

DESIGN MANUAL

For 3D Construction Printing
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1. INTRODUCTION

This is a manual for the design of 3D printed buildings. If the following design criteria are taken into consideration from the early design phase, the design will easily be “printable” with any of the machines provided by COBOD International A/S. This guide acts as a manual for architects, designers, engineers, or anyone interested in understanding the process of designing the architecture for this construction method.

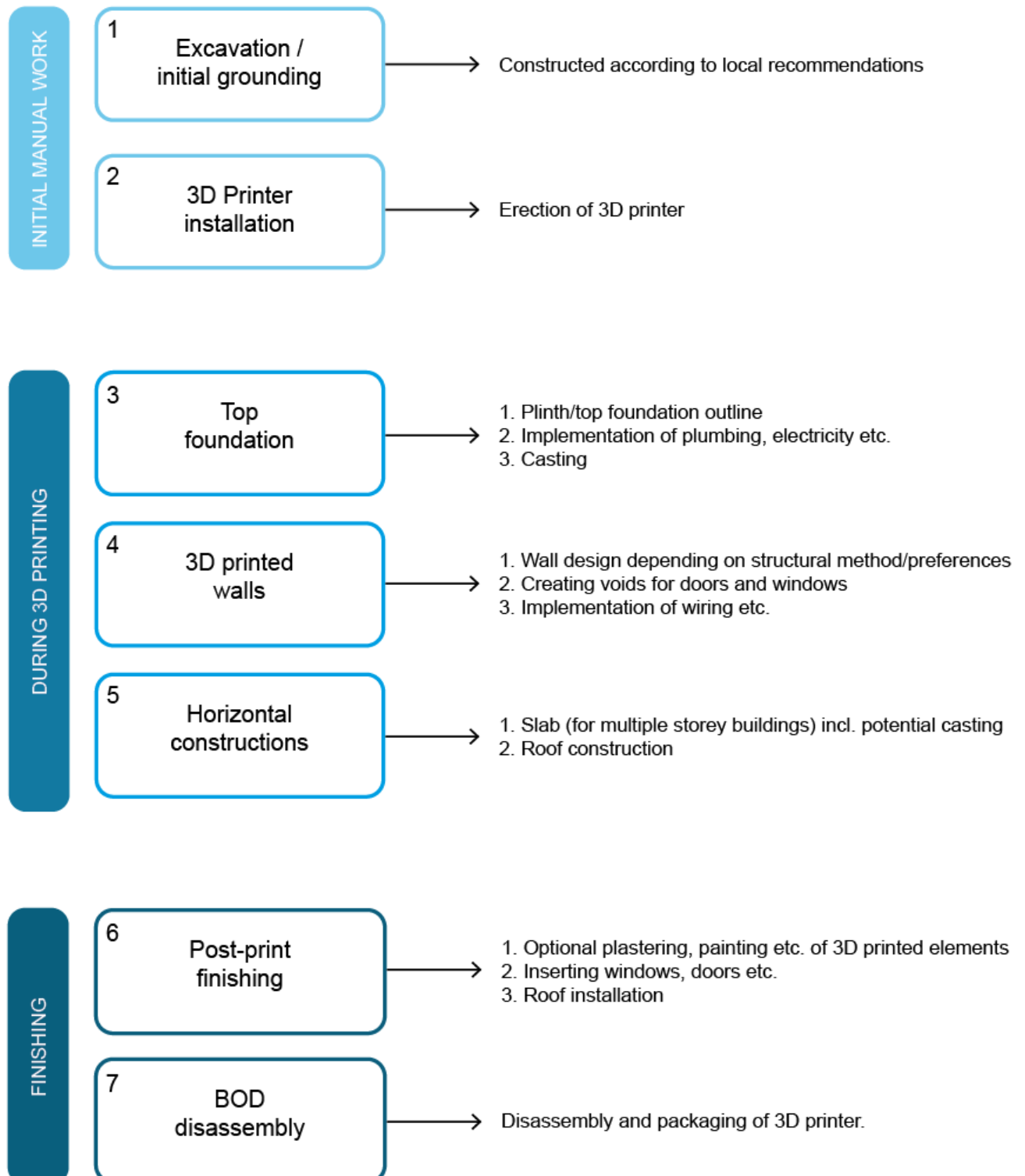
3D printing architecture requires a holistic design approach, where everything possible is embedded in the model created for the 3D printer.

As 3D printing is a relatively different construction method compared to conventional methods, the constraints and information provided in this guide should be considered criteria to design by as the construction method will have consequences for the design.

Please note that COBOD International is a technology provider and not a construction company. We will gladly support our customers with the necessary information about how to use their 3D printers, including this document which should be studied carefully before embarking on the design of your building. This manual is a brief providing an overview of the basic construction principles, and the level of detailing is set hereafter to communicate these in the most straightforward way possible. However, 3DCP as a construction method provides endless opportunities, and you can exceed the examples shown in this material to fit exactly your needs.

Before constructing any buildings using our machines, we want to note that one should consult local advisors/authorities to approve the building plans. Furthermore, be aware that certain parts of the building will require manual labor done by local construction companies.

2. 3DCP WORKFLOW SCHEME



3. DESIGNING FOR 3DCP

How do you make architectural designs for 3D concrete printing?

The building can be designed using conventional methods, preferably in consideration of the constraints that the construction method (3DCP) provides.

A series of surfaces representing the center of each 3D printed element is additionally required. These surfaces will then be imported into COBOD Slice, where they will be “sliced”. Slicing the surface means dividing it into individual horizontal layers, which will act as toolpaths for the 3D printer to deposit material layer by layer.

When modelling the surfaces in your respective CAD software, an inwards offset of each designed wall edge is created. The distance of the offset is determined by the width of the 3D printed layer. For example, if the 3D printed wall is intended to have a width of 50 mm, the wall should be offset 50 mm divided by 2 = 25 mm. The width of the 3D printed wall can vary as desired.

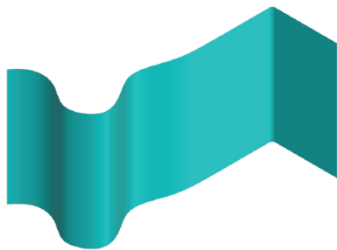


Figure 1 - Surface/centerline designed in CAD.

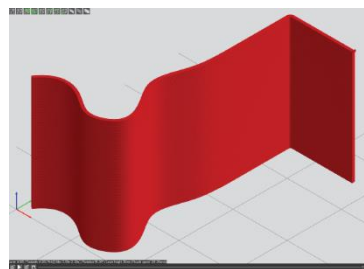


Figure 2 - Surface imported in COBOD Slice and sliced by certain layer height and width.

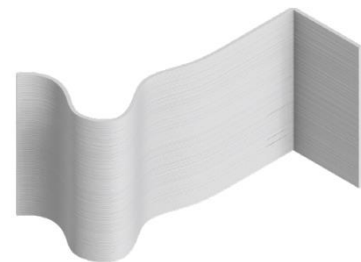
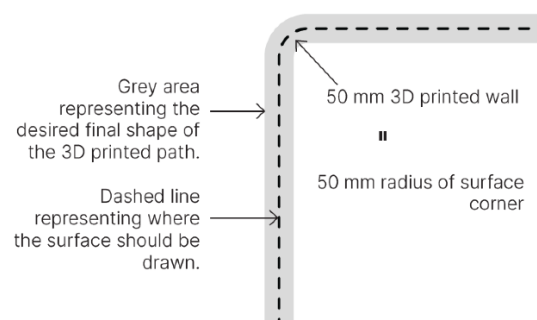


Figure 3 - 3D printed wall.

Each sharp corner of the offset surfaces should have a radius equivalent to the width of the 3D printed layer (typically 50 mm) for the printer to reach the desired shape most optimally.

As mentioned, the offset surfaces will be imported into COBOD Slice, where the software will automatically generate the file for the 3D printer. In COBOD Slice, it will be possible to adjust the print parameters (layer width, layer height etc.) and evaluate the design based on the statistics (print time, material consumption etc.) provided by the software.



3.1 PRINTABLE AREA AND INSTALLATION AREA

Every printer has its own printable area (PA). It is very important to consider the printable area before designing the building. Besides that, it is also important to leave 80-100 cm in the Y direction to ensure the space needed for the X-Axis to go down without colliding with the printed building while cleaning the print head. Thus, the printer cannot print in that area.

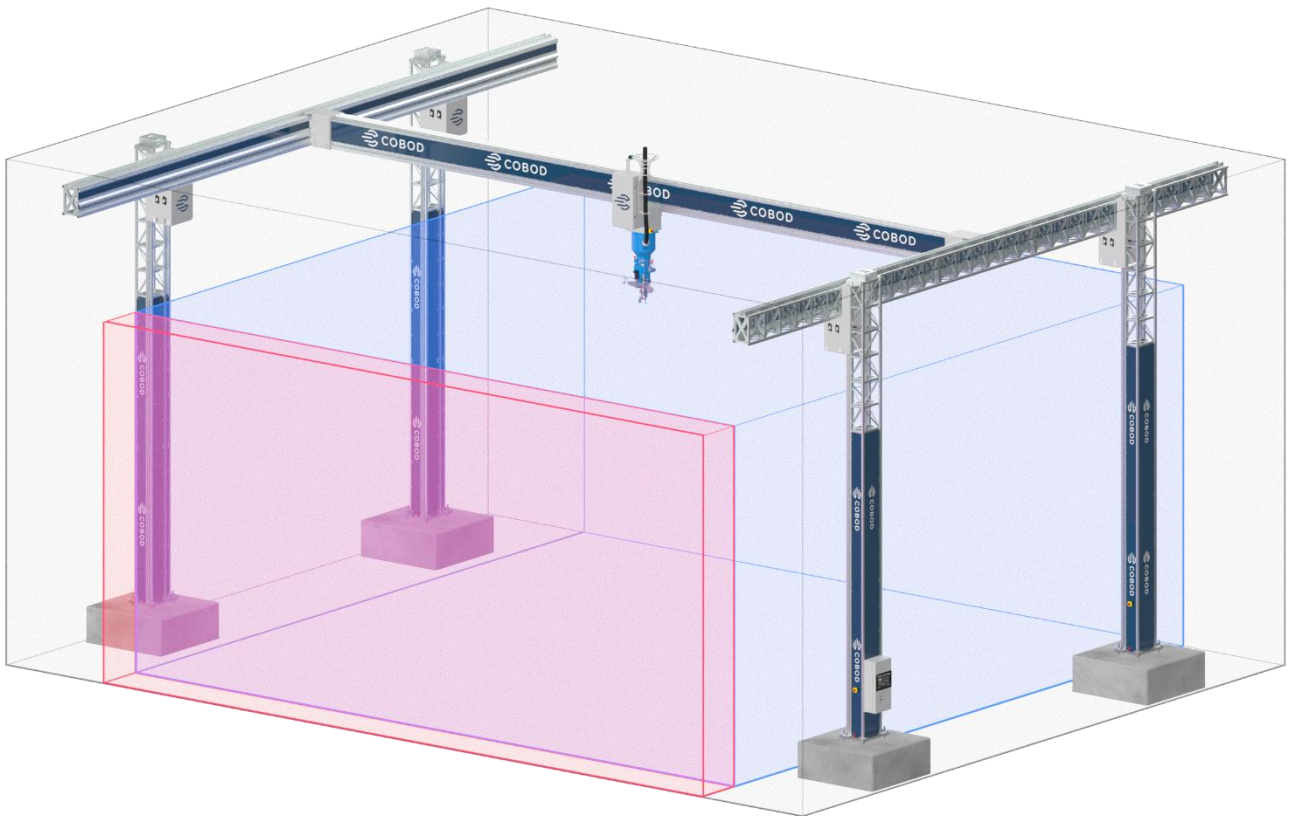


Figure 2 - Areas of the printer

► **Installation area:**

The minimum three-dimensional volumetric space required by the printer.
Its maximum outer dimensions.

► **Printing area:**

The maximum printing area. This area is the same as the operational area, excluding space for cleaning and maintenance operations.

► **Cleaning area:**

An area reserved for cleaning and maintenance. This area is needed to allow the X-axis to move down to ground level.

Can be anywhere inside the print area. By aligning openings (doors, windows etc.) it is possible to have the cleaning area anywhere inside the operational area.

► Operational area:  

The maximum three-dimensional space of which the printer can move.

While installing the base of the printer, make sure that the base plane is even. A noticeable change in the elevation of the plane can create a loss in height, which can damage the printer.

Fig.05 shows a loss in height due to differential base elevation.

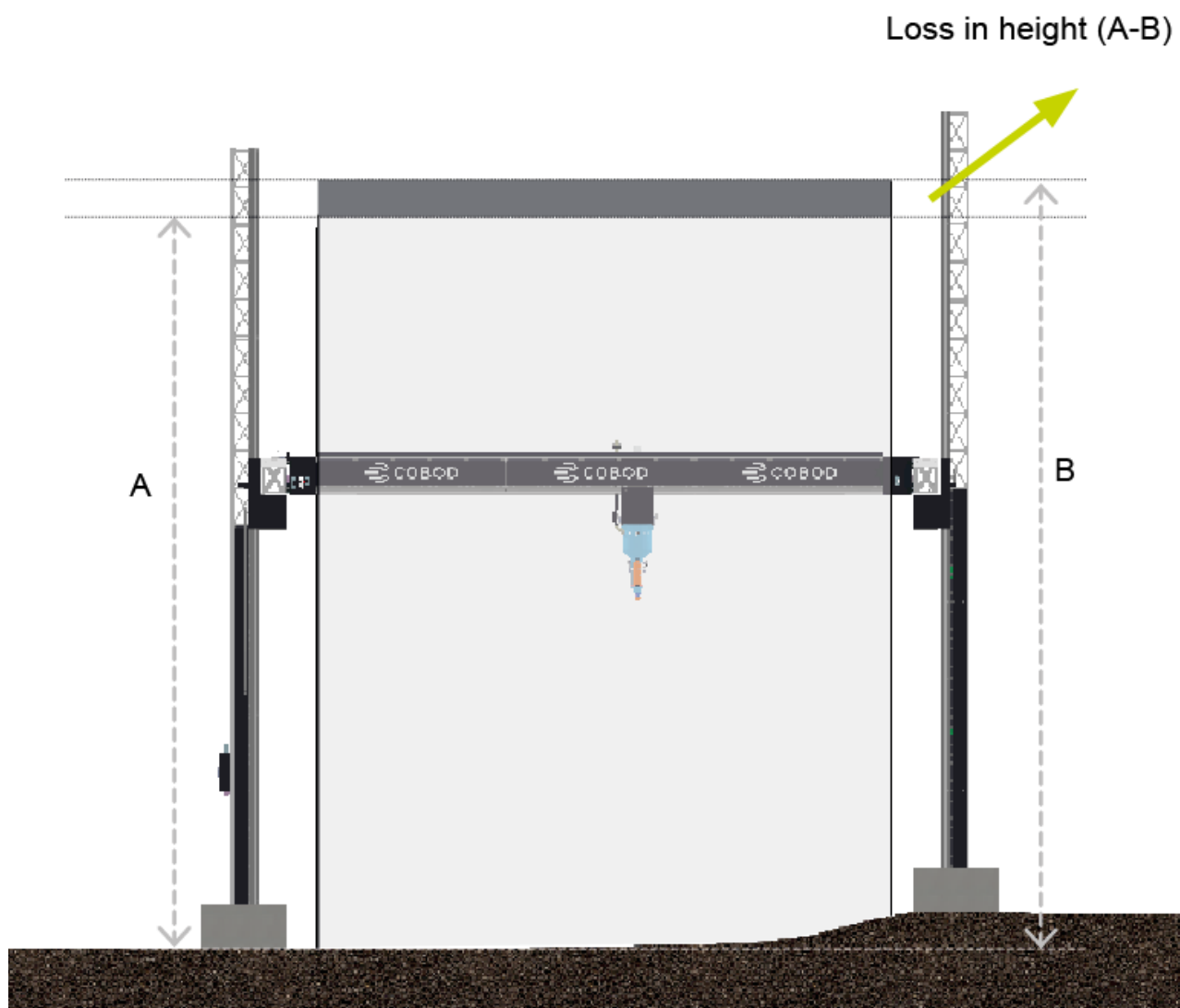


Figure 3 - Loss in height due to differential base elevation

-  Printable area (PA)
-  Loss in height

4. FOUNDATION

We highly recommend using the 3D printer to print the outline border of at least the top part of the foundation, both for orthogonal and more complex shapes. 3D printing the outline of the foundation will make printing the vertical structures a lot easier. It will also eliminate the need for creating complex formwork to cast the foundation.

In case manual work is chosen for the foundation, please note that the digital file loaded into the printer should be checked and potentially modified to fit the built foundation. Potentially modifying the file is done to avoid any mistakes or collisions with the already established constructions.

4.1 BASE CASTED FOUNDATION

The building's type of base foundation would be determined and constructed according to professional local methods and recommendations. The selected method will primarily depend on:

- ▶ Soil
- ▶ Structural load (height and size of the building)
- ▶ Shape and size of the building

The type of base foundation could, for example, be one of the following:

- ▶ Isolated foundation
- ▶ Piles foundation
- ▶ Raft foundation
- ▶ Slab on grade

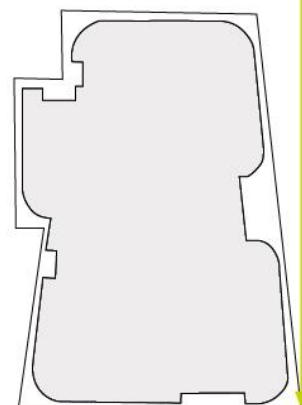
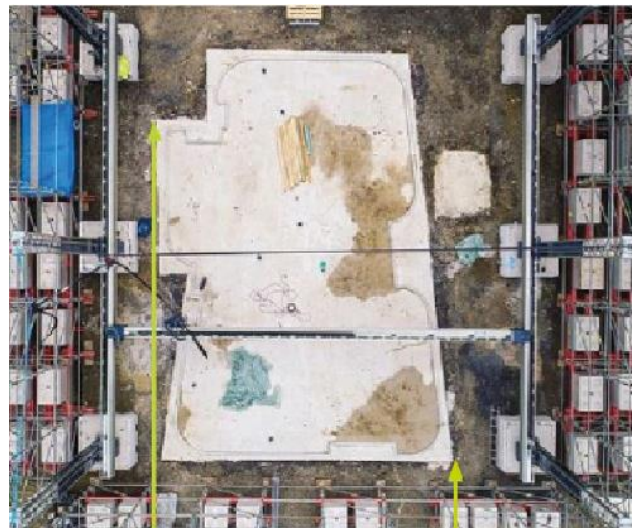


Figure 4 - Base foundation size limited to just fit the shape of the building but simplified to be made manually.

4.2 3D PRINTED FORMWORK FOUNDATION

The soil can be dug out to make room for the foundation. As previously described, the base foundation can then be cast in conventional ways, and the top part can be 3D printed for an easy transition into 3D printing the walls of the building.

As you can see in Fig. 7., the 3D printer can be installed on concrete feet. This will increase the reach of the height of the 3D printer used for each project. The use of concrete feet will typically add 60 cm of printing height.

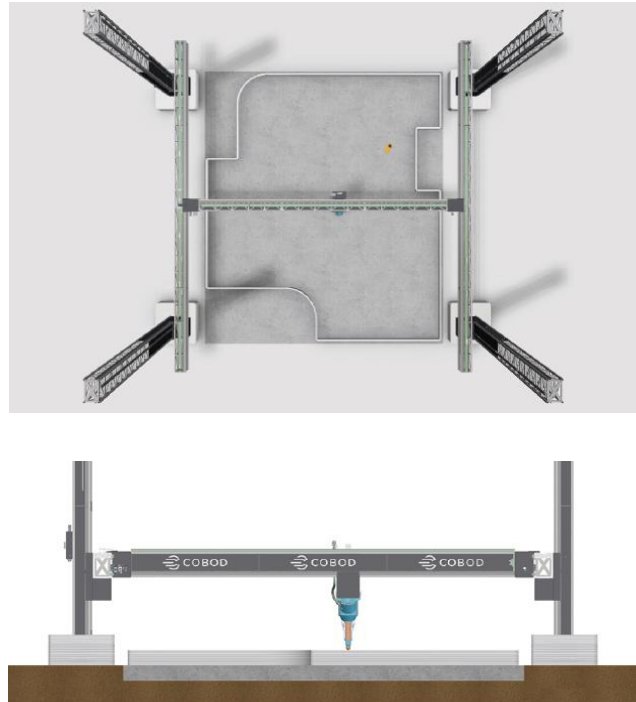


Figure 5 - 3D printed formwork.

4.3 3D PRINTING A PLINTH BEAM FOUNDATION

Very similar to the 3D printed formwork foundation for casting, the plinth foundation is essentially the formwork for the plinth foundation, which will be cast afterwards.

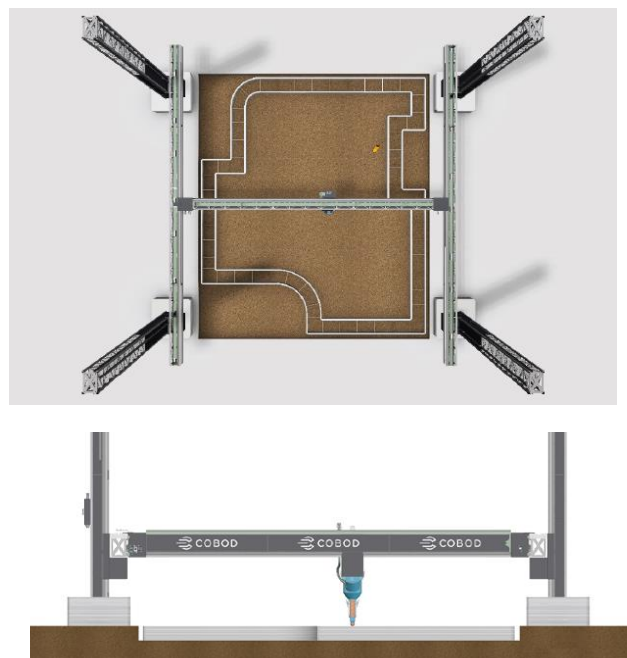
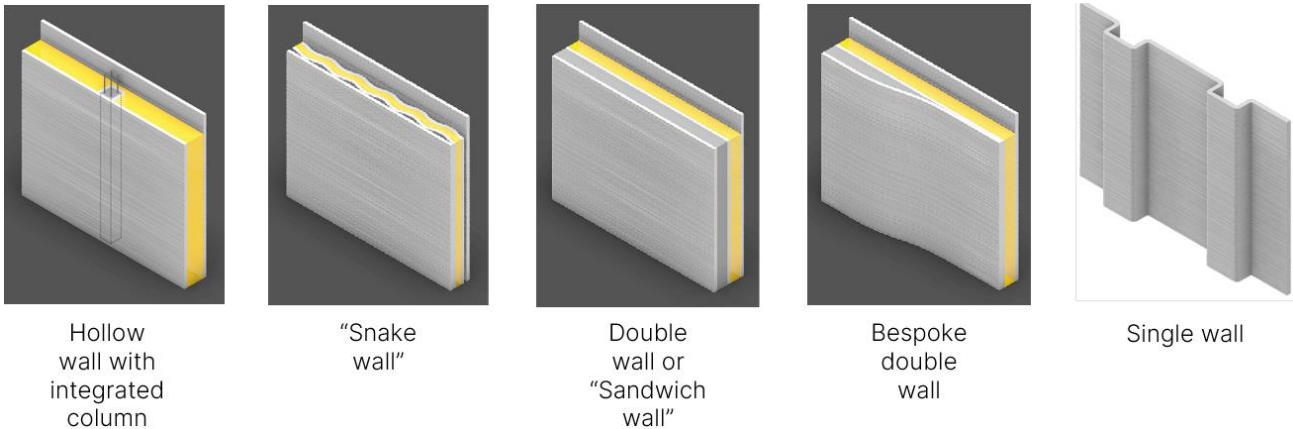


Figure 6 - 3D printed plinth beam foundation.

5. 3D PRINTED WALLS

3D printing offers almost unlimited opportunities for how you can design the walls. In this section, five different types of walls are illustrated. These can be combined or altered as desired.

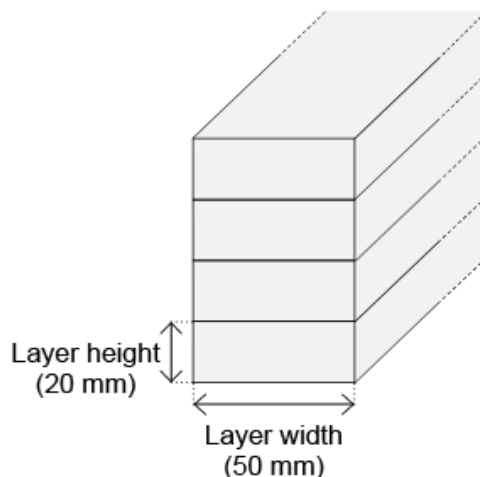
Wall type examples:



There are various advantages and disadvantages for each wall type, and the choice will depend on the overall design and local requirements.

Factors to take into consideration when designing the 3D printed walls:

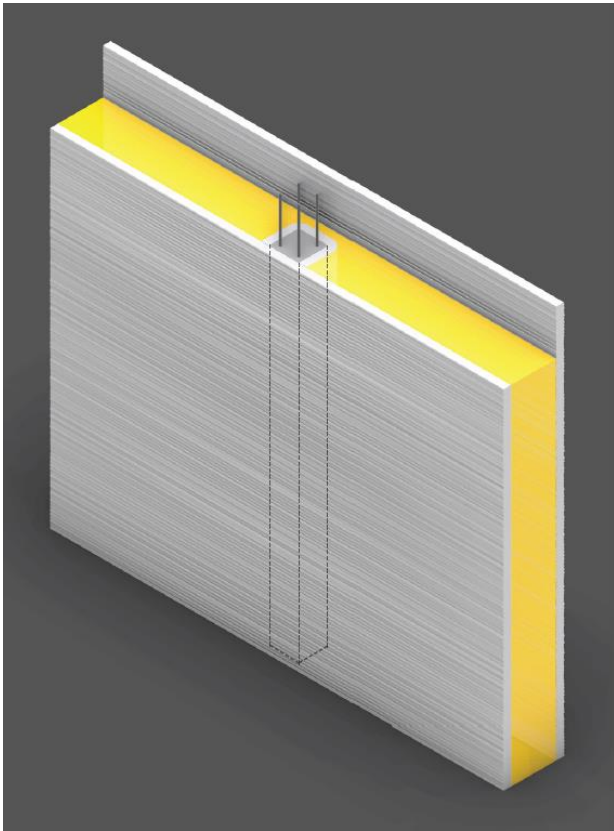
- ▶ Wall type (loadbearing/non-load bearing)
- ▶ Wall thickness
- ▶ Insulation type and local requirements
- ▶ Avoiding thermal bridges if necessary (depending on local building code)
- ▶ Layer height
- ▶ Layer width



Layer height and width of the 3D printed layer can vary depending on the design criterias.

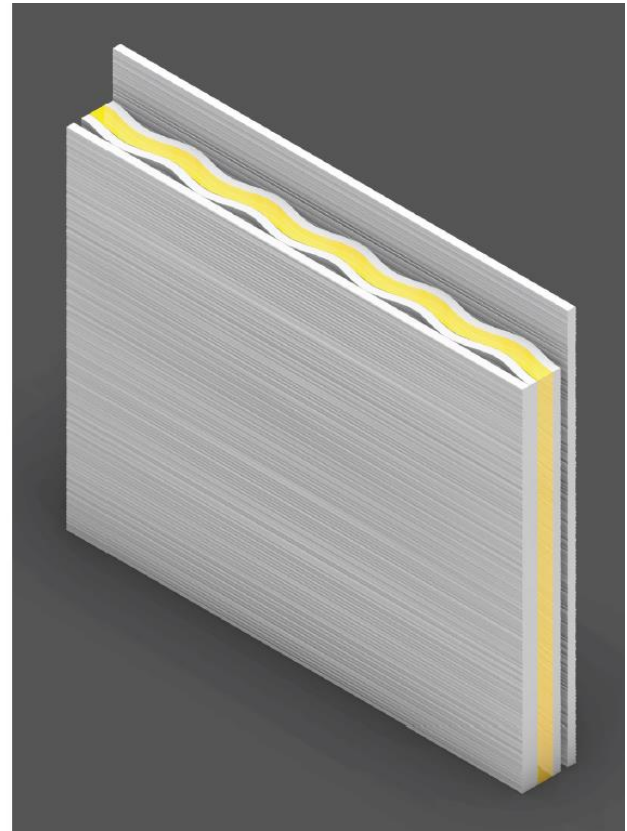
The most common dimensions are layer height = 20 mm and layer width = 50 mm.

5.1 SELECTION OF WALL TYPES



A. Hollow wall with integrated columns

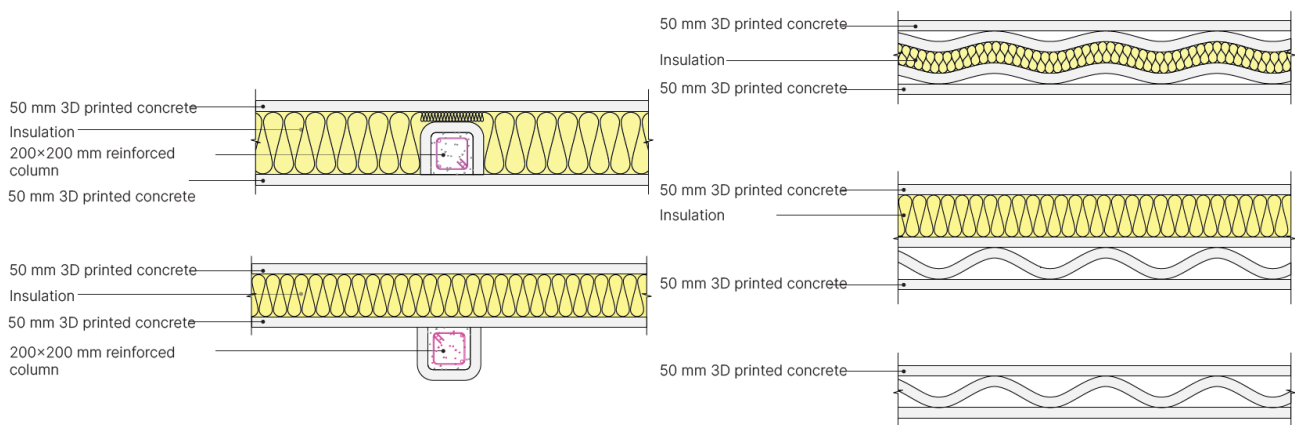
The integration of columns makes it possible to apply load calculations based on column placement (easy to get approved by local authorities, since the columns acts as load bearing traditional elements).

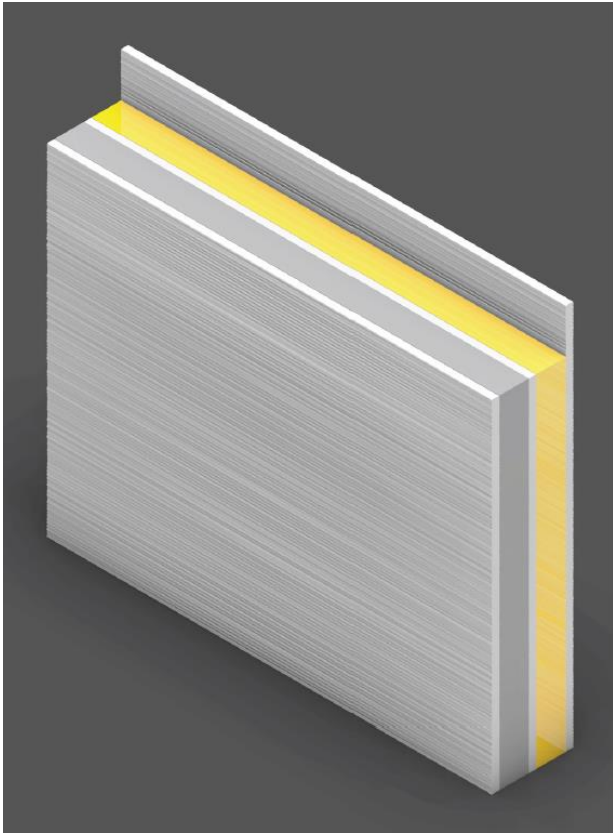


B. "Snake wall"

Creating internal curvy wall sections acting as structural elements.

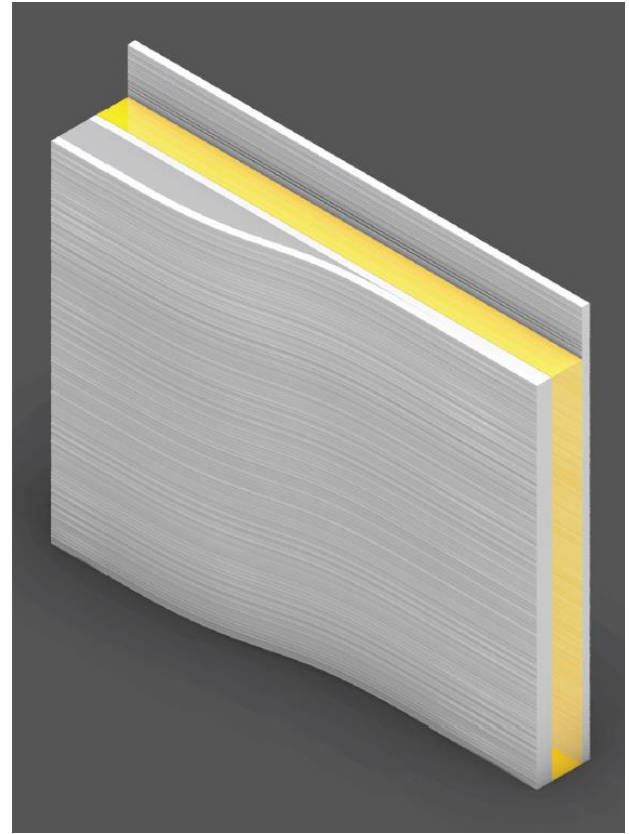
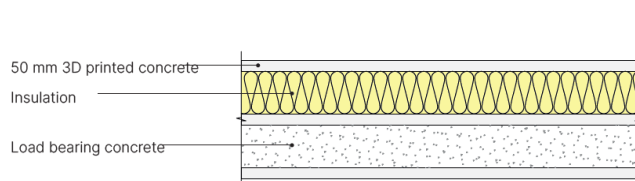
Three variations are illustrated, showcasing different ways of creating this type of wall.





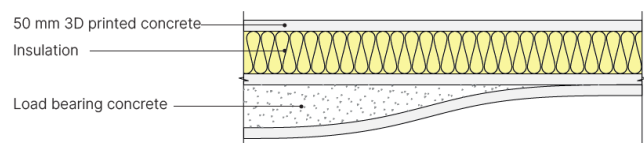
C. Double wall or "sandwich wall"

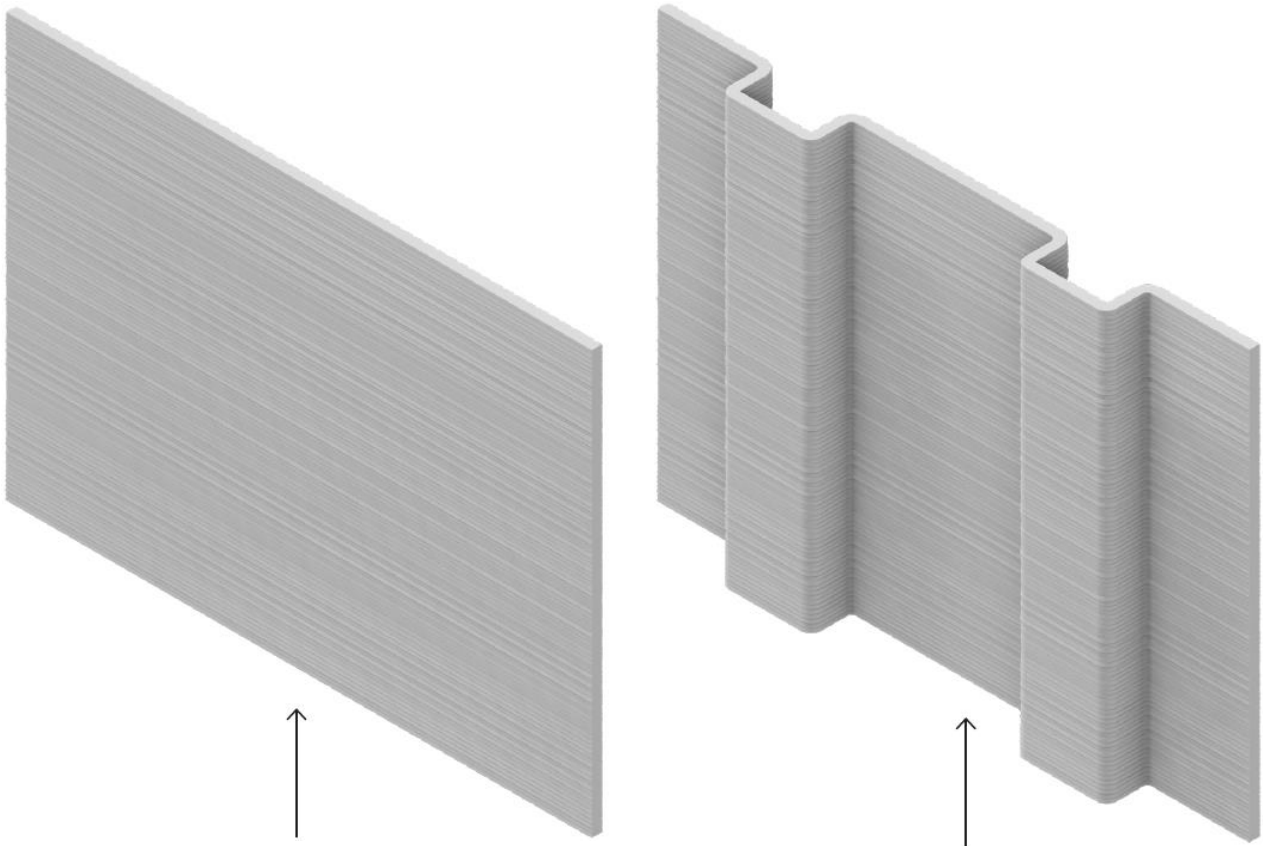
Three 3D printed walls, forming 2 cavities. One is filled with reinforcement and concrete, and the other with insulation.



D. Bespoke double wall

Insulation layer with loadbearing wall sections in selected areas.

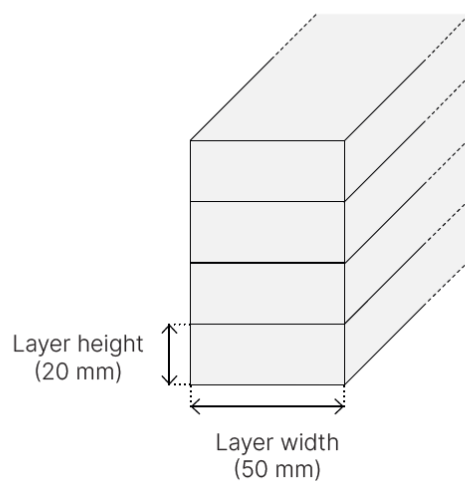




E. Single walls

The exterior walls will typically consist of multiple rows of 3D printed walls. However, it is naturally also possible to 3D print single walls.

Straight single 3D printed walls can easily be printed but will be less stable than a wall, with a differentiating path.



Layer height and width of the 3D printed layer can vary depending on the design criterias.

The most common dimensions are

layer height = 20 mm and
layer width = 50 mm.

6. WINDOWS

Voids for both windows and doors should be subtracted from the modelled surfaces. Underlying walls should be created individually (Fig 9) as a part of the surfaces to support the 3D printed walls around the window.

A lintel should be placed during the 3D printing process to support the concrete that will be 3D printed on top of the void for either doors or windows. There are multiple solutions in this context. The lintel can either be a precast concrete lintel or a piece of steel installed after the print has reached the window's height (Fig 10). The lintel can also be cast in situ. This method will typically be used when the window width exceeds the span of the two first mentioned lintel options.

After a lintel has been installed, the rest of the wall can be 3D printed directly on top (Fig 11).

If casting the lintel in situ, temporary formwork will be inserted, and the 3D printer can print the formwork for the cast in situ lintels on top of the formwork.

Otherwise, another simple solution is to add a board above the window or let the top window height be equivalent to the ceiling height, eliminating the need to print on top of the window.

If a floor to ceiling window is desired, there will naturally be no need for underlying support in the form of 3D printed walls. Therefore, the void can be created in similarity with an opening for a door.

Factors that will affect the method of implementing windows or doors should be defined during the design process. Things to consider in this context are:

- ▶ Wall thickness and type (see Wall types section)
- ▶ Avoiding thermal bridges (if necessary)
- ▶ Window span and height
- ▶ Window sill
- ▶ Frame location (towards the exterior or interior)
- ▶ Window side support
- ▶ Lintel design

3D printing of base part of wall, including support for window sides

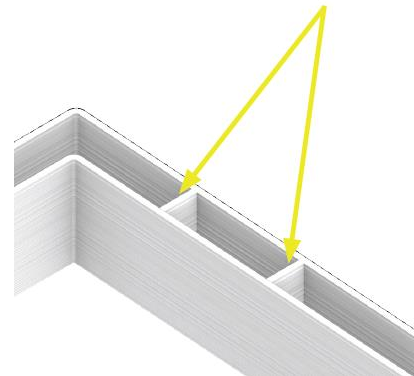


Figure 7 - Window supports.

3D printing sides around window and placement of lintels

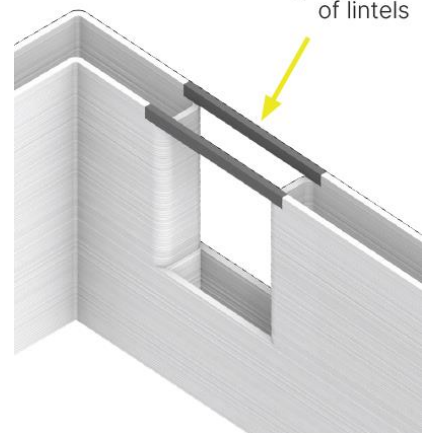


Figure 8 - Lintels

3D printing top part of wall on top of lintel plus installation of window

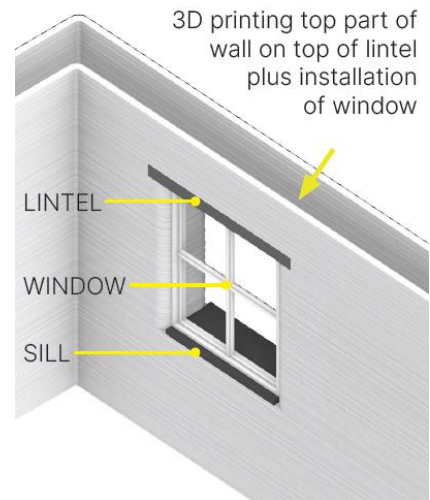
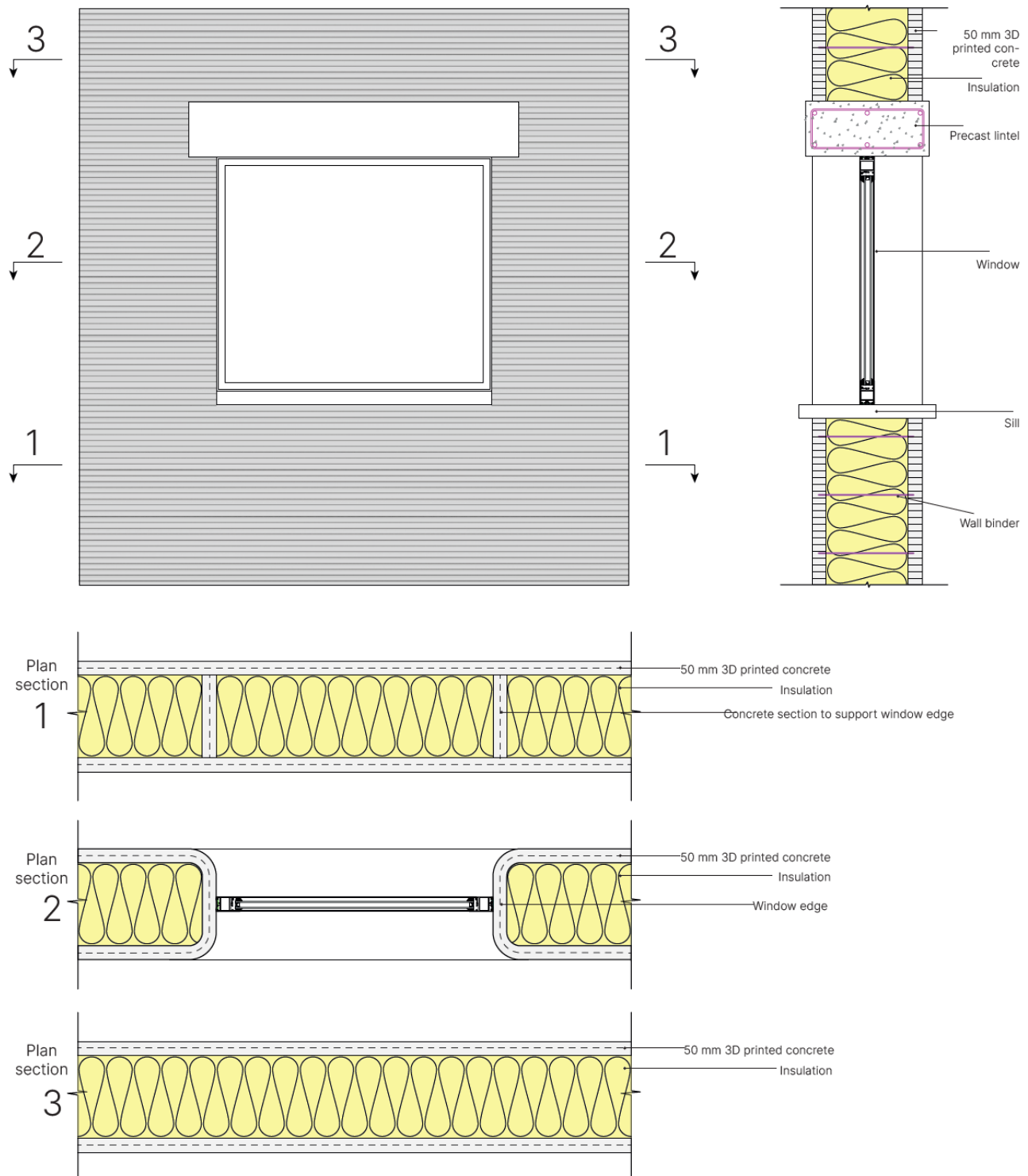


Figure 9 - Finished window

6.1 PRECAST CONCRETE LINTEL

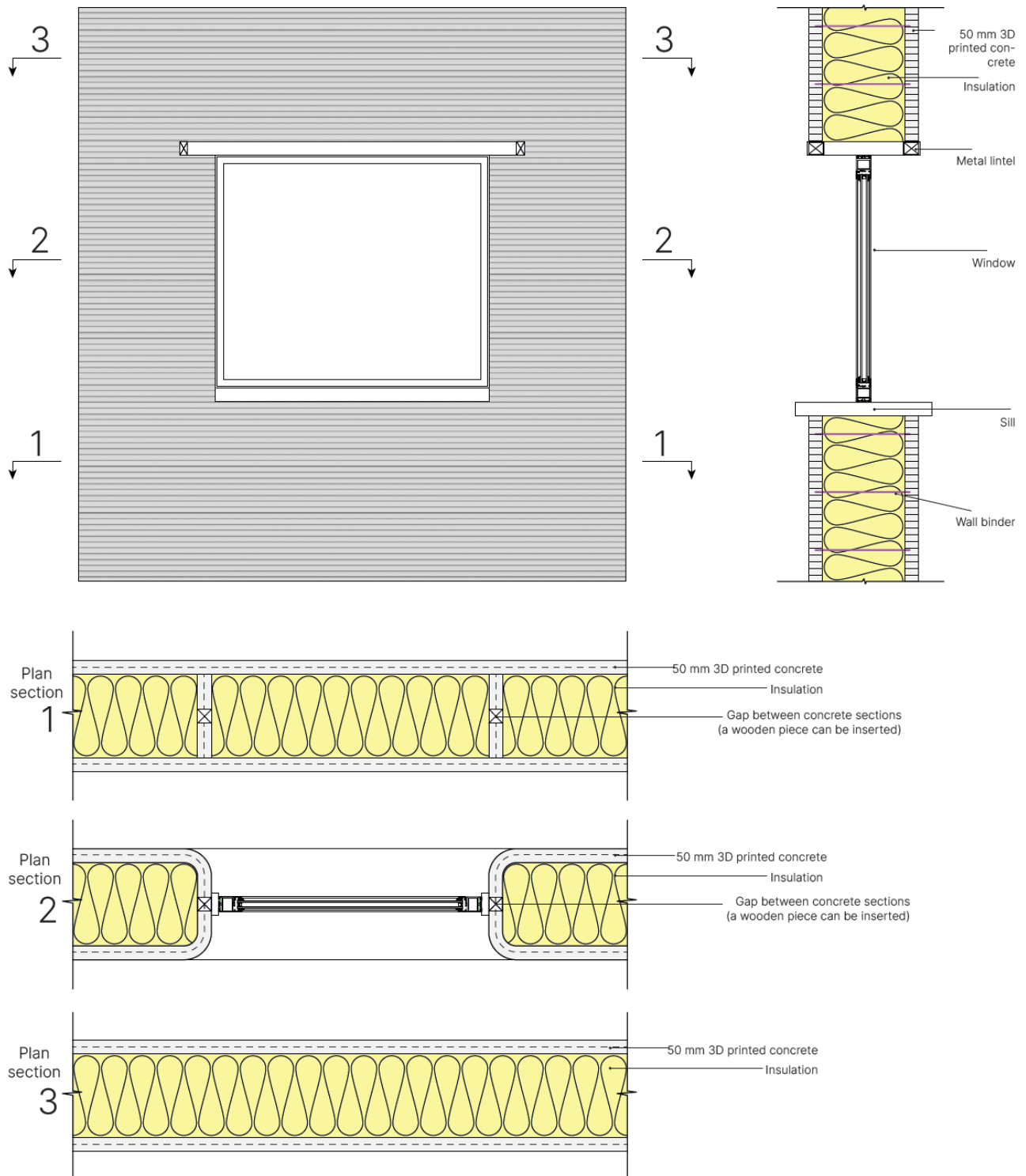
Using a precast concrete lintel will typically result in the lintel being visible. Post-print treatment of the wall can hide the lintel if desired.



6.2 METAL LINTEL

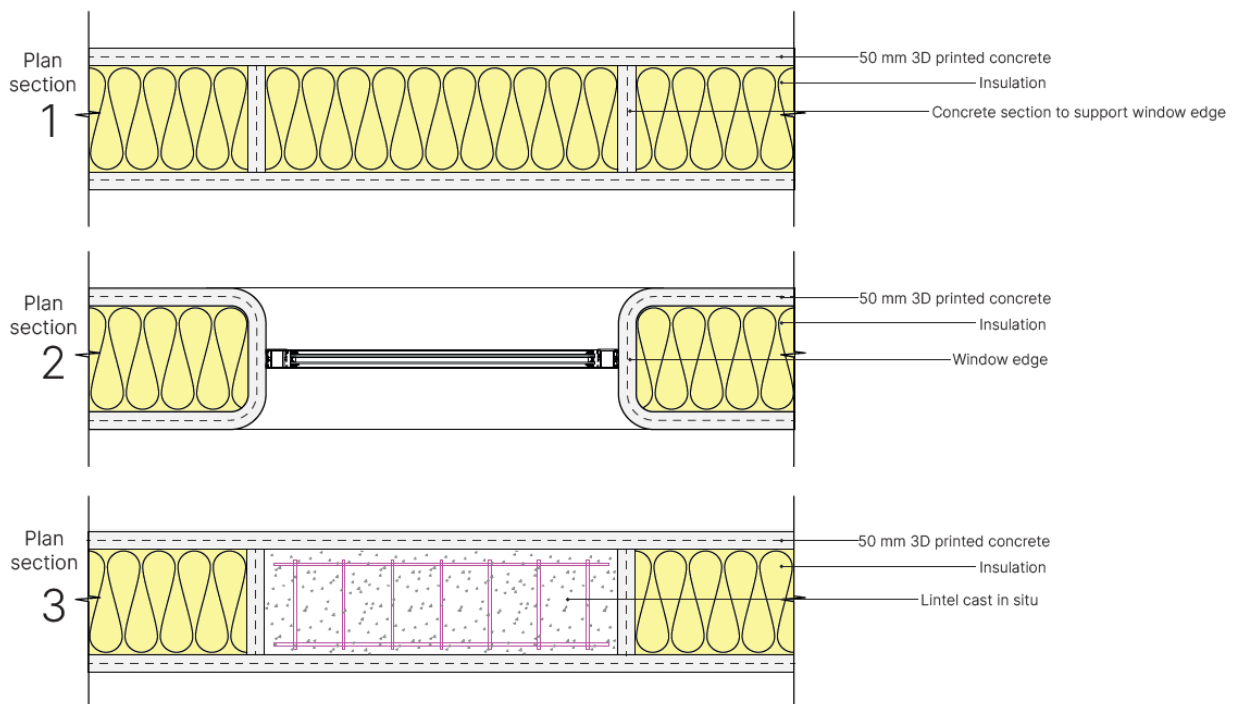
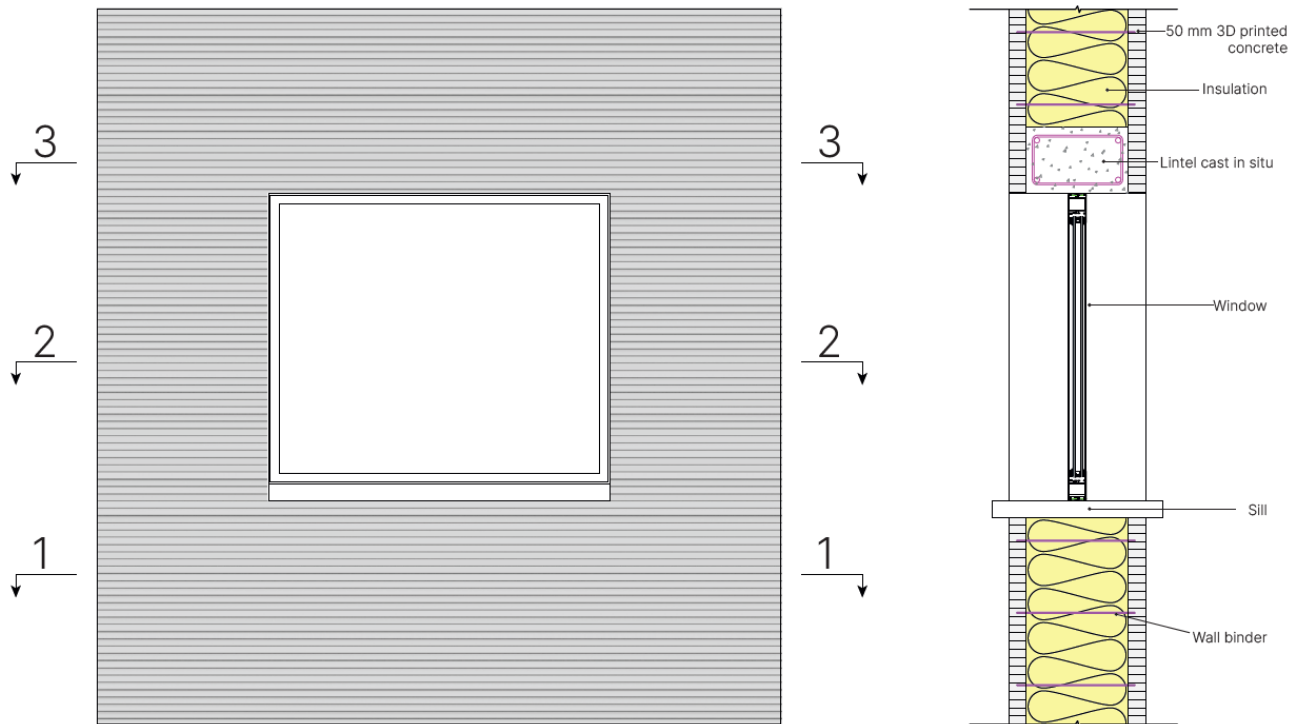
Using a metal lintel allows for a very slim expression, since the size of the lintel can be limited.

In this example, a method to avoid thermal bridges is shown. L-shaped profile steel lintels can also be used.



6.3 LINTEL CAST IN SITU

This method is typically used for windows with a horizontal span that requires significant support. It should be reinforced and requires underlying formwork during casting.

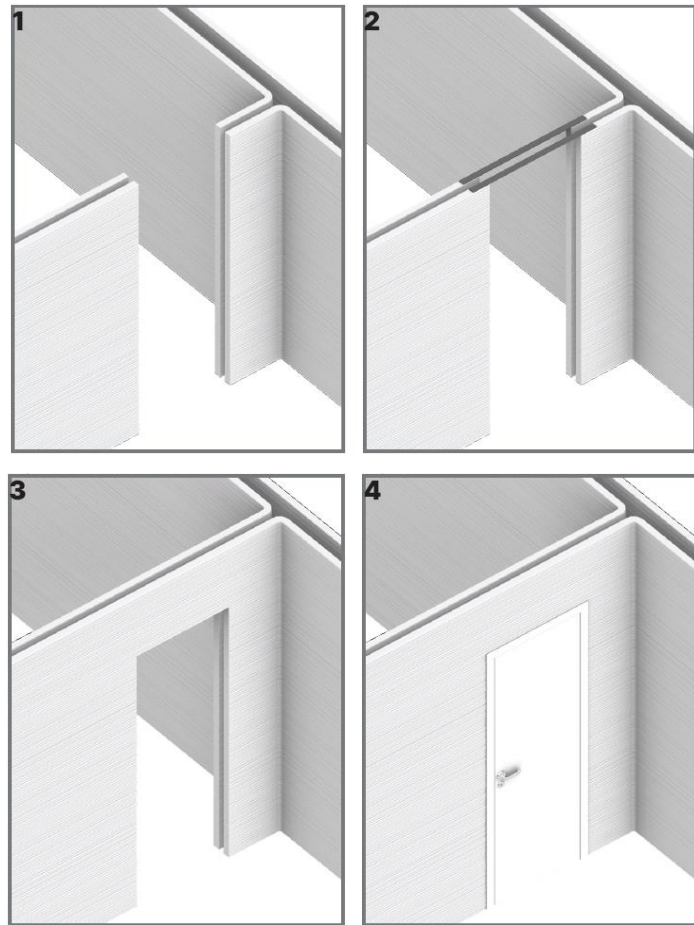


7. DOORS

Voids for doors should be created in the same way as voids for windows, with the only exception that doors will require no underlying support in the form of 3D printed walls.

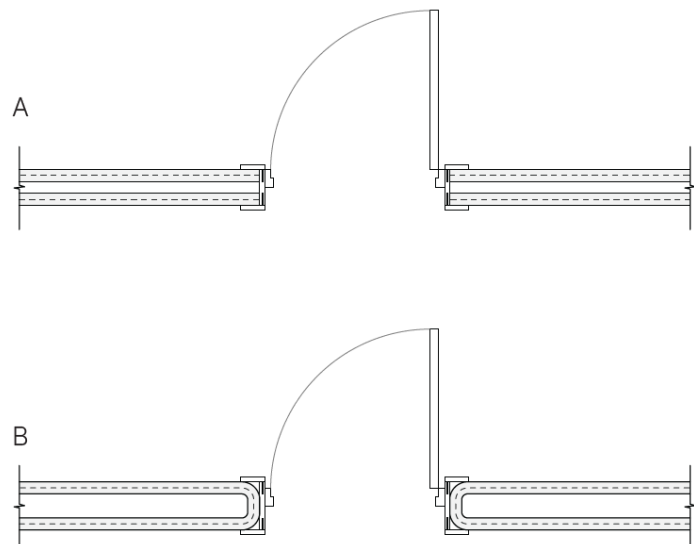
Overall, the same criteria apply for doors. As shown in illustration 1, the walls around the door will be 3D printed, and a lintel will be added to bridge the void (illustration 2) to allow the top part of the wall to be 3D printed (illustration 3).

The door will be installed after the 3D printing is done, as shown in illustration 4. As an alternative solution, the void can be extended to match the height of the walls, and a board or a small window can be inserted. This is dependent on the design requirements.



Two different methods for creating the walls around the door opening:

- A)** The 3D printed wall ends abruptly at the opening edge. This allows for slimmer double walls but will require manual finishing since the edges of these walls will most likely need to be cut even or plastered to allow for smooth installation of the door.

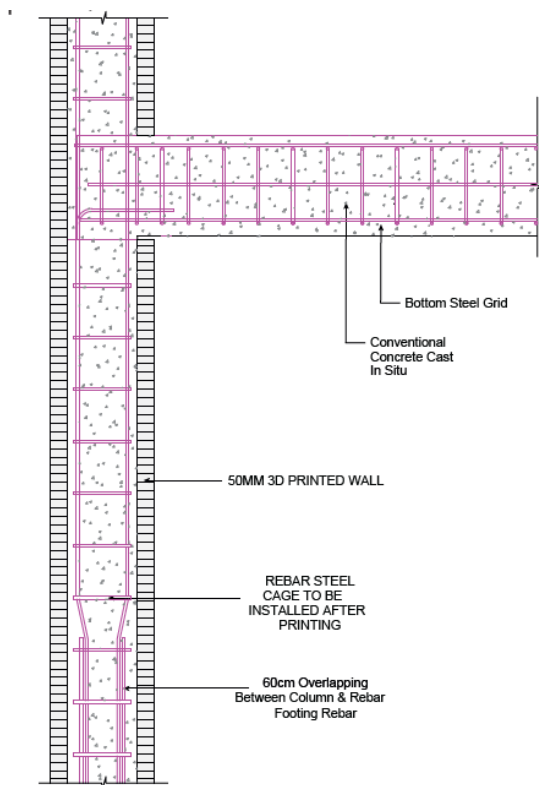


- B)** The 3D printed wall is created as shown. This will require no manual finishing work after printing but will result in a thicker wall to create an even edge for the door to be easily installed.

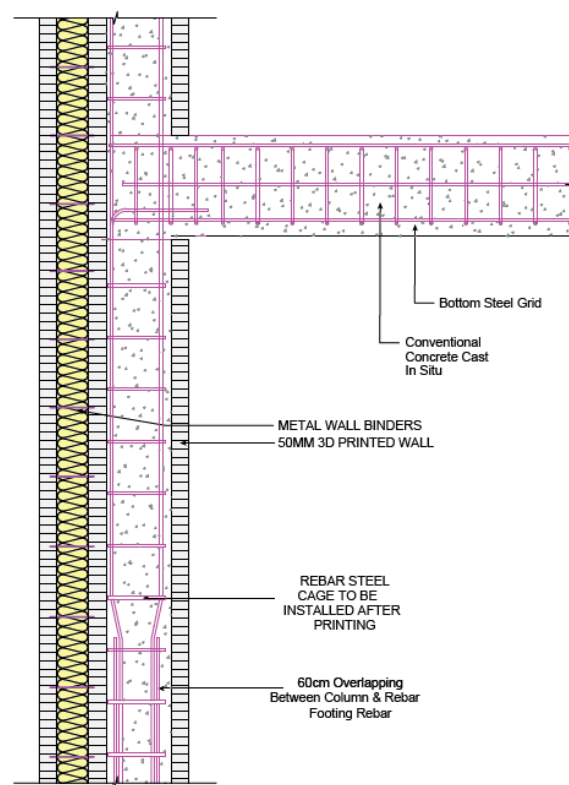
8. SLABS

Slabs will be constructed by your local contractor. Different slabs can be used, including:

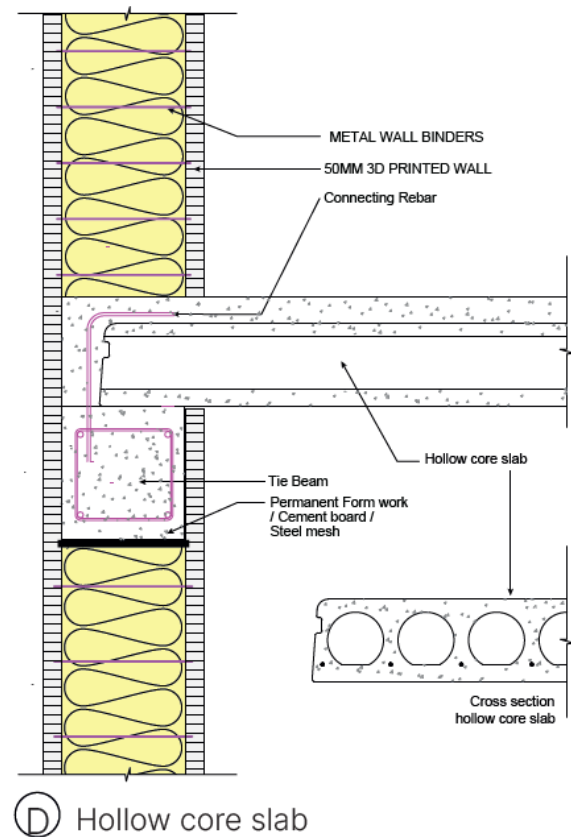
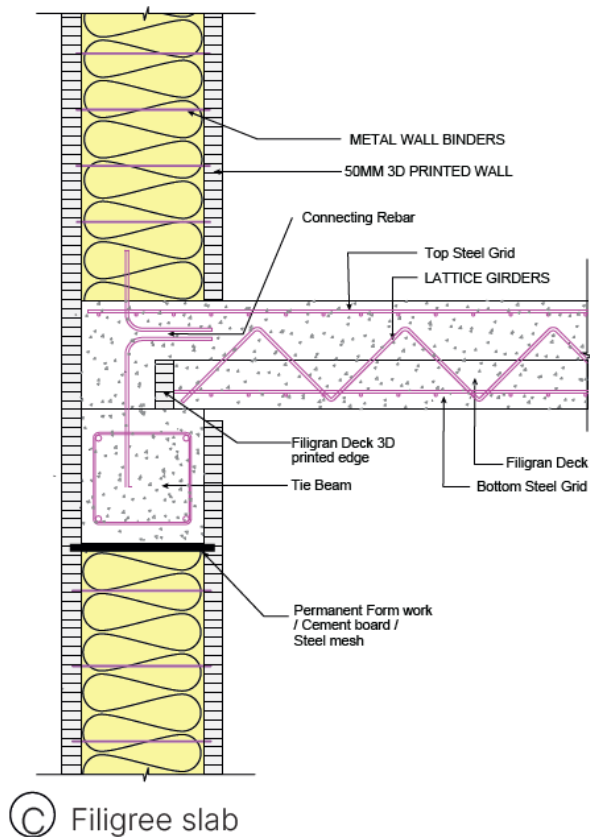
1. Cast in situ RCC slab (example A + B)
2. Precast slabs (hollow core, double T, etc.) (example C)
3. Filigree slabs (recommended when the shape of the building is complex and can be 3d printed) (example D)
4. Composite slabs (using the printer to cast the concrete in place)
6. Steel or wooden decks



(A) Concrete slab/reinforced column connection



(B) Concrete slab/reinforced column connection with additional insulation

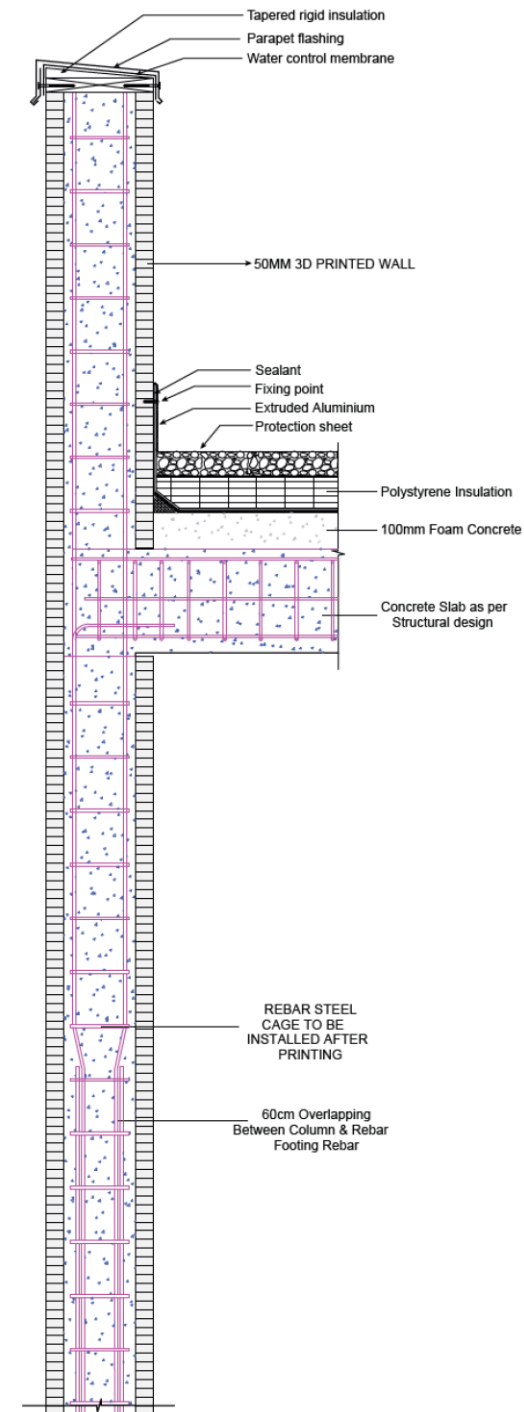


Filigree slabs can be made with the 3D printer, by printing the formwork in any shape, adding the reinforcement, and casting 1/3 of the slab.

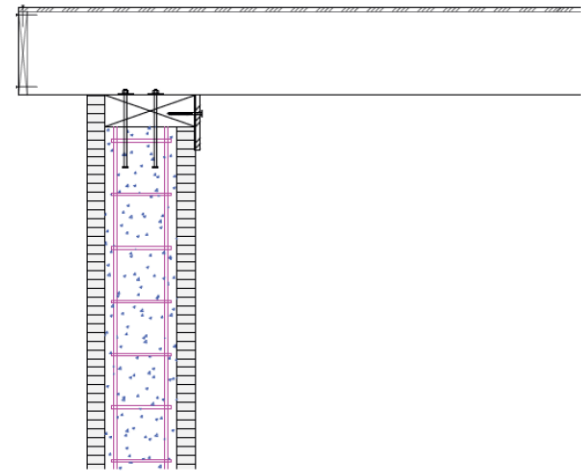
This way, the elements are lighter, but have enough strength to hold the assembly. After the modules are successfully installed, the rest of the slab can be cast.

9. ROOF

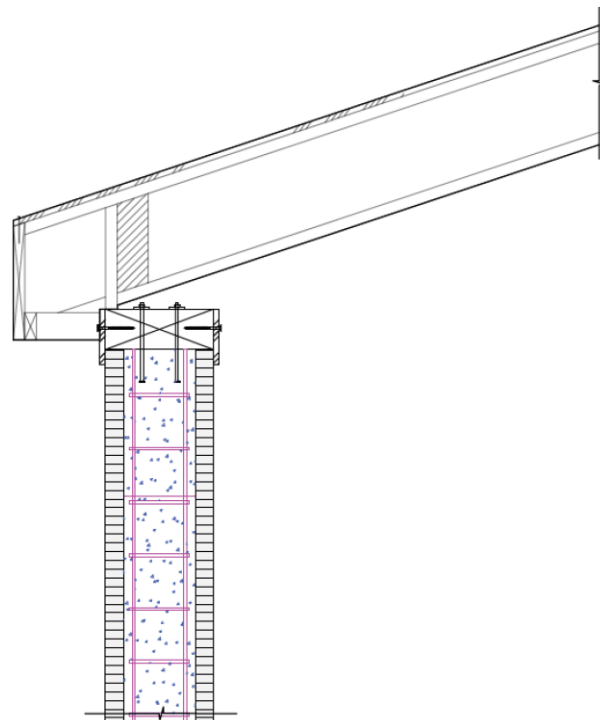
In roof example A and B, the type of roof has not been specified and is referred to as a 'generic roof'. The choice of roof structure will depend on local recommendations. What is shown is the joint connection between the roof and the 3D printed walls underlying the roof. The type of roof could be a wooden or steel structure or a reinforced concrete structure.



Ⓐ Flat roof with parapet (can vary in height)



Ⓑ Example of roof joint connection for a generic flat roof



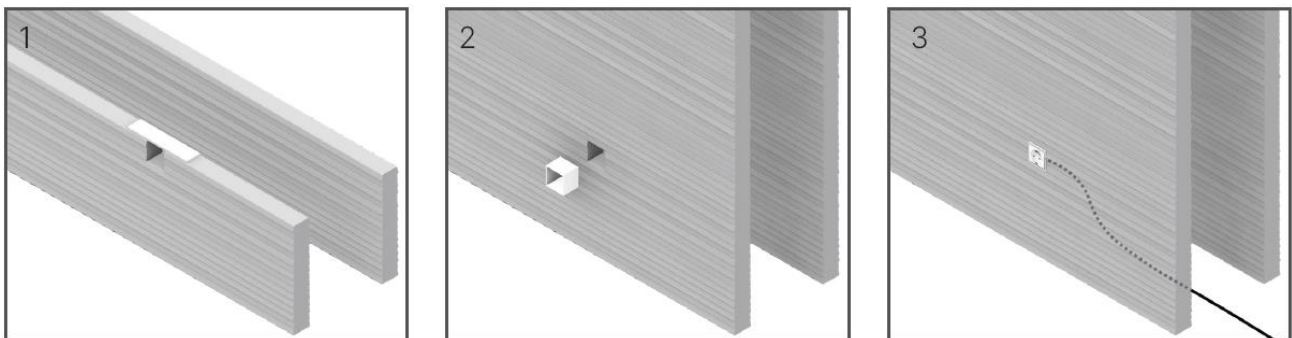
Ⓒ Example of roof joint connection for a generic slanted roof

10. HVAC

10.1 WIRING

To make the installation of electrical outlets as easy as possible, the necessary voids for these should also be included and planned in the CAD file. This automatically eliminates the need to drill or cut holes in the 3D printed walls to allow for various installations. The wires can be placed on the inside both external walls and interior walls if designed as double walls.

The same method can be used for other applications such as plumbing and HVAC systems.



Step 1: A void for the electrical sockets has been made in the CAD file from which the g-code for the 3D printer is created. At the point where the print reaches the top of the electrical socket, a metal piece is inserted.

Step 2: This allows for the rest of the wall to be printed on top, and the socket can then be inserted.

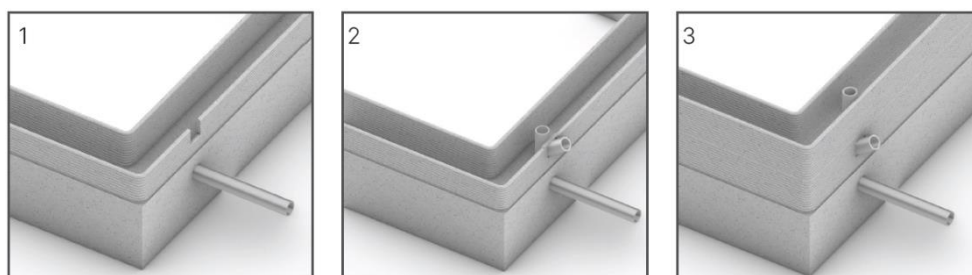
Step 3: Place the wires in between the walls.

10.2 PLUMBING

Main plumbing work would take place while working with the foundation. A complete water piping network can be placed before casting the foundations. Pipes up-rises would take place in the void between the double walls - similar case to wiring.

Openings for water outlets, cleanouts and valves can be included and planned in the CAD file, eliminating the need to drill, or cut holes in the 3d printed walls.

Other options are also possible. Like having the wiring and plumbing under the roof/slab and covered later by a false ceiling.



11. WALL FINISHING

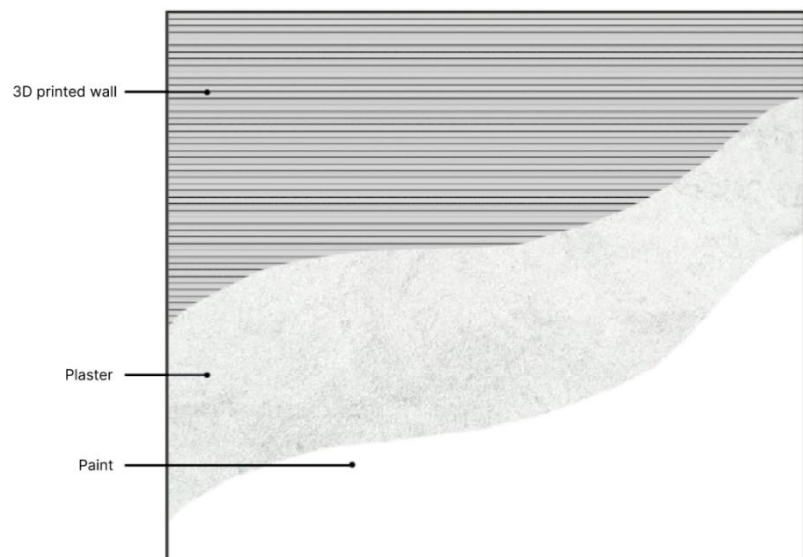
11.1 PRINT USING FLAPS OR NO FLAPS

The nozzle width defines the width of a single wall, and the nozzle type defines the texture of an untreated 3D printed wall. Two layered flaps attached to the nozzle can produce more even plane texture. This can minimize the manual labour of finishing after post printing.



The 3D printed walls can be left untreated, leaving the indications of the horizontal layers visible.

If a different surface expression is desired, conventional methods for wall finishing such as applying plaster and/or paint to the wall after it has been 3D printed can also be applied.



11.2 PROPERTIES OF A 3D PRINTED DOUBLE WALL

The profile of a 3D printed wall usually consists of the Indoor layer, insulation, and external layer. The thermal conductivity (U-Value) of 1cm of the concrete layer without any insulation is $2.4\text{W/m}^2\text{K}$ which produces a thermal phase shift of approx. 14 minutes. This characteristic is important to prevent overheating/cooling of indoor spaces.

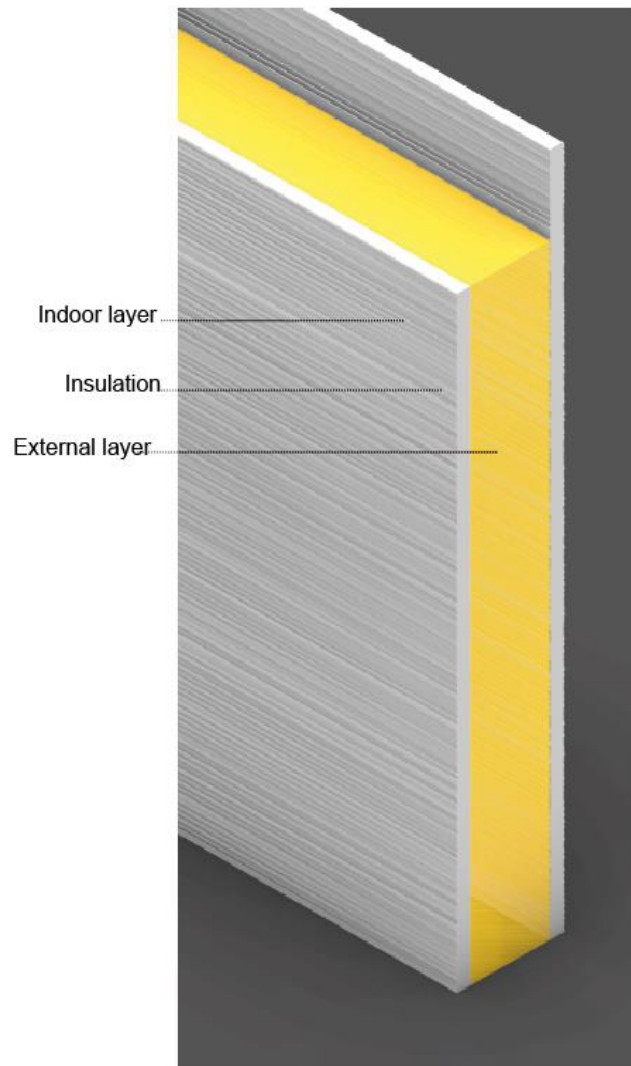
The thermal properties of a 3D printed wall depends upon:

- ▶ Thickness of the individual layers
- ▶ Thickness and properties of the insulation material used.
- ▶ Density and U-value of the insulation material

Different insulating materials can be used for example:

- ▶ Polyurethane foam insulation
- ▶ Rockwool
- ▶ Foam Concrete
- ▶ Cellulose insulation
- ▶ Other insulation materials

It is recommended to use flowable insulating materials as it will be easier to fill the void in a 3D printed wall.

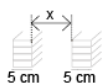
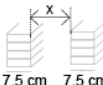
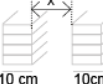
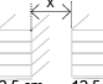
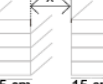


Thermal properties of a 3D printed double wall excluding insulation.

	Metric Unit	Imperial Units
Density	2400 kg/m ³	137 lbs/ft ³
Thermal conductivity (u)	~ 2.4 W/m ² K	~ 1.39 BTU/(h ² ft ² °F)
	For one cm	For one inch
Thermal Resistance (r)	~ 0.004 m ² K/W	~ 0.060 h ² ft ² °F/BTUT
Thermal Phase Shift	~ 14 minutes	~35 minutes

11.3 CONCRETE THICKNESSES VS THERMAL PHASE SHIFT

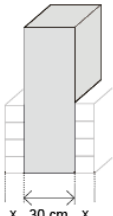
The table shows the Thermal resistance (R-value) of the printed concrete with different layer width without the insulation material.

	Total concrete thickness	Thermal Resistance		Thermal Phase Shift
	10 cm / ~4 inches	0.04 m ² *K/W	0.23 ft ² *h [°] F/ BTU	2 hours, 20 min
	15 cm / ~6 inches	0.06 m ² *K/W	0.35 ft ² *h [°] F/ BTU	3 hours, 30 min
	20 cm / ~8 inches	0.08 m ² *K/W	0.47 ft ² *h [°] F/ BTU	4 hours, 39 min
	25 cm / ~10 inches	0.10 m ² *K/W	0.59 ft ² *h [°] F/ BTU	5 hours, 49 min
	30 cm / ~12 inches	0.12 m ² *K/W	0.71 ft ² *h [°] F/ BTU	6 hours, 59 min

Note: X is the width of insulation and here the phase shift value is independent of r value.

Depending upon the thickness of layers printed, the thermal properties of the wall can be changed accordingly. The 3D printed outer walls are usually printed with 5-10 cm per layer. This gave an approx. thermal phase shift of 2 - 5 hour without insulation.

Insulation Properties:

	Insulation type (loose fill)	Blown Cellulose, 30 cm		Mineral Wool, 30 cm	
	Total u-Value	0.14 W/m ² *K		0.12 W/m ² *K	
	Total r-Value	7.54 m ² *K/W	42.8 ft ² *h [°] F/ BTU	8.61 m ² *K/W	48.9 ft ² *h [°] F/ BTU
	Total Phase Shift	10 hours, 50 minutes		7 hours, 40 minutes	

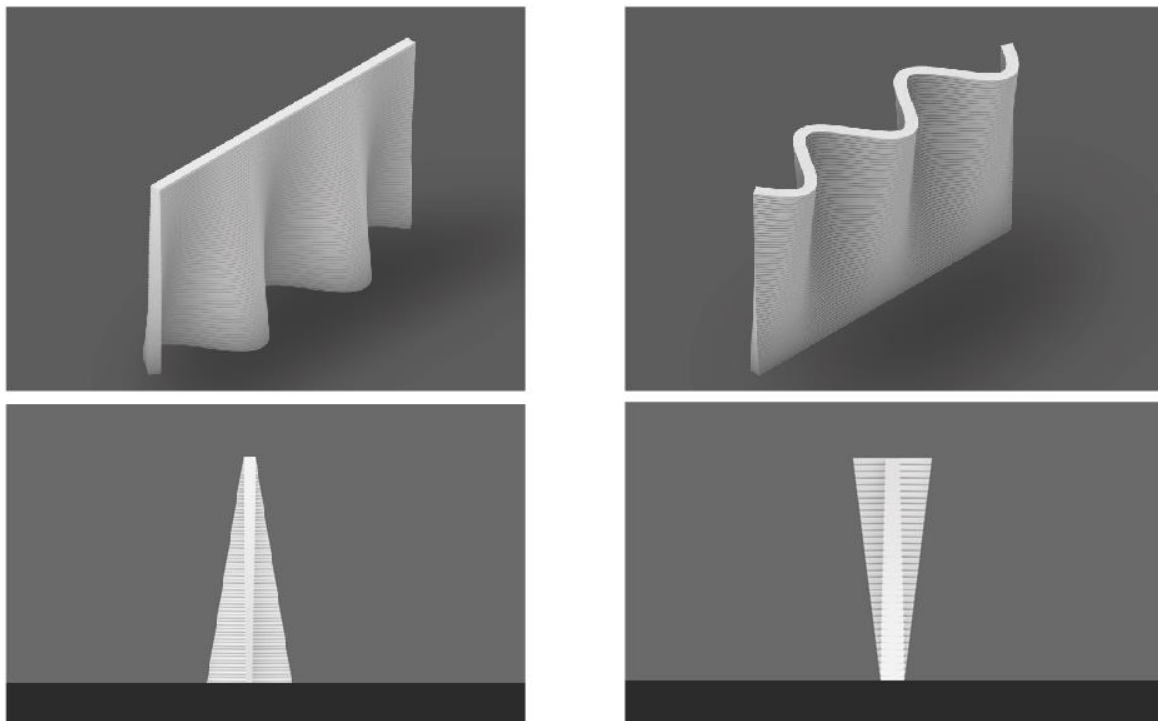
A 3D printed double wall with 30cm insulation has a u-value range between 0.12-0.14 W/m²*K.

11.4 STABILITY OF A 3D PRINTED WALL

Stability is one of the most important factors that need to be considered for a 3D concrete printing project.

- ▶ Fresh concrete has extremely low strength and stiffness.
- ▶ Concrete is thixotropic, which means vibrations will further weaken the structure in the early stage.
- ▶ For unstable structures, very small uncertainties in materials can influence the success of the print.

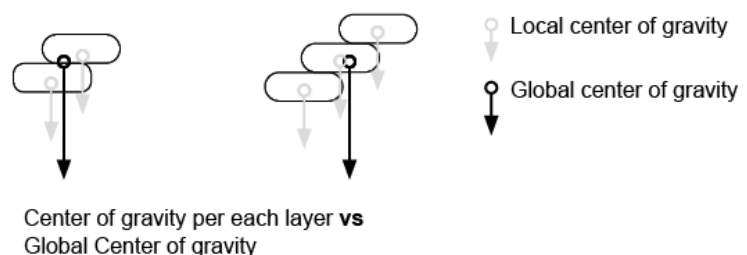
Geometry with a higher surface area on the bottom has more stability. To print an unstable wall, it needs accurate material and controlled environment.



11.5 OVERHANGS

The overhang in 3D printing means the extension of projection from the global centre of gravity. For printing a successful overhang, the global centre of gravity should be inside the support area.

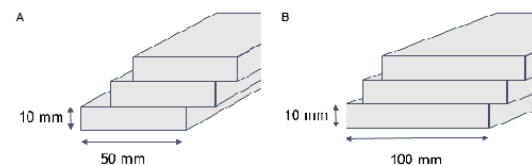
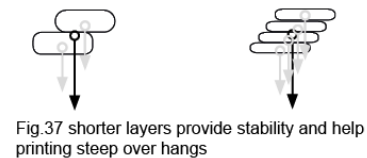
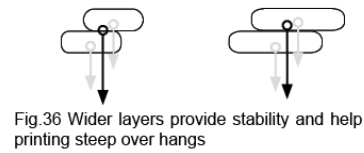
While printing an overhanging wall, it is not recommended to use the flaps with the nozzles. The flaps might cut off the layer below, which can ruin the entire print.



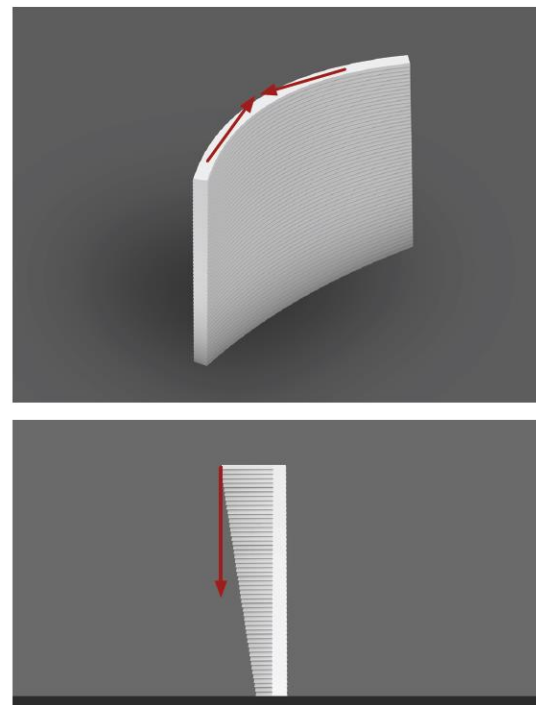
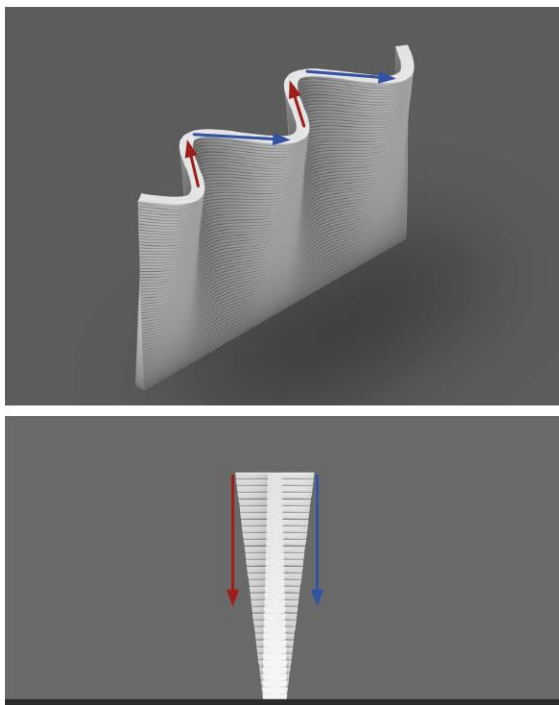
Printability of overhangs

The printability of overhang depends upon the following factors:

- ▶ Layer width: Wider layers help carry out steeper overhangs.
- ▶ Layer height: Lower layer height also play an important role in carrying out overhangs.
- ▶ Layer time: which is time needed to print one layer, this also relates to the size of the printed object. Larger objects would have a longer layer time, allowing the concrete to set initially and be ready for the next layers.
- ▶ Material properties: Shorter initial setting time can help printing steeper overhangs.
- ▶ Environmental condition: Controlled environmental conditions could ensure a successful print (Like temperature and humidity).



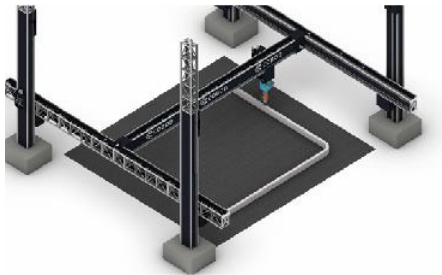
Normally, overhangs around 10 to 20 degrees are achievable.



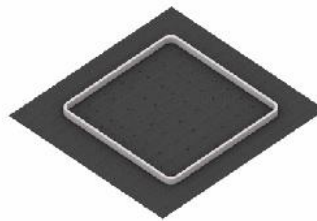
On the left, the load is evenly distributed on both sides of support base, and on the right the load is large and uneven which will make the model collapse.

11.6 3D PRINTED ROOF SLAB

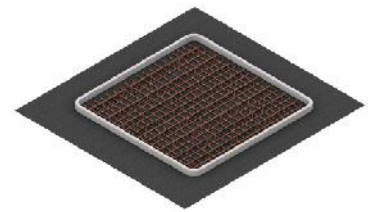
The workflow for a 3D printed precast roof slab consists of two stages. The initial stage/ prefabrication includes printing the formwork, inserting spacers for the reinforcement, reinforcement placement, and first layers of concrete. The second stage/onsite includes placement of the member over the building and the addition of the remaining concrete layer.



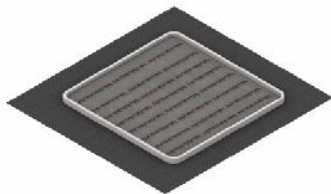
3D printing of the slab form work. The height of the form work printed depends on the thickness of the slab needed.



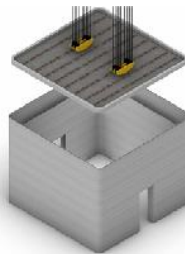
Spacers are placed at a regular interval. The spacers give an offset for the reinforcement from the floor level.



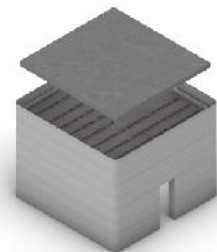
Reinforcement is placed over the spacers. The quantity and specification of the reinforcement should be according to structural drawing.



A first layer of concrete added over the reinforcement. For 20cm slab, 6-8 cm are usually filled with concrete offsite. There should be proper hooks for lifting the casted slabs.



The casted slabs are assembled onsite using lifting mechanism.



Prior to the final casting a similar layer of mesh reinforcement was placed on top of the existing reinforcement. This mesh reinforcement will be tied with structural reinforcement (Column) for structural integrity.

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