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Abstract:	3D concrete printing is an additive manufacturing method which reduces the time and improves the efficiency of the construction process. Structural behavior of printed elements is strongly influenced by the properties of the material and the interface surfaces. The printing process creates interface surfaces between layers in the horizontal and vertical directions. The bond strength between layers is the most critical property of printed elements. In this paper, the structural behavior of printed elements is studied using the Discrete Element Method (DEM). The material is modelled using discrete particles with bonding between them. A new discrete model of a multilayer geometry is presented to study the behavior of the interfaces of printed concrete. The layers are made up of randomly placed particles to simulate the heterogeneous nature of concrete. The numerical model is developed to simulate the flexural behavior of multilayer specimens. A four-point flexural test is simulated considering the interface surfaces between layers. This numerical model provides relevant results to improve the behavior of this kind of structural elements. The aim of this work is to provide a discrete element model to predict the mechanical behavior of 3D concrete printed components.

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Article

Numerical study of the interfaces of 3D-printed concrete using discrete element method

Numerische Analyse von Grenzflächen in 3D gedrucktem Beton mittels der Diskrete-Elemente-Methode

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3D concrete printing is an additive manufacturing method which reduces the time and improves the efficiency of the construction process. Structural behavior of printed elements is strongly influenced by the properties of the material and the interface surfaces. The printing process creates interface surfaces between layers in the horizontal and vertical directions. The bond strength between layers is the most critical property of printed elements. In this paper, the structural behavior of printed elements is studied using the Discrete Element Method (DEM). The material is modelled using discrete particles with bonding between them. A new discrete model of a multilayer geometry is presented to study the behavior of the interfaces of printed concrete. The layers are made up of randomly placed particles to simulate the heterogeneous nature of concrete. The numerical model is developed to simulate the flexural behavior of multilayer specimens. A four-point flexural test is simulated considering the interface surfaces between layers. This numerical model provides relevant results to improve the behavior of this kind of structural elements. The aim of this work is to provide a discrete element model to predict the mechanical behavior of 3D concrete printed components.

Zusammenfassung:

Der 3D-Betondruck ist eine additive Fertigungsmethode, die die Zeit reduziert und die Effizienz des Bauprozesses verbessert. Das strukturelle Verhalten von gedruckten Elementen wird stark durch die Eigenschaften des Materials und der Grenzflächen beeinflusst. Durch den Druckprozess werden Grenzflächen zwischen Ebenen in horizontaler und vertikaler Richtung erstellt. Die Haftfestigkeit zwischen den Schichten ist die kritischste Eigenschaft von gedruckten Elementen. Das Druckmuster wird in dieser Arbeit untersucht, um die strukturelle Gesamtleistung zu verbessern. Frühere experimentelle Untersuchungen im Betondruck bestimmten den Einfluss der Zeit auf das Grenzflächenverhalten zwischen aufeinanderfolgenden Schichten. In dieser Arbeit wird das Strukturverhalten von gedruckten Elementen mit der Methode der diskreten Elemente (DEM) untersucht. Das Material wird mit diskreten Partikeln mit Verbindung zwischen ihnen modelliert. Ein neues diskretes Modell einer Mehrschichtgeometrie wird vorgestellt, um das Verhalten der Grenzflächen von bedrucktem Beton zu untersuchen. Die Schichten bestehen aus zufällig angeordneten Partikeln, um die heterogene Natur von Beton zu simulieren. Das numerische Modell wurde entwickelt, um das Biegeverhalten von Mehrschichtproben zu simulieren. Ein Vierpunkt-Biegeversuch wird unter Berücksichtigung der Grenzflächen zwischen den Schichten simuliert. Dieses numerische Modell liefert relevante Ergebnisse zur Verbesserung des Verhaltens dieser Art von Strukturelementen. Ziel dieser Arbeit ist es, ein diskretes

Elementmodell bereitzustellen, um das mechanische Verhalten von 3D-Betondruckkomponenten vorherzusagen.

Keywords: Discrete Element Method (DEM) / 3D concrete printing / interfaces / numerical modelling / cement-based materials

Schlüsselwörter: Diskrete-Elemente-Methode / 3D-Druck von Beton / Grenzfläche / Numerische Modellierung / Zementartige Materialen

1 Introduction

New construction methods, such as additive manufacturing, have recently been developed to reduce costs and time and to improve sustainability [1]. The main principle of this technology is the deposition of successive layers of material. In the 3D concrete printing process, cement-based material is extruded through a nozzle and printed layer by layer following a printing pattern. The fresh properties of the material are relevant in this process. Although 3D concrete printing reduces construction time, the structural behavior of the printed components is affected by the interfaces between layers.

The experimental literature shows that the material properties, especially compressive and flexural strengths, are affected by the layered structure of the components. The effect of the printing process on compressive strength, flexural strength and tensile bond strength was studied and it was found that bond strength between layers is the most critical property of cement-based components produced by 3D printing [2]. The geometrical and structural characteristics of 3D-printed concrete were also studied to analyze the anisotropic behavior resulting from the bond interfaces [3]. In addition, it was analyzed how significant interlocking on bond strength between layers is in 3D printing of concrete [4].

The authors of this paper have studied the structural behavior of concrete using numerical methods for many years [5]. In continuum approaches, the material is assumed to be continuous. However, discrete approaches are more appropriate for simulating the behavior of cement-based materials, because they are heterogeneous at the microscopic scale. The Discrete Element Method (DEM) models the material as an assembly of particles. The macroscopic behavior of the material is determined by contact laws and particle scale parameters.

In this work, discrete numerical models are presented to study the flexural behavior of 3D-printed structural components. These models are compared with bulk material models with no layers. The main contribution of this paper is the numerical simulation of the interlayer behavior of 3D-printed concrete using Discrete Element Method.

2 Numerical model

In this work, the flexural strength of the structural components is studied according to the methodology described in the standard UNE EN 12390-5 [6]. In this standard, the specimens are tested under 4-point bending and the flexural strength is determined using equation (1).

$$f_{cf} = \frac{F \cdot l}{d^3} \quad (1)$$

Where F is the maximum load, l is the distance between the supports, and d is the dimension of the cross-sectional area of the specimen.

A geometry of 100×100×400 mm is studied under 4-point bending with a span of 300 mm. The specimen is made up of 2 layers with 2 print filaments in each layer. In this approach, a layer 50 mm thick and a print filament 50 mm wide are studied, as shown in *Figure 1*. The upper rollers move down at a constant velocity of 1 mm s^{-1} until failure occurs.

The numerical model uses spherical particles of different radii to simulate the flexural behavior of a concrete beam. The most influential material properties in this model are shear modulus, Poisson's ratio and density. The particles are randomly arranged to simulate the heterogeneity of the material.

In discrete approaches, Newton's second law determines the motion of the particles and the interaction laws define the behavior between particles in the contacts [7]. In this study, the model is based on the bonded-particle model for rock [8]. The interaction model between particles includes both contact and bonding. The bonds are elastic beams between the centers of the particles and their properties are stiffness per unit area, critical stress and bond radius. The stiffness is defined using a scaling relation following equation (2). The critical stress depends on material properties, bond geometry and the configuration of the bond network.

$$k = \frac{E_c}{R_A + R_B}, \tag{2}$$

where k is the stiffness, E_c is the Young's modulus and R is the particle radius.

The discrete model of this work studies a layered component manufactured by 3D printing. Three types of bonding are defined to model the 3D-printed concrete beam. Firstly, the bulk material bonding models the structural behavior of the material. Secondly, the interlayer bonding simulates the adhesion between horizontal layers. Thirdly, the vertical bonding models the interaction between the printed filaments of the same layer. The discrete numerical model of 3D-printed concrete is shown in *Figure 2*.

The model properties are chosen to match the macroscopic behavior of concrete. Bulk material properties are: density, ρ; shear modulus, *G*; Poisson's ratio, υ; friction coefficient, μ; and particle radius, *R*. Bonding properties of bulk material are: stiffness per unit area, *k*; critical stress, σ; and bond radius, R_b. The values of these properties are shown in *Table 1*.

Tables

Table 1 The influence of the interface bonding properties on the flexural behavior of the printed components is analyzed in this work. The influence of interlayer bonding and vertical interface bonding is assessed separately. The critical stress of interlayer bonding varies between 10% and 25% of the critical stress of bulk material bonding, and between 25% and 50% for vertical interface bonding. The stiffness of interlayer bonding varies between 80% and 100% of the stiffness of bulk material bonding, and between 80% and 100% for vertical interface. Eight numerical models are designed to study the influence of interface properties, as shown in *Table 2.*

3 Results and discussion

The simulations are performed to determine the maximum load applied and the maximum deflection of the beam. In this approach, the maximum load is obtained by calculating the total contact force applied by the upper rollers to the bonded particles. The position of the particles in the central bottom volume is obtained to determine the maximum deflection of the beam.

The results of maximum load and maximum deflection are compared in *Table 3* with a discrete numerical model of concrete with no layers (BM). The flexural strength is calculated using equation (1). Both interfaces of 3D-printed concrete influence the flexural strength, especially the interlayer bonding. Independent of the bonding properties, the parallel bond network has a great influence on the flexural behavior of the structural components.

3D-printed concrete beams subjected to 4-point bending fail when the tensile stress is higher than the normal strength of concrete. The longitudinal bonds in the central bottom volume break progressively. The stress distribution in the bond network on the

YZ plane at the instant just before the specimen breaks is shown in *Figure 3(a)*. The mechanical fracture occurs when the broken bonds concentrate in a section and the crack progresses upwards, as shown in *Figure 3(b)* in different simulations. The fracture always happens between the inner rollers.

The load-deflection behavior of 3D-printed concrete beams is similar up to 8.0 kN load. However, VI simulations reach higher values of maximum load and maximum deflection than IA simulations, as shown in *Figure 4*. The maximum load in the numerical models of 3D-printed concrete varies between 79.7% and 84.2% of the maximum load in the model with no layers (BM). The computation time of the numerical models is determined by the fixed time-step and the time it takes to calculate 1 time-step. These factors are influenced by model properties and the simulator engine (hardware). In this work, the mean computation time to solve a numerical model is 9.8 h.

4 Conclusions

The flexural behavior of 3D-printed concrete beams is studied in this paper using the Discrete Element Method. Three types of bonding are configured to study the influence of the layered structure of the components on the flexural behavior of the beams. The results are compared with a numerical model of concrete with no layers.

The flexural strength of the printed components is lower than the flexural strength of concrete with no layers. The influence of the defined interface properties is significant, but it is the configuration of the bond network to model the layered structure of the 3D-printed beams that determines the stress distribution in the bond network.

In the numerical models, the 3D-printed beams always fracture between the inner rollers. Therefore, the interfaces of 3D-printed components do not affect the flexural failure mode of the beam in this numerical study.

Future work includes determining the influence of different printing patterns on the flexural behavior of printed components using the same modelling methodology.

Acknowledgements

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Tables

Table 1. Model properties

Tabelle 1. Modelleigenschaften

Material	Bonding (bulk material)
$\rho = 2000$ kg m^{-3}	$k = 1e+12$ N m^{-3} (scaling)
$G = 1e+08$ Pa	$\sigma = 1e+12$ Pa
$\nu = 0.21$	$R_b = 5$ mm
$\mu = 0.1$	
$R = 4$ mm	

Table 2. Bonding properties of simulations

Tabelle 2. Bindungseigenschaften für Simulationen

	Interlayer bonding		Vertical interface bonding	
	Stiffness (N m^{-3})	Critical stress (Pa)	Stiffness (N m^{-3})	Critical stress (Pa)
IA01	$8 \cdot 10^{11}$	$1 \cdot 10^{11}$	Same as bulk material bonding	
IA02	$8 \cdot 10^{11}$	$2.5 \cdot 10^{11}$		
IA03	$1 \cdot 10^{12}$	$1 \cdot 10^{11}$		
IA04	$1 \cdot 10^{12}$	$2.5 \cdot 10^{11}$		
VI01	Same as bulk material bonding		$8 \cdot 10^{11}$	$2.5 \cdot 10^{11}$
VI02			$8 \cdot 10^{11}$	$5 \cdot 10^{11}$
VI03			$1 \cdot 10^{12}$	$2.5 \cdot 10^{11}$
VI04			$1 \cdot 10^{12}$	$5 \cdot 10^{11}$

Table 3. Results of maximum load and maximum deflection

Tabelle 3. Ergebnisse der maximalen Belastung und maximalen Durchbiegung

	Maximum load (kN)	Flexural strength (MPa)	Maximum deflection (mm)
IA01	8.33	2.50	1.082
IA02	8.41	2.52	1.097
IA03	8.40	2.52	1.086
IA04	8.40	2.52	1.086
VI01	8.80	2.64	1.096
VI02	8.63	2.59	1.085
VI03	8.55	2.57	1.128
VI04	8.67	2.60	1.123
BM	10.45	3.14	1.429

Figures

Figure 1. 4-point bending test of printed concrete

Abbildung 1. 4-Punkt-Biegeversuch an bedrucktem Beton

Figure 2. Bonding types in the model

Abbildung 2. Verbindungstypen im Modell

Figure 3. Stress distribution in bond network on YZ plane (a) and fracture of 3D-printed concrete beams (b)

Abbildung 3. Spannungsverteilung im Bindungsnetzwerk in der YZ-Ebene (a) und Bruch von 3D-gedruckten Betonträgern (b)

Figure 4. Load-deflection behavior

Abbildung 4. Federkennlinie

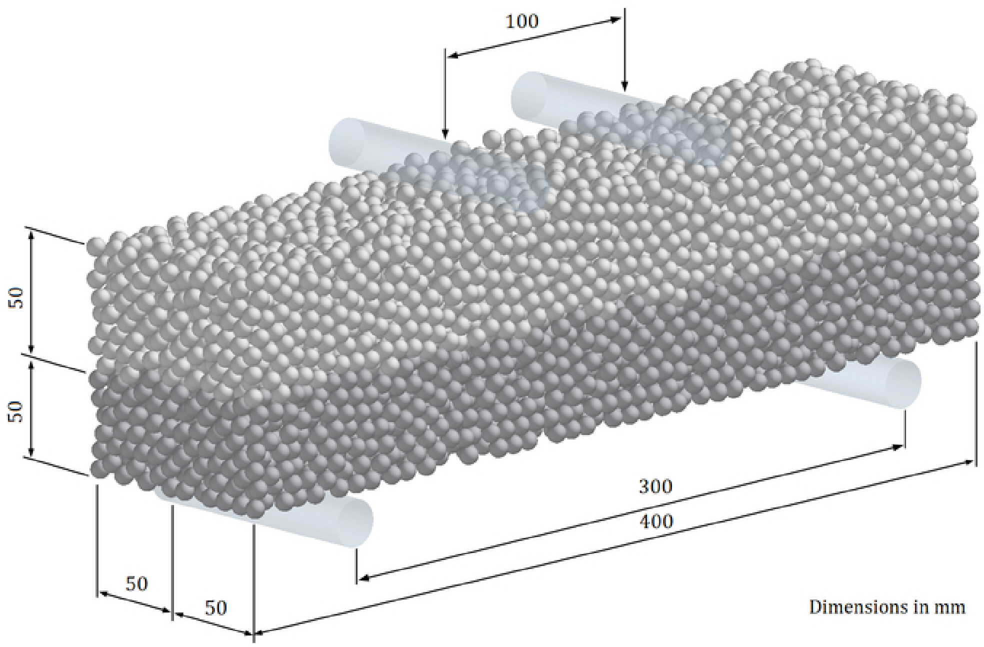

Figure 1. 4-point bending test of printed concrete

58x38mm (300 x 300 DPI)

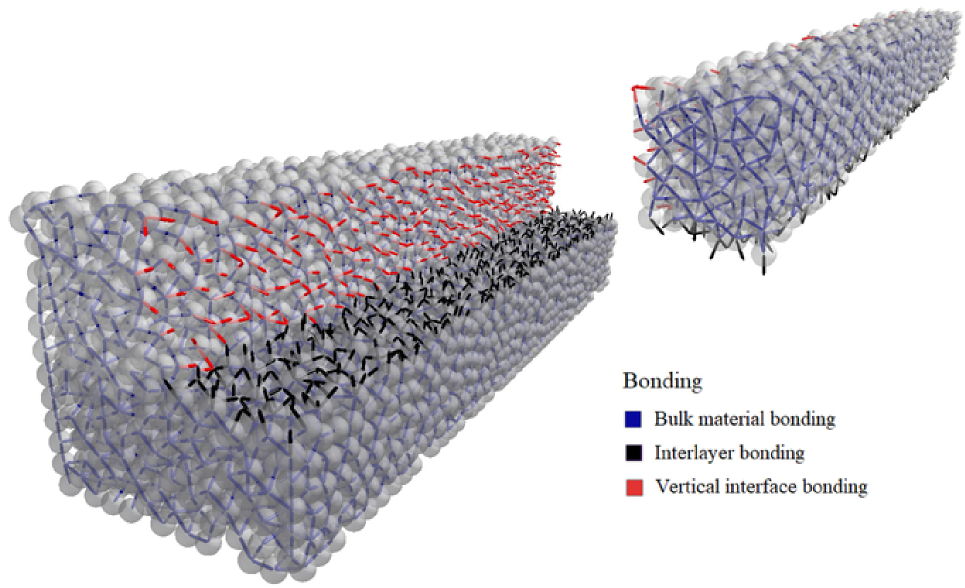

Figure 2. Bonding types in the model

59x36mm (300 x 300 DPI)

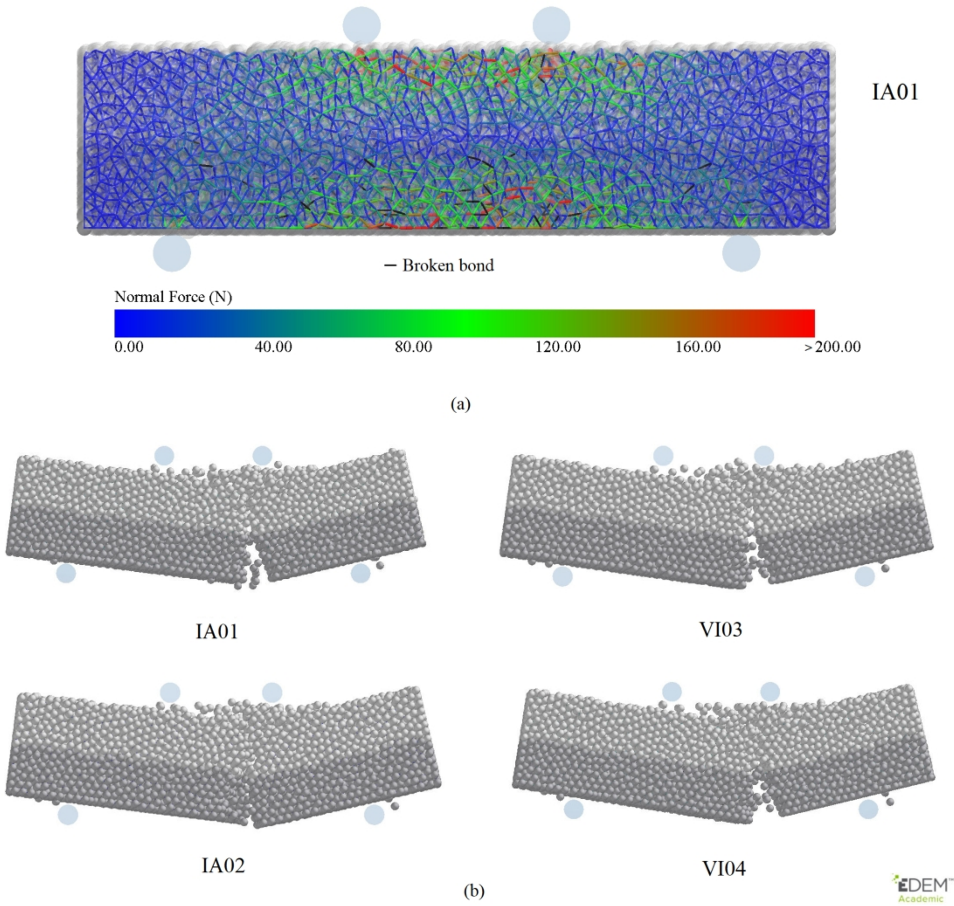

Figure 3. Stress distribution in bond network on YZ plane (a) and fracture of 3D-printed concrete beams (b)

169x157mm (300 x 300 DPI)

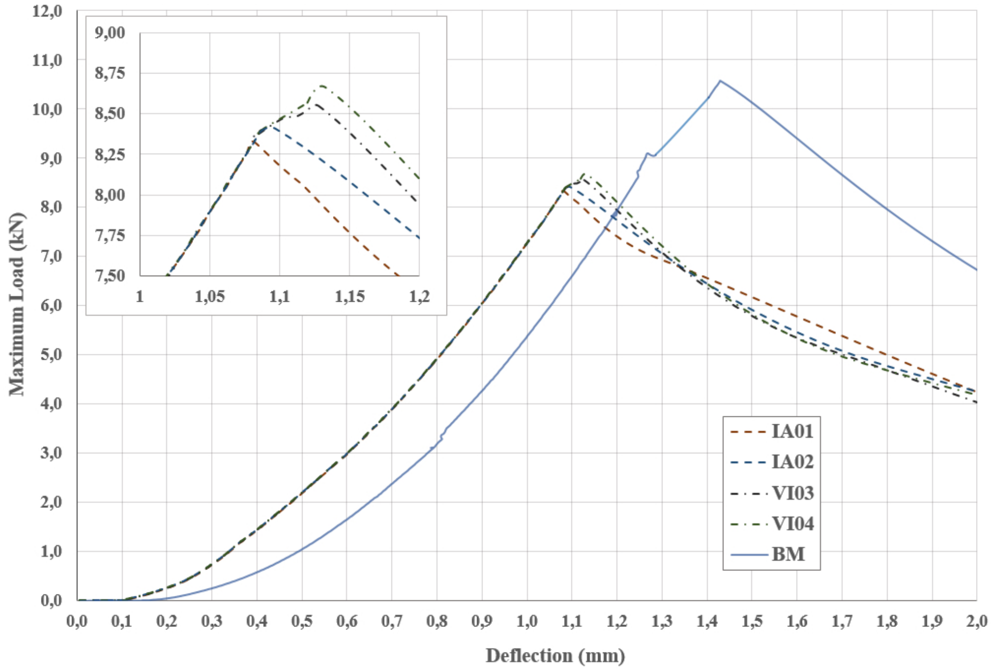

Figure 4. Load-deflection behavior

86x57mm (300 x 300 DPI)