Figure 1: One major challenge to 3D printing with fresh concrete in a layer-based extrusion process is to overcome buckling and collapsing of the currently printed structure as there is no formwork to support it.

BUCKLING SIMULATION

3D printing in fresh concrete

3D concrete printing technology has opened up a new era for the construction industry as a new approach to manufacture concrete structures, eliminating the need to customise one-way formwork for non-standard geometries. One major challenge to 3D printing with fresh concrete in a layer-based extrusion process is to overcome buckling and collapsing of the currently printed structure as there is no formwork to support it. The present article will focus on how to avoid buckling in 3D printing through Finite Element Analysis using Karamba3D.

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There are two modes of potential failure in the 3D concrete printing process: elastic and plastic buckling. Elastic buckling means that the structure is bending and failing due to instability; plastic buckling means exceeding the material's strength limit, which in turn causes bending and failing of the structure. Physical experiments by the author show that plastic buckling is less likely to occur during the 3D concrete printing process, elastic buckling usually dominates the printing failure.

Figures 2-4 give an idea of the kind of buckling the article is dealing with. The goal here was to print a straight wall, but it tumbled down as the fresh concrete was not stiff enough to support the self-weight of the concrete deposited on top of each layer.

There are two stages shown in the buckling process:

- Onset of buckling – subtle settlement occurring as buckling.
- Collapsing – structure failing.

Figures 2-4: Buckling process in 3D concrete printing

The task therefore is to numerically simulate the onset of buckling and to avoid the subsequent collapsing stage. This became an interesting topic because traditionally fresh concrete can be checked in a slump test, which allows to measure the workability of freshly made concrete. In contrast there are no such official tests available to predict the 3D print performance of a concrete mixture. However, alternatively, if one considers the fresh concrete as soil, one can make use of existing geotechnical testing methods, that will not be discussed here further.

The 3D concrete printing research program at Eindhoven University of Technology (TU/e), has published pioneering research results for studying the structural behaviour of 3D printed concrete elements. Two papers relevant to the earlier described buckling simulation tools are published by TU/e:

- Early age mechanical behaviour of 3D printed concrete: numerical modeling and experimental testing.
- Mechanical performance of wall structures in 3D printing processes: theory, design tools and experiments.

Simulation inputs

To perform and verify the buckling simulation with the software of the author of the present article, he used the following data from the papers from TU/e.

1. Material: Weber Beamix 145-1
2. Printing speed: 5,000 mm/min
3. Print width: 5 cm
4. Geometry: cylinder in radius 25 cm
5. Layer height: 1 cm
6. The following two graphs (Fig. 5-6) indicating early initial strength of fresh concrete and strength development.

Initial strength of fresh concrete and strength development of fresh concrete are two important factors to determine the structural behaviour during the 3D printing process. They both have a direct impact on the setting of time-dependent material properties. This means that the strength and stiffness of fresh concrete are increasing during the printing process.

Based on the two graphs mentioned before (Fig. 5-6), the following early age properties of the fresh concrete can be derived from it:

- Stiffness Module [MPa] = 0.0781 + 0.0012 t
- Compressive Strength[kPa] = 5.984 + 0.147 t

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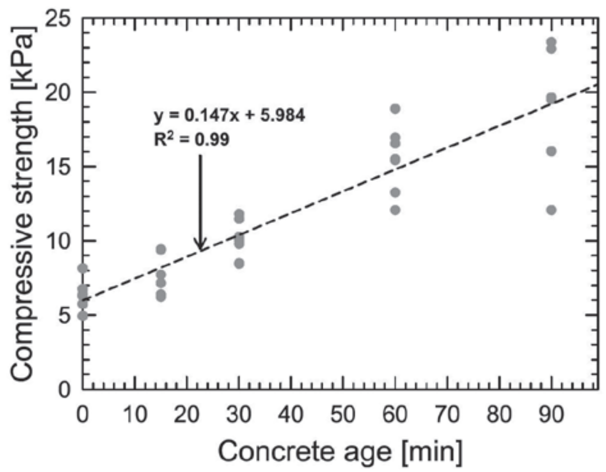
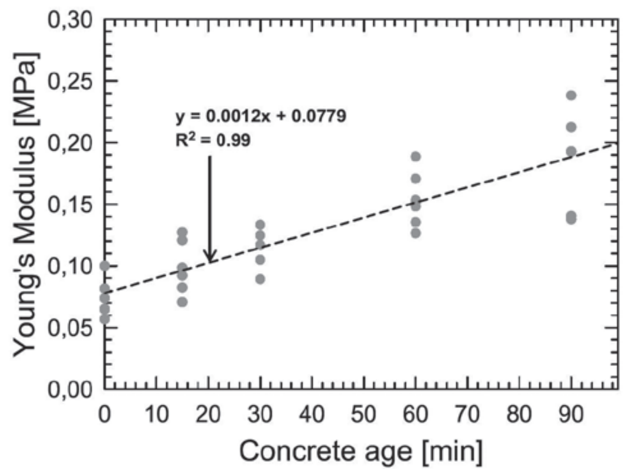




Figures 5 and 6: Early initial strength of fresh concrete and strength development (Source: Eindhoven University of Technology, TU/e)

Based on the printing path length and the printing speed of each layer, one can calculate the actual age of each layer as follows:

```
concreteAging= [ ]
for min in mins:
    if len (concreteAging) == 0:
      concreteAging.append (min)
    else:
      for i in range(len(concreteAging)):
          concreteAging[i] += min
      concreteAging.append (min)
```

With the age of each layer, one can acquire the actual young's module and compressive strength of each layer:

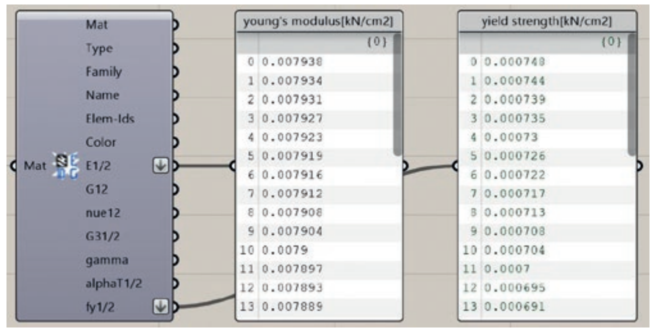
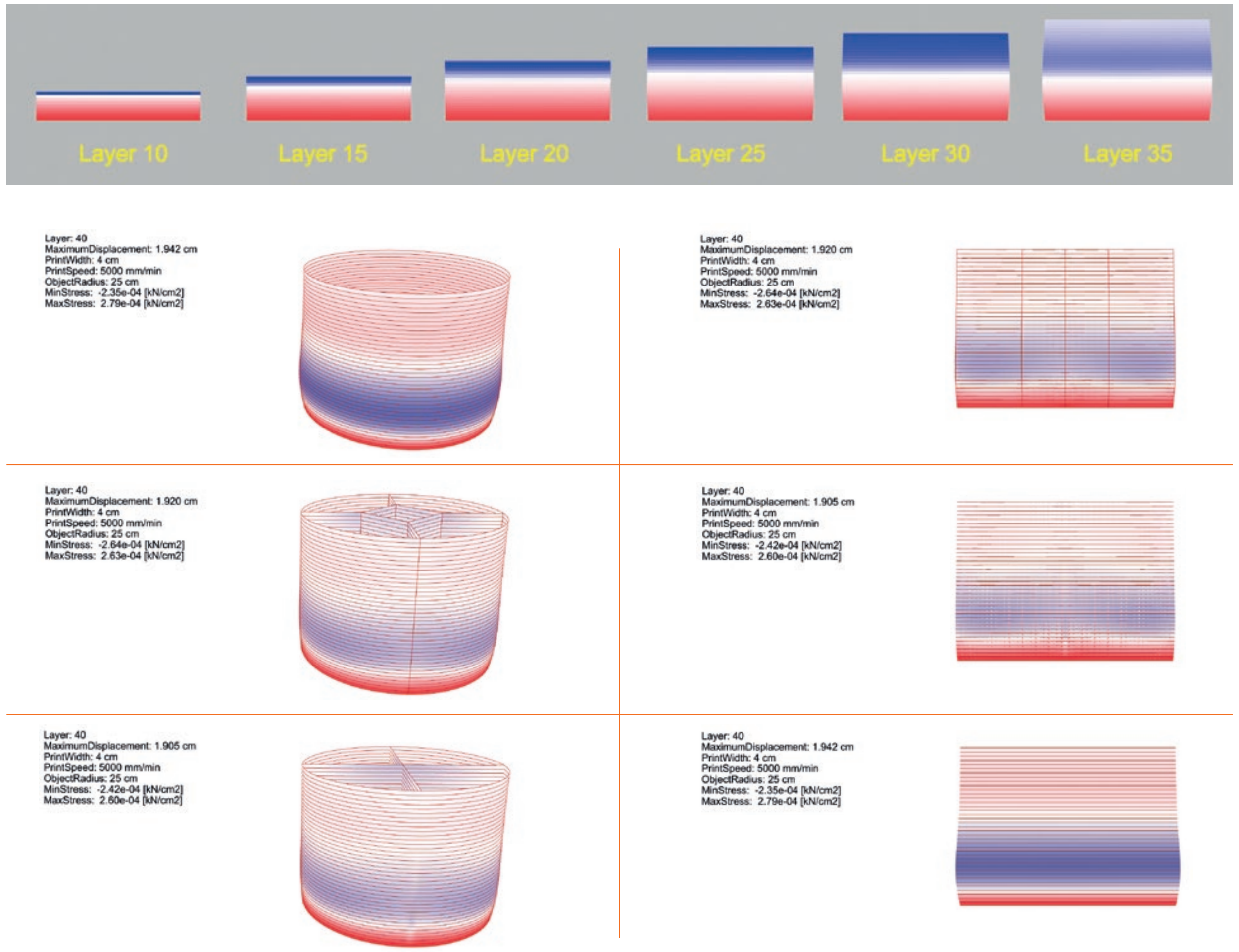


Figure 7: Derivation of the actual young's module and compressive strength

Now that the properties of each layer are known, the next step is to parametrically develop a numerical model to automate the steps. The benefit of parametric modelling is that one does not have to rebuild repetitive tasks for future applications, if the principle remains the same.

Outcomes

When looking at the simulation results (Fig. 8-14), the maximum displacement is the failure indicator since the present argumentation focuses on elastic buckling. For the simulations, a maximum displacement limit of 1cm is assumed, but this limit will be updated and verified in a later stage with physical experiments.



Figures 8-14: Simulation results

There are a few things that must be pointed out when going to use Karamba in such simulations:

- A zero-thickness shell structure was selected as a cross-section element with a constant height applied. Since Karamba does not support volumetric elements, as such, the layer centre line needs to be used to generate the shell structure instead of the 3D layer geometry.
- Spring cross-section was applied at the footing in order to define the stiffness relation over the buckling shapes.
- Karamba's FEA (finite element analysis) calculations are based on the assumptions of small displacements in a ratio of about 10 % compared to cross-section's dimension (in this case: the cross-section of the print layer), as such, complete failure of the structure will not be visualised in the simulation.

One may ask, how the maximum printable height can be improved before elastic buckling occurs? And indeed, there are some factors to work on:

- Print slower: the slower the printer prints, the higher strength and stiffness are developed during printing.
- Widen print layer width: the wider the printer prints, the more stable the structure will be.
- Add internal structure.
- Avoid long straight walls.
- Tweak material properties, e.g. mixing cement accelerator.

Validation

To validate the buckling simulation tool of the author of this article, the Karamba outcomes are compared to the mentioned papers from TU/e. The comparison is made in two parts:

- Digital comparison with another commercially available FEA software Abaqus.
- Physical comparison with a 3D concrete printing experiment.

Figure 15 shows, that in the Karamba model the structure at layer 32 is having a maximum radial displacement of 12 mm, which is three times larger compared to the Abaqus value of 4 mm. If you take one step back comparing at layer 20, it is 6.3 mm in Karamba versus 2 mm in Abaqus, the difference remains roughly three times larger.

The next step is to compare the Karamba model with the physical printing process. At layer 29, Karamba is showing a maximum radial displacement of 10 mm, which is smaller than the physical printing process of on average 15 mm.

These differences show that both Karamba and Abaqus models overestimate the stability of the structure compared to the results of the physical printing process, but Karamba's results are significantly closer to the physical printing process. It was mentioned in the TU/e paper that the reason is likely due to the compaction of homogeneous testing samples made for geotechnical testing methods, which typically does not apply to the actual printing process. As a result, the input of customised material properties for compacted concrete might seem to be stronger than the printed concrete is in reality in terms of strength and stiffness.

Conclusion

To conclude, this buckling simulation can be used as a quick analytical tool, allowing to digitally predict what would happen prior to the physical experiments. This does not only minimise the chance of unnecessary trial and error but also gives a better understanding of improving the 3D concrete printing process.

Concerning the validation process, it seems, that the Karamba models slightly overestimate the stability of the printed structure. The difference is approximately in control of 10 mm, which is considered acceptable for a preliminary analytical tool.

The benefit of using Karamba3D in a Grasshopper environment in such simulations is that computation time is significantly reduced as it takes a matter of seconds to calculate the results. The second benefit is that it provides designers to conduct comprehensive analysis within the design environment, eliminating the need of data transferring from one software to another, which often causes data loss during the transition process. Last but not least, the tool is built in the parametrical process, the script can be reused by simply inputting given geometries without the need to rebuild the numerical model from scratch again and again.

In collaboration with: Witteveen+Bos, Karamba3D and Nanyang Technological University.

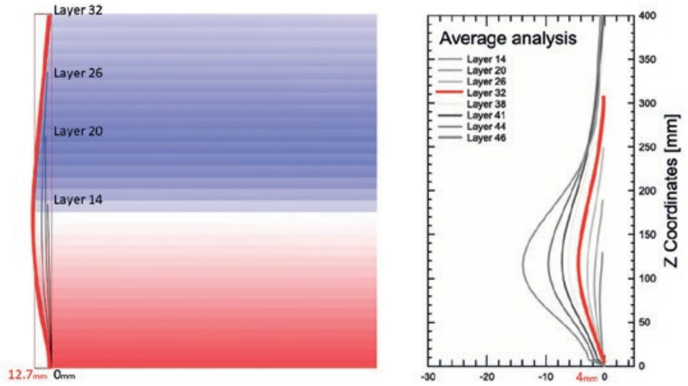


Figure 15: Comparison between Karamba and Abaqus in buckling shape (Right figure source: TU/Eindhoven)

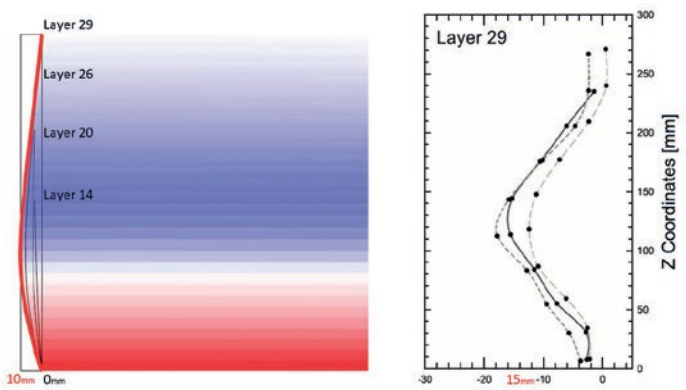


Figure 16: Comparison between Karamba and physical printing process in buckling shape (Right figure source: TU/Eindhoven)