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The structural feasibility of 3D-printing houses using printable polymers

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Abstract

At this point in time, 3D-printing techniques in general, but especially applied for the building industry, still are in a phase of early experiments. One of the experimental attempts is to print a full-scale, three-story high, house in Amsterdam, using an up scaled version of a FDM-printer that is able to print blocks of 1.8 x 1.8 x 3.0 meters using printable polymers. The paper focuses on answering the initial structural question that appears around this project, which is a research to the behavior of the currently applied printing material. The outcome of this research will be used to give recommendations for the structural design of printable geometries.
The material research emphasis on obtaining the material properties that are most essential to be known for this particular printing material and the application of the material within this particular building project. These basically are the mechanical (strength) properties of the material and its thermal behavior. Since the FDM-printer lays down the material layer by layer, the hypothesis was that the material would show anisotropic behavior. Therefore the strength properties are researched in different orientations relative to the direction of the printed lines. Furthermore, it was expected that the strength properties would differ for the horizontal plane and vertical plane in which there can be printed, as the resolutions in both planes differ as well.

For the vertical printing plane, the material indeed shows clear anisotropic behavior, as the tensile, shear and flexural strength values and the failure modes parallel and perpendicular to the printing direction differ significantly. Material that is printed within the horizontal printing plane shows more isotropic behavior than material that is printed in the vertical plane, due to more and better adhesive connections between the different layers. For the compressive strength it holds that not much difference is noticed between the different orientations, especially because the tested samples are composed of multiple printed layers in both the horizontal and vertical plane. This result leads to an important recommendation to compose printable building-blocks out of 3D-elements instead of only 2D-plate elements, which so far has been the case. This actually leads to a stronger, more isotropic, more homogeneous and therefore better predictable material behavior. Throughout the research this recommendation is further confirmed by outcomes of the absorption test, geometry tests and insulation requirements. The absorption test shows that the material becomes watertight in case multiple printing layers are applied in the horizontal direction. The performed bending and pressure tests on printed geometries demonstrate that geometries, which are build up by a single layer, fail due to local effects: they either fail on local buckling or local bending of an individual member of the geometry or they fail at the location of local inaccuracies, which often occur within printed geometries. The stress level at which these failure modes take place can be significantly increased by composing individual geometry members out of multiple printed layers. Finally, to meet the requirements for heat and sound insulation, a certain wall and floor thickness is required which only can be achieved by printing multiple layers within the horizontal printing direction.

The performed temperature-strength test and DSC-test show that current thermal behavior of the material is the most important point of concern regarding the applied printing material. The material is applied in the rubber phase, it softens at 60 degrees Celsius and at a surface temperature of 40 degrees Celsius, the material has lost already about 70% of the material strength it has at room temperature. It is obvious that further research on the improvement of the temperature behavior of the building material is essential to make printable polymers suitable for structural applications. Also the comparison with general structural materials and polymers applied in the construction practice, confirms that the printing material in its current form, is not structurally applicable. Furthermore, the comparison shows that the stiffness of the material needs to be improved, as the Young’s Modulus is relatively low.

Although the essence of further research should lie on the improvement of the printing material, it still can be valuable to continue the structural design process parallel to the material development. Based on the performed material research, recommendations are given for design improvements. These recommendations can be used as a starting point for a possible future study to the structural design of printable geometries, chambers and complete houses.

Keywords: 3D-printing, additive manufacturing, FDM-printing, polymers, printable polymers, housing, material testing, 3D printed specimens, material behavior, 3D print canal house,

1. Introduction

These days, there is a growing attention for 3D-printing (or Additive Manufacturing) techniques [1] [2]. While these techniques are already applied for years in the mechanical industry, the development of relatively cheap consumer 3D-printers has given additive manufacturing techniques a new boost. A lot of people nowadays expect a great future for 3D-printing. Some experts believe that these techniques can cause a new industrial revolution and others say that in the future, our buildings and construction works will be printed on the building site.

In spite of these very promising stories about 3D printing in general and 3D printing in the building industry in particular, it seems that these stories so far mainly are based on general progressive belief instead of being founded by research to the actual possibilities of 3D printing in the Construction Industry.
When taking a closer look to the current state of additive manufacturing techniques it becomes obvious that some huge steps need to be taken on technical side before one arrives at a point that printing (parts) of buildings or construction works becomes feasible. Disruptive innovations will be needed both for the 3D-printing techniques itself as in the field of materials science, to give additive manufacturing a future in the building industry. Once printing (parts) of constructions actually would become technically feasible, then still the question remains whether these techniques add value to or reduce costs of building projects.

In all cases, it is clear that large amounts of research and development need to be performed to take further steps. Long-term developments like this require a combination of theoretical and practical studies, for which both theoretical researchers as more practical engineers are needed parallel to each other. At this moment, 3D-printing techniques in general, but especially applied for the building industry, still are in a phase of early experiments. At different places around the world first attempts are made to print houses with the use of a 3D-printer. These first 3D-printed houses probably will not meet all the requirements of general housing and therefore will not function as an actual house, but more as an experimental building or pavilion. These practical and experimental attempts have two main functions: one is that experimenting leads to new knowledge and insights, such that the techniques can be further evolved and another important function is that techniques need certain exposing and imaginative milestones in order to attract enough attention, enthusiasm, people and money to set further steps. Printing a full-scale house is such a milestone that triggers the imagination. One of the experimental attempts to print a full scale house is situated in Amsterdam, where the goal is to print a full-scale, three-story high Canal House. Where in other places around the world there are experiments in printing houses with sand or concrete [3] [4], the aim in Amsterdam is to print a house out of polymers. Although this is quite an unusual material when it comes to building structures, the choice for this material is made because the conclusion was drawn that 3D-printing techniques currently are most evolved for printing with plastics. Therefore, an up scaled version of an Ultimaker Printer, which is a consumer FDM printer, is build, a building site is furnished and the attempt to reach the milestone of a printed canal house is started.

This paper strives to contribute to this particular experiment that is currently ongoing in Amsterdam, by performing early technical research for this 3D-printed housing project. Although technically contributing to one particular test case forms only a small research area, it hopefully is a helpful step within the overall development of what at least is a promising innovative technique.

2. Research Content

2.1. Problem Definition

By studying the state of the 3D Print Canal House Project at the start of this research, an analysis is made of the problems that are present in the project on structural side.

The reason DUS Architects has closed a partnership with Tentech in this project, is simply to validate their plans for a 3D-printed Canal House on structural side and to receive structural advice that can be used as input for the further design of the house. This overall problem of verifying the structural design of the Canal House, can be subdivided into the following two main problems:

1. Every Chamber should individually be capable of transferring the loads that are working on it towards the ground/foundation. This, because the building will be build up chamber by chamber.
2. Chambers together should cooperate in such a way that the building as a whole is capable of transferring the loads that are working on it to the ground/foundation.

Important remarks allied to these main problems:

- Since the dimensions of printable elements are limited to 1.8 x 1.8 x 3.0 m, an individual chamber is build up by elements, since these dimensions are not sufficient for printing a whole room in one print.
- It is desired that the house is detachable, on the level of chambers, or even on the level of printable elements.
- It is desired that the house is build up out of printable elements/parts as much as possible. Only there where use of the printer is not sufficient to arrive at a solution that meet the structural requirements, supporting materials and elements can be used to come to a structural satisfactory solution.
- DUS Architects desires to come towards an integrated computer model in which the architecture, material use and structure are coupled in such a way that modifications made in the architectural design or material use automatically leads to changes on structural side, and vice versa.
- There is a wish to, if possible, combine the printable building elements with service ducts.
- The 3D Print Canal house is designed and built in an iterative way. Therefore, it is important to offer structural solutions that allow some flexibility in choices on the side of architecture and material use.

2.2. Research Objectives

The steps that need to be taken within the scope of this research can be put under three main objectives:

- Find the elementary properties of the printing material, that are required for structural design with this material.
- Test the behavior of the material on the level of printed blocks/geometry.
- Give recommendations for structural design of an optimal printable, two-dimensional wall- and floor-element and a possible coupling between those two.

3. Expected influence of 3D printing on material properties

The printing process of the 3D Printer will probably lead to different material properties in different directions. Therefore, the printing process and the possible consequential direction-dependent behavior are explained in this chapter.

First, since it is a 3D-printer which is used here, there are 3 directions in which there can be printed, the x-, y- and z-direction, and two planes: the xy-plane and the xz-plane.
The possible printing resolution-ranges differ in these two planes, for the reason that when laying down the material, the material will spread due to gravity, before it is hardened. Due to this spreading of the material, the printed lines will become thicker in the xy-direction than in the xz-direction, which lead to less lines per meter in the xy-plane than in the xz-plane and therefore a lower resolution in the xy-plane than in the xz-plane.

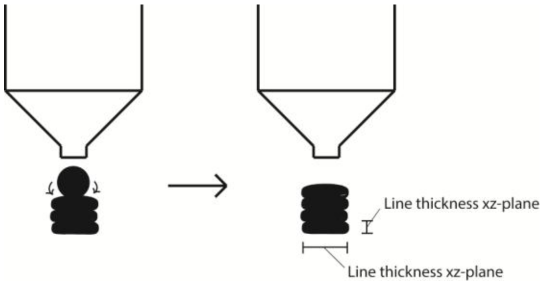

Figure 1: Due to gravity and consequential spreading of the material, different line thicknesses and resolutions are obtained in the xy-plane and the xz-plane

Apart from the difference in resolution, also differences in connectivity can be expected between the two different directions. Due to gravity, the layers might better connect in the xz-plane, since the gravity force pushes the layers on each other, which is not the case in the xy-plane.
On the other hand also the hardening process might play a role here. When a line is not solidified yet before the line next to it or on top of it will be printed, than the two lines will better connect than in case that the previous line is already solidified. In the xy-direction it is more likely that a line is not solidified yet before the new line next to it will be printed out, because the printer head first prints everything in xy-direction, before it moves in the z-direction to a higher level. What also can have an influence is the end connectivity between the lines which is present in the xy-direction and not in the xz-direction. This will also be advantageous for the strength in xy-direction.

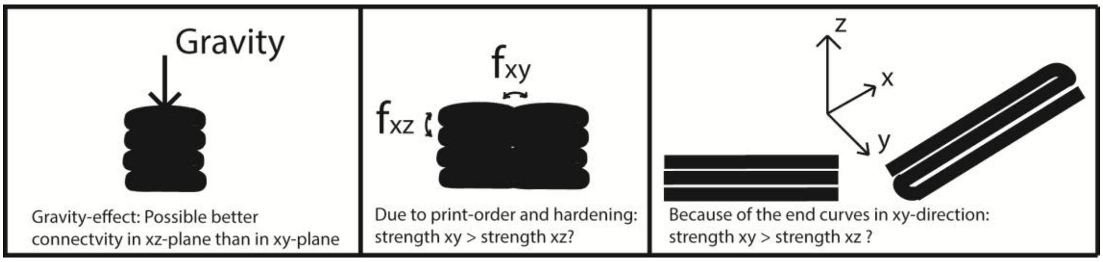

Figure 2: These three processes probably cause a difference in layer-connectivity between the xy-plane and the xz-plane

Because of the difference in resolution and the difference in connectivity between the xz-plane and the xy-plane, a difference between the strength in the xz-plane and the xy-plane can be expected.
The hypotheses is that the strength of the material in xz-plane will be higher than in the xy-plane, because it is expected that the higher resolution in the xz-plane and the connectivity between the layers due to gravity will play a bigger role than the other mentioned effects that seemed to be advantageous for the strength in the xy-direction.

Then, within a single plane, also a direction dependent behavior can be expected: Because the printer prints line by line or layer by layer, different strength capacities can be expected in the direction parallel to the printed lines and the direction perpendicular to the printed lines. So the material is expected to be anisotropic within both of the 2D-planes.

So, to summarize: A difference in mechanical properties can be expected between the two planes (xy- and xz-plane) in which there can be printed. Furthermore, within both of the planes it holds that there probably will be an anisotropic behavior.

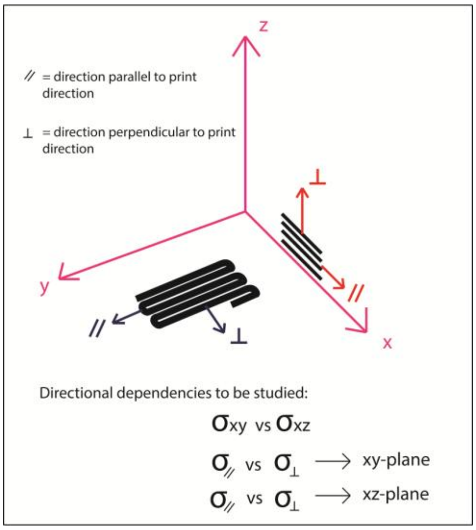

Figure 3: A difference in strength properties is expected between the two printed planes and between the ‘grain’ directions

These directional dependencies all should be taken into account during the material tests, which means for most of the mechanical properties that they have to be obtained for the different directions/configurations.

4. 3D-printed and Laser-cut Test Specimens

4.1. Innovative production methods of test specimens

Since the innovative production method of 3D-printing enables the opportunity to fabricate samples in every desired form, 3D printing offers the advantage that complex sample-forms can be easily fabricated such that testing methods can be simplified. For that reason, for the performance of the shear tests, a sample in the form and dimensions as used in [5] has been produced.

In chapter 3 it is explained that the 3D-printing method leads to the following parameters that possibly have an influence on the mechanical behavior of the material:
- A difference in mechanical properties is expected between the xy- and xz-plane in which there can be printed.
- The material probably will show anisotropic behavior.
- Different resolutions can be set.

To test if these three factors indeed influence the mechanical behavior, the properties of some of the test specimens should be varied such that these three possible parameters of influence will be included. So at first, this means that the samples used to test the directional dependencies should be printed both in the xy- and the xz-plane and within these both planes, also with a grain-direction of 0°, 90° and 45°. Furthermore it is desired that the printing resolution is varied. However, due to a limited amount of available printing time, there has been decided to not include a resolution-variation as part of this research.

In the horizontal xy-plane, test specimens can be 3D-printed directly within the desired form. However, since 3D-printing doesn’t allow the possibility to create spans/cantilevers, in the vertical xy-direction, a different fabrication method is conceived: By first printing out vertical plates in the xz-plane and after that cut-out the samples out of the plates with a computer-controlled laser-cutter, samples printed within the xz-plane can be obtained.
3D printing of test specimens as well as laser-cutting test specimens out of printed plates, form two innovative production methods for test specimens. In the following paragraph the output results for these innovative production methods are given.

4.2. Evaluation of the innovative production Methods

When looking at the process and the results of both methods, it can be concluded that for this particular printer it is recommended to use the laser-cutting method in the future for both directions. This, because the laser-cutting method leads to samples of a better quality, which means that the dimensions are more accurate and the grain-direction is better noticeable. This also means for the laser cut samples, that the size fluctuations between the different copies of the same sample type are less and that these laser cut samples lead to more reliable testing results than the direct printed samples.

However, in case a more accurate 3D-pritner is used that is able to print cantilevers and spans as well, then it is really considerable to use a 3D-pritner to print out test specimens directly, because it is a simple and quick way to obtain complex-formed samples.

Figure 4: Left: the specimens that are directly printed within the xy-plane. Right: Specimens that are laser-cut from plates that are printed within the xz-plane.

5. Performed Material Tests

Two types of material tests have been performed: material tests in order to define the elementary material properties of the printing material and materials tests on block/geometry level.

With elementary properties, the basic properties of the material are meant that are independent of the dimensions and form of printed geometries. A selection of elementary properties, that are found to be essential for the judgement of the printing material as a building material, have been made in order to determine the material tests that need to be performed.

Because the mechanical properties of the material can be dependent of the size, form and dimensions of the geometry in which the material is applied, also large blocks/geometries composed of the printing material are tested. In this way it can be studied whether the elementary compressive, shear and tensile strength as determined in the elementary material tests, are in line with the test results that are obtained for tests of large geometries. This comparison between elementary strength properties and strength performance of larger blocks is important to be known, because it defines the predictability of the mechanical behavior of designed printing geometries within the 3D printed house.

The tests that have been performed are:

Material Tests- Elementary Level

1. Tensile test
2. Shear Test
3. Compressive Test
4. Determination of the Young’s moduli
5. Determination Density
6. Absorption and Drying Test
7. Temperature – Strength Test
8. Differential Scanning Calorimetry Test
9. Creep Test

Material Block/Geometry level

1. Compressive/Buckling Tests
2. Bending Tests

Figure 5: Left: One of the Elementary test-setups, the performance of a Tensile test. Right: One of the tests on Block/Geometry level: the bending test of a square tube beam with an inner triangular structure.

6. Conclusions and Recommendations

6.1. Conclusions

1. The behavior of the printing material under high temperatures is much less than for traditional structural materials. A softening point of only 60 degrees Celsius and a strength degradation of 70% at a temperature of 40 degrees are unacceptable low properties for structural applications. Also, the Young's Modulus and thus the material stiffness are poor compared to common structural materials. These poor thermal behavior and low stiffness are caused by the fact that the printing material is applied in the rubber phase as the glass temperature lies around 5 degrees. This while other plastics in the construction practice are applied in the solid phase, as their glass temperatures lie above the maximum temperature of sun-heated parts in The Netherlands (80 degrees). Applying a polymer structurally in its rubber phase, is unfeasible, as the low Young's Modulus and poor temperature behavior already evidenced. Therefore the current printing material cannot be applied to create (housing) structures.
2. The printing material shows clear anisotropic behavior, which means that the strength properties parallel and perpendicular to the direction of the printed lines differ significantly.
3. No problems are expected for the material being exposed towards rain and frost, as the printing material blocks almost all the water. A requirement for the water tightness of the material however is that the printed elements are build up with at least 3 printed layers in the horizontal direction, as often present holes in single printed layers will be filled in that case with a high certainty.
4. The specific heat capacity of the printing material is relatively low, which means that the material insulates air heat well. For a winter situation this is a positive given, but for the

situation in the summer it means that measurements need to be taken to prevent the inner of the building for becoming too warm.

5. As the softening point of the material lies on 60 degrees, elements made of the printing material should never be directly exposed to the sun. This means for The Netherlands that this material may never be located in the outer layer of facades that are directed to the East, South or West.
6. The printing material is very sensitive for locally applied forces. This in particular has consequences for the design of connections. Connecting by means of bolts should be avoided.
7. Geometries consisting of members with a thickness of a single printed layer are very sensitive for local failure mechanisms. Local failure mechanism are buckling and bending of individual members or failure at the location of a local inaccuracy. By building up geometries by members consisting of multiple layers instead of one layer, the members will become stiffer, the local and overall strength of geometries become higher and the material is more homogeneous and less sensitive to local inaccuracies.
8. Keeping the span of the individual members within a geometry low, is crucial for increasing the structural performance, because the local spans often form the normative property for structural failure of geometries.
9. For house separating walls between connected houses, the sound insulation requirement is normative and leads to separating walls and floors of about 0.70 m. For façade thicknesses of detached houses, the heat insulation requirement, that leads to a façade-thickness of about 0.30 m, is normative above the sound insulation requirement. Whether the heat insulation requirement for facades also is normative above the structural requirements will depend on the applied dimensions, form and loads of the particular structure.

6.2. Recommendations

6.2.1. General Recommendations

1. In case one actually wants to build a house with the current applied printing material, the material is only applicable as a permanent mold for concrete. In that case, the inner holes of a printed geometry can be filled with reinforced concrete and insulating materials. On the outside of the permanent formwork, at least a heat-resistant façade-covering needs to be added.

6.2.2. Design Recommendations

1. One should always try as much as possible to load the material in the direction of the printed lines, especially when the material is loaded in tension or bending. This because, the material is significantly stronger in this direction and often fails after an initial deformation instead of in a brittle manner.
2. It is strongly recommended to create building blocks that exist of multiple printed layers that are connected to each other within the xy-direction instead of blocks that are built up by only single layers, which so far has been the case. Using multiple layers within the xy-direction

leads to a stronger, stiffer, more isotropic, more homogeneous and therefore better predictable material behavior. Another good reason to apply multiple layers in the xy-direction is that the building blocks will become waterproof, that the material becomes less sensitive to local inaccuracies and that the material can easier meet the heat and sound insulation requirements for housing.
This means that all individual walls/members of printed geometries should consist of multiple printed layers in the horizontal direction. By this, the individual members become stiffer and the local and overall strength of geometries will become higher.
It is advised not to continue with printing single-layer-walled blocks, as these geometries are sensitive to local failure mechanisms. Due to these local failure mechanisms, the material by far is not loaded to its strength capacity. By building up geometry walls with multiple layers, the material capacity is better utilized.

3. One should build up geometries such that multicarrier roads are created within a printed element and spans of the individual members are minimized.

6.2.3. Recommendations – Next Steps/Future Research

1. Further research on the improvement of the thermal behavior of printable materials should be performed. Also, the stiffness (Young's Modulus) of the applied printing material needs to be increased. These improvements can probably be made by experimenting with printing of materials that are in a solid state under normal circumstances. The current applied material is in a rubber phase, which leads to the low stiffness and poor strength-temperature behavior.
2. For printability of a material, a low glass, softening and melting temperature and a low molecular weight are preferred. However, for structural application of a material, high temperatures and a high molecular weight are required. The most important challenge for enabling 3d-printing of houses with polymers, is to solve this contradistinction and find an optimum material that is printable and structurally applicable. It therefore is strongly advised to focus future research on the feasibility of 3d-printing with structural applicable polymers. The test results and conclusions of this paper can be used as a starting point for this future research.
3. On the moment it would turn out not to be feasible to print structural applicable polymers within a desired time span, then it is recommended to change the focus of the 3D Print Canal House Project from printing a complete house with printable polymers to the printing of formwork using printable polymers. In that case, the material and printing technique would need to be optimised for printing molds. For formwork, the requirements are significantly lower and therefore simpler achievable than the requirements for structural application.
4. The particular situation of the 3D Print Canal House project can act as an interesting case study for performing next steps towards an integrated computational design tool for (at least) architectural and structural design.
5. Finally it can be interesting to perform a study to the economical/commercial feasibility of 3d-printing houses and other structures, by using printable polymers.

6.2.4. Practical recommendations that support future research

1. On the moment a new printing material is developed, it is recommended to first and foremost perform the strength-temperature test (on this new material. This because, the temperature

behavior is the weakest and therefore most critical characteristic of the current printing material so new materials should especially show improvement for this property.

2. It is advised to study the influence of the printing resolution on the strength properties of the material.
3. It is recommended to experiment with printing perpendicular printed layers on top of each other. This means that if a layer is directed to the x-direction, the layer on top of it is directed in the y-direction (other horizontal direction) and the next layer again in the x-direction etc. In this way, it might be the case that the anisotropic behavior of the material will be reduced or even eliminated.
4. More extensive research on the creep behavior of the material is required before it can be applied with full safety.
5. Once the designing parties decide to continue building up geometries by thin members consisting of only one printed layer, it is highly recommended to perform research on the hardness of the printing material.
6. It is recommended for future research to study the fatigue behavior of the printing material, because this can be a normative failure mechanism, especially around connections.

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