공학석사 학위논문

Optimizing 3D Printer Depending on 3D Printing Concrete Property

3D 프린팅 콘트리트에 따른 3D 프린터 최적화

2018 년 8 월

서울대학교 대학원

건축학과

박 문 용

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이 논문을 공학석사 학위논문으로 제출함

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Abstract

Optimizing 3D Printer Depending on 3D Printing Concrete Property

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As the digital technologies such as AI and automation are developed, the boundary lines between the physical, digital, and biological technologies are weakening. This weakening of boundary lines is considered as the Fourth Industrial Revolution. With this new industrial revolution, new technologies are born. Among new technologies, 3D printing is viewed as one of leading technologies for the Fourth Industrial Revolution. 3D printing is a technology which creates a three-dimensional object by joining material using computer controlled machine. When applied to the Architecture, it is expected to provide financial profit by reducing construction cost, construction time and by simplifying production process.

The purpose of this study is to evaluate limitation for current 3D printing technologies when used in the Architecture and suggest solutions. 3D printing is an Additive Manufacturing (AM) process which stacks layers of materials upon each other to create an object. Currently used 3D printing methods are Concrete Printing, and D-Shape. When applied at large-scale 3D printing, each methods has own advantages and disadvantages. The main focus of this research is to evaluate 3D printing methods and introduce suggestions for improving structural stability of 3D printed model.

In this research, Concrete Printing method showed high potential to be used in the Architecture. However, depending on multiple factors like material properties, printer performance, and model shape, there are limitation to Concrete Printing. Each factor cause failure during 3D printing process.

As a method for form optimization, Topology Analysis and Modularization are suggested. Through Topology Analysis, optimal form to resist give load case could be achieved along with reduced material use and production time. On the other hand, Modularization could relieve 3D printable form limitation. Performing structural analysis for 3D model considering limitations of 3D printer is recommended before printing the model and through further research form optimization algorithm for 3D printed model can be acquired.

To be able to apply these solutions, 3D printer property and 3D printing material property must be defined. This paper tests different 3D printing concrete mixture to check the outcome of each mixture suggests how to optimize 3D printing property.

Keywords : 3D print, optimization, form finding

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Chapter 1. Introduction

1.1 Backgrounds

Concrete is the most used building material worldwide. It is strong in compression, durable, and fire resistant. Also, due to its fluid state before setting, concrete can be used for 3D printing. 3D printing is receiving a high expectation as the leading technology of the Fourth Industrial Revolution. It is one of Additive Manufacturing (AM) technology which stacks materials layer-by-layer method. With its simple process, it is expected to bring financial profit in the Architecture by reducing construction cost, construction time, and by simplifying production process. Also, its unnecessary for moulds makes it possible to construct free-form model which are limited to current construction methods.

As for the reinforced concrete method, the construction are done repeating following process; placing of reinforcing bars, construction moulds, casting wet concrete, curing of concrete and removing moulds. During this process, it requires considerable labour to position the reinforcement and construct the mould. The mould could be re-used, but not always. However, for 3D printing method, need for constructing moulds are gone and required setting time for concrete is greatly reduced due to use of fast-setting and low slump concrete. With the path-data to direct where to extrude the material, the model could be constructed without any supporting object by stacking layers.

Fig. 1-2 Reinforced Concrete Building

Fig. 1-1 3D Printed Building

Research on building a 3D printer to apply these benefits to the Architecture is widely practiced to construct residential buildings. To use concrete as the printing material, Concrete Printing and D-Shape methods are used. However, there are limitations depending on printer size, printing material and model shape. Although there are model cases for 3D printed buildings, those cases are limited to simple shaped buildings.

1.2 Scope and Objectives

The main goal of this research is to examine the process and limitations in 3D printer and evaluate to propose optimal process to relieve limitation and achieve structural safety of 3D printed models. Current 3D printing method simply place the new layer of material on top of placed layers. Although, this method is viable at printing simple structures, it is strenuous to print complex structures.

Through analyzing possible failure cases in 3D printing, key factors for stable printing condition can be defined and used as guideline to distinguish printable model and unprintable model. Once model is analyzed, unprintable model could be adjusted to meet print requirements.

Chapter 2. Literature Review

2.1 3D Printing Method

To use concrete as 3D printing material, Contour Crafting, Concrete Printing, and D-shape are used as common methods. Each methods is related to an Additive Manufacturing process with different method in how to stack the material.

2.1.1 Contour Crafting

Contour Crafting has been in development for some years and is based on extruding a cement-based paste against a trowel that allows a smooth surface finish created through the build up of subsequent layers. Its deposition head is mounted on either frame, robot-are, or crane. The material is extruded along the outline footprint of the wall layer by layer. At specific intervals, metal support are placed across the hollow gap. Concrete is then poured into the empty space in the wall. It has been developed to address the issue of high-speed automated construction and the current deposition head is capable of laying down material to create a full width structural wall with the minimum use of material. When creating an overhang, a lintel is placed to bridge the gap.

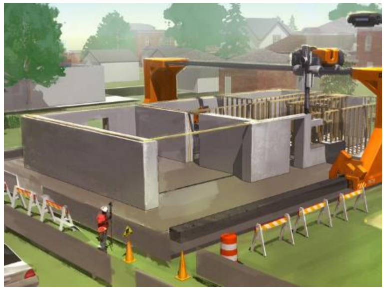
2.1.2 Concrete Printing

Concrete Printing is also based on the extrusion of cement mortar. However, the process has been developed to retain 3-dimensional freedom and has a smaller resolution of deposition which allow for greater control of internal and external geometries. When printing a model, the material is extruded along printing path. Unlike Contour Crafting, inner part of outline is filled which removes requirement to pause printing process to provide support. However, similar to Contour Crafting, a support is required to when creating an overhang.

2.1.3 D-Shape

D-Shape method uses a powder deposition process which is selectively hardened using a binder. Each layer of build material is laid to the desired thickness, compacted and then the nozzles mounted on a gantry frame deposit the binder where the part is to be solid. Once a part is complete, it is dug out of the loose powder bed. Unused powder can be reused for later production. Unlike previous methods, unused material functions as a support when creating an overhang.

Table 1 3D printing method comparison

	 Contour Crafting	 Concrete Printing	 D-Shape
Process	Extrusion	Extrusion	3D Printing
Use of mould	Yes (Become a part of component)	No	No
Binder	None	None	Chorine-based liquid
Pros	- Smooth surface by trowel	- High strength - Minimum printing process	- High strength
Cons	- Extra process - Weak bonding between batches	- Limited Printing dimension	- Slow process - Rough surface - Limited printing dimension - Massive material placement - Removal of unused material

2.2 Key Factors

2.2.1 Stacking Angle

As a part of Additive Manufacturing process, 3D printing stacks the material vertically upon existing material to create 3D objects. Under straight stacking, layers beneath a currently printed layer provide firm support and all layers have same point of gravity which cause even deformation to unsolidified layers.

When stacking occurs at an angle, shift of point of gravity occurs which significantly effects stability of layers. In a 2D consideration, the limit of cantilevering is determined by the shifting of the point of gravity outside the supports. However, the actual limit at 3D printing is significantly lower as shifting of the point of gravity outside to mid-point of the support introduces uneven compressive stresses, causing uneven deformation. Accumulation of uneven deformation would cause layers to slant which eventually result in premature failure in 3D printing.

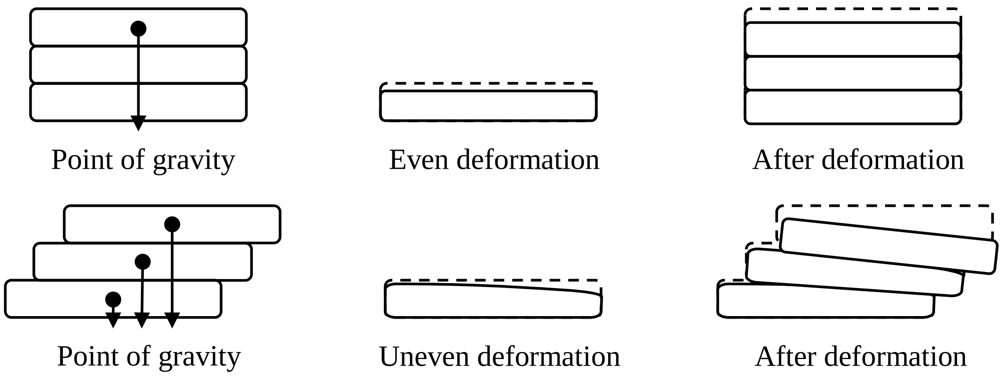


Fig. 2-1 Effect of shift of the point of gravity

2.2.2 Printing Speed

The bond between layers is key factor in deciding structural performance of printed model. It is highly dependent on the adhesion which is varies depending on time between extrusions. The influence of time between layers was investigated by printing layers at different time gap (in increments of 15, 30 minutes, 1, 2, 4, 8, 18 hours and 1, 3, 7 days). The results showed inverse relationship between printing time gap and bond strength between layers. The tensile bond strength is reduced as printing gap between layers are increased. Although it is ideal to minimize time gap between each layers, careful balance is required as printed layers could fail to support its self-weight when sufficient rigidity of material is not developed.

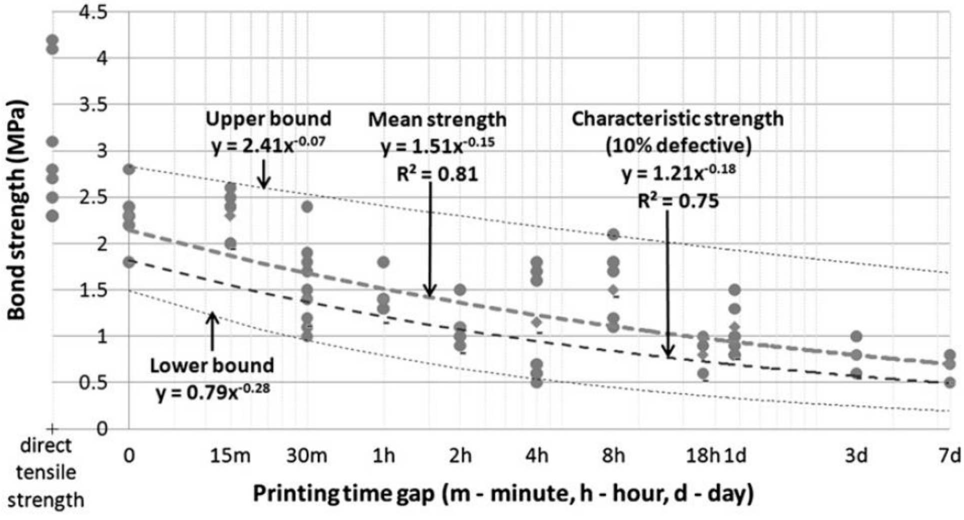


Fig. 2-2 Relationship between printing time gap and bond strength (Le, 2011)

2.2.3 Self-load

Although fully set layers could be considered to be sufficiently stiff and strong enough to withstand additional stacking, unsolidified layers have unstable nature. Each layers has different stiffness and strength depending on the time laps until it is fully set. Due to this unstable nature, adjusting printing speed to acquire stiffness and strength of printing material is required. Without any adjustments, additional stacking could occur while there is not enough stiffness and strength on beneath layer, which would cause premature failure during 3D printing.

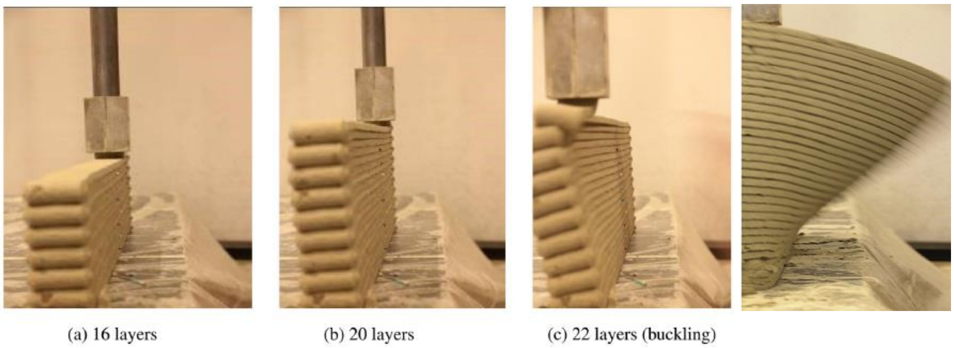
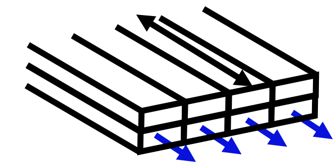
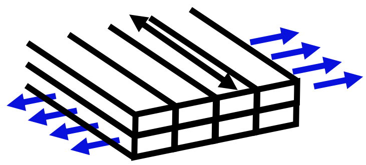
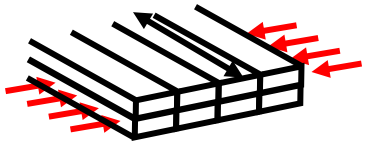
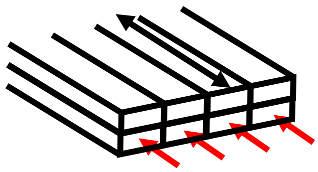


Fig. 2-3 Stacking of layers

2.2.4 Printing Direction

As each layers has different stiffness and strength depending on the time laps until it is fully set, connectivity between printed filaments differs depending on locations. When printing each filaments, horizontally placed filaments bond together before vertically placed filaments does. Thus causing printed model to show strong resistance against tension stress when printing direction and loading direction match. When printing direction and loading direction are perpendicular to each other, printed model showed strong resistance against compression stress

Table 2 Tension and compression behavior depending on printing direction

	Strong	Weak
Tension		
Compression		

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2.2 In Case of Failure

In case of premature failure during 3D printing, it causes whole process to start over as printed materials bond at the moment of extrusion. Failure could occur due to mechanical and material issue. The gantry could fail to move to designated location due to motor failure or distraction in printing path. Even though gantry function as it is designed to be, premature failure could still occur due to factors mentioned above. When these failures occur, faulty placed material bonds to normally placed materials which cause whole model to be unusable.

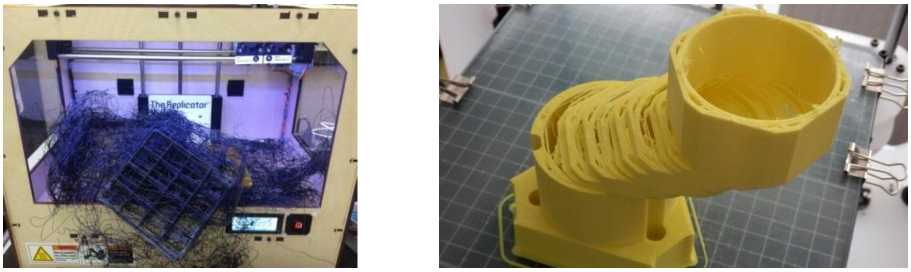


Fig. 2-4 Failure cases for PLA based 3D printed model

Fig. 2-5 Failure case for concrete based 3D printed model (Le, 2011)

Chapter 3. Form Optimization

3.1 Introduction

Even though material and 3D printer are ready to used, if the model is not suitable to be 3D printed, every fails from start. To relieve this problem, form optimization for model is require to make is suitable to 3D print.

Premature failure during 3D printing could cause significant setback to process and throw away worked product. Although few failure causes could be reduced by adjusting 3D printer and material property. However, this method could not consider every possible combinations of variables. To minimize these variables adjustments at 3D printed model are needed.

3.2 Topology Optimization

As 3D printing is receiving a high expectation as leading technology of Fourth Industrial Revolution, methods for optimizing 3D printing process has been studied. Topology Optimization is mathematical method to optimized form for given set of loads. It has a wide range of application in medical, mechanical, and civil engineering. For a given form, its internal behaviors are analyzed to determine significant parts to resist given conditions and puts material where it is needed, in order to maximize the stiffness of structure under prescribed external force. When used for 3D printing, Topology Optimization could achieve optimal 3D printable model with minimal use of material. For example, in medical field, Topology Optimization is used to simulate how bone reacts to external body forces. With this optimization amount internal structures are reduced to bare minimum.

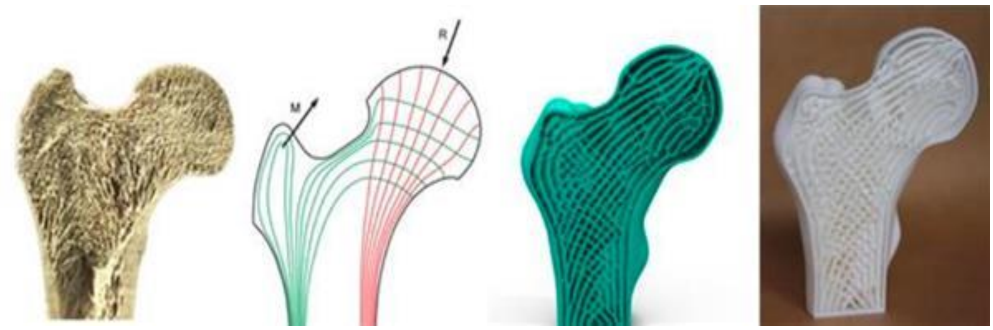


Fig. 3-1 Infill optimization for bone

By performing Topology Optimization, general idea of compression and tension field could be distinguished. Applying interaction between printing direction and loading direction in chapter 2, 3D printing path can be design to gain strong resistance against loads.

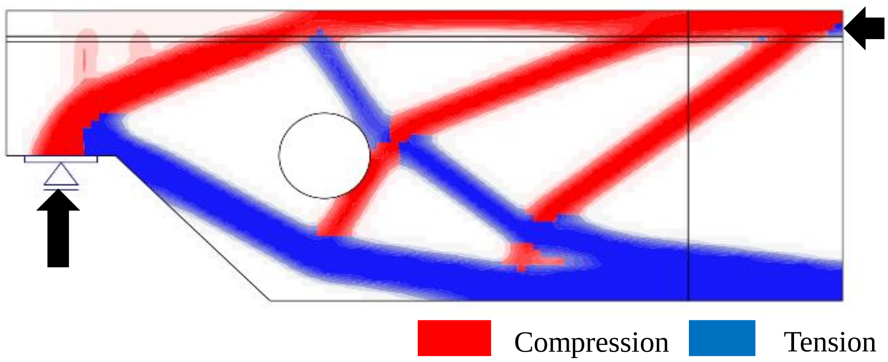
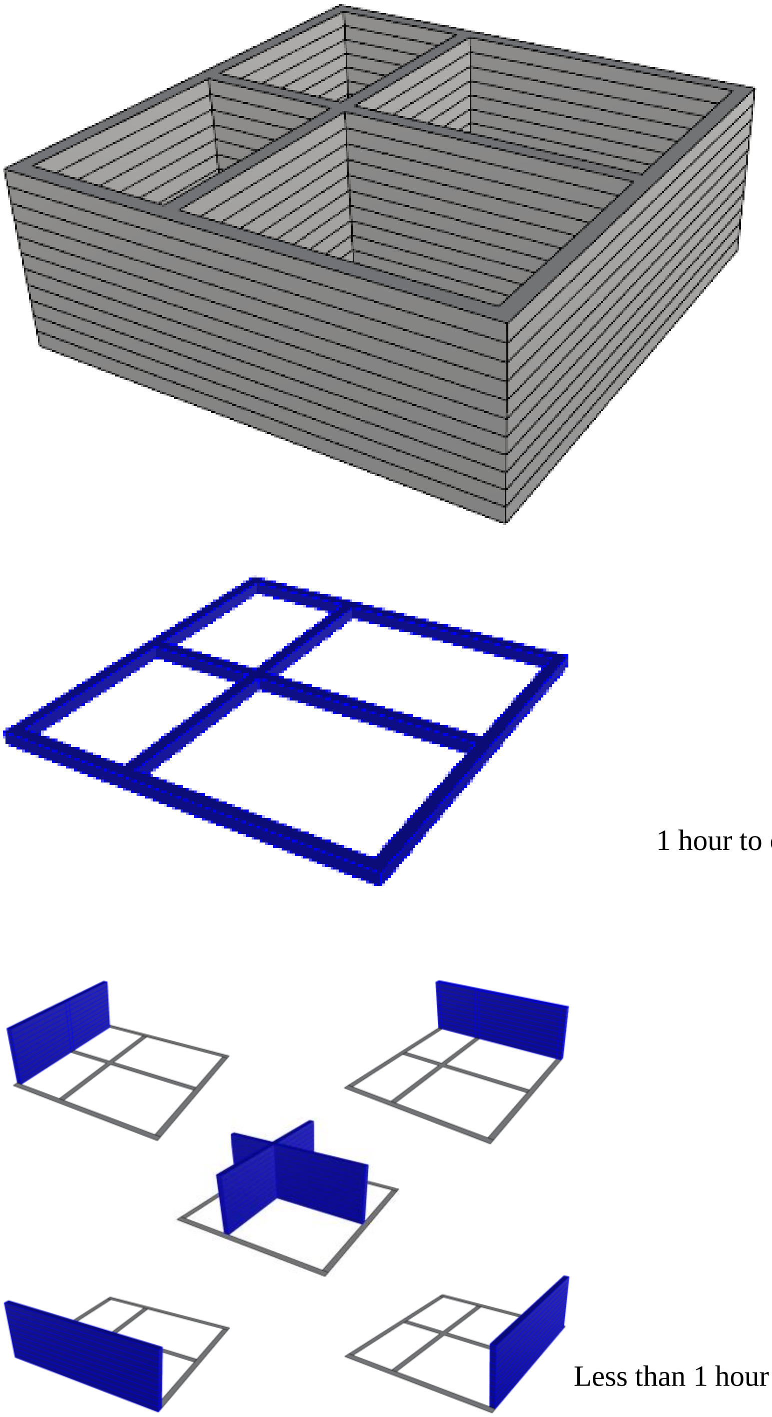


Fig. 3-2 Topology optimization of beam

3.3 Modular

Modular method uses series of modules to construct larger model by connecting each modules. By applying this method to 3D printing, limitations on printable shape could be moderated. Due to key factors mentioned in chapter 2, stacking layers at an angle is troublesome at 3D printing. Using modularization to the model, this limitation could be resolved by dividing angled part into printable parts and joining together after completing the printing process. Also, by dividing model before collapsing occurs due to excessive stacking of layer, failure due to self-weight could be minimized.

For designed model, time required to complete single layer takes an hour to complete which exceeds open time of material. To complete single layer with in the open time, the model is redesigned into modules with layer which take shorter amount of time to complete. Once each modules are completed, they can be joined together to form original designed model.



1 hour to complete

Less than 1 hour to complete

Fig. 3-3 Modularizing designed model

As for angled part of model, the tangential angle to ground should be checked beforehand to locate angles that exceed stackable angle. At the point where tangential angle exceeds stackable angle, the exceeding part could be cut off and placed to set a newly guideline to measure tangential angle. By repeating this method, 3D printing of angle parts with tangential angle larger than stackable angle could be processed.

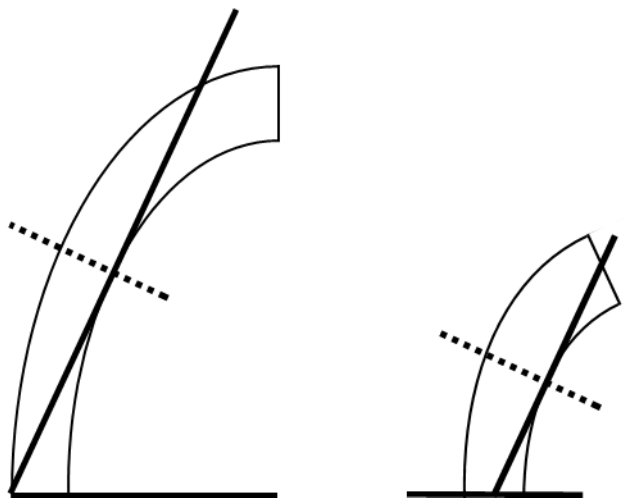


Fig. 3-4 Dividing angled parts

Chapter 4. Print Experiment

4.1 Introduction

For 3D printing, key properties for the printing materials are extrudability, flowability, open time, and buildabilty.

4.1.1 Extrudability

It defines the capacity of the concrete to be extruded through the printer nozzle. The concrete should be able to be printed without any blockage and crack while being extruded.

4.1.2 Flowability

It is the measurement of slump flow test result of concrete. The required time for concrete mix to spread to specific diameter is measured and the rate of flow can subsequently be obstained.

4.1.3 Open Time

It is obtained by using the slump flow test to get the flowability over specific time intervals. As the concrete is poured layer-by-layer method, it is important to specify the open time of the concrete for 3D printing.

4.1.4 Buildabilty

It refers to the number of layers that can be printed without collapse. The desired average number of layers is five.

Achieving maximum value for each properties are desired to produce fine work quality of 3D printing. However, improving value of one property cause lowering of other properties. For example, by maximizing flowability of the concrete, it would provide smooth extrusion through 3D printer nozzle along with fine surface. However, it would lower buildabilty of material which could cause collapse of materials before reaching desired layer stack. Before preceding to 3D printing designed model, the property of concrete paste needs to be defined due to inverse relationship between key properties of concrete paste.

In addition to balancing key properties of concrete paste, the material needs to be checked whether it could be applied to 3D printer or not. In this experiment, concrete mixtures with different Superplasticizer ratio are used to check how print result differs depending on concrete mixture.

Table 3 3D printed material mixture portion

	Binder(kg/m^3)			Sand (kg/m^3)	Sand/Binder	Water-Binder	SP /binder weight	Retarder /binder weight	PP Fiber
	Cement	Fly ash	Silica fume						
Material1	315	90	45	550	55:45	0.35	0.01	0	$0.53g/m^3$
Material2	315	90	45	550	55:45	0.35	0.005	0	$0.53g/m^3$
Material2	315	90	45	550	55:45	0.35	0.005	0	$0.53g/m^3$

4.2 Printing Process

Each mixture is extruded by using 3D concrete printer. The printer is set to extrude $30 \times 10^{\wedge 3}mm^3$ of mixture per second while moving at 10 mm/sec in single direction. Each layer thickness is set to 30mm to meet the nozzle diameter of 30mm. Once printer set up is done, the mixture is extruded as 300mm segments to verify whether the material is suitable to be used for 3D printing. It is expected that as the flowability of mixture is lowered, total print quality would be poor and unstable.

Table 4 3D Printer Property

Nozzle Diameter	**30 mm**
Nozzle Speed	**10 mm/sec**
Extrusion Rate	**30×10^3 mm^3/sec**
Layer Thickness	**30 mm**

4.3 Printing Results

4.3.1 Mixture 1

The mixture 1 has SP/binder weight ratio of 0.001 to ensure that the mixture is extrudable through the nozzle without any blockage. As planned, it was able to be extruded with smooth surface. However, the width of extruded segments exceeded 30mm which is the diameter of the nozzle due to pressure from extruding the material from the tank.

Fig. 4-1 Printing Result of Mixture 1

Although, the mixture 1 showed fine extrusion quality throughout printing process, when stacking 10th layer, it bottom layer became unstable which caused whole print result to collapse.

Fig. 4-2 Printing Result of Mixture 1 (Failure Case)

4.3.2 Mixture 2

As shown in figures, mixture 2 showed poor print quality compared to print result of mixture 1 due to lower amount of SP used. Due to its lower flowability, the concrete paste seemed to be compacted during extrusion process. This cause less layers stacked with same amount of mixture. However, this compacting caused extruded segments to be more stable.

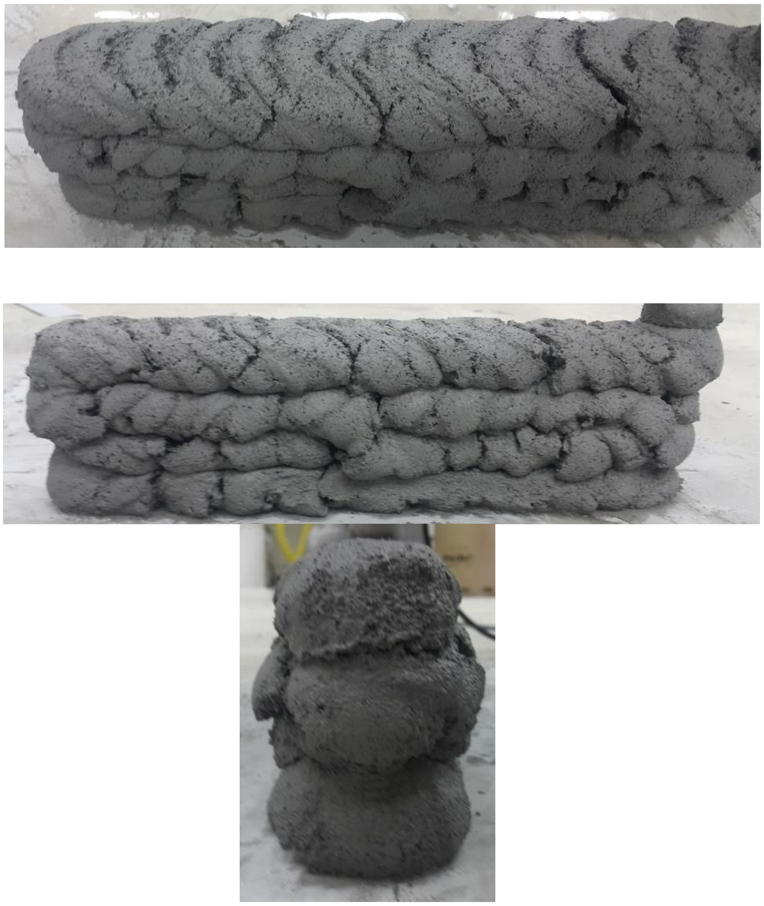


Fig. 4-3 Printing Result of Mixture 2

4.3.3 Mixture 3

With lowest ratio of SP/binder weight ratio among three mixtures, mixture 3 showed the roughest quality of all. During the extrusion, it showed stepped extrusion through nozzle as block of concrete. The separation occurred between each crack as if it was an individual blocks. Although, it was not able to produce smooth print result, it was able to hold its form firmly compared to mixture 1 which failed due to its own weight.

Fig. 4-4 Printing Result of Mixture 3

4.3.4 Overall

As expected before the experiment, lower flowability of material caused the print quality to decrease when printing at same printer condition. In mixture 1, the print result showed smooth finished along the sides without any separation which would be ideal result for field application. However, the stability of printed object seems to be lacking as it collapsed due to its own weight. The mixtures with less flowability showed rough finished along the sides but have better stability.

Also, all test result showed segment width larger than nozzle dimension. When the material is initially extruded from the nozzle, it maintains nozzle width and shape. However, as it is stacked along the printing path, the segment gets pressed by following material which is constantly extruded. This excess pressure cause segments to spread beyond its initial width.

Chapter 5. Follow-up Experiment

5.1 Introduction

From experiment in Chapter 4, the pressure from nozzle seemed to cause decrease extra deformation to printed segments. To verify effect of excessive pressure from nozzle, additional experiment was done by manually stacking materials to check how each material would behave under perfect printing condition. To simulate 3D printing without excessive pressure, mixture 1 and mixture 3 are stacked using 200 mm × 40 mm × 30 mm mold.

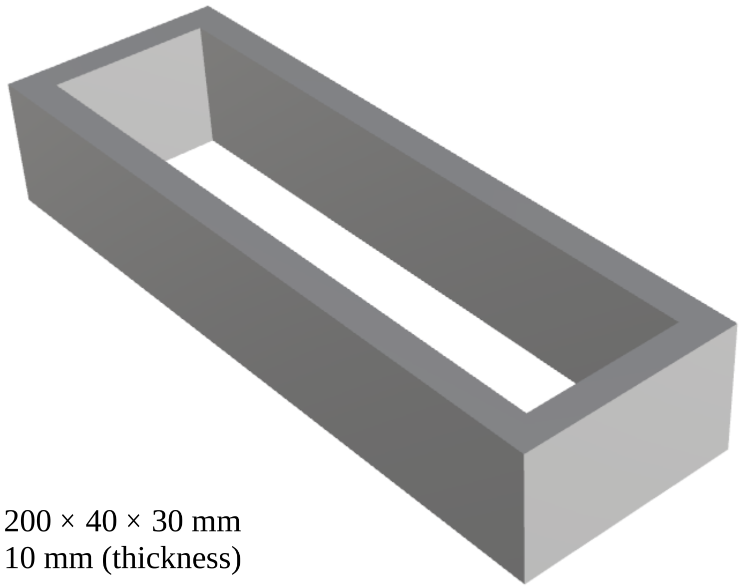


Fig. 5-1 Test Mold for Manual Stacking

5.2 Results

5.2.1 Mixture 1

Although it was able to stack firmly when stack layers were low, when it was stacked manually using the mold, mixture 1 failed to hold its form due to shaking caused when removing the mold. This outcome suggests that failure during 3D printing in Chapter 4 is caused by material unstability

Fig. 5-2 Test Result of Mixture 1

5.2.2 Mixture 3

When stacking mixture 3 by using mold, unlike mixture 1, it did not collapsed when removing the mold. Although, it was not suitable to 3D printing by using printer property in Chapter 4, it could be more suitable with printer property set for this mixture.

Fig. 5-3 Test Result of Mixture 3

5.3 Suggestion

From combining result from two experiments, it is clear that 3D printed outcome quality depends on printing material property. However, when adjusting material property to 3D printer, although the material might be printable, it does not mean that the material is suitable for the field application. To ensure working 3D printing process, it is recommended that 3D printer setting is adjusted to 3D printing material, rather than adjusting material property to 3D printer.

Chapter 6. Conclusion

Although 3D printing is expected to bring financial profit by reducing construction cost, construction time and by simplifying production process compared to current construction method, current 3D printing methods in the Architecture is still in development stage. In this study, 3D printing methods were evaluated to address stacking angle, printing speed, self-load and printing direction as key factors in printing process in chapter 2.

In chapter 3, Topology Optimization and Modular methods are introduced as tool to minimize premature failure regarding key factors. For given 3D printer and material properties, there is limit to make an adjustment to those value. The simplest way to achieve successful 3D printing is by adjusting the 3D printing model to make it suitable for 3D printing. Through Topology Optimization, required material for model could be reduced to minimum amount which lights the model weight. Also, it could present critical area which needs to be reinforced to resist stress. However, with Additive Manufacturing method, there are limitation to forms that could be printed using Topology Optimization.

Modular method divides 3D printing model into smaller parts that are suitable for 3D printing. Considering key factors in chapter 2, there are limits to angle and size of model which could be printed. By modularizing 3D printing model, the form limitation could be met as well as reducing time loss in case of premature failure occurs during printing process.

In order to modularize 3D printing model, the values of printing speed of 3D printer, open time of material, and stackable angle of material need to be verified. Printing speed and open time provides maximum layer area that could be printed and stackable angle provides maximum angle that could be printed without causing premature failure. When at least one criteria is not met, the 3D printing model requires modularization to satisfy the criteria.

To be able to apply these solutions, 3D printer setting needs to be adjusted rather than adjusting the material to be 3D printable. When adjusting material property to make it printable, although it might seem to be printed smoothly, its stability might not meet the required guidelines. In order to successfully 3D print concrete, the material property of print material needs to be tested beforehand than adjust 3D printer setting to extrude material properly.

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초 록

3D 프린팅 콘크리트에 따른 3D 프린터 최적화

박 문 용

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AI와 자동화 기술의 발전이 이루어짐에 따라 과학기술, 디지털기술, 생물학적 기술 간의 경계가 희미해지고 있다. 이러한 기술간 경계의 희미해짐을 4차 산업혁명으로 여겨지고 있다. 새로운 산업혁명과 함께 새로운 기술의 발전이 생겨나고 있으며, 그 중 3D 프린팅은 이러한 신기술들 대표하는 기술로서 자리 잡고 있다. 3D 프린팅은 컴퓨터 제어를 사용한 재료를 결합 방식으로 입체적으로 모형을 제작하는 기술이다. 3D 프린팅 기술을 건축분야에 적용할 시 공사비 절감, 공사기간 단축, 제조과정의 단순화를 통한 경제적 이익을 불러 올 것으로 기대되고 있다.

본 연구는 현재 사용되고 있는 3D 프린팅 방식을 건축분야에 적용하였을 경우 발생할 제한사항을 분류하고 그에 따른 해결 방안을 제시하고자 한다. 3D 프린팅은 재료를 적층하여 모형을 제작하는 첨삭가공 방식으로 Contour Crafting, Concrete Printing, D-Shape의 제작 방법이 대규모 모형 제작에 적합한 방법으로 사용 되고 있다. 본 연구의 주요 중점으로 3D 프린팅 시에 고려하여 할 사항과 제작 모형의 안정성을 확

보하긴 위한 방한을 제시 하고자 한다.

3D 프린팅은 건축분야에 적용할 시 높은 가능성을 보여주지만 재료 특성, 프린터 성능, 모형의 형상에 따라 제작 실패를 일으킬 가능성이 있다. 이러한 제작 실패를 최소화 하기 위하여 Topology Optimization과 모듈화를 적용하는 것을 제안한다. Topology 분석을 통하여 디자인된 모형을 하중에 최적화된 형상으로 다시 디자인하여 사용 재료와 제작시작을 감소 할 수 있다. 또한 모듈화를 통하여 기존 제작 불가능한 형상을 제작 가능 단위로 모듈화하여 보다 자유로운 형상의 모형의 제작이 가능하다.

이러한 해결방안을 적용하기 위해서는 우선 3D 프린팅 재료의 특성과 3D 프린터의 특성을 확인하여야 한다. 본 논문에서는 각각의 다른 3D 프린팅용 재료의 사용에 따른 결과물의 차이점을 확인하고 이를 해소하기 위한 방안을 제시하고자 한다.

핵심용어 : 3D 프린트, 최적화, 형태 발견

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