Time dependent modelling of concrete for the simulation of 3D printing

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Abstract

Digital 3D printing is a new way of constructing concrete and reinforced concrete structures. This paper introduces an integrated approach that combines a time-dependent material model for curing concrete with a finite element method (FEM) nonlinear solver. This solver progressively activates finite elements along the printing path. The material behaviour model is directly based on the hydration mechanism. Additionally, interface elements with time-dependent material properties are inserted between layers to account for the weaker mechanical properties of layer connections. A case study demonstrating the layer-by-layer construction of a structure is presented to validate this framework.

1 Introduction

The adoption of additive manufacturing has marked a significant breakthrough in modern engineering practice. Traditionally, prototyping was expensive and time-intensive, relying on handcrafted models or injection moulding. These conventional methods demanded substantial resources, both in terms of materials and labour. However, introducing 3D printing has drastically reduced both the cost and time required for prototyping, making the process far more efficient. Beyond efficiency, 3D printing provides an unprecedented level of customization, enabling the production of highly tailored designs without excessive additional costs. This aspect is particularly beneficial for low-volume manufacturing, where traditional methods would be economically unfeasible.

A major contributing factor to the widespread adoption of 3D printing is the advancement of modern, user-friendly CAD software. Previously, the creation of complex 3D-printed components was limited to a select group of highly specialized engineers. Today, intuitive CAD tools have democratized access to 3D printing technology, allowing designers, architects, and even hobbyists to develop intricate models without requiring extensive technical expertise. This broader accessibility has accelerated innovation across multiple fields, from product design to biomedical applications.

More recently, the principles of additive manufacturing have also been successfully integrated into the construction industry, where the process is known as 3D concrete printing (3DCP). This emerging technology offers several compelling advantages. Among the most notable benefits is the efficient utilization of construction materials, significantly reducing waste. Additionally, 3DCP minimizes labour demands, an especially relevant factor given the ongoing labour shortages in the construction sector. Furthermore, this technology enables the realization of highly ambitious architectural designs that would be difficult or impossible to achieve using traditional methods. Unlike conventional construction techniques that require extensive formwork, 3DCP allows for direct layer-by-layer fabrication, streamlining the building process while maintaining design flexibility.

The rapid expansion of 3DCP technology is evident in the growing volume of research and industry applications. A comprehensive review conducted by Ma et al. [1] on the state of 3DCP technology revealed a dramatic increase in academic interest. Before 2016, fewer than 40 scientific papers had been published on the topic. By 2021, the total number of journal publications exceeded 400, demonstrating an exponential rise in research activity. This growing interest is not confined to academia alone; industry engagement has also surged, as evidenced by the increasing number of patents and real-world 3DCP construction projects. The concurrent rise in research, innovation, and commercial application underscores the strong potential of this technology to disrupt the conventional construction landscape.

As 3DCP continues to evolve, there is a pressing need for reliable numerical simulation tools to support further advancements. While additive manufacturing with polymer-based materials has been well-established, 3DCP presents unique challenges that must be addressed. The complex behaviour of concrete, particularly its time-dependent hardening process, introduces additional factors that must be incorporated into simulation models. This study examines key aspects of numerical simulation for 3DCP, focusing on challenges such as material behaviour, structural stability, and process optimization. It also proposes a specialized simulation framework integrating a time-dependent nonlinear material model with a finite element method (FEM) solver. This framework has been successfully implemented within the ATENA software package [2], enabling detailed simulations of the additive manufacturing process. Its effectiveness is demonstrated through an example featuring real-world construction using 3DCP, showcasing its practical applicability and potential for further industry adoption.

2 Constitutive equations

Digitally printed structures are typically computed by a step-by-step procedure [3]. The structures are assessed in many time-steps, each for a particular time (i.e. age), ranging from time zero to time corresponding to the end of life of the structure. After updating the shape, material parameters, etc. concerning the current age of the structure, each such time step is computed by the standard finite element method.

As far as the material model is concerned, we are using a fracture-plastic material model with an orthotropic smeared tensile crack model and a compressive plasticity model. After exceeding the tensile strength, it is evaluated based on the amount of dissipated fracture energy, while the maximum compressive displacement controls the crushing in compression [4].

Simulation of printed concrete structures requires a material model that covers time immediately after printing, but service life assessment of term behaviour needs to be considered as well. To address temporal material behaviour, its parameters are adjusted by time-dependent scaling functions. Their values range from zero for fresh to one for fully mature material conditions.

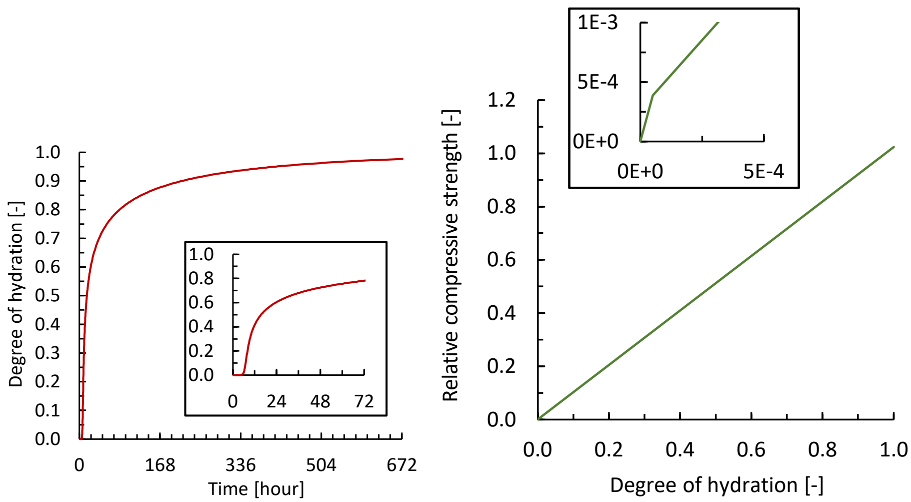

Fig. 1 Example of a hydration curve within 28 days of hydration, (left), and a bi-linear function relating the degree of hydration on relative compressive strength, (right).

In the proposed model, a strategy has been developed for the generation of the kinetic material model whose parameters are properly fitted to cover the whole time span of the structure (incl. its hydration kinetics at an early age). This approach combines a cement hydration curve with a function relating to the degree of hydration (DoH) and the relative compressive strength. The hydration kinetics can be either imputed directly based on laboratory data such as direct XRD-Rietveld analysis or indirect techniques such as electron microscopy or calorimetric measurements can be employed [5]. When lacking experimental data, the hydration curve can be estimated based on the chemical affinity model CEMHYD3D SW model [6] previously implemented in ATENA software package [2, 3].

The material parameters for the fracture-plastic material model [4] can be generated based on compression strength using the assumptions presented in Table 1. Fig. 1 shows their typical time dependency on the degree of hydration and relative compression hydration of concrete.

Table 1 Summary of the constitutive material laws for the fracture-plastic model [4].

Parameter: symbol [unit]	Formula
Compression strength: f_c [MPa]	Input
Young's modulus: E [MPa]	$\left(6000 - 15.5 f_{c,28}\right)\sqrt{f_c}$
Tensile strength: f_t [MPa]	$0.3 f_c^{\frac{2}{3}}$
Specific fracture energy: G_F [N/m]	$73 f_c^{0.18}$
Critical compressive displacement: w_d [mm]	-0.5
Onset of non-linearity in compression: f_{c0} [MPa]	$\frac{2}{3} f_c$
Plastic strain at compressive strength: ε_{cp} [MPa]	f_c / E_{28}

3 Sample analysis

The problem of modelling and simulation of the digitally printed structure was discussed in several recent papers, e.g., [7-12]. The authors presented the proposed approach in more detail, including validation by experimental data in [6,8,9,10]. This section demonstrates the application to a sample analysis, which investigates the stability of a concrete lower box with inclined overhanging outer walls. The process of the box's printing together with its subsequent service was simulated by the presented software. The study should confirm the feasibility of the box and provide some guidelines about required material properties and printing parameters akin printing speed etc.

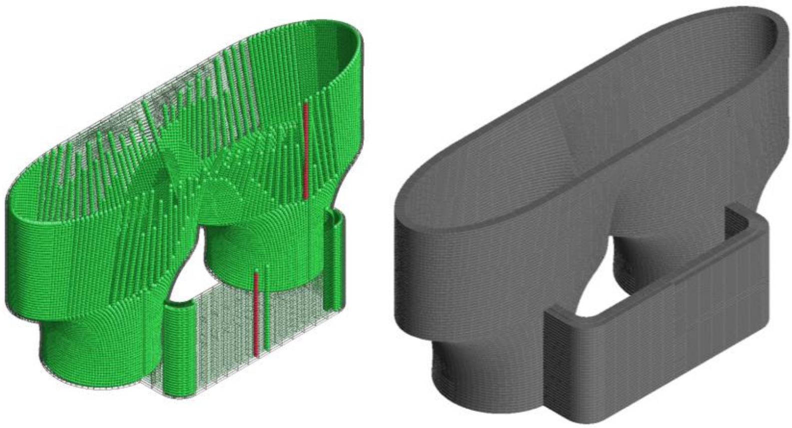

Fig. 2 The box for flowers: the polygon of G-code coordinates used for its modelling and printing and its final FEM model.

The box is shown in Fig. 2. It has a length of about 1.6 m, a width 0.254 and a height of 0.712 m. Note that FEM model of the box, Fig. 2 (right), is created automatically based on a polygon of G-code coordinates, Fig. 2 (left).

The box is digitally printed by extrusion layer by layer from the bottom to the top. Each layer has a width of 0.03 m, and its height is 0.01 m with planar layers. The assumed printing speed is 0.02 m/s. The structure is supported at the bottom and loaded by its self-weight, i.e. 0.0257MN/m^3. Throughout the analysis the constant time step of 250 s is used.

Material parameters for concrete used in the simulation are given in Table 2 and Fig. 3.

Table 2 Material parameters for concrete at 28 days.

Parameter: symbol [unit]	Value
Compression strength: f_c [MPa]	50
Young's modulus: E [MPa]	36 900
Tensile strength: f_t [MPa]	4.07
Specific fracture energy: G_F [N/m]	148
Critical compressive displacement: w_d [mm]	–0.5
Onset of non-linearity in compression: f_{c0} [MPa]	33
Plastic strain at compressive strength: ε_{cp} [MPa]	0.00135

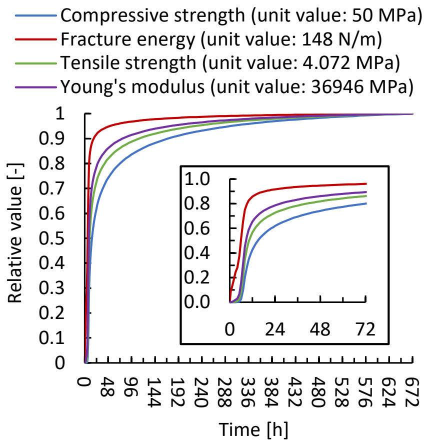

Fig. 3 Material parameters for concrete and their development in time.

In practice, the link between printed neighbouring layers is not perfect, and hence, the presented simulation inserts between the concrete layers a layer of interface elements with a special interface material [3], Fig. 4, (1). This process is fully automatic. The interface material is based on Mohr-Coulomb criterion with tension cut off. The constitutive relation for a general three-dimensional case is given in terms of tractions on interface planes and relative sliding and opening displacements.

The initial failure surface corresponds to Mohr-Coulomb condition with an ellipsoid in tension regime. After stress violates this condition, this surface collapses to a residual surface, which corresponds to dry friction. In tension, the failure criterion is replaced by an ellipsoid, which intersects the normal stress axis at the value of f_t with the vertical tangent and the shear axis is intersected at the value of c (i.e. cohesion) with the tangent equivalent to $-\phi$. Note that the parameters for the interface model cannot be defined arbitrarily; there is a certain dependence of some parameters on others.

The parameters for the interface material are given in Table 3. They are scaled in time by scaling function for f_c, see blue line in Fig. 3 for compression strength of concrete.

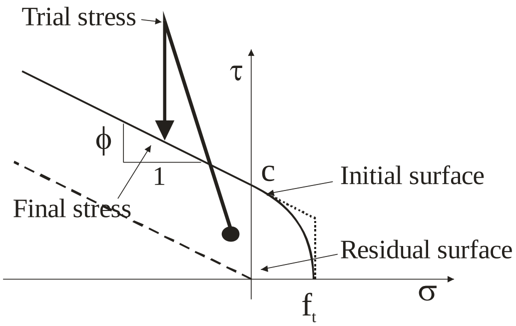

Fig. 4 Mohr-Coulomb failure criterion for interface elements.

$$\begin{Bmatrix} \tau_1 \\ \tau_2 \\ \sigma \end{Bmatrix} = \begin{bmatrix} K_{tt} & 0 & 0 \\ 0 & K_{tt} & 0 \\ 0 & 0 & K_{nn} \end{bmatrix} \begin{Bmatrix} \Delta v_1 \\ \Delta v_2 \\ \Delta u \end{Bmatrix} \tag{1}$$

Table 3 Material parameters for interface material at 28 days.

Parameter: symbol [unit]	Value
Normal stiffness K_{nn} [MN/m^3]	3.7e+07
Tangential stiffness K_{tt} [MN/m^3]	3.e+06
Tensile strength: f_t [MPa]	4.07163
Cohesion c, [MPa]	4.
Min. normal stiffness $K_{nn,\min}$ [MN/m^3]	370000
Min. tangential stiffness $K_{tt,\min}$ [MN/m^3]	30000
Friction	0.8

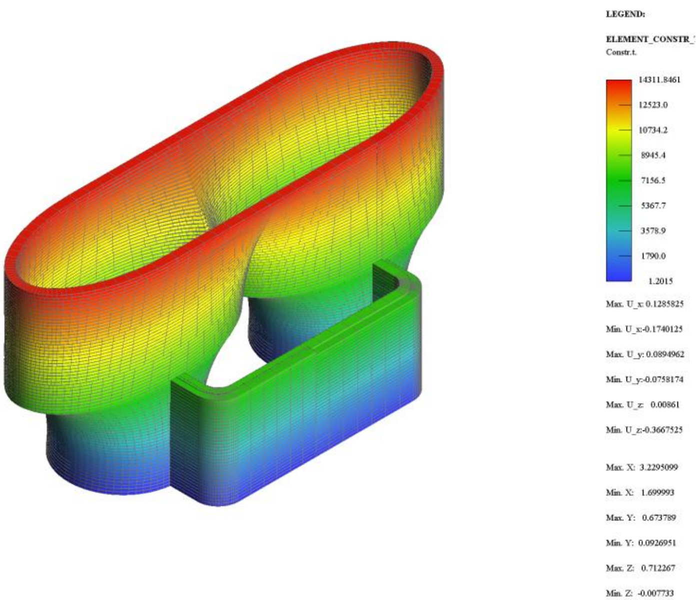

Fig. 5 Element construction time, [s].

The actual simulation of the investigated structure proceeds as follows: The additive manufacturing process is simulated using G-code data, typically assembled to control also the printer. The numerical finite element model is automatically generated from G-code. Activations of the created finite elements occur according to printing speed and positioning. Additionally, interface elements with time-dependent material properties are inserted between layers to account for the weaker mechanical properties of layer connections. The solver is designed to consider second-order effects, enabling the simulation of potential stability failures during printing. It is very important because collapse due to loss of stability is the most common cause of failure. Another failure mode of digitally printed structure is exceeding material compression stiffness. It often happens at very early ages just after the printing. In later times, buckling or loss of stability failure usually prevails.

The remaining part of this section presents the results of the analysis. The total time of printing was slightly below 4 hours. Fig. 5 shows the printing time of individual finite elements during the printing simulation process.

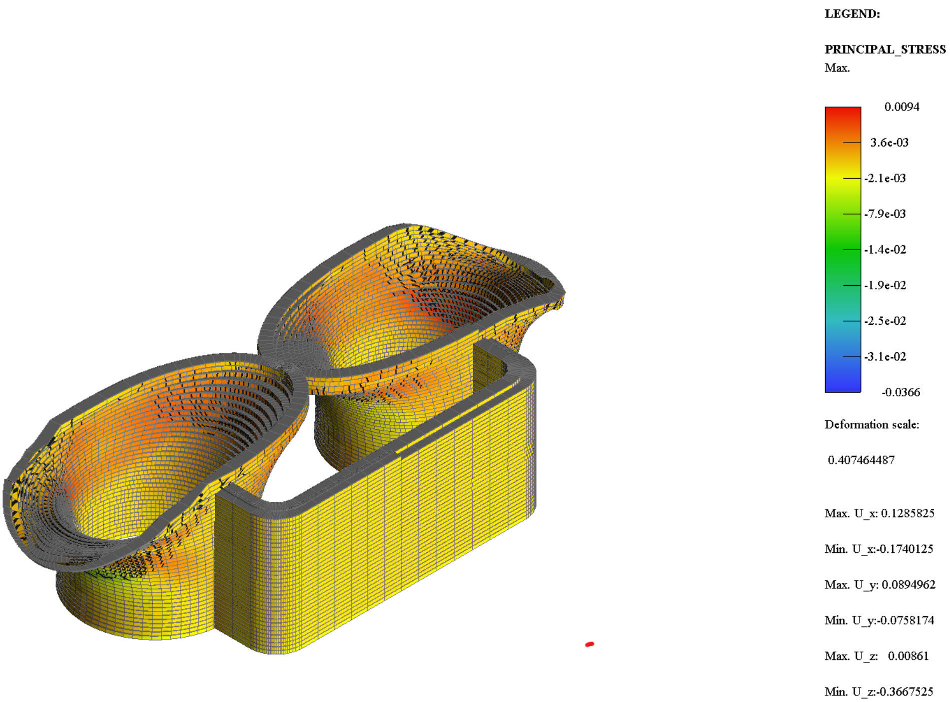

Fig. 6 Structural conditions at the time of failure.

The box collapsed after 8250 s, ie. 2 hours, 17 minutes and 24 seconds of printing. Its current height was 0.36m, which is about half of the final height. It failed due to loss of stability, see Fig. 6. The figure also shows maximum principal stress at the failure together with cracks that were already largely developed.

For comparison, the same box was also analysed for the case of printing speed 10 times slower. This time, the printing procedure was successful up to its full height (see Fig. 7), even though quite large deformations can be observed at the bottom overhanging edges of the analysed structure.

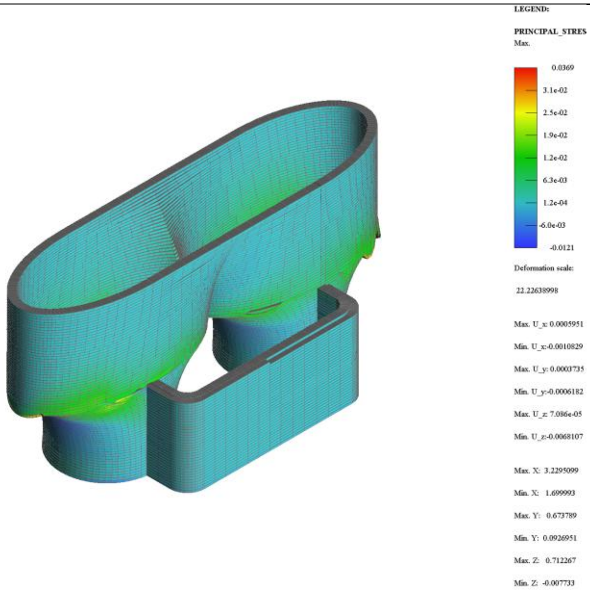

Fig. 7 Structural conditions at the end for printing for the case of one-tenth printing speed.

4 Conclusion

The paper presents a procedure for the simulation of digitally fabricated concrete structures produced by 3D extrusion. It discusses material models suitable for digitally printed concrete structures and presents methods for the evaluation of time dependent material parameters for the selected fracture-plastic concrete material.

The described analysis has been fully implemented in the ATENA software package for the comfortable and transparent simulation of the concrete 3D printing construction process up to the end of its lifetime. The numerical model is automatically generated directly from the G-code data for the printing machine. During the simulation, the finite elements are gradually activated along the printing trajectory, and the nonlinear constitutive model is evaluated based on the unique element construction time. Utilizing this method, the software [2, 3] allows for the assessment of the integrity of the structures constructed by concrete 3D printing.

The presented sample analysis of a concrete box with overhanging walls demonstrates a practical use of the developed framework for laboratory tests as well as for real engineering structures.

Acknowledgments

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