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보강재가 있는 3D 프린팅 콘크리트의 구조거동
Structural Behavior of 3D Printed Concrete Specimens with Reinforcement

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This paper examines the structural behavior of 3D printed concrete specimens with focus on the bond between the layers. The tensile bond and flexural strengths were investigated experimentally and compared with those of specimens made by conventional mold casting. The test parameters were the time gap between printing layers and the reinforcement between vertical layers. The results showed the 3D printed specimens had voids between layers and confirmed the strength reduction due to printing time gap and the stress concentration caused by the voids. Most of the reduction in tensile bond strength between layers was due to the stress concentration at least up to certain printing time gap. Moreover, beyond a certain printing time gap (24hours), the additional reduction in tensile bond strength reached a level that could affect the structural behavior. The reinforcement between layers was helpful to increase the ductile behavior which is essential to prevent the sudden collapse of the structure. In addition, the reduction in flexural strength due to the stress concentration by the voids was observed and should be considered in the design of 3D printed wall structures against the lateral load.

키워드 : 3D 콘크리트 프린팅, 프린트 시간차, 응력 집중, 인장부착 거동, 보강재

Keywords : 3D Concrete Printing, Printing time gap, Stress concentration, Tensile bond behavior, Reinforcement

1. INTRODUCTION

Additive manufacturing(AM) or 3D printing(3DP) technology is now widely used for rapid prototyping or the fabrication of mechanical and medical parts(Ngo et al. 2018; Park et al. 2016). Owing to the possibility to adopt a freeform construction, cement-based AM technology has recognized rapid development in the construction sector since late 1990's(Pegna 1997; Khoshnevis 2004; Cesaretti et al. 2014; Gosselin et al. 2016; Salet et al. 2017) with promising recent applications like the construction of 2-story and 5-story buildings in China among others(Bos et al. 2016). The most common method in 3D concrete printing(3DCP) is the cement-based deposit method(CDM), which resembles the prominent fused deposition modelling(FDM) in 3DP technology (Bos et al. 2016). Contour Crafting(http://contourcrafting.com/) is one of typical CDM technologies(Khoshnevis 2004). This method deposits successively one-by-one the filaments of the cement-based mix by a nozzle to form the intended structure. Another 3DCP method similar to the selective laser sintering (SLS) in 3DP is D-Shape https://d-shape.com/), which creates the structure layer-by-layer by depositing the binder from the nozzle to the part of layered building material to be made solid(Cesaretti et al. 2014). The 3D printed structures and/or members erected by such printing processes present generally layers composed of filaments with voids between filaments. Their structural integrity relies thus on the bond between the

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layers and between the filaments. In addition, the bond itself depends on the time gap elapsed between the printing of the successive layers which can vary from several minutes to several days according to the printing conditions. Note that reinforcement can be added between the filaments to improve the bond behavior.

The printing procedure by nature makes the structural behavior of 3D printed structures different from that of ordinary structures(Le et al. 2012). investigated the structural behavior of 3D printed concrete specimens in terms of the tensile and flexural strengths and showed that the 3D printed specimen developed reduced flexural strength compared to that of a mold-cast specimen when the tension applied perpendicularly to the extruded filaments. Their results indicated that the stress concentration induced by the voids affected the structural behavior of 3D printed structures and that the tensile bond strength between the layers reduced with longer printing time gap(Feng et al. 2015). evaluated the mechanical properties of 3D specimens printed by a method similar to D-Shape and showed that the layers induced orthotropic behavior. Their FEM analyses based on the stress-strain relation and maximum stress criterion from the test results also demonstrated that the printing direction had significant effects on the load bearing capacity of the structure.

Researches intending to increase the material strength by adding reinforcement such as fibers and wire are also being conducted(Hambach and Volmer. 2017). used a cement-based mix with carbon fibers and succeeded in improving the flexural strength by aligning effectively the fibers through the extrusion procedure. Nevertheless, they pointed out the necessity to arrange conventional steel reinforcement for the load bearing structures(Bos et al. 2017). developed a device to place steel wires into the filament of the printed concrete. The so-reinforced 3D printed concrete members exhibited increased post-crack moment capacity and enhanced ductility but underwent limited improvement of the bond between layers.

Accordingly, this paper examines the structural behavior of 3D printed concrete specimens with focus on the bond between the layers(or filaments). The tensile bond strength and flexural strength were investigated experimentally and compared with those of specimens made by conventional mold casting. The test parameters were the time gap between printing layers(hereafter designated as “printing time gap”) and the reinforcement between vertical layers(filaments). Based on the results, the conditions to be considered in the design of 3D printed structures are discussed.

2. EXPERIMENTAL STUDY

2.1 Design and fabrication of the 3D printed specimens

The cement-based mix used in this study was developed by Korea Institute of Civil Engineering and Building Technology (KICT). The composition is shown in Table 1. The 3DCP device in this study is composed of the nozzle with circular cross-section (diameter=25mm), the frame that supports the nozzle and guides the horizontal and vertical movements of the nozzle by manual control, and the pump that supplies the cement-based mix to the nozzle with a constant delivery rate. Fig. 1 shows the fabrication process of 3D printed specimens. The nozzle extrudes the filament 30mm above the previously

Table 1. Cement-based mix composition for 3D printing

Component	W	C	FA	SF	S	AD	VA
kg/m^3	232.0	580.0	165.7	82.9	1146.0	0.001	0.0002

W=Water, C=Cement (OPC-1), FA=Fly ash, SF=Silica fume, S=Sand, AD=High water reduction agent (HWRA), VA=Viscosity agent

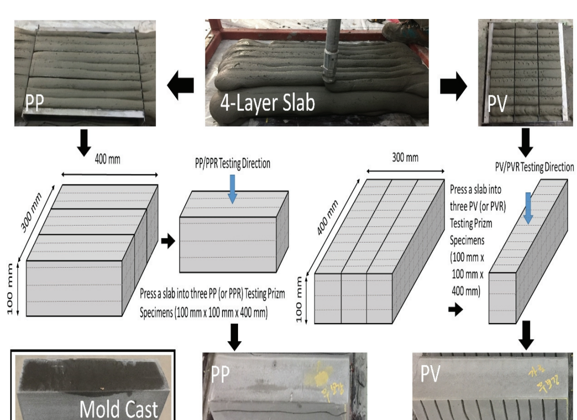

Fig. 1. Fabrication of 3D printed specimens

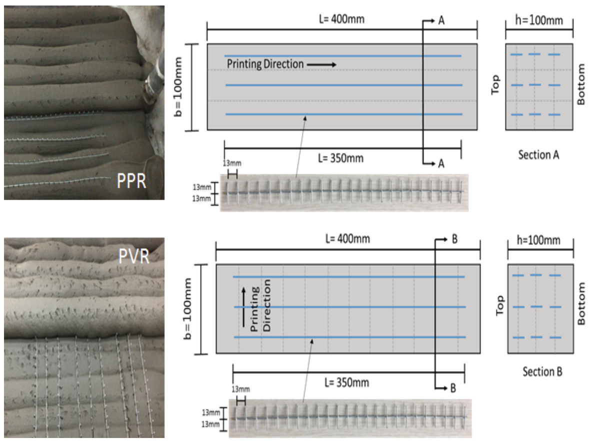

Fig. 2. Flexural specimens with reinforcement

extruded(i.e. printed) filament(or layer). Each layer of the slab is composed of horizontally aligned filaments and is printed with designated printing time gaps(5, 30, 60minutes) to simulate the conditions that might occur in the actual printing situation.

The flexural test specimens(100mm×100mm×400mm) were sampled from a 4-layer slab right after printing as shown tn the 1^{st} row of Fig. 1. For the specimens with reinforcement between layers, fishbone-shaped steel reinforcement was placed manually between the vertical layers(Fig. 2). This fishbone-shaped reinforcement was adopted for the short ribs of the reinforcement to increase the bond between layers, and the long backbone to facilitate the placement and increase the flexural behavior. The reinforcement made from ordinary steel mesh is composed of a plain round bar with a diameter of 1.08 mm. The height and interval of the ribs are 13mm. Note that only short ribs can be placed using a nail gun-like device for the future automation of the process.

In the designation of the 3D printed flexural specimens(Figs. 1 & 2), the first character 'P' stands for printed and the second character 'P' or 'V' indicates respectively parallel or vertical to stress direction. The third character 'R' is reserved for the specimens with reinforcement. The mold cast specimens to represent conventional method are designated by 'MC'. The details of the considered specimens are shown in Table 2. Fig. 3 shows the 3D printed tensile specimens cored from the flexural specimens with printing time gaps and/or reinforcement. The cores were sampled to include voids between vertical and horizontal filaments so as to simulate the least favorable

Table 2. Flexural test specimens

Specimen	Reinforcement	Time gap between printing layers(min)	No. of specimens
Printed parallel to stress direction(PP)	No	5	3
		30	3
		60	3
Printed parallel to stress direction with reinforcement(PPR)	Yes	5	3
		30	3
		60	3
Printed vertical to stress direction(PV)	No	5	3
		30	3
		60	3
Printed vertical to stress direction with reinforcement(PVR)	Yes	5	3
		30	3
		60	3
Mold Cast(MC)	No	0	16

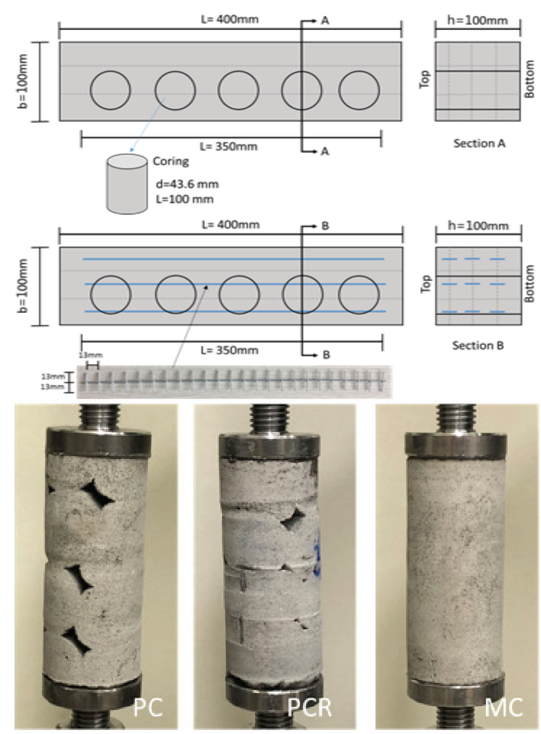

Fig. 3. Tensile specimens from coring

Table 3. Tensile test specimens

Specimen	Reinforcement	Time gap between printing layers(min)	No. of specimens
Printed core(PC)	No	5	5
		30	7
		60	6
Printed core with reinforcement(PCR)	Yes	5	4
		30	7
		60	7
Mold cast core(MC)	No	0	6

condition and, as a result, the reinforced ones have two lines of reinforcement at each edge. The diameter of the specimens is 43.6mm in average. For the tensile specimens, the first character 'P' indicates the 3D printed specimen, the second character 'C' means coring, and the third character 'R' indicates reinforcement. Table 3 arranges the details of the specimens. All the 3D printed and mold cast specimens were cured under water for 72hours at 60 degree after 24hours room temperature curing.

2.2 Test setup

For flexural behavior, the typical 4-point bending test procedure is used(Fig. 4 left) and for tensile behavior, the uniaxial test procedure is used with epoxy bonded steel ends (Fig. 4 right). Displacement-controlled loading is applied for both tests.

3. TEST RESULTS AND DISCUSSION

3.1 Compressive strength

The material behavior of the mix itself was tested using mold cast cylinder specimens (d=100mm, h=200mm) with the same

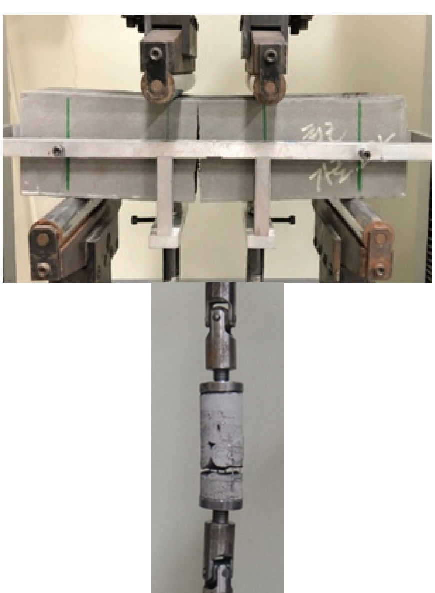

Fig. 4. Test setups for flexural (up) and tensile (down) behavior

curing procedure. The average compressive strength of the mix from 14 cylinder tests is 54.3MPa.

3.2 Tensile bond behavior

Fig. 5 shows typical fractured tensile specimens with their cross sections. For the 3D printed ones(PC and PCR), fracture occurred at the bond between vertical layers due to the stress concentration caused by the voids. The size oof the void can be reduced considering various factors such as early viscosity of the mix after extrusion, the size and shape of the nozzle, the reinforcement, the pressure applied from the nozzle and the printing time gap. Note that the size and shape of the voids of the specimens in Fig. 3 and Fig. 5 are different. Fig. 6 plots the tensile bond strength of the 3D printed specimens without reinforcement(PC) according to the printing time gap. The tensile strength was estimated with respect to the original

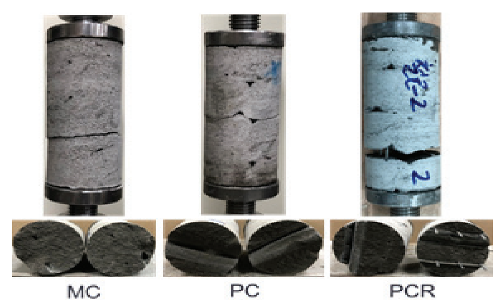

Fig. 5. Typical tensile specimens after test

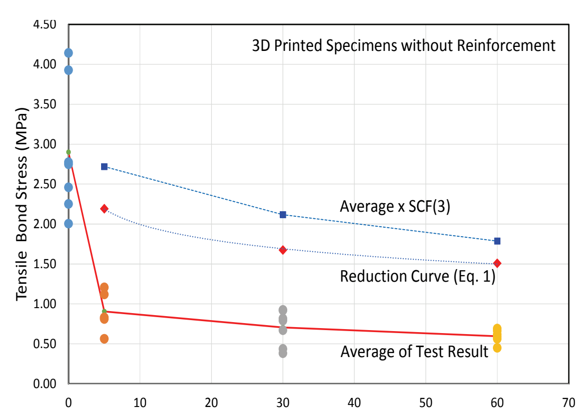

Fig. 6. Tensile Bond strength of 3D printed specimens without reinforcement

cross section of the specimens (A=1492.3mm^2). As expected, MC specimens show higher strength than the 3D printed ones, and the tensile strength in average is 2.9MPa.

The 3D printed specimens without reinforcement show gradual reduction in tensile strength with longer printing time gap. It is noteworthy that the specimens saw their strength reduced by more than a half when the printing time gap exceeded only 5minutes, which is a very short delay that can happen frequently on site considering the current printing procedures. For printing time gap longer than 5minutes, the strength loss is seen to become less pronounced. This strength loss was already reported by(Le et al. 2012) who suggested Eq. 1 predicting the tensile bond strength reduction in function of the printing time gap.

$$y = 1.51x^{-0.15} \qquad \text{(Eq.1)}$$

where y=average tensile bond strength(MPa); and, x= printing time gap(hour) except near zero time gap.

The tensile bond strength predicted by Eq. 1 is also indicated in Fig. 6. Except the absolute value of tensile bond strength, the reduction curve is similar to the test results in spite of different mix composition and the nozzle. For the effects of the voids between layers on the tensile bond strength, a stress concentration factor(SCF) is considered. Because the shape and size of the voids between layers are varied from a very small elliptic shape to a large star-like one, the formula that fits exactly this case is not found from the reference(Pilkey 2005). Therefore, this study assumes a value of 3 for the representative SCF of the 3DCP specimens which is the minimum value from the formula for a transverse circular hole in a round bar from the reference(Pilkey 2005). The estimated tensile strengths considering the SCF of 3 are also shown in Fig. 6. It appears that the stress concentration due to the voids is the major cause of the reduction in tensile bond strength rather than the printing time gap at least up to 60 minutes. However, in practice, delays longer than 60minutes or even 24hours may happen, which results in 38% reduction compared to the tensile bond strength at 60minutes delay according to Eq. 1. Fig. 7 shows the tensile bond strength of 3D printed specimens with reinforcement(PCR). In general, the reduction in strength is similar to that of the specimens without reinforcement. The particular feature is that the tensile bond strength of the specimens with 30min-printing time gap is smaller than that of the ones with 60min-printing time gap.

In spite of reinforcement, little increase in tensile bond strength is observed. However, the load-displacement curves of the 3D printed specimens in Fig. 8 reveal another aspect of tensile behavior according to the presence of reinforcement. The specimens without reinforcement broke when they reached their tensile bond strength, whereas the ones with reinforcement continued to resist the load although relatively small post-cracking strength. Moreover, these specimens

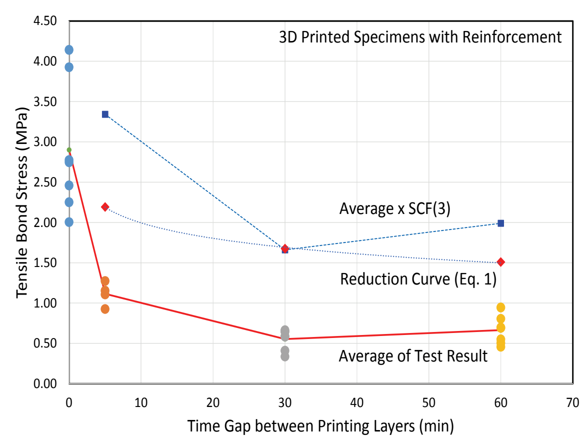

Fig. 7. Tensile bond strength of 3D printed specimens with reinforcement

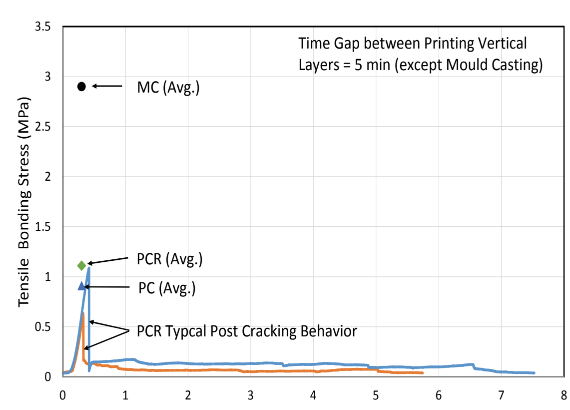

Fig. 8. Load-displacement relation of 3D printed tensile specimens

failed through bond slip and not fracture nor yield of the reinforcement. Because the inserted length of the reinforcement is limited by the thickness of the filament, the embedded length is insufficient to resist the pullout force. As a result, the reinforcement in this study contributed little to increase the tensile bond strength. However, by introducing a deformed bar or a small anchor like a head at the end of reinforcement, the behavior of reinforcement can be improved and so would the behavior of 3D printed structure.

3.3 Flexural behavior

Fig. 9 shows the failed surfaces of flexural specimens. In 3D printed specimens(PP, PPR, PV and PVR), the voids created by the deposit of filaments can be observed with shape and size varying from small elliptic to large star-like shapes. For PV and PVR specimens, crack-like defects are also found at the bottom of the specimen where the largest tensile stress is directly applied. In addition, the surface of PP specimen indicates that the vertical stacking of filaments is not easy without lateral support from other filaments, especially for the filament with the elliptic cross section. In this case, the reinforcement(PPR specimen) can help to support the filament vertically. The water on the fractures surface comes from steam curing.

Fig. 10 compares the flexural strength of 3D printed specimens. The time gap between printing layers did not affect the flexural strength. When the stress is applied parallel to the printing direction(PP and PPR specimens), the variation in flexural strength is limited as well. Both are primary because only the strength of the lowest layer contributed to the flexural strength. However, when the stress is applied perpendicularly to the printing direction, the flexural strength is reduced nearly by half due to the crack-like defects along the bottom of the specimens. Since a 3D printed wall might be in similar situation under lateral loading, this reduction of strength should be considered in the structural design. In addition, it is likely that the wall structure made by 3D printing will develop reduced strength due to the presence of the voids and the irregular vertical alignment that might induce buckling before the compressive strength. The reinforcement does not increase the flexural strength both in PPR and PVR specimens, because the dispersed reinforcement over the section cannot resist effectively to the stress after cracking of the specimens. To increase the post-cracking strength, conventional reinforcement could be an option.

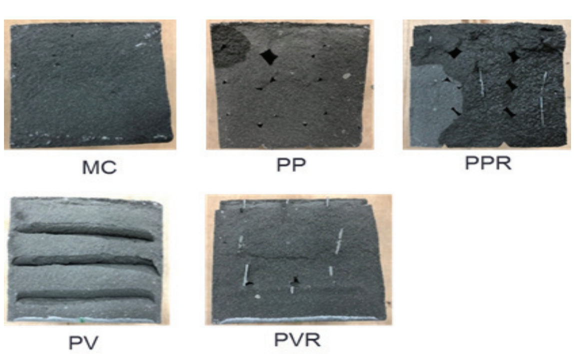

Fig. 9. Fracture surface of flexural specimens

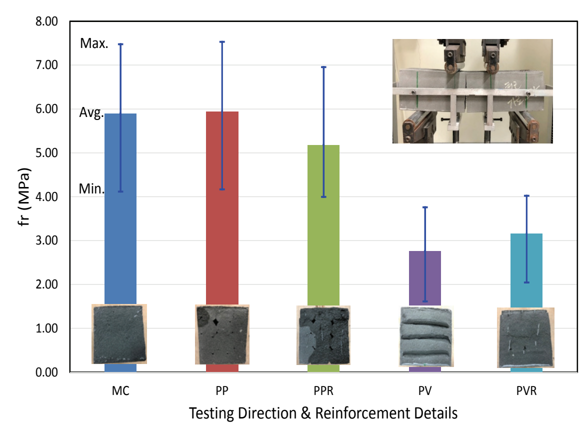

Fig. 10. Modulus of rupture (f_r) from flexural tests

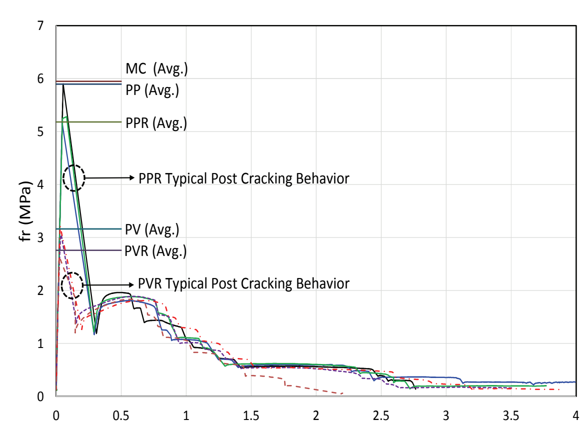

Fig. 11. Load-displacement relation from flexural tests

Similar to the reinforcement in tensile bond specimens, the main purpose of the reinforcement between vertical layers is to increase the ductility after cracking. Fig. 11 shows the improvement of the post-cracking behavior of the reinforced specimens(PPR and PVR). As expected, the specimens experienced brittle failure, but the reinforced specimens exhibited post-cracking behavior. Regardless of the direction of the applied stress, the post-cracking behaviors are similar to each other, because after cracking most of the stress is undertaken by the reinforcement. Considering that the reinforcement used in this study is a simple round bar without any wedge to increase the bond strength, more advanced reinforcement using other detail and/or new material can be expected to improve further the ductility and/or the strength.

4. CONCLUSIONS

This paper examined the structural behavior of 3D printed specimens considering the effect of stress concentration due to the voids, the printing time gap and the reinforcement between vertical layers. The main conclusions are as follows:

1) The fracture surface of the 3D printed specimens both from tensile and flexural tests showed voids between layers, and test results confirmed the strength reduction due to printing time gap and the stress concentration caused by the voids. Most of the reduction in tensile bond strength between layers was due to the stress concentration at least up to certain printing time gap. But, with longer printing time gap such as 24hours, the additional reduction in tensile bond strength reached a significant level that may affect the structural behavior.
2) The reinforcement between layers was helpful to increase the ductile behavior which is essential to design safe structures by preventing sudden collapse. Considering the simple reinforcement used in this study, more advanced reinforcement in shape and material will undoubtedly improve drastically the ductility of 3D printed structures.
3) The eduction in flexural strength due to the stress concentration by the voids was observed. This strength reduction should be considered in the design of 3D printed wall structures again the lateral load, and the addition of conventional reinforcement can be an alternative option to the designer.

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보강재가 있는 3D 프린팅 콘크리트의 구조거동

본 연구에서는 프린트 층 사이에 부착에 초점을 두고 3D 프린팅 콘크리트의 구조거동 연구를 수행하였다. 3D 프린팅 콘크리트의 부착 및 인장강도 실험을 수행하고 일괄 타설 콘크리트 실험결과와 비교하였다. 실험변수는 콘크리트 층 사이의 프린트 시간차와 철근 보강 여부이다. 콘크리트 층 사이에는 공극이 존재하고 이에 따라, 강도 감소가 발생한다. 층 사이 대부분의 인장부착 강도 감소는 응력 집중과 프린트 시간차에 기인한다. 프린트 시간차가 24시간을 초과할 때 인장부착 강도의 감소는 구조거동에 영향을 미친다. 층 사이 철근 보강은 연성거동 증진에 유용하고 구조물의 갑작스런 파괴를 예방한다. 또한, 공극이 유발한 응력 집중에 기인한 휨 강도 감소는 횡방향 하중을 받는 3D 프린트 벽체 구조물 설계시에 고려되어야 한다.