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Time dependent modelling and simulation of digital concrete

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Abstract:
3D concrete printing (3DCP) is an innovative construction technology with the potential to revolutionize the concrete industry. As the research and development of 3DCP accelerate, there is a growing need for suitable numerical tools for the simulation of the process. In response to this need, this paper presents an integrated approach, combining a time-dependent material model for hardening concrete with a finite element method (FEM) solver, capable of progressively activating finite elements along the printing trajectory.
The numerical model for the material behavior is derived directly from the underlying hydration mechanism. The simulation of the additive manufacturing process is directly driven and controlled by the G-code data, which is normally used to drive the printing machine. The finite element numerical model is automatically generated using the G-code commands as individual finite element layers. Each finite element is activated according to the printing speed and its position along the printing path. Interface elements with time-dependent material laws can be automatically introduced between the layers to simulate the influence of the reduced mechanical properties of the printing layer connection.
The proposed solver is formulated to account for second-order effects to be able to simulate possible stability collapse during the printing process. To demonstrate the effectiveness of the proposed framework, an example simulating layer-by-layer construction of a real pilot house will be shown.

Keywords: 3D concrete printing, time dependent analysis, finite element method.

1 Introduction

Additive manufacturing, or 3D printing, has transformed prototyping by offering faster, cheaper, and more customizable production. This technology, accessible through user-friendly CAD software, has been embraced by the construction industry as 3D Concrete Printing (3DCP). 3DCP offers benefits like optimized material usage, reduced labor demands, and the ability to create complex designs without formwork. The rapid growth of 3DCP is evident, with scientific publications increasing from fewer than 40 before 2016 to over 400 by 2021 [1].
However, 3DCP presents challenges in structural assessment due to material inhomogeneity and geometrical imperfections. The non-linear finite element method (FEM) provides valuable insights into these issues. This study proposes a simulation framework using a time-dependent material model and FEM solver to address these challenges. By incorporating non-linear material models, the framework can replicate buckling collapse and simulate real house structures, accounting for material hardening through the hydration mechanism and compressive strength. This paper details the proposed framework, implemented in the ATENA software [2], and demonstrates its application with two examples.

2 Time dependent simulation of concrete printing by FEM

This study introduces a finite element method (FEM) framework for simulating 3D concrete printing (3DCP), which can effectively assess structural performance both during the early stages of printing and in the mature state.

2.1 Non-linear material model for concrete

Non-linear FEM is used for designing new structures and assessing existing ones by integrating non-linear material laws, providing realistic insights into structural responses under load. Reinforced concrete shows non-linear behavior, including cracking under tensile stress, crushing under compression, and steel reinforcement yielding or rupturing. The model by Červenka et al.[2] in the ATENA software [3] simulates tensile crack development using the smeared crack approach, with tensile softening controlled by dissipated fracture energy. Interface elements with the Mohr-Coulomb model simulate contact between printed layers, allowing for user-defined softening after exceeding tensile or shear strength, thus simulating potential interlayer openings or slips.

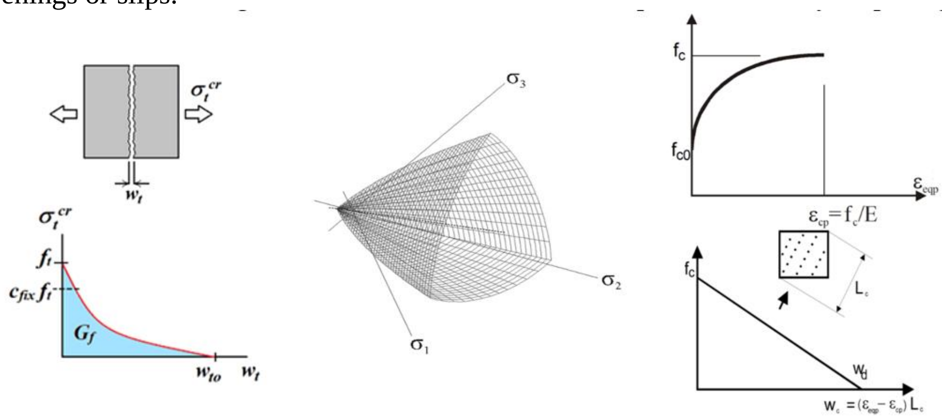

Fig. 1 Main features of the used fracture-plastic material model

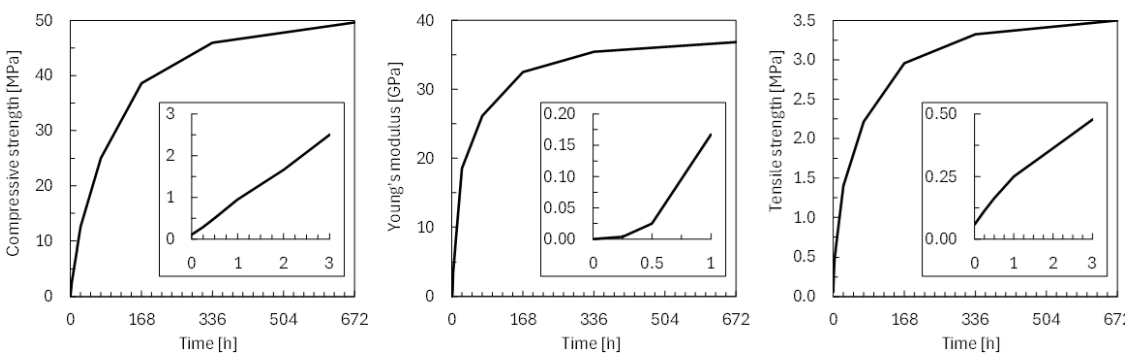

Fig. 2 Time dependent evolution of main material parameters f_c, E, f_t.

2.2 Simulation of 3D concrete printing.

The presented FEM approach for 3DCP effectively simulates the actual construction process. Unlike traditional static analyses with instantaneous load applications, non-linear FEM uses a step-by-step method. Loads are incrementally increased, allowing for the development of non-linear material behavior and redistribution of internal forces. For 3DCP, each simulation step corresponds to a specific time during printing, with elements activated according to the printing speed and trajectory. The element construction time, crucial for estimating loads and material model parameters, allows for the simulation of material maturing and shrinkage. This time-dependent, stepwise approach provides a realistic view of stresses and strains developing during printing.

2.3 Time dependent material model

Accurately modeling material behavior is crucial for numerical simulations, especially in 3DCP, where the material transitions from a thixotropic, non-Newtonian fluid to a solid paste. This study extends Červenka et al.'s model [2] with a time-dependent component to simulate the hardening process in 3D concrete printing. The material model accounts for the gradual increase in performance. Initially, the material's characteristics are determined by its thixotropic nature, divided into re-flocculation and structuration phases, which dominate during the early hours of printing [4][5]. As the paste hardens, the material model parameters are updated for each finite element at each solution step, reflecting the evolving state based on the element construction time.

3 Examples of application

A wall segment was prepared at the Klokner Institute, Prague, Czech Republic using 3DCP, with dimensions of 300×970×800 mm and a material thickness of 20 mm. It featured two internal stiffeners and had a compressive strength of 50 MPa after 28 days. Once matured, compressive strength testing assessed its load-bearing capacity.

A finite element model replicating the experimental behavior was developed, consisting of 27,680 quadratic elements with eight nodes each. Interface elements simulated interlayer slips, with a vertical interface in the middle of the stiffeners and a loading plate at the top. Printing was simulated at 120 mm/sec, with a total printing time of 30 minutes, followed by a loading test at 28 days.

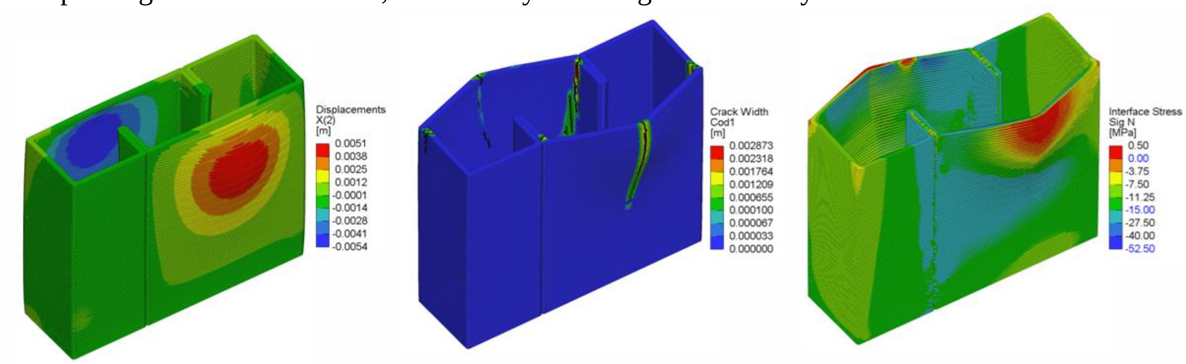

Fig. 3 Simulation and failure mechanism of 3D printed concrete wall during compression test.

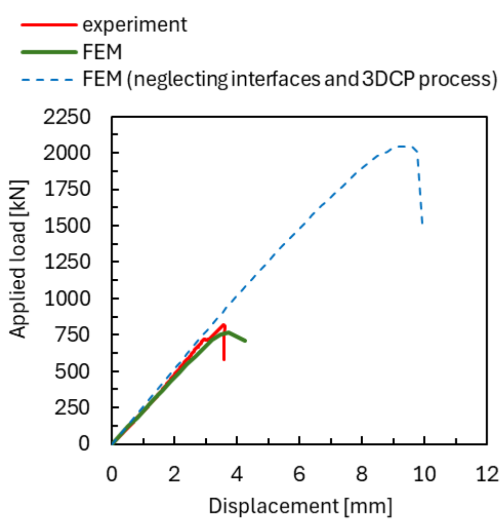

Fig. 4 Comparison of experimental and numerical load-displacement diagrams for the analyses with and without the consideration of the imperfections and weak layer interfaces

In Fig. 4, the load-displacement diagrams from the experiment and simulation are compared. The experimental sample's maximum load-bearing capacity is approximately 800 kN, well reproduced by the simulation. Fig. 4 (left) shows the out-of-plane deformation in the longitudinal wall, with a maximum deformation of about 5.5 mm after printing. As the material matures and is loaded, vertical cracks develop in the middle and corners, leading to out-of-plane brittle buckling and collapse (Fig. 2, middle). Fig. 2 (right) illustrates the normal stress in the interface elements, showing load transfer mainly through the

internal stiffening columns and corners, while the part with the initial imperfection is less stiff and thus less loaded.
The simulation framework was applied to the printing process of the Prvok (Protozoan) House in Prague, Czech Republic, which was the first large-scale 3DCP application in the country and references the house's design, inspired by single-celled organisms. It features a sandwich wall structure with outer and inner surfaces connected by stirrup reinforcement. Each layer is 45 mm thick and 12 mm high. The outer wall's wavy geometry enhances architectural aesthetics and out-of-plane stability, while the inner wall, supported by sigma-shaped columns spaced every half meter, lacks this design. A photo of the Prvok House is shown in Fig. 5.

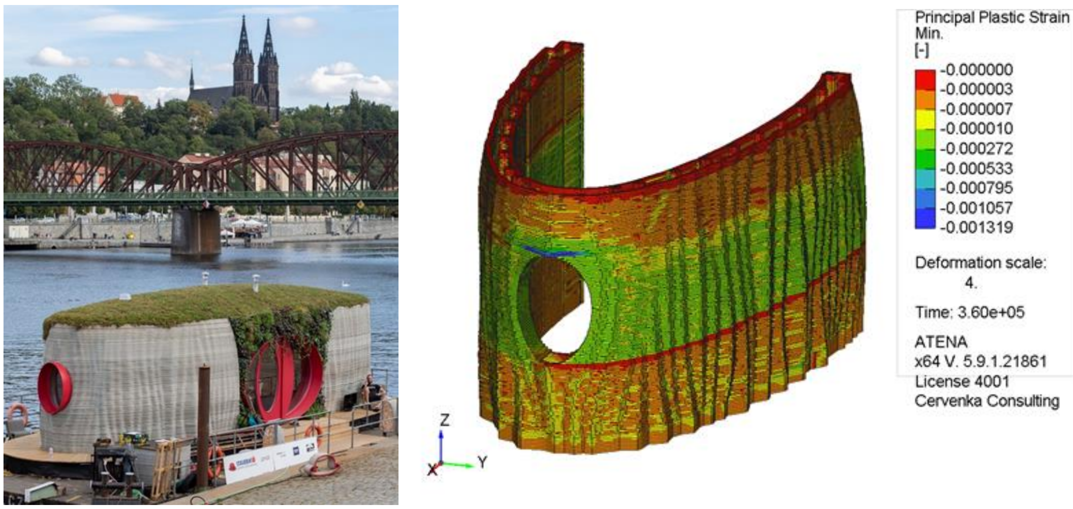

Fig. 5 Photo of the Prvok House and the result of numerical simulation.

5 Conclusion

This study examines the structural behavior of 3DCP elements using a non-linear finite element method analysis. A time-dependent material model captures the hardening process, allowing assessment of structural integrity during both early and mature stages. The simulation activates elements along the printing path, assessing stability and accounting for weaker interlayer connections. Early deformations are included, influencing the mature-stage response as demonstrated on two example structures from laboratory and practice.
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