Experimental study on layer bonding property of 3D printing building materials

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Abstract. Bonding properties between 3D printing building materials layers are tested, including tensile strength test, shear strength and bending strength test of 3D printing building materials. The failure process and failure modes of 3D printing building materials are focused on analysis in this paper. Experimental results indicate that there are weak adhesive layers in the 3D printing building materials, specimen failure occurs in the weak adhesive layer. The tensile strength average value of 3D printing building materials is 0.74N/mm². The shear failure of 3D printing specimen is not occurred, but bending failure. The bending strength average value of 3D printing building materials is 0.88N/mm².

1. Introduction

3D printing is known as rapid prototyping or additive manufacturing [1]. The process of printing a three-dimensional is achieved by layer-by-layer with equipment. 3D printing technology is revolutionary and digital technology. Thus, 3D printing technology is called important for core for promoting the "Third Industrial Revolution" because of its digital, network, personalized and customized features [2]

At present, 3D printing technology has gradually entered the field of building construction. Behrokh Khoshnevis has been studying the application of rapid prototyping technology in buildings, that is, how to build a house like making a model. Professor Rupert Soar is also conducting similar studies. The Hacked lab laboratory shows a house that has been printed and assembled [2].

Compared with traditional architecture, the advantages of 3D printing technology not only reflect fast speed, do not need to use the template, which can save the cost greatly, and has the characteristics of low carbon, green and environmental protection. 3D printing technology does not need a large number of construction workers, the production efficiency is improved greatly. It can be very easy to print high cost curve buildings that are difficult to build in other ways, and the higher strength and lighter weight concrete buildings can be printed out easily [3-6]. The application of 3D printing technology in the construction field will be the direction of the development of the construction industry in the future, but at the same time, there are many technical problems. The research and development of 3D printing materials will become a restrictive factor for the comprehensive promotion of 3D printing technology.

The research and development of 3D printing building materials have become the core technology to realize 3D printing building. At present, some scholars at home and abroad have carried out the tentative research and development on 3D printing building materials, for example, experts from Holland use resin and plastic materials for research and development, and experts from U.S. use resin
mortar, clay and concrete materials to carry out 3D printing test. T.T.Le et al. study the performance of concrete materials for printing.

2. 3D printing materials and printing process
The 3D printing building materials used in this test are made of waste materials of building, which is formed by adding cement, fiber and organic adhesives into the crushed and grinded waste materials of building to make the toothpaste like ink.

The 3D printing building materials is sprayed out through the printer nozzle by using contour 3D printing process, and the three-dimensional building components or architectural form are formed by printing layer by layer, and layer upon layer accumulation eventually.

The bonding properties of the printed building materials are tested. The inter-laminar bond tensile strength, shear strength and bending strength of the 3D printing building materials are analyzed, which can provide the basis for the application of 3D printing technology in the building field.

3. Material testing

3.1 Specimen production
Three specimens are designed for bonding tensile test of 3D printing building material. The specimen is composed of two parts: 3D printing shell (test object) and core part (transfer device). As shown in Figure 1, the specimens are numbered L1~L3.

![Figure 1. Diagram of the specimen.](image1)

The finished specimens are made up of 3D printing shell, plastic board, upper and lower parts of core concrete and drawing rebar (as shown in Figure 2). The lubricating oil is applied to the upper and lower surfaces of the plastic board to prevent the bond between the upper and lower parts of the core concrete and to ensure the accuracy of the tensile strength test of the 3D printing shell material.

![Figure 2. Fabrication and composition of specimen.](image2)
the picture, the ①, ② and ③ are the pouring sequence for the core part of concrete, and air cushion film is placed between each layer of concrete. The air cushion film can prevent the contact bond between each layer of concrete and ensure that there is no concrete at the shear surface.

1-jack, 2-specimen, 3-plate block, 4-universal testing machine, 5-loading steel plate

Figure 3. Specimen composition and loading diagram.

The 3D printing specimen design parameters for bond tensile and inter-laminar shear test are shown in Table 1.

| Specimen No. | Specimen peripheral dimension (mm³) | Printing width (mm) | Printing thickness (mm) |
|--------------|------------------------------------|--------------------|------------------------|
| L1           | 180×180×280                        | 30                 | 18                     |
| L2           | 180×180×280                        | 30                 | 18                     |
| L3           | 180×180×280                        | 30                 | 18                     |
| J1           | 200×200×270                        | 30                 | 18                     |
| J2           | 200×200×270                        | 30                 | 18                     |
| J3           | 200×200×270                        | 30                 | 18                     |

3.2 Test method
The tensile loading of the bond tensile test is carried out by hydraulic material testing machine. The loading rate keeps 0.02MPa/s until the specimen is failure. The maximum pulling force of the component is recorded and accurate to 0.01kN when the specimen is failure. During the loading process, the axle center of component is subjected to the force.

The inter-laminar shear bond strength test is loaded by the 20t universal testing machine. The jack applies the force to the upper part of the middle part, and the bottom of the left and right parts is placed on the steel plate pad. First, loading 0.5kN to check whether the instrument is working normally and whether the specimen is in the center; second, unloading after checking without problems, then re-level the instruments into the formal test stage. The formal loading stage uses the method of load control with 0.05kN/s loading speed, and the whole process is uniform loading.

3.3 Bearing capacity calculation
The maximum tensile force F is measured when the bond tensile strength is tested. The expected location of the tensile failure should be at the contact interface of the two layers of printing material. The core part dose not bear the tension because of the existence of plastic plate, the external load is transferred to the 3D printing shell through the bonding between the core part and the 3D printing shell. According to the specimen section size shown in Figure 1 (a), tensile stress is given as:

\[ \sigma = \frac{F}{(2d + l)^2 - l^2} \]

During the inter-laminar shear strength testing, when the load of the jack obviously decreases and the middle part has obvious displacement relative to the left and right parts, the shear surface can be considered to be failure. The load applied by the jack at this time is the shear bearing capacity F between the 3D printing template interlayers. F/A is the inter-laminar shear bond strength, and A is contact area of the 3D printing template interlayer.
4. Analysis of test results

4.1 Test process and destruction phenomenon

The 3D printing shell is made up of the layer by layer stacking building material that is sprayed by the 3D printing nozzle. Therefore, the bond property between the layers of the 3D printing material may have a weak link. In the three bond tensile strength tests, all of the failures are the tension separation between the printing layers, which is in accordance with the test expectation. The 3D printing specimen after the test failure is shown in Figure 4.

![Figure 4. Specimen damage along the section.](image)

The specimens of the 3D printing shear strength test are equipped with two layers of air cushion film to prevent the contact bonding between concrete. The location of the air cushion film is the expected shear failure position. However, the failure of the specimen is bending failure rather than the expected shear failure in the loading test, which occurs in the middle of the span, and not in the position of the air cushion film. The loading process and the failure of the specimen are shown in Figure 5.

![Figure 5. The loading process and specimen failure.](image)

The 3D printing specimen occurs bending failure rather than shear failure, there are several reasons for the following reasons:

1. The 3D printing has a pause process, and the 3D printing material is quickly condensed when pause. The bond force between new layer and old layer deceases when the new layer is printed, and the bond force is stronger between layers on non-pause process.

2. Due to the 3D printing process, the shear failure cross section is wavy rather than planar. The shear strength is increased due to the interlock force between the layers. The wavy section is shown in Figure 6 (a).

3. Due to the construction reasons, the hollow section of the internal concrete is a curved surface, which is located at the shear failure, and the internal interlock force existing in the interior further improves the shear strength. The inner concrete hollow section is shown in Figure 6 (b).

4. The specimen is knocked off after the specimen is destroyed, it is found that there is a clear layer trace in the 3D printing shell except the pause surface in the midspan, and the other part is a whole with strong inter-laminar bonding force. Therefore, the specimen is easy to crack from the printing pause surface and may cause bending failure.
The above mentioned reasons result in the failure of the test as bending failure rather than the expected shear failure, therefore, the test value of the inter-laminar bending tensile strength of 3D printing material is obtained.

![Wavy section](a) Wavy section ![Internal concrete section form](b) Internal concrete section form

**Figure 6.** Specimen failure section.

### 4.2 Test results

Figure 7 shows the loading force variation curve during the test of bond tensile strength, which is basically uniform loading. Figure 8 is the variation curve of the loading force during the test of the shear strength of the specimen (the actual failure is shown as the bending failure). There are obviously jumping loads during the loading process. It shows that the shell of the 3D printing specimen appears cracking and presents brittle behavior. Finally, the whole specimen is failure and the loading is ended owing to the internal concrete fracture.

![Loading curves of bond tensile strength test](a) Specimen L1 loading ![Loading curves of bond tensile strength test](b) Specimen L2 loading ![Loading curves of bond tensile strength test](c) Specimen L3 loading

**Figure 7.** Loading curves of bond tensile strength test.

![Loading curves of bond shear strength test](a) Specimen L1 loading ![Loading curves of bond shear strength test](b) Specimen L2 loading ![Loading curves of bond shear strength test](c) Specimen L3 loading

**Figure 8.** Loading curves of bond shear strength test.

After the failure of the specimen, due to the error of the 3D printing process, it is found that the actual section size has greater error compared with the design section size according to the site test. For convenient calculation, the section size is simplified, and the average of the actual specimen is approximate to the rectangular section. The section calculation is shown in Figure 9.
No shear failure occurs in the shear strength test of the 3D printing specimen, therefore, the interlaminar bending tensile strength of 3D printing material can only be analyzed. It is assumed that the 3D printing shell is fracture when the 3D printing shell edge stress reaches the ultimate tensile stress $f_t$, and the inter-laminar bending tensile strength of 3D printing can be obtained by establishing the equilibrium equation of the bending moment and force.

The test results of bond tensile strength and bending tensile strength of 3D printing specimens are shown in table 2 and table 3 respectively.

| Specimen No. | Failure load (kN) | Bond tensile strength (N/mm²) | Average value (N/mm²) |
|--------------|------------------|------------------------------|----------------------|
| L1           | 22.04            | 0.82                         |
| L2           | 16.20            | 0.64                         | 0.74                 |
| L3           | 20.81            | 0.76                         |

| Specimen No. | Failure load (kN) | Bending tensile strength (N/mm²) | Average value (N/mm²) |
|--------------|-------------------|---------------------------------|----------------------|
| J1           | 40.54             | 1.22                            |
| J2           | 22.58             | 0.79                            | 0.88                 |
| J3           | 19.23             | 0.64                            |

5. Conclusions
(1) By the bond tensile strength test of 3D printing specimens, it shows that the fracture occurs between the layers and the axial tensile strength is 0.74N/mm².
(2) No shear failure is observed during the shear strength test of 3D printing specimen, the bending failure strength is obtained, and the average value is 0.88N/mm².
(3) The cross section of the specimen caused by 3D printing process is uneven and wavy. During the 3D printing of the specimen, the value of the strength of the specimen has a deviation because of the disproportion of the bond strength caused by the pause.

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