SIMULATION OF 3D-PRINTED CONCRETE STRUCTURES

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INTRODUCTION

Additive manufacturing is an emerging technology that has been already widely adopted in many technological fields, including concrete engineering. 3D concrete printing has the potential to automatize the construction process and reduce labor demands while allowing the production of ambitious architectural designs. As the number of projects in 3D concrete printing rapidly grows (1), the size of the market is booming. Based on Business Wire analysis, the global 3D concrete printing market size was valued at about $20 million in 2020 and is expected to reach over $470 billion by 2027.

The printing process can be assessed by the digital twin approach, where a numerical simulation is run either before or even concurrently with the actual printing. It can reproduce the lab experiments and further predict new printing scenarios saving time and costs or preventing potential construction issues at the site. Furthermore, it allows for optimizing the process by predicting necessary interruptions or adjustments of the printing speed during the construction process. For this purpose, a new module for the ATENA software package (2) was developed and its most important aspects are discussed in this paper.

NUMERICAL SIMULATION

Like the structural evaluation of reinforced concrete structures constructed by traditional technologies, the finite element method (FEM) can be adopted to assess the integrity of the structures constructed by the concrete printing process. A module for simulation of the 3D printing process was implemented into the ATENA software (2), which is already well established in the field of non-linear modeling of reinforced concrete structures. The software can capture realistic concrete behavior (3), including cracking when subjected to stresses exceeding the tensile strength or crushing when subjected to severe compression loading. The fracture-plastic material model simulates the tensile cracking based on the amount of the fracture energy dissipated in the process and the plastic crushing in compression is controlled by the critical compressive displacement. Except for the fixed material parameters suitable for simulations of fully hardened material, the ATENA material models allow for parameter adjustment during the solution run and thus for the simulation of the strength gain of the hardening concrete material.

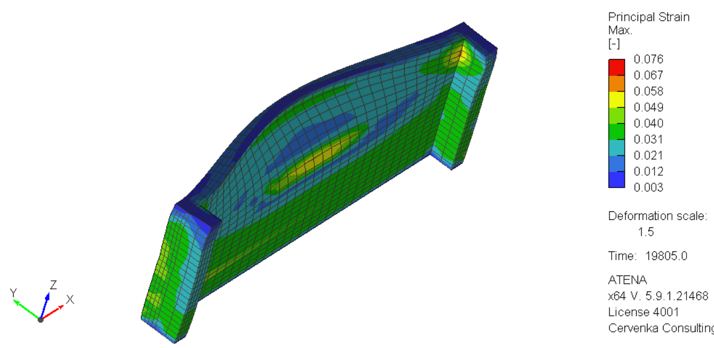

Fig. 1 Buckling failure mechanism captured by the simulation of 3D printing (scaled by 150%).

In non-linear simulations, the loads are commonly applied to the model in several computational steps to ensure that the material non-linearities are captured correctly. For the simulation of concrete 3D printing, the solution steps also represent the time during the printing process. Apart from the potential failure mechanism originating from exceeding the material performance at a given moment, the adopted approach is capable of simulation the failure due to the loss of stability. During the step-by-step solution process, each subsequent step is based on the geometry obtained in the previous step thus capturing the geometrical non-linearity (i.e., second-order effects). Therefore, the progressive increase of the horizontal deflection leading to the buckling collapse can be simulated as shown in Fig.1.

Definition of the Extrusion Process

The numerical FEM simulation relies on the gradual activation of the finite elements along the trajectory of the printing head. This trajectory can be either defined manually or extracted from the standardized G-code file. Based on this trajectory, each finite element is assigned a construction time, which is a key parameter for the evaluation of the material characteristics or certain load types. Since the G-code also contains information about the geometry, it can be directly used for creating the model and generating the mesh.

Hardening Material Model

The material model used for the simulation must capture the ongoing property change of the fresh concrete. Therefore, kinetic constitutive material laws need to be provided as an input for the simulations. The material parameters describe the material from the moment of printing through the rapid gain of mechanical properties during the first hours up to the final strength of the fully hardened concrete. Using the element's activation time, the material age is calculated to get the material parameters at each step of the solution.

The fundamental material parameter governing the material performance characteristics is the degree of hydration (i.e., maturity) of the concrete. It can be directly related to the strength of concrete using the models reported in the literature, such as (4). Then, based on the compressive strength, it is possible to deduce the remaining parameters of the fracture-plastic material model at any given time using constitutive relationships (2). Furthermore, if the reference development of the degree of hydration is known, it can be easily transferred to different temperature and humidity conditions using the equivalent degree of hydration concept and basic principles of physical chemistry. Alternatively, it is possible to input the time-dependent material characteristics directly based on the laboratory data for each parameter of the material model.

Loads on Printed Structure

The element's construction time and material age are also the governing parameters of certain load types. While the self-weight is applied to each element at the moment of its activation, the time-dependent shrinkage, which is greatly responsible for the early age cracking, is applied gradually. After the simulation of the extrusion process, the curing period can be simulated followed by the application of the standard static loads to model experimental testing in the lab conditions or loading at the construction site.

FROM THE LAB TO THE FIELD

Before the utilization of the 3D concrete printing technology at the industrial level, R&D effort is required to develop a suitable material as well as to test the 3D printing machine for placing the fresh concrete. This is typically done during laboratory tests such as the one presented by Wolf et. al (5), Similarly, if the FEM numerical simulations should be a reliable tool for structural assessment of the products constructed by 3D concrete printing technology, they should be verified against such data. The ATENA module presented here was already subjected to this validation (6) and a figure from the simulation is shown in Fig.2a.

After validation, the analysis objective can be scaled to individual structural elements such as walls or columns. An example of a sandwich wall with an inner stiffener is shown in Fig. 2b. Typical goal of such analysis is to optimize the length of the inner stiffener concerning the printing velocity. For large-scale concrete printing technologies such as those developed by the TU Dresden team (Germany) (7), the same simulation approach is suitable (Fig. 2c).

When it comes to the application in bridge engineering, 3D printing has the potential to automatize the construction process of certain substructure elements such as pillars. The 3D printing process can be used for the construction of the formwork, which, upon hardening, is used for placing the main load-bearing reinforced concrete core. In such a scenario, the FEM simulations by the ATENA software can be used for checking the stability of the formwork during its printing as well as its resistance against the pressure generated by the fresh concrete placed inside. Finally, the overall load-bearing capacity of the column is checked at the mature age by simulating the uniaxial load test.

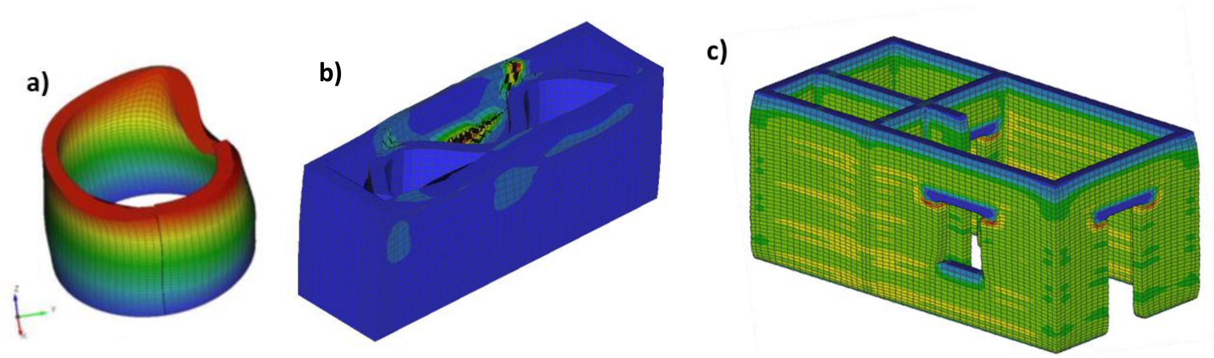

Fig. 2 Example of simulation of the 3D concrete printing at different scales: a) printing of a cylinder in a material test, b) a wall with inner stiffener, and c) a full-scale house (from right).

SUMMARY

This text presents a general overview of the framework implemented in the ATENA software for the simulation of 3D concrete printing by the extrusion process. The simulation relies on the time-dependent non-linear material model and the definition of the trajectory of the printing head, which can be either defined manually or based on the widely accepted G-code standard. The presented software module can be used to assess the integrity of the products constructed by 3D printing from the scale of laboratory experiments and single structural elements up to the structural scale.

ACKNOWLEDGMENT

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