Simulation of 3D Concrete Printing Using Discrete Element Method

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Abstract. The article at hand presents an approach for analyzing the 3D Concrete Printing (3DCP) by means of the Discrete Element Method (DEM). An advanced user-defined simulation material model for fresh printable concrete has been developed to simulate extrusion, discharge and deposition. In addition, a calibration procedure is shown to find a fitting parameter set for the material model parameters based on experimental data. The calibration of the latter is an iterative adaption process, leading to a realistic representation of real printable concrete. Finally, an extrusion-based 3DCP process is exemplary simulated to show the potential of the simulation method for process analyses and to verify the applicability of the model. The developed simulation tool enables a better understanding of the extrusion process during 3DCP and a profound analysis of the material flow within the extruder. Based on this information, improvements in the machine layout and the process parameter settings can be identified, allowing for further printing process optimizations.

Keywords: 3D concrete printing · Digital concrete · Discrete element method · Extrusion · Calibration

1 Introduction

The importance of 3D Concrete Printing (3DCP) has been continuously increasing over the last years. As the shortage of construction labor becomes more and more obvious, alternative ways of construction technologies must be developed based on automated processing of building materials. The concrete used for 3DCP usually differs considerably from conventional vibrated concrete.

The lack of sound knowledge on the complex rheological behavior of printable concrete makes it difficult to predict its interaction with the processing equipment, such as pumping pipeline, extruder and nozzle. Thus, numerical simulation is a promising tool to predict the material flow depending on consistency, machine layout and processing parameters [1].

So far, simulations are predominantly limited to the prediction of the stability of printed layers and their failure behavior depending on the number of layers that are printed on top of it and the time at rest [2–5]. Mostly, such concrete layers are "artificial"

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as they are created explicitly in their given shape, but are not "printed", simulating the corresponding material flow completely. These simulation approaches neglect phenomena related to the process-dependent material deposition and flow.

The main goal of the present research is to develop a material model that is capable to simulate 3D-printable concrete within the printing process, covering the extrusion process and the discharge of the concrete at the nozzle. This approach should enable the analysis and optimization of the flow inside the extruder as well as an estimation of the layer shape and stability after material deposition.

To realistically simulate the 3DCP, the material model needs to be calibrated with respect to the concrete that is actually used. Obtaining the required rheological parameters from experiments and transfer them into the numerical simulation represent challenging aspects in the framework of DEM and, therefore, require a suitable calibration procedure. A calibration procedure must be developed to iteratively fit real material behavior and the parameters of the simulation material model.

2 Modelling Approach

To enable valuable, realistic simulations of 3DCP, a numerical material model must correctly capture the rheological behavior of printable, fresh concrete. For that, the Bingham model with its determining parameters yield stress and plastic viscosity offers a suitable basis. In general, there are two established simulation techniques to model fresh concrete, namely, the Computational Fluid Dynamics (CFD) and the Discrete Element Method (DEM). Both exhibit specific advantages and shortcomings regarding the modeling accuracy of fresh concrete [6, 7]. For optimizing the printing head including the extruder for 3D concrete printing, the DEM seems to be the technique of choice because of its low computational costs with respect to the complexity of the machine geometry and movement compared with CFD.

The IAB Weimar and the TU Dresden completed successfully several research projects by investigating approaches to cover the behavior of fresh concrete [7–10]. The therein-developed models with two-layer particles and shear rate estimation are the basis for the contact model at hand for printable concrete. First trials regarding their application to 3DCP revealed that the so-called stickiness as a strong cohesion factor should be additionally considered, besides the rheological parameters prescribed in the Bingham model. Noteworthy, the thixotropic behavior and the structural build-up upon material deposition or during process interruptions are not considered in the present study, but will be included in future analyses.

3 Material Model Calibration

The material parameters required for the material model calibration were obtained in several experiments focusing on the rheological behavior of a printable concrete consisting of 392 kg CEM I 52.5 R, 214 kg Fly Ash (Steament H4), 107 kg Microsilicasuspension (Elkem 9/1), 253 kg fine Sand 0.06–0.2 (BCS 413), 253 kg local Sand 0–1, 759 kg local Sand 0–2, 246 kg H_2O and 9 kg superplasticizer (BASF Sky 593) for 1 m^3 of concrete. All tests were repeated several times to capture the sensitivity of material and measurement variations. In the following, the most relevant tests are described (also see Fig. 1). For the uniaxial compression tests, a cylinder (h = 80 mm, r = 25 mm) was filled with printed concrete. The subsequent steps were as follows: (1) remove the cylinder, (2) press a plate on the top of the concrete sample with a fixed speed of 0.5 mm/s and (3) measure the height dependent force on the plate. The test yields a force-displacement diagram (see Fig. 2) and the final shape (see Fig. 1).

The inclined plane test captures the interaction between fresh concrete and wall surfaces of a machine, such as the extruder or nozzle. The printed concrete sample was put on an adjustable plane and the angle was continuously increased until the sample started to slide down the plane. This angle of the plane was documented for different plane materials and wetness states of the plane (see Fig. 1). The angles varied between 18° and 36°.

The flow table test was performed regarding to DIN EN 12350-5 (see Fig. 1). The final diameter varied from 355 mm to 397 mm.

The “break-off” behavior of the fresh concrete was captured during the extrusion process. A visual evaluation of the video recording enabled the capturing of the maximum overhang of the extruded concrete strand extruded before the material broke off and fell (see Fig. 1). The maximum overhang varied from 70 mm to 110 mm.

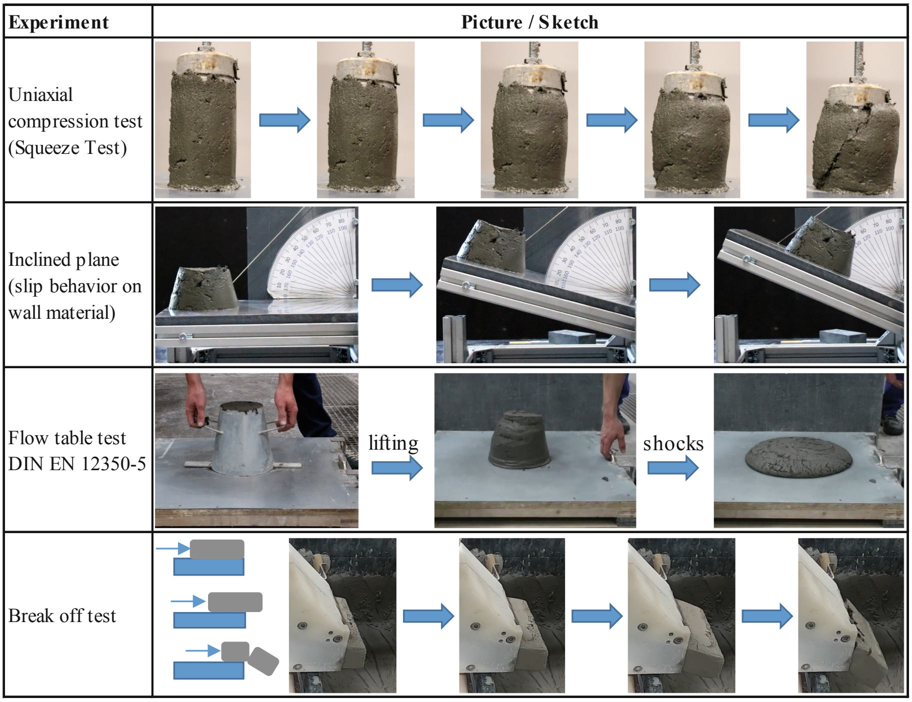

Fig. 1. Experimental setup of the calibration experiments.

The described experiments were simulated using the DEM by recreating the geometry with CAD, importing it into the simulation software and defining the geometry movement of the relevant parts.

For the simulations representing the calibration experiments, a sensitivity analysis was performed to determine the most relevant material model parameters on the respective results. As expected, yield stress and cohesion exhibit a strong influence, but also the elastic modulus of the outer particle shell had a high impact. The effect of the viscosity indeed was lower. Further parameters did not have a significant effect on the results. Subsequently, a swarm optimization algorithm was initiated for fitting the relevant input parameters of the DEM material model. The fitted parameter sets showed a good agreement between the experimental and the simulation results of the individual experiments. In Fig. 2, the results of the uniaxial compression tests are shown. The same quality of agreement was reached for the inclined plane test and the break off test.

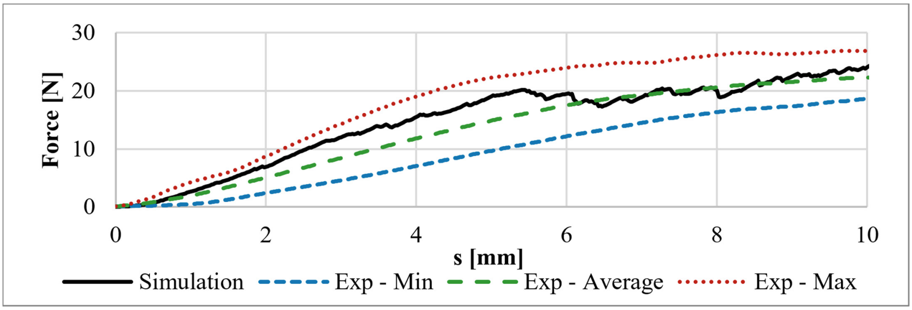

Fig. 2. Comparison of the force-displacement curves in the uniaxial compression test: the best-fit simulation result and the lower, average and upper values of the experimental results.

All three optimized parameter sets were similar, so that a single set of simulation material model parameters was determined by using a pareto optimization. This set could fit all three tests reasonably well.

In contrast, the additionally performed simulation of the flow table test did not yield satisfactory results, i.e. the experimental data could not be achieved. The authors believe that this may be due to the missing consideration of the thixotropy effects in the current simulation model.

4 Simulating 3D Concrete Printing

The fitted material parameter set and the above-described material model were used to simulate the 3DCP. For this purpose, the extruder-based printhead developed at the TU Dresden was reproduced within the simulation environment; see Fig. 3. The extruder conveys the material down to the nozzle where it is placed on the ground or the previously printed concrete layers. The printer nozzle creates a concrete layer with sharp edges and a dimension of about 50 × 150 mm.

A good visual match between real and simulated concrete layers was found. This is illustrated by (i) the sharp shape of the simulated concrete layers and the low deformation under self-weight observed, (ii) the clearly distinguishable layer boundaries, and (iii) an increased height of each beginning layer; see Fig. 3. Furthermore, the discharge speed at the nozzle was similar in the simulation and the experiment, indicating that the material behavior is correctly modeled.

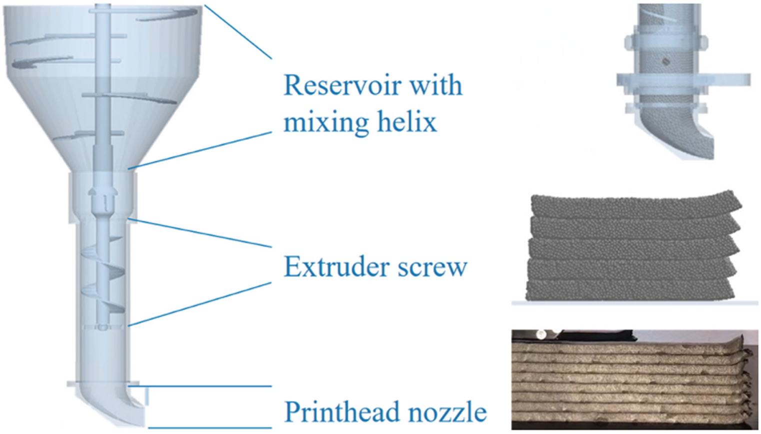

Fig. 3. Digital geometry of the concrete printer (left), the simulated printed concrete layers (top right) and the real printed layers from the experiment (bottom right)

After printing several layers of concrete, the self-buckling failure scenario known from the experiments occurred within the simulation too, leading to an instability and a tilt of the printed wall; see Fig. 4.

Fig. 4. DEM simulation (left) and real application (right) of a multi-layer concrete print with insufficient material stability leading to a collapse of the layers, shown from different angles.

5 Conclusions and Outlook

A novel simulation material model for 3D concrete printing was developed based on previous works at the IAB Weimar and TU Dresden. The newly adapted model yields the distinction between different wetness states of the material-wall interactions and an adapted cohesion property, which represents the increased stickiness of the printable concrete in comparison to ordinary concrete.

A series of experiments was performed to determine the rheological behavior of a fresh printable concrete. A pareto optimization was used to find a fitting parameter set to achieve a good agreement for several simulation experiments at the same time.

The 3D concrete printing was successfully simulated within the Discrete Element Method, showing a good qualitative agreement with the experimental findings regarding the shape of the printed layers and the speed of the material flow during extrusion.

The integration of a thixotropy function into the simulation model is the target of further research to increase the predictability of layer stability over time.

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