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Structural performance of a three dimensional bio-based parametric structural element, through additive manufacturing

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Abstract

The work presented investigates the application of a 3D printed bio-based material for construction purposes. A new printable bio-based material is being developed for the Direct Ink Writing (DIW) method, whose material properties are then determined through mechanical testing. The focus is on 3D printing wood with the main components cellulose and lignin. With the new printable mixture, a structural element (column) was printed to load in axial compression. The column was numerically optimized to maximize buckling resistance. The optimized design was fabricated by additive manufacturing. Additive manufacturing offers opportunities for the built environment to create innovative structural elements in a fully digitised manufacturing process. Moreover, the combination of numerical optimization, innovative structural design and robotic printing with bio-based materials enables the design and production of structures with a high degree of freedom. This leads to less environmental pollution caused by traditional design and manufacturing processes in the construction industry. The printed column of bio-based material was tested in axial compression after curing, resulting in a maximum compressive strength of 46.82 kN. Although the structural behaviour of the bio-based printed column was promising, further research needs to be conducted to conclude whether the printed material is suitable for large-scale construction purposes.

Keywords: Additive manufacturing, DIW method, bio-based material, mechanical testing, innovative structural design, optimization, axial compression, parametric design

1. Introduction

The world is faced with global warming of the atmosphere, forest fires, heavier rain outside, lack of resources and energy, longer dry periods, pollution of air, water and soil. More and more attention should be paid to being more climate conscious, as the limits are gradually being reached. The construction industry is responsible for 39% of total CO_2 emissions worldwide, contributing significantly to environmental pollution [1]. The pollution involves greenhouse gas emissions, waste generation, energy consumption and material depletion. In the construction industry, there are two types of categories of energy that can be encountered. The first category is operational energy, which is the energy required for the operation of the building (cooling, ventilation, heating, etc.) [2]. The second category consists of embodied energy [2]. This includes the energy needed to construct and maintain the building and the energy needed to produce and transport the materials [3]. Reducing the consumption of these two types of energy in the construction industry also reduces the CO_2 emissions released into the atmosphere as a result of construction activity. In the Netherlands, the government has set a goal (in the climate agreement) for the Dutch economy to be fully circular by 2050. Reducing CO_2 emissions only works if other countries also participate. Hence, the UN Paris Climate Accord was signed by almost all countries in the world [4].

In recent years, many efficient and innovative technologies have been developed to minimize the operational energy of buildings [5]. This research focuses only on embodied energy. Reducing the embodied energy consumption of buildings is still a major challenge. However, bio-based and low-carbon materials have been used to reduce the consumption of embodied energy in buildings, which produce more CO_2 emissions. A bio-based material is a material made from plant or other biomass sources rather than from fossil fuel sources. These materials can be used in a wide range of applications, including the production of plastics, textiles, paper, and fuels. Because bio-based materials can be replaced more quickly and do not rely on limited fossil fuel supplies, bio-based materials are usually considered to be more sustainable than traditional materials. Additionally, the production of bio-based materials can often result in fewer greenhouse gas emissions than the production of traditional materials. Bioplastics, bamboo, hemp, and wood are a few types of bio-based materials [6].

The transition to a low-carbon economy is essential to address the environmental crisis. Therefore, this project will introduce a new bio-based material and print a structural element from this material using additive manufacturing. To print this structural element (design), the printing parameters and mechanical properties must be determined by testing. Additive manufacturing can be used to automate the manufacturing process and to create structures with a large degree of freedom. Through additive manufacturing, higher levels of precision can be achieved which could lead to reduced physical labor, waste production and increased construction speed [7]. Apart from the fact that bio-based materials have been successfully introduced into the construction industry and have been used for numerous structural applications, society's perception of the reliability and robustness of these types of building materials has not yet changed. Experimental testing of bio-based materials is needed to know the mechanical properties and ensure structural safety.

The goal of this project is to design a 3D parametric structural element consisting of bio-based material. The 3D structural element will be realized by additive manufacturing. This project is part of the Innovative Structural Engineering and Design (ISD) field and focuses on a new printable bio-based material and integrating architectural and structural design.

2. Literature study

2.1 Types of additive manufacturing

Additive manufacturing methods using bio-based composite as feedstock are classified into five different categories [8], see figure 1. The categories are: material extrusion, powder bed fusion, photopolymerization, binder jetting and sheet lamination. Applications, material composition and

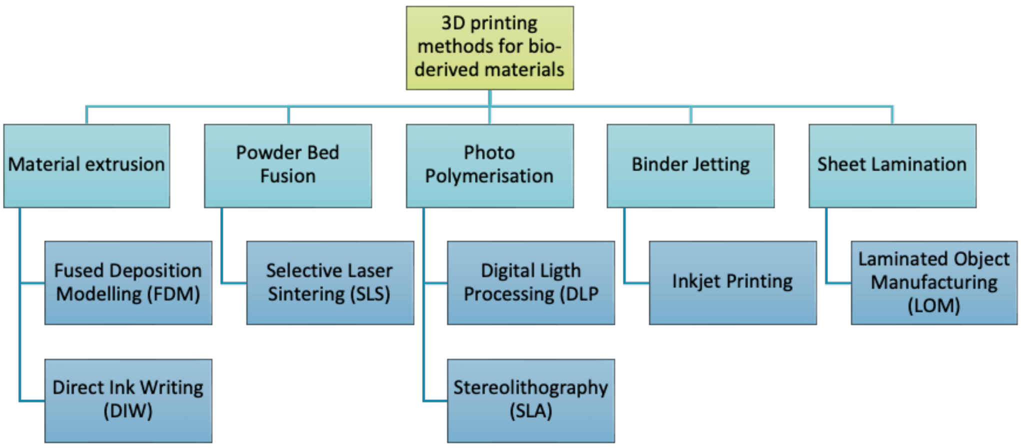


Figure 1. Methods and types of additive manufacturing [8]

properties should be considered to determine the method to be employed on the fabrication of each product.

2.1.1 Material extrusion

For this research, the first category of additive manufacturing is chosen, namely material extrusion – Direct Ink Writing (DIW). This is chosen because the research on which this project is based was also related to extrusion-based 3D printing. This is also chosen because the TU Eindhoven has a lot of knowledge regarding extrusion-based 3D printing with concrete and clay.

Extrusion-based 3D printing methods, such as (DIW), is one of the most widespread method. This method use the principle that a viscous liquid is extruded through a nozzle that can travel in X, Y and Z directions. Based on the CAD model of the product, the nozzle follows a path defined by the 3D printing software. Layer by layer, the final product is built up in the vertical direction (see figure 2) [9]. For optimal printing results, the viscous liquid must quickly turn into a solid or have solid-like behaviour after extrusion.

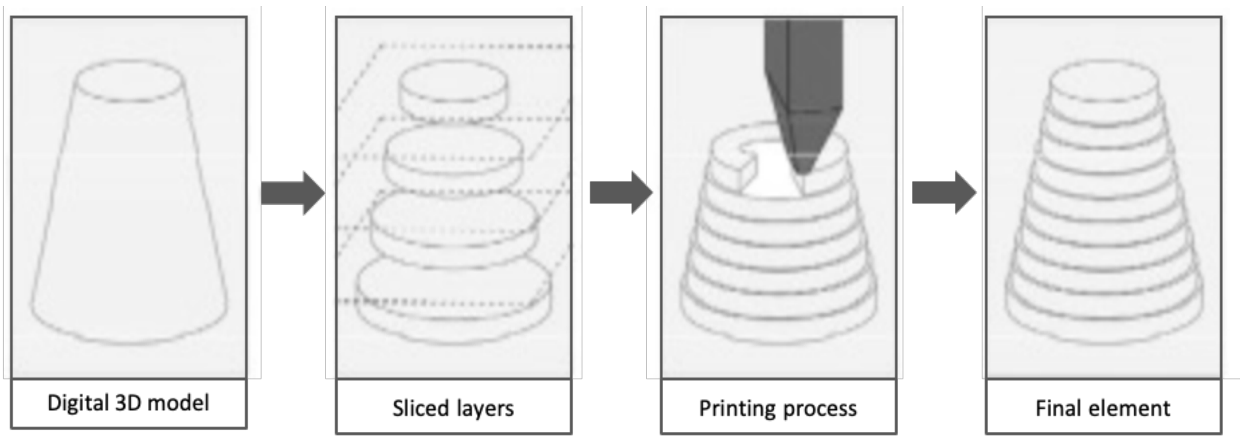


Figure 2. Material extrusion process workflow [9]

2.2 Printable bio-based materials with DIW method

There are several ways to make a printable material. In this case (see figure 3), a gel is prepared from a raw material combined with a binder and with a liquid. These ingredients are mixed until a homogeneous gel is formed. A responsible for structural rigidity is then added. Mixing is done again until a homogeneous composite mix is formed.

Nowadays, three basic requirements for 3D printed elements are widely accepted: 1) excellent extrudability to ensure a continuous paste; 2) sufficient build behavior to resist structural deformation; 3) sufficient strength to compensate for external damage.

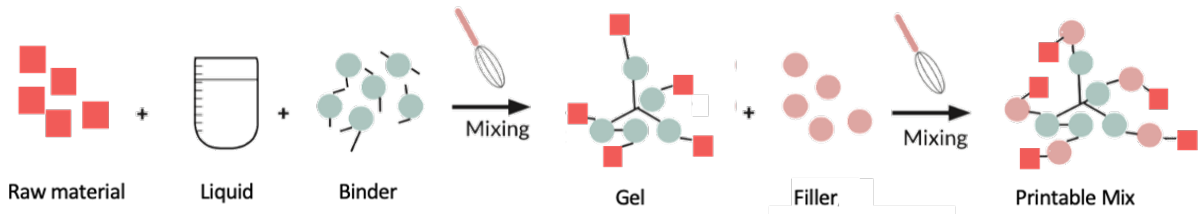


Figure 3. Creating printable mix

2.2.1 Mixtures TU Delft

A number of printable bio-based mixtures have already been developed, such as printing with mycelium, printing with raw earth, printing with wood pulp, printing with residual raw material streams, etc. The two most promising mixtures from the literature were developed by two former students of TU delft. Their research looked at wood printing using cellulose and lignin.

Cellulose and lignin, separately, have been continuously exploited as reinforcing fibers and fillers, respectively [10]. However, as a single combined compound, there are not many references available and the state-of-art thesis research in this area was published by T. Liebrand [11]. A follow-up to this thesis research was conducted by C. Bierach [12] and A. Alberts Coelho [13]. Both students focused on exploring wood as a natural alternative raw material for additive manufacturing and its potential for architectural applications.

The experiments were based on soda lignin and bleached kraft cellulose sheets as raw material, pulped and mixed with water and binders at different ratios to create a printable paste. The recipes were evaluated in terms of homogeneity, bonding, viscosity and water absorption through manual and visual tests, graded and compared, indicating the most promising materials to be further explored. From the 12 recipes initially explored, two were considered adequate and further tested on a cold extrusion process with the robot, simulating a liquid deposition modelling AM process.

The methylcellulose mix (see table 1) had been chosen because this mix is 100% bio-based and compared to the other mixes scored well on the points mentioned above. The woodglue mix (see table 2) had been chosen because this mix had the best mechanical properties and also scored well on the points mentioned above.

Table 1. Methylcellulose mix TU Delft

Material 1 (Raw material)	Material 2 (Liquid)	Material 3 (Binder)	Material 4 (Filler)
• Cellulose (3g) • Lignin (30g)	• Water (65g)	• Methylcellulose (5g)	• -

Table 2. Woodglue mix TU Delft

Material 1 (Raw material)	Material 2 (Liquid)	Material 3 (Binder)	Material 4 (Filler)
• Cellulose (3g) • Lignin (30g)	• Water (20g)	• Woodglue (100g)	• -

3. Material exploration

The aim of the material exploration phase is to improve TU Delft's mixtures.

3.1 Process

The process of the material experiments is shown in figure 4. Quantities are determined by ratios and observations during mixing of the material. The mixtures are assessed with eye-observation in the fresh state for homogeneity, extrudability and adhesion and in the hardened state for brittleness and curing time. The outcome of each recipe is a stable bio-based mixture, with optimal viscosity and binding properties for extrusion by a DIW process.

Figure 4. Material research process

3.2 Improvement mixture methylcellulose

Several iterations were carried out to maximize the amount of lignin and cellulose and minimize the water content to optimize material properties while retaining the amount of binder. Lignin improved viscosity and adhesion, but it also increased friability and turned it into a dry mix. An increased amount of fibre reduced homogeneity and formed lumps. Reducing the water content resulted in a dry mixture and reduced extrudability of the material.
Despite many iterations, we failed to get a good printable mixture. Moreover, the cured material went mouldy after several weeks (this happened also in the mixture of TU Delft). To counteract moulding, a print was cured in the oven. This print did not go mouldy, but during testing it turned out to be much too brittle. Also, no fibres were visible in the print, which probably burned away in the oven.
Due to the low scores and the moulding of the printed material, this is not a very promising mixture and it was decided not to continue with this mixture. All focus was put on the mixture with woodglue.

3.2 Improvement mixture woodglue

3.2.1 Woodglue

Several iterations were performed to maximize the amount of lignin and cellulose and minimize woodglue to optimize material properties with Valida L,3%. On all points, the mixture scores high.

The percentage of woodglue was reduced from 65,4% to 43,3%, making the majority of the mixture composed of bio-based material. Although the mixture is still not completely 100% bio-based, it is concluded that this is a promising mixture. This mixture (see table 3) is considered as the first reference mix to be further developed in this study.

Table 3. Reference mix woodglue

Material 1 (Raw material)	Material 2 (Liquid)	Material 3 (Binder)	Material 4 (Filler)
• Cellulose (5g) • Lignin (40g)	• Valida L,3% (60g)	• Woodglue (80g)	• -

3.2.2 Bio-glue

Several iterations were carried out to optimize the mixture with bio-based glue. On all points, the mixture scores high.
By replacing woodglue with bio-based glue, this mixture is 100% bio-based and fulfils the principle of bio-based printing. This mixture (see table 4) is considered as the second reference mix to be further developed in this study.

Table 4. Reference mix bio-glue

Material 1 (Raw material)	Material 2 (Liquid)	Material 3 (Binder)	Material 4 (Filler)
• Cellulose (4g) • Lignin (40g)	• Valida L,3% (40g)	• Bio-glue (60g)	• -

4. Material properties

The elements of the two tests performed (comprresion and flexural test) and the test direction is shown in figure 5.

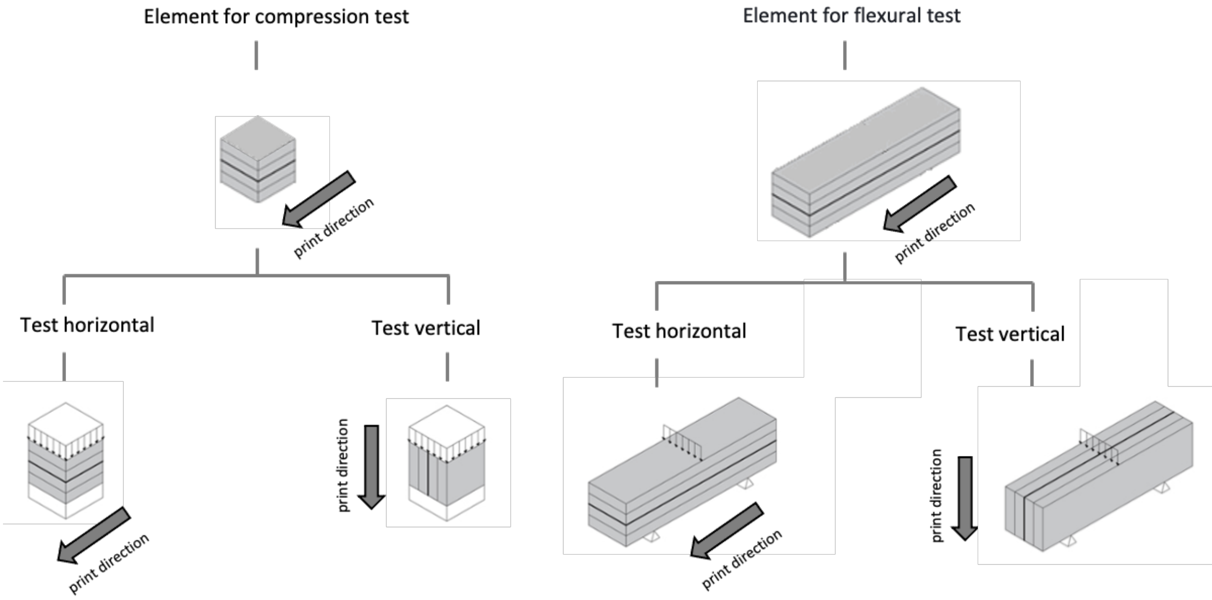


Figure 5. Different tests and print directions

4.1 Woodglue versus bio-glue

4.1.1 Compression test

The compression tests were performed on cubic specimens of ± 40 x ± 40 x ± 40 mm in an available rigid steel frame. Within the range of loads required to collapse the specimens, the rigid frame will not deform. The punch with which force is applied can move a maximum of 15mm. Because of this, it was decided to measure three times compressive stresses at displacements of 4mm (cycle 1.1), 8mm (cycle 2.1) and 12mm (cycle 3.1). The measured deformations in the frame are the deformations of the specimens.

The results of the compression tests of cycle 1.1, 2.1 and 3.1 are shown in a box-and-whisker graph in figure 6, for the horizontal and vertical directions.

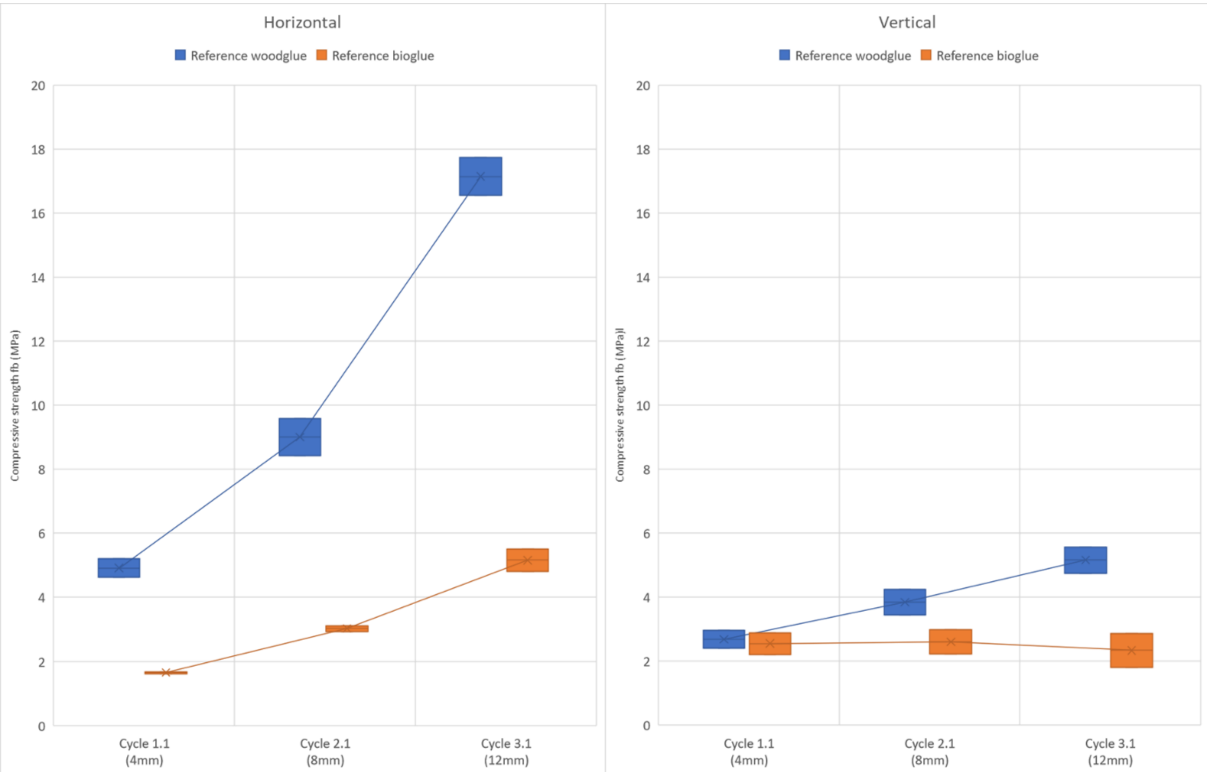


Figure 6. Results of the compressive strength of the mix with woodglue and bio-glue in horizontal and vertical direction

4.1.2 Flexural test

Flexural strength was determined by performing three-point bending tests on prismatic specimens, according to NEN-EN 196-1 [14]. The printed specimens has the dimensions of ± 40 × ± 40 × ± 160 mm.

The results of the flexural strength are shown in a box-and-whisker graph in figure 7, for the horizontal and vertical directions.

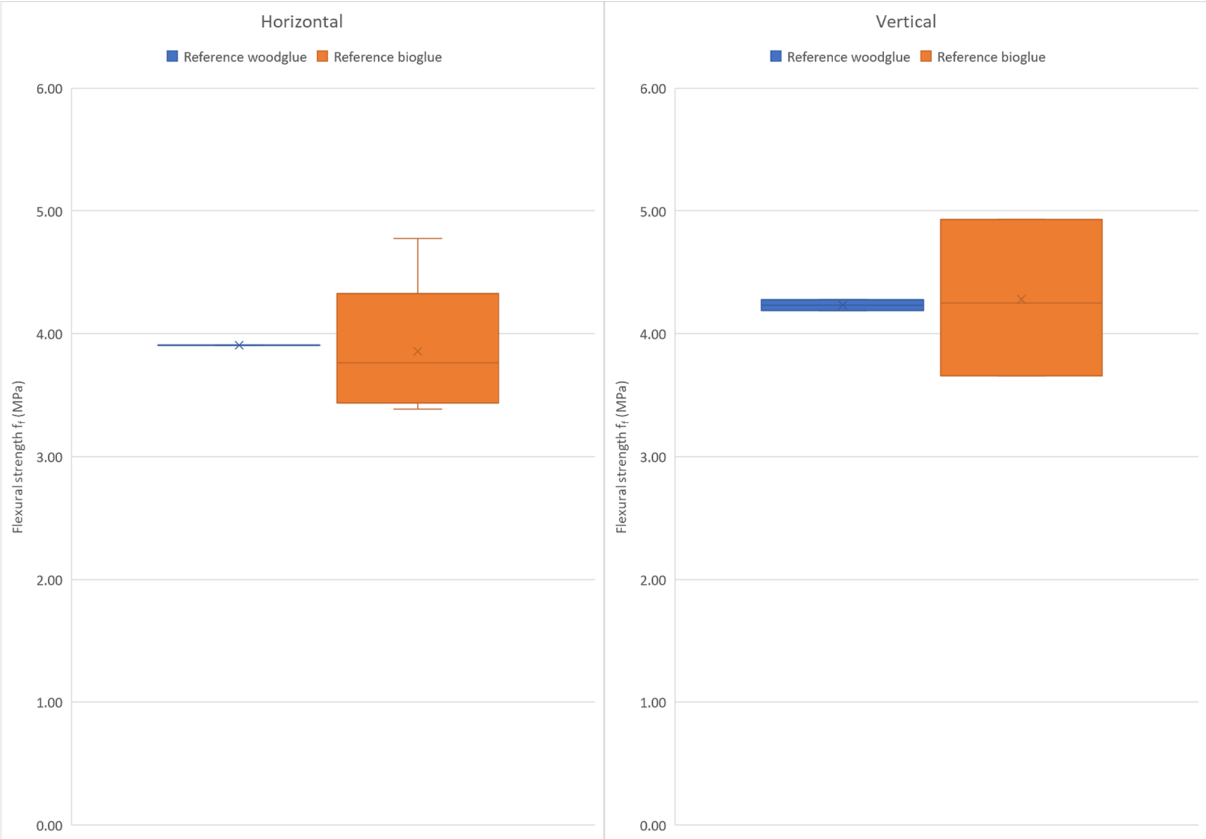


Figure 7. Results of the flexural strength of the mix with woodglue and bio-glue in horizontal and vertical direction

4.1.3 Conclusion woodglue versus bio-glue

Compression test:

- The compressive strength of the mixture with woodglue is higher in both vertical and horizontal directions than the mixture with bio-glue.
- The compressive strength for both mixtures is stronger in the horizontal direction than in the vertical direction.

Flexural test:

- The flexural strength of the mixture with bio-glue shows a greater variation and therefore has values where it is stronger than woodglue, but it also gives values where it is weaker than woodglue.
- The flexural strength is almost the same for both mixtures in both horizontal direction and vertical direction.

It can be concluded on the points mentioned above that the compressive strength of the mixtures with woodglue is higher than the mixture with bio-glue. The flexural strength is almost the same for the two mixtures. Based on the research question, it was chosen to continue with the mixture with bio-glue in the remaining part of the research, since this mixture is more bio-based than the mixture with woodglue.

4.2 Bioglue + filler(s)

By adding a filler, the aim is to see if the material properties of the bio-glue mixture can be improved. It was decided to look at up to 3 new bio-glue mixtures. In the first new bio-glue mixture, the addition of 5-10g bentonite is being considered. Bentonite will make the mixture denser and stronger, also increasing its stiffness. The second new bio-glue mixture involves the addition of 1,5g flax. This natural fiber reinforcement with long threads (length more than 10mm) should increase the material properties in tensile. The last new bio-adhesive mixture consists of a combination of both fillers (5g bentonite + 1,5g flax).

4.2.1 Compression test

The results of the compression tests of cycle 1.1, 2.1 and 3.1 are shown in a box-and-whisker graph in figure 8, for the horizontal and vertical directions.

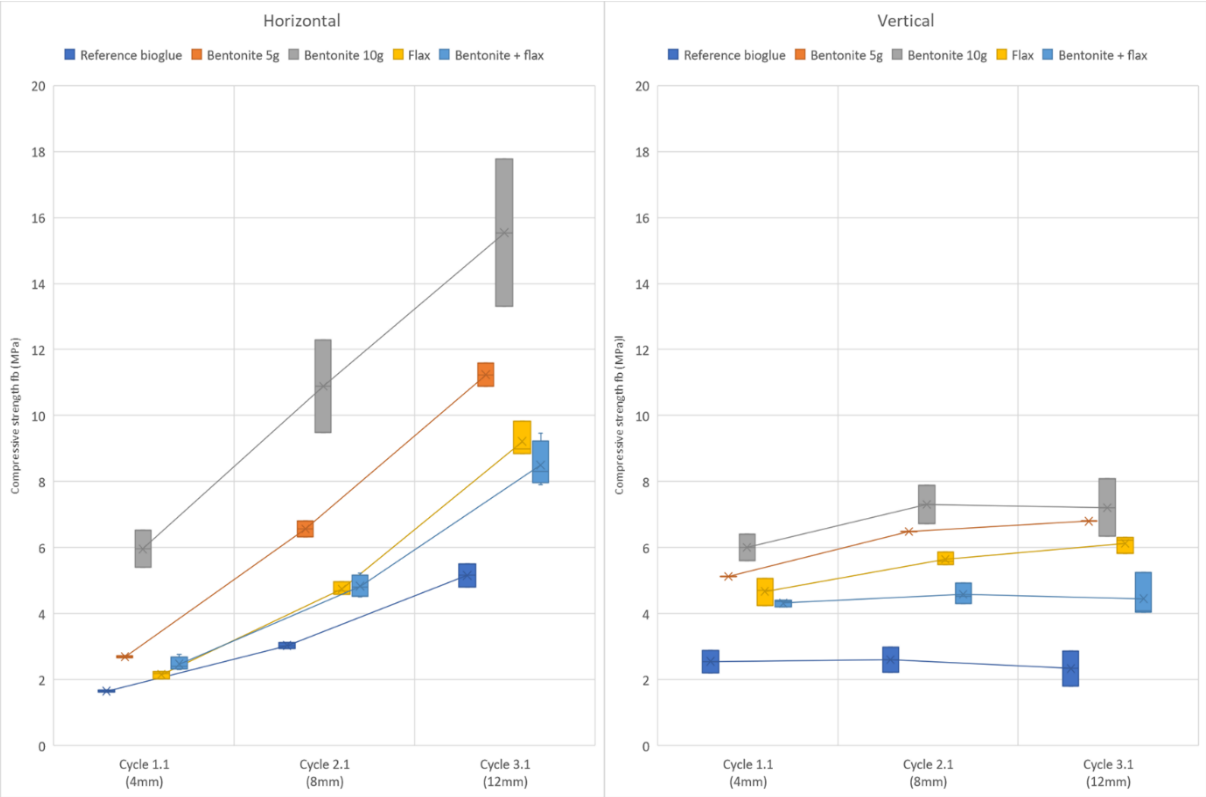


Figure 8. Results of the compressive strength of the mix with bio-glue + fillers in horizontal and vertical direction

4.2.2 flexural test

The results of the flexural strength are shown in a box-and-whisker graph in figure 9, for the horizontal and vertical directions.

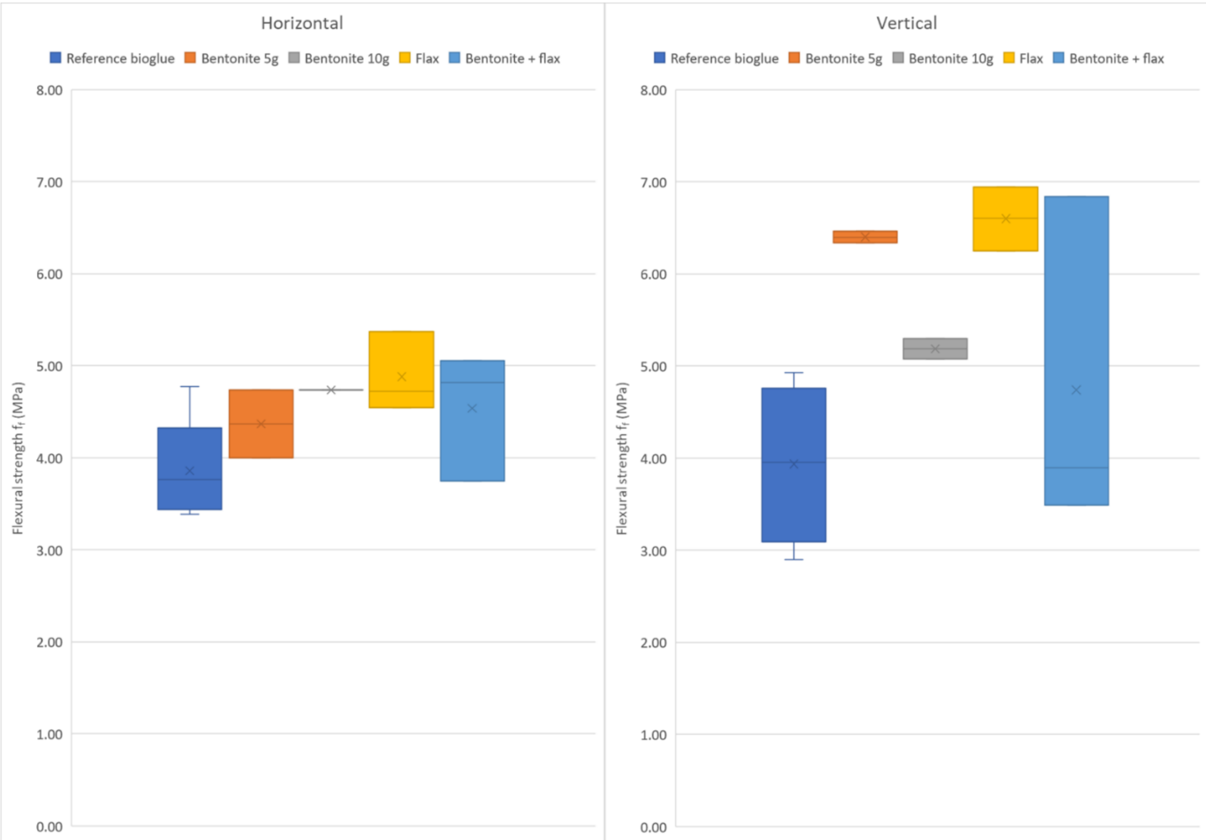


Figure 9. Results of the flexural strength of the mix with bio-glue + fillers in horizontal and vertical direction

4.2.3 Conclusion bio-glue + filler(s)

Compression test:

- The fillers have a strengthening effect on strength, with the bio-glue mixture + 10g bentonite being the strongest. But this mixture did not comply with the printing process because there is no good adhesion and, as a result, the mixture is too dry. Due to this it is concluded that the bio-glue mixture + 5g bentonite is the strongest.
- The horizontal direction is stronger than the vertical direction.

Flexural test:

- The fillers have a strengthening effect on the strength, with the bio-glue mixture + flax being the strongest.
- The vertical direction is stronger than the horizontal direction.

The structural element consists of a column loaded in axial compression, therefore the compression tests are decisive. It can be concluded that mixture used to print the final element consists of the bio-glue mixture + 5g bentonite. It can also be concluded that the layers of the final element should be printed in horizontal direction.

5. Numerical model

5.1 Numerical optimization

The design of the final element consists of a simple supported one meter bio-based column and is robotically fabricated by additive manufacturing. The structural column is optimized for the cross-section based on axial compression (cross-section remains the same over the full height). Cross-sectional optimization is performed using Galapagos, see figure 10. The component is based on a genome input and a fitness input. The genomes (parameters: 1) radius; 2) number of corners; 3) rounding of corners; 4) depth of corners) are numeric values within a certain range (sliders with minimum and maximum values) that Galapagos can try out in different combinations. Each combination, or genome, produces a unique object. The second input requires the fitness, which is the variable to be maximized or minimized. In this study, it is the Karamba3D resulting value for the buckling load factor that is maximized

The Karamba3D structural calculation results are verified in GSA. This is done because the results of Karamba3D will be compared with the test results at a later stage. The results of the structural calculation are shown in table 5. In the first buckling modes are compared in figure 10.

Table 5. Verification of Karamba3D structural analysis in GSA

	Reaction force (kN)	Buckling load factor (-)
Karamba3D (B)	5	6,12
GSA (C)	5	5,59

Table 5 shows that the resulting value for the reaction force exactly match. However, there is a slight difference in the buckling load factor. Figure 10 shows that the first buckling mode for both analyses results in global buckling. The differences between the structural analyses are negligible (< 10%). Therefore, it can be concluded that GSA verifies the structural calculation of Karamba3D.

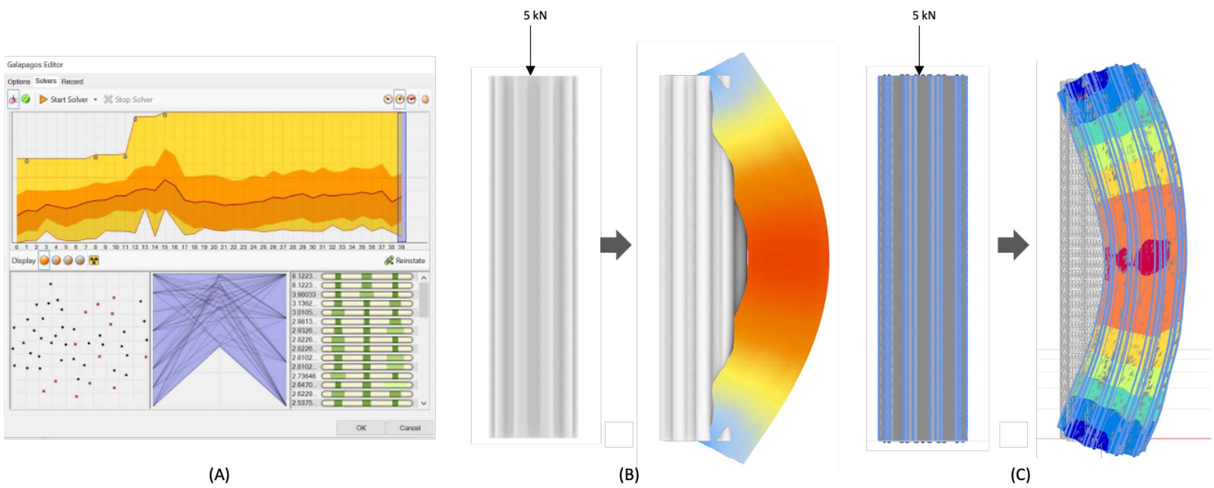
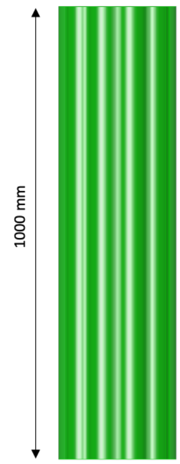
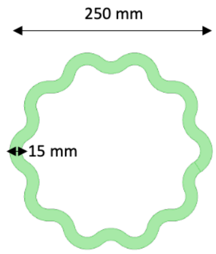
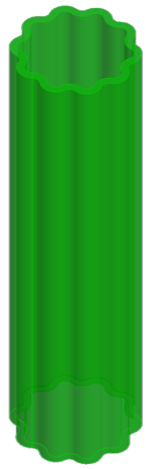


Figure 10. (A) Optimization Galapagos, (B) First buckling mode Karamba3D, (C) First buckling mode GSA

5.2 Final design

The Galapagos optimization results in a single solution where the buckling load factor is as high as possible. The geometry of the final design is shown in table 6.

Table 6. Final design

Front view	Top view	3D view
		

6. Robotic printing

6.1 ABB Robot

The robot used to produce the column is an ABB IRB 1200- 5/0.9, see figure 11. This robot is available in TU/e's Structural Engineering and Design lab. The robot can move in six different degrees of freedom (DOF). To enable interaction between the robot and the environment, an end-effector is attached to the robot arm. This end-effector ensures that the Makita stays in place and is guided to specific points. The Makita is for applying the printable material to the print bed. With the Makita extrusion takes place using a piston. This is the simplest method for extrusion. In piston-based extrusion, a vertical force is applied so that the mixture can be extruded through a small nozzle. The choice was made to print with a round nozzle with a 10 mm diameter so that the cross-section of the nozzle is the same at every point. As a result, a round nozzle has greater design freedom that allows all shapes to be printed.

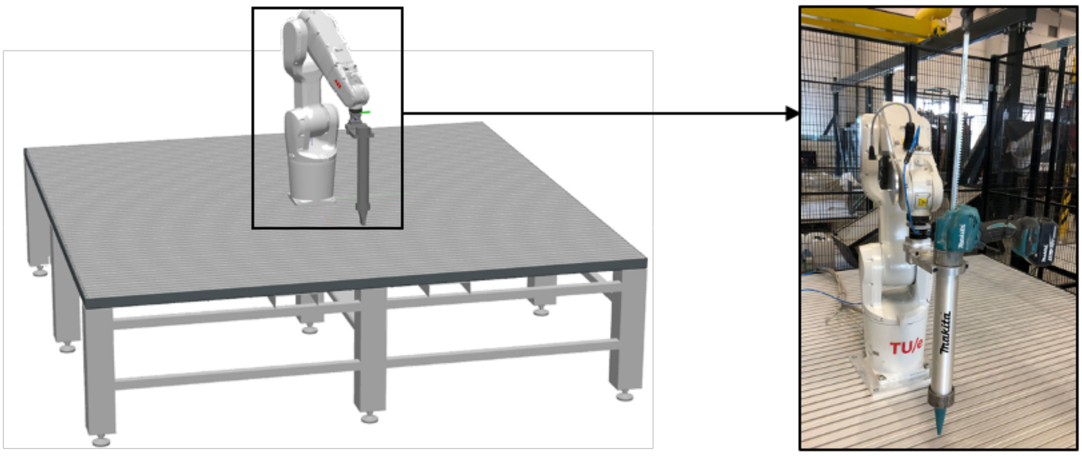


Figure 11. ABB IRB 1200-5/0.9 + Makita

6.2 Print path

To manufacture the structure by robotic printing, a printh path is defined to be able to print the column in one continuous session. The RobotComponents plug-in is used to define a print path for multiple layers to control the print sequence. This results in a list of points that define the robot path with a start and end point. After all the plane orientations are correctly defined, a list of robot targets is created. This list is used to create movements. The created movements and the defined ABB robot are combined into a list of actions. Using the Robot components plug-in, the RAPID Generator component generates a RAPID script that the robot software understands. The RAPID script consists of a RAPID Program Module (PM) and a RAPID System Module (SM). The PM script (MainModule) defines the robot movements and the SM script (BASE code) determines the orientation of the robot head based on the end-effector tool.

6.3 Manufacturing

The question is how many layers can be printed on top of each other. The final element is one meter high, this consists of +/- 200 printed layers. A maximum of 6 layers can be printed with a full cartridge. After filling a new cartridge and reapplying 6 layers to the first 6 layers, the element starts plastic collapsing at the 8th layer. From this, it is concluded that 6 layers can be printed as they also come from one cartridge. 7 layers could also have been chosen, but filling a cartridge to print 1 layer takes too much time. As a result, the final element consists of 36 elements of 6 layers that are joined together after curing. Printing an element is shown in figure 12.

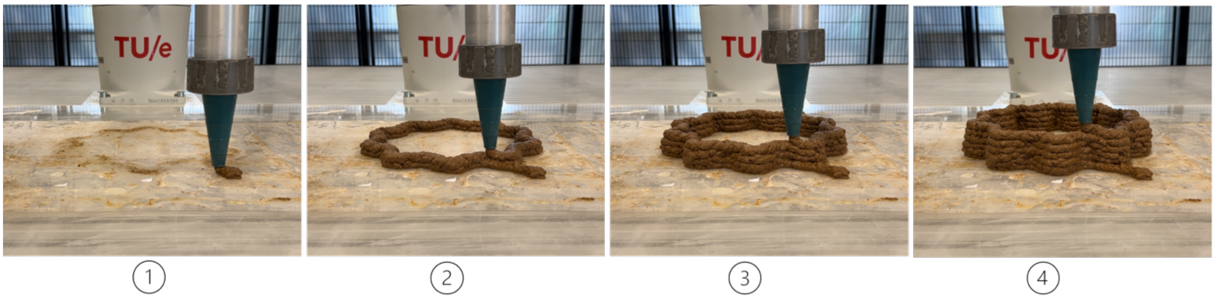


Figure 12. Print process

After the element is printed, the element is leveled. This is done by placing a wooden square on the element. After which the wooden element is pushed until it is levelled. The leveling of each element is done so that after curing it doesn't have to undergo any operation of sawing and sanding. This allows faster construction of the final element.

After printing, the elements were kept under a plastic film in the climate room for 7 days. In the climate room it is 20 °C and the average relative humidity (RH) is 60%. is. After 7 days, the elements were turned over so that the bottom side could also cure. After turning them over, the elements cure for another ±7 days after which they can be connected to each other.

7. Final element

7.1 Assembly final element

Bison PU Bruislijm is used to join the 36 printed wood elements together. The top and bottom of the final element are provided with a square wooden plate. The center of the of both wooden plates is provided with a spherical hinge, this allows the column to be placed centrally in the compression testing machine. The wooden plate also ensures that the point load is transferred optimally to the column. Gluing elements is less common than screws or nails, but is still used in wood construction [15]. The joint is quite simple and can achieve good strength. After all elements are glued, the column should be provided with a pressing pressure of 2-5 kg/cm^2 for 4 hours. In this study, a press pressure of 2 kg/cm^2 was chosen because the behavior of the material was not known. The cross section of the final element is rounded up to 150 cm^2, this means that the pressing pressure should be 3 kN. The final strength of the glue is reached after 24 hours at 20 ˚C.

7.2 Buckling test

The 3D printed bio-based column was tested in axial compression in the compression testing machine in TU/e's SED lab. The column must be easily supported. Therefore, the final element at the column supports must be free to rotate, but fixed to move. Figure 13 shows the experimental set-up for the buckling test of the column. The bottom is fitted with a spherical hinge with a steel plate. The wooden plate of the column fits exactly on this steel plate. The top is also provided with a spherical hinge. Attached to this hinge is a steel plate that fits exactly on the wooden plate and covers the column. The axial pressure point load is transferred through the steel plate to the wooden plate which distributes the load to the column.

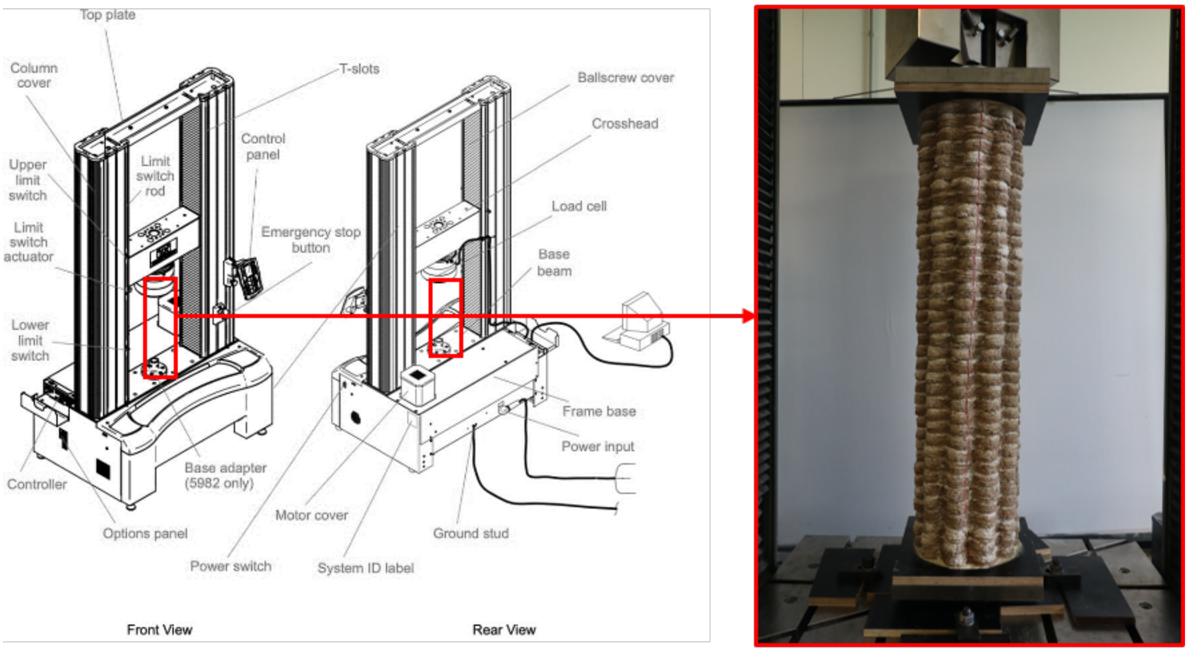


Figure 13. Test set-up buckling test

7.3 Result

Figure 14 shows the results of the axial compression test (buckling test) of the column in a force-displacement diagram.

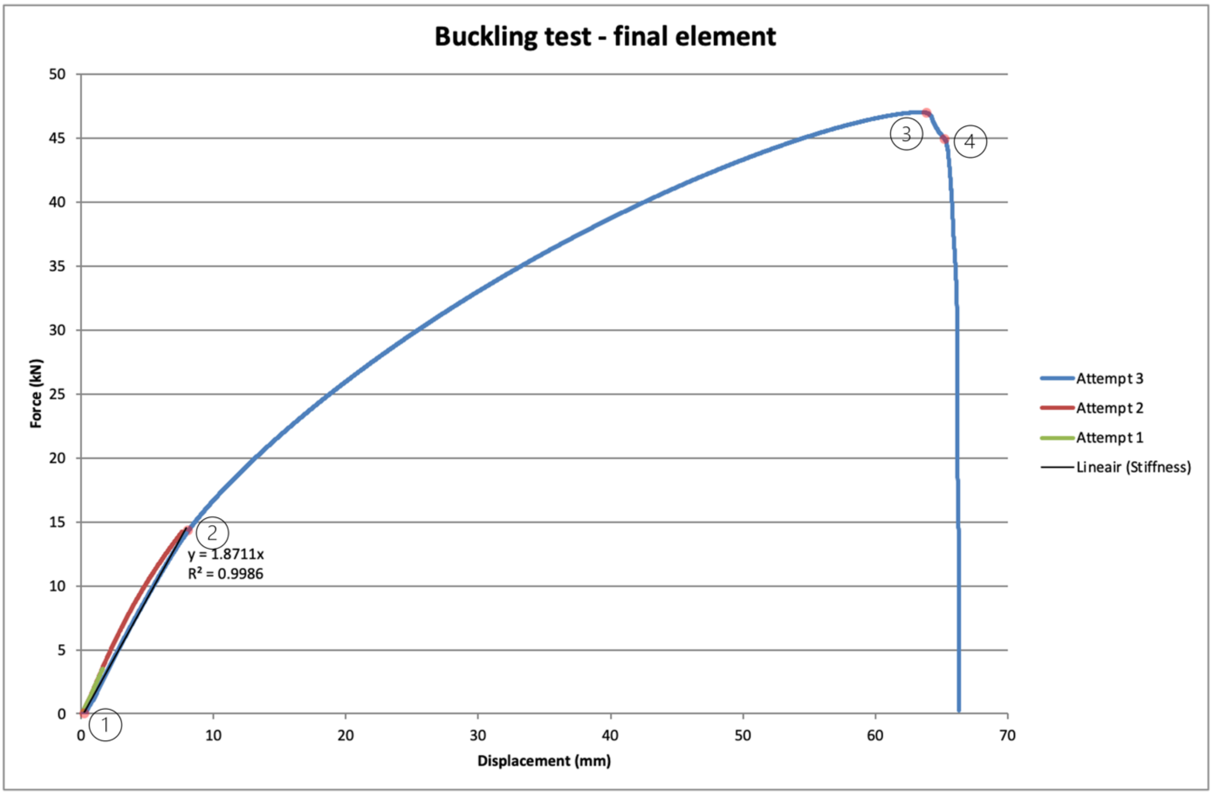


Figure 14. Force displacement diagram buckling test - column

Figure 15 shows the test situation at points 1,2,3 and 4 indicated in the graph. The column was placed in the compression testing machine between two spherical hinges, see figure 15.1. Between points 1 and 2 up to 15 kN, a stiff behavior (stiffness is 1,87 kN/mm) can be observed and the force increases rectilinearly with the deformation. The linear part between point 1 and 2 was caused by the failure of attempts 1 and 2 of the buckling test. In attempts 1 and 2, the photo camera did not work and this caused them to stop early. When starting attempt 3, this created a linear part first. Between figure 15.1 and figure 15.2 it can be seen that the vertical displacement of 10 mm caused by the compression testing machine does not represent horizontal deformation of the column yet. Between points 2 and 3, the displacement increases more than the force increases, creating a decreasing rise. The peak load is reached in point 3 at 46.2 kN and the stress is 312,2 MPa. Figure 15.3 (photo was taken from different angle to clearly show the horizontal displacement) shows that column collapses on global buckling due to the horizontal deformation. After the peak load is reached, the displacement increases and the force decreases. As the displacement continues to increase, pressure in the upper right side of the column (see figure 15.4) becomes so great that a vertical crack is created through the printed layers. Then, on the other side of the column (see upper left figure 15.4), the glue seam between the elements lets go and the column collapses on local buckling. After the column collapsed, the measurements of force and displacement stopped.

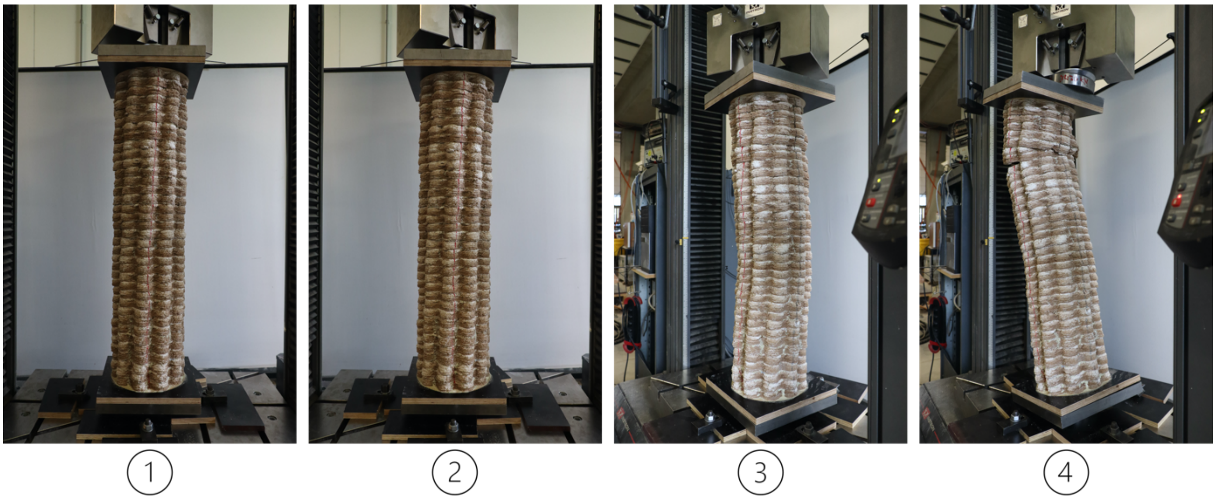


Figure 15. Pictures buckling test

Table 7 summarizes the results of the buckling test, showing the maximum compressive force achieved and the maximum force according to the numerical model.

Table 7. Test result of buckling test

Sample name	Buckling length (mm)	Expected compressive force (kN)	Tested compressive force (kN)	Factor difference
Buckling test	960	41,84	46,82	1,12

8. Conclusion

The aim of this research project was to design and assess the structural performance of an optimized three-dimensional parametric structural element (column) consisting of bio-based material. This one-meter-high column was made by additive manufacturing.

The final mixture used to print the column consists of the materials cellulose, lignin, valida L,3%, bio-glue and bentonite. It is a 100% bio-based material, combined with nice homogeneity, high viscosity and good adhesion, which were successfully demonstrated in the printability tests, shows the potential of this material as a raw material for additive manufacturing.

Also, in horizontal print direction with a value of 11,58 MPa and in vertical print direction with a value of 6,80 MPa, this mixture showed the highest values for compression strength compared to the other bio-based mixtures.

The focus of the column was on stacking the elements to arrive at one meter, where the resistance to buckling should be as high as possible until it collapses globally. Parameters and the optimization target were used to set up the numerical model in the parametric modelling software Rhino, via a script written in grasshopper. While changing the geometric parameters, the script searches for an optimized structure to accommodate an axial compression force. This resulted in a final design where the buckling resistance is as high as possible.

Printing the column is possible, but with limitations regarding to the total height. As a result, the column consists of 36 elements of six layers glued together after curing. If the column needs to be printed in one go in the future, more research needs to be done on material optimization.

The cured bio-based column was tested for buckling in the compression testing machine as this is the main failure mechanism for a slender structure loaded in axial compression. At a force of 46,82 kN, the column failed. The main failure mechanism of the axial compression test was global buckling. The calculated force in the numerical model was 41,81 kN, after which an average factor difference of 1,12 was found between the test and numerical results for the axial force. The cured bio-based material has a Young's modulus of 19,71 MPa. The density of the material is 1.0 Mg/m3. This places the material under natural materials with an overlap with polymers. It can also be concluded that the bio-based material is still far from being as strong as structural building materials such as wood, steel and concrete.

After this, it can be concluded that it is feasible to create a bio-based optimized column design through additive manufacturing. It has good potential in the construction industry, but further research and refinement of the properties is needed for large-scale structural applications.

9. Discussion

This research is a continuation of the thesis project by C. Bierach and A. Coelho started in 2022 using woodglue and methylcellulose as a binder. Significant progress has been made in improving the mixture with woodglue, although much more research needs to be done before it can be used in structures.

TU Delft mix methylcellulose getting mould-free
Mix methylcellulose starts to mould a few days after it is cured. In the case of the two former Delft students, the cured mix also started to mould. The cause of the moulding is probably due to the methylcellulose, since if it is not applied the moulding does not occur. Our study did not address this further because the focus immediately turned to the mixture with woodglue. An investigation can be conducted into how the mould occurs and how it can be prevented.

Mixture with bio-glue turns white
Before printing, the bio-glue mixture has a brown colour. On top of the brown printed layers, a kind of white powder appears during curing, which causes the printed element to turn white. The whitening is not mould, but it does stain clothes, for example. The cause of the whitening is probably due to the addition of Valida L,3%, since if it is not applied the non-mixture does not whiten. In the continuation of the study, no further research was done on whitening as it had no effects on the printing process and mechanical properties. An investigation can be conducted into how the white powder occurs and how it can be prevented.

Getting printed mixture bubble-free
When the mixture is rotated in the cartridge, the mixture contains small air bubbles, these small air bubbles are reflected in the printed elements. The options of vibrating, stamping and kneading were described in the report. From this, it was concluded that these methods did not get the mixture bubble-free. One option that does get the air bubbles out of the mixture is through a vacuum plug mill, but this device is too expensive to buy. Another option not considered in this study is printing with a pump instead of a Makita cartridge. Within the 3D concrete printing department within TU/e, MAI 2 pump pictor is extensively used. This pump ensures that no air bubbles are present when it is printed. In this study, this pump was not applied because only a maximum of 6 layers could be printed and a lot of material was left behind in the connected hose from the robot to the mixing bowl.

Interval time between printed layers
This study did not look at the interval time between the printed layers. An interval time between the printed layers of 15s, 1h, 4h, 7h and 24h was examined by R. Wolfs at TU/e in 3D concrete printing. From this, it was concluded that the higher the interval time between the printed layers, the more the

flexural tensile and tensile splitting strength decreases. This study can also be performed on the mixture bio-glue + bentonite. As already shown in this study, 6 new layers could be printed on the first 6 layers after 24 hours.

Material properties
More research into the material properties of the mixture is needed to be fully integrated as a structural building material. The material properties elasticity, tensile strength, brittleness, toughness, creep, hardness, resistance to oxidation and application in aggressive environments still need to be investigated. The tests for compressive strength and flexural strength will have to be carried out several more times to increase reliability. The stiffness of the printed material needs to be increased to come close to the stiffness of wood. Also, the shrinkage is on the high side at 14-16%, this can be reduced by reducing Valida L.3%. Other fibers can be tested as reinforcement. Besides mechanical properties, chemical properties such as moisture resistance, fire safety, corrosion resistance etc. should also be investigated. In short, the structural properties of the mixture need to be improved before it can be used constructively.

Using prestressing to join the printed elements
In the final element (column), all 36 elements are glued together. In 3D concrete printing, it is common for elements to be joined together using internal prestressing. A new study could look into joining elements using internal prestressing..

Time between mix process and print process
The time between the mix process and the print process should be optimized so that the behaviour of the mixture is always the same. In this study, the time between mixing the mix and printing the mix was not always the same. From this, it was concluded that the material changes the print behaviour during this phase. As a result, the printing speed of the robot was adjusted according to the mix to be printed. A study should be conducted on what is the optimal time between the mixing and printing process so that the behaviour of the mix is always the same.

Freshly printed bio-based material
This study did not investigate the printed properties of the mixture in the fresh state. Once the fresh state properties are known, a structural analysis of the printed object can be made. In R. Wolfs' research, five time-dependent material properties were obtained from experimental tests to analyse the behaviour of the print object. These five properties are poisson's ratio, Young's modulus, cohesion between particles, angle of internal fraction and angle of dilatancy. These five material properties in the fresh state can also be investigated for this mixture to analyse the print object.

Curing time material
In this study, it was chosen to cure the elements in the following way: 7 days under plastic foil, then 7 days without plastic foil and after it, turn the elements over and let them cure for another 7 days. Research can be done on the optimal curing time of the elements observing the shrinkage of the elements.

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