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On site deployment of 3D printing for the building construction – The case of Yhnova^{TM}

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Abstract. The University of Nantes has developed a 3D printing technique (BatiPrint3D^{TM}) dedicated to the construction of the walls of a house. This innovative on site construction technique is based on the deposition of two layers of expansive foam used as a formwork for a third concrete layer. It allows to build at the same time the structure and the insulation. This new construction technology has first been developed at the laboratory, but rapidly, we decided to deploy it on site, in order to demonstrate its technical viability. We present the technology Batiprint3D^{TM} and the demonstrator Yhnova^{TM}, a 95m² social dwelling built for the social landlord Nantes Métropole Habitat (NMH).

1 Introduction

According to Chaparro-Pelaez et al. [1], the crisis has caused a slowdown in the building industry and a way for small and medium enterprises to survive is to be flexible, specialized and innovative. This concept applies especially for services and relation to the client but could be extrapolated to specialization and innovation in the techniques of construction. Moreover, in a recent report published by the McKinsey Institute [2], it is shown that the building industry has known nearly zero gains of productivity during the last decades. The McKinsey report gives sevens areas to improve the construction productivity and boost it by 50-60%, such that [2]: rethink design of construction, improve onsite execution, infuse technology and innovation, reskill workers.

The burgeoning technology of large scale additive manufacturing could be a tool for a new impulse in the construction industry.

ASTM standards define additive manufacturing as a process of joining materials to make objects from 3D model data, usually layer upon layer [3]. It englobes various manufacturing techniques like binder jetting, direct energy deposition, material extrusion, powder bed fusion…

Large scale additive manufacturing presents potentially many advantages towards other construction technologies, as it is supposed to *reduce the environmental impact* of the

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manufacturing industry as the amount of used material is adjusted to the need (no losses) or the shape of the object fits exactly the need (topologic optimization [4]), *produce complex parts or objects without increase in the cost of the process* [5–8], *increase building rates* [6], *reduce the arduousness* for workers on construction plants [7, 9], give the opportunity to architects to *release creativity* [9], *allow the functionalization of the printed parts* of the building (acoustic or thermal properties) [10].

During the last decade, many projects of additive manufacturing of buildings have arised particularly in the United States, China, Russia and Europe. In a recent comprehensive paper, Labonnote et al. [7] have carried out a review of the scientific works, publications, projects, web pages in the field of 3D printing, thanks to scientific search engines. The aim was to determine the evolution in the interest of the academia and industrials for this topic. The article shows that large scale additive manufacturing has known a growing interest since the development of the first 3D printing technique by Khoshnevis in the middle of the 1990's, the so-called Contour Crafting [11], and especially since five years.

Among these projects, we can cite for example Contour Crafting [11–13], WinSun [14], Loughborough University [15–16], D-Shape [17], Skanska [18], 3D-Construction [19], XTreeE [10, 20], Apis Core [21], Cazza Construction [22], BatiPrint3D™ [9, 23], Total Kustom [24], MIT [25], CyBe [26], BET Abram [27], 3D Printhuset [28], Ja-Wa [29]...

The technologies developed by these universities or enterprises split into three main techniques : *binder jetting* (a thin bed of sand is aspersed with a binder layer by layer [18]), *material extrusion* (a material – cementitious or clayey – is deposited and stiffens after deposition enough to support the upper layers [10–17, 19–22, 25, 27–29]), *filled formwork* (a formwork is 3D printed and a material is poured into it [9, 24, 26]).

Most of these techniques of 3D printing for building are based on cementitious material extrusion using cartesian printer, poly-articulated arms or cable robot [7]. The cementitious material has to exhibit particular properties, as well at early age (rheological or flow properties) as at late age (mechanical and durability properties) such that [17]:

• it is *pumpable* to the printer head in ducts

• it is *printable* : it can keep its shape once deposited and support the upper deposited layers

• its *open time* is long enough to fulfill the previous conditions

• it is *buildable* : its properties are adapted to the mechanical load of the wall and to the regulation requirements.

To match 3D printing requirements, the cementitious materials have to contain a large amount of cement and a low water content. Thus, the cementitious materials used have for now an unfavorable environmental impact as the production of cement involves the use of large amounts of energy. The expensiveness of these materials and of the technique is also still an obstacle for the development of building 3D printing. Moreover, the deposition of a cementitious material layer by layer produces a layered structure that is not taken into account by the Eurocode. As a consequence, the material extrusion techniques still need to be investigated to solve these issues.

To withdraw the technical and economical drawbacks of material extrusion applied to the construction of building walls, we developed a new technique through the project Batiprint3D™ funded by the Society for the Acceleration of Technology Transfer (SATT Ouest Valorisation). It is based on the deposition by a nozzle of poly-urethane foam that expanses and stiffens rapidly. The deposition of two parallel layers of polyurethane (PU) foam creates a FW in which the concrete is poured. This technique, first developed at laboratory, has been applied in september 2017 to build the walls of Yhnova™, a 95m² social dwelling for the social landlord Nantes Métropole Habitat.

This paper first presents the technology Batiprint3D^{TM} by describing the principle of the three-layer wall and the way it is deployed on the construction site. Then, we present the demonstrator Yhnova^{TM}, the different stakeholders of the project, some pictures of the construction site and the main problems encountered during the construction.

2 BATIPRINT3D^{TM}

In this section, we describe the innovative technology of construction named Batiprint3D^{TM}. This technology was developed by two laboratories from the University of Nantes (France), the LS2N (Laboratory for the Sciences of Numerics) and the GeM (Research Institute in Civil Engineering and Mechanics). First, the research project involved only the laboratories but rapidly, other stakeholders joined the consortium such that institutionals, private firms, financing entities… The technology Batiprint3D^{TM} has been developed to build the walls of building and has been applied for now for the construction of dwellings.

2.1 Composition of the wall

The wall created by the technique Batiprint3D^{TM} is composed of a layer of self-compacting concrete between two layers of polyurethane (PU) foam (figure 1). The layers of polyurethane foam are first deposited to create a formwork (FW) in which the concrete is poured with a slight time delay to ensure that the foam has acquired sufficient stiffness to support the pressure exerted by the fresh concrete with deformations of the FW lower than the maximum value accepted by the standards of construction (5<mm).

2.2 Polyurethane foam

The polyurethane is a polymer bi component material obtained by mixing together isocyanate and polyol. Mixing is performed in a dynamic mixer and the compound is then deposited on the surface of the slab or on the sublayers (figure 1). The material then expanses (3s) and acquire stiffness in a few seconds (45s), depending on the temperature of the mix and on the reactivity of the compound.

The density of the foam is 35kg/m^3, its thermal conductivity is 0.027W/m.K and the Young modulus is 7MPa. Due to the low thermal conductivity of the PU foam, the thermal resistance of the wall (PU foam+concrete) is equal to approximately 6.5m^2.K/W.

The minimum width of one PU wall created by foam deposition is 80mm obtained by adapting the flow rates of isocyanate and polyol, the distance between the nozzle and the speed of displacement of the nozzle. Figure 2 shows the 3D scan of the surface acquired on a 300×300mm^2 sample extracted from a larger wall to ensure the representativity of the sample. The height of each layer is 35mm (10 layers for 350mm). The sample shows foam cushions distributed on the whole surface. The analysis of the surface shows that the mean height of the cushions is 15.7mm with a standard deviation of 3.7mm. The space periodic analysis of the cushions (obtained by picture autocorrelation) shows that the surface is periodic in the direction:

• *perpendicular to the displacement* of the nozzle corresponding to the height of a foam layer

• *parallel to the displacement* of the nozzle. This periodic scheme is due to instabilities in the deposition and in the expansion of the foam.

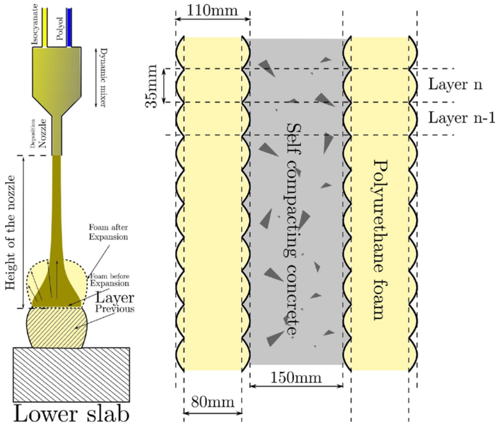

Fig. 1. Wall – vertical cut.

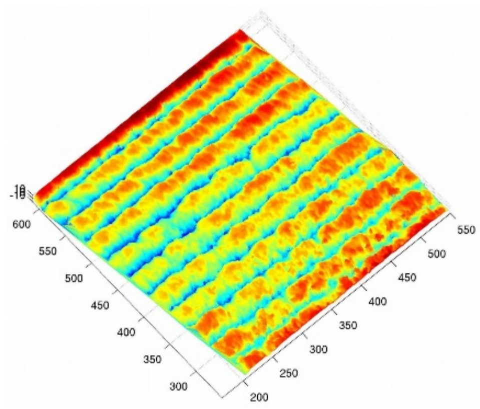

Fig. 2. 3D Scan of the polyurethane foam surface.

2.3 Concrete

The concrete is a self-compacting concrete (SCC) with a slump flow property SF=600mm. It is composed of cement CEM III 42.5, limestone filler, sand (0-4mm), gravel (4-10mm), water and set accelerator. The composition of the concrete allows it to be pumped and to flow in the FW in order to fill it with a plane horizontal free surface without the need of vibrations.

As the FW is made of an insulation material, it is important to design the concrete in such a way that the heat of hydration liberated yields a low temperature increase of the material. Indeed, if the cure temperature is too high, long term pathologies can arise and can lower the life time of the wall.

2.4 Robotics

The robotic part (see figure 4) is composed of a poly-articulated arm by Staübli (PAA) and an Automatic Guided Vehicle by BA Systèmes (AGV). The PAA is used for the deposition of the polyurethane foam and is equipped with a dynamic mixer linked to the isocyanate and polyol containers. It is carried by the AGV that can then move the PAA to different locations on the lower slab. The inaccurate positioning of the PAA induced by defaults in the flatness of the slab is corrected by first playing the deposition paths and measuring the true position of the nozzle. A correction matrix for each position is then calculated and stored.

A laser beam guidance system composed of a laser, a sensor and a set of 11 targets allows the AGV to track its location with an accuracy of 1mm on the construction site.

2.5 Process

The process Batiprint3D™ is dedicated to the construction of the walls only and requires the casting of the lower concrete slab prior to the installation of the equipment necessary to the erection of the walls.

As mentioned in the ASTM standards [3], the 3D printing of the building requires the 3D model data relative to the project. They are obtained from the Building Information Model (BIM). These data are then converted into trajectories defining the displacements of the AGV and the deposition procedures of the PAA. This essential phase is performed at desk.

After casting of the lower slab, positioning targets are placed around the slab and the AGV is brought onto the slab. A calibration phase is necessary so that the AGV can track its location on the slab.

Then, the dynamic mixer and the nozzle mounted on the PAA are linked to the polyol and isocyanate containers. The AGV and the PAA deposit the polyurethane foam according to the deposition path. The number of layers *N* dropped down depends on different parameters : stiffness of the foam, set time of the SCC, density of the SCC, class of fluidity of the SCC, time necessary to drop down *N* layers of foam depending on the geometry of the building. Indeed, as the polyurethane foam exhibits weak mechanical properties, the height of concrete deposited must be determined in order to keep the deformation of the FW under a value depending on the local construction tolerance about the deformation of FWs. Once the *N* layers are deposited, the PAA is equipped with a duct linked to a concrete pump and the concrete is poured into the FW up to the predefined height. Then, the AGV together with the PAA, go on depositing the next *N* layers.

At the end of the whole casting, the polyurethane FW is kept in place as the external and internal insulation of the building.

The final rendering of the outer surface is obtained by applying a traditional coating like those used for external insulation techniques. For the inner surface, plaster boards are used.

Figure 3 presents the different phases necessary to build the wall.

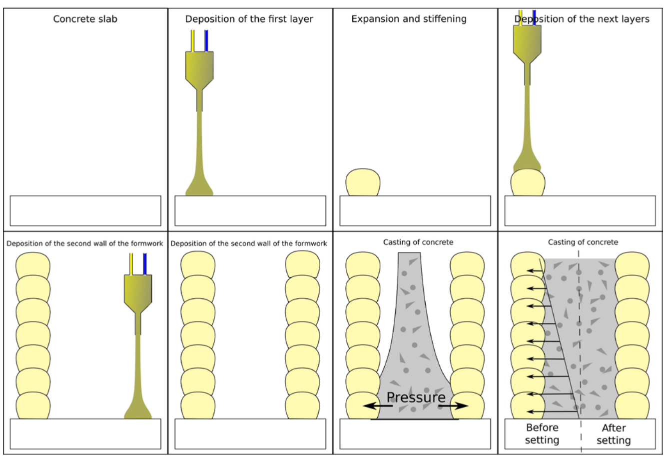

Fig. 3. – Different phases for the erection of the wall.

Fig. 4. – Different parts for the material deposition.

3 Yhnova^{TM}

3.1 A social house

The technique Batiprint3D^{TM} has been applied in september 2017 to the construction of a social house for NMH called Yhnova^{TM}. The name has been chosen as the house has the shape of a Y and because its construction is based on an in-NOVA-tive technique. It is a one level 95m^2 dwelling located in Nantes in a social housing neighbourhood. Figure 5 and 6 show different views of the house designed by TICA architecture. It is located on a parcel with protected trees (aerial part and root system). Consequently, TICA designed a house that does not invade the tree area. Therefore, Yhnova™ will respect not only the trees but also the environment of people who are used to benefit the proximity of the park. Tica tried to fulfil its credo of respect of both the environment and the social context of the building.

Yhnova™ is one of the three projects granted by Nantes City Lab, an action that aims to promote the innovation in the Metropole of Nantes and the collaboration between public and private partners. It encourages the partners (University, firms, SME, startups, associations, users and institutions) *to build together the city of tomorrow*.

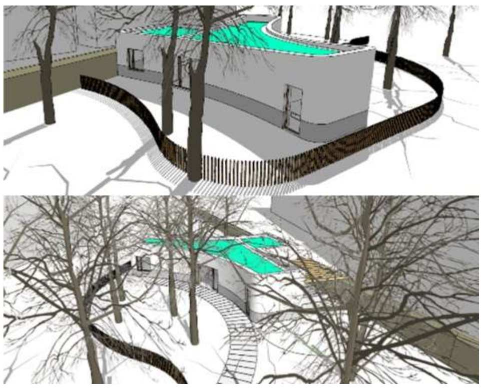

Fig. 5. Views of Yhnova™.

Fig. 6. Plan of Yhnova™.

3.2 Partners of the project

Yhnova™ involves many actors: academic partners, institutional partners, federations, private firms.

3.2.1 Academic partners

The technology Batiprint3D™ has been developed at the University of Nantes (France) by two research teams from:

• the GeM (Research Institute in Civil Engineering and Mechanics – UMR CNRS 6183 University of Nantes/Centrale Nantes/CNRS)

• the LS2N (Laboratory for the Sciences of Numerics – UMR CNRS 6004 University of Nantes/Centrale Nantes/Institut Mines Telecom Altlantique/INRIA/CNRS)

3.2.2 Institutional partners

CSTB – It is the French Building Research Institute. Its role is to guarantee the quality and the security of buildings. It is an expert of the techniques of construction and is in charge of evaluate the projects Batiprint3D™ and Yhnova™, and especially the impact of the technique on the other subtrades or its reliability regarding the seismic behaviour of Yhnova™.

Nantes Metropole (NM) – Nantes is the sixth metropole in France with 600.000 inhabitants. Its population is young as 36% of the population is less than 25 years old. The mayor of Nantes Johanna Rolland aims at having Nantes become a major actor of the evolution of the society by promoting social cohesion, sustainable development and innovation. In this latter aim, Nantes Metropole inaugurated in march 2017 the Nantes City Lab, a new manner to encourage innovation.

Nantes Metropole Habitat (NMH) – It is a social landlord located in Nantes. It owns around 25.000 dwellings (houses or apartments) in the Metropole of Nantes and dwells nearly 50.000 persons. NMH is always in search of innovation directly applicable to the dwellings and was interested in participating to the development of our technique of additive manufacturing for the construction. It will be the owner of Yhnova™.

SATT Ouest Valorisation – It is a public society dedicated to the transfer of technologies from the universitary laboratories to the industrial environment. It aims at helping the researchers to increase the TRL (Technology Readiness Level) of their developments and promote the intellectual protection of the discoveries.

3.2.3 Federations

French Building Federation (FFB) – It gathers 50.000 subscribers and 45.000 enterprises, acting in the sector of the construction of buildings.

Novabuild – It is a cluster in the Region Pays de la Loire (France), which promotes the eco-construction, the energy transition, the environmental transition, the numerical transition and the social transition in the context of the building industry

3.2.4 Private firms

BA Systèmes – It is specialized in the mobile robotics and in particular in the manufacturing and the development of AGV.

Bouygues Bâtiment – It is a global actor of the construction and is present in 80 countries. It claims that innovation is the first additional value for construction. It is part of several projects of additive manufacturing or robotization, applied as well to the construction of buildings as to the construction of infrastructures.

Carretero Meyer – It is a construction enterprise located in the region of Nantes. Even if it is a SME, it promotes innovation and has been part of the project since the beginning. The main interest of the enterprise for the development of additive manufacturing for the construction of dwellings is the fact that in the developed countries, it is more and more difficult to renew the retired employees, due to the arduousness of the jobs. Additive manufacturing could be a solution to this problem of unattractiveness.

Lafarge-Holcim – It is one of the worldwide leading provider of construction materials (cement, gravels, concrete). In the project, it supports the development of the concrete mix.

PRB – It is a manufacturer and supplier of building coatings.

TICA Architecture – It is the architect of the project Yhnova™. TICA is preoccupied by the social and the environmental aspects of a project of construction. TICA designed the house Yhnova™.

3.3 Deployment on the construction site

The figure 7 show different steps of the construction of Yhnova™. We can notice that the whole construction site is protected by a tent so that the robots can work in safe environmental conditions. In this section we point out the main problems that occurred during the construction of Yhnova™.

3.3.1 Construction site nuisance

During the construction of the walls, the robots worked a total of 54h. Nevertheless, the robot worked from 8AM to 7PM and did not work at the week end, as the owner did not want to disturb the neighbourhood with working noises. Especially, the need for an air compressor and an electrical power unit that are quite noisy, impeached the robot to work at night. Moreover, the concrete delivery could not occur at night because the concrete plant was closed and because this is also a noisy operation (engine noise, reverse beeper…). This shows that even if we have the means to make the robots work continuously, we cannot do so because of the neighbourhood and because of the opening time of the concrete plant. For now, the increase in the building rates allowed by 3D printing is thus still a mean term objective. But, even if the industrial context evolves to match the requirement of a continuous work of the robots, the concern in the quietness for the neighbourhood will be difficult to manage at night.

3.3.2 Interferences with the printhead

Prior to bring the robots on the construction plant, the lower slab have to be cast and set and the reinforcing bars must be placed, especially near the wood frames placed at the location of the openings.

When we brought the robots on the slab, we noticed that the slab had not the predefined shape. The tolerance on the staking out of the slab the workers are used to do not match the tolerance required by the robots. Indeed, as explained above, the robots can accurately position the print head with a tolerance of 1mm. This was not the case nor for the slab neither for the reinforcement bars. As a consequence, we had to make the masonry enterprise move the rebars prior to play the deposition paths, in order to avoid interference between the print head and the rebars.

Moreover, a ancient wall as close to the slab and the true position of the wall had not been determined accurately, in particular the vertical shape of this wall was irregular. There were thus differences between the true shape and the shape taken into account to generate the trajectories of the print head. This obliged us to redefine the trajectories on site.

The same problem occurred with the fluid networks (water and heat supply).

We can see that the tolerances in the staking out of the different elements of the building and the consideration of existing elements close to the robots operating zone is of major importance. This will oblige the construction sector to lower the tolerances to match those of an automated construction of the building.

4 Conclusions

In this paper, we presented briefly the projects Batiprint3D^{TM} and Yhnova^{TM}. The first was dedicated to the development of a new technology of construction based on 3D printing. The second was dedicated to the use of this technology to build a social dwelling for a social landlord in Nantes.

In Batiprint3D^{TM}, to use a PU FW in which the SCC is poured allowed us to work with a concrete with simpler properties than those usually required by the extrusion of cementitious or clayey materials. Moreover, it allowed us to obtain more easily the authorizations to build our house as the justification of the structural safety of the walls relied on usual calculation procedures. Indeed, we had not to justify the structural safety of a layered concrete wall but of a wall very similar to those poured in classical formworks.

The fact to deploy our technology on a real construction site after development at the laboratory taught us a lot about the context of construction and how the 3D printing can match the standards of construction or how the standards of construction have to evolve to include this new construction technology.

Nevertheless, the development of 3D printing in order to increase the construction rates is for now still a potential objective as this requires to rethink the management of the construction phase, the delivery of concrete and the opening time of the concrete plant, but also to find a way to limit the noise nuisance for the neighbourhood.

Thus, even if we did the job and delivered the walls of Yhnova™ on time, a lot is still to do to make of 3D printing a mature construction technology.

Fig. 7. The construction site of Yhnova™ – a) Deposition of the 6 first layers on the slab showing the reinforcement bars – b) Deposition of PU showing the AGV, the PAA and the protective tent – c) Timber frame for the roof – d) Inner curved plaster boards – e) Outer view of the walls – f) View of the wall covered with external coating.

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