Filament geometry control in extrusion-based additive manufacturing of concrete: The good, the bad and the ugly

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1. Introduction

The architecture, engineering and construction (AEC) industry is increasingly digitizing its processes to answer the call for a more sustainable and more efficient design and construction of the built environment. In this digital transformation, one of the most promising and rapidly developing innovations is 3D concrete printing (3DCP) [1,2,3]. Although a variety of methods is available, the majority of applications concerns extrusion-based 3D concrete printing, an additive manufacturing technology where successive filaments of cementitious materials are extruded by a robotic system based on a digital 3D model [4]. For the technology of 3DCP to develop beyond showcase projects and its novelty characteristic, quality control of the process and product is essential to increase productivity and compete with existing technologies. This control starts at the level of a single filament, as the final geometrical conformity of a 3D printed object is dictated by the sum of the individual filaments’ conformities. Moreover, the filament geometry influences the aesthetical quality of the final product, and is expected to impact the structural properties (bond strength) and durability performance (ingress of harmful substances) [5–10] of the resulting printed object.

Various geometric instabilities have been reported in literature in the simpler case of visco-elastic inks printing [11]. Very similar instabilities were also reported in literature in the more complex case of the deposition of elastic-visco-plastic materials such as ceramics or concrete [12,13]. In the case of polymer filament deposition, some regimes for these instabilities were defined experimentally along with their boundaries as a function of the deposition parameters [11]. The aim of the present paper is to carry out a similar analysis in the case of concrete or mortar filament deposition. The specificity of the present work lies in its computational nature. The numerical simulations carried out here allow for the exploration of a large printing parameters range. This work also accounts for the non-Newtonian behaviour of the printed material in the definition of the conditions, under which geometrical instabilities are expected to occur. Finally, the results are gathered into a unique map allowing for the assessment of a so-called “safe” printing zone as a function of printing parameters and material parameters, in which none of the above geometric instabilities are expected to occur.

2. Background: free flow versus infinite brick extrusion

The majority of all extrusion-based 3D concrete printing processes is expected to be close to one of the two following asymptotic regimes at the level of the nozzle [14,15], schematically represented in Fig. 1.

In the first case (Fig. 1 left), the material is unsheared before extrusion. A so-called lubrication layer is formed at the vicinity of the extruder wall. The material leaves therefore the nozzle as a stiff continuous filament, the cross section of which is imposed by the...
velocity is unable to keep up with the speed of the nozzle and thus, will however falls beyond the scope of the present study, and we assume here the nozzle (Fig. 2 right). This situation is similar to traditional deposition processes, as the sheared material exiting the nozzle, for instance by a contraction or a screw mixer. This is referred to in literature as ‘infinite brick extrusion’ [14].

In the second case (Fig. 1 right), the material is sheared prior to exiting the nozzle, for instance by a contraction or a screw mixer. This situation is similar to traditional deposition processes, as the sheared material flows onto the print bed or the previous layer, and reaches its final shape dictated by the competition between gravity and its yield stress (Fig. 2 left). This case is referred to as ‘free flow deposition’ [14].

Note that, in some cases, the material is constraint horizontally between trowels during extrusion, or the filament is vertically squeezed by the nozzle (‘lace pressing’), to enhance geometrical control [13]. This however falls beyond the scope of the present study, and we assume here that the nozzle is located at a certain level above the upper surface of the deposited filament (no pressure overshoot occurs), and constraining trowels are not applied.

In the infinite brick regime, the printing process is typically performed at nominal speed, i.e. the flow of the material is tuned to the speed at the level of the nozzle, or vice versa, such that a constant filament cross section is maintained. However, in certain cases the speed may be non-nominal, either deliberately or due to an uncontrolled process. The nozzle speed may be increased in a strive towards higher productivity or decreased to cover up a lack of material in previous layers [16]. Moreover, there is often a lack of control on material flow at the level of the nozzle in relation to other parameters, as typical 3DCP setups only control the material upstream, for instance through frequency control in the mixer-pump. In such cases, the nozzle speed may vary accidentally from ‘too fast’ to ‘too slow’ in relation to the targeted material flow. Above a certain threshold nozzle speed, the material flow velocity is unable to keep up with the speed of the nozzle and thus, will lead to a cross section reduction and, ultimately, to filament tearing, illustrated in Fig. 3, left. When the nozzle speed is below a certain threshold value, the material flow is too high to be deposited freely, and corresponding local increment of material pressure seems to induce a local filament instability, illustrated in Fig. 3, right.

While these are often undesirable features that may compromise the esthetical or structural quality of the printed object, in certain cases, a controlled occurrence is in fact desired. The instability patterns were shown to produce expressive architectural patterns [17], whereas filament tearing can be used to create, voluntarily, weak parts that act as temporary support that can be easily removed afterward [18]. When printing sharp turns, both situations can occur simultaneously on each side of the filament: the inside part of the filament may be prone to instability, while the outside curvature may induce tearing.

It is worth noting that, for most 3DCP processes in practice, the filament width to thickness ratio is larger than one, and as such, there is a preferential instability direction. In those cases where the filament is cylindrical, instability could occur in any direction, or lead to coiling. This feature has been studied in the case of simpler fluids, such as Newtonian or visco-elastic fluids, and is typified by a wide range of repetitive coiling patterns [11,19–21].

In addition to the printing process parameters (i.e. nozzle speed and material flow), the geometrical features of the filament (which, for the infinite brick regime, are imposed by the nozzle geometry), as well as the material properties should define to which extent the filament may be subject to tearing or instability. In the present paper, a numerical study is performed to map the influence of all these parameters in the infinite brick extrusion regime and allow for an a priori prediction of the conditions under which these features do not appear, or to define the conditions required to create them on purpose.

3. Numerical model

A numerical study of the extrusion-based 3D printing process was performed using computational fluid dynamics (CFD) software FLOW-3D®. The CFD method is commonly applied to study the flow of concrete in standardized tests [22–26] or during casting into a formwork [12,27–29], as well as to analyse the filament geometry in extrusion based additive manufacturing of polymers [30–32], and more recently for concrete as well [33].

For the present study, the Finite Volume Method (FVM) was used to analyse the concrete as an incompressible, homogeneous Non-Newtonian fluid, as the characteristic dimension of the flow (e.g. nozzle dimensions, thickness of the flow) is high compared to the maximum aggregate size typically observed in 3D printable mixture compositions. The flow equations were solved by means of a reconstruction-based Volume of Fluid (VOF) method [12], with implicit numerical approximation.

The incremental elastic stress model used here computes the elastic stress using linear Hookean theory. Although this simple constitutive equation predicts linear responses to stress, implementation as an incremental model allows for the prediction of highly nonlinear responses because the response within each small time-step can be well

Fig. 1. Two asymptotic regimes in extrusion-based 3D concrete printing: infinite brick extrusion (left) and free flow deposition (right). Reproduced from [14].

Fig. 2. Free flow deposition (left) and infinite brick extrusion (right) as observed in 3D concrete printing experiments.
approximated as linear, since the incremental strain during each time step is small. In order to predict yielding effects, the von Mises yield condition is used (Cf. Fig. 4).

Viscous stress is solely based on the instantaneous strain rate at every point in the studied domain at a particular point in time, and thus need not be stored during the course of the simulation. Elastic stress, on the other hand, must be stored since the history over time of a material point needs to be known to compute the current state of elastic stress. As the materials studied here are isotropic in nature, the Cauchy stress is symmetric, so there are 6 unique components of the elastic stress tensor, which are advected along with the flow of the material through the domain. Please note that only the deviatoric part of the elastic stress is stored; the isotropic part is merely the pressure, and is solved via the enforcement of the continuity equation as with any viscous liquid.

First, the numerical study was performed based on a 2D representation of the printing process, see Fig. 5. The nozzle was placed at a static position in the analysed domain, with height H above the print bed. The bottom (Z min) and back (X min) surfaces were given a constant velocity $V_P$ in negative X direction, representing the movement of the nozzle. The bottom surface was modelled as a wall boundary condition, with no slip shear boundary conditions [34]. All other surfaces in the X and Z plane were subject to in/outflow boundary conditions, while those in the Y direction were subjected to symmetry, to decrease computational costs. The flow of the material was modelled as a mass momentum source, maintaining a constant flow velocity $V_P$ in negative Z direction at the position of the nozzle. The width of the nozzle and thickness of the deposited filament are represented by D and $\delta$ respectively.

The analysed domain was meshed by an orthogonal gradient grid, with the highest density below the nozzle, gradually reducing towards the outer surfaces of the domain. Additionally, local mesh refinements were applied near the interface regions of the nozzle. A typical mesh distribution of the 2D CFD analyses is illustrated in Fig. 6.

![Fig. 3. Filament tearing (left) and filament instability (right).](image)

Potential thixotropic behaviour was not considered in these studies. It is assumed to be negligible in the time span of the extrusion (typically in the order of a few seconds) [35–38]. This could not hold true for extremely fast stiffening material that may be used in some printing processes [39,40]. The material was subject to gravity-induced stresses, based on the gravitational acceleration $g$ of 9.81 m/s$^2$ in negative Z direction and the material density $\rho$ is equal to 2000 kg/m$^3$.

We varied the ratio between the nozzle speed $V_N$ and material flow velocity $V_P$, such that the dimensionless velocity $V^* = V_N/V_P$ was smaller than, larger than, or equal to unity. We assume here that it is the ratio between the two velocities that is critical for filament geometry control, and thus, have maintained a constant material flow velocity and only varied the nozzle speed. The influence of the nozzle position and geometry was studied through variations of the vertical position $H$, and the nozzle width $D$. Their ratio is expressed through the dimensionless thickness $H^* = H/D$. A wide range of material behaviour was included through variations of the yield stress $\tau_0$, critical strain $\gamma_c$, viscosity $\eta_p$, and shear modulus $G$. Please note that the material behaviour here is assumed fully symmetrical, i.e. the same in compressive and tensile state.

It can be noted here that, in practice, the nozzle velocity $V_N$ is constrained between a lower limit, below which the process is not acceptable from an industrial productivity point of view, and an upper limit due to kinematic robot constrains and the occurrence of inertia effects [14]. The material flow velocity $V_P$ is typically tuned through trial-and-error, such that the velocity ratio equals 1.

The nozzle height $H$ can be relatively low for layer-pressing strategies [13], in which the layer is shaped by the contact with the nozzle itself, whereas the upper limit is defined by the height at which slug (gravity induced instabilities) occurs [41].

The minimal width $D$ of the nozzle opening (often of the same order as the filament thickness) is, like the nozzle velocity, defined by the productivity of the process, while an upper limit is defined by the initial yield strength requirement for the filament to be stable immediately after extrusion (i.e. thick layers require high initial yield stress) [14,36].

Finally, the range of yield stress $\tau_0$ and critical strain $\gamma_c$, and thus shear modulus $G$ as they relate through $\tau_0/\gamma_c = G$, follows from the typical material mix design strategies observed in practice. This spans, for infinite brick extrusion (Cf. Fig. 1, left) from high sand content mortars (high yield stress and stiffness, low critical strain), to compositions with a large amount of viscosity modifiers (high yield stress and low stiffness, high critical strain). Some other technologies in the field of free flow deposition (Cf. Fig. 1, right) rely on low yield stress materials containing an accelerating compound allowing for a fast yield stress increase after deposition [39].

The plastic viscosity $\eta_p$ is typically governed by the water-cement ratio and sand dosage. We consider here that plastic viscosity for printable materials covers a range that does not differ much from standard cement-based materials (from fine mortars to ultra-high performance concretes).
The adopted range of values of all studied parameters was selected as the middle range of what we estimated to be the typical values observed in practice, and is conveniently summarized in Table 1. In total, 55 combinations were selected and studied numerically in 2D.

Additionally, three numerical studies were performed to assess the suitability of the numerical model to capture the three extreme regimes (filament tearing, filament instability, and nominal extrusion) in 3D. For these studies, the model definition was similar to the 2D situation, with the exception of the mesh and boundary conditions in Y direction. Here, again because of symmetry, half of the extrusion process was modelled, whereby the Y min surface was subject to symmetry boundary conditions and the Y max surface to outflow conditions. Similar to the X-Z plane, the mesh in Y direction was defined as an orthogonal graded grid, with a high density below the nozzle and reduction towards the outer surface.

4. Numerical results (2D)

The results of the numerical studies indicate a clear influence of the process parameters, geometrical features and material properties on the geometry control of a 3D printed filament.

Generally, when $V^* = 1$ and, thus, when the process is performed at nominal speed, the filament is extruded properly and neither tearing nor buckling occurs. An illustrative example of a well-controlled extrusion process is shown in Fig. 7. The thickness of the filament $\delta$ is constant throughout the extrusion, and equal to the width of the nozzle $D$. Moreover, no variations in stress distribution are present in the extruded filament, as indicated by the constant stress profile depicted in Fig. 7. These observations appeared to be independent of the studied range of material properties and nozzle features, given that a nominal speed is maintained.

However, when the printing process is performed below nominal speed, the filament geometry may no longer be controlled. When $V^* \ll 1$, the filament was observed to display periodic instabilities in both geometry and stress distribution throughout the extrusion, illustrated in Fig. 8. We suggest here from the shape of the filament and the stress distribution that they find their origin in a local buckling phenomenon. Indeed, as shown in Fig. 8, right below the nozzle, the filament deforms laterally, despite the expected material flow in vertical direction. The vertical stress distribution below the nozzle confirms this flexural

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Typical value range in practice</th>
<th>Value range in this paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle velocity</td>
<td>$V_N$</td>
<td>m/s</td>
<td>0.01–0.5</td>
<td>(0.06–0.4)</td>
</tr>
<tr>
<td>Material flow velocity</td>
<td>$V_F$</td>
<td>m/s</td>
<td>0.01–0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Dimensionless velocity ($V_N/V_F$)</td>
<td>$V^*$</td>
<td></td>
<td>In theory, around 1</td>
<td>(0.60–4)</td>
</tr>
<tr>
<td>Nozzle height</td>
<td>$H$</td>
<td>m</td>
<td>0.005–0.1</td>
<td>(0.01–0.03)</td>
</tr>
<tr>
<td>Nozzle width (around filament thickness)</td>
<td>$D$</td>
<td>m</td>
<td>0.01–0.05</td>
<td>(0.005–0.01)</td>
</tr>
<tr>
<td>Dimensionless thickness ($H/D$)</td>
<td>$H^*$</td>
<td></td>
<td>0.5–2</td>
<td>(1–3)</td>
</tr>
<tr>
<td>Yield stress</td>
<td>$\tau_0$</td>
<td>Pa</td>
<td>50–10,000</td>
<td>(100–5000)</td>
</tr>
<tr>
<td>Critical strain</td>
<td>$\gamma_c$</td>
<td>%</td>
<td>1–10</td>
<td>(2.5–5)</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>$G$</td>
<td>kPa</td>
<td>1–500</td>
<td>(2–200)</td>
</tr>
<tr>
<td>Plastic viscosity</td>
<td>$\eta_p$</td>
<td>kg/m/s</td>
<td>0.5–100</td>
<td>(1–25)</td>
</tr>
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</table>
behaviour, as the nature of the stress switches from compression to tension across the filament thickness. The direction, in which the filament ‘buckles’, was observed to continuously alternate horizontally following a periodic pattern, below the nozzle. The corresponding sign of stresses changed accordingly throughout the extrusion. This alternating pattern trace is visible in the periodic thickness variations observed at the top surface of the deposited filament.

An increment in nozzle height $H$ has a profound effect on the filament buckling feature (both geometrically and related to stress in-homogeneity), likewise observed for a reduction of nozzle width $D$. Similarly, increasing the material consistency (i.e. larger stiffness, yield stress or viscosity), enhances the occurrence of filament buckling. For the lower range of nozzle heights studied, where $H$ is equal to or slightly larger than $D$, the buckling features did not occur. In those cases, however, the resulting deposited filament thickness $\delta$ increases inversely proportional to dimensionless velocity $V^*$, compared to the nozzle width $D$.

Finally, when the printing process is performed above nominal speed, such that $V^* \gg 1$, the filament is susceptible to tearing as illustrated in Fig. 9. As the filament touches the bottom surface, the gradient between interface and material velocities results in a local stress increment as depicted in the top of Fig. 9, which, when exceeding the material yield stress, leads to extremely localized strain rates and ultimately to filament tearing, as illustrated in the bottom of Fig. 9.

An increment in material stiffness, or reduction in the materials’ critical strain, has a profound effect on the occurrence of tearing. No obvious influence of the vertical position of the nozzle on the occurrence of tearing was observed. In all cases observed, the filament thickness $\delta$ decreases proportionally to $V^*$, compared to the nozzle width $D$, until the conditions for tearing are fulfilled. This is illustrated in Fig. 10, where the dimensionless velocity is plotted versus the dimensionless filament thickness $\delta/D$ for the studied range of material parameters where $V^* \geq 1$, and the dashed line indicates when tearing occurred in our numerical studies. From these results, it is clearly observed that conservation of mass, cf. $1/V^* = \delta/D$, holds for both simulations where no tearing occurred, as well as for the simulations where tearing did occur, for the filament geometry in between cracks. Note that for $V^* < 1$ the filament geometry and thus resulting thickness $\delta$ is no longer constant throughout the extrusion due to the buckling effects.

5. Analysis

a. Preliminary observations and notations

If we consider the extrusion-based 3D printing process as a 2D case, depicted in Fig. 11, conservation of mass, for a non-compressional fluid, writes:

$$\frac{V_F}{H} = \frac{V_N}{L}$$

(1)

where $L$ is the length of the deposition zone, i.e. the horizontal distance between the vertical initiation of flow (point A in Fig. 11) and the position where the filament touches the print bed (point B in Fig. 11).

No matter the curvature of the filament in this deposition zone, we model it as shown in Fig. 12. The dimensionless velocity $V^*$ can range from a value higher than 1 (cf. Fig. 12 left where the nozzle is moving at
a higher velocity than the one of the fluid in the nozzle) to a value lower than 1 (cf. Fig. 12 right where the fluid in the nozzle is flowing at a higher velocity than the one at which the nozzle moves).

The average magnitude of the strain rate in the free part of the filament induced by the differential velocity can be written as follows [11]:

$$\dot{\varepsilon} = \frac{V_F}{H} \ln V^*$$

Please note that we ignore here any strain rate induced by gravity effects or by the curvature induced by the deposition process. Only the strain induced by the differential velocity is considered in Eq. (2). This strain rate is considered to apply to the material for a time $t$ equal to:

$$t \cong \frac{L}{V_N} \text{ or } \frac{H}{V_F}$$

b. Definition of a tearing factor

To define whether tearing occurs, we integrate the strain rate from Eq. (2) over a time $t = H/V_F$ (cf. Eq. (3)) and we obtain a strain value $\varepsilon = \ln V^*$.

In the case when $V^* > 1$, the tearing factor $N_T$ is derived by dividing the above strain by the critical strain of the material $N_T = \varepsilon/\varepsilon_c$, which can then be written as a function of material rheological parameters as follows:

$$N_T = \frac{\ln V^* G}{\tau_0}$$

We expect that filament tearing will not occur when the above number is far lower than 1. This threshold is confirmed by our simulation results as shown in Fig. 13. The transition value between the no tearing and tearing regimes appears to be around 5 for the above tearing factor.

c. Definition of a buckling factor

It must be noted that all relations below only apply if $V^* < 1$ and the stress induced by the differential velocity $G\varepsilon = G \ln V^*$ is higher than yield stress. To derive the buckling factor, we start from the average strain rate $\dot{\varepsilon}$ given by Eq. (2). The resulting stress $\sigma$ (compression) is then

Fig. 9. Horizontal stress $\sigma_{xx}$ distribution of a 3D printing process performed at non-nominal speed, where $V_N > V_F$, illustrating filament tearing. The top figure shows a stress concentration just before tearing, whereas the bottom figure illustrates filament tearing.

Fig. 10. Dimensionless velocity $V^*$ versus dimensionless filament thickness $\delta/D$ (between cracks when tearing occurs), for the numerical studies with $V^* > 1$. The vertical line indicates the occurrence of tearing in our numerical studies. The dashed curve represents conservation of mass, where $1/V^* = \delta/D$.

Fig. 11. Schematic and simplified representation of the flow below the nozzle.
proportional to:
\[ \sigma = \eta \dot{\varepsilon} \] (5)
which, for our 2D case, leads to an acting force per meter equal to:
\[ F = \sigma D = \eta \dot{\varepsilon} \dot{\varepsilon} D \] (6)

The critical buckling load per meter \( F_c \), following Euler’s criterium, is given by \( F_c = \frac{\pi^2 \nu}{12} \frac{E}{H} \). We can then define a buckling factor \( N_B \) by dividing the force from Eq. (6) by the critical buckling load, \( N_B = \frac{F}{F_c} \), as follows:
\[ N_B = \frac{12 \eta \dot{\varepsilon} \dot{\varepsilon} H^2}{\pi^2 E D^2} \] (7)

which, by substituting the apparent viscosity \( \eta(\dot{\varepsilon}) \) by its Bingham expression as function of strain rate turns into:
\[ N_B = \frac{12 H^2}{\pi^2 E D^2} \left( \tau_0 + \eta \dot{\varepsilon} \right) \] (8)

Finally, we can derive the buckling factor \( N_B \) by substituting Eq. (2) into Eq. (8), as follows:
\[ N_B = \frac{12 H^2}{\pi^2 E D^2} \left( \tau_0 + \eta \frac{V}{H} \dot{\varepsilon} \right) \] (9)

We expect that filament buckling will not occur when the above number is far lower than 1. This threshold is confirmed by our simulation results as shown in Fig. 14. The transition value between the no buckling and buckling regimes seems to be around 0.05 for the above buckling factor. Note that this transition value is chosen conservatively as the lower bound of the two dashed vertical lines in Fig. 14. For the numerical results in the transition regime (i.e. where \( N_B \) is between 0.05 and 0.1) that have been marked ‘no buckling’, the duration of the simulations may have been insufficiently long to reveal any instabilities with relatively long wavelengths.

From the simulations it was found that buckling typically occurs when \( H \) is large (as discussed in Section 4), with a relatively high yield stress. This means that, for values observed in practice (cf. Table 1) the contribution of second term between parentheses in Eq. (9) is negligible. Thus, for the regime of infinite brick extrusion (i.e. high yield stress materials), the buckling factor may be simplified, as follows:
\[ N_B = \frac{12 H^2 \tau_0}{\pi^2 E D^2} \] (10)

In this case both the tearing factor \( N_T \) and buckling factor \( N_B \) can be written as a function of critical strain \( \varepsilon_c \). Here, similar to the numerical model, we assume that the material behaviour is fully symmetrical, i.e. equal in compression and tension. Considering that \( 12/\pi^2 \) equals approximately 1, and using the dimensionless notation \( H^* \) for \( H/D \), we
obtain the following, simplified criteria:

\[ N_T = \frac{\ln V^*}{\varepsilon_c} < 5 \]  \hfill (11)

\[ N_B = H^2 \varepsilon_c < 0.1 \]  \hfill (12)

Finally, we provide in Fig. 15 a graphical map of the studied regimes by plotting the buckling factor versus the tearing factor. Here, the dashed lines indicate the transition between regimes as observed in the numerical simulations. Note that the situation where both factors are negative cannot occur, nor can the situation where both factors are above their respective transition value. A filament printed in a straight line cannot therefore be susceptible to both tearing and buckling at the same time. These regimes are hatched in grey in Fig. 15, and denoted N/A.

Nominal extrusion is defined as the point where both tearing factor and buckling factor are equal to zero, illustrated by the black dot in Fig. 15. At nominal extrusion, the size of the filament is equal to the size of the nozzle and a well-controlled filament geometry is obtained. There exists however a quasi-nominal regime, in which these two velocities are not equal, but this difference does not induce any major variations in the resulting overall geometry. Of course, the filament cross section could slightly increase or decrease (see Fig. 10), but no filament tearing, nor filament buckling, is expected to occur.

6. From 2D to 3D

The three additional CFD simulations that were performed in 3D are plotted as triangles in the graphs of Figs. 13 and 14. Note that the 3D simulation of nominal extrusion (\(V^* = 1\)) results in a tearing and buckling factor which is not visible in these graphs. The results of these simulations indicate that the CFD model indeed provides the potential to study the various regimes in 3D. The occurrence of a controlled extrusion, filament tearing, as well as filament buckling, was clearly observed in the numerical simulations and is illustrated in Fig. 16.

It can be noted that all Equations from (1) to (12) do hold in 3D, as introducing a typical width (or an additional Y length scale) in these equations does not change the tearing and buckling factors, as long as the preferred buckling direction stays within the X-Z plane.

However, the price of this detailed insight is paid in computational time, which is significantly longer for 3D analyses (around a time factor of 10). As the behaviour of the filaments is typically (approximately) constant over the filament width, a 2D analysis may be sufficient to assess the filament geometry control and provide rapid insight in the occurrence of these features.

7. Towards practical applications: sensitivity analysis and printing curves

In this section, we discuss the impact of variations occurring in the printing process observed in practice on the susceptibility of the filament to buckling and tearing based on the buckling and tearing factors defined in the previous sections.

We consider here some constant material properties. It appears then from Eq. (4) that tearing robustness is mostly depending on the consistency of the feeding process, and its consequence on the ratio between flow velocity and nozzle velocity. As the variation between the two velocities increases, the risk of tearing grows correspondingly. The occurrence of tearing is expected to be more obvious for brittle materials. This suggests that, if the robot feeding system is an uncertainty in the process, a ductile material should be preferred.

As an example, we consider here two materials with a critical strain of 1% and 5% respectively. In Fig. 17, we show that, for the 1% critical strain material, minor increments of the dimensionless velocity \(V^*\) can quickly lead to exceeding the transition value that was found to indicate the tearing regime, represented by the dashed horizontal line. If we increase \(V^*\) from a nominal speed by a mere 10%, the filament will already be in the tearing regime. In contrast, the 5% critical strain material is more robust and can withstand much larger variations before tearing occurs. Here, dimensionless velocity should be increased by approximately 50% before tearing can be critical. While these values are specific for this particular case, they can easily be assessed for any range of process parameters and material properties, using the relations given in the previous sections.

The occurrence of filament buckling is far more complex, as Eq. (9) involves many printing and material parameters. If we once more consider constant material properties, a low feeding robustness will influence the risk of buckling, much like the occurrence of tearing discussed above. However, the nozzle height \(H\), raised to the second power in Eq. (11), appears to be another critical factor to control. It is known that the distance between the nozzle and the last layer can progressively increase during a 3D printing process, due to the accumulated deformations of previous layers under the effect of their own weight [14,42]. As such, we expect the risk of filament buckling to be higher towards the end of a printing process. The nozzle width \(D\) plays an important role as well, but is expected to be constant during printing for a given printing equipment.

As an example, we consider here two materials with a critical strain of 2.5%. The first, with a yield stress of 2500 Pa and a plastic viscosity of 25 Pa/s, and the second, with a yield stress of 500 Pa and a plastic

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Fig. 16. Results of 3D CFD analyses, indicating nominal extrusion, and filament tearing, filament buckling, respectively.
The viscosity of 100 Pa/s. In Fig. 18, we show for a constant nozzle width of 0.01 m, and two velocity ratios of 0.5 and 0.75, the influence of an increasing nozzle height $H$ on the buckling factor. Here, we gradually increase the height starting from a typical value equal to the nozzle width $D$. For this nozzle height, there is no risk of filament buckling for the cases considered. When we increase this value by the value of a single filament thickness, such that $H = 2D$, the buckling factor increases significantly and approaches or even exceeds the transition value of buckling, indicated by the dashed horizontal line. For high yield stress materials, this appears to be approximately independent of the dimensionless velocity $V^*$. This is in agreement with Eq. (10) established for high yield stress materials, where the buckling number becomes independent of $V^*$. For low yield stress materials, with a relatively high plastic viscosity, the influence of $V^*$ on the buckling factor is more pronounced, as indicated by the divergence of the buckling factor for increasing nozzle height, for the two velocity ratios considered. As such, the influence of the feeding robustness is dependent on the material mix design strategy, and the corresponding rheological parameters. In any case, an increasing nozzle height $H$ has a significant impact on the buckling factor and risk of filament buckling. Correspondingly, first solutions have been presented in practice where a height sensor is attached to the nozzle which corrects the vertical position of the nozzle in real time during 3D printing [42].

As an example, we consider once more a material with a critical strain of 5%, a yield stress of 500 Pa and a plastic viscosity of 100 Pa/s, printed by a nozzle width $D = 0.01$ m, at a nozzle height $H = 1.0D$, at a nominal speed of $V^* = 1.0$. If we then assume that the width of the deposited layer is equal to 0.05 m, we show in Fig. 19 the effect of toolpath radius on the tearing factor (on the filament external perimeter) and buckling factor (on the filament internal perimeter).

As the radius of the toolpath decreases, the local velocity at the filament external perimeter increases. Correspondingly, the tearing factor grows, and, in this particular case, exceeds the transition value once the radius equals 1.5 times the layer width. When a radius much smaller than the filament width is printed, the tearing factor increases drastically, caused by the steep increment of velocity at the external perimeter of the curvature.

Similarly, for a decreasing radius, the local velocity at the filament internal perimeter decreases, which leads to an increase in the buckling factor. For the case considered here, the transition value is exceeded when the curvature radius is equal to the layer width. In line with the observations for tearing, the buckling factor increases drastically for a curvature radius below the filament width. It should be noted here that the influence of variations in velocity on the buckling factor are most pronounced for materials with low yield stress and high plastic viscosity, in correspondence with the discussion on nozzle height above. Nevertheless, even when filament buckling does not occur, at very small radii, the velocity at the internal perimeter approaches zero and thus can lead to local accumulation of material, which is detrimental for geometric conformity, and can cause imperfections induced failure at the printed object scale.

In any case, to minimize the risk of filament tearing and filament buckling in curved toolpaths, it can be recommended to maintain a minimum curvature radius, the value of which can be assessed by the relations given in the previous section.

Fig. 18. The influence of variations in nozzle height on the buckling factor, illustrated for two materials with a relatively high and low yield stress, respectively, for two velocity ratios. The horizontal dashed line indicates the transition value for filament buckling as observed in the numerical simulations.

Fig. 19. The influence of the radius of printed curvature on the tearing factor (at the filament external perimeter) and the buckling factor (at the filament internal perimeter). The horizontal dashed line indicates the respective transition values as observed in the numerical simulations.
8. Conclusions

Control of filament geometry in extrusion based additive manufacturing is essential to guarantee the desired quality of the printing process and the final product. Depending on the selected process parameters, material strategy and geometrical features, the printing process can however be susceptible to filament tearing and filament buckling. To allow for an a priori prediction of the conditions under which these features do not appear, or to define the conditions required to create them on purpose, 2D and 3D CFD simulations have been used to map the influence of all these parameters in the infinite brick regime of 3D concrete printing processes. The results of these simulations indicate that numerical analyses are indeed a suitable strategy to predict and control the filament geometry under various conditions.

To indicate the transition of regimes, from a well-controlled nominal extrusion, to both filament tearing and filament buckling, analytical derivations of a tearing factor and buckling factor were presented. The potential use of these analytical tools was then illustrated, by applying and control the filament geometry under various conditions.

Finally, the risk of both filament tearing and buckling of a single filament when printing sharp turns was discussed. It was shown that, when the curvature radius reduces with respect to the filament width, both the tearing factor (at the filament external perimeter) and the buckling factor (at the filament internal perimeter) can increase drastically due to the local change in velocity ratios. As such, even when all parameters are selected right for geometry control of straight filaments, more complex tool paths require additional assessment through the presented analytical and numerical methods.

CRediT authorship contribution statement

R.J.M. Wolfs: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. T.A.M. Salet: Writing – review & editing.
N. Roussel: Conceptualization, Methodology, Formal analysis, Writing – review & editing.

Declaration of competing interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cemconres.2021.106615.

References


