ALMA MATER STUDIORUM-UNIVERSITA DI BOLOGNA
SCUOLA DI INGEGNERIA E ARCHITETTURA

**Corso di Laurea Magistrale in**

**Ingegneria dei Processi e dei Sistemi Edilizi**

**Curriculum Historic Building Rehabilitation**

# APPLICATIONS OF ADDITIVE MANUFACTURING IN CONSTRUCTION AND HISTORIC BUILDING RESTORATION / REHABILITATION

**Tesi di Laurea Magistrale in Research on Historic Building M**

| | |
|---|---|
| **Relatore** | **Presentata da** |
| **Prof. Ernesto Antonini** | **Fuat Emre Kaya** |
| **Correlatori** | |
| **Prof. Michele Palermo** | |
| **Prof. Marco Pretelli** | |

**Anno Accademico 2019/2020**

**15/03/2021**

# Abstract

The term “Additive Manufacturing” is described as the layered production of parts from a 3D file. Over the past century, this technology has evolved from a complement tool for conventional product development into an independent production method. Whereas high technology industries such as aerospace and medicine were already embraced additive manufacturing, structural engineering and architecture are lagging. Additive manufacturing has the potential to revolutionize the construction and restoration of historic buildings, with foreseeable benefits including highly complex and efficient structures with the reduction in material use and wastage, streamlining and expedition of the design-build process, improved customization. However, there are also challenges and demands: a new way of thinking for design and verifications for stability and serviceability of printed elements, the cost, the need for well-educated engineers.

In this dissertation, the current state of additive manufacturing in construction and historic building restoration/rehabilitation is reviewed as a combination of qualitative and quantitative-based studies. The research aims to give confidence to additive manufacturing applicability in these fields and stimulate further research. The opportunities and challenges are discussed by analysing concrete, polymer, and metal-based processes and their applications of additive manufacturing in the construction sector. A review of structural and non-structural applications in restoration projects, possible future applications in terms of structural strengthening are analysed and opportunities and challenges are identified and discussed. Based on the literature review and experimental lab tests, the outcome was obtained as the tensile mechanical properties are adequate for structural engineering applications. However, further interdisciplinary research on additive manufacturing is necessary to build confidence in structural engineers and architects.

# Acknowledgements

Even though the master’s thesis is based on individual academic research, I could not arrive at the end of it without the help and guidance of many people.

Firstly, I want to express my gratitude to my thesis supervisor Prof. Ernesto Antonini. His knowledge, guidance, and insightful comments challenged me to get the best out of myself. Furthermore, I am very grateful to Prof. Michele Palermo for guiding me through the unfamiliar territory of wire and arc additive manufacturing. My sincere thanks to Prof. Marco Pretelli, for his expert insight into the restoration and conservation of historic buildings, and all the time he invested.

I am indebted to the generosity of Vittoria Laghi, who supported me in my internship even in the hardest periods of quarantine.

My sincere thanks to my mother Dr. Aysegul Tanriverdi Kaya, and to my father Prof. Dr. Murat Kaya who are always inspired me to pursue my career in the academic direction. Moreover, I would like to thank my sister Zeynep Sila Kaya for her love and support.

I want to thank Gorkem Muslu, Cansu Samsun, Esra Nur Eda Kucuk, and Pelin Kesim. Their infinite support and love were always with me.

I want to thank Enrico Cardillo, Maria Samareva, Zelan Li, Luisa Hammond, Remzi Mert Polatcelik, Berfin Tutku Ozcan, Ulker Basak, and Bensu Berk for their patience, kindness, and love. Finally, I want to thank my flatmate, Elisabetta Antonino for making me feel at home.

# Content

# Chapter 1

# Introduction

## 1.1 Motivation

Additive manufacturing (AM) technologies have been developing over the past three decades, and today 3D printers have become as common as 2D printers. This technology allows the building of objects efficiently and with reduced material waste. AM provides a significant level of geometric and material freedom; thus, virtually any desired shape can be designed and produced without being restricted to standard elements. This feature can reconsider standard construction parts like joints, I-beams, or other construction materials. According to Strauss (Strauss 2013), "*AM technology even allows us to engineer the parts integrally; for example, the functionality of a hinge could be derived from the material properties rather than from fittings, bolts, and joints added to the part. Additive methods allow for structures that are not realizable with the traditional manufacturing methods. AM can integrate complex functions into components without additional work expenditure. No longer taking place at the construction site, the assembly does in the virtual model*". (p.21) [1]. However, not all the construction parts or materials are possible or cost-effective to be produced by AM. For this reason, AM's possible applications are many, but some of them are still very challenging and not yet suitable for widespread application. Much research has been performed to implement AM in the construction industry successfully. However, only very few AM applications target the restoration field. This dissertation aims to discuss AM's opportunities in the construction sector and explore its applicability in the restoration of historical buildings.

## 1.2 Methodology and Approach

This thesis combines qualitative and quantitative-based studies; the data is obtained from reliable published sources and tests carried in the laboratory.

Following this first introductory chapter, Chapter 2 describes the current state of AM. The Chapter defines AM and describes AM's generic process step by step from the CAD file generation to the final physical model. The developments in AM throughout history are also discussed as well as its current state. A classification of the AM available technologies is finally drawn up, pointing out and discussing each class of processes' features and benefits.

---

[1] Strauss, 2013

Chapter 3 focuses on AM in the construction sector, analysing concrete, polymer, and metal-based processes, as they are the most utilized for applications in the field. A review of the existing concrete, polymer, and metal AM technologies is provided, then each of them is analysed with special regards to their implications within the building sector. Finally, opportunities and challenges are identified and discussed.

The main topic of Chapter 4 is AM in the restoration of historic buildings, especially rehabilitation of historic buildings, to strengthen structural elements. A qualitative approach is adopted due to a lack of available and reliable data sources regarding this topic. A review of possible structural and non-structural applications is provided, and potential applications are analysed, then opportunities and challenges are identified and discussed.

Chapter 5 adopts a quantitative approach by providing the results of a lab test campaign on specimens of metallic building elements shaped by the AM wire and arc technique. Brief information on the wire and arc additive manufacturing (WAAM) is provided. A comparison is then made for the mechanical properties (yield, ultimate strength, and modulus of elasticity) of conventionally and WAAM produced metal specimens. The data for the conventional and additive manufactured elements are derived from the literature review. Additionally, the detailed data issued from lab tests regarding the 0°, 10°, and 45° tensile properties of WAAM produced metal specimen are provided. The main output is to identify the level of strength and modulus of elasticity that WAAM can achieve, aiming at assessing its suitable applicability in the construction and restoration field.

This thesis in structural engineering and architecture explores the AM in building construction and restoration, aiming to encourage AM applications in these fields and stimulate further research.

# Chapter 2

# Additive Manufacturing Technologies

This chapter aims to introduce basic additive manufacturing concepts and generic manufacturing processes from design to application. It continues to discuss the developments in additive manufacturing throughout history and its current state. The chapter concludes with the classification of additive manufacturing technologies and their benefits.

## 2.1 Definition of Additive Manufacturing

Additive manufacturing is a term used to describe rapid prototyping or, more commonly, 3D printing. Rapid prototyping is used in various software, management, and manufacturing fields to define the rapid manufacturing process or part of the product before its release. However, rapid prototyping is no longer adequate to describe the new technologies developed in this field. For this reason, a Technical Committee within ASTM international has adopted the term additive manufacturing, aiming to better cover the widening use of rapid prototyping techniques and its permeation across various industrial sectors.

According to ISO/ASTM 52900(2015), additive manufacturing (AM) is defined as a "*process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies*" (p.9) [1]. This technology's basic principle is to fabricate a three-dimensional computer-aided design model (3D CAD) directly by avoiding planning and making a multi-step process. Therefore, the additive manufacturing process can be considered an alternative technique to the conventional manufacturing process, which involves moulding and shaping an object by subtractive processing.

## 2.2 Generic Process of Additive Manufacturing

AM involves many steps from virtual CAD description to a final physical model (Fig.1). In this part, each of these steps is explained. As shown in Table 1, the main steps are the CAD model's generation, the transformation of the CAD file to the acceptable format, file transfer to the machine, machine setup, the building of desired objects, object removal, post-processing, and application [1]. However, the process can be grouped or broken down to adapt to each case, and evolve with new technologies, while still following the same general order [2].

---

[1] ISO/ASTM 52900:2015, 2017

[2] Yang, Hsu, Baughman, Godfrey, Medina, Menon, Wiener, 2017

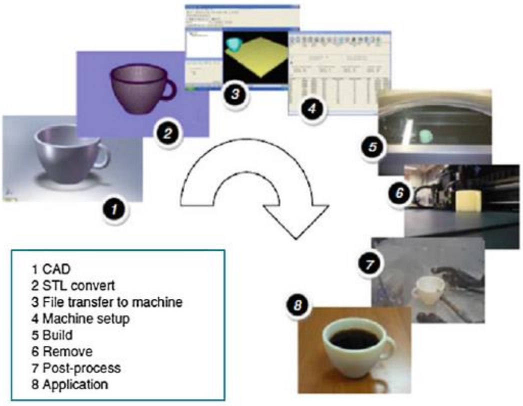


Figure 1: Additive Manufacturing Stages [1]

Table 1: Generic Process of Additive Manufacturing [1] [3]

| Step Name | Stage Output |
|---|---|
| Generation of CAD model of design | A 3D solid representation of external geometry |
| Converting of CAD file to STL format | STL format of the external closed surface of the object |
| STL file transformation to machine | Transferred STL format with corrections of the file in terms of dimension, orientation, and position |
| Machine setup | Setup regarding energy source, energy constraints, and layer thickness |
| Build | Built desired object |
| Removal of object | Removed object |
| Postprocessing | Cleaning of the surface of the removed object |
| Application | Additional treatment |

The first step is the description of the external geometry of the output. External geometry can be provided using CAD solid modelling software or reverse-engineering equipment like laser and optical scanning to obtain 3D solid or surface representation. A representative output of CAD modelling software is illustrated in Figure 2.

Figure 2: Representative CAD Image [1]

The CAD model must then be converted to STL format, which describes the object's external closed surfaces. It provides the basis for the slice calculation. Figure 3 illustrates a representative object as converted to STL format from CAD.

Figure 3: Representative CAD (Left) AND STL Image (Right) [1]

In the next step, the STL file should be transferred to the additive manufacturing machine, and manipulation of files is done to achieve the correct size, position, and orientation after the transfer. Then machine setup in terms of energy source, energy constraints, and layer thickness should be performed. When the setup of the machine is completed, the build process of the desired object can start. Build process is taken care of automatically by the machine itself without any supervision. However, the machine's superficial monitoring should be done based on ASTM F42 to ensure no errors occur. As soon as the build process finishes, the final model can be removed from the machine, and the post-processing step can start. This step aims to clean the produced object before it is acceptable for use. Within the last step, called application, the produced and cleaned objects may require an additional treatment like priming or painting to make the surface have a certain texture and finishing.

## 2.3 Milestones in Additive Manufacturing

The concept of AM can be traced back to the 1860s when two-dimensional photos were used to produce three-dimensional sculptures [3]. Research efforts have resulted in the development of the concept of proof and patents. In the 1960s, photopolymerization was invented, and in the 1970s, powder bed fusion and sheet lamination for ceramics, metals, and polymers were developed [4]. In the late 1980s, the first commercialized additive manufacturing technology, stereolithography (Fig.4), was invented by Charles Hull [1]. New AM technologies started to increase rapidly in the 1980s when the number of both publications and filed patents recorded a strong increase [5]. For example, laminated object manufacturing (LOM) was patented in 1986 by Helisys; in the same year, Cubital patented solid ground curing, and DTM patented selective laser sintering (SLS). However, only selective laser sintering remains commercial today [1]. Moreover, fused deposition modelling (FDM), also called material extrusion, and the 3D printing process, also known as binder jetting, have been patented by different companies in

---

[3] Gao, Zhang, Ramanujan, Ramani, Chen, Williams, Wang, Shin, Zhang, Zavattieri, 2015

[4] Thompson, Moroni, Vaneker, Fadel, Campbell, Gibson, Bernard, Schulz, Graf, Ahuja, Martina, 2016

1986. In the 1990s and 2000s, AM continued to evolve with other commercialized technologies such as electron beam melting [5]. In 2005, the RepRap project developed the first AM machine suitable as a personal usage hobby, thanks to the easy dissemination of information resulting from internet development [5]. AM technologies and their products are used in various fields today, such as product manufacturing, energy, transportation, medicine, and the construction sector, including restoration.

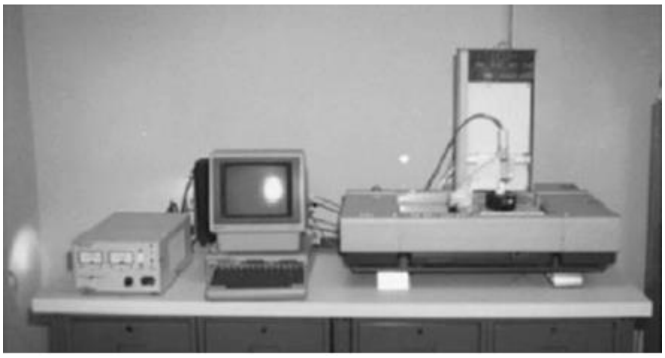


Figure 4: First Commercialized Technology with Stereolithography found by Hull [1]

There have been numerous failures and successes in the history of AM, but according to Gibson (2016), "*some of them may have failed due to poor business models or poor timing, not because of poor process*" (p.38) [1]. An attempt to categorize AM has been made by ISO/ASTM 52900, which identifies seven key groups of technologies: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat polymerization [5].

## 2.4 Classification of Available Technologies

The seven key groups of AM based on ISO/ASTM 52900 are discussed in the following paragraph, while the specific technologies used in construction and restoration are expanded upon in Chapters 3 and 4.

### Material Extrusion

ISO/ASTM 52900(2015) defines material extrusion as an "*additive manufacturing process in which material is selectively dispensed through a nozzle or orifice*" (p.10) [2]. In other words, it deposits the layers with a mechanically extruded molten thermoplastic material, mainly ABS (Acrylonitrile Butadiene Styrene) or PLA (Polylactic Acid), onto a substrate [1 4 5 6].

---

[5] Buchanan, Gardner, 2019

[6] Loughborough University. Additive Manufacturing Research Group. Retrieved from https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialextrusion/

The first layer should be built as nozzle deposits material, and then the following layers should be added layer by layer (Fig.5). Finally, layers are integrated during a deposition when the material is still in the melted state [1 4 5 7]. The material extrusion process is operated at high temperatures; thus, the final product may exhibit high porosity [1 4 5 7].

This process's advantages are inexpensiveness and flexibility. Besides that, the thermoplastic materials, especially ABS, are easily accessible and provide good structural properties. However, accuracy and speed are low compared to other systems [1 4 5 7].

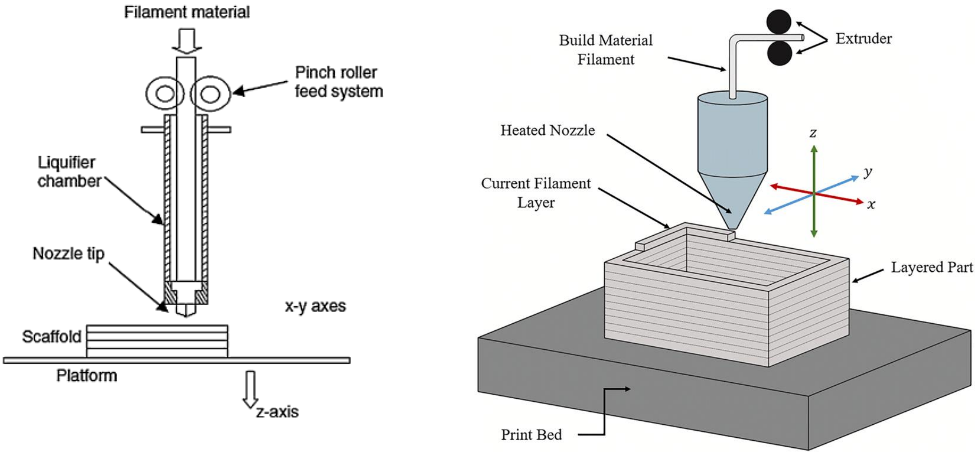


Figure 5: Material Extrusion Process Illustration [1]

### Powder Bed Fusion

According to ISO/ASTM 52900(2015), powder bed fusion is an "*additive manufacturing process in which thermal energy selectively fuses regions of a powder bed*" (p.11) [2].

The most popular powder bed fusion technologies are direct metal laser sintering, selective laser melting, and electron melting. In these technologies, after scanning of a layer, the subsequent layer is spread by using a rolling mechanism and fused to the previous layer (Fig.6). During the procedure, a high temperature is required to sinter the structural powder fully [1 4 5 7].

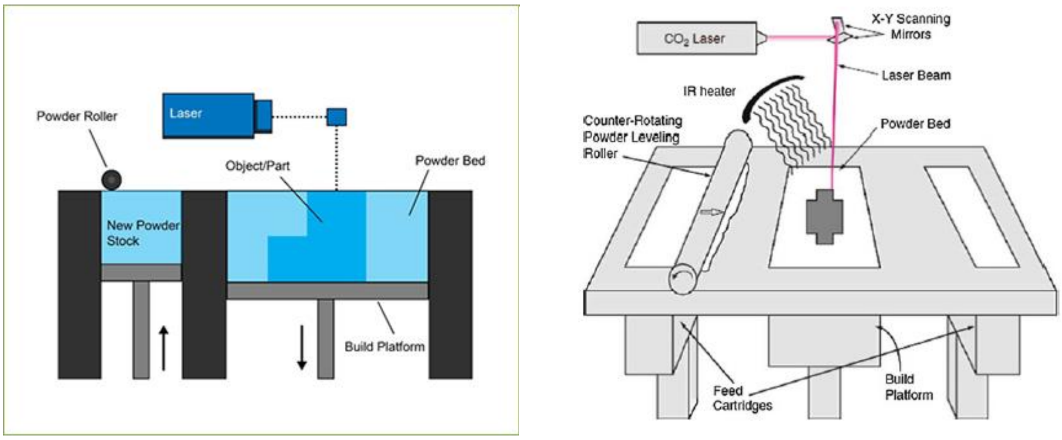


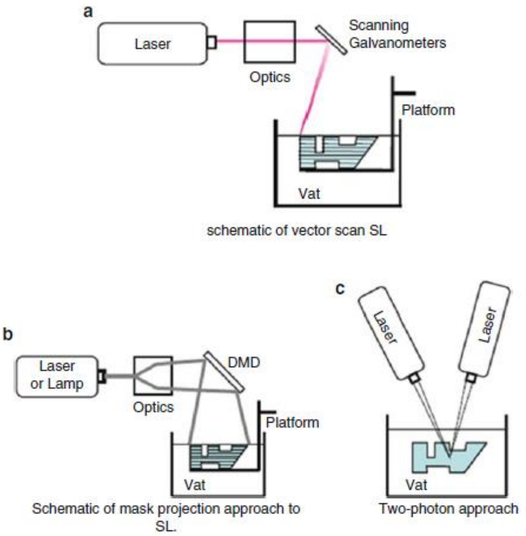
Figure 6: Powder Bed Fusion Process Illustration [1]

Advantages of the process are its inexpensiveness and a large variety of material options. Even though powder bed fusion mainly uses powder-based material, common metals such as stainless steel, titanium, aluminium, cobalt chrome, and polymers can also be used [1 4 5 7]. However, the main disadvantage of this process is its slow speed [1 4 5 7].

### Vat Photopolymerization

According to ISO/ASTM 52900(2015), vat photopolymerization is an "*additive manufacturing process in which liquid polymer in a vat is selectively cured by light-activated polymerization*" (p.11) [2]. In this process, a liquid polymer resin is used to construct the model layer by layer. The resin is cured and hardened using ultraviolet light while the object is constructed downward on the moving platform. The layers are continually constructed and cured until the model is complete.

Two main configurations and one additional configuration have been developed for the vat photopolymerization process [1]. These configurations are vector scan approach, mask projection approach, and two-photon approach (Fig. 7). One of the main differences in these three configurations is that the vector scan and two-photon approaches utilize a scanning laser beam, while the mask projection approach utilizes a radiation beam. Furthermore, photopolymerization occurs in the intersection point of two laser beams in the two-photon approach, while the other two approaches use just one laser beam and different photopolymerization concepts. Unlike the other two approaches, the two-photon approach makes the recoating unnecessary; thus, it is faster than the other two approaches [1]. However, resin discharge from the vat and final model removal after completion is obligatory and common in these three approaches.



schematic of vector scan SL

Schematic of mask projection approach to SL.

Two-photon approach

Figure 7: Vat Photopolymerization Processes Illustration [1]

Overall, the vat photopolymerization process is relatively quick, and it provides high-level accuracy, good finishing, and it can be used for typically large build areas. However, it uses particularly UV curable polymer resin, which is expensive to be supplied, and requires unbound material support since there is no structural support from the material itself [1 4 5 7].

### Binder Jetting

According to ISO/ASTM 52900(2015), binder jetting is defined as an "*additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials*" (p.10) [2]. Binder jetting was developed at MIT, and the original name was three-dimensional printing [1]. During the process, the first layer is built by spreading powder material using a roller over the build platform. Then, binder adhesive is deposited by using the print head over the powder. The liquid from the binder acts as an adhesive to bond the powder form. Once the first layer is finished, the platform should be lowered down, then the deposition of the subsequent layers follows the same procedure (Fig.8) until the final model is achieved. However, postprocessing is needed to remove the final product model from the powder bed and remove unbound powder by using pressurized water. Finally, the printed final model requires infiltration to gain sufficient strength since it is composed of bound powder.

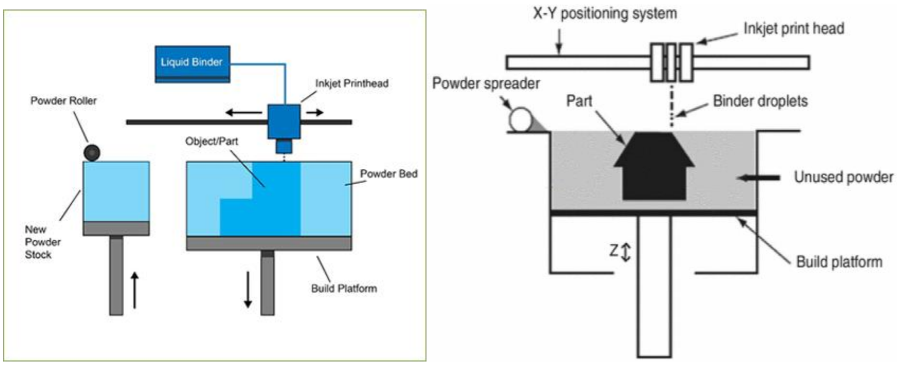


Figure 8: Binder Jetting Process [1]

A wide range of composite polymers (ABS, PA, PC), metals (stainless steel), and ceramics can be used in this system [1 4 5 7]. Additionally, support structures are not needed since the parts are self-supporting [1 4 5 7]. Binder jetting process is faster than the other processes, and the use of two different materials can result in different combinations of binder-powder, different mechanical properties, and different colours [1 4 5 7]. However, this process may not be appropriate for the structural parts depending on the binder type used [1 4 5 7].

## Material Jetting

According to ISO/ASTM 52900(2015), material jetting is defined as an "*additive manufacturing process in which droplets of feedstock are selectively deposited*" (p.11) [2]. In the material jetting process, droplets of the material are released by a nozzle that moves horizontally along the building platform, and then droplets are cured through photocuring or heating (Fig.9). The same process continues with the further layers by building them subsequently. As a final step, the layers are left to harden and cured using ultraviolet light, then support material should be removed as a postprocessing step.

This process can only use the materials that can be deposited in drop form such as polymers and waxes, meaning only a limited number of materials can be utilized [1 4 5 7]. High accuracy can be achieved thanks to the usage of droplets [1 4 5 7]. However, this process requires a support.

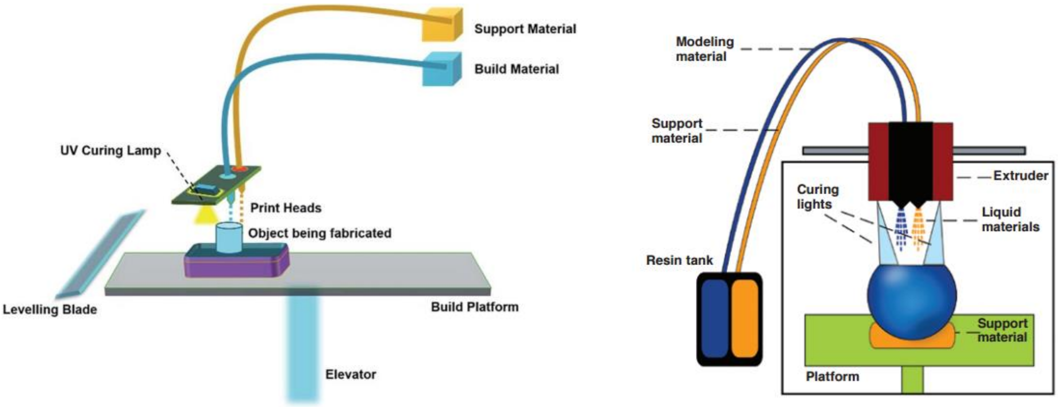


Figure 9: Material Jetting Process Illustration

## Sheet Lamination

According to ISO/ASTM 52900(2015), sheet lamination is defined as an "*additive manufacturing process in which sheets of material are bonded to form a functional element that could constitute all or a section of an intended product*" (p.10) [2]. The sheet lamination process has two technologies: laminated object manufacturing (LOM) and ultrasonic additive manufacturing (UAM). Laminated object manufacturing is one of the first commercialized technology. Layer by layer lamination of paper material sheets are cut by using a carbon dioxide laser, and each sheet is represented as a cross-sectional layer of CAD model. This technology uses the cross-cutting method, in which the paper sheet is sliced into cubes, to remove the final element easily (Fig.10).

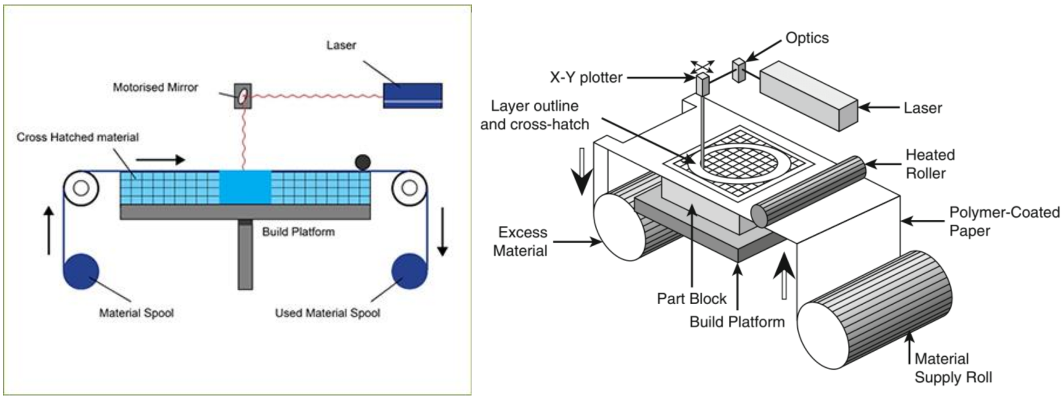


Figure 10: Sheet Lamination (Laminated Object Manufacturing) Process [1]

Laminated object manufacturing helps to achieve low internal tension and low fragility of elements. It provides high surface finish details and machines, and it can be considered inexpensive due to the low cost of the process, material, and machine.

Ultrasonic additive manufacturing involves bonding the metallic sheets by ultrasonic welding, CNC milling, and removing unbound metal parts (Fig.11). The object parts are constructed from bottom to top on a base plate bolted on a heated plate during the process. Each layer contains several metal foils laid side by side, and layers are trimmed using CNC milling.

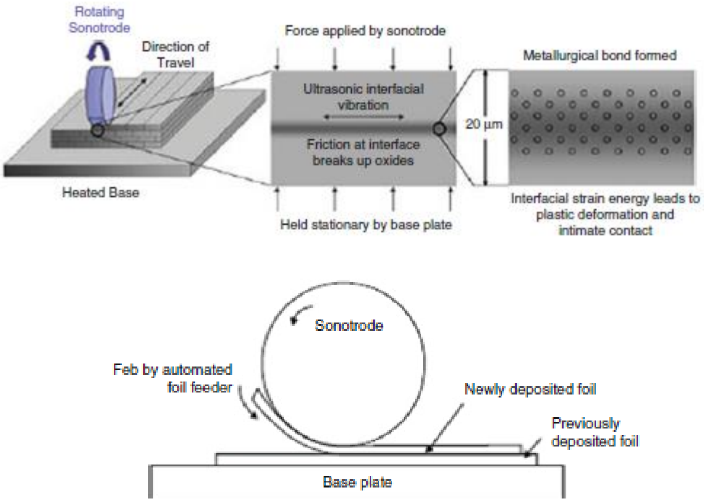


Figure 11: Ultrasonic Additive Manufacturing Process [1]

Ultrasonic additive manufacturing does not require high temperature. Generally, the temperature is not required to be higher than 50% of the melting temperature of the joined metals [1 4 5 7]. Thus, thermally induced internal stresses and deformations are not a major problem; in fact, the technology allows for internal geometries [1 4 5 7].

### Directed Energy Deposition

According to ISO/ASTM 52900(2015), directed energy deposition is defined as an "*additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited*" (p.10) [2]. In other words, directed energy deposition's working principle is based on creating the new model by melting the material as it is deposited [1]. This process is predominantly used for metal powders, but also ceramics and polymers can be utilized. For this reason, the technique can be called "metal deposition technology."

A typical directed energy deposition machine (Fig.12 (a)) contains a nozzle located on a multi-axis arm, enabling the nozzle to move in different directions. The multi-axis arm works as structural support to build complex three-dimensional objects. Metallic powder or wire is generally used as a feedstock material. A laser beam, an electron beam, or a plasma arc is used as an energy source.

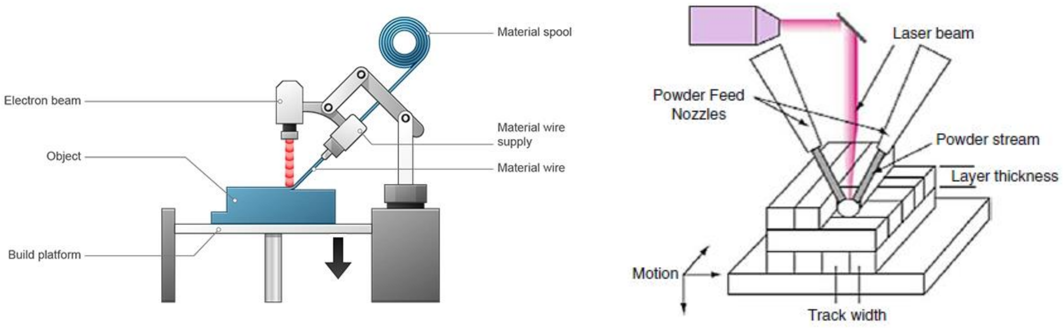


Figure 12: (a) Directed Energy Deposition Machine (Left) [1], (b) Directed Energy Deposition Process (Right) [1]

During the production process of directed energy deposition, wire or powder material is deposited using the multi-axis nozzle on the surface. Then, the deposited material is fed into the energy source's focal point to create a molten pool (Fig.12 (b)). The process continues layer by layer until the final model is achieved.

Directed energy deposition machines enable the production of complex three-dimensional objects directly from CAD files, unlike conventional welding and cladding technologies [1 4 5 7]. Another advantage of this process is that it can be used to repair and maintain structural parts. As a result of the local melting and rapid cooling, the resultant microstructure becomes well-refined; the resultant parts have high density and strength. Attained strength can be 30% higher than the ones produced with casting [6]. Furthermore, this process can add coatings to an existing structure to increase the tribological performance of structural elements [6]. However, limited material usage and postprocessing applications, such as milling of the final product surface, are considered disadvantages of this technology [1 4 5 7].

A summary of the main points of each additive manufacturing technology, including the materials, advantages, and disadvantages, is provided in Table 2.

Table 2: Additive Manufacturing Classification of Technologies [4]

| **Categories** | **Technologies** | **Stamped Material** | **Power Source** | **Adv.** | **Disadv.** |
|---|---|---|---|---|---|
| ***Material Extrusion*** | Fused Deposition Modelling<br>Contour Crafting | • Thermoplastics<br>• Ceramics<br>• Metals | Thermal Energy | • Inexpensive cost<br>• Multi-material usage | • Limited part resolution<br>• Poor surface finish |
| ***Powder Bed Fusion*** | Selective Laser Sintering | Polyamides/polymers | A high-powered laser beams. | • High accuracy<br>• High density and strength | • Support structure need |
| | Direct Metal Laser Sintering | Metals | | | |
| | Selective Laser Melting | | | | |
| | Electron Beam Melting | | Electron beam | • High density and strength | |
| ***Vat Photopolymerization*** | Stereolithography | • Polymer<br>• Ceramics | Ultraviolet Laser | • High Speed<br>• High resolution | • High Cost |
| ***Material Jetting*** | Polyjet/Inkjet Printing | • Photopolymer<br>• Wax | • Thermal Energy<br>• Photocuring | • Multi-material printing<br>• High surface finishing | • Low-strength material |
| ***Binder Jetting*** | Indirect Inkjet Printing | • Polymer powder<br>• Ceramic powder<br>• Metallic powder | Thermal energy | • Full-colour object<br>• Wide material selection | • Infiltration of the final object<br>• The high porosity of the final object |
| ***Sheet Lamination*** | Laminated Object Manufacturing | • Plastic film<br>• Metallic sheet<br>• Ceramic tape | Laser beam | • High surface finish<br>• Low cost | • De-cubing issues |
| ***Directed Energy Deposition*** | Laser Engineered Energy Shaping<br>Electronic Beam Welding | Molten metal powder | Laser beam | • Repairment of damaged parts<br>• The functionality of graded metal printing | • Requirement of postprocessing |

## 2.5 Discussion

Even though there are still challenges regarding the AM process, it provides advantages over traditional additive manufacturing [1 4 5 7]. It is seen as a more precise way to predict the time required to produce the object and speed the cutting, forming, and casting process [1 4 5 7]. It also reduces the material waste; thus, the production cost [1 4 5 7].

# Chapter 3

# Additive Manufacturing in Construction

The chapter consists of three main parts outlining concrete, polymer, and metal additive manufacturing processes in the construction sector. Their features and characteristics are presented and discussed within the chapter, aiming to clarify the suitable technologies and strategies, the opportunities, and challenges for their application in the specific field.

Additive manufacturing applications in construction varies from a single structural element such as walls and columns to completely 3D printed buildings and bridges by using different technologies and materials.

### 3.1 Additive Manufacturing of Concrete Elements in Construction

Concrete is one of the most utilized materials in construction thanks to its low cost and worldwide availability of its raw materials. Concrete elements can be shaped by different techniques such as pouring on-site, offsite pre-casting, spraying, or tilt-up. However, most current techniques require formworks and moulds in which the concrete is shaped when poured inside in the fluid state. Especially for on-site casted concrete, the formwork placing and tearing down accounts for 35 to 60 % of the element production cost [1] [2] [3]. In construction, only simple geometries with a constant cross-section are mostly used; thus, formworks can be re-used, and formwork cost can be minimized [4] [5]. However, additive manufacturing does not involve the use of formwork, and it brings several potential advantages such as lower labour cost, the possibility of more complex element geometries, reduced construction time, high accuracy, and less material wasting. The additive manufacturing process of concrete elements is a layer-based manufacturing technique allowing the freeform construction [2] [3]. Historically, the first attempt to print concrete elements was made by Pegna in the late 1990s [6] [7] [8]. He presented the freeform construction idea in which a layer fabricated concrete element by layer selective deposition of cement. The later developed technologies in construction are discussed in the following section.

---

[1] Buchanan, Gardner, 2019
[2] Kreiger E., Kreiger M., Case, 2019
[3] Rael, Fratello, 2018
[4] Lowke, Dini, Perrot, Weger, Gehlen, Dillenburger, 2018
[5] Le, Austin, Lim, Buswell, Gibb, Thorpe, 2012
[6] Lim, Buswell, Le, Austin, Gibb, Thorpe, 2012
[7] Buswell, Soar, Gibb, Thorpe, 2007
[8] GuoWei, Li, Yang, 2017

### 3.1.1 Concrete Additive Manufacturing Techniques and Strategies

In recent years, AM has been developed to meet the demand in construction and architecture. Currently, the AM process targeted at large-scale building elements mainly includes three types: Concrete Printing and Contour Crafting, which both adopt the material extrusion process, and the D-shape method, which applies the powder bed fusion process.

### Material Extrusion

The material extrusion process has been explained in Chapter 2, while concrete extrusion is addressed here. The concrete extrusion method (Fig. 13) enables creating an element layer of fresh cementitious material by a nozzle that deposits it along the defined path. Specific requirements for both fresh and hardened concrete must comply so that a high quality of printed elements can be ensured. To perform a successful printing process, possible particle segregation must be prevented so a blockage in hose and nozzle (pumpability) can be avoided, the easy extrusion of cementitious material into layer must be allowed (extrudability), as well as the superposition of multiple layers (buildability) [5] [6] [9]. Besides that, material and process-related parameters, admixtures, and printing head should be chosen carefully.

Figure 13: Concrete Extrusion Process [5] [9]

According to Paolini (Paolini 2019), "*concrete extrusion processes can be divided into three based on the filament size. These are deposition of fine filaments with less than 1 mm, deposition of medium-sized filaments with cross-sectional dimensions up to several cm, and deposition of coarse filaments in the range of several dm"* (p.2) [9]. 3D Concrete Printing (3DCP), Contour Crafting, and CONPrint3D, which are the most utilized concrete extrusion techniques, belong respectively to the three-subgroups mentioned above. However, in this dissertation, only Concrete Printing and Contour Crafting are discussed under the material extrusion part, as they are the AM technologies mainly used in construction and architecture.

---

[9] Paolini, Kollmansberger, Rank, 2019

### Concrete Printing (3DCP)

Concrete printing (Fig.14) is a large-scale process used in construction, based on concrete extrusion done by a print head with three-dimensional moving freedom, which is mounted on an overhead crane. The fresh concrete is delivered to a pump through a deliver pipe, then to the nozzle via the pump. The nozzle so deposits fresh concrete to form the desired structural element.

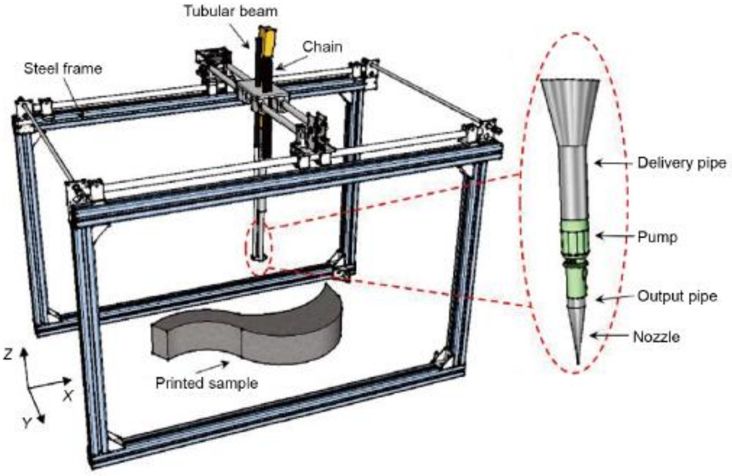


Figure 14: Illustration of Concrete Printing with the Deposition System [8]

The deposition resolution is low, but this feature causes a high control over complicated geometries [6] [8]. For this reason, 3DCP has the potential to be used in the manufacturing of structural elements.

### Existing 3DCP Manufactured Structural Elements

#### a) Wonder Bench

A curved shape wall-bench element with a dimension of 2.0 x 0.9 x 0.8 meters was designed using 3DCP technology by Loughborough University. The 3D model of the wall-bench can be seen in Figure 16. A total of 128 layers of the wall-bench element were printed layer by layer in approximately 42 hours with a 20 min/layer printing speed.

Figure 15: The 3D Model Wall-Bench

The wall-bench has a smooth surface front with a seat and a backside with a square wave superimposed on the surface (Fig. 16).

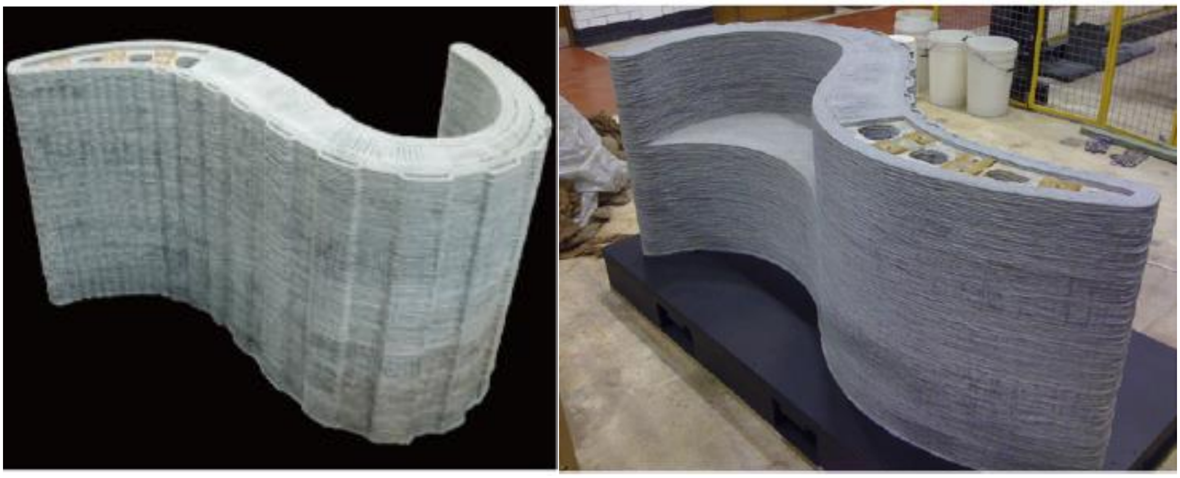


Figure 16: Final Form of Wall-Bench

The top layer partially hides the 12 functional white-coloured voids of the internal structure and their reinforcements (Fig. 17) and having different sizes and shapes to follow the element's curve geometry. The voids' main purpose is to minimize the element weight and provide it acoustic and thermal insulation performances and space to house technical installations [6]. Besides that, there are 23 grey-coloured voids in which 8 mm reinforcing bars have been inserted.

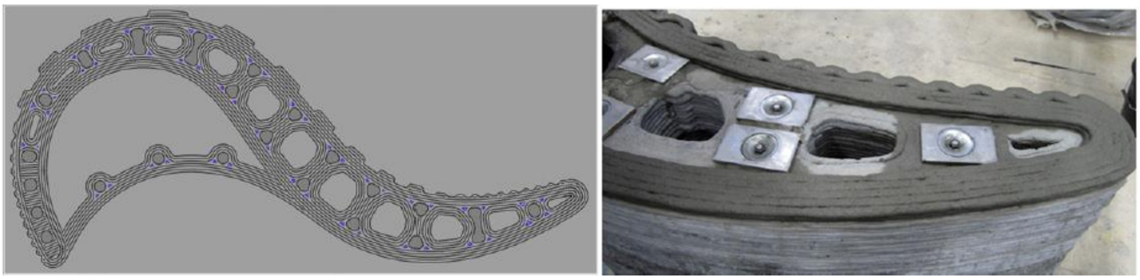
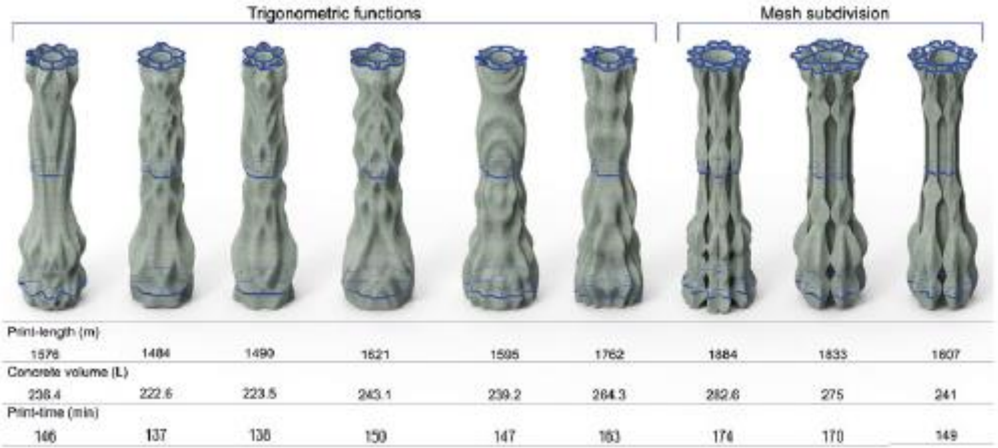


Figure 17: Internal Structure with Functional Voids and Reinforcements

According to Lim (Lim 2011), "*This approach offers a simple, workable method of incorporating tensile capacity into large cement-based components, demonstrating the potential for automated manufacture of large construction components*" (p.6) [6]. The wonder bench has been presented in two international exhibitions, as the main purpose of this wall element with a curved bench was to show the possibilities of additive manufacturing compared to conventional techniques [5].

### b) 3D Printed Concrete Columns (Concrete Choreography)

The design and fabrication of these columns were performed at ETH Zurich. The research's main aim was to investigate a new concrete typology, thus demonstrating remarkable architectural qualities achievable through 3DCP [10]. The procedural computational design engines based on trigonometric functions and mesh subdivision were developed and utilized (Fig.18) [10].



| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Print-length (m) | 1576 | 1484 | 1490 | 1621 | 1595 | 1762 | 1884 | 1833 | 1807 |
| Concrete volume (L) | 238.4 | 222.6 | 223.5 | 243.1 | 239.2 | 264.3 | 282.6 | 275 | 241 |
| Print-time (min) | 146 | 137 | 138 | 150 | 147 | 163 | 174 | 170 | 149 |

Figure 18: Trigonometric Functions and Mesh Subdivision [10]

Each column has been designed as a composition of a double shell and an internal bracing (Fig.19) [10]. The outer shell is sized in a range of 0.25 m to 0.6 m, with an ornamental exterior, and the inner shell was designed as a cavity for traditional reinforced concrete. In each layer, these shells were connected with internal bracing. The internal bracing supports the adjacent layers, provides a closed core and increases the overhang for column geometry [10].

Figure 19: Double Shell Composition and Internal Bracing [10]

---

[10] Burry, Sabin, Sheil, Skavara, 2020

Trigonometric functions were used to design highly differentiated ornaments on the external shell. Moreover, the characteristic dripping behavior of concrete has helped to subvert the horizontal layer of aesthetics. This behavior was used to create a dramatic effect at column capital and base to distinguish them from the shaft by emphasizing their ornamental purpose [10]. In the fabrication stage, columns were printed in 2.5 hours/column printing speed. In the end, a total of 9 columns with a total height of 2.7 m were fabricated in ten weeks [11].

### c) Acoustic Damping Wall Element

The acoustic damping wall element (Fig. 20) was designed and manufactured by C.Gosselin in France for structural and acoustic purposes. A total of 26 layers of the element were printed layer by layer in approximately 2 hours with a 4.6 min/layer speed. It contains different hole geometries providing soundproofing properties by damping the acoustics waves [11].

Figure 20: Acoustic Damping Wall Element

---

[11] Gosselin, Duballet, Roux, GaudilliEre, Dirrenberger, 2016

## Contour Crafting (CC)

Contour Crafting is a large-scale process used in construction, based on concrete extrusion done by a multi-axis deposition head to fabricate large objects with dimensions of several meters [6 7 8]. Contour Crafting offers high-speed production in construction scale, a wide range of utilized materials, and good quality surface finish [6 7 8]. According to Buswell (Buswell 2006), "*More recently, Contour Crafting has been demonstrated to produce large (>1 m) structures. In essence, the process produces a replacement for the structural concrete block wall commonly used in UK house construction*" (p.4) [7].

Contour Crafting combines extrusion and filling. Two trowels are installed on the printing nozzle, and then the printing nozzle starts to move in the pre-defined path to print the external edges. After that, another cementitious paste fills inside the internal volume, which is created by outer edges. The construction process is illustrated in Figure 21.

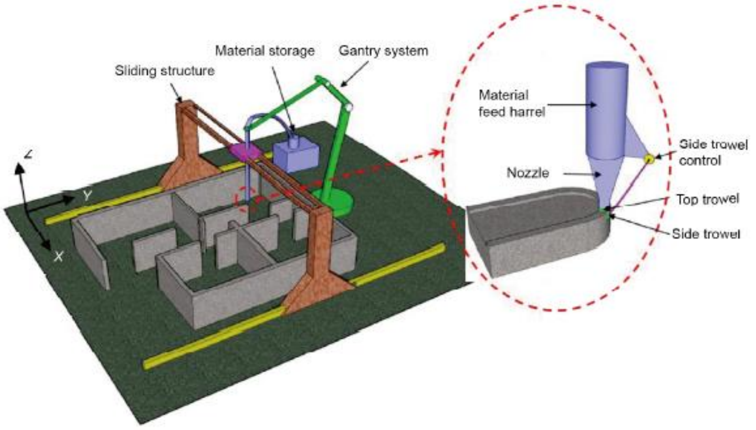


Figure 21: Illustration of Contour Crafting with the Deposition System[8]

This technology currently leads the construction field, and it has been successfully applied in on-site applications.

## Existing Contour Crafting Manufactured Structural Elements

### a) 3D Printed Concrete Castle

Andrey Rudenko has designed, and 3D printed a concrete castle with dimensions of 15 $m^2$ in Minnesota/USA. It consists of three towers and walls which surround the castle. The parts were printed separately and assembled into one single structure (Fig. 22). The concrete castle is life-size and capable of habitation.

Rudenko (Rudenko 2014) states that" *it is possible to print limitless amounts of classical décor as well as brand new elements and shapes, whereas previous technology made innovative constructions difficult and expensive."* [12]

---

[12] Azzarello, 2014. Andrey Rudenko constructs 3D printed concrete castle in Minnesota. Retrieved October 19, 2020, from https://www.designboom.com/technology/3d-printed-concrete-castle-minnesota-andrey-rudenko-08-28-2014/.

Figure 22: 3D Printed Concrete Castle [12]

### b) 3D Printed Structures by Winsun

One of the leading Chinese advanced material suppliers, Winsun Decoration Design and Engineering Company, after their research in AM invented a printing nozzle and an automatic material feeding system in 2005. Their experience in the construction industry helped them to become an architecture firm with innovative additive manufactured constructions. In 2014, the company constructed a set of ten single-story residential buildings in under 24 hours [13]. The residential buildings (Fig. 23 (a)) were printed firstly as panels with a cement-based mixture containing construction waste and glass fiber, then printed panels were assembled on-site. Then, electrical systems, insulation, and plumbing were added to all buildings. Moreover, in 2015 the company constructed the tallest 3D printed building with five stories (Fig. 23 (b)) and a complete mansion of 1.100 $m^2$, including external and internal decorations (Fig. 23 (c)). Both of these structures were constructed using a cement-based mixture [13]. In 2016, the company constructed the first additive manufactured office (Fig. 24) [13]. The office building walls were printed separately with a cement-based mixture containing reinforced glass fiber, and then the printed parts were assembled and transferred to Dubai [13]. Buchanan states that the office building reduced 80% of the construction cost, 60% of labor cost, and produced 60% less waste material than a conventionally manufactured building [1].

---

[13] Retrieved December 16, 2020, from http://www.winsun3d.com/En/About/.

Figure 23: (a) First 3D Printed Residental Building (Shown in Top Left),

(b) 3D Printed Five-Story Apartment (Top Right),

(c) 3D Printed Mansion (Bottom)

Figure 24: The First 3D Printed Office Building

### c) The Concrete Wall and The Hollow Wall

Behrokh Khoshnev has designed and printed a concrete wall, with dimensions of 1.52 x 0.61 m, using a cement paste. Firstly, the external wall has been extruded, and then concrete was manually poured incrementally with one-hour intervals to complete the wall (Fig. 25). Furthermore, in 2013, Khoshnev has designed and fabricated a wall with a corrugated internal structure with a cement paste (Fig. 26).

Figure 25: 3D Printed Wall by Contour Crafting

Figure 26: The Wall with Corrugated Internal Structure

## Powder Bed Fusion

The powder bed fusion process has been explained in Chapter 2, while the concrete powder bed process is addressed here. The powder bed fusion process is an AM deposition process for fabricating automatically large-scale free-form structures. The principle consists of creating a dry particle layer and then selectively depositing fluid to make the dry particles bond. These two repetitive steps continue until all layers are completed. As a final step, loose particles are removed, and heating or infiltration may be required as postprocessing. In contrast to the material extrusion process, the powder bed fusion process allows more design freedom because of mechanically stable dry-packed particles. For example, inclined structures, overhangs, suspended beams, arches, and vaults can be fabricated easily [4]. However, construction space is more limited due to being filled with dry particles, but it provides high resolution and possible high accuracy even under 0.1 mm [9].

### D-Shape

D-shape is a large-scale 3D printer with 300 nozzles and a 6 m wide printing head to print objects up to 6 m in width [6] [9]. The printing head can move freely in the x-direction along the horizontal beam and in the z-direction along the vertical beams through four stepper motors, as is shown in Figure 27.

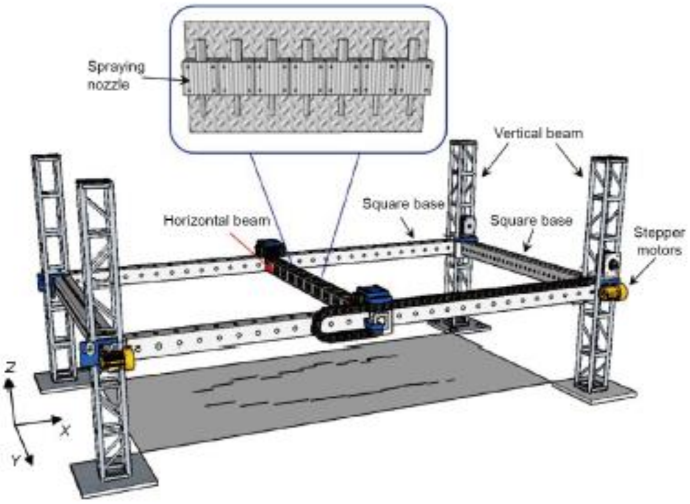


Figure 27: Schematic Illustration of D-shape Technology [8]

## Existing D-Shape Manufactured Structural Elements

### a) Castilla La Mancha 3D Bridge

The Castilla La Mancha bridge (Fig. 28) is the first 3D printed pedestrian bridge located in the urban park of Castilla La Mancha in Alcobendas, Madrid/Spain. Institute of Advanced Architecture of Catalonia directed the bridge's fabrication, and the project was completed in 2 months. The bridge was built using the powder bed fusion process utilizing concrete powder and polypropylene reinforcement. The structure consists of eight portions with a dimension of 2x2 m, and it has a total span of 12 m and a width of 1.75 m [1] [14] [15].

Figure 28: Castilla La Mancha 3D Printed Pedestrian Bridge

---

[14] Valencia, 2017, World's First 3D Printed Bridge Opens in Spain. Retrieved October 23, 2020, from https://www.archdaily.com/804596/worlds-first-3d-printed-bridge-opens-in-spain.

[15] 3D printed bridge. (2020, April 20). Retrieved October 23, 2020, from https://iaac.net/project/3d-printed-bridge/.

The bridge construction was designed to optimize the distribution of materials and minimize waste material by recycling raw material during manufacture [1 14 15]. The design process also allowed using generative algorithms to maximize the structural performance [1].

### b) One Single Process Printed House (La Casa Tutta di Un Pezzo)

The building with dimensions of 2.4x4.0x3.5 m (Fig. 29) has been designed by Marco Ferreri and printed based on powder bed deposition of cement paste in one shot in three weeks. It consists of four walls and a roof, and it is composed of free space for a bathroom, bedroom, and kitchen. After the fabrication, the structure was presented in the Triennale Museum of Milan/Italy; currently, it is located in Marco Ferreri's property in Milan.

Figure 29: One Single Printed House

### 3.1.2 Comparison Between Existing Techniques in Large Scale Construction

The techniques in large-scale construction and architecture, namely Concrete printing, Contour crafting, and D-shape, were described in the above section. These three large-scale AM techniques have similarities in how they fabricate the components in an automotive and layer-by-layer manner, but each has unique features, results, and applications. Table 3 provides a summary of the similarities and differences between these three large-scale AM techniques.

Table 3: Similarities and Differences in Large Scale AM Techniques in Construction and Architecture

| | **Concrete Printing** | **Contour Crafting** | **D-Shape** |
|---|---|---|---|
| **Process** | Extrusion based | Extrusion based | Particle-based |
| **Support** | A second material | Lintel in horizontal | Unused powder |
| **Printing Resolution** | 9-20 mm | 15 mm | 0.15 mm |
| **Layer Thickness** | 5-25 mm | 13 mm | 4-6 mm |
| **Print Head** | 1 | 1 | 300 |
| **Nozzle Diameter** | 9-20 mm | 15 mm | 0.15 mm |
| **Printing Speed** | Slow | Fast | Slow |
| **Printing Dimension** | Limited scale by frame | Mega scale | Limited scale by frame |

During the AM process, support may be required to carry the weight of the overhanging part of the 3D object. Contour crafting can fabricate vertical elements in compression without any need for a support structure, while in the horizontal direction, it needs a lintel to be placed in a gap right above the doorways or windows and walls. Even though the cantilever problem can be solved in this way, contour crafting cannot fabricate a structure with windows and roof all at once [8]. In contrast, D-shape uses surrounding unconsolidated materials to support the object. Thus, D-shape prints an object within a single process [8]. In comparison, Concrete Printing requires support using a second material. However, this feature results in a disadvantage since it requires an additional deposition device and postprocessing operation for secondary support structure [6].

Contour crafting uses a single and large diameter nozzle that prints a whole layer with two deposition head passes. Therefore, it has a higher printing speed and minimized operating time, but it has low printing resolution and large layer thickness. In comparison, D-shape uses multiple nozzles with a small diameter, which prints an entire layer by a single transverse. For this reason, this feature results in a lower printing speed but having a higher printing resolution and small layer thickness. Concrete printing uses a single and large diameter nozzle like Contour crafting. However, it limits the operating speed because it needs to transverse the whole build area. Therefore, it has a low printing speed and long operating time, low printing resolution, and large layer thickness due to single and large diameter nozzles.

Contour crafting can fabricate mega-scale structural elements by multi-axis robotic arm compared to Concrete Printing and D-shape, in which the mechanical frame limits the printing scale.

As a final comparison, Contour crafting does not require further postprocessing steps since the deposition head allows surface finishing and smoothing during the production. While in the other two techniques, printed surfaces may be required to post-process in terms of surface polishing and grinding. Each of the discussed techniques utilizes different methods and processes and results in different construction industry opportunities and challenges.

### 3.1.3 Opportunities and Challenges of Concrete Additive Manufacturing in Construction

Additive manufacturing of concrete elements is an innovative and promising tool for real-life large-scale constructions. However, although AM has many opportunities in the industry, there are still some challenges.

**Opportunities**

**a) Design Flexibility**

Layer manufacturing technique of AM results in new opportunities for constructing structures without formworks and shaping of materials. This feature gives an unlimited power to design complex geometries that can improve functionality. For instance, as in the case of wonder bench and acoustic damping wall elements, different shaped and sized voids can be added to achieve acoustic features, air conduits, or even wiring conduits. New geometric forms can be obtained, like in the Winsun Dubai office and Castilla La Mancha 3D bridge.

### b) Construction Cost and Time

AM techniques offer overall cost reduction by reducing the amount of time, materials, and labour needed. AM applications accelerate the construction process. According to GuoWei (GuoWei 2017), "*The building process takes a quarter of the time required to build an equivalent structure with traditional means."* (p.15) [8]. Besides that, even though expensive raw materials and equipment used in AM may cause a higher construction cost, AM can still reduce material cost. Compared to conventional techniques, lower material usage resulted in decreased material consumption and produced less waste material [8]. Moreover, the use of waste material and recycling of unused material is another parameter that reduces the material cost [1]. In terms of labour cost, it reduces the labour requirement in construction and its cost since it offers an automated construction system. Camille (Camille 2016) performed a cost comparison between traditional and additive manufacturing techniques in terms of wall construction from 40 MPa concrete, as is shown in Table 4, by assuming the cost of formwork as %30-60 of the total cost [16].

Table 4: Cost Estimates for Construction a Wall from 40 MPa Concrete Using Traditional Method and 3D Printing [8] [16]

| | **Conventional Manufacturing** | | | **Additive Manufacturing** | | |
|---|---|---|---|---|---|---|
| | **Cost** | **Amount** | **Price** | **Cost** | **Amount** | **Price** |
| **Concrete Supply** | \$200 $m^3$ | 150 $m^3$ | \$30000 | \$250 $m^3$ | 150 $m^3$ | \$37500 |
| **Pumping** | \$20 $m^3$ | 150 $m^3$ | \$3000 | \$20 $m^3$ | 150 $m^3$ | \$3000 |
| **Labor** | \$20 $m^3$ | 150 $m^3$ | \$3000 | | | |
| **Formwork** | \$100 $m^3$ | 1500 $m^3$ | \$150000 | | | |
| **Total** | | | \$186000 | | | \$40500 |

As Table 4 states, labour and formwork costs are almost reduced to zero using additive manufacturing. Moreover, with additive manufacturing, the total cost can be reduced to almost a quarter of that of conventional manufacturing based on the data presented.

---

[16] Camile, Kalven, Lloyd, 2016

### c) Environmental and Social Impact

There are a series of advantages of AM over traditional manufacturing in terms of environmental and social impact. 3D printing can produce almost zero waste materials due to 3D printers having an electrically powered machine without any emission. Besides, it also reduces noises created by construction.

## Challenges

### a) Size of The Printer

Nowadays, AM applications at large-scale constructions are limited to structural elements or low-rise buildings because the size of the 3D printer restricts the scale of a structure that could be built [8]. The innovation of mega-scale 3D printers for cementitious material continues to develop and expands the technique's applicability at a construction scale.

### b) Cementitious Material Compatible with 3D Printer

Compatible cementitious material used in 3D printing should have all the properties of fresh cement: easy-pumping, easy-flowing, easy-deposition, dimension stability, and low shrinkage coordinate the printing system. Cementitious material, or concrete, can be modified by controlling the fresh properties through chemical admixtures, deposition, and printing speed so that cementitious material can be effective printing material with sufficient flowability, extrudability, buildability, and strength. However, printing material has become different from the conventional cementitious material due to the types of raw materials and admixtures, and 3D printed structures have become more expensive than conventional ones. For this reason, further research is necessary for AM concrete to find a cheap and easy solution.

### c) Standards and Tests

Evaluation standards and tests for traditional concrete can no longer be suitable for additively manufactured concrete and concrete structures since the composition of printing cementitious material are quite different from the traditional ones. For this reason, new regulations and standards are required to measure and assess mechanical properties depending on the chosen feedstock, printing process, and parameters. Additionally, the development of simulation models for long-term service life prediction and structural behaviour for 3D printed concrete structures is necessary [8] [9].

#### d) Reinforcement Implementation

3D printed concrete is brittle and weak in tension like casted concrete. Despite fiber reinforcement improving ductility and crack control, improved tensile behaviour cannot be achieved by fiber reinforcement. However, Contour crafting can solve the problem by inserting steel reinforcements using multiple arms during construction [8]. Concrete printing can create different shapes with different-sized voids. Steel reinforcements are placed inside the voids so that the tensile capacity of concrete can be improved [8].

#### e) Printing Precision and Efficiency

Printing precision can be defined as the smallest element that can be fabricated by a 3D printer, and it is directly proportional to printing accuracy and inversely proportional to printing speed. However, even though an increase in printing precision increases printing accuracy, it decreases the construction efficiency and increases the final cost. Therefore, this relation between printing precision and the other factors should be considered well so that maximum performance of 3D printing can be achieved [8].

### 3.1.4 Discussion

Additive manufacturing of concrete elements is a promising and innovative technique that may change the conventional construction processes and methods [1] [8] [9]. There are several possible applications for the future, such as integrating 3D Printing with Business Information Modelling (BIM) to reduce printing time and repeatable delivery path. Besides that, the collaborative study of NASA and ESA on a research project uses lunar material in the application of planetary construction by using Contour crafting and D-shape [9] [17]. Even though concrete additive manufacturing technology still faces some problems regarding the size of the printer, reinforcement implementation, compatible cementitious material, standards, tests, and printing precision, these challenges can be tackled with further research to focus on the interdisciplinary area between material science, architecture, and civil engineering [1] [8] [9] [17].

---

[17] Cesaretti, Dini, De Kestelier, Colla, Pambaguian, 2014

## 3.2 Additive Manufacturing for Polymer-Based Materials in Construction

Polymer-based material additive manufacturing is one of the most common additive manufacturing techniques since it combines low cost, low density, widespread equipment availability, and unlike concrete additive manufacturing, it enables storage in a controllable, ready to be used state [1] [18] [19]. The polymer AM techniques are the vat photopolymerization method with stereolithography, material extrusion method with fused deposition modelling process, powder bed fusion method with selective laser sintering, and binder jetting method. Different polymer materials are suitable for different methods: stereolithography utilizes liquid polymers, thermoplastics such as ABS, PLA are generally used by fused deposition modelling process and binder jetting, and thermoplastic polyamide 12 is used in selective laser sintering.

Additive manufacturing of polymer elements has been discovered in various applications, from aerospace engineering to medicine. The construction sector uses it to generate structural models, facades, and mechanical and electrical systems by architectural companies. However, many 3D printed polymers are generally used as conceptual prototypes since they cannot be used in heavily loaded parts due to their low stiffness and strength as a result of voids in printed parts [1] [18] [19]. However, various methods such as material extrusion and powder bed fusion processes and advanced polymers with improved mechanical properties such as carbon-reinforced ABS (CF-ABS) have been developed to increase the construction sector's effectiveness.

### 3.2.1 Polymer Additive Manufacturing Techniques and Strategies

### Material Extrusion

The material extrusion process has been explained in Chapter 2, while the polymer extrusion process is addressed here.

**Big Area Additive Manufacturing**

Big area additive manufacturing (Fig. 30) is a large-scale 3D printer developed by OAK Ridge National Laboratory for thermoplastics and composite materials. The BAAM can produce large polymer components with dimensions up to 6.0x2.4x1.8 m, which is almost ten times larger than most commercial techniques [9] [20].

---

[18] Ghaffar, Corker, Fan, 2018
[19] Ngo, Kashani, Imbalzano, Nguyen, Hui, 2018
[20] Duty, Kunc, Compton, Post, Erdman, Smith, Lind, Love, Lloyd, 2017

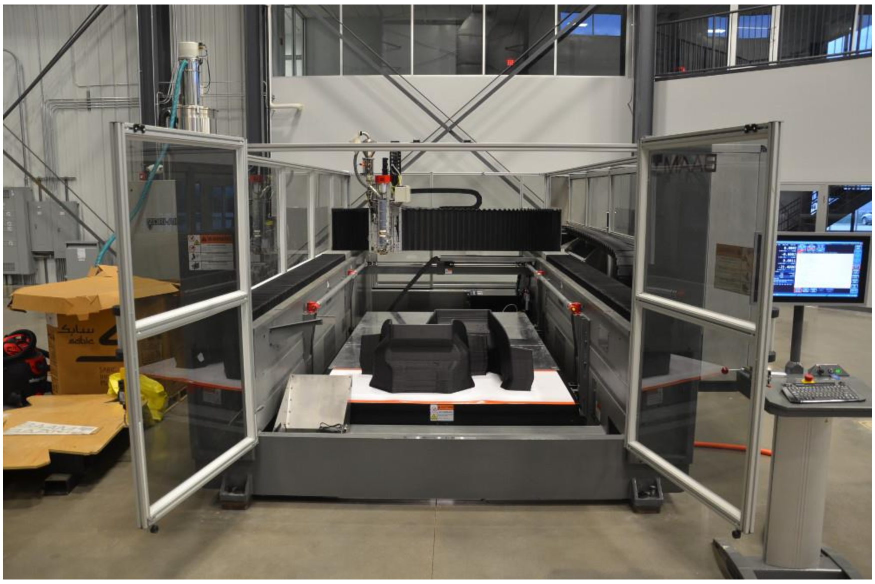


Figure 30: Big Area Additive Manufacturing System

In the BAAM system, the pelletized thermoplastic feedstock is melted, and melted material is deposited in thick beds of melted thermoplastic material along the path by using a single-screw extruder. With this technology, feedstock cost can be decreased by 20 times, build volumes can exceed 28.3 $m^3$, and deposition rate, which can exceed 41.000 $m^3$ per hour, can be increased almost 200 times compared to conventional polymer AM systems [1 20 21]. The BAAM printed elements have been investigated in terms of strength and stiffness, and results show that BAAM products can be utilized for certain limited-stiffness applications in construction [22].

### Existing BAAM Manufactured Structural Elements

#### a) AMIE

As a result of the Additive Manufacturing Integrated Energy Project (AMIE), which is performed by collaboration between the US Department of Energy's OAK National Laboratory and architectural company SOM, a cylindrical-single floor building (Fig. 31), which is the world's largest polymer 3D printed structure has been fabricated [21 23]. The structure has a footprint of 19.5 $m^2$ and a height of 2.8 m, and it contains ring-like segments in the interior section (Fig. 32).

---

[21] Biswas, Rose, Eikevik, Guerguis, Enquist, Lee, Love, 2016
[22] Compton, Post, Duty, Love, Kunc, 2017
[23] 3D Printed Building from Polymer for Off-Grid Living: SOM, 2020 Retrieved November 06, 2020, from https://www.arch2o.com/3d-printed-polymer-building-off-grid-living-som/.

Figure 31: Additive Manufacturing Integrated Energy Project

The segments were printed as half-rings with carbon fiber-reinforced acrylonitrile butadiene styrene (CF-ABS) by using BAAM. More than 6 tons of CF-ABS have been used, and printing took almost 225 hours [9]. After that, printed half-ring segments have been assembled to form a full ring shape, and then they have been joined with four steel roads along the direction of the building (perpendicular to the printing plane of the segments). The structure consists of half ring-shaped eleven major, nine interior segments, and two end walls (Fig.32).

Each printed C-shaped segment aims to constitute the building envelope and act as a surface membrane and ensure moisture protection and isolation within the structure [21] [23]. Apart from that, low strength and stiffness in the building direction (z-axis) of segments due to partial cooling of the extruded polymer were solved using the four steel roads along the length of structure [9].

Figure 32: Interior Section of AMIE, Components, and Sections

**Other Examples of Large-Scale 3D-Printers of Polymer Extrusion**

### a) Kamermaker

The ongoing polymer additive manufactured canal house (Fig. 33(a, b)) has started in Amsterdam/ Netherland in 2014 by DUS Architects. The company has been using its own 6 m tall large-scale 3D printer, which is called KamerMaker. The 3D printer can fabricate the 2.2x2.2 x3.5 m propylene blocks with 180 kg weight using the principle of extruding layers of molten biodegradable plastics [1] [24]. The project is aimed to be "zero waste" since all the blocks of it can be recycled, and the individual parts of the canal house will be completed on-site so that transportation cost can be eliminated [1] [25]. Exploded isometric view of the canal house is illustrated in Figure 33(c). The final structure will be a design museum with a footprint of 700 $m^2$, and it will be able to be disassembled, transported, and reassembled at another location.

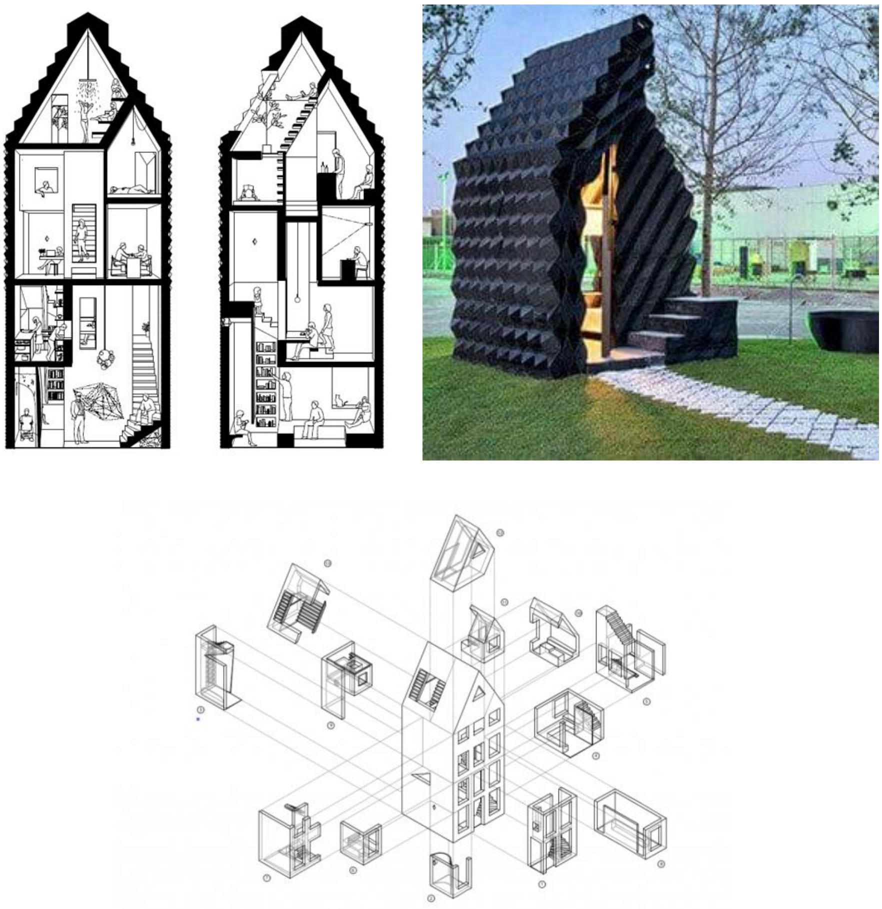


Figure 33: (a) Section of the Final Canal House (Top Left), (b) A 3D Printed Canal House Model, (c) Isometric View of the Canal House

---

[24] DUS, 2013, Work. Retrieved November 06, 2020, from https://houseofdus.com/work/.

[25] Hager, Golonka. Putanowicz, 2016

### b) The Digital Construction Platform (DCP)

The DCP is a 3D large-scale printer based on the extrusion of polymer-based materials created by the Massachusetts Institute of Technology. It consists of an extrusion nozzle controlled by a 6-axis robotic arm attached to a 5-axis hydraulic arm mounted on a mobile platform (Fig. 34) [9] [26].

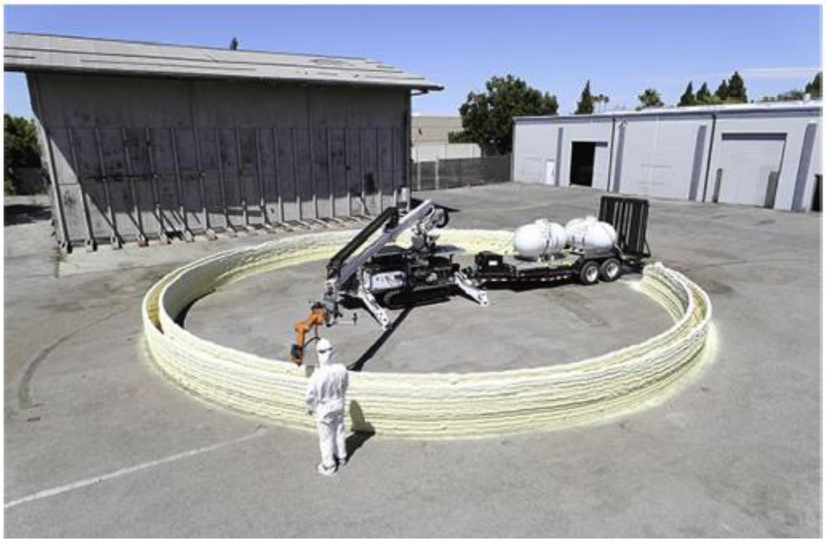


Figure 34: The Digital Construction Platform

A polymeric dome (Fig.35) with 14.6 m diameter and 3.5 m height was constructed in 13.5 hours [9] [26]. The dome has been constructed by using a two-component polyurethane closed-cell form.

Figure 35: The Dome Constructed by DCP

---

[26] Keating, 2016, Project Overview ' Digital Construction Platform. Retrieved November 06, 2020, from https://www.media.mit.edu/projects/digital-construction-platform-v-2/overview/.

## Powder Bed Fusion

While the powder bed fusion process has been explained in Chapter 2, a sub-technique of powder bed fusion is addressed here. Large-scale construction applications of the powder bed fusion process are performed by selective laser sintering (SLS), in which layers are applied repetitively on top of each other. In each layer, a selective laser heats the polymer particles, which then are fused in certain areas. With this technique, high resolution and quality can be achieved, but it is more expensive and slower than the material extrusion process [9]. Even though SLS applications are not common for structural elements due to their low strength and stiffness, they can be used as aesthetical and architectural applications.

### Existing SLS Manufactured Structural Elements

#### a) Polymer Cladding on Metal Connections

For the 6 Bevis Marks Building in London, SLS printed polymer cladding pieces were fabricated for welded steel nodes on column/roof junctions (Fig. 36) [27]. Even though the 3D printed cladding does not have a structural function, its principal aim is to protect structural elements from rain, heat, and sunlight action [9]. The construction company states that the SLS technique proved to be cost and time-saving compared to traditional cast iron solution [27].

Figure 36: (a) 6 Bevis Marks Building (Top)
(b) Column/Roof Connections of 6 Bevis Marks Building (Bottom)

The achievements with polymer additive manufacturing have been presented in this part. The following section discusses opportunities and challenges with polymer additive manufacturing at large-scale applications in construction.

---

[27] Skanska UK, n.d., Retrieved November 07, 2020, from https://www.skanska.co.uk/.

### 3.2.2 Opportunities and Challenges of Polymer Additive Manufacturing in Construction

With polymer additive manufacturing, deposition rate and feedstock cost are decreased, but it has also been shown that polymer additive manufactured elements can be used as load-bearing members by themselves, like in AMIE [9].

However, there are two major challenges related to the BAAM system. The first constraint can be the limitation of no unsupported horizontal overhang. A maximum 40-45° horizontal angle between subsequent layers of printed material is required while cantilever or overhang is over the unsupported space so that an insufficient contact can occur, and printed material can sag [21]. For this reason, straight walls with corners or edges can be a challenge for 3D polymer printing because of maximum angle limitation between subsequent layers during cantilevering. However, the problem was solved in AMIE's case by keeping the cantilever angle of exterior rings less than 40° [21]. The second challenge can be anisotropic mechanical properties in the axis. In other words, it is the structural weakness of printed CF-ABS in building direction due to partial cooling. However, the problem was solved thanks to four steel post-tension roads running the complete length of the structure [21].

One of the major challenges is the environmental impact of construction materials production, which often requires a high demand of cumulative energy, and they are hard to recycle. However, recent studies show that manufacturing polymer materials' cumulative energy demand can be reduced by 41-64%, and emissions during manufacturing can be reduced by almost 89% by using additive manufacturing alternative to conventional additive manufacturing [28]. 3D printed canal house showed that waste material could be reduced to zero since all the utilized materials can be recyclable.

### 3.2.3 Discussion

Even though polymer additive manufacturing brought opportunities with recent research and attempts to the construction sector, there are remaining challenges related to cost, material, and design [1 9 21 28 29]. With the low-cost sustainable materials with high structural efficiency, advanced 3D printers with proper software should be converged to accelerate the development of 3D printing polymer materials and enrich the functionality and integration of 3D printed polymer structures design [1 9 21 28 29].

---

[28] Kreiger, Pearce, 2013

[29] Zhou, Fu, He, 2020

## 3.3 Additive Manufacturing of Metal Elements in Construction

Metal additive manufacturing is one of the most common techniques used within the construction sector, thanks to its high mechanical properties and great flexibility in designing structural elements. Certain metals such as stainless steel, carbon steel, titanium, and aluminium are more used in additive manufacturing than soft metals like copper and bronze. Steel products can be applied for general purposes and for places where high strength is required. Titanium and its alloys are also used for high strength required areas. Besides that, since their traditional production is costly, additive manufacturing can lead to major cost-saving [9] [30]. In comparison, aluminium and its alloys are easy to manufacture conventionally, so they are not so common as titanium in 3D printing [9] [30].

In 3D printing metallic elements at large-scale construction, powder bed fusion (PBF), and directed energy deposition (DED) are the most suitable approaches. These approaches have different practicality, scalability in the construction sector, and their specific deposition processes, limitations, and characteristics are discussed in the following section.

### 3.3.1 Metal Additive Manufacturing Techniques and Strategies

Powder bed fusion (PBF) and directed energy deposition (DED) have already been discussed in Chapter 2, but their application with metals is addressed here, respectively.

### Powder Bed Fusion

Powder bed fusion is a metal additive manufacturing process. The main technologies for metals are laser beam sintering, electron beam sintering, and direct metal laser sintering. The main procedure starts with spreading metal powder across the work area to create a powder bed in all techniques. Then, depending on the used technique, the powder bed is melted or sintered using a thermal energy source (which can be a laser or an electron source) to make the powder become the desired final shape and continues until the final 3D object is fabricated. PBF process utilizes metal powders with particle sizes between 45-100 microns, so this feature makes the process provide high resolution, high-quality control, and effectiveness in fine details [1] [30] [31]. As a result, surface roughness can be achieved as less than 20 µm [3]. However, the deposition rate is relatively low, and it can be only suitable for small sizes with complex geometries [1] [31]. In the early uses of metal additive manufacturing, mainly powder bed fusion has been used to fabricate modest scale structural components.

---

[30] Menges, Sheil, Glynn, Skavara, 2017

[31] Frazier, 2014

## Existing PBF Manufactured Structural Elements

### a) Nematox Façade Node

The Nematox façade node is fabricated thanks to a cooperative research project at the University of Applied Sciences at Detmold from 2008 to 2010. The idea has been evolved to show the applicability of additive manufacturing to achieve façades with geometrical freedom [32] [33]. The final full-size prototype (Fig. 37) was printed 76.5 hours by utilizing aluminium powder using the powder bed fusion process.

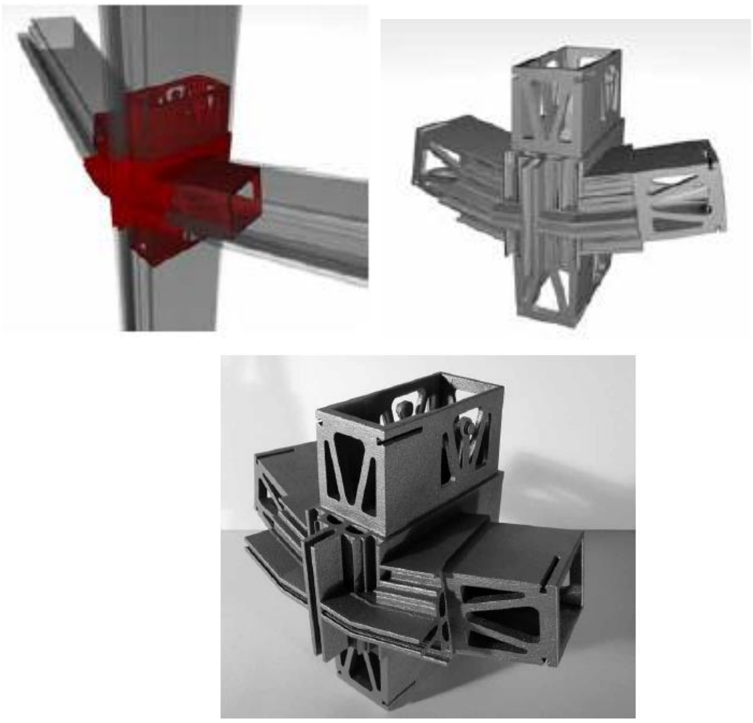


Figure 37: (a) A Rendering of Nematox Façade Node (Left),
(b)A Full-Size Aluminium Prototype (Right), (c) Printed Node (Bottom)

### b) Arup Lighting Node

The research is based on the redesign of an existing tensegrity lighting node to take advantage of new production opportunities presented by additive manufacturing. Arup was responsible for designing tensegrity (tensional integrity) street lighting structures in Grote Marktstraat in Hague /Netherland. The original design (Fig. 38(a)) was an irregular shape of structure with slightly different shapes of 1.600 structural nodes and 1200 variations of attached cables in terms of angle and position. The nodes aimed to contain up to seven conventionally manufactured unique steel plates welded on a central tube [1] [34]. Figure 38(b, c) illustrates the original design of one of the structural nodes.

---

[32] Strauss, 2013
[33] Strauss, Partner, Knaack, 2016
[34] Galjaard, Hofman, Ren, 2015

Figure 38: (a) Rendering of One of The Original Tengerity Lighting Structures (Top),
(b) Model of Structural Node and Light Fixture (Bottom Left),
(c) A Model of Traditional Node (Bottom Right)

The Arup Lighting Node research project has been started and executed separately from the original design project. During the research project, a three-step method has been followed: topology optimization, production of optimized design, and detailing the original design for comparison. Firstly, topology optimization has been applied to the previous design to generate an optimal form. The design was then adjusted to reduce utilized materials, minimize production cost, speed up the deposition, and make the structure self-supporting in the additive manufacturing process. The optimized node on a 40% scale was then fabricated using powder bed fusion with ultra-high strength maraging steel powder. On a 40% scale, the original design node was produced with galvanized steel using the traditional technique of cutting and welding in order to compare the original and optimized design in terms of economy and production. Both of the structural nodes and their design in the structure are illustrated in Figures 39 and 40.

Figure 39: A Model for Traditional Node on 40% Scale (Left) and A Model for Optimized Node on 40% Scale (Right)

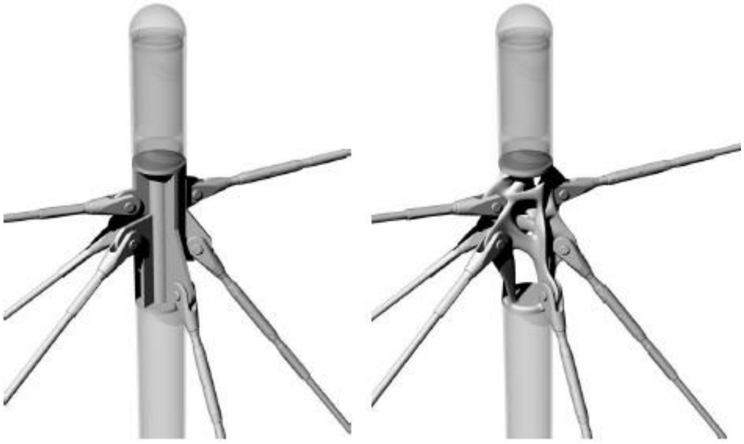


Figure 40: Model of Traditional Structural Node (Left) and Model of Optimized Structural Node and Light Fixture (Right)

In terms of cost comparison, according to results in 2014, the AM structural node was almost three times more expensive than the conventional one [1] [34]. In terms of mechanical properties, it was noted that both of the nodes could bear the same design loads and forces by demonstrating the calculated stresses, as shown in Figure 41. In the Figure blue areas correspond to lower stress areas and the red areas are for high stress.

At the end of the first iteration, the ARUP team decided to redesign the node to reduce the total size by removing 60% material from lower stress areas so that weight and the cost can be reduced [34].

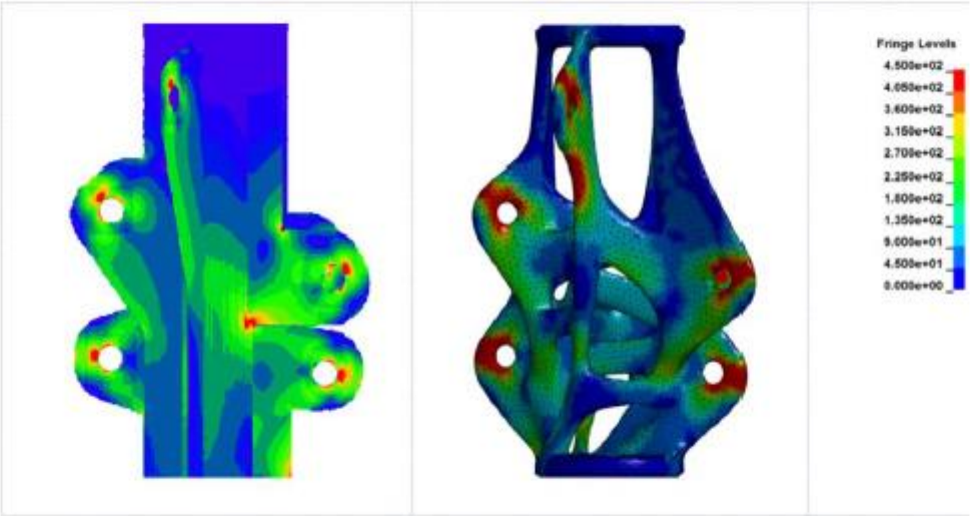


Figure 41: Calculated Stresses on Traditional Design (Left) and Optimized Design (Right) [34]

A second iteration of the structural node redesign was performed to benefit from the lessons learned from the first iteration. The new design (Fig. 42(a)) was produced utilizing topology optimization, and afterward, it was manufactured with 316L stainless steel powder using the powder bed fusion process. Its cost was more expensive than the conventionally manufactured node, but it was 75% lighter with and half the height. Therefore, the second iteration led to the entire tensegrity lighting structure to be 40% lighter and less expensive [1 9]. Besides that, tensile strength and ductility have resulted as sufficient based on testing on 3D printed specimens [9]. However, all the tree nodes (Fig. 42(b)) can carry the same design load, even though they have different heights and weights [35].

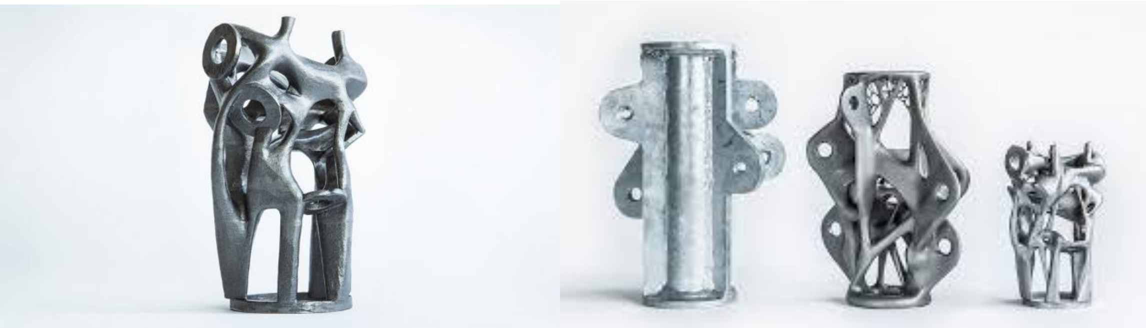


Figure 42: (a) The Second Design of Structural Node (Left), (b) Evaluation of The Node from Conventionally Manufactured to Second Iteration from Left to Right (Right)

---

[35] Design method for critical structural steel elements, n.d, Retrieved November 12, 2020, from https://www.arup.com/projects/additive-manufacturing

## Directed Energy Deposition (DED)

As discussed in Chapter 2, in directed energy deposition, a metallic powder or a wire is being fed into a focal point of a laser, an electron beam, or electric arc that results in a molten pool on the printed surface structure to generate an additional layer. There are two techniques: laser metal deposition (LMD) that utilizes a laser and a metal powder, and wire and arc additive manufacturing (WAAM) that utilizes an electron beam and a wire [1] [9]. In contrast to the powder bed fusion process, the directed energy deposition process, particularly wire and arc additive manufacturing, is faster and well-situated for large scale structural applications [1] [36].

### Wire and Arc Additive Manufacturing

According to ASTM F 2792-10, WAAM is categorized under the category of directed energy deposition [37]. It is the combination of an electric arc as a thermal source and a wire as a feedstock [38] [39]. Furthermore, it can be sorted into three main groups based on different heat sources adopted: Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding, and Plasma Arc Welding (PAW). WAAM's layer height ranges from 1 to 2 mm with a high deposition rate (4-9 kg/h), which can be used to manufacture limited part sizes with expected surface roughness around 0.5 µm [1] [36] [38]. It cannot be considered a net shape process since built parts must be machined so that the desired shape and surface finish can be achieved [1] [36] [38]. Thus, it is suitable for medium to large scale parts with low to medium geometric complexity [1] [36] [38]. Compared to other AM processes, WAAM is considered cost-effective since the use of standard off-the-shelf welding equipment such as welding power source, torches, and wire feeding system makes WAAM even more suitable for the construction sector [1] [36].

### Existing WAAM Manufactured Structural Elements

#### a) The MX3D Bridge

A good example of AM large-scale application is the MX3D bridge (Fig. 43 (a, b)), developed in partnership with MX3D, ARUP, and researchers from Imperial College (London/United Kingdom) [40]. The bridge is the first additively manufactured fully functional stainless-steel bridge with a width of 2.5 m and a span of 10 m, which is planned to cross one of the oldest and most famous canals in Amsterdam/Netherland [1] [9] [40]. Continuous printing strategy, which means the material is deposited continuously, is used with 308LSi austenitic stainless steel as the utilized welding wire using a 6-axis robotic welding arm [1] [36].

---

[36] Laghi, Palermo, Gasparini, Girelli, Trombetti, 2020
[37] ASTM F2792-10, 2010
[38] Williams, Martina, Addison, Ding, Pardal, Colegrove, 2016
[39] Laghi, Palermo, Tonelli, Gasparini, Ceschini, Trombetti, 2020
[40] MX3D Bridge. n.d., Retrieved November 14, 2020, from https://mx3d.com/projects/mx3d-bridge/.

Figure 43: (a) The Frame (Top) and (b) The Completed Form (Bottom) of MX3D Bridge

After completing the bridge, it was exhibited in Dutch Design Week in 2018, and after passing the last 20 tons of load test conducted by UT Twente, the bridge is aimed to be placed.

### b) MX3D Takenaka Connector

After the accomplishment in the MX3D bridge, a structural steel connector has been manufactured in collaboration with MX3D and engineers from Takenaka (a Japanese architecture and construction company) with the help of topology optimization (Fig. 44), to generate the most efficient shape, and using robotic 3D printing system in WAAM process [41].

---

[41] TAKENAKA CONNECTOR, n.d., Retrieved November 14, 2020, from https://mx3d.com/projects/takenaka-connector

Figure 44: Topology Optimization of The Steel Connector

After reaching the connector's optimal hollow structural shape (Fig. 45), it has been printed with duplex stainless steel due to its good mechanical properties and corrosion resistance. It has a net weight of 40 kg, but the hollow geometry has been filled post-print with concrete since inner concrete prevents the local buckling of steel and load the outer steel in bending and in tension, thus the final weight is 45 kg [41] [42].

Figure 45: The Final Form of The Structural Steel Connector [1]

---

[42] MX3D Takenaka Connector. Retrieved November 14, 2020, from http://additivemanufacturing.com/2019/12/11/mx3d-takenaka-connector/

### 3.3.2 Opportunities and Challenges of Metal Additive Manufacturing in Construction

Metal additive manufacturing offers tremendous opportunities within the construction sector, but it brings challenges related to the current state of technology and inherit problems in manufacturing techniques such as anisotropy in material mechanical properties and residual stresses.

**Opportunities**

#### a) Design Flexibility and Optimization of Material Properties

Additive manufacturing's geometric flexibility allows highly efficient and optimized structures by topology optimization, a computational process that varies from material placement to attain specific mechanical properties under specified loadings and geometric constraints [1 9 34]. AM combines topology optimization and manufacturing to fabricate optimized structures for their desired function without the usual fabrication restrictions [1 33 38]. Besides that, more controlled mechanical behaviour can be obtained by modifications in construction materials. In other words, strength and ductility within the structure can be optimized by using high strength materials in the areas where high forces and moment are present such as midspan of a beam, and by using higher ductility in which ductility demand is high or to fabricate structural components with specific thermal and acoustic purposes. Furthermore, this feature can reduce stiffness so that the forces and bending moments are distributed most conveniently, and energy-absorbing elements for structures can be produced in seismic zones [1].

The ability to place materials where it is required to match the most structurally optimum locations' demands can reduce the material consumption and waste and, consequently, the cost [1]. As discussed in the ARUP lighting node research project, with topology optimization, a more efficient structural node with less material usage, thus lower weight, by eliminating lower stress regions and the same mechanical properties has been obtained [38].

#### b) Mass Customization

With AM's help, highly individualized structural components can be fabricated at the same cost as a standard part since cost/price does not depend on the complexity [1 38]. In other words, the manufacturing cost for two identical components or two different variations of the same component is the same. According to Buchanan (Buchanan 2018), "AM offers far greater customization opportunities than traditional manufacturing methods, and this customization will likely create additional demand for additive manufacturing, which in turn will help to lower costs" (p.12) [1].

### c) Structural Strengthening and Repair

Metal additive manufacturing techniques, particularly the directed energy deposition (DED) process, offer an opportunity to repair or strengthen damaged or corroded structural metal elements; thus, the repair or strengthening cost can be reduced [1 9]. This opportunity of AM to restore historical buildings is discussed in detail in Chapter 4.

Apart from the opportunities specifically for metal additive manufacturing, as discussed in the concrete and polymer additive manufacturing, it reduces the labour costs and reduces the risk of human error during the manufacturing process [1 31 38]. It consumes less energy, and the environmental impact is relatively low compared to traditional manufacturing [1 31 38].

### Challenges

### a) Anisotropic Behaviour and Residual Stress

With the help of metal AM, it is possible to obtain almost the same mechanical properties as conventional manufacturing [1 9]. However, a printed metal part's tensile property depends on the microstructure built by complex thermal cycles with repeatedly heating and cooling processes because of overlying the layers. Because of the higher cooling rate, microstructures are finer than the traditional manufacturing ones, and in this way, high tensile mechanical properties can be obtained [1 9]. However, the thermal cycles cause anisotropic behaviour in mechanical properties, particularly in the perpendicular direction to the printing plane, but it can be solved by heat treatment [1 9].

As a second negative consequence of high heat input associated with arc sources: the residual stresses and distortions which result in shrinkage during cooling and present largely in deposition direction [1 9 31]. However, residual stresses can be mitigated using three principal methods: symmetrical building (moving outward from the axis of symmetry), back-to-back building (building two identical components symmetrically back-to-back simultaneously), and heat treatment [1 9 31].

### b) Standards and Tests

A current major challenge of metal additive manufacturing, as also discussed in concrete additive manufacturing, is the lack of standards and guidelines to design, and existing structural design methods will need to be updated and rethought for the verification of metal AM construction [1].

### c) Cost

The cost differences between additive manufacturing and conventional manufacturing in terms of manufactured structures vary in each project, depending on the individual cost implications for design, labour, material, and equipment cost [1].

Buchanan (Buchanan 2019) states that additive manufacturing can be competitive with traditional manufacturing in low volume production within the construction sector, even though it is not common in non-complex standard elements production due to traditional manufacturing techniques are very rapid and effective for them [1].

From a similar point of view, Frazier (Frazier 2014) states that if manufacturing cost can be divided as a fixed cost and recurring cost [31]. The fixed cost compensates the cost over the number of manufactured items such as tools, dies, and buildings [31]. While the recurring costs depend on the part produced, such as materials and labour costs [31]. In terms of fixed costs, conventional manufacturing would have a higher cost than additive manufacturing, but it is less expensive than additive manufacturing in recurring cost [31]. Thus, conventional manufacturing is more suitable for large scale volumes, and additive manufacturing becomes more suitable for small scale volumes [31]. However, he adds that additive manufacturing has opportunities in logistical footprint, cost, and energy in storage, packing, and transportation [31]. Table 5 explains the theory based on the cost analysis of Frazier.

Table 5: Factors Favoring Additive Manufacturing Vice Conventional Manufacturing [31]

| **FAVOR ADDITIVE MANUFACTURING** | **FAVOR CONVENTIONAL MANUFACTURING** |
|---|---|
| Low production volumes | Large production volumes |
| High material cost | Low material cost |
| High machine cost | Easily processed /machined materials |
| Capital investment | Centralized manufacturing |
| Logistic cost | |
| Transportation cost | |
| Prototyping | |

In order to show the cost differences between these two-manufacturing methods, Mrazovic (Mrazovic, 2018) has manufactured two independent metallic components, which are a window frame with dimensions of 1.5 × 4 × 0.1 m and a bracket that is 25 × 30 × 1 cm in both techniques separately [43]. At the end of the case studies, Mrazovic states that the cost to produce the bracket with additive manufacturing was 4 to 10 times greater than CM, and the duration of the manufacturing phase was 2 to 8 times longer, while the cost to produce the frame with additive manufacturing is almost 7 times greater [43]. However, he states that additive manufacturing is feasible to reduce environmental impact [43].

---

[43] Mrazovic, Baumers, Hague, Fischer, 2018

To sum up, even though metal additive manufacturing is considered expensive compared to conventional manufacturing, it presents a potential for cost and material saving in the future, and further cost reductions are expected due to the rapid pace of new developments in technology [1 9 31 43].

### 3.3.3 Discussion

Metal additive manufacturing is a rapidly growing technique allowing new geometrical forms produced relatively cheaply and quickly and providing increased variability in dimension and surface for structural and architectural applications [1 30.] Powder bed fusion (PFB) and directed energy deposition (DED) are the two most suitable techniques for the sector as the MX3D 3D printed metal bridge proved; thus, they have been utilized to build very highly optimized, light, efficient structural parts, as ARUP lighting node [1 9 31 35 43]. Further research and studies are needed so that the current challenges like cost and production time can be tackled [1 9 31 35]. However, the design freedom, material savings, limited storage, and transport costs and possible installation benefits and the completed 3D metal projects are concrete proofs that show that metal additive manufacturing can be compatible with the conventional metal manufacturing [1 9 31 35]. Thanks to further research, metal additive manufacturing can become much more economical and efficient in the construction sector [1 9 31 35 43].

To conclude Chapter 3, Table 6 summarizes the discussed opportunities and challenges of concrete, polymer, and metal additive manufacturing in the construction sector.

Table 6: A Summary of Opportunities and Challenges of Concrete, Polymer and Metal Additive Manufacturing in Construction [19]

| MATERIAL | CONCRETE | POLYMER | METAL |
|---|---|---|---|
| OPPORTUNITIES | • Good control on microstructure and composition<br>• Mass customization<br>• No formwork<br>• Less labour requirement | • Fast prototyping<br>• Cost-effective<br>• Complex structures | • Multifunctional optimization<br>• Mass customization<br>• Reduced material waste<br>• Possibility to use in strengthening applications |
| CHALLENGES | • Layer by layer appearance<br>• Anisotropic mechanical properties<br>• A limited number of techniques<br>• Difficulties in upscaling the larger buildings mass customization | • Weak mechanical properties<br>• A limited selection of polymers<br>• Anisotropic mechanical properties | • A limited selection of metals<br>• Anisotropic mechanical properties<br>• Post-treatment might be required |

# Chapter 4

# Additive Manufacturing in Restoration

The conservation of historic buildings encompasses a complex and wide set of interventions, spanning seven levels of intensity: prevention of deterioration, preservation, consolidation, restoration, rehabilitation, reproduction, and reconstruction [1] [2] [3]. These different actions are intended to be adopted in different scenarios, according to the large variety of shapes, conditions, and materials in historic buildings [1] [2] [3]. The restoration can involve manufacturing and replacement of a damaged or missing element of a historic building, but there are many deontological discussions regarding this degree of intervention. Currently, the replacement is often manually performed by skilled workers. After showing great potential in construction, additive manufacturing has started to be investigated as a promising option in the restoration of historical buildings, especially for repair and restoration of ornamental elements, in-situ structural strengthening, or reconstruction of damaged parts due to war or natural disasters [2] [4] [5] [6]. Even though this technology is still new in the restoration of historical buildings, the additive manufacturing techniques using concrete, metals by the directed energy deposition process, and polymers appear applicable in this field [3] [7] [8]. This chapter provides an overview of the possible AM applications for the restoration of facade ornaments and structural strengthening of historic buildings' load-bearing elements. The challenges and opportunities of AM in historic buildings restoration are presented, then the available techniques and their applications are discussed. The aim is not to replace craftsmanship by additive manufacturing but to exploit AM's potential in shaping elements based on original form and material, therefore able to better comply with the conservation requirements by mixing tradition and technology in optimizing the restoration process.

---

[1] Feilden, 2009
[2] Xu, Ding, Love, 2017
[3] Tomlan, Jokilehto, 2004
[4] Wahab, Azman, 2019
[5] Utesena, Pernicova, 2018
[6] Vanhellemont, 2016
[7] Buchanan, Gardner, 2019
[8] Paolini, Kollmansberger, Rank, 2019

## 4.1 Possible Non-Structural and Structural Applications of Additive Manufacturing in Historic Building Restoration

Many studies have been carried on digital manufacturing to support intervention projects to restore cultural heritage, especially using photogrammetry or 3D scanners as a source. However, additive manufacturing is still new in this field, and it is currently used only as a tool in the intermediate stage of the restoration process of architectural or structural elements [6] [9].

### 4.1.1 Non-Structural Applications

**Rapidly Forming a Prototype**

Prototype manufacturing has two principal steps: creating a 3D digital model using a CAD program or 3D scanning, and prototype manufacturing of a desired historical object based on the created digital model. Using the manufactured prototype, the aimed historical element can be restored in a traditional manner or an additive manner [5] [6].

**a) Reproduction of a Gothic Arch**

In Czech Republic, the National Technical Museum (NTM-Prague) and 3Dess 3D printing company were reproduced a gothic arch (Fig. 46) for the occasion of the exhibition "Civitas Carolina or construction period of Charles IV." The arch reproduction has been performed using 3D scanning (Artec Eva optimal scanner) and 3D printing with fused deposition modelling (FDM) process [5] [10]. During the reproduction process, a composite powder was utilized to achieve the tactile touch-feeling proximity of original sandstone material for blind visitors [5] [10]. The printed arch (Fig. 46) was then cleaned and impregnated with epoxy from the excess powder [5] [10].

---

[9] Moreira, Vieira, Xavier, Cardoso, Nogueira, 2017

[10] 3D tisk v praxi - Portál reference, n.d., Retrieved November 26, 2020, from https://www.3dees.cz/3d-tisk-v-praxi/spoluprace-narodniho-technickeho-muzea-a-3dees-3d-skenovani-a-3d-tisk-artefaktu-a-jejich-vyuziti-nejen-pro-zrakove-postizene-navstevniky.

Figure 46: The Reproduction of Gothic Arch (Left), The Original Gothic Arch (Right) [10]

### b) Reproduction of Stone Pedestal (Plinth) of a Historic Column

Curved shape stone plinths (Fig. 47) are commonly used in historical Chinese timber construction with the purpose of delivering the upper load, water resistance, collision avoidance, lateral support, and aesthetics.

Figure 47: Curved Shape Stone Plinths

At Huazhong University of Science and Technology, a curved surface damaged stone plinth has been used as part of additive manufacturing research to show the digital reproduction process's feasibility. First, to reproduce the column plinth, dimensional and geometrical information has been obtained by a handheld light structure 3D scanner (Creaform MetraSCAN 3D) to create the digital model. It has been manufactured as two half plinths by material extrusion process with a fine aggregate fiber cement mortar. The aim was to reproduce the plinth with the similar physical properties of the original stone in terms of color, tone, texture, form, and scale; thus, the requirements embedded in conservation ethics can be satisfied [2] [5]. After the reproduction of two plinth parts, they were polished and painted to obtain an effective surface finish, then they were joined (Fig. 48). The final printed plinth has a shape of a curved cup with four layers of circular hollow inside it, and it has a width of 70 cm in diameter of the bottom surface and an approximate height of 40 to 80 mm[2]. As a final step, two halves of the plinth to enclose the column were assembled using a structural adhesive (Fig. 49).

Figure 48: The Final Printed Plinth [2]

Figure 49: Installation of the Plinth [2]

According to conducted compressive tests on the printed plinth, ultimate compressive strength ($f_{cu, concrete}$) in vertical and lateral direction was 19.8 MPa and 15.6 MPa, respectively [2]. Even though the compressive strength of the printed cement base plinth is lower than the original stone plinth, the research has presented additive manufacturing potential to restore historical architectural elements [2] [5].

**Rapidly Forming a Mould + a Prototype**

For the complex geometrical forms such as eclectic ornaments, additive manufacturing offers a great opportunity for the reproduction of moulds+prototypes alternative to classical production techniques [6] [9]. The 3D printed moulds are stable, easily transportable, and the mould dimensions can be produced slightly bigger than the aimed prototype to consider the final 3D printed element's shrinkage. The technique is commonly used to produce concrete moulds in the restoration of historic buildings. Thus, it can produce complex-shaped metal elements with rich details such as columns and balconies, as well [6] [9].

### a) Modern Ornamental: A New Form of Digital Structure

A New York based architectural firm EDG has an ongoing restoration project on a building's façade dating from 1940 on 574 5th avenue in New York City/ USA. Before the restoration project by EDG, the building (Fig. 53(a)) was set to be demolished due to the high cost of traditional restoration and difficulties in reproducing complex ornamental elements on the façade. Intending to perform restoration of the facade, the company has developed a "Modern Ornamental" technique.

The technique involves rendering software coupled with algorithmic modelling programs to obtain renders of an aimed element [11] [12] [13]. Then, based on obtained renders, ornamental elements were printed by using Replicator Z18 3D printer. In the printing stage, the fused deposition modelling process was used to manufacture plastic moulds with different shapes (Fig. 50).

Figure 50: One of The 3D Printed Plastic Moulds [13]

After completing the final form of 3D printed plastic moulds, 3D printed stirrups integrated with 1/16 laser cut wire mesh were placed inside the moulds to work as reinforcements. Afterwards, the moulds were respectively filled with standard and coloured concrete by Voxel Jet VX100 3D printer. Figures 52 and 53 illustrate the procedure, and one of the printed ornamental elements, respectively.

---

[11] Martel, 2018, 3D printing takes on the restoration of a historic building. Retrieved November 27, 2020, from https://www.3dnatives.com/en/edg-architecture-3d-printing110620184/.

[12] Chi, 2018, Modern Ornamental - A New Form of Digital Sculpture: EDG Architecture: Engineering. Retrieved November 27, 2020, from https://archinect.com/firms/release/53511492/modern-ornamental-a-new-form-of-digital-sculpture/150063267.

[13] Architecture, Engineering and Consulting Firm: EDG Architecture and Engineering, n.d., Retrieved November 27, 2020, from https://edgnyc.com/?case_studies=607.

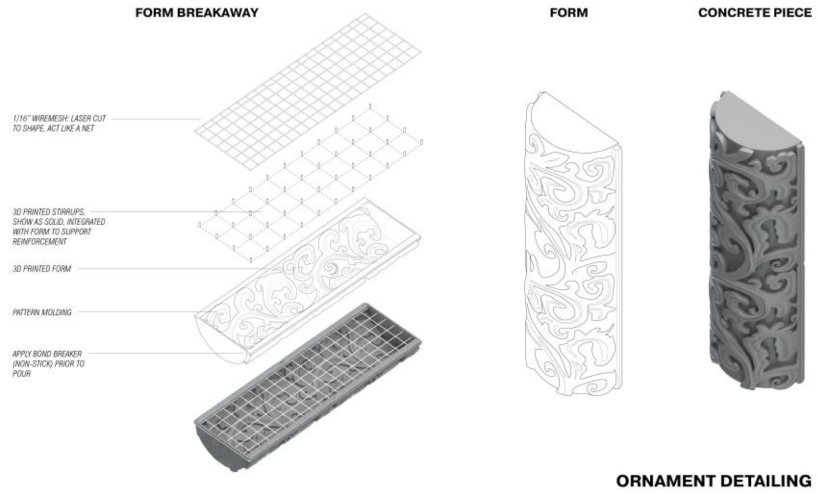


Figure 51: The Procedure of 3D Printed Concrete Façade Ornaments [13]

Figure 52:3D Printed Facade Ornament [13]

The building is still undergoing the restoration project, but a rendered image of the building's final form is illustrated in Figure 53(b).

Figure 53: (a) Original Form of The Building's Façade (Left), (b) The Rendering Image of The Buildings' Façade (Right)

### b) Comparative Analysis on Reproduction of Eclectic Ornament

The Foundry Laboratory of the Federal University of Ceará has conducted a comparative analysis to reproduce an eclectic metal ornament (Fig. 54 (a)) using low wax casting. The element is located on top of a pillar, outside of the Mercado dos Pinholes in Fatoleza/Brazil (Fig. 54 (b)). The low wax casting principle is based on producing a wax counter mould placed inside a container and filled with plaster or similar material. As soon as it hardens, the set is heated until the wax melts and leaves the mould. Finally, the metal is melted and poured into space inside the mould to produce the final metal object.

Therefore, the aim was to find the most suitable technique to reproduce a wax counter mould to reproduce the metal element. A comparative analysis was performed between additive manufacturing and CNC machine.

Figure 54: (a) Chosen Metal Eclectic Ornament [9] (Left), (b) Mercado dos Pinholes in Fatoleza/Brazil (Right)

The workflow was started with the photogrammetry to generate a 3D digital model of the chosen ornament with dimension of 0.26x0.12x0.1 mm, then additive manufacturing and CNC machine were performed respectively [9]. In the additive manufacturing stage, the model (Fig. 56) was fabricated half-scale. The fiber deposition modeling process has been used by utilizing PLA filament in Felix Printer 3.1. After that, the mould was printed to make possible the wax copies. In the traditional manufacturing stage, a CNC machine was used to mill three different materials: a block of wax, styrofoam, and MDF to manufacture the model [9].

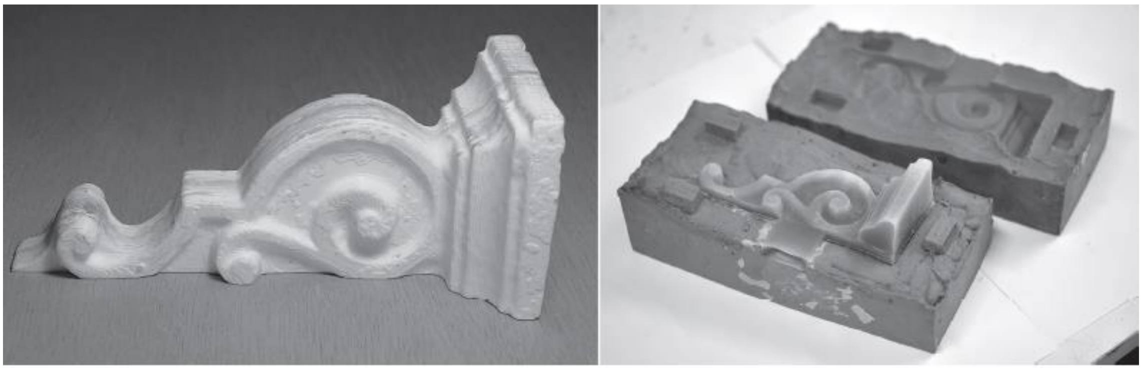


Figure 55: The Printed Model (Left) and The Silicone Mould (Right) [9]

Figure 56: Final Metallic Element in 1:2 scale [9]

At the end of the comparative analysis, it was concluded that the use of 3D printing to produce a mould was easier, but the procedure took more time [9]. However, higher-quality results could be achieved with other types of 3D-printers or other additive manufacturing techniques [9].

### 4.1.2 Structural Applications

Current applications presented in the published articles mainly concern non-structural applications of additive manufacturing. However, it is currently beginning to be used in structural applications as well. An external structural wall was manufactured using additive manufacturing to connect two floors to a damaged building's structural rehabilitation. Moreover, 3D printed secondary structures like formworks are planning to be used in restoration projects of Orthodox churches in Ukraine.

#### a) 3D Printed Formwork for Erecting Vaulted Covering

In Ukraine, a research team at Kharkiv National University of Civil Engineering and Architecture has started an ongoing theoretical justification of applying additive manufacturing to fabricate formworks of vaults in Orthodox churches. With this aim, formworks with dimensions of 1.2x1.2x1.2 m are planned to be manufactured in an additive manner by using a composition of secondary polyethylene and secondary polystyrene [14] [15]. Using additive manufactured formworks, they aim to solve several problems associated with the restoration of Orthodox churches' vaulted structures dating before 1920 in Ukraine [14] [15].

#### b) Democrite Wall

Democrite is a wall element sized by 1.36x1.5x0.17 m, which was the first achievement of the XtreeE team. It was built in 42 hours, using a 6-axis robot arm [16]. Democrite wall was designed to be used as an external structural wall connecting two floors in the rehabilitation project of a damaged building [17]. The architectural context and the CAD drawing of this element are illustrated in Figure 57.

---

[14] Lykhohrai, Goncharenko, Varanenko, 2017.

[15] Lykhohrai, Spirande, Goncharenko, 2017.

[16] Democrite wall. Retrieved October 18, 2020, from https://xtreee.com/en/project/mur-democrite/.

[17] Gosselin, Duballet, Roux, GaudilliEre, Dirrenberger, 2016

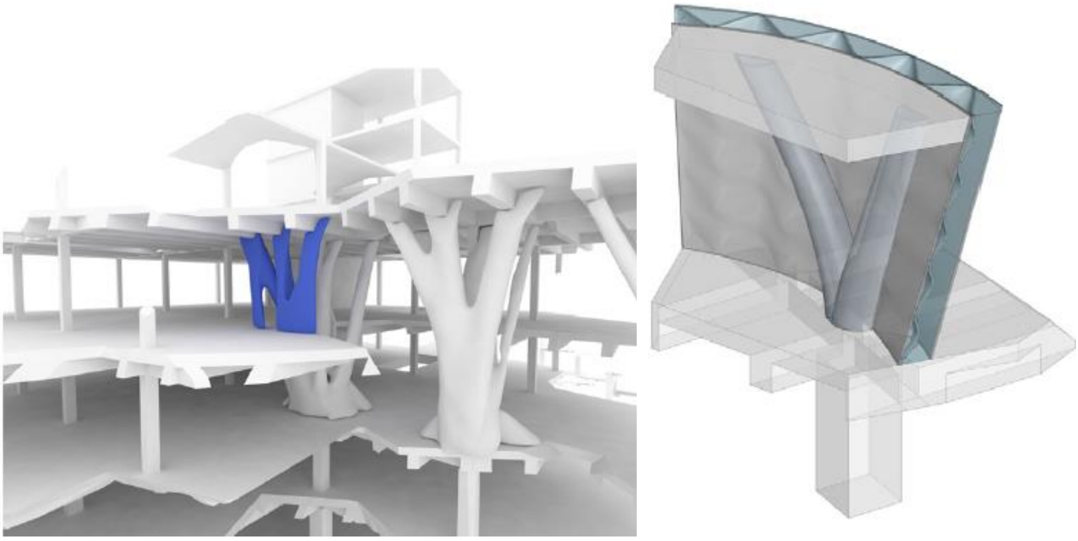


Figure 57: Architectural Contex (Left) and CAD Model of Democrite Wall (Right) [16]

The democrite wall is made up of fiber reinforced concrete poured in absorptive formwork using the 3DCP technique. The absorptive formwork contains two column-like parts linked to two straight plates where a bi-sinusoidal shell is formed in between (Fig. 57). The shell acts as a load-bearing member since it contains straight reinforcements that form a truss. Furthermore, It improves flexural rigidity of the systems since it acts as a double corrugated reinforcement. Apart from the structural point of view, it could be used for thermal insulation due to its geometrically optimized shape if an insulating material like foam was used. Moreover, some parts are intentionally left to insert cables or electrical wires, as is illustrated in Figure 58.

Figure 58: 3DCP Democrite Multifunctional Wall Element [16]

## 4.2 Potential Applications

Additive manufacturing presents a great opportunity beyond the discussed structural and non-structural examples, and in the following section, potential applications are discussed.

### a) In Situ Repair and Restoration

Potential benefits of using additive manufacturing for repairing damaged structures / structural elements by updating the design and structurally strengthen are significant opportunities [7] [8] [18]. In other industries like marine, aerospace, and automation, the potential of repairing parts using additive manufacturing has already begun to be investigated, such as Siemens Energy, where additive manufacturing technology is used to repair industrial gas turbines and compressors up to 60% faster and even upgraded to the latest part design [19]. With the additive manufacturing technology, maintenance or in-situ repairs can be performed using machines that can scan the structure, detect the areas needing a repair, and perform the repairs [4] [7] [8] [18] [19] [20].

### b) Infrastructure Repair

Additive manufacturing has a future opportunity to be used in limited access areas and tough conditions. It can be achieved with robotic arms that can add repair material and avoid labor exposure in damaged structures due to natural disasters [18] [20]. Besides that, additive manufacturing can be utilized to construct a temporary support structure inside the damaged building so that inspection and restoration can decrease the risk to human life [18] [20].

### c) More Elaborated Techniques in Moulding

3D printed complex concrete moulds with 3D printed reinforcements and 3D printing applications for lost moulds of structural or non-structural elements can be future applications to restore historic buildings with the new developments [6].

---

[18] Camacho, Clayton, O'Brien, Seepersad, Juanger, Ferron, Salamone, 2018

[19] Additive Manufacturing (AM) opens up huge opportunities by revolutionizing the manufacturing and repair of components., n.d., Retrieved November 29, 2020, from https://www.siemens-energy.com/global/en/news/key-topics/additive-manufacturing.html.

[20] Yang, Hsu, Baughman, Godfrey, Medina, Menon, Wiener, 2017

### 4.3 Risks and Opportunities of Additive Manufacturing in Restoration

When it comes to the restoration of historic buildings, in the light of discussed both current and future applications of additive manufacturing, it should be noted that even though current applications are still in the testing process, it is still possible to use additive manufacturing to produce moulds and reproductions or prototypes of structural and non-structural elements. While in the future, it might become possible to use it directly for in situ repairs, structural strengthening, and restoration work based on conservation ethics. It becomes popular slowly in the restoration sector. However, even in this stage, it brings some opportunities to make traditional techniques faster, cheaper, less of an environmental burden, with lower error rates, and therefore it presents a great opportunity to be used collaboratively with conventional techniques [5 6 14 18].

Conventional methods such as manual drawings or "expert naked eye" can be insufficient and ineffective due to missing original documentation, location, or construction of the element. Moreover, some cultural heritage properties are forbidden to direct contact due to conservation reasons or because either they are too small to understand or too large. Therefore, these reasons lead to a demand for non-contact or indirect access or interpretation to elements, which can be overcome with additive manufacturing as a tool to multi-sensory access to reproduce elements to help restoration stages [2 21].

Historical buildings, in particular, stone masonry structures widely exist with curved surfaces, complex asymmetrical shapes with irregularities, and reproduction or reconstruction of these components can be a difficult task. However, additive manufacturing can achieve the complexity by eliminating the need for skilled and experienced labour to undertake the work and decreasing the cost of manufacturing templates like reproducing plinth in China [2 6 21].

On the other hand, it is still a developing tool for the restoration of historic buildings because of several questions related to its wider use. First of all, restoration of historic buildings requires using similar material based on originality in terms of texture and colour, which is not always possible with 3D printable materials [2]. Even if a similar material is provided, postprocessing is required on 3D printed component due to its layered texture [2]. Moreover, historical buildings might have intricate patterns that are difficult to reproduce with the "relatively crude" products of the 3D printing technique. Therefore, further carving by hand is needed, so that printed components replicate the original aesthetics [2]. Challenges also emerge from the absence of technical standards, extensive testing, and evaluation of different production techniques and strategies for additive manufacturing [21].

---

[21] Ioannides, Quak, 2014

## 4.4. Discussion

Additive manufacturing is becoming a complementary method, without replacing the craftsmanship, to traditional restoration. However, additive manufacturing is still in its infancy, without standardized testing and quality control to compare the recent developments [2 5 6 18 21]. Moreover, most of the existing projects are not scientifically published, or they lack detailed information on the methodology and the quality of final part. Thus, it makes comparison or evaluation of new additive manufacturing technologies more limited [2 5 6 16 18]. Even though further research is needed to realize additive manufacturing as a cost-effective and reliable option in the restoration of historic buildings, the potential opportunities show that it is worthy of further research and development. However, only further research will confirm or reject this technology's future development to restore historic buildings [2 5 6 18 21].

# Chapter 5

# Literature Review and Laboratory Test Data

As it has been discussed in Chapter 3, wire and arc additive manufacturing (WAAM) is a metal additive manufacturing process sorted under directed energy deposition technique. Within additive manufacturing, WAAM is one of the most suitable techniques for realizing medium to large scale structural parts with low to medium geometric complexity in the construction sector because it is considered to be cost-effective and use of standard off-the-shelf welding equipment such as welding power source, torches, and wire feeding system [1] [2] [3] [4] [5]. With the help of the research about the WAAM process conducted by MX3D, two different strategies have been developed so far: "continuous" or "layer by layer" printing in which material is deposited continuous, and "dot by dot" printing in which successive points deposit material [6]. In detail, the continuous printing strategy is used in the printing of planar elements. However, the process causes geometric defects like surface roughness and lack of straightness due to the need for high velocity to manufacture structural elements in a layer-by-layer manner [7]. The material's intrinsic characteristic from its' microstructure causes anisotropic behaviour in the printed element [7]. While dot by dot printing strategy is used in printing rod (line) elements with nominal diameter along on axis without any node interruption and it does not cause an anisotropic behaviour in printed element [7]. Therefore, to compare wrought metal specimens and evaluate anisotropic behaviour in tensile mechanical properties in planar metal elements manufactured in a layer-by-layer manner. The first part of Chapter 5 presents the state-of-the-art literature review results about the tensile mechanical properties of metal specimens, in particular stainless steel, carbon steel, and duplex steel. The second part of Chapter 5 discusses the tensile testing results obtained at the University of Bologna Structural and Geotechnical Laboratory from 6 mm diameter full circular rods produced with ER308LSi by MX3D company in 0°, 10°, 45° orientations to the vertical direction, and their calibration results to evaluate the influence of a possible misalignment of the printing head from the longitudinal axis of the printed element.

---

[1] Laghi, Palermo, Gasparini, Girelli, Trombetti, 2020
[2] Laghi, Palermo, Tonelli, Gasparini, Ceschini, Trombetti, 2020
[3] Buchanan, Gardner, 2019
[4] Paolini, Kollmansberger, Rank, 2019
[5] Williams, Martina, Addison, Ding, Pardal, Colegrove, 2016
[6] MX3D Webpage n.d., www.mx3d.com.
[7] Laghi, Palermo, Gasparini, Trombetti, 2020

## 5.1 Literature Review

A literature review has been conducted to evaluate the tensile mechanical behaviour of WAAM produced metal specimens, in particular stainless steel, carbon steel, and duplex steel, in published articles and to observe the anisotropy induced by the continuous printing process. Thus, with this main aim, Tables 7, 8, and 9 were created. In the tables, L, T, and D are the main orientations referring to the longitudinal direction in which specimens cut along the longitudinal direction along with printing layer, transversal directions which specimens cut along the transversal direction, and diagonal direction in which specimens cut along the diagonal direction.

Table 7: Summary of Stainless-Steel Tensile Properties from Literature Review

| **Feedstock Material** | **Process Type** | **Surface Condition** | **Specimen Orientation** | **E [GPa] (Average)** | **σ Yielding [MPa] (Average)** | **σ Ultimate [MPa] (Average)** | **Reference** |
|---|---|---|---|---|---|---|---|
| ER308LSi | WAAM | Artificially Smoothened Surface | L | 113 | 353 | 554 | [1] |
| | | | T | 108 | 355 | 535 | |
| | | Rough Surface | L | 128 | 347 | 569 | |
| | | | T | 104 | 303 | 521 | |
| ER308LSi | WAAM | Mechanically Milled Surface | L | 129 | 356 | 553 | [2] |
| | | | T | 105 | 352 | 527 | |
| | | | D | 228 | 403 | 585 | |
| ER308LSi | WAAM | Mechanically Milled Surface | L | 143 | 356 | 575 | [8] |
| | | | T | 140 | 338 | 554 | |
| | | | D | 220 | 407 | 626 | |
| | | Rough Surface | L | 137 | 325 | 535 | |
| | | | T | 109 | 271 | 423 | |
| | | | D | 201 | 351 | 539 | |
| ER308LSi | GMAW-WAAM | / | L | / | 231 | 622 | [9] |
| | | | T | / | 235 | 678 | |
| ***Wrought 304LSi*** | */* | */* | */* | ***200*** | ***190-230*** | ***500-540*** | [10] |
| ***Wrought 316LSi*** | */* | */* | */* | ***200*** | ***200-240*** | ***500-530*** | [3] |

The results of ER308LSi are compared with the wrought 304L and 316 L stainless steels because conventional manufacturing of ER308LSi achieves tensile mechanical behaviour within the range of them, and it is used as a filler wire in the traditional welding process of wrought 304L stainless steel.

---

[8] Kyvelou, Slack, Mountanou, Wadee, Britton, Buchanan, Gardner, 2020

[9] Ji, Lu, Liu, Jing, Fan, Ma, 2017

[10] EN 1993 1-4: Eurocode 3: Design of steel structures, part 1-4: General rules, supplementary rules for stainless steel, 2015

Table 8: Summary of Carbon-Steel Tensile Properties from Literature Review

| **Feedstock Material** | **Process Type** | **Surface Condition** | **Specimen Orientation** | **E [GPa] (Average)** | **σ Yielding [MPa] (Average)** | **σ Ultimate [MPa] (Average)** | **Reference** |
|---|---|---|---|---|---|---|---|
| Medium Carbon Steel (Grade XC-45) | GMAW-WAAM | / | L | / | 553 | 710 | [11] |
| | | | T | | 545 | 602 | |
| ***Wrought XC45*** | ***Quenched*** | / | / | / | ***630*** | ***683*** | [11] |
| | ***Annealed*** | | | | ***343*** | ***500*** | |
| | ***Hot Rolled*** | | | | ***300*** | ***563*** | |
| | ***Cold Rolled*** | | | | ***450*** | ***585*** | |

Table 9: Summary of Duplex-Steel Tensile Properties from Literature Review

| **Feedstock Material** | **Process Type** | **Surface Condition** | **Specimen Orientation** | **E [GPa] (Average)** | **σ Yielding [MPa] (Average)** | **σ Ultimate [MPa] (Average)** | **Reference** |
|---|---|---|---|---|---|---|---|
| Duplex Stainless Steel 2209 | GMAW-WAAM | Artificially Smoothened Surface | L | / | 508 | 480 | [12] |
| | | | T | | 771 | 682 | |
| ***Wrought 2209*** | / | / | / | / | ***590*** | ***786*** | [12] |
| Super Duplex Stainless Steel ER2594 | WAAM | Artificially Smoothened Surface | L | / | 500 | 850 | [13] |
| | | | T | | 500 | 800 | |
| ***Wrought ER2594*** | / | / | / | / | ***450*** | ***700*** | ***[14]*** |

---

[11] Lin, Goulas,Ya, Hermans, 2019

[12] Hejripour, Binesh, Hebel, Aidun, 2019

[13] Zhang, Wang, Zhou, Ding, Ganguly, Marzio, Williams, 2019

[14] Aircraft Materials, 2018. Stainless Steel ER2209 Technical Data Sheet. pp. 2–3. https://www.aircraftmaterials.com/data/weld/er2209.html.

## 5.2 Laboratory Data and Their Calibration

To observe the tensile mechanical behaviour of WAAM produced "dot by dot" metal elements, full circular metal rod elements with 6mm diameter have been printed using ER308LSi as wire feedstock in three different orientations 0°, 10°, 45° [7]. After the manufacturing process, 60 specimens, 20 per each direction, have been tested on a universal testing machine of 500 kN load capacity at the Structural Engineering Laboratory of the University of Bologna [7]. The printed metal roads and the testing process are illustrated in Figure 57.

Figure 58 shows the mean values (before calibration) of these three different specimen types in terms of 0.2% proof stress, ultimate tensile stress, and modulus of elasticity as a histogram.

Figure 57: (a) Printed Metal Rod Element (Left), (b) Tensile Testing (Right) [7]

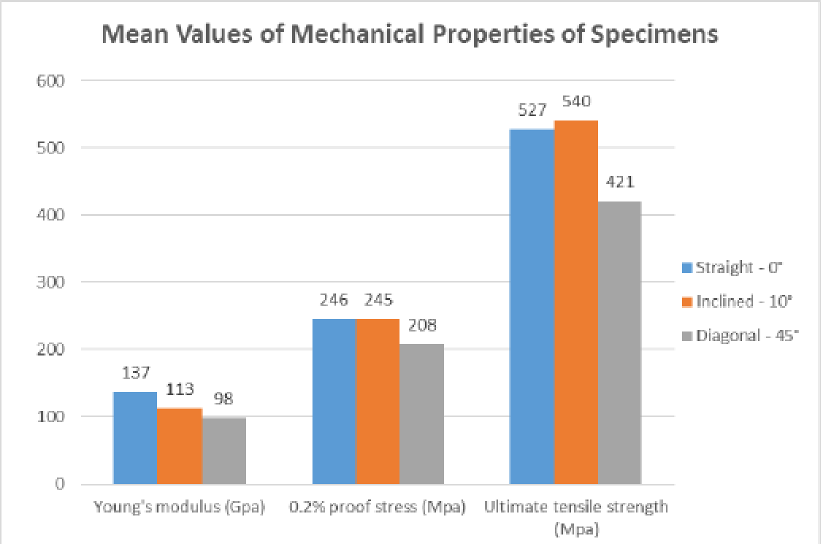


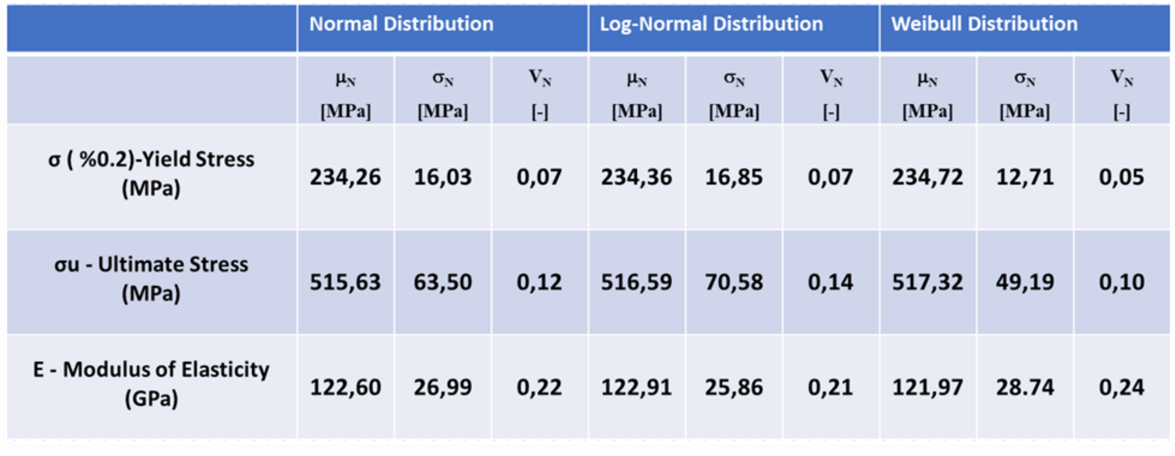
Figure 58: Comparison of Mean Values of 0°, 10° and 45° Specimens Before Calibration

Calibration design values and partial safety factors have been performed. A total of 30 specimens' test result, 10 results per each orientation, was selected to perform calibration. In this dissertation, the calibration process of only 0° specimens is given. However, the same method has been applied to the other two types as well, and calibration results are presented in table format at the end of Chapter 5. For this work, results from 10 good quality tensile test results of 0° specimens. Calibration of design values of 0.2% proof stress, ultimate tensile stress, modulus of elasticity, and corresponding partial safety factors was carried out based on considering two approaches: the best-fit statistical distributions and Eurocode 0.

### 5.2.1 Calibration of Design Values Based on Best-Fit Statistical Distribution

A statistical analysis of the experimental results was carried out, deriving the best fit distributions of Normal, Weibull, and Log-normal according to the maximum likelihood estimators. The choice of the distribution models has been made according to the indications provided in Annex C and D of Eurocode 0 for strength data. Table 10 summarizes the mean values and standard deviations of the best-fit distributions.

Table 10: Mean and Standard Deviation of Normal, Log-normal, and Weibull Best Fit Statistical Distributions of the Mechanical Properties



| | **Normal Distribution** | | | **Log-Normal Distribution** | | | **Weibull Distribution** | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\mu_N$ [MPa] | $\sigma_N$ [MPa] | $V_N$ [-] | $\mu_N$ [MPa] | $\sigma_N$ [MPa] | $V_N$ [-] | $\mu_N$ [MPa] | $\sigma_N$ [MPa] | $V_N$ [-] |
| **σ ( %0.2)-Yield Stress (MPa)** | **234,26** | **16,03** | **0,07** | **234,36** | **16,85** | **0,07** | **234,72** | **12,71** | **0,05** |
| **σu - Ultimate Stress (MPa)** | **515,63** | **63,50** | **0,12** | **516,59** | **70,58** | **0,14** | **517,32** | **49,19** | **0,10** |
| **E - Modulus of Elasticity (GPa)** | **122,60** | **26,99** | **0,22** | **122,91** | **25,86** | **0,21** | **121,97** | **28.74** | **0,24** |

Figure 60 provides a comparison between experimental and best-fit cumulative distribution functions (CDF) and probability density functions (PDF) as obtained for yielding (0.2% proof) stress, ultimate tensile strength, and Young's modulus.

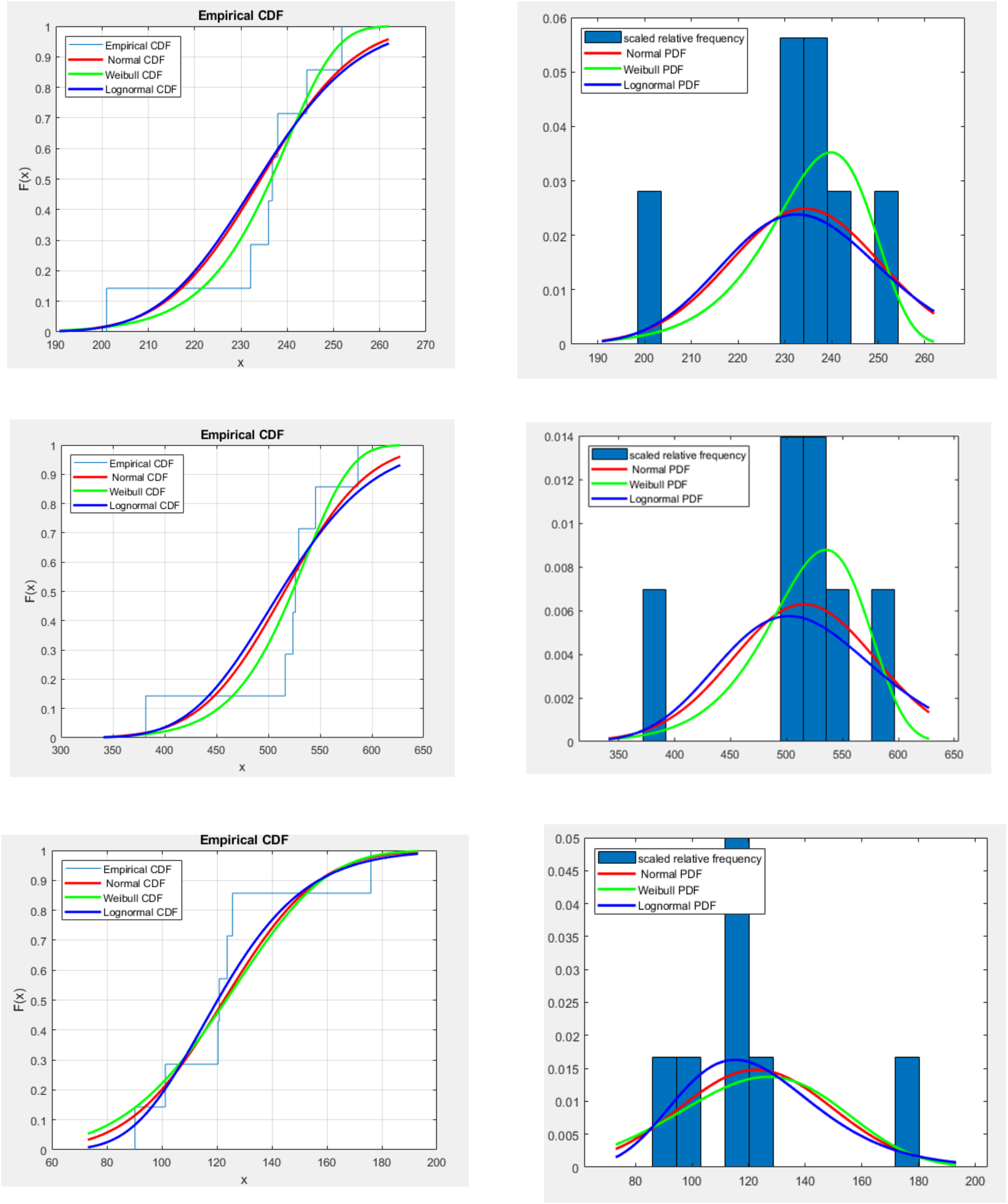
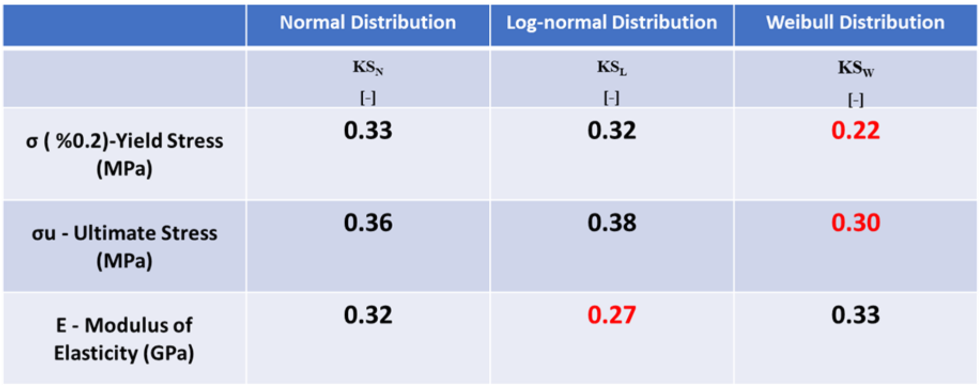


Figure 60: (a) CDF and PDF of 0.2% Proof Stress (Top), (b) CDF and PDF of Ultimate Tensile Stress (Middle);(c) CDF and PDF of Modulus of Elasticity (Bottom)

As a next step, Table 11 provides the results of the Kolmogorov-Smirnov test in terms of coefficient KS of the best-fit distributions evaluated from maximum likelihood estimators for the experimental data. Even though the smallest KS values should have used to calibrate design values, the Log-normal distributions were considered to calibrate the design values due to slight differences in KS values and to be in accordance with the recommendations provided in Eurocode 0 for calibration of design values for strength.

Table 11: Kolmogorov-Smirnov Test of the Normal, Log-normal, and Weibull Best Fit Statistical Distributions



| | Normal Distribution | Log-normal Distribution | Weibull Distribution |
|---|---|---|---|
| | $KS_N$ [-] | $KS_L$ [-] | $KS_W$ [-] |
| σ ( %0.2)-Yield Stress (MPa) | 0.33 | 0.32 | 0.22 |
| σu - Ultimate Stress (MPa) | 0.36 | 0.38 | 0.30 |
| E - Modulus of Elasticity (GPa) | 0.32 | 0.27 | 0.33 |

The fractiles corresponding to the key material parameters' characteristic and design values have been computed from best-fit statistical distributions. From their ratio, the estimation of the partial factor of safety was evaluated and illustrated in Table 12.

### 5.2.2 Calibration of Design Values Based on Eurocode 0

Calibration of design values based on Eurocode 0 has been performed by considering a Log-normal distribution. The formulas are given in Figure 61; Table 12 provides an overview of the calibration results according to Eurocode 0 by comparing them with fractiles' values from the statistical distribution of the experimental results.

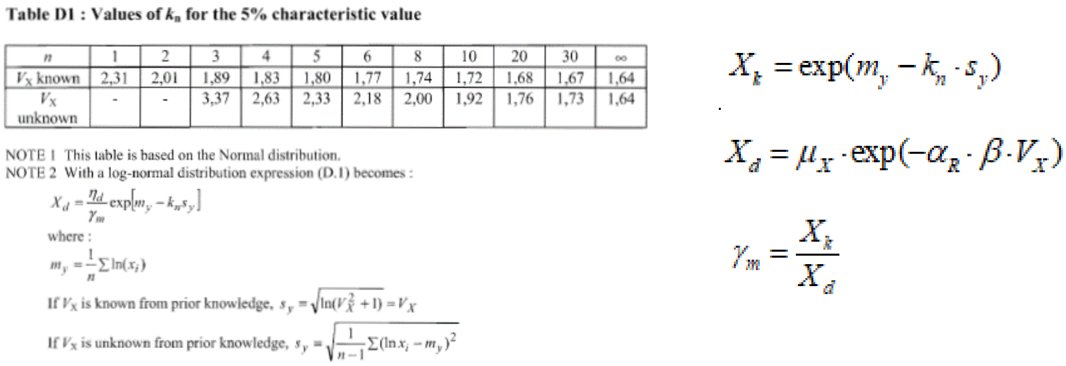


**Table D1 : Values of $k_n$ for the 5% characteristic value**

| $n$ | 1 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 20 | 30 | $\infty$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_X$ known | 2,31 | 2,01 | 1,89 | 1,83 | 1,80 | 1,77 | 1,74 | 1,72 | 1,68 | 1,67 | 1,64 |
| $V_X$ unknown | - | - | 3,37 | 2,63 | 2,33 | 2,18 | 2,00 | 1,92 | 1,76 | 1,73 | 1,64 |

NOTE 1 This table is based on the Normal distribution.
NOTE 2 With a log-normal distribution expression (D.1) becomes :

$$X_d = \frac{\eta_d}{\gamma_m} \exp\left[m_y - k_n s_y\right]$$

where :

$$m_y = \frac{1}{n} \sum \ln(x_i)$$

If $V_X$ is known from prior knowledge, $s_y = \sqrt{\ln(V_X^2 + 1)} = V_X$

If $V_X$ is unknown from prior knowledge, $s_y = \sqrt{\frac{1}{n-1} \sum (\ln x_i - m_y)^2}$

$$X_k = \exp(m_y - k_n \cdot s_y)$$

$$X_d = \mu_X \cdot \exp(-\alpha_R \cdot \beta \cdot V_X)$$

$$\gamma_m = \frac{X_k}{X_d}$$

Figure 61: Used Chart and Formulas [15]

Table 12: Overview of Results of Calibration of Design Values of 0° Specimens

| | 5% and 0.1% fractiles from statistical distribution | | | Characteristic value, design value and safety factors according to EC0 | | |
|---|---|---|---|---|---|---|
| | $f_{5\%}$ | $f_{0.1\%}$ | $f_{5\%}/ f_{0.1\%}$ | Xk | Xd | γ |
| σ ( %0.2)-Yield Stress (MPa) | 208,22 | 188,35 | 1,11 | 201,20 | 190,26 | 1,06 |
| σu - Ultimate Stress (MPa) | 414,60 | 341,00 | 1,21 | 385,16 | 354,61 | 1,09 |
| E - Modulus of Elasticity (GPa) | 86,95 | 64,84 | 1,34 | 77,85 | 62,77 | 1,24 |
| | 173,73 | 232,99 | 0,75 | | | |

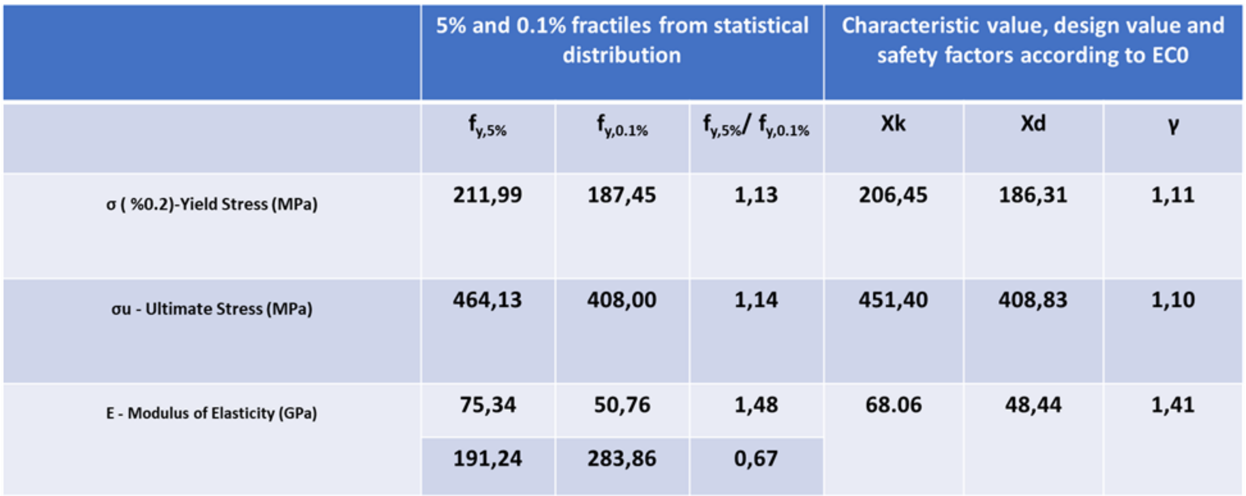
Table 12: Overview of Results of Calibration of Design Values of 0° Specimens

For the calibration of design values of 10°, 45° metal specimens produced by wire and arc additive manufacturing in dot-by-dot strategy were done with the same process. The calibrated tensile mechanical properties are given in Tables 13 and 14, respectively, to compare results.

---

[15] European Committee for Standardization (CEN), EN 1990: Eurocode 0 - Basis of Structural Design, 2002.

Table 13: Overview of Results of Calibration of Design Values of 10° Specimens



| | 5% and 0.1% fractiles from statistical distribution | | | Characteristic value, design value and safety factors according to EC0 | | |
|---|---|---|---|---|---|---|
| | $f_{y,5\%}$ | $f_{y,0.1\%}$ | $f_{y,5\%}/ f_{y,0.1\%}$ | Xk | Xd | γ |
| σ ( %0.2)-Yield Stress (MPa) | 211,99 | 187,45 | 1,13 | 206,45 | 186,31 | 1,11 |
| σu - Ultimate Stress (MPa) | 464,13 | 408,00 | 1,14 | 451,40 | 408,83 | 1,10 |
| E - Modulus of Elasticity (GPa) | 75,34 | 50,76 | 1,48 | 68.06 | 48,44 | 1,41 |
| | 191,24 | 283,86 | 0,67 | | | |

Table 14: Overview of Results of Calibration of Design Values of 45° Specimens

| | 5% and 0.1% fractiles from statistical distribution | | | Characteristic value, design value and safety factors according to EC0 | | |
|---|---|---|---|---|---|---|
| | $f_{y,5\%}$ | $f_{y,0.1\%}$ | $f_{y,5\%}/ f_{y,0.1\%}$ | Xk | Xd | γ |
| σ ( %0.2)-Yield Stress (MPa) | 175,87 | 152,64 | 1,15 | 169,55 | 156,03 | 1,08 |
| σu - Ultimate Stress (MPa) | 373,68 | 339,06 | 1,10 | 364,76 | 339,11 | 1,08 |
| E - Modulus of Elasticity (GPa) | 61,18 | 41,03 | 1,49 | 51,97 | 41,03 | 1,30 |
| | 156,95 | 234,02 | 0,67 | | | |

# Results

The construction industry has begun to explore additive manufacturing applications to mitigate current challenges such as worker safety in tough conditions, skilled workers, and waste material. In other words, currently, additive manufacturing is addressed to overcome construction productivity challenges.

The most recent construction industry works focused on concrete printing, particularly the material extrusion process and powder bed fusion process. Large-scale applications are elaborated with material extrusion, while powder bed fusion allows great design freedom and higher accuracy. Various projects of structures and structural components integrated with reinforcements have been constructed.

Additive manufacturing of polymer-based materials for building components is performed based on material extrusion and powder bed fusion processes. Powder bed fusion offers unique designs serving non-structural applications. In contrast, material extrusion, in particular, BAAM, is the process of manufacturing building components. BAAM produced elements can be fiber-reinforced or combined with steel components for load-bearing purposes. Additionally, the use of thermoplastic pellets reduces the cost of feedstock and deposition rate.

Additive manufacturing of metallic elements is a newly explored field for large-scale building components. Mainly powder bed fusion process and directed energy deposition processes WAAM are used. WAAM offers fast and better-suited applications in the construction industry. WAAM produced metal specimens can attain the tensile mechanical behavior close to the ones made with conventional manufacturing. However, based on the literature review, the outcome shows that specimens exhibit anisotropic behaviour resulting in higher tensile mechanical properties in the longitudinal direction than transversal direction. The experimental results from the key material properties (Young’s Modulus, yielding, and tensile strength) of “dot-by-dot” WAAM rods indicate that tensile mechanical properties are adequate for structural engineering applications.

The restoration and rehabilitation of historic buildings are currently performed manually. Additive manufacturing offers possible future applications in terms of in-situ repair, infrastructure repair. The non-structural and structural applications of additive manufacturing exist, but they are still in their testing process. Furthermore, the printed elements and their replacements should comply with the national restoration standards and rules. In the restoration sector, additive manufacturing is not as applicable as in the construction sector since current challenges are more than the opportunities.

# Conclusions

In this dissertation, the current state of additive manufacturing in construction and historic building restoration/rehabilitation was reviewed. The main target of the research was to discuss AM's opportunities in the construction sector and explore its applicability in the restoration of historical buildings.

In both construction and restoration sectors, Additive manufacturing complements, rather than replace, traditional production processes, with potential applications such as considerable freedom of design, optimized topologies, customized parts, and in-situ repair. It offers the possible potential for hybrid solutions and structural strengthening and repairs. The remaining challenges are, for instance, the reduction of the cost, the lack of standards and quality control to verify stability and serviceability of printed elements, and a significant lack of publicly available experimental data and validated models to make comparisons and evaluation of additive manufacturing technologies.

For this reason, further work is needed to overcome the current challenges, facilitate its implementation, and realize possible applications. With interdisciplinary research, additive manufacturing can be a cost-effective and reliable technology in the construction and restoration of historic buildings.

# References

(n.d.). Retrieved December 22, 2020, from http://www.winsun3d.com/En/About/.

3D printed bridge. (2020, April 20). Retrieved December 22, 2020, from https://iaac.net/project/3d-printed-bridge/.

3D Printed Building from Polymer for Off-Grid Living: SOM. (2020, October 24). Retrieved December 22, 2020, from https://www.arch2o.com/3d-printed-polymer-building-off-grid-living-som/.

3D Research Challenges in Cultural Heritage. (2014). Lecture Notes in Computer Science. doi:10.1007/978-3-662-44630-0

3D tisk v praxi - Portál referencí. (n.d.). Retrieved December 22, 2020, from https://www.3dees.cz/3d-tisk-v-praxi/spoluprace-narodniho-technickeho-muzea-a-3dees-3d-skenovani-a-3d-tisk-artefaktu-a-jejich-vyuziti-nejen-pro-zrakove-postizene-navstevniky.

The 7 categories of Additive Manufacturing: Additive Manufacturing Research Group: Loughborough University. (n.d.). Retrieved December 22, 2020, https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturig

Additive Manufacturing (AM) opens up huge opportunities by revolutionizing the manufacturing and repair of components. (n.d.). Retrieved December 22, 2020, from https://www.siemens-energy.com/global/en/news/key-topics/additive manufacturing.html

Aircraft Materials, (2018), Stainless Steel ER2209 Technical Data Sheet. pp. 2–3. https://www.aircraftmaterials.com/data/weld/er2209.html.

Am, & Am. (2019, December 11). MX3D Takenaka Connector. Retrieved December 22, 2020, from http://additivemanufacturing.com/2019/12/11/mx3d-takenaka connector/

Architecture, Engineering and Consulting Firm: EDG Architecture and Engineering. (n.d.). Retrieved December 22, 2020, from https://edgnyc.com/?case_studies=607

ASTM International, ISO/ASTM 52900:2015: Standard Terminology for Additive Manufacturing Technologies e General Principles - Terminology, American Society for Testing and Materials, ASTM International, 2015

ASTM, ASTM F 2792-10 Standard Terminology for Additive Manufacturing Technologies, American Society for Testing and Materials, ASTM International, West Conshohocken, PA, 2010.

Azzarello, N. (2014, August 28). Andrey Rudenko constructs 3D printed concrete castle in Minnesota. Retrieved December 22, 2020, from https://www.designboom.com/technology/3d-printed-concrete-castle-minnesota Andrey-Rudenko-08-28-2014/

Biswas, K., Rose, J., Eikevik, L., Guerguis, M., Enquist, P., Lee, B., . . . Jackson, R. (2016). Additive Manufacturing Integrated Energy—Enabling Innovative Solutions for Buildings of the Future. Journal of Solar Energy Engineering, 139(1). doi:10.1115/1.4034980

Bos, F., Wolfs, R., Ahmed, Z., Salet, T. (2016). Additive manufacturing of concrete in construction: Potentials and challenges of 3D concrete printing. Virtual and Physical Prototyping, 11(3), 209-225. Doi: https://doi.org/10.1080/17452759.2016.1209867

Buchanan, C., Gardner, L. (2019). Metal 3D printing in construction: A review of methods, research, applications, opportunities, and challenges. Engineering Structures, 180, 332-348. DOI: 10.1016/j.engstruct.2018.11.045

Burry, J., Sabin, J., Sheil, R., Skavara, M., (2020). Fabricate, London: UCL Press. DOI: https://doi.org/10.14324/111.9781787358119

Buswell, R., Silva, W. L., Jones, S., Dirrenberger, J. (2018). 3D printing using concrete extrusion: A roadmap for research. Cement and Concrete Research, 112, 37-49. DOI: 10.1016/j.cemconres.2018.05.006

Buswell, R., Soar, R., Gibb, A., Thorpe, A. (2007). Freeform Construction: Mega-scale Rapid Manufacturing for construction. Automation in Construction, 16(2), 224-231. doi: 10.1016/j.autcon.2006.05.002

Camacho, D. D., Clayton, P., O'brien, W. J., Seepersad, C., Juenger, M., Ferron, R., Salamone, S. (2018). Applications of additive manufacturing in the construction industry – A forward-looking review. Automation in Construction, 89, 110-119. DOI: 10.1016/j.autcon.2017.12.031

Camile, H. L., Kalven, L.E., Lloyd R., (2016), Redmond Lloyd. Construction 3D printing. Concr Australia, 42: 30–35

Cesaretti, G., Dini, E., Kestelier, X. D., Colla, V., Pambaguian, L. (2014). Building components for an outpost on the Lunar soil by means of a novel 3D printing technology. Acta Astronautica, 93, 430-450. http://dx.doi.org/10.1016/j.actaastro.2013.07.034

Compton, B. G., Post, B. K., Duty, C. E., Love, L., Kunc, V. (2017). Thermal analysis of additive manufacturing of large-scale thermoplastic polymer composites. Additive Manufacturing, 17, 77-86. doi: 10.1016/j.addma.2017.07.006

Democrite wall. (n.d.). Retrieved December 22, 2020, from https://xtreee.com/en/project/mur-democrite/.

Design method for critical structural steel elements. (n.d.). Retrieved December 22, 2020, from https://www.arup.com/projects/additive-manufacturing.

Duballet, R., Baverel, O., Dirrenberger, J. (2017). Classification of building systems for concrete 3D printing. Automation in Construction, 83, 247-258. doi: 10.1016/j.autcon.2017.08.018

DUS, H. (n.d.). Work. Retrieved December 22, 2020, from https://houseofdus.com/work/

Duty, C. E., Kunc, V., Compton, B., Post, B., Erdman, D., Smith, R., . . . Love, L. (2017). Structure and mechanical behavior of Big Area Additive Manufacturing (BAAM) materials. Rapid Prototyping Journal, 23(1), 181-189. doi:10.1108/rpj-12-2015-0183

European Committee for Standardization (CEN), EN 1990: Eurocode 0 - Basis of Structural Design, (2002).

European Committee for Standardization (CEN), EN 1993 1-4: Eurocode 3 – Design of Steel Structures, Part 1-4: General Rules, Supplementary Rules for Stainless Steel, (2015).

Everett, H., Magrone, I., Sertoglu, K., 3D Printing Industry, Petch, M., Vialva, T., . . . Clarke, C. (2017, January 31). Restoring historic buildings using 3D printing and 3D scanning. Retrieved December 22, 2020, from https://3dprintingindustry.com/news/restoring-historic-buildings-using-3d-printing-3d-scanning-104687/.

Everett, H., Magrone, I., Sertoglu, K., 3D Printing Industry, Petch, M., Vialva, T., . . . Harangozó, O. (2017, June 19). Royal BAM Group use a 3D printer to make concrete bicycle bridge with TU Eindhoven. Retrieved December 22, 2020, from https://3dprintingindustry.com/news/royal-bam-group-concrete-3d-printer-concrete-bicycle-bridge-with-tu-eindhoven-116359/.

Feilden, B. M. (2009). Conservation of historic buildings. London: Butterworths Scientific.

Frazier, W. E. (2014). Metal Additive Manufacturing: A Review. Journal of Materials Engineering and Performance, 23(6), 1917-1928. doi:10.1007/s11665-014-0958-z

Galjaard, S., Hofman, S., Ren, S., (2015). New Opportunities to Optimize Structural Designs in Metal by Using Additive Manufacturing. 10.1007/978-3-319-11418-7_6.

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., . . . Zavattieri, P. D. (2015). The status, challenges, and future of additive manufacturing in engineering. Computer-Aided Design, 69, 65-89. http://dx.doi.org/10.1016/j.cad.2015.04.001

Ghaffar, S. H., Corker, J., Fan, M. (2018). Additive manufacturing technology and its implementation in construction as an eco-innovative solution. Automation in Construction, 93, 1-11. doi: 10.1016/j.autcon.2018.05.005

Gibson, I., Rosen, D. W., Stucker, B. (2015). Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. New York, USA: Springer. doi:10.1007/978-1-4939-2113-3

Gosselin, C., Duballet, R., Roux, P., Gaudillière, N., Dirrenberger, J., Morel, P. (2016). Large-scale 3D printing of ultra-high-performance concrete – a new processing route for architects and builders. Materials & Design, 100, 102-109. doi: 10.1016/j.matdes.2016.03.097

GuoWei, M., Li, W., Yang, J. (2018). State-of-the-art of 3D printing technology of cementitious material—An emerging technique for construction. Science China Technological Sciences, 61, 475-495. doi: https://doi.org/10.1007/s11431-016-9077-7

Hager, I., Golonka, A., Putanowicz, R. (2016). 3D Printing of Buildings and Building Components as the Future of Sustainable Construction? Procedia Engineering, 151, 292-299. doi: 10.1016/j.proeng.2016.07.357

Hejripour, F., Binesh, F., Hebel, M., Aidun, D. K. (2019). Thermal modeling and characterization of wire arc additive manufactured duplex stainless steel. Journal of Materials Processing Technology, 272, 58-71. doi: https://doi.org/10.1016/j.jmatprotec.2019.05.003

Ioannides, M., Quak, E. (2014). 3D research challenges in cultural heritage a roadmap in digital heritage preservation. Berlin, Heidelberg: Springer. doi: DOI 10.1007/978-3-662-44630-0

Ji, L., Lu, J., Liu, C., Jing, C., Fan, H., Ma, S. (2017) Microstructure and mechanical properties of 304L steel fabricated by arc additive manufacturing, MATEC Web Conf. 128. https://doi.org/10.1051/matecconf/201712803006

Jokilehto, J. (1999). History of Architectural Conservation. Boston: Butterworth-Heinemann.

Keating, S. (2016). Project Overview ' Digital Construction Platform. Retrieved December 22, 2020, from https://www.media.mit.edu/projects/digital-construction-platform-v-2/overview/.

Kreiger, E. L., Kreiger, M. A., Case, M. P. (2019). Development of the construction processes for reinforced additively constructed concrete. Additive Manufacturing, 28, 39-49. doi: 10.1016/j.addma.2019.02.015

Kreiger, M., Pearce, J. M. (2013). Environmental Life Cycle Analysis of Distributed Three-Dimensional Printing and Conventional Manufacturing of Polymer Products. ACS Sustainable Chemistry & Engineering, 1(12), 1511-1519. doi:10.1021/sc400093k

Kyvelou, P., Slack, H., Mountanou, D. D., Wadee, M. A., Britton, T. B., Buchanan, C., Gardner, L. (2020). Mechanical and microstructural testing of wire and arc additively manufactured sheet material. Materials & Design, 192. doi: https://doi.org/10.1016/j.matdes.2020.108675.

Laghi, V., Palermo, M., Gasparini, G., Trombetti, T. (2020). Computational design and manufacturing of a half-scaled 3D-printed stainless-steel diagrid column. Additive Manufacturing, 36, 101505. doi: 10.1016/j.addma.2020.101505

Laghi, V., Palermo, M., Gasparini, G., Girelli, V. A., Trombetti, T. (2020). Experimental results for the structural design of Wire-and-Arc Additive Manufactured stainless steel members. Journal of Constructional Steel Research, 167, 105858. doi: 10.1016/j.jcsr.2019.105858

Laghi, V., Palermo, M., Tonelli, L., Gasparini, G., Ceschini, L., Trombetti, T. (2020). Tensile properties and microstructural features of 304L austenitic stainless steel produced by wire-and-arc additive manufacturing. The International Journal of Advanced Manufacturing Technology, 106(9-10), 3693-3705. doi:10.1007/s00170-019-04868-8

Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Gibb, A. G., Thorpe, T. (2012). Mix design and fresh properties for high-performance printing concrete. Materials and Structures, 45(8), 1221-1232. doi:10.1617/s11527-012-9828-z

Lim, S., Buswell, R., Le, T., Austin, S., Gibb, A., Thorpe, T. (2012). Developments in construction-scale additive manufacturing processes. Automation in Construction, 21, 262-268. doi: 10.1016/j.autcon.2011.06.010

Lin, Z., Goulas, C. Y., Hermans, M., (2019). Microstructure and Mechanical Properties of Medium Carbon Steel Deposits Obtained via Wire and Arc Additive Manufacturing Using Metal-Cored Wire. Metals. 9. 673. 10.3390/met9060673

Lowke, D., Dini, E., Perrot, A., Weger, D., Gehlen, C., Dillenburger, B. (2018). Particle-bed 3D printing in concrete construction – Possibilities and challenges. Cement and Concrete Research, 112, 50-65. doi: 10.1016/j.cemconres.2018.05.018

Lykhohrai, V.V., Goncharenko, D. F., Varanenko, K. O, (2017), Technology of manufacturing the formworks for erecting vaulted covering of Orthodox Churches, – №2(88). – С. 105–109.

Lykhohrai, V. V., Spirande, K. V., Goncharenko, D. F., (2017), The bearing capacity of the formwork for implementation of restoration work on the Orthodox Churches vaults, №33/1. – C. 29–35

Marinos, I., Quak, E. (2014). 3D Research Challenges in Cultural Heritage. Lecture Notes in Computer Science. doi:10.1007/978-3-662-44630-0

Martel, A. (2018, June 11). 3D printing takes on the restoration of a historic building. Retrieved December 22, 2020, from https://www.3dnatives.com/en/edg-architecture-3d-printing110620184/.

Meboldt, M., Klahn, C. (2018). Industrializing Additive Manufacturing - Proceedings of Additive Manufacturing in Products and Applications - AMPA2017. Cham: Springer International Publishing.

Moreira, E., Vieira, R., Xavier, M., Cardoso, D., Nogueira, J. (2017). Documentation and digital fabrication methods for restoration of eclectic metal ornaments. Frontiers of Science and Technology, 186-198. doi:10.1515/9783110537680-013

Mrazović, N., Baumers, M., Hague, R., Fischer, M. (2018). Guiding building professionals in selecting additive manufacturing technologies to produce building components. Materials Today Communications, 15, 199-202. doi: 10.1016/j.mtcomm.2018.02.012

MX3D Bridge. (n.d.). Retrieved December 22, 2020, from https://mx3d.com/projects/mx3d-bridge/

Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T., Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications, and challenges. Composites Part B: Engineering, 143, 172-196. doi: 10.1016/j.compositesb.2018.02.012

Paolini, A., Kollmannsberger, S., Rank, E. (2019). Additive manufacturing in construction: A review on processes, applications, and digital planning methods. Additive Manufacturing, 30, 100894. doi: 10.1016/j.addma.2019.100894

Rael, R., Fratello, V. S. (2017). Clay Bodies: Crafting the Future with 3D Printing. Architectural Design, 87(6), 92-97. doi:10.1002/ad.2243

Skanska UK. (n.d.). Retrieved December 22, 2020, from https://www.skanska.co.uk/

Sheil, B., Menges A, Glynn, R., Skavara, M., (2017), Fabricate. London, UCL Press, DOI: https://doi.org/10.14324/111. 9781787350014

Strauss, H., (2013). AM Envelope. The potential of Additive Manufacturing for facade constructions. A+BE: Architecture and the Built Environment. 3. 10.7480/abe.2013.1.

Strauss, H., Knaack, U. (2016). Additive Manufacturing for Future Facades: The potential of 3D printed parts for the building envelope. Journal of Facade Design and Engineering, 3(3-4), 225-235. doi:10.3233/fde-150042

TAKENAKA CONNECTOR. (n.d.). Retrieved December 22, 2020, from https://mx3d.com/projects/takenaka-connector/.

Thompson, M., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., . . . Martina, F. (2016). Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. CIRP Annals - Manufacturing Technology, 65(2), 737-760. http://dx.doi.org/10.1016/j.cirp.2016.05.004

Utěšená, M., Pernicova, R. (2018). Technology of 3D Print in Field of Renovation of Architectural Structures and Historical Buildings. Key Engineering Materials, 776, 201-206. doi: 10.4028/www.scientific.net/kem.776.201

Valencia, N. (2017, February 07). World's First 3D Printed Bridge Opens in Spain (1140783347 859004672 M. Valletta, Trans.). Retrieved December 22, 2020, from https://www.archdaily.com/804596/worlds-first-3d-printed-bridge-opens-in-spain.

Vanhellemont, Y., Bouw, M. D., Dekeyser, L., Dubois, S., Vermeir, S., Damme, P. V., Have, J. V. (2016). Application of Digital Technologies in the Restoration of Historic Buildings and Heritage Objects. Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection Lecture Notes in Computer Science, 141-150. doi:10.1007/978-3-319-48974-2_16

Wahab, R. D., Azman, A. (2019). Additive Manufacturing for Repair and Restoration in Remanufacturing: An Overview from Object Design and Systems Perspectives. Processes, 7(11), 802. doi:10.3390/pr7110802

Walsh, N. (2019, July 23). ETH Zurich Develops 3D-Printed Concrete Columns. Retrieved December 22, 2020, from https://www.archdaily.com/921635/eth-zurich-develops-3d-printed-concrete-columns.

Williams, S. W., Martina, F., Addison, A. C., Ding, J., Pardal, G., Colegrove, P. (2016). Wire + Arc Additive Manufacturing. Materials Science and Technology, 32(7), 641-647. doi:10.1179/1743284715y.0000000073

Wimpenny, D. I., Pandey, P. M., Kumar, L. J. (2017). Advances in 3D Printing & Additive Manufacturing Technologies. Singapore, Singapore: Springer Singapore. doi:10.1007/978-981-10-0812-2

Woensel, R. N., Oirschot, T. V., Burgmans, M. J., D, M. M., Hermans, K. (2018). Printing Architecture: An Overview of Existing and Promising Additive Manufacturing Methods and Their Application in the Building Industry. The International Journal of the Constructed Environment, 9(1), 57-81. doi:10.18848/2154-8587/cgp/v09i01/57-81

Xu, J., Ding, L., Love, P. E. (2017). Digital reproduction of historical building ornamental components: From 3D scanning to 3D printing. Automation in Construction, 76, 85-96. doi: 10.1016/j.autcon.2017.01.010

Yang, L., Hsu, K., Baughman, B., Godfrey, D., Medina, F., Menon, M., Wiener, S. (2017). Additive manufacturing of metals: The technology, materials, design, and production. Cham, AG: Springer International Publishing. doi:10.1007/978-3-319-55128-9

Zhang, J., Khoshnevis, B. (2013). Optimal machine operation planning for construction by Contour Crafting. Automation in Construction, 29, 50-67. doi: 10.1016/j.autcon.2012.08.006

Zhang, X., Wang, K., Zhou, Q., Ding, J., Ganguly, S., Yang, D., . . . Williams, S. W. (2019). Microstructure and mechanical properties of TOP-TIG-wire and arc additive manufactured super duplex stainless steel (ER2594). Materials Science and Engineering: A, 762. doi: https://doi.org/10.1016/j.msea.2019.138097

Zhou, L., Fu, J., He, Y. (2020). A Review of 3D Printing Technologies for Soft Polymer Materials. Advanced Functional Materials, 30(28), 2000187. doi:10.1002/adfm.202000187