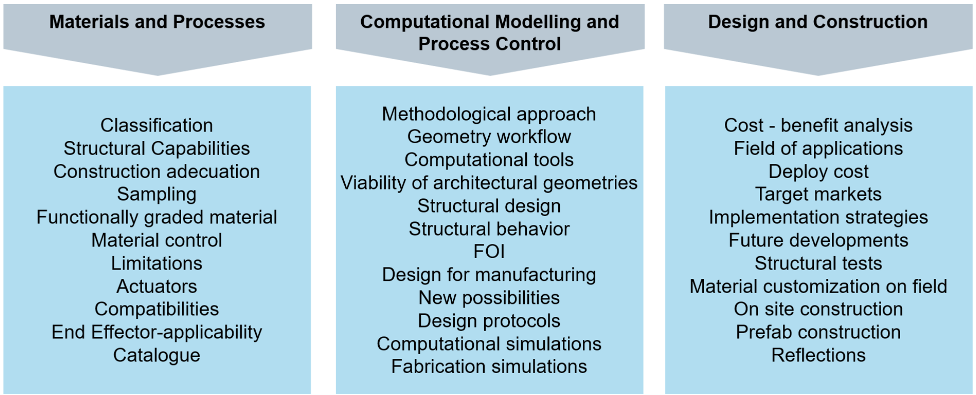
Applications of high structural or lightweights structures needs, topological optimized or material graded elements that outperforms standard construction solutions could benefit from the impact of this research.

The research addresses this outlook by exploring the possibility of a spatial extrusion for complex space mesh high-performance structures. The diverse, partly overlapping aims can be classified into the following:

- Materiality research on fast curing deployable 3D printing composites
- Develop a range of fabrication strategies suitable to obtain continuous fibre high-end digitalization of composite parts by spatial structural frame algorithms
- Definition of geometrical design and structural performance parameters that comprehend construction industry graded functional elements
- To explore and categorise the fabrication technology in the absence of moulds
- Possibility to create tailor-made objects from micro to macro-level geometrical point of view and states in between.
- Implementation of these fabrication strategies from a direct structural application to possible use as performative formwork for jammed architectural structures or leaking formwork.
- Ultra-lightweight thin section encapsulating lost formwork.
- Outperform traditional load-bearing construction elements reaching the target of construction market applications.
- The reduction or elimination of the fabrication limits thanks to the absence of the typical mould constrictions, undercuts, etc.

V. Research Methodology

This research follows a learning by doing methodology/experimental research methodology. The development of such a framework is established by carefully comparing both theoretical and practice-based research in three main research areas, materials, manufacturing methods and design protocols. Drawing attention to the critical analysis of possible technique implementation not only from a feasibility point of view but also adequacy to the construction sector. This is a methodology approach in which every step is feeding the consequent next one.



Materials and Processes

- Classification
- Structural Capabilities
- Construction adecuation
- Sampling
- Functionally graded material
- Material control
- Limitations
- Actuators
- Compatibilities
- End Effector-applicability
- Catalogue

Computational Modelling and Process Control

- Methodological approach
- Geometry workflow
- Computational tools
- Viability of architectural geometries
- Structural design
- Structural behavior
- FOI
- Design for manufacturing
- New possibilities
- Design protocols
- Computational simulations
- Fabrication simulations

Design and Construction

- Cost - benefit analysis
- Field of applications
- Deploy cost
- Target markets
- Implementation strategies
- Future developments
- Structural tests
- Material customization on field
- On site construction
- Prefab construction
- Reflections

Figure V.1. Research areas framework

Those three areas are investigated separately following a bottom-up approach, whilst keeping a comprehensive top-down approach at the combination of them. The listed areas of interest are represented in the figure V.1 diagram, including a secondary category of research futurely addressed in the development of this thesis.

The development of the research starts with an in-depth analysis of the latest implementation on continuous fibre integration on manufacturing and its possible applications, seeking for processes that could be merged or reinterpreted with similar approaches on a geometrical basis of structural performance currently employed in the construction industry or under research at the architectural academia. Additionally, a deconstruction of continuous fibre manufacturing principles is intended to assist the author in developing work-flows that can be easily implemented in the construction industry.

In order to gain specificity in the aims and objectives of the research, a reflection period was followed by background study, literature review, and the state-of-the-art analysis.

As to what technologies, materials and processes may be implemented as a consequence of such analysis, it is systematically tested and implemented per several probes, as workshops, demonstrations and by per to per reviews.

Using the conclusions of the test, quantitative data will be gathered and used to develop the first design protocol. As the research under that field clarifies,a categorization of the geometrical and structural performance integration on this fabrication and material process will take place aiming to establish possible applications or constraints in architecture.

A series of manufacturing probes and demonstrator tests through robotic attempts, at per today, with both successful and failed results, are allowing the definition of this theoretical but with a high physical prototyping implication methodology, to be characterized by the combination of physical and digital exploration, in a continuous, open-ended process.

In more detail, the research explores design strategies aimed at the realization of load-bearing elements for architecture.This is a crucial step in the development of the design workflow which currently looks into three fields that can respectively inform the fabrication process; material implementation, freeform geometry lattices and structural behaviour.
All strategies are aimed at optimizing structural performance, minimizing material cost impact, enhancing spatial freedom and when necessary, minimizing path planning complexity.

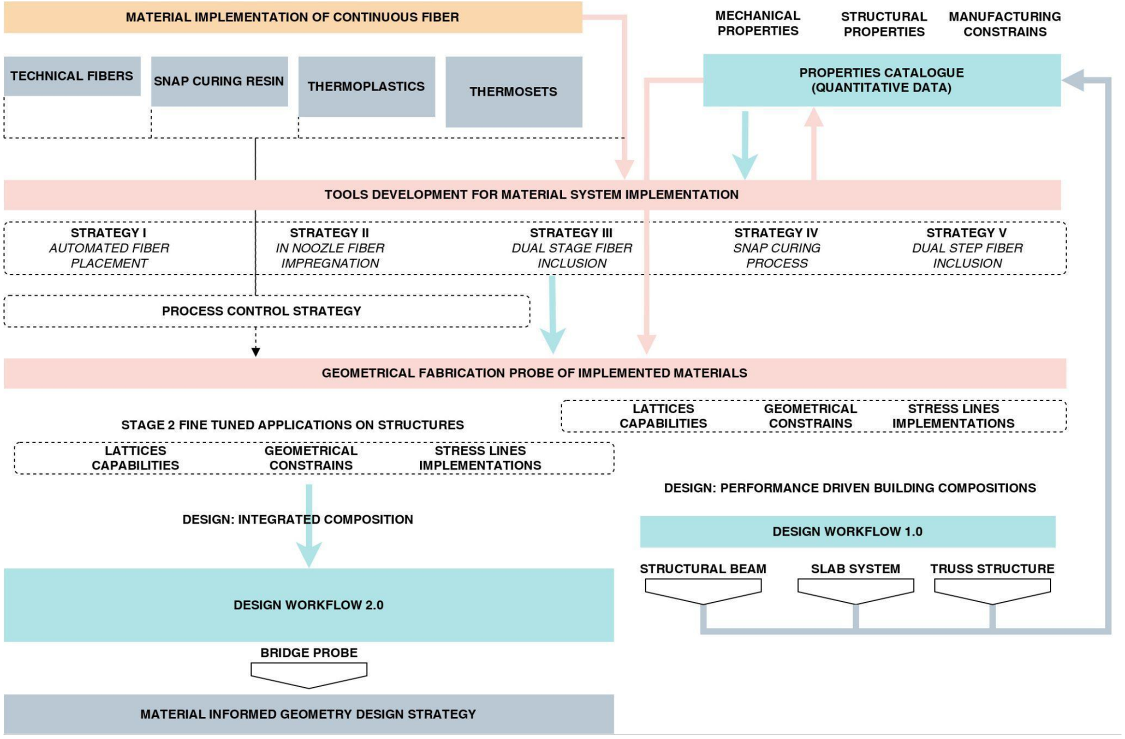


Figure V.2. Methodology mind map

Analyzing the history of material implementation in construction towards establishing the key goals that allowed a newer material to be adopted as a feasible solution in the market. This aids in making informed predictions of the further applications of such as material based technologies. Aiming to conclude with a catalogue of the material-geometry-fabrication system and their optimized possible applications. Design solutions will be tested through a range of case studies in which the context and needs will determine the design solutions.

VI. Expected results

As a consequence of the thesis development, some technological artefacts provided in combination with a collection of open-source extruders/end effectors that allowed the fabrication of 1:1 scale structural elements (beam and slab) will be provided as part of the contribution with the goal of fostering future developments on the subject. As well as minor probes of the aforementioned artefacts which will focus on specific elements of those. Accounting as per today, the mentioned probes will test the following topics: material adhesion, material resistances, geometrical lattice formation topology, topology form findings. In addition, and in relation to the research interest of this thesis, getting hands-on experience with newer fabrication technologies and finding new applications of them, will help in fostering knowledge and dissemination of these material-design techniques among the architecture academia.

Exposing, through research by design process, the capabilities of such as technologies is leading to:

Academic contributions

- Methodology for continuous fibre integration manufacturing processes in architecture structural elements and its possible applications.
- A catalogue of possible outputs as well an interpretation of current and in development AM techniques that could be applied among the construction industry.
- A design-fabrication methodology for composite construction without moulds, in order to reduce waste as result of fabrication processes, aiming to be suitable and easily integrated within the construction sector
- Set of several 1:2 scale prototypes and 1:1 demonstrators of the above-mentioned methods establishing the capabilities of such technology implementations

Industry contributions

- Optimized/democratized framework applicability of high-end fabrication and materials in the construction industry.
- Feasibility study in onsite implementation through the presentation of the aforementioned demonstrators as case studies.
- A detailed procedure for operational structure on advanced fabrication techniques involving design for manufacturing processes. Based on the utilization of robotic arms for construction as a combined tool for offsite-onsite manufacturing.

Fabrication contributions

- The development of several ad hoc open-source extruders for continuous fibre 3d printing that allows multiple AM processes. Use of the so-called end effectors as a working prototype of affordable, open-source manufacturing solutions.
- A catalogue of material implementation in these processes, indicating the qualitative and quantitative properties of these based on literature review and process testing through probes.

Computational contributions

- Computational design protocols of geometrical implementation form-finding, based on the structural behaviour of geometric spatial lattice output models
- A computational design protocol of multi-objective optimization for continuous fibre allocation in architectural elements and structures balancing out the mechanical, cost and design properties of the developed material processes.
- The capability of integrating high cost per weight material through a material optimization technique from a structural perspective, involving in the process the structural analysis by finite elements of sample models.

VII. Research plan

According to the research methodology, the investigation is built on a cascade of asynchronous but interdependent stages. All will be conducted under the spiral development process model for all of the aforementioned research fields, following an evolutionary prototyping methodology. Analyzing the project's progression chronologically, the research phase starts with the conceptual design of the baseline spiral accounted for here and building up the state of the art of the research as setting the theoretical background involving architectural design, logical design with additive manufacturing, physical construction processes and the final list of design morphologies for subsequent spirals. Research for this section will run from January 2021 to May 2022. It will be sufficient time in this period to revisit and redefine the work's foundation, and to complete all essential reading. Material, fabrication, and design are the three areas of practical research.

The fabrication of additive manufacturing tools flows almost parallel to the state of the art research. This is because the journey to a workable set of tools involves several reiterations over the hardware prototypes, taking lessons from each. Currently, this part of the research is expected to be concluded by July 2022, when various extrusion systems will be thoroughly tested in the advanced steps of the research. Additionally, as the material system is developed and tools are tested, the structural design system's computational plan and geometrical algorithm implementations for structural path planning are being developed as well. The design is informed by the material properties, however, it will be speculative and will evolve as the research progresses. This area will take place from October 2021 to May 2022. Manufacturing and design approximation are highly interconnected.

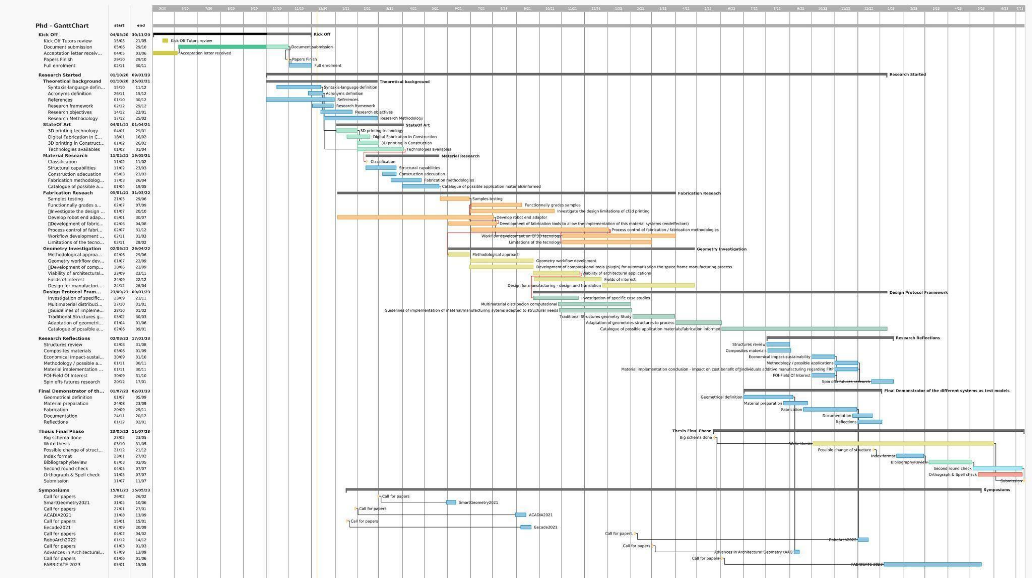


Figure VII.1. Gantt Chart of the predicted thesis research plan and future progress

By September 2022 the integration of manufacturing, design and construction constraint elements will be studied and developed further until a new language is set here, as the establishment of methods and workflows for hardware-software integration are set.
A series of probes in the form of case studies will be presented, divided into two main categories: planning and experimentation. Including detailed documentation of the fabrication process, the methods and algorithms developed for the various typologies.

The research will establish the design protocols to follow, culminating in the development of final demonstrators that showcase the fabrication processes. This will take place from December 2022 to July 2023. A workshop will be conducted with students to provide multiple insights into the design opportunities offered by such a process. This will be prior to the final stage of the probe fabrication process.

The writing of the thesis, which is scheduled for July 2023 to December 2023, is the last and final part of the research. Since the pre-confirmation review, the text has been continuously developed and revised, whereas, towards the end of the research, the compilation of the final thesis is expected to take 5 months.

VIII. Summary of publications (Publication plans)

Throughout the research, there will be several publications related to the development of minor chapters of the thesis, where the author will submit scientific papers and entries. Those papers will be annexed or embedded as part of the thesis delivery as they are directly related to three main areas, “Topological design modelling of spatial lattices, Path-planning strategies of continuous fibre integration, Continuous composites for architectural elements, etc”

The publication of the manuscripts, on the research chapters, serves as a validation point carried out by experts associated with the respective topics, of the quantitative or qualitative experimental results attained in the forthcoming developed parts of the thesis. Therefore methodology can be validated, as well as the theoretical build of the research framework can be verified via peer-review process.

Ongoing journals and conferences publications

- JIDA 21 - Workshop on Educational Innovation in Architecture

Paper published - "Hyper-connected hybrid educational models for distributed learning through prototyping"
DOI10.5821/jida.2021.10585

- Design Modelling Symposium 2022

Note: Abstract submitted - "Continuous stress lines spatial lattices formation on fabrication-informed manufacturing"

Conferences of possible publications

- Roboarch 2022

Note: Abstract submission estimated to be opened in February 2022

- Fabricate 2023 (Conference)

Note: Abstract submission estimated to be opened in July 2022

- ACADIA (Conference)
- SimAUD (Conference)

Journals of possible publications

- Data, Matter, Design: Strategies in Computational Design; Journal (https://www.routledge.com/Data-Matter-Design-Strategies-in-Computational-Design/Melendez-Diniz-Signore/p/book/9780367369095)
- Materials & Design; Journal (https://www.sciencedirect.com/journal/materials-and-design)
- Construction and Building Materials; Journal (https://www.journals.elsevier.com/construction-and-building-materials)

THESIS

1. State of the art

1.1. Digital fabrication in constructions

In order to steer from the current profession of architecture, a new generation is emerging with a need to rethink architecture and design. These architects must be able to address the human context appropriately in order to create a more sustainable world adapted to its times. Digitalization and robotic fabrication have opened up a world of possibilities for designing, making, assembling and indeed, changing the whole spectrum of architectural production.

Since the 1960s, robots, particularly industrial robots, have had a major impact on manufacturing but is not until the 2000s that they have been directly linked to the design process, and later in 2020s as possible construction co-workers. As a result, robotic fabrication is nowadays in the paradigm of newer forms of production integration at diverse modes of material engagement, which can convey a new approach to designing and thinking.

Therefore, the use of these newer tools for the construction industry as tools to implement complex fabrication strategies resulting as a result of complex computational models becomes ever more present. Building in today´s context, where the computational design tools are fully integrated in the architectural practice and looking towards the even further integration of them of the construction among the whole sector. This leads us to the manufacturing processes relationship between production and material integration, which is capable of offering great potential in its implementation through robotic fabrication.

The implication of additive manufacturing (AM), also known as 3D printing, spans the entire product lifecycle and compels us to reimagine how products are designed, produced and delivered to users around the globe. Emerging industrial AM processes can be used with polymers, metals, composites, and other advanced materials. The combination of such technology with advanced digital design tools is poised for newer architectural opportunities, allowing reducing cost compared to traditional processes, for futures construction deployments.

1.2. 3D printing technology

In recent years, there has been a surge of interest in 3D printing as a new form of manufacturing. Mainly because of its capability to print virtually any shape as per high complex geometries and produce anything from toys to clothes.

- AM processes
- Overview of the all-mayor AM processes and comparison of their performance
- Modules on the fundamentals, materials, design guidelines
- AM application examples from different technical fields.
- Methodology for selecting and classifying potential applications/usage in the construction industry

1.2.1. Small scale-product oriented

The following chapter discusses several additive manufacturing techniques that allow fabricating arbitrary 3D objects with near-zero constraints on their complexity.

1.2.2. Large scale

The following chapter discusses large additive manufacturing techniques that allow the production of large scale batches or large unique parts.

1.3. 3D printing in construction

3D printing technologies have been applied to a variety of fields in recent years, such as construction, engineering and medicine. The use of 3D printing in architecture is becoming popular with its potential to revolutionize architectural design and construction (Arakawa, 2016; Bayley et al., 2013).

Ongoing construction of large standalone dwellings as the 100 single-story houses "printed" on-site using advanced robotic construction and concrete-based mix as building material by homebuilding company Lennar and ICON or the five homes built by the construction firm Saint-Gobain Weber Beamix in the Eindhoven suburb of Bosrijk, among others, prove some of the benefits of this technology adoption. Additive manufacturing in the construction industry is a growing field that finds itself at the early stages of development compared to other sectors such as aerospace and medical. In which the technology maturity state is well-understood, proven and key standards have been developed enabling repeatable quality at scale.

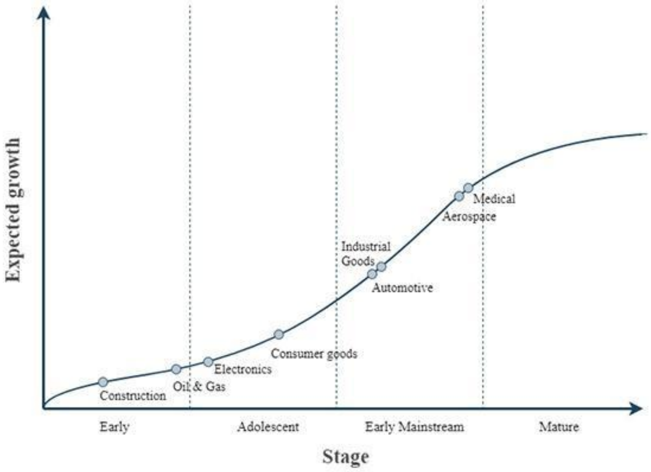


Fig 1.3.1: Chart illustrating the adoption rates of 3D printing across different industries.
Image Credit: AMFG

On average the global construction industry has an annual revenue gain of 10 trillion dollars, whilst the value of the academic and industry demonstrators using additive manufacturing technologies only engross a few hundred million dollars. The construction sector is still looking for the opportunities offered by 3D printing through the development of specific processes needed in the sector. Undeniably, research and development are still needed for the future adoption of such technology. The yearly frequency of research papers published at the academic level and projects developments has exponentially increased over the years. Being the majority of those construction projects built for demonstration purposes. Being the initiator of those state of the art probe demonstrators, urban furniture 3D printed elements using traditional construction materials like concrete and state of the art bridges which were fabricated around the year 2016.

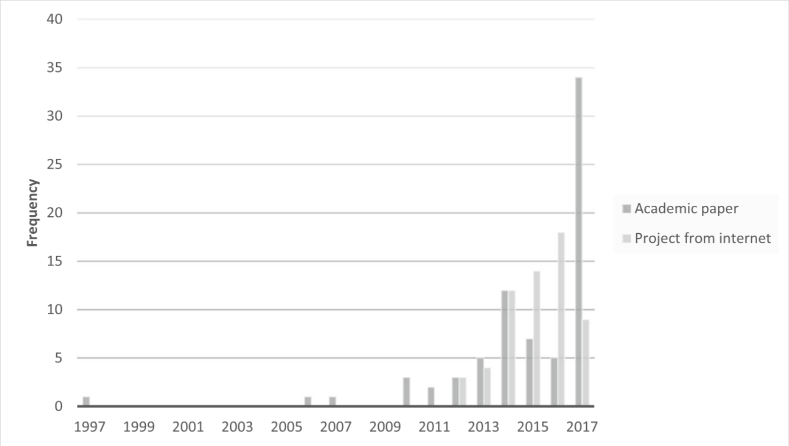


Fig 1.3.2: Yearly frequencies of research papers and projects on construction 3D printing (1988–2017)
Image Credit:Pan2021

The experimentation gained through those demonstrators proves that creating complex structures with additive manufacturing (AM) provides architects and engineers with many benefits. as it allows for flexibility and customization of the final design with a marginal cost increment. The Acciona concrete bridge spanning over 12 meters at 1.75m wide single piece load-bearing architectural element was designed by the Institute of Advanced Architecture of Catalonia using biomimicry and organic design workflows. Show as design strategy looking for material usage optimization the clear example of inherent capabilities associated with AM in this case large-scale binder jetting technology, as the natural shapes found in the public demonstrator located in Alcobendas, Madrid(Spain) would have multiplied the fabrication cost of the bridge if another technique was used. Therefore the public legislation of structural and accessibility design was not adapted to the technological capabilities, leading the public administration to an over dimensioning of the whole structure in order to be able to open the bridge to the public.

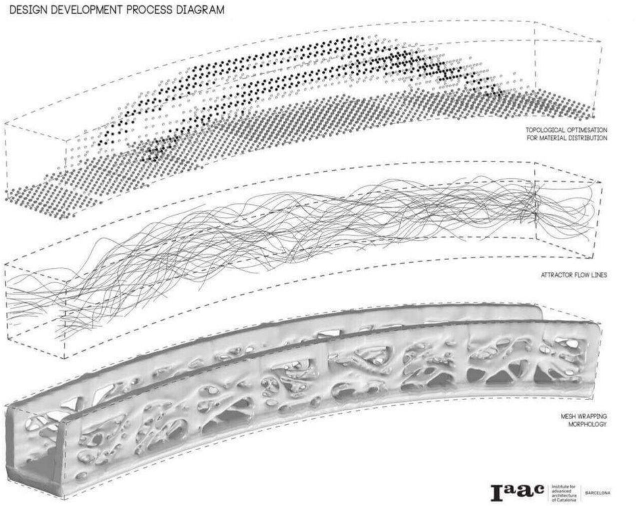


Fig 1.3.3: Acciona+IaaC design mimicry process. Image Credit: IaaC 2016

For example, it allows them to print the structure in one piece, as discussed below, without any joints or connections necessary, which decreases the chance of potential errors. Additionally, it produces structures that are more lightweight and stronger whilst using traditional construction materials which save on building costs and increase material efficiency. Usually, the material optimization comes to topological optimization of the structure maximizing the carrying load and minimizing the material usage as a design driver, reducing in the process the C02 footprint, as structurally optimized construction example can we found in the pedestrian bridge built by VERTICO and the University of Ghent printed in concrete of 4.5 x 2 x 2.5m dimensions. Their technology allows to save 60% of concrete by removing all the unnecessary material but is still limited in terms of work cell or their process, being the sample bridge made out of smaller parts combined later on. A similar strategy but focused on manufacturing speed rather than material performance is the Saint-Gobain Weber Beamix bridge designed by Michiel van der Kley together with Summun Engineering y Witteveen + Bos in collaboration with the Technological University of Eindhoven (TU/e) where Theo

Salet, professor of Concrete Structures at TU Eindhoven stated the “The printing of concrete can drastically increase the construction speed.” as the 3D printing technology matures.

Alternative construction materials into additive manufacturing are also the subject of research among both academia and the building industry. To this material implementation there is associated custom 3D printing modules that need to be tested by one to one fabrication probes to check the reliability and repeatability of the process, in case the Shanghai Digital future pedestrian bridges printed by Shangai Architecture School thermoplastic was used for its construction being that, one of the most utilized materials associated with AM technology, in particular together with robotic cell as the well established Branch Technology fabrication provider company shows trough its portfolio of facade components using it´s C-Fab patented method. This application is currently being adopted as a stable solution for composite insulating panels and also exhibited by its technological demonstrator for the Miami Design pavilion,oneC1TY Pavilion designed respectively Shop Architects and Thornton Tomasetti architects. For its ABS thermoplastic extrusion Branch embeds micro chopped carbon fibres among the material mixture to improve the performance of the material incrementing the structural capacity of its cellular grids.

The inclusion of fibres in the AM materials is a new growing field, specifically when talking about the inclusion of continuous fibre in AM as the earliest patents of such as material technology date from 2013. As therefore exiguous architectural applications can be found, being a collaboration between Royal HaskoningDVC, CEAD and Covestro using fibre glass-filled thermoplastic composite material probe pedestrian bridge part of it. Composite materials in AM allow to augment the lifetime expectancy and lower life cycle cost of build elements compared to steel, a traditional material for bridge implementation Currently, the bridge only exists as a prototype and is being tested under laboratory conditions.

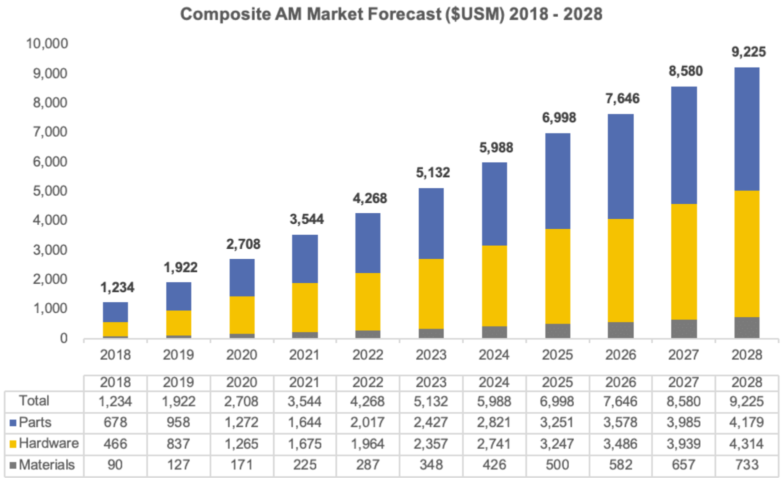
1.4. Current fabrication technologies

1.5. Technologies in development

One of the major updates, when we analyze the current technologies underdevelopment for high resistant and lightweight materials available for additive manufacturing, is the introduction and enlargement of continuous fibre manufacturing processes. The current researches on this topic exist in the engineering and material scientist fields(Matsuzaki2016, Novo2016) and have been focused on the underlying mechanics(Heidari-Rarani2019) chemistry(Thakur2020, ZOCCHI G.2016), and performance of the physical output (Dickson2020, Heidari-Rarani2019), as well as material behaviour properties (Kruschmitz2021, Li2016, Adumitroaie2019).

With the development of additive manufacturing deposition techniques and material implementation processes for continuous fibre 3D printing, the possibility of more structural efficient lightweight architectures bears high potential as newer techniques enhance design freedom and flexibility on geometry design (Eichenhofer2015).

The introduction of continuous fibres for 3D printing has opened up a world of possibilities for new applications of this technology, including materials that are stronger than steel, composites with less than 2% carbon content, and even electronics integrated into a printed circuit board. The introduction of continuous fibre in 3d printing is the next step of additive manufacturing. In that way, the industry will be able to produce larger and stronger parts, at a lower cost by reducing the material deposited maximizing its capabilities. The companies working in this area are using different techniques and materials, from metals, plastics, resins, polymers and composite materials to new carbon-based materials like CNTs. This is producing a major impact among high technical object demanding industries such as automotive, aerospace and medical. In spite of the advanced industry requirements for such a field, the list of companies commercializing or researching on their I+D departments continues to grow, as so the spectrum of processes, capabilities, materials and new markets applications.



	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Total	1,234	1,922	2,708	3,544	4,268	5,132	5,988	6,998	7,646	8,580	9,225
■ Parts	678	958	1,272	1,644	2,017	2,427	2,821	3,251	3,578	3,985	4,179
■ Hardware	466	837	1,265	1,675	1,964	2,357	2,741	3,247	3,486	3,939	4,314
■ Materials	90	127	171	225	287	348	426	500	582	657	733

Fig 1.5.2: Composite AM market forecast. Image Credit: SmarTechAnalysis 2018

The innovation connoted at the industry of the technology development on composites, focused in this scenario on continuous fibre 3D printing succeeds to consequentially produced a multitudinous among of technical acronyms for each minor process improvement among multiple companies, directly related to industry patenting processes and right claims on processes developments. Therefore an effort to standarize conceptual integration of continuous fibre in 3D printing processes has been done by the research associate and expert for Additive Manufacturing at TU Munich and the Chair for Carbon Composites (LCC) Alexander Matschinski.As stated bellow. “Due to the company-specific nuances in how these processes are implemented, categorization is difficult,” he concedes. “But there are some trends, especially if we focus on how the fibre matrix is brought into the print nozzle and how they are deposited.”

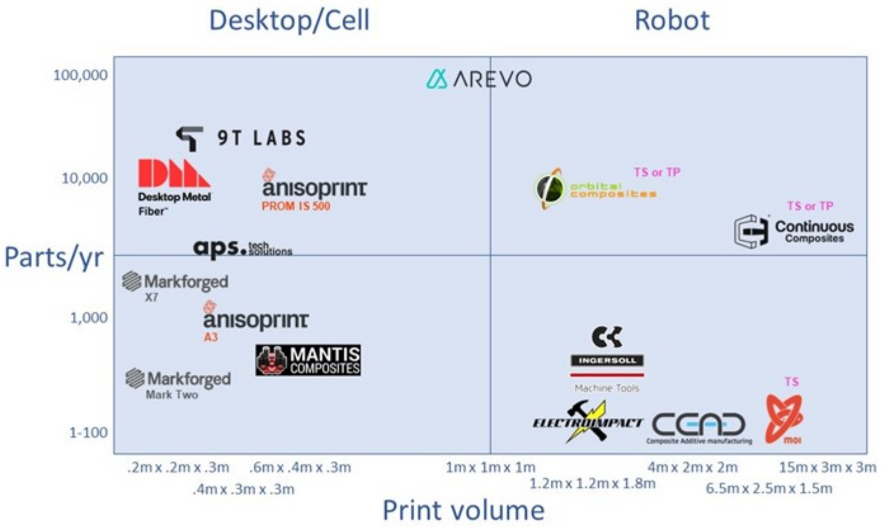


Fig 1.5.1: Classification of processes among industry leaders. Image Credit: CompositesWorld Magazine

Fibre integration methodologies

In-situ impregnation. Dry fibre is fed into the nozzle while a matrix material is injected through one or more inflows during deposition by co-extrusion. The matrix is thus introduced, heated and in-situ impregnates the fibre prior to being deposited.

Co-extrusion with towpreg. Instead of dry fibre, towpreg/thin prepreg tape is fed into the nozzle, heated and co-extruded with an additional matrix material. Typically, the matrix in the towpreg is identical to that in the co-extrusion. An exception is Anisoprint, where the towpreg matrix is thermoset and the co-extrusion is thermoplastic.

Towpreg extrusion. The towpreg input material is heated and extruded without any additional material. This commonly used process is the most expanded technology in non-continuous fibre integration due to its large development rute and simpler technical design, could also be described as fused deposition modelling (FDM), a term trademarked by Stratasys (Eden Prairie, Minn., U.S.)

In-situ consolidation. Essentially a scaled-down version automated fibre placement (AFP) which can include the use of a thermoplastic instead of thermoset resin. In this process, the material is fed in as a towpreg/prepreg tape that is consolidated in-situ when deposited. The feed-stock is heated or irradiated by an external energy source at the nozzle during the feeding process and is then placed and consolidated by a pressure roller during deposition. This process doesn´t account for a high degree of flexibility as the compaction roller or roller device needs a surface wheter to stand against. As result in this cited process, only surfaces of layer by layer manufacturing can be implemented.

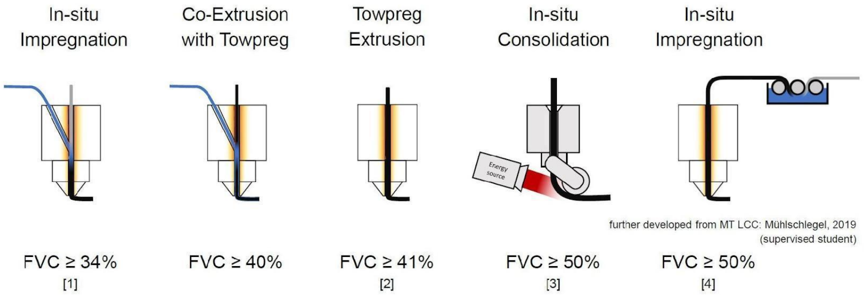


Fig 1.5.2: Concepts for direct fibre integration. Image Credit: Alexander Matschinski, Virtual Symposium on AFP and AM, TU Munich, Chair of Carbon Composites (LCC), Sep. 2020.

Inline Impregnation. The fibre is impregnated while it is transported into the print head or in the printhead by a thermal o chemistry-based polymer, similar to 3D filament winding. As with towpreg extrusion, the deposition takes place via a nozzle that can actively activate the polymeric chemical reaction.

The aforementioned process could be embedded as part of their dual step fibre embedded process a commonly found technique called fused filament fabrication (FFF). As one of the materials of the process usually accounted as the matrix reinforcement is produced by printing a line of a polymer called filament as used in equality as FDM. However, FF can describe processes where there is no inclusion of continuous fibres but in a chopped state at different scale levels. Where the inclusion of continuous fibre transforms the terminology in continuous filament fabrication (CFF)

CF3D processes an industry overview

The development of these techniques is in the foreword driven by the industry demands of highly engineered parts. The commercial solutions and advancements are directly related in most of the accounted companies stated below by academic research fellows who lately founded or are associated at a certain level on the foundation of these newer commercial companies.

Stated here, is a technical analysis of the processes implemented by the companies leading the sector and their possible, if existing, architectural applications. The analysis follows a sequence of the companies description based on the maximum volumetric the companies are able to achieve.

A twin-nozzle design of Composite fibre Co-extrusion (CFC) from Anisoprint (Esch-Sur-Alzette, Luxembourg) combines FFF and co-extrusion with carbon or basalt towpregs made from a range of thermoplastics including PLA (polylactic acid) and PEEK (polyetheretherketone). This is a technology employed for the fabrication of small size parts on a batch production basis. This process enforces his own software for the material deposition using a layer by layer traditional approach whilst embedding specific reinforcement on high-stress zones. A similar approach is taken in Markforged's (Watertown, Mass., U.S.) Continuous fibre Reinforcement (CFR) technology, where a twin-nozzle CFR nozzle is used to lay down continuous CF, GF, or AF and PA onto an FFF-printed object. The company produces desktop and industrial 3D printers, focusing on technical prototyping of technical parts rather than a mass production line. Following the same development, Desktop Metal's (Burlington, Mass., U.S.) and APS Tech Solutions (Höchst, Austria) integrate fibres on cartesian 3D printers embedding in the process the use of a robotic tool changer to switch between FFF and µAFP (micro AFP) deposition heads and an integrated inline cutting mechanism and automated tool-changing system with four print heads respectively. These desktop size solutions allow for multiple types of material inputs such as carbon fibre (CF), glass fibre (GF), aramid fibre (AF), copper wires combined with high technical bonding matrices as PA, PEEK, PLA, ABS, PEKE and ceramic for sintering applications. The developed processes mentioned above are too focused on both methodological implementations of the continuous fibre integration and manufacturing techniques on producing small scale accurate objects.The possibilities of producing larger scale objects for an architectural application that this freeform layer by layer fabrication methods offer are narrow.

The methodology implemented here, by those companies cannot scale up without exponentially increasing both equipment and object cost, yielding to no or low architectural opportunities in them.

9T Labs' (Zurich, Switzerland) was founded after the thesis completion of Martin Eichenhofer on "Additive Manufacturing of Continuous Fibre-Reinforced Thermoplastic Composites (FRTPC)". The large improvements and implications of the thesis on coextrusion processes for lattice fabrication were only implemented for employing AFP-like deposition with infinite rotation. The company intends to produce relatively large numbers of high-performance parts, as attested to by its partnership with advanced metal parts manufacturer Setforge (L'Horme, France).

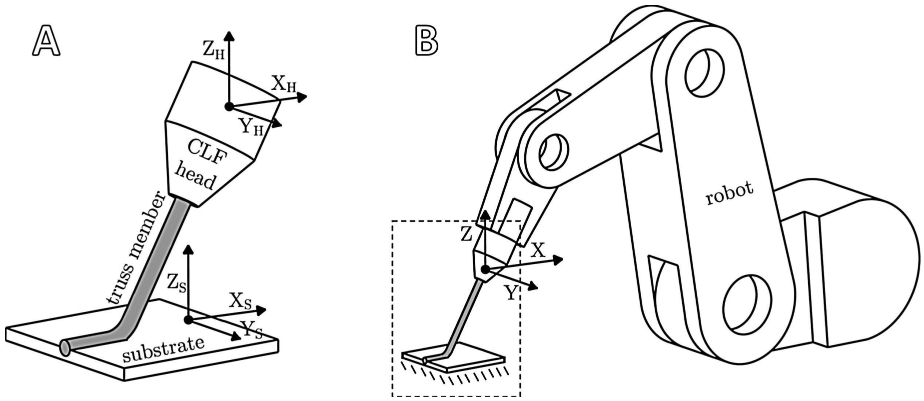


Fig 1.5.3: Extrudate shape is determined by the relative movement between the CLF processing head and the substrate in three-dimensional space. Information source: Eichenhofer2017

Compared to the previously mentioned companies the following ones don´t rely on three-axis custom machines but on hybrids cell and industrial robot arms for their material placement. This provides Arevo´s (Santa Clara, Calif., U.S.) the capability to achieve true 3D paths and z-direction reinforcement currently allowing the company to fabricate the direct-to-consumer Superstrata bicycles, the first fully continuous fibre bicycle frame produced of carbon fibre and PA, PEEK and PEKK. This method allows to fabricate fully freeform fabrication of monoblock parts at a large scale, yielding to the opportunity of replacement of metallic elements in architecture to reduce the overall weight and transportation cost associated. Mantis Composites (San Luis Obispo, Calif., U.S.), uses a five-axis FFF machine for the placement of 3D complex parts primarily made of carbon fibre and thermoplastics such as PEEK, though the materials vary per product.

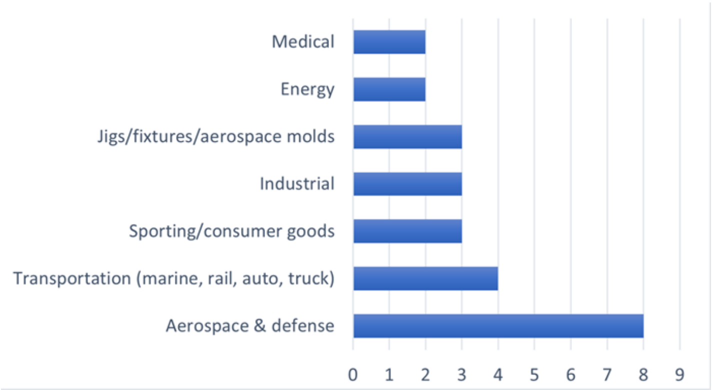


Fig 1.5.4: Top targeted markets. Based on responses to the CompositesWorld Magazine poll of 13 companies supplying continuous fibre 3D printing technology. Image Credit: CompositesWorld Magazine

An Ingersoll Machine Tool (Rockford, IL, U.S.) system uses a dual-head multi-axis robotic continuous filament system to create complex 3D shapes and to embed continuous fibre reinforcement over existing structures through overprinting. Additional options include an external axis turntable and an additional nozzle for printing support and locating structures. The ORB 1 system from Orbital Composites (San Jose, Calif., U.S.) operates with in-situ impregnation and FFF nozzles to process PA, PEI, PPS and PEEK, along with thermosets reinforced with CF (3K to 100K tow), GF, metal wires and fibre optics. Several larger systems are being developed on the modular platform to allow easy scalability, being the technology employed by this technology the one that allow the higher fiber count integration among their competitors.

CEAD's (Delft, Netherlands) Continuous fiber Additive Manufacturing (CFAM) Prime cell is gantry-based, while its AM Flexbot is robot-based. Both combine pellet extrusion with unidirectional (UD) tapes.Both systems allow to a certain extent the volumetric print cell size for producing architectural elements as pieces subdivision (2x2x4 meters) as proved in it recent association with the Royal HaskoningDHV (Amersfoort, Netherlands) and DSM (Heerlen, Netherlands) that allow them to print a GF/PET (polyethylene terephthalate) prototype bridge, including chopped and continuous fibres. Stating as future development the launch of a larger version of their systems.
A continuous fibre 3D Printing (CF3D) system from Continuous Composites (Coeur d'Alene, Idaho, U.S.) impregnates continuous dry fibres in-situ with liquid thermoset resin in a print head, displacing a wetted tow before snap-polymerization by a high-intensity cure source. This solution allows the use of a variety of dry continuous fibres - including wires and fibre optics - and snap-curing resins developed in partnership with Arkema (Colombes, France) and its Sartomer subsidiary. The above company holds in actually more than 70 patents in the field of continuous fibre 3D printing, established as the leading developer of the topic.

With a similar approach, MOI composites' (Milan, Italy) Continuous fibre Manufacturing (CFM) technology uses an inline impregnation method or 2-pass extrusion for continuous fibres and thermoset resins. To date, its largest print is the 6.5-by-2.25-meter MAMBO (Motor Additive Manufacturing BOat), printed in GF and vinyl ester with partners such as Autodesk, Owens Corning and Catmarine Shipyard. Being this, the biggest object printed with this technology.

The later three companies stay as the accounting ones with a deposition method that is enoughly developed and in a curated state that could allow the fabrication of composite larger parts.

1.6. Methodologies & applications

Several academic institutions accounted as Digital Structures Group and MediaLab at MIT, ICD ITKE, Gramazio Kohler research group and Laboratory of Composite Materials and Adaptive Structures, among others have researched on the geometrical capabilities of lattices structures with additive manufacturing or sequential assembly and its high load-bearing capabilities to material per weight. Newer geometrical path-planning approaches allow for irregular lattices which are even more optimized for strength to weight ratios. “Developing new processes for the application of lightweight materials in construction, such as prefabricated pre-finished volumetric construction, can further facilitate off-site fabrication” (MGI, 2017).

1.7. Structural performance and 3d printing

Truss structures and space frames have long been the preferred solutions to the problem of maximizing structural efficiency, as they allow to multiply in the flexural rigidity and loadbearing capacity achievable from a given amount of material (Woods, 2017). Systems assembled from basic components that make up structures featuring multiple elements have been used only to a very limited extent in architecture and building construction, “One of the primary drawbacks of existing truss structures is the difficulty and expense of manufacturing them from separate individual members“ (Woods,2017). One of the primary drawbacks of existing truss structures is the difficulty and expense of manufacturing them from separate individual members, often numbering in the dozens, hundreds, or even thousands, which require to be individually attached together at a series of nodes. By utilizing carefully-oriented bar-type elements, the material can be directly aligned with the carried load and in situations where little material is required for the stress constraint, (J.Solly 2018) That geometrical complexity could be achieved with additive manufacturing techniques.

1.8. Patents

Although the listed patents don´t correspond to the total of inventions or manufacturing methods in the field associated with this research. The following one is intended to provide a general description of key points processes, as some of the claimed subject matter in each patent is determinant for the tools and processes developed in this experimental based part of the research. The open-tool development conducted through experimentation is an expected contribution and should avoid any patent collision. The patents in AM of continuous fibre reinforced composites presented here are classified into two fields: patents related to continuous fibre technique methods and patents on application methodology, related to or with the possibility to influence the construction industry.

Continuous fiber patents

- **U.S. Patent No. 9511543-B2**
  The patent “Method and Apparatus for Continuous Composite Three-dimensional Printing” describes a fabrication approach of manufacturing dual or multiple materials using a path-following strategy rather than a slicing one. Focusing on the usage of composite materials with UV light hardening of the curable liquid resin. The path planning strategy follows a multipath construction method for producing three-dimensional objects. Held by Continuous Composites Inc- Cc3d LLC (United States Patent No.US-9511543-B2. 2013).

- **U.S. Patent No.20220009163**
  The patent “Control Methods For Additive Manufacturing System” describes material control methods for selective curing of discharged material along trajectory deposition included in the system a secondary workflow of deactivation of such system for controlled deposition. Held by Continuous Composites Inc- Cc3d LLC (United States Patent No.US-20220009163. 2021).

- **U.S. Patent No.20160144565**
  The patent “Methods for composite filament threading in three-dimensional printing” describes a step process or additive manufacturing of a part that includes supplying an unmelted void-free fibre reinforced composite filament including one or more axial fibre strands extending within a matrix material of the filament, having no substantial air gaps within the matrix material. a.Held by MARKFORGED, INC. LLC (United States Patent No.US-20160144565. 2014).

- **U.S. Patent No.20210370594**
  The patent “System And Print Head For Continuously Manufacturing Composite Structure” describes a hardware system to discharge a continuous fibre reinforcement coated matrix as part of a print head mechanism. The system described contains a matrix reservoir for the material coating as well as several sensors along with the system on a pulltrusion print head. Held by Continuous Composites Inc- Cc3d LLC (United States Patent No.US-20210370594. 2021).

- **U.S. Patent No.10232551B2**
  The patent “Head and system for continuously manufacturing composite hollow structure” discloses a print head for the manufacture of hollow structures with continuous matrix-coated fibre passing through a fibre guide head. Held by Continuous Composites Inc-Cc3d. (United States Patent No.US10232551B2, 2016).

Application methods patents

- **U.S. Patent No.10363704-B2**
  The patent “Systems and Methods for Determining Tool Paths in Three-dimensional Printing” describes a methodology for printing three-dimensional objects, the parametric

trajectory calculation of 3D toolpaths on a complex curved surface in an automated fashion.(United States Patent No.US-201816052945-A, 2019).

- **WO 2017085649 A1**

  The patent" Apparatus and method for three-dimensional printing of continuous fibre composite materials" describes both apparatus and method for three. dimensional printing with the usage of continuous fibre directly fed in the print head which deposition if exerted by the drawing force of the three-dimensional object.The application was field by Levi Marinella, Natale Gabriele, Postiglione Giovanni in 2016-11-17 Politecnico Di Milano (Internation patent WO2017085649A1)

- **U.S. Patent No. 7641461 B2**

  The patent US 7641461 B2, "Robotic systems for automated construction", specifies a mechanical system composed of a frame describing a large scale 3D printer for construction. The robotic system may further include a position controller configured to control the position and movement of the gantry robot and the nozzle assembly. (United States Patent No. US 7641461 B2, 2010).

- **U.S. Patent No. 5121329**

  Held by Stratasys Inc., the Patent describes an "Apparatus incorporating a movable dispensing head provided with a supply of material which solidifies at a predetermined temperature, and a base member, which are moved relative to each other along "X," "Y," and "Z" axes in a predetermined pattern to create three-dimensional objects by building up material discharged from the dispensing head onto the base member at a controlled rate." (United States Patent No. US 5121329, 1992)

  This Patent has currently expired. This patent expiration is considered one of the main starting development points of open-source FDM technologies and the community development of the Reprap project. FDM technology can be considered the basis of large scale additive manufacturing using thermoplastics.

- **U.S. Patent No. 5402351 A**

  The patent "*Model generation system having closed-loop extrusion nozzle positioning"* discloses methods and apparatus for fabricating three-dimensional objects which geometrical model definition is memory stored. The memorized definition includes steps of tool fabrication movement, support and unsupported path generating feedback of the prior fabricated portion of the object.

  The patent was filed 18th January 1994 and published 28th March 1995 by International Business Machines Corporation (IBM) holding John S. Batchelder, Huntington W. Curtis, Douglas S. Goodman, Franklin Gracer, Robert R. Jackson, George M. Koppelman, and John D. Mackay as the inventors (United States Patent No. US5402351 A, 1995).

- **U.S. Patent No. 11230032**

  The patent "*Cable-driven additive manufacturing system"* discloses A cable-driven additive manufacturing system includes an end effector configured for linear translation within a three-dimensional workspace, an aerial hoist suspending the end effector by at least one suspension cable, a plurality of base stations disposed below the aerial hoist, and control cables running from each of the base stations to the end effector.

The patent was filed 12th April 2019 and published by Oak Ridge National Laboratory (ORNL) and UT-Battelle, LLC (UT-BATTELLE) (United States Patent No. 11230032, 2019).

A majority of the patents under the field of continuous fibre in AM sits on the inclusion of methodological and hardware implementation on material deposition technologies being Continuous Composites the world's earliest granted patents owners on CF3D®. The company continues to emphasize patent protection and currently holds 75 granted U.S. Patents and 30 granted international patents establishing a hold on companies in the use of the cited processes as shown in the patent file lawsuit against competitor Markforged, Inc. The different patents on robotic systems for AM in construction expose the rise in interest for research innovation in the field rather than backward the applications of specific processes.

1.9. Conclusions

2. High performance in construction, frame of reference

2.1. Implications of new materials approach

These so-called high-performance materials have properties large beyond the traditional materials used in the construction industry and are difficult to justify the usage of those in a low-performance field as architecture compared to aerospatial engineering fields. Therefore it is important to consider how these materials could influence the architectural form and function, expanding possible geometrical vocabulary led by this new to use generation of materials.

The use of high-performance materials opens up new avenues for developing new geometrical elements suited for specific architectural contexts that are not possible with other manufacturing techniques, such as traditional manufacturing or prefabrication.

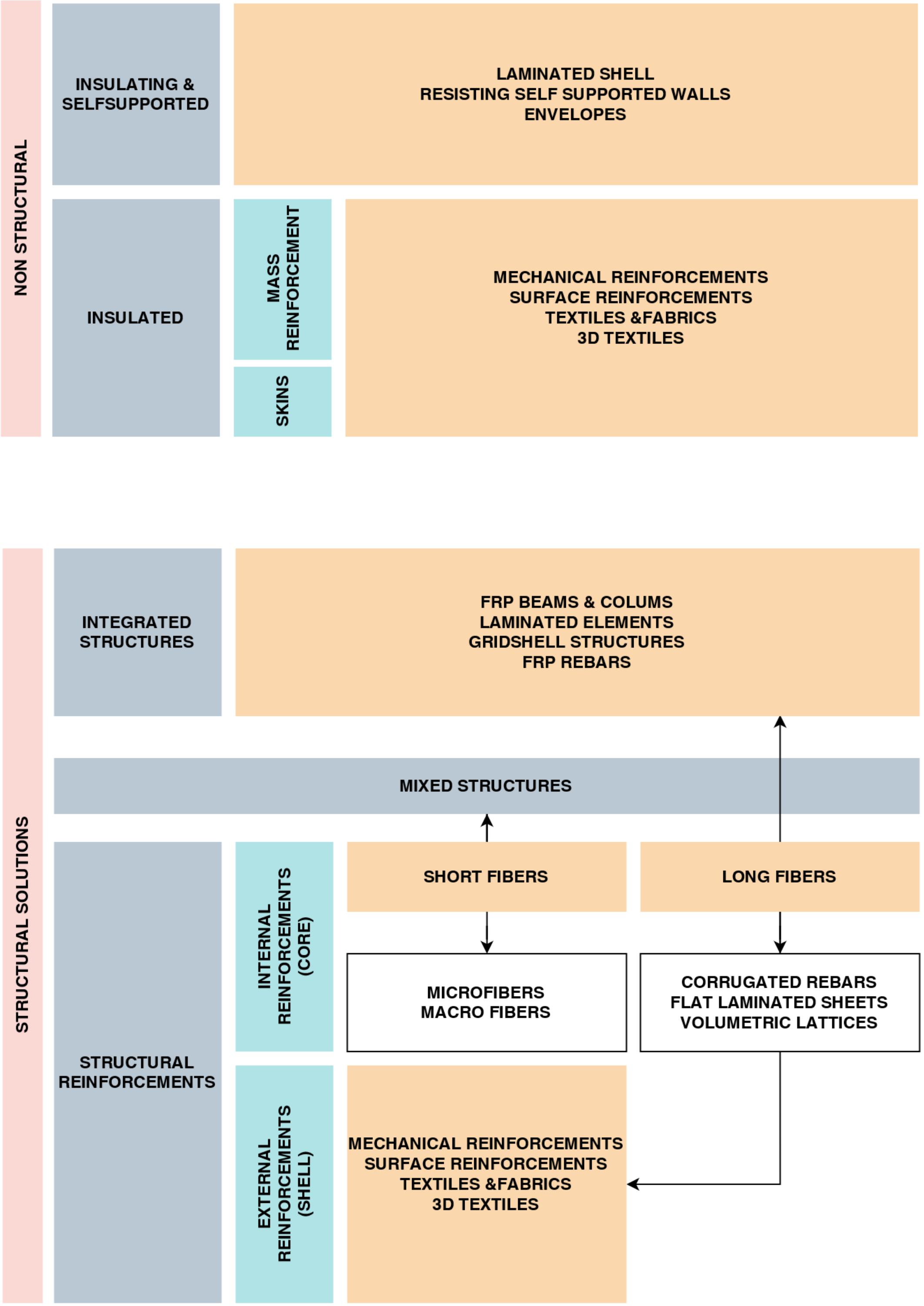


Fig 2.1.1: Usage of FRP in construction diagram

2.2. Automatization processes

2.3. Critical analysis of possible adoptions

2.4. Technologies, materials, catalogues

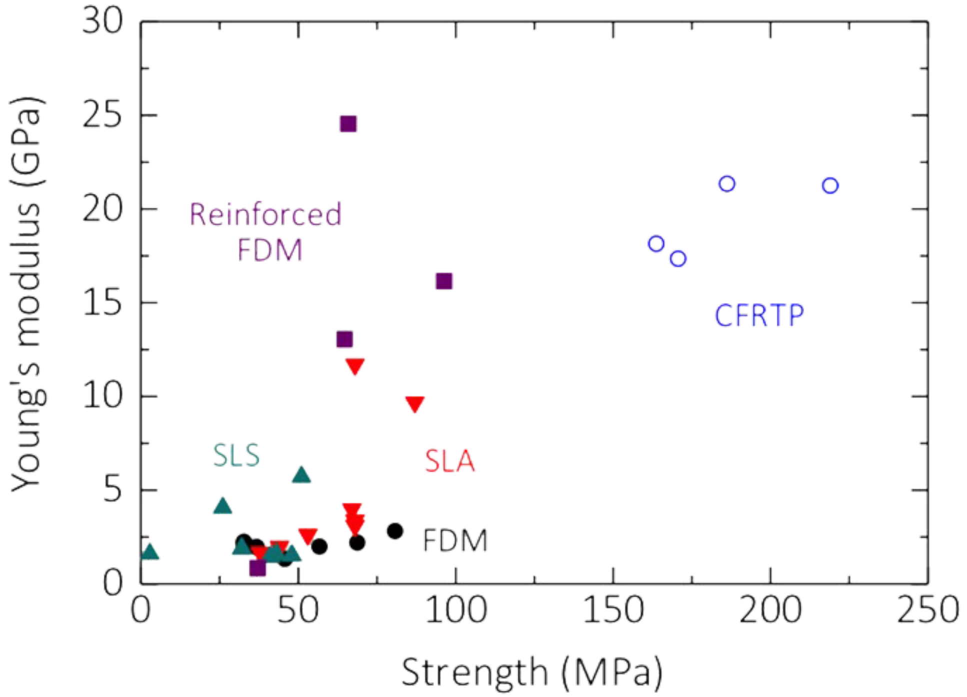


Fig 2.4.x: Additive manufacturing techniques physical properties analysis. Source:Omuro, 2017

2.5. 3d printing opportunities

2.6. Conclusions

3. Composite additive manufacturing materiality in architecture

Composites are materials comprised of strong load-carrying materials (known as reinforcement) embedded in a weaker material (known as matrix). Where the fibre reinforcement endorses the strength and increments the rigidity, accounting for the major structural load support. The matrix, or resin, preserves the position and orientation of the fibre reinforcement, balances loads between the elements, encapsulates the fibres against environmental degradation, and establish the main position, form and shape of the structure.

3.1. Material selections
3.2. Catalogue of performance and adequation
3.3. Description and results
3.4. Methodology for testing
3.5. Fabrication adequation
3.6. Conclusions

4. Fabrication

4.1. Introduction

In this chapter, we will analyze the limitations of current 3D printing processes and how they can be improved upon newer underdevelopment approaches to create high-performance 3D printed structures through the use of robotic arms manufacturing. Building on this methodology, towards the implementation into robotic fabrication, the 3D printing process is the end effector also known as a tool that does the work of the robot.

4.2. Existing technologies

- Mold implementation in actuality AFP/ATL
- Curing processes

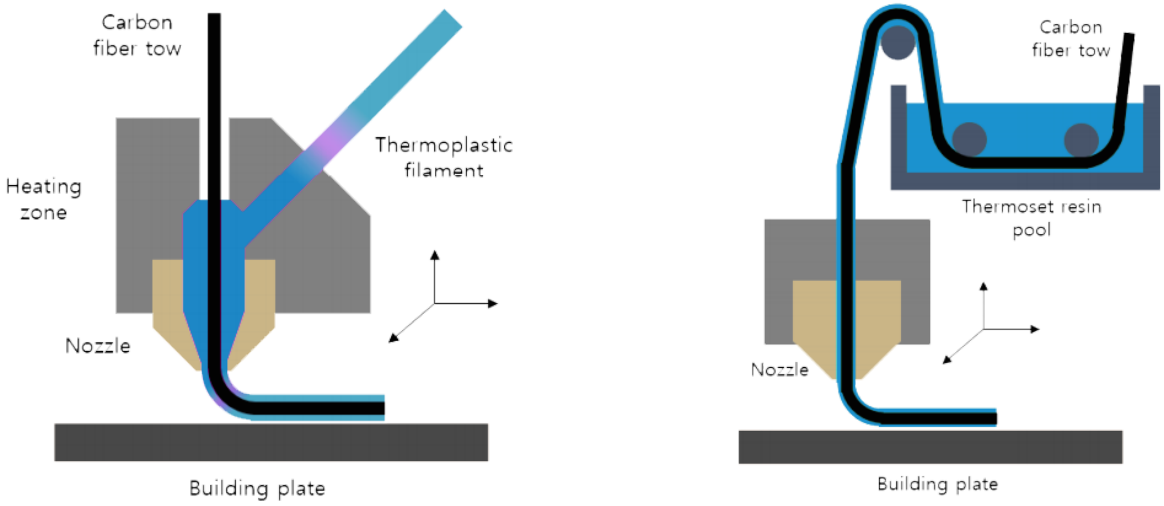


Fig 4.2.x: CFRP & CFF3D diagramatic material deposition techniques, respectively. Source: ????

4.3. The methodological approach based on material selection

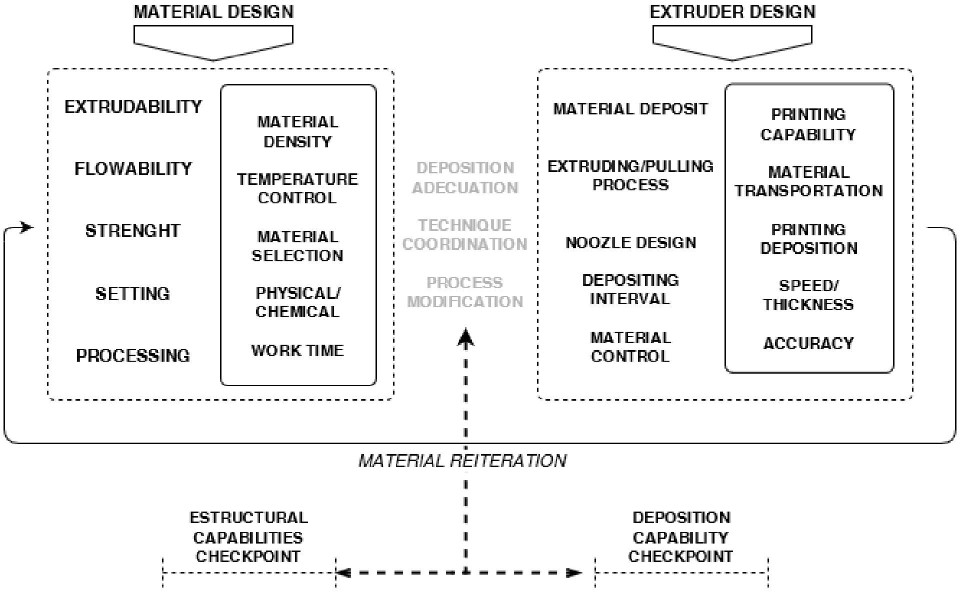


Fig 4.3.x: Material-Fabrication informed selection flow chart

4.4. Characterization and design concerns associate with fabrications processes

4.5. Tools development

This chapter describes the development of the tools developed along with this thesis that allow to demonstrate the feasibility of these techniques at a hardware level. Several methods and apparatus for continuous fibre manufacturing have been developed in consequence of this research adapting highly technical and non disclose industrial methodologies.

Two “families” of extruders can be found to allow this characterization to be separated by the main binder material processed in the composite. Being those categorized into two families, thermoplastics and UV curing thermosets.

Both technologies shared common grounds as they have been designed from scratch with several beta versions and iterations behind each one of those, leading to the finalized presented tools. This common ground is worth to be mentioned as the goal of user-friendly and open-source hardware (OSHW) has characterized their development. Stablishing the opportunity for other researchers to take the aforementioned endeffectors research and replicate it. Serving as a proof of concept research tool that allows further investigation on design for fiber integrative methods with ability for others freely use and edit it.

The major drivers of this endeffector investigation are stated below:

- The designs leading to the presented output are publicly available at the stage of this research publication, which encompasses the general public access intention of the knowledge gained through its development.
- The hardware comprising the source is made from other OSHW.
- Using readily available components found in the commercial industry, using standard fabrication processes such as 3d printing, CNC milling and laser cutting for the material transformation that could be studied, modified, distributed and reproduced to maximize the ability of individuals to make and use hardware.
- Avoiding any possible patent infringement in the development of the thesis as the date as this is presented publicly.
- Any possible code controlling this hardware is easily accessible for manipulation and modification for its adaptation or adjustment.

4.5.1. Thermoplastics extruders

4.5.1.1. Thermoplastics single strain V.1

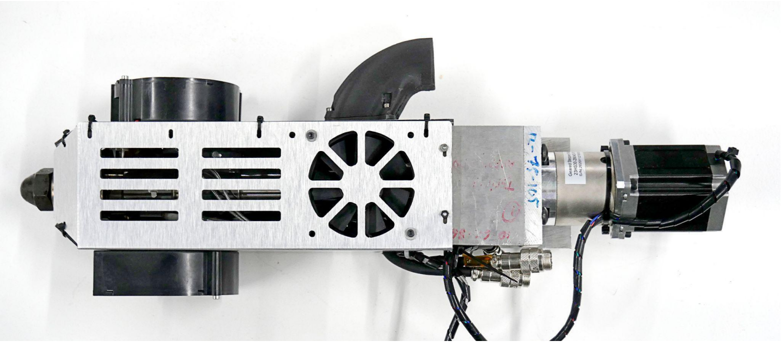


Fig 4.5.1.1.1: Continuous fibre high flow pellet extruder

4.5.1.2. Thermoplastics multiple strain

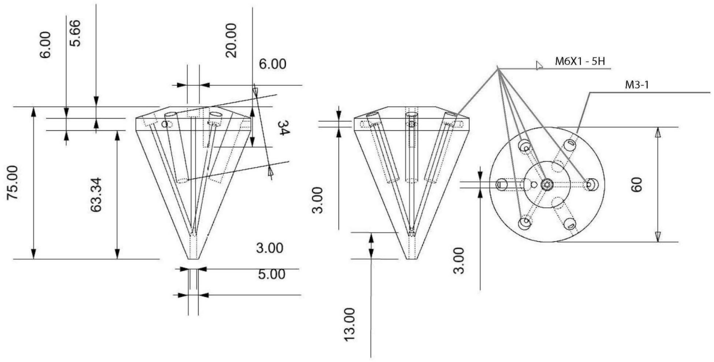


Fig 4.5.1.2.1: Converging filament continuous fibre impregnation nozzle plans

4.5.2. UV Curing resin extruders

This section details the fabrication development of a hardware extruder for ultraviolet (UV) light-assisted additive manufacturing deposition modeling method. Being the deposited material a compound material composed of a fibre reinforcement, in this scenario glass fiber (GF) and carbon fiber (CF) filaments which are bonded together with a UV reactive epoxy or acrylate base matrix material.The entire approach is based on the continuous bath impregnation of a dry yarn of fiber in a photosensible resin by a pulltrusion force and it´s later consolidation with the assistance of a UV light source irradiation as activator of the polymer. The final polymeration and crosslinking reaction comes either from a catonic reaction initiated by the initial polymeration or bya re-irradiation secondary treatment of the pre-cured material. Based on this, the entire approach consists on the additive deposition of acontinuous fiber resin composite, which is rapidly consolidated upon exiting the printer nozzle to form a solid three-dimensional (3D) composite.

Herein, the UV deposition method, material bonding and consolidation methods techniques used on the development of the extruders a explained.

In the instance of continuous fiber UV 3D printing, UV resin irradiation with its snap-curing polymerization provide a fast, feasible, and effective cure solution.

4.6. Workflow analysis and characterization

4.7. Technologies limitations and possible best cases applicability

Both two different developed extruder types, thermoset and thermoplastic, have obvious limitations in terms of deposition accuracy, deposition speed and long term reliability. Those limitations are therefore limitations inherent to the academic research facilities serviced on this research and could be easily troubleshoot at an industrial level with the appropriate or heavy industry equipment & facilities. Being the focus of this work develop extruders to serve as an opensource, low-cost variant of highly technical extruders currently in development or patented as stated in chapter 1.5 of this research.

5. A computational geometric approach based on fabrication and material constraints

An integrated structural computational design workflow is proposed for continuous fibre integration. The chapter also describes the related algorithm implementations.

5.1. Introduction

The chapter of the research starts with the implementation of stress lines topologies on structural case study models, seeking attributes that could be merged or reinterpreted with similar approaches on a geometrical basis of structural performance currently employed in the construction industry or under research at the architectural academia. In this aforementioned modelling workflow, in contrast to conventional cad - cam workflows, where the fabrication model is usually treated as a separate entity, the geometrical model is deeply driven by the structural load flow of the Finite Elements Method (FEM) analysis among its constituent parts and integrated through fabrication aware syntax with tridimensional interconnecting members in post of an efficient material deposition organization. Giving, as a result, variation of the cellular topologies, which respond to structural needs. In this custom process, the organization and fabrication data is deeply integrated into the geometry and design model, triggering alignment path-planning strategies.

5.2. DFM in architecture

“In architecture, functionality is still mainly achieved through the addition of functionally discrete elements. The use of fibre composites with its strong bond between the matrix and the fibres, allows designing functionally graded materials on a macro-level” (Schwinn, 2016). The integration of different winding types as well as, varying the fibre matrix ratio or even the matrix constituents,per the use of additive fabrication process allows us to specifically design local material properties with the aim of producing functionally integrative lightweight structural parts. “This system allows a high degree of adaptability and performance due to the differentiation of its geometric components” (Schwinn,2016). In contrast to conventional cad-cam workflows, where the fabrication model is usually treated as a separate entity, design for manufacturing workflows based on fabrication constrains implies the adequation of the continuous fibre placement. "In the parametric design workflow, the syntax becomes the interface between design, analysis, and fabrication through the algorithmic description of the winding sequence: its digital representation then serves as the input for the finite element (FE) formfinding simulation and structural analysis".(Schwinn 2013) By utilizing carefully-oriented bar-type elements, the material can be directly aligned with the carried load and in situations where little material is required for the stress constraint, (J.Solly2018)

5.3. Integrative structural optimization design workflows for continuous fibre fabrication approaches

A mixed technique of spatial frame also called spatial lattices (ref) together with stress lines reinforcement produced by topological optimization as geometry driver, is proposed for the usage of continuous fibre manufacturing, In this morphological driven process, the fabrication is controlled at each point on the digital volume of a target mesh using a topology optimization analysis, where the major stress lines flowing through the analyzed initial shape have direct to model translation and overall connection of the in though lattice reinforcements. This technique enables efficient fabrication on the material usage of complex geometries with high volumetric dimensions (large parts), whilst taking advantage of generative design principles to produce structurally optimized parts.

The topology optimization analysis as part of the design workflow proposed uses finite element analysis and stress line additive manufacturing (SLAM) techniques already proven to be “highly compatible with additive manufacturing of structurally-performative design prototypes by FDM”{Naboni2019} although the cited research only focuses on the feasibility of traditional catenary and single shell element, the study exposes clear interrelation of increased structural performance based on the additive deposition path and the potential to embedded local parameter variation of those enabling structurally-performative and geometrically-compelling geometries upon the improvement of the path generation technique.

Allowing the cited process, for an equally interconnected, geometrical fluidity embedded in the free-form extrusion capabilities inherited to AM technologies and its structural capacity usually emended by the usage of performative materials and not by the deposition methodology of it.

This under-development workflow will be tested by fabricating probes of traditional architectural elements, accounted as beams and columns, which volumetric geometry stress line flows are combined with a pseudo-patterned lattice structure to ensure structural stability, in the quest of enhancing the material efficiency of the optimized geometrical design of the initial target geometry whilst taking into consideration additive manufacturing constraints.

To achieve the desired design optimization, HPFS3D employs a novel adaptive design workflow that allows selecting optimal geometric print toolpaths, balancing fabrication and structural performance during the design process to maintain an optimal balance between material amount and strength throughout the print process.

5.4. Software capabilities and robotic arms integration

The continuous fibre-reinforced additively manufacturing methods for topological optimization structures with robotic path planning depositions strategies is discussed over this chapter

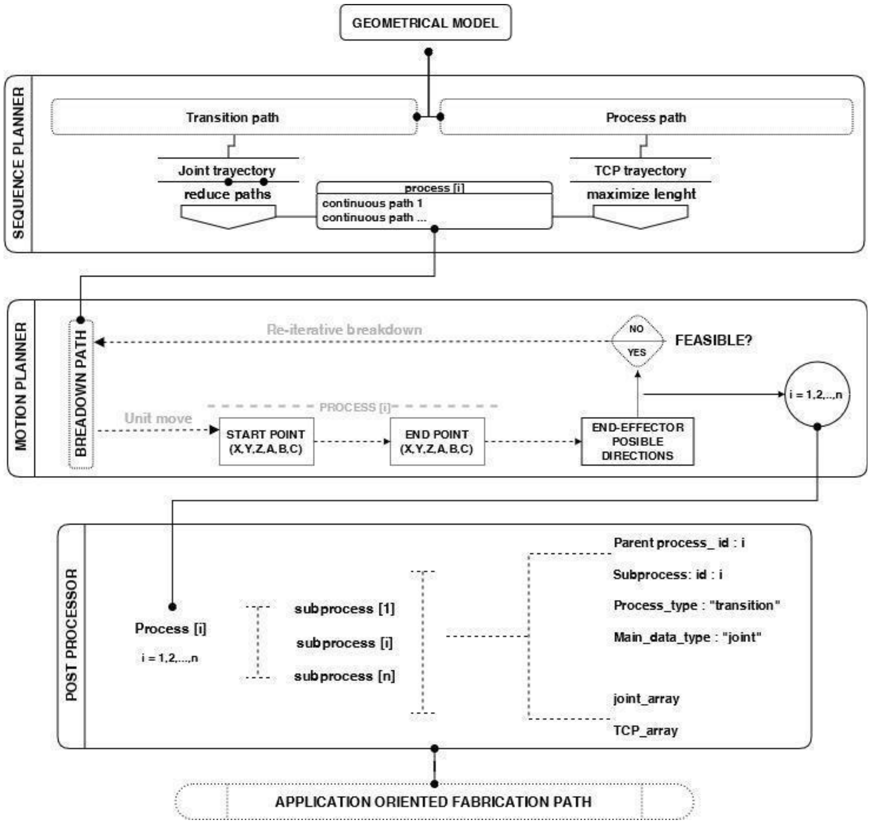


Fig 5.4.x: Geometrical dispatchement for fabrication flow chart

5.5. Design approaches considerations

5.6. Technical computational factors

5.7. Native design suites to fabrication processes integrations

5.8. Structural validation of models

To overcome the proposed model's structural validations challenges, the path geometry generated is debugged through a reiterative process of structural analysis- path generation - sequential ordering of the path planning strategies to the later confirmation of the structural analysis as valid output by several iterations of load testing and finite element analysis comparison. Whether in this model is identified that three-point joint load case algorithms models out-performs the one-point joint calculation in all the tested approaches.As the load is distributed evenly among the under compression nodes of the forced. This comparison is directly correlated to the physical tested specimens whether the higher distribution of the load is allocated among multiple nodes the probes manifest better holding capabilities.

5.9. Material characterization and performance digital models

6. Design protocols

6.1. Viability methodology

A performance-based categorization, pursued in this chapter on geometry aware topological structural analysis as a driver of integrative design modelling tools, based on fabrication and material process is conducted in order to identify the possible architectural applications or constraints. The number of geometrical test does not seem to be statistically significant, but these geometrical demonstrators do suggest that the geometrical design methodology ought to be explored further.

The probed design workflow lead to improvement in the weight by material usage performance compared to more traditional AM methods or continuous fibre integrations.

Presenting included in this research, various computational design protocols of geometrical implementation form-finding, based on the structural behaviour of geometric spatial lattice output analyzed models.

6.2. Conclusions

6.3. Multimaterial

6.4. Implementation guidelines

6.5. Structural performance comparison

7. Designed workflow analysis

7.1. Adoption of technologies in construction industry possibilities

This chapter analyzes the implementation of high performance spatial frame 3D printing through two case studies: one is for architectural structures, where it is applied to optimize the design of a building façade; the other is for lightweight structural elements, where the objects manufactured work as a bearing load component.

7.2. Case study catalogue based on applications

8. Contextualized findings

This chapter will address the the findings of the presented research that come from development of the artefact production as an analysis of construction cost, assessing the quantitative outcomes of the design protocols methods used as part of the conceptual framework of AM applicability for structural architecture applications of composites. As well as a critical review of the state of the art of both historical and contemporary literature on implication of composite AM among construction site,operation and fabrication models.

8.1. Structural performance-automatization of processes

8.2. 3d printed Composites in architecture

8.3. Economic impact

8.4. Sustainability

9. Conclusions and outlooks

9.1. Conclusions

9.2. Future work, space of improvement

10. Research Overview

11. List of Graphs

12. List of Tables

13. List of Acronyms

The acronyms listed below are common terminology in the field and are stated here as widely employed in the development of this thesis.

A

ABS Acrylonitrile-Butadiene-Styrene

AM Additive Manufacturing

AFP Automatic Fibre Placement

ATL Automatic Tape Layering

B

C

CAD Computer-Aided Design

CAM Computer-Aided Manufacturing

CLF Continuous Lattice Fabrication

CF Carbon fibre

CFAM Continuous fibre Additive Manufacturing

CFM Continuous fibre Manufacturing

CFF Continuous Filament Fabrication

CFR Continuous fibre Reinforcement

CFRP Continuous fibre Reinforced Printing

CFRP Carbon fibre Reinforced Plastic

CNT Carbon Nano Tube

CSG Construction of Solid Geometry

D

DED Direct Energy Deposition

DF Digital Fabrication

DLP Digital light processing

E

F

FDM Fused Deposition Modeling

FFF Fused filament fabrication

FILL 100 Glass fibre 100 μm

FILL 200F Glass fibre 200 μm

FM fibre Matrix

FRC fibre Reinforced Composites

FRP fibre Reinforced Plastic

G

GF Glass fibre

GFRP Glass fibre Reinforced Plastic

GLY Glycerol

H

I

ISO International Organization for Standardization

ISC In Situ Consolidation

J

K

L

LDM Liquid Deposition Modeling

LS Laser Sintering

M

MJ Material Jetting

MJM Multi Jet Modeling

N

NDI Non-Destructive Inspection

NURBS Non-Uniform Rational B-Splines

O

OBJ Object File

OSHW Open Source Hardware

OS Open Source

P

PA Polyamide or Phthalic Anhydride

PEEK Polyetherketoneketone

PET Polyethylene Terephthalate

PJ PolyJet

PLA Polylactic Acid

PVA Polyvinyl Alcohol

Q

R

RDFO Random Discontinuous fibre Orientation

RE Reverse Engineering

RP Rapid Prototyping

S

SMA Shape Memory Alloys

SCM Spiral Cylinder Model

SFR Short fibre Reinforcement

SL Stereolithography

SLA Stereolithography Apparatus

SLAM Stress Line Additive Manufacturing

SLS Selective Laser Sintering

STL Standard Triangulation Language

T

3DP Three-Dimensional Printing

TPU Thermoplastic Polyurethane

U

UD Unidirectional fibres

V

W
X
Y
Z

14. List of Definitions

The definitions listed below are used terminology in the field and need further explanation. As the definition might have possible interpretation depending on the author of consultation and therefore need to be stated through a critical analysis of the definition per se and interpreted among how the author defines its meaning during the development of this thesis as they set up the basis of this research.

High performance

Freeform

Additive manufacturing

3D printing

Spatial lattice

Spatial matrix

Spatial frame

Materiality

Structural

Optimization

15. List of Figures

16. Bibliography

Geometry Articles/Research Papers

- Woods, B., Hill, I. and Friswell, M. (2016). Ultra-efficient wound composite truss structures. Composites Part A: Applied Science and Manufacturing, 90, pp.111-124.

- Solly, J., Früh, N., Saffarian, S., Aldinger, L., Margariti, G. and Knippers, J. (2019). Structural design of a lattice composite cantilever. Structures, 18, pp.28-40.

- Schwinn, T., La Magna, R., Reichert, S., Waimer, F., Knippers, J., Menges, A.: (2013), Prototyping Biomimetic Structures for Architecture, in Stacey, M. (Ed.), Prototyping Architecture: The Conference Papers, Building Centre Trust, London, 2013, pp 224-244. (ISBN 978-0-901919-17-5)

- Marin, Philippe & Philippe, Liveneau & Blanchi, Yann. (2012). Digital Materiality: Conception, fabrication, perception.

- Beorkrem, C. (2013) Material strategies in digital fabrication. Routledge, New York

- Soar, R. and Andreen, D. (2012). The Role of Additive Manufacturing and Physiomimetic Computational Design for Digital Construction. Architectural Design, 82(2), pp.126-135.

- Menges, A. (2012). Material Computation: Higher Integration in Morphogenetic Design. Architectural Design, 82(2), pp.14-21.

- Tam, Kam Ming Mark, Caitlin T. Mueller, James R. Coleman, and Nicholas W. Fine. 2016. "Stress Line Additive Manufacturing (SLAM) for 2.5-D Shells." *Journal of the International Association for Shell and Spatial Structures* 57 (4): 249–59. https://doi.org/10.20898/j.iass.2016.190.856.

Material -Fabrication Articles/Research Papers

- Eichenhofer, Martin, Jesus I Maldonado, Florian Klunker, Paolo Ermanni, Composite Materials, fibre Composite Extrusion, Free Form Structures, and Thermoplastic Composites. 2015. "Analysis of Processing Conditions for a Novel 3D-." *20th International Conference on Composite Materials*, no. July: 19–24.
- Invernizzi, M., Natale, G., Levi, M., Turri, S. and Griffini, G. (2016). UV-Assisted 3D Printing of Glass and Carbon fibre-Reinforced Dual-Cure Polymer Composites. Materials, 9(7), p.583.
- ZOCCHI G.(2016), New Developments in 3D Printing of Composites: Photocurable Resins for UV-Assisted Processes, Department of Chemistry, Materials, and Chemical Engineering
- Moi Composites (2018) Continuous fibre Manufacturing (CFM) for 3D Printing.Moi Composites.Politecnico di Milano
- Gaikwad, Ajay & Kenjale, Akshay & Bhosale, Ajinkya & Dumbre, Tushar & Arakerimath, Rachayya & Roy, Sajal. (2015). Design Analysis & Manufacturing Of Carbon Composite Isotruss For Bending Analysis. IJEMR. 133-136.
- Omuro, Ryo, Masahito Ueda, Ryosuke Matsuzaki, Akira Todoroki, and Yoshiyasu Hirano. 2017. "Three-Dimensional Printing of Continuous Carbon fibre Reinforced Thermoplastics by in-Nozzle Impregnation with Compaction Roller." *ICCM International Conferences on Composite Materials* 2017-Augus (August): 20–25.

Construction industry Articles/Research Papers

- Kroner, W. (1997). An intelligent and responsive architecture. Automation in Construction, 6(5-6), pp.381-393.
- Grosso Stegna,L.,Meinero,D., Volontà,M.,(2019) Reinventing construction through a productivity revolution. CECE
- MGI: Barbosa F., Woetzel J. , Mischke J. , Ribeirinho M.J., Sridhar M., Parsons M. ,Bertram N. , Brown S.(2017) MGI Reinventing Construction Full Report.
- Pan, Yifan, and Yulu Zhang. 2021. "3D Printing in Construction: State of the Art and Applications," 1329–48.
- Analysis, Smart Tech. 2018. "3d Printed Composites Materials Markets." https://www.smartechanalysis.com/reports/3d-printed-composites-materials-markets-2018/.

Design protocols Articles/Research Papers

- Hermann, C. (2004). Branko Kolarevic, ed.—Architecture in the Digital Age: Design and Manufacturing. Nexus Network Journal, 6(2), pp.131-134.

- Rusenova, G., Wittel, F., Aejmelaeus-Lindström, P., Gramazio, F. and Kohler, M. (2018). Load-Bearing Capacity and Deformation of Jammed Architectural Structures. 3D Printing and Additive Manufacturing, 5(4), pp.257-267.

- Hacka,N., Wanglerb,T., Mata-Falcónc,T., Dörflera,T., Kumard,N.,Nikolas Walzera,A., Grasere,K.,
  Reiterb,L., Richnerb,H., Buchlid,J., Kaufmann,W., J. Flattb,R., Gramazioa,F., Kohler,M.(2017) , Mesh Mould: An On-Site, Robotically Fabricated, Functional Formwork. Chair of Architecture and Digital Fabrication, Department of Architecture, ETH Zurich

- Hack, N., Lauer, W.V.: Mesh-mould: robotically fabricated spatial meshes as reinforced concrete formwork. Archit. (2014)

- Braumann, J., Brell-Cokcan, S., (2015) Adaptive Robot Control New Parametric Workflows Directly from Design to KUKA Robots, University for Arts and Design Linz2Robots in Architecture | RWTH Aachen University

- Ginger Gardiner. (2020). 3D printing with continuous fibre: A landscape | CompositesWorld. *CompositesWorld Magazine*, (November), 24–26. Retrieved from https://www.compositesworld.com/articles/3d-printing-with-continuous-fibre-a-landscape

17. Appendix