Outline of “Development and Practical Application of 3D Printing Technology for Construction”

「建設用3D プリンティング技術の開発と実用化」の概要

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1. Introduction

In recent years, the research and development of construction-scale three-dimensional (3D) printing technology have been pursued aggressively around the world. The technology of 3D printing involves calculating a sliced 2D cross-section shape based on data representing a 3D object on a computer and using the 2D shape to layer and mold materials into the 3D shape. While there are various methods of construction-scale 3D printing, the mainstream technology is the material extrusion method. This involves taking fresh cementitious material, extruding it through a nozzle, and layering it to create a 3D shape. Because this technology enables mechanized construction without the need for molds in concrete work, it not only contributes to labor-saving and productivity improvements but also improves the degree of design freedom, rationalization of layout, and reduction of the environmental burden by eliminating mold waste.

The authors have developed 3D printing technology that can fabricate laminated structures with structural characteristics and mass transfer resistance equivalent to or better than those of ordinary concrete. Moreover, for the first time in Japan, 3D printing technology was applied to the formwork of concrete columns for actual service. The target columns had a height of 4.3 m and a 3D curved surface, which is difficult to achieve by conventional construction methods using wooden formwork.

2. Outline of the Study

(1) 3D-printable Cement-Based Material

When printing cementitious materials by the material extrusion method, its required properties differ from those of conventional concrete. One required property is extrudability, which enables the material to be easily transferred through a thin hose or a print head nozzle; if this property is inferior, then the material might block the nozzle. Also, the deformation of the printed material caused by the dead weight of the next (upper) layer to be printed must be minimized; this is because the deformation due to the dead weight may cause the deposited fresh material to collapse. If the deposited fresh material has resistance to this, then it is said to have high buildability.

Both numerical analysis and an experiment were conducted to search for a mix proportion that satisfies both extrudability and buildability, leading to the development of the fiber-reinforced cementitious composite called LACTM® (Laminatable Cement-based Tough Material). It is suitable for 3D printing in its fresh state and exhibits superior mechanical characteristics.

The state of fabrication of a laminated structure with a square cross-section (500 mm × 700 mm) is shown in **Fig. 1**. The printed column could be stacked up to 2 m in height; it maintained a constant shape during and after printing, and no signs of disintegration were observed.

Fig. 1 Printing status of a 2-m-high column

(2) Mechanical Tests

Mechanical tests were performed on specimens that were cored and cut out from printed elements and mold-cast specimens, with the purpose of assessing the basic properties of 3D-printed elements made from LACTM®.

Compression tests were performed on specimens cored out of the 3D-printed elements in the vertical direction with a diameter of 50 mm. These exhibited behavior equivalent to that of specimens made through casting, yielding a compressive strength of 109 MPa. Compared with the mold-cast specimens, the coefficients of variation of the compressive strength and Young's modulus were smaller, suggesting that there was less disparity in the quality of the 3D-printed elements.

In three-point bending tests, it is found that the cracking strength and bending strength were equivalent to those of the mold-cast specimens. **Fig. 2** shows the stress–strain relationship obtained from the printed specimens. No specimens fractured at the same time as cracking, and the bridging effect of the fibers caused the stress to rise again, leading to breakage. The bending strength of the printed specimens was 14.4 MPa.

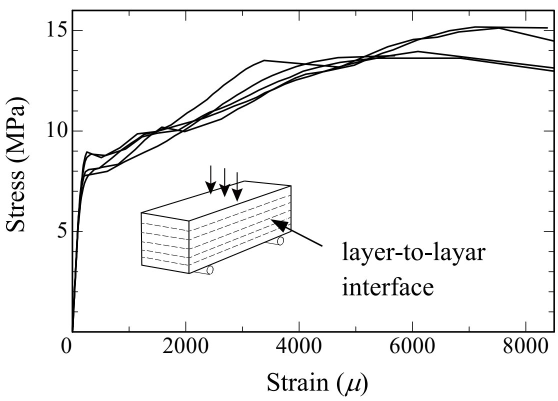

Fig. 2 Bending stress–strain relationship

(3) Practical Application

3D printing technology was applied to the formwork of concrete columns for practical applications. The target columns had a height of 4.3 m and a 3D curved surface that would be difficult to achieve by conventional construction methods using wooden formwork, with a shape that flares out into a petal-like shape while twisting from the bottom to the top. Through the manufacture of the formwork for columns and the evaluation of the finished shape and quality, the authors demonstrated that 3D printing technology can be used to construct laminated structures with a free-form surface to a high level of quality, and they confirmed the practical applicability of this technology (**Figs. 3** and **4**).

Fig. 3 Fabrication of formwork using a 3D printer

Fig. 4 Columns constructed using the printed formwork

3. Conclusion

The authors have developed a fiber-reinforced cementitious composite suitable for 3D printing and constructed a 3D printing technology that can print large-scale elements with excellent mechanical characteristics and durability.