COBOD

Design manual

for 3D Construction Printing (3DCP)
October 2021

Introduction

This is a manual for the design of 3D printed buildings. If the following design criterias 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 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 labour done by local construction companies.

Index

1.Workflow scheme

Typical workflow for 3DCP

INITIAL MANUAL WORK

1 Excavation / initial grounding → Constructed according to local recommendations

2 BOD2 installation → Erection of 3D printer

DURING 3D PRINTING

3 Top foundation →
1. Plinth/top foundation outline
2. Implementation of plumbing, electricity etc.
3. Casting

4 3D printed walls →
1. Wall design depending on structural method/preferences
2. Creating voids for doors and windows
3. Implementation of wiring etc.

5 Horizontal constructions →
1. Slab (for multiple storey buildings) incl. potential casting
2. Roof construction

FINISHING

6 Post-print finishing →
1. Optional plastering, painting etc. of 3D printed elements
2. Inserting windows, doors etc.
3. Roof installation

7 BOD disassembly → Disassembly and packaging of 3D printer.

2. 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 centre 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. 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.

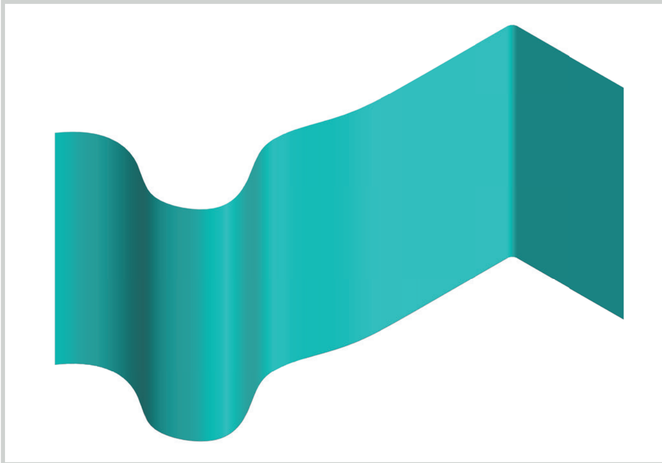


Fig 01 : Surface representing the axis of the 3D printed wall in CAD

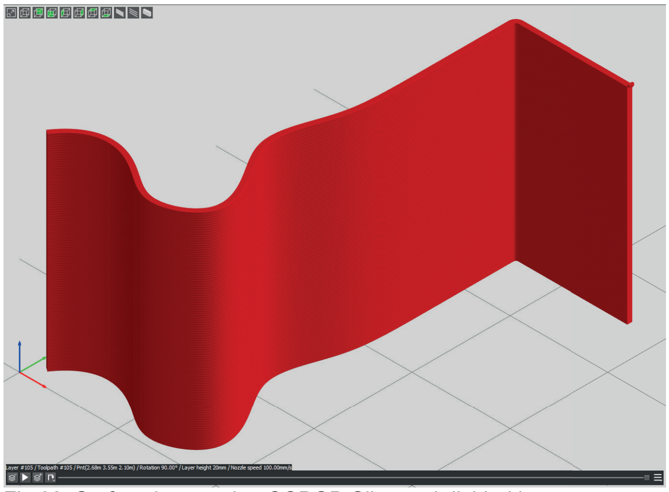


Fig 02 :Surface imported to COBOD Slice and divided into layers of certain height and width

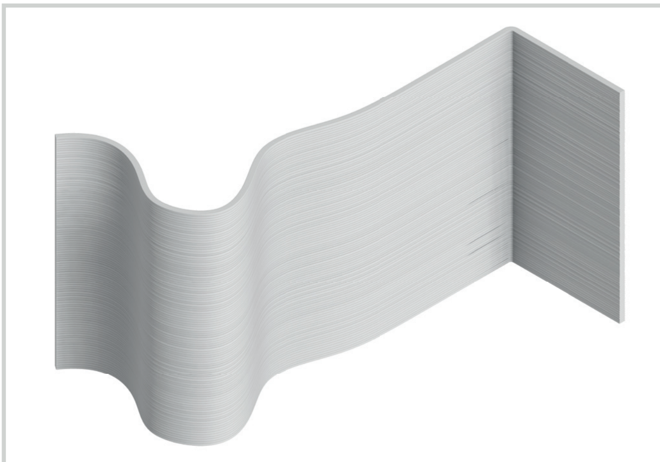
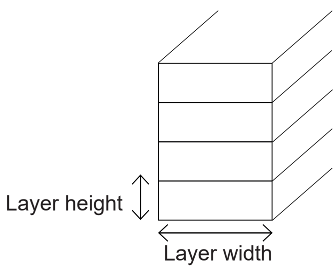
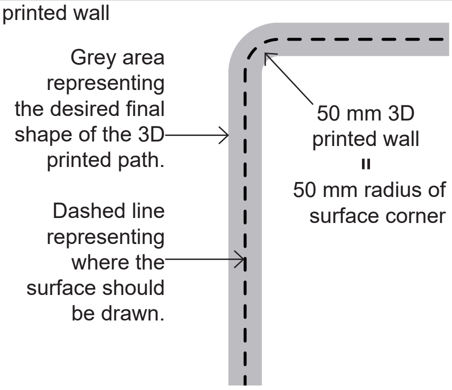


Fig 03. 3D printed wall

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.





2.1 Printable area and installation

Every printer has its own printable areas(PA).It is very important to consider the printable area before designing the building. Besides that, It is also important to leave 60-80 cm in the Y direction to ensure the sapace needed for the X-Axis to go down without coliding with the printed building while cleaning the print head.Thus, the printer can not print in that area.

Fig.04 shows the loss in printable area

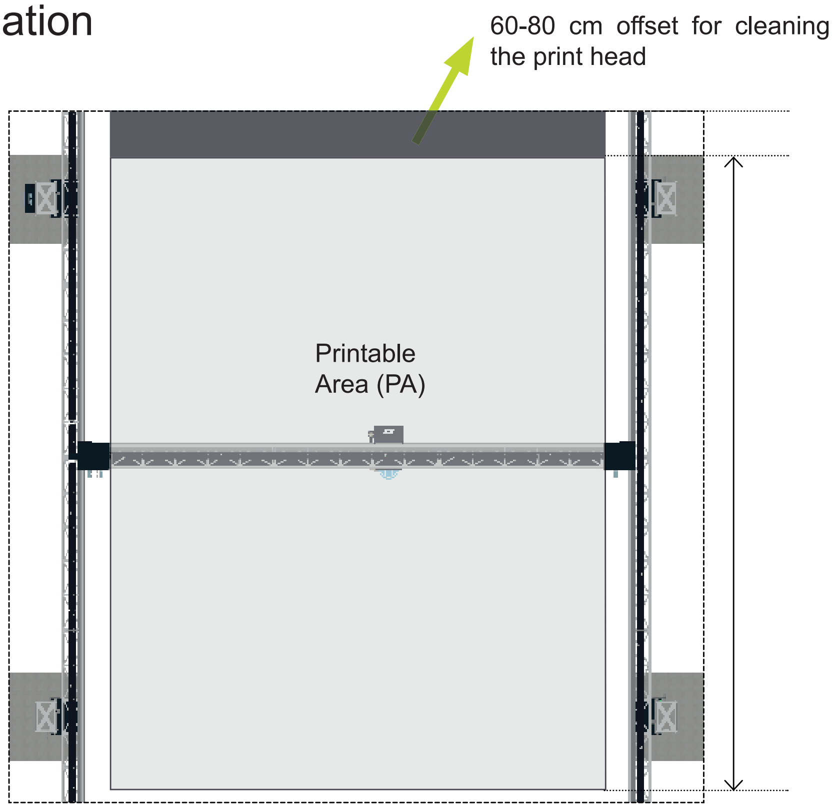


Fig 04. Printable area

Printable area (PA)
Offset area

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.

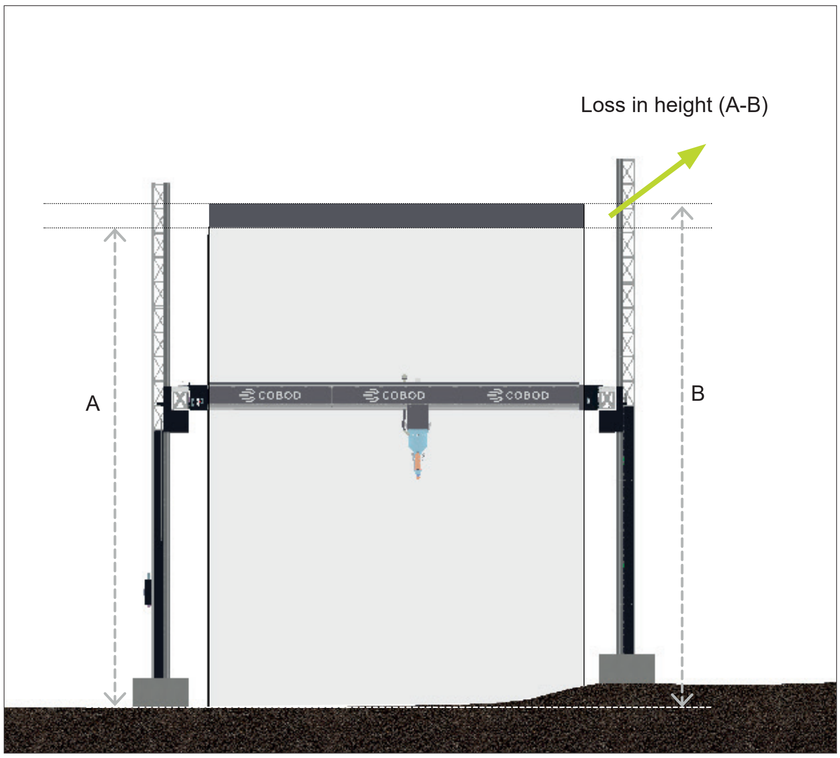


Fig 05. Loss in height due to differential base elevation.

Printable area (PA)
Loss in height

3. 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.

3.1 Base 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:

A. Soil
B. Structural load (height and size of building)
C. Shape and size of the building

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

1. Isolated foundation
2. Piles foundation
3. Raft foundation
4. Slab on grade

3.2 Top foundation

For the top part of the foundation, waterproofing and insulation (if required by the local building code) should be implemented before casting the slab. Figure 4 shows the plumbing pipe sticking out of the base foundation and the 3D printed top part.

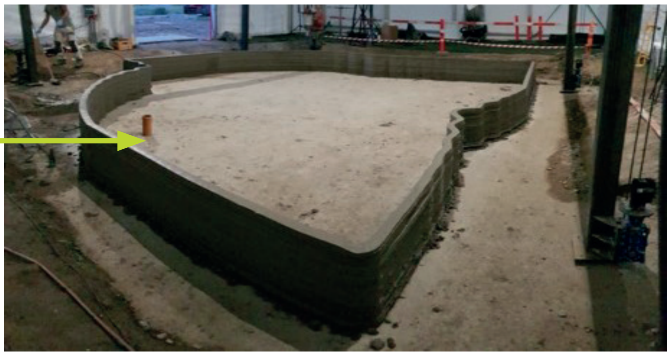


Fig. 6: 3D printed outline for the foundation of the BOD building

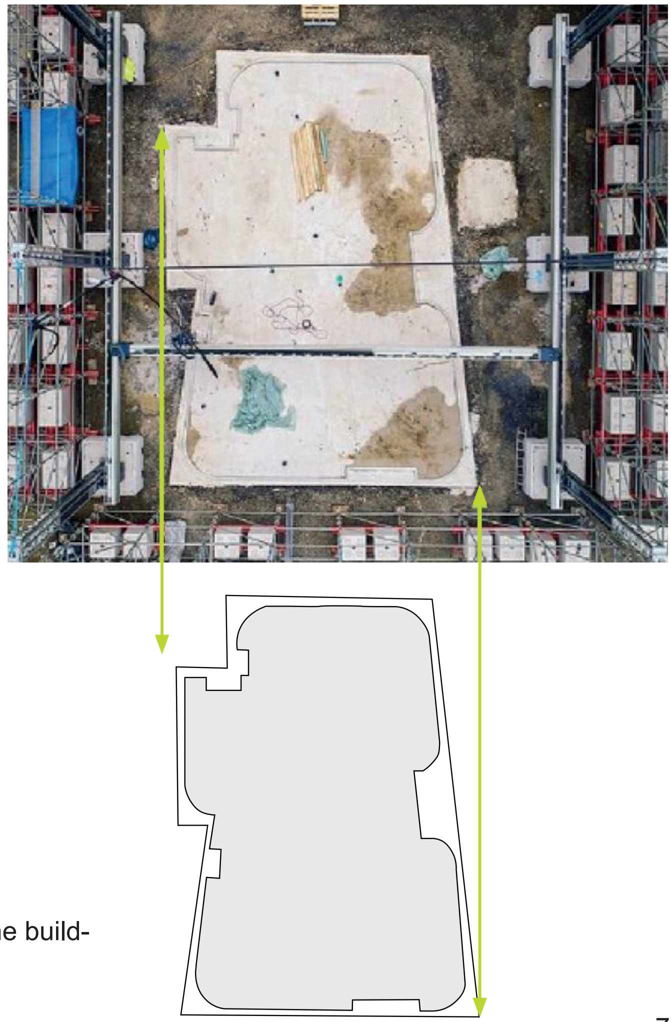


Figure 7.Base foundation size limited to just fit the shape of the building, but simplified to be made manually.
Top part of the foundation printed by the 3D printer.

3.3 3D printing formwork for casting of foundation

Fig. 6 and 7

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. 6., 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.

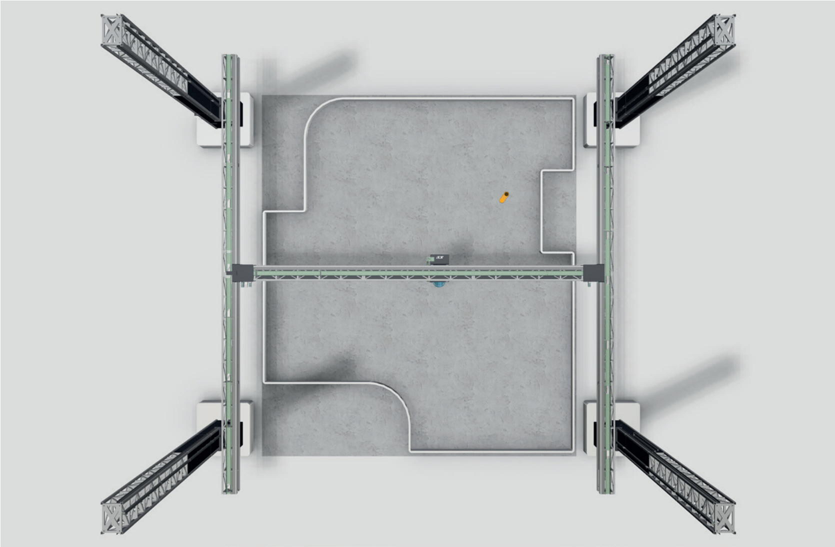


Fig. 6

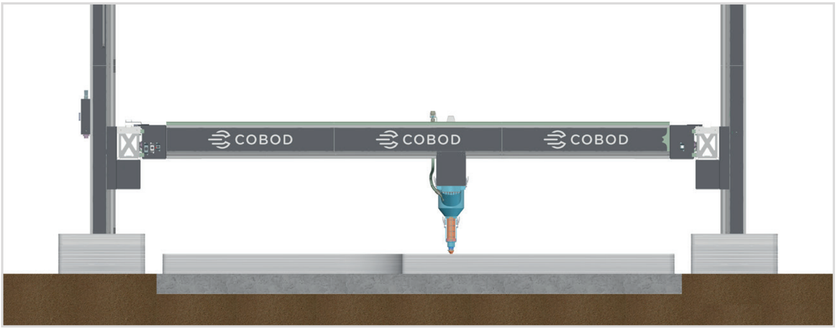


Fig. 7

3.4 3D printing a plinth beam foundation

Fig. 8 and 9

The height of the extruder allows the 3D printer to go below ground level.

Allowing the 3D printer to go below ground level can be utilized as shown in the referenced figures.

In this example, a double wall is created as a formwork for the plinth.

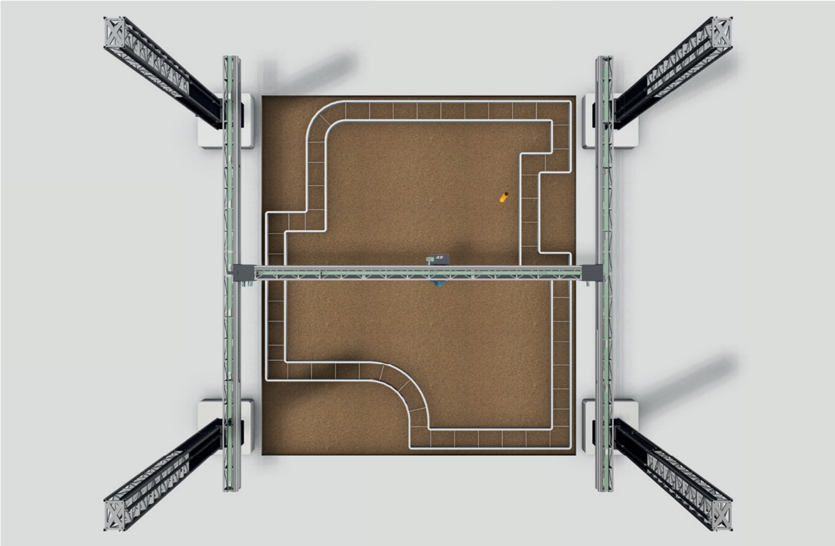


Fig. 8

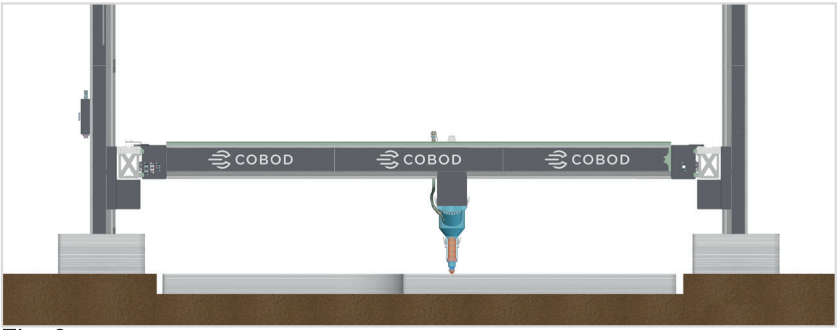


Fig. 9

4. 3D printed walls

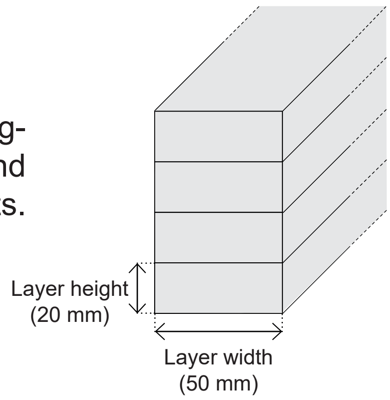
3D printing offers almost unlimited opportunities for how you can design the walls. In this section, five different types of walls are illustrated. These can be combined or altered as desired.

Wall type examples:
A. Hollow double wall with reinforced columns
B. “Snake wall” (different variations)
C. Double wall, also known as a sandwich wall
D. Bespoke double wall
E.Single wall

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:

1. Wall type (loadbearing/non-load bearing)
2. Wall thickness
3. Insulation type and local requirements
4. Avoiding thermal bridges if necessary (depending on local building code)
5. Layer height
6. 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.

4.1 Wall types

Based on the structural performance and Easness of production different wall types are used.

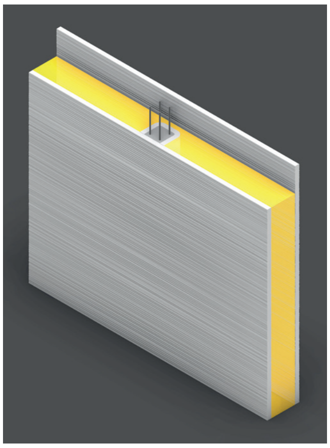


Fig 12. Hollow wall with integrated columns

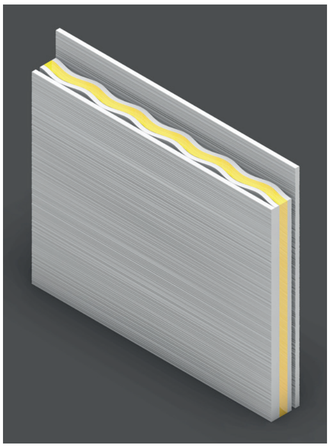


Fig 13. “Snake wall”

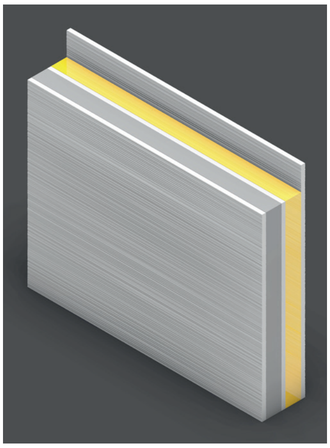


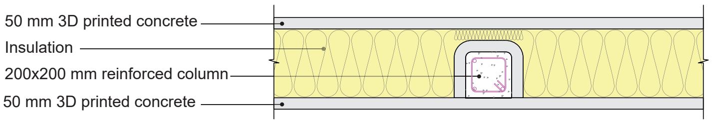
Fig 14. Double wall or “sandwich wall”

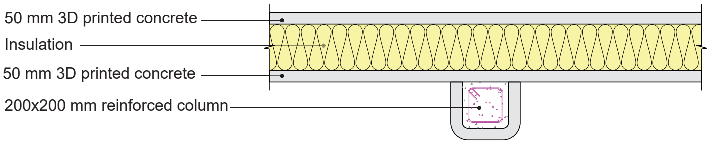
Fig 15. Bespoke double wall

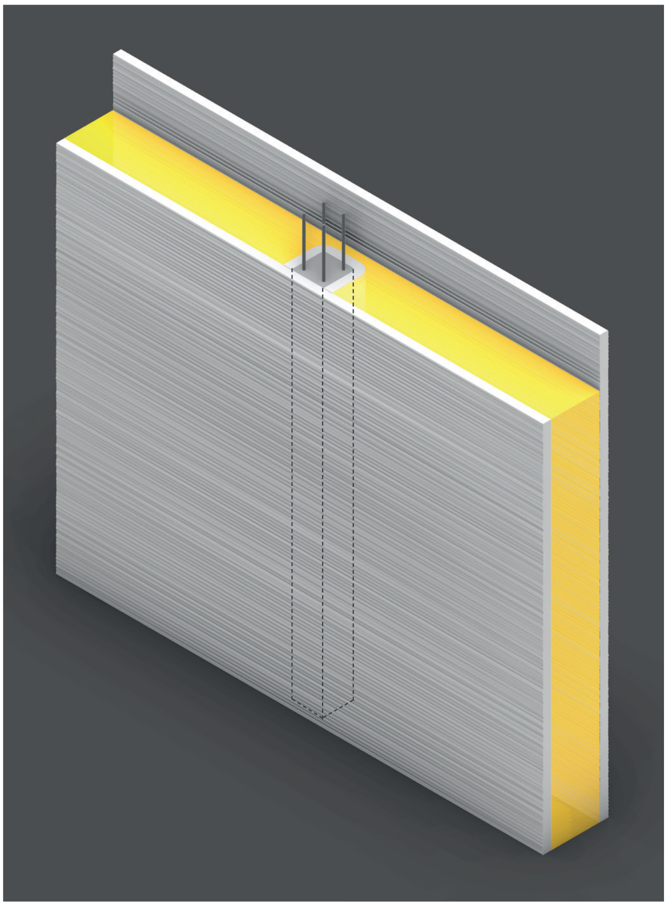
4.2 Selection of different wall types

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).



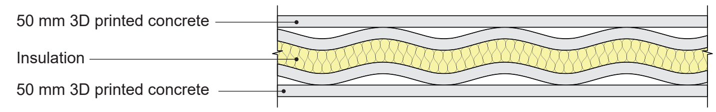


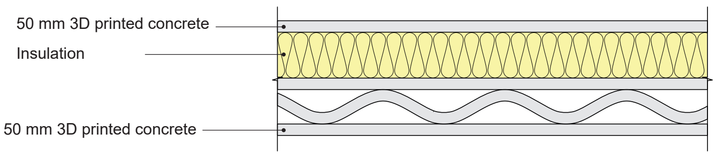


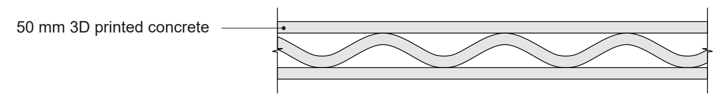
B. “Snake wall”

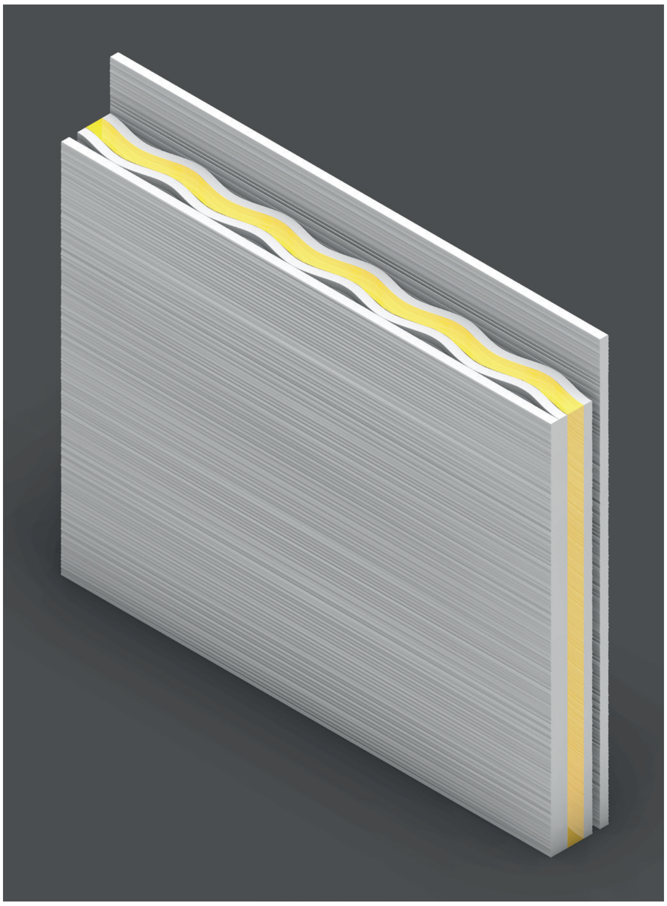
Creating internal curvy wall sections acting as structural elements.

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



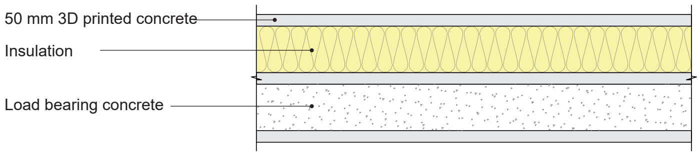


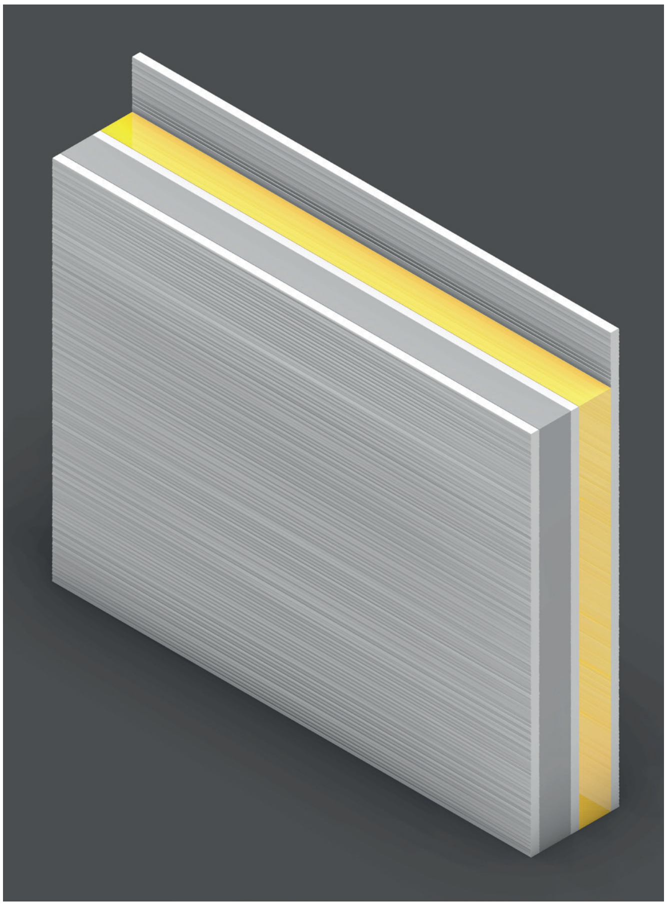




C. Double wall or “sandwich wall”

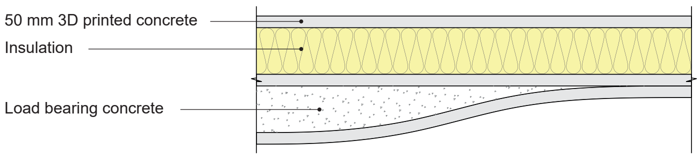
Loadbearing concrete back wall with parallel insulation layer.





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.

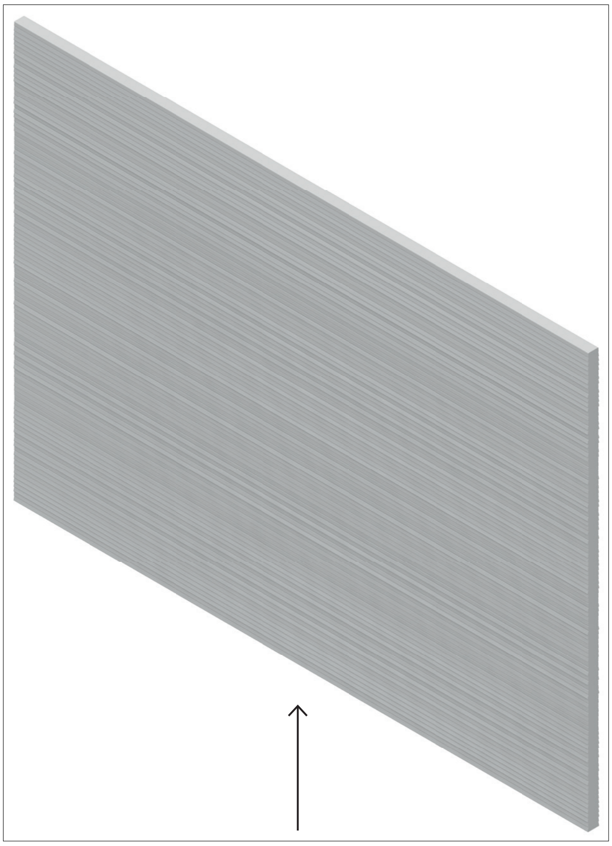


Fig 16. Straight single wall

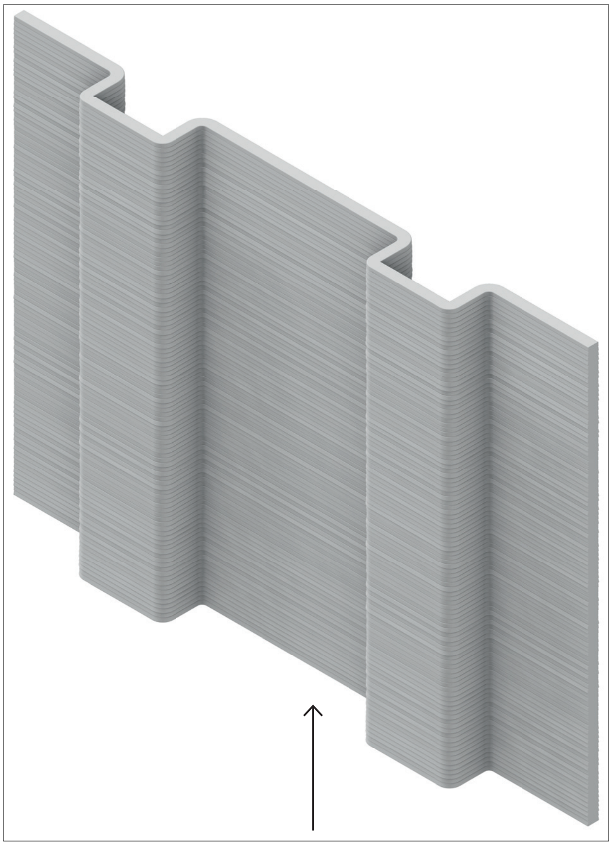
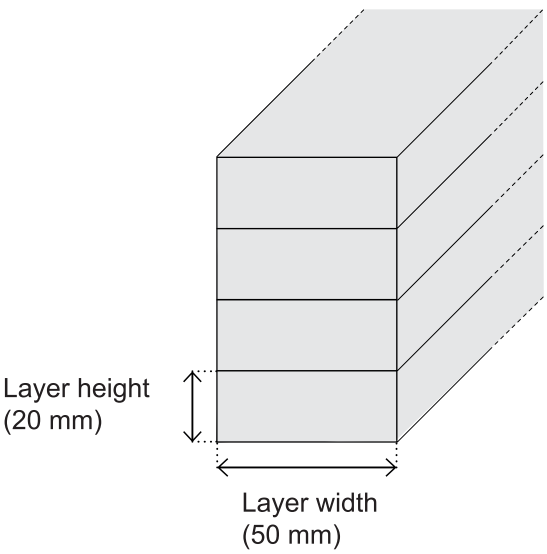


Fig 17. Example of single wall with stabilizing path



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.

5. Windows

Voids for both windows and doors should be subtracted from the modelled surfaces. Underlying walls should be created individually (Fig 18) 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 19). 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 20). 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:

1. Wall thickness and type (see Wall types section)
2. Avoiding thermal bridges (if necessary)
3. Window span and height
4. Window sill
5. Frame location (towards the exterior or interior)
6. Window side support
7. Lintel design

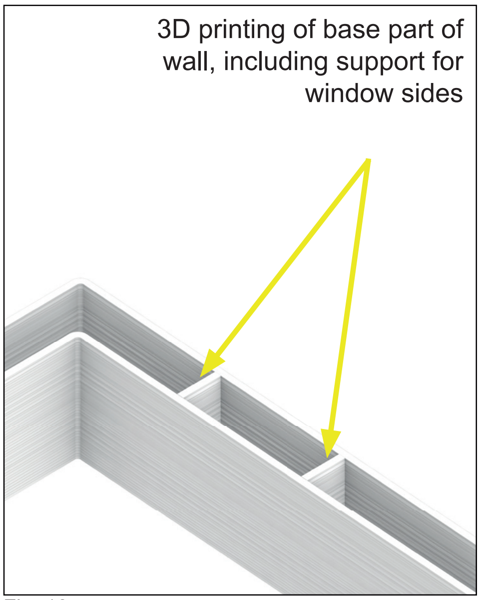


Fig. 18

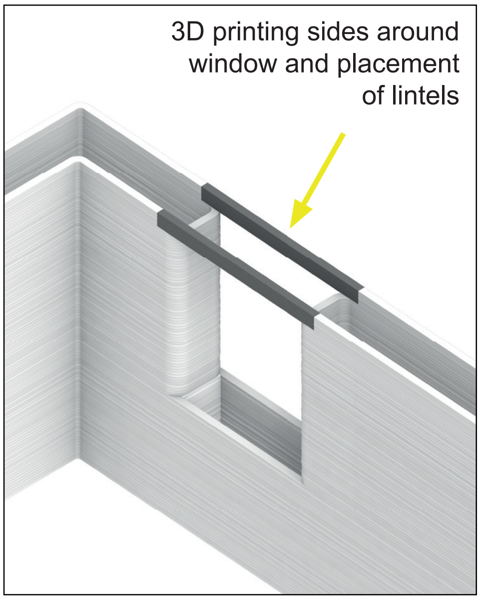


Fig. 19

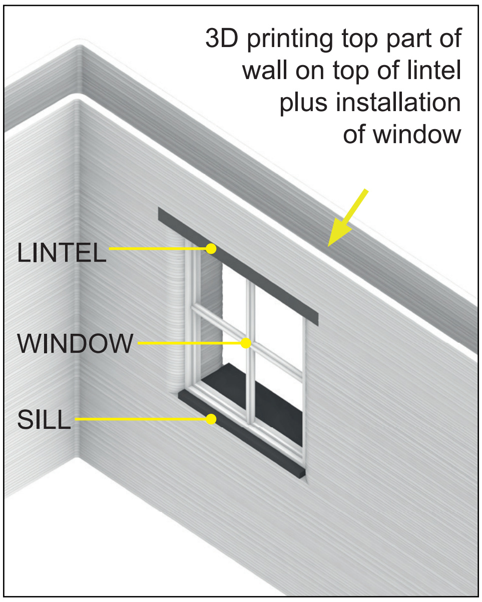
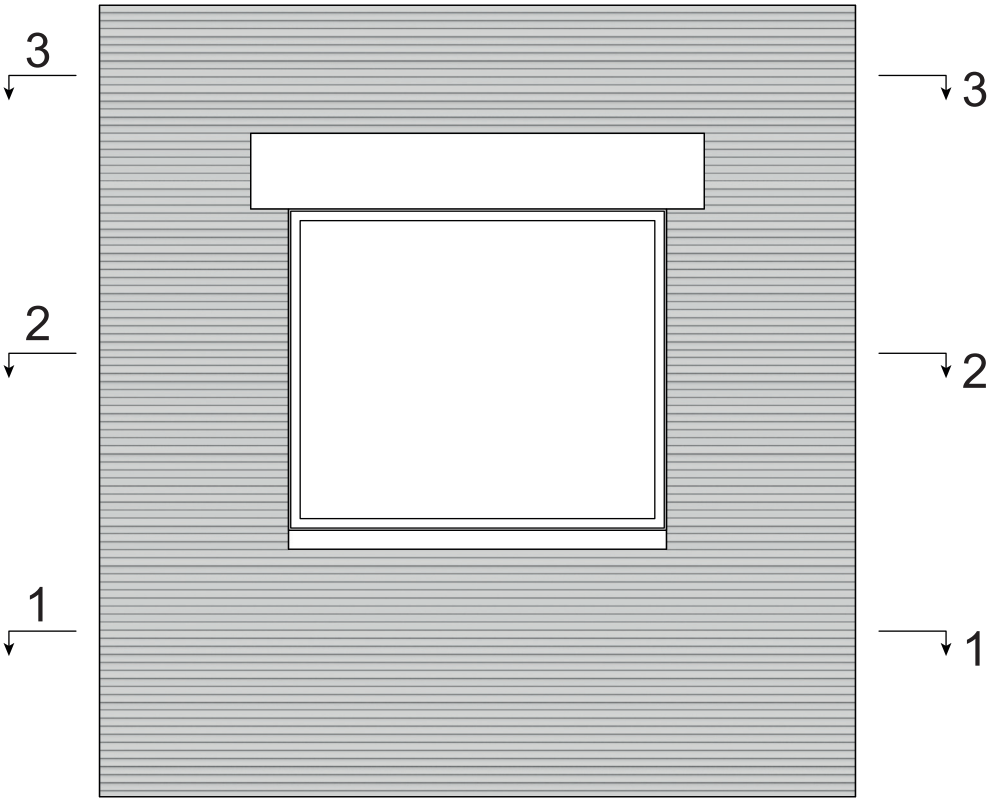
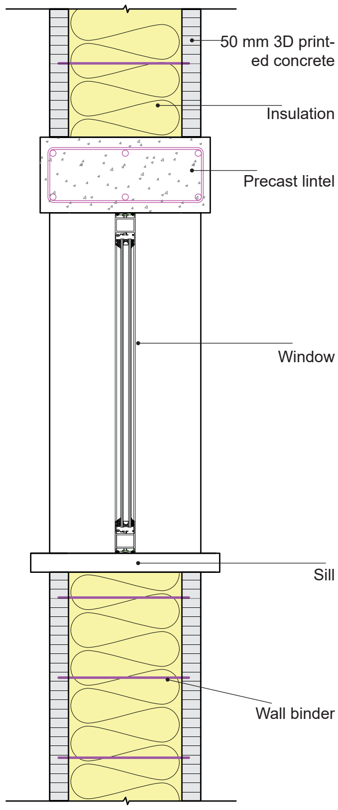


Fig. 20

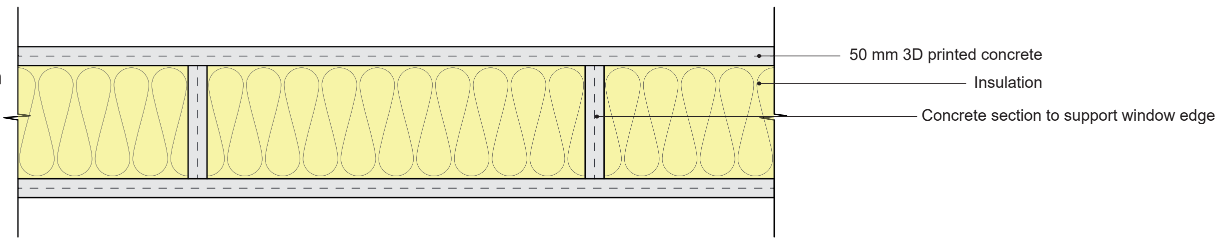
5.1 Precast concrete lintel

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.

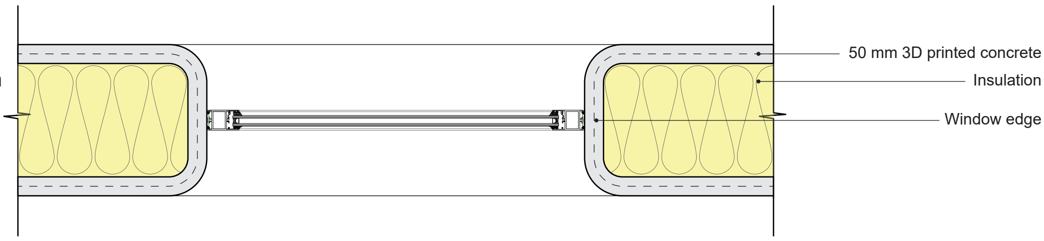




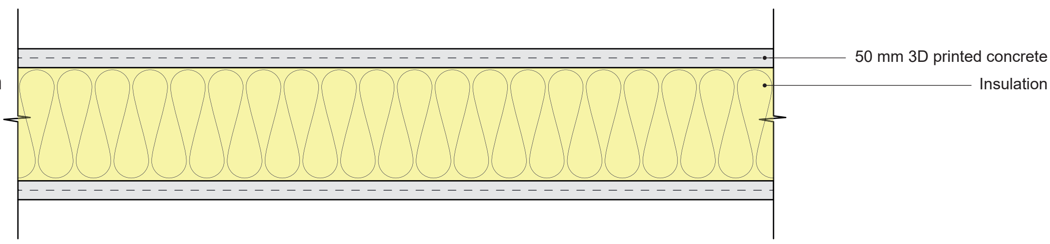
Plan section 1



Plan section 2

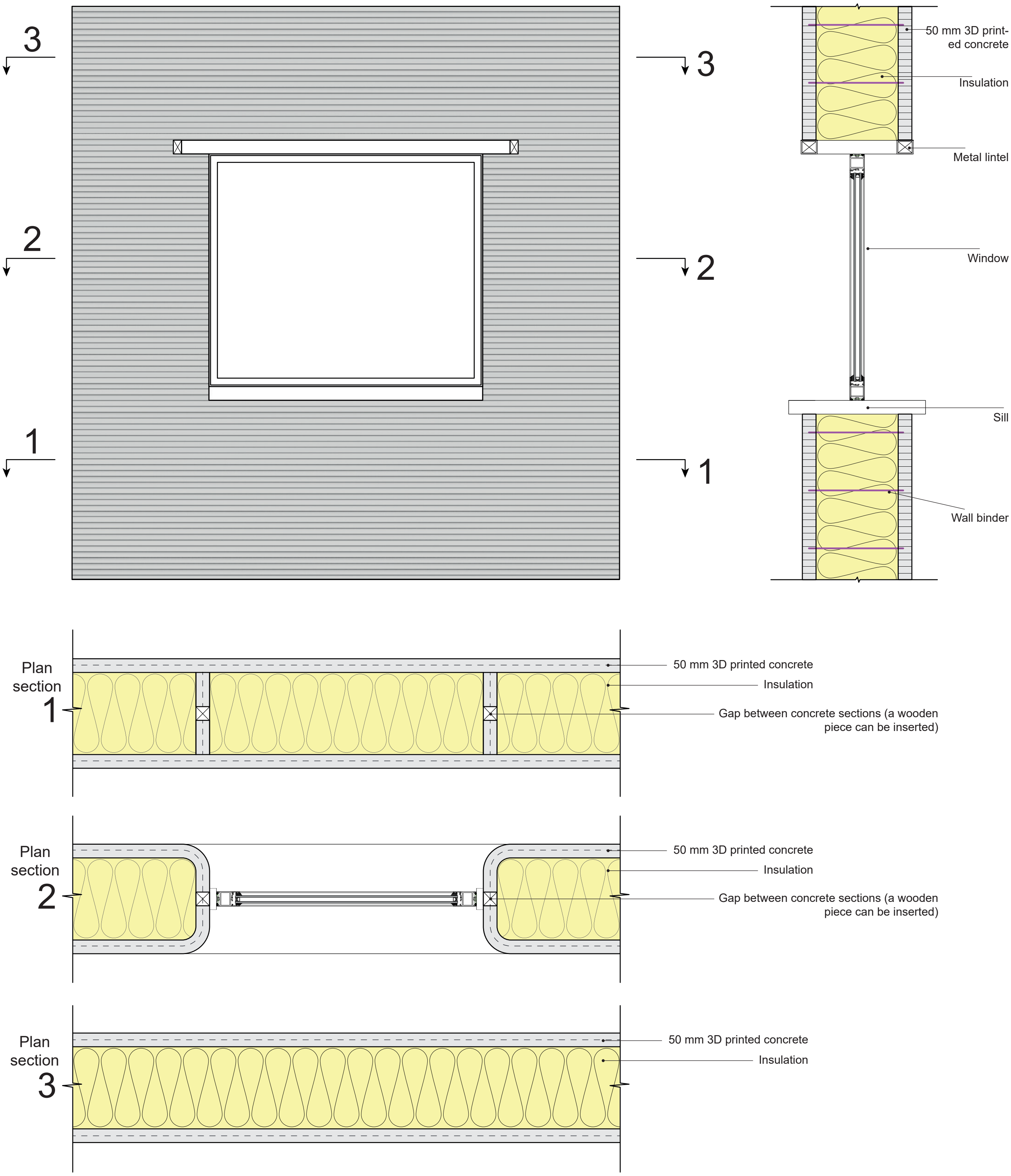


Plan section 3



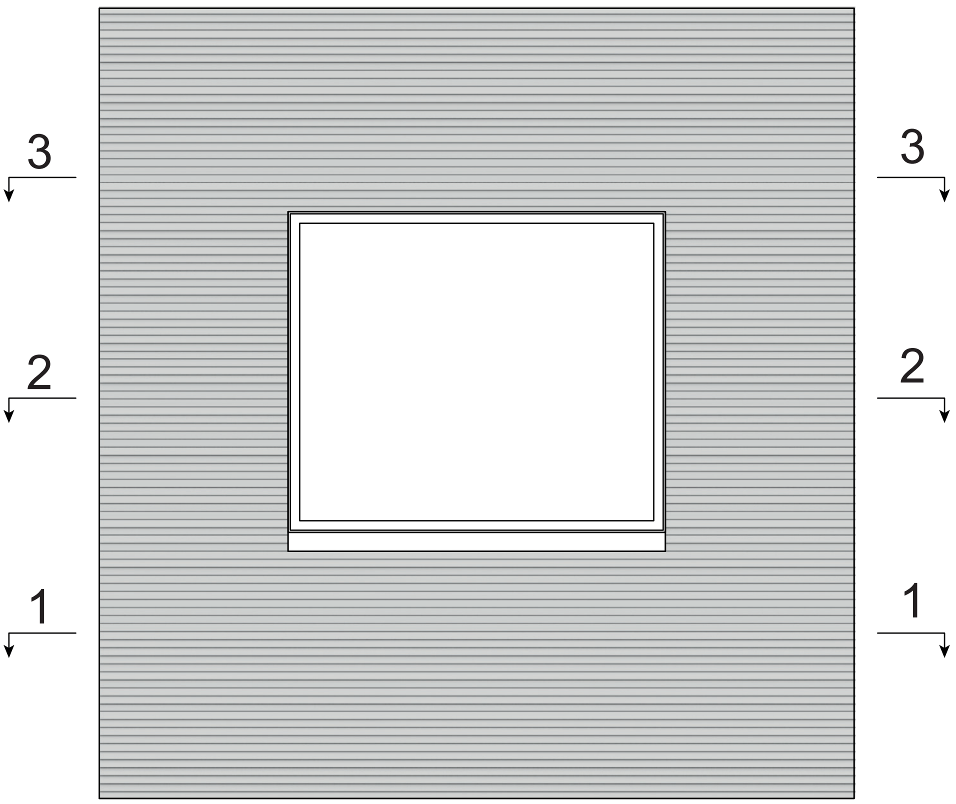
5.2 Metal lintel

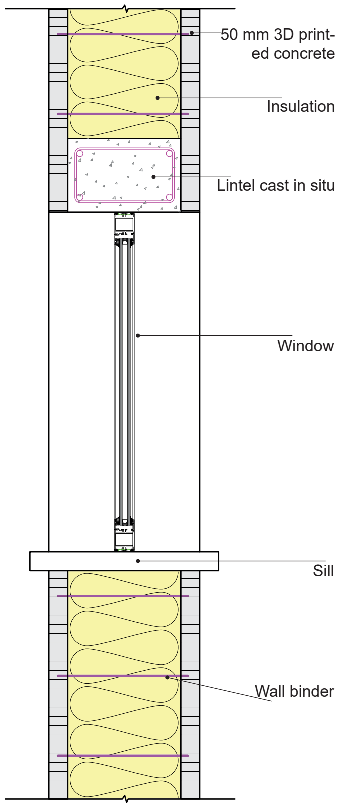
Using a metal lintel allows for a very slim expression, since the size of the lintel can be limited.
In this example, a method to avoid thermal bridges is shown.



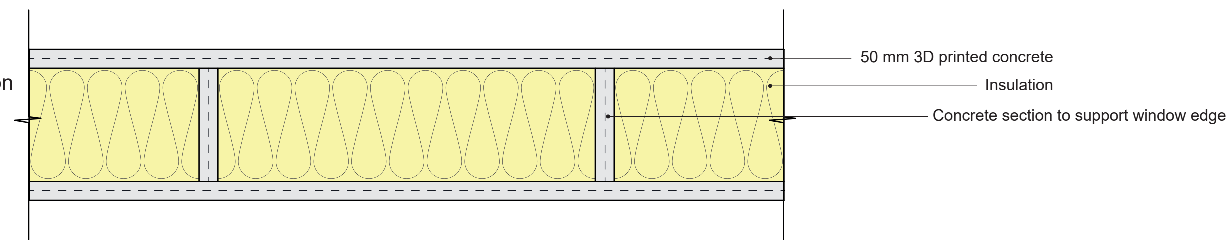
5.3 Lintel cast in situ

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.

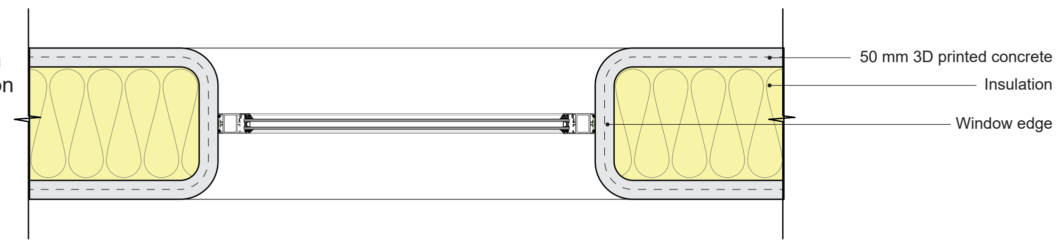




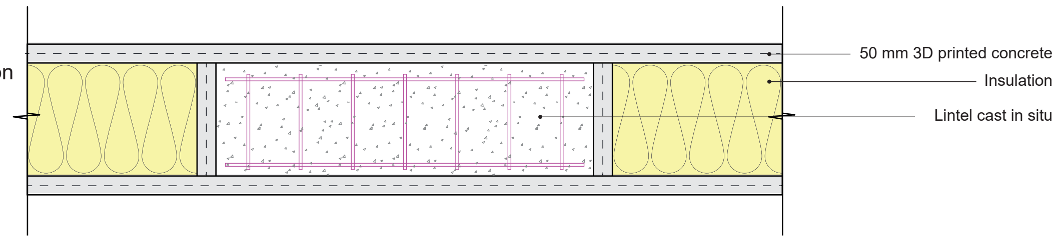
Plan section 1



Plan section 2



Plan section 3



6. Doors

6. 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 dependant on the design acquirements.

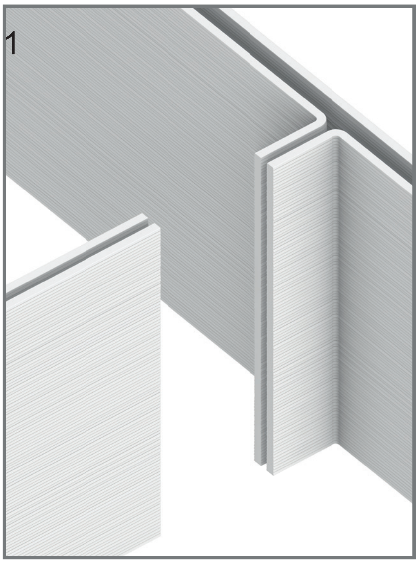


Fig. 21

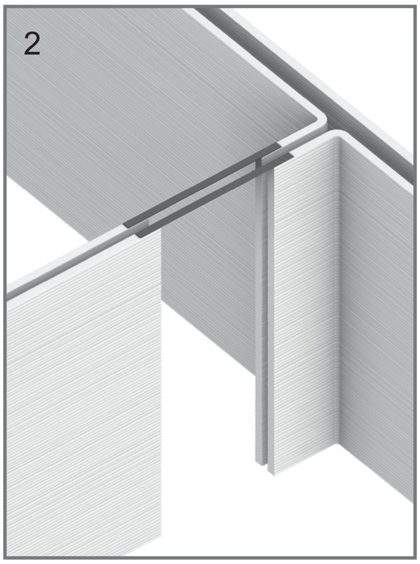


Fig. 22

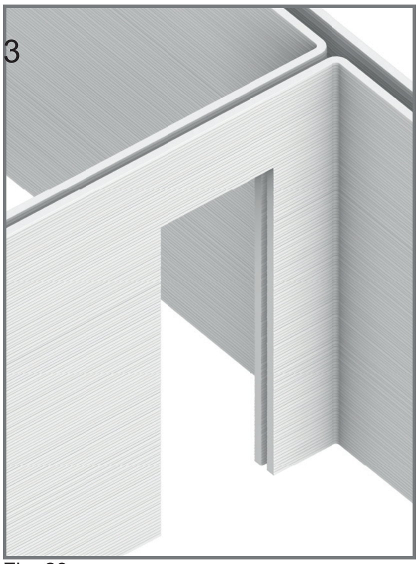


Fig. 23

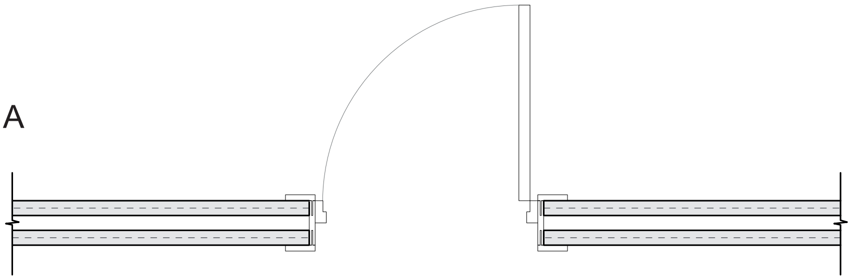
Fig. 24

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

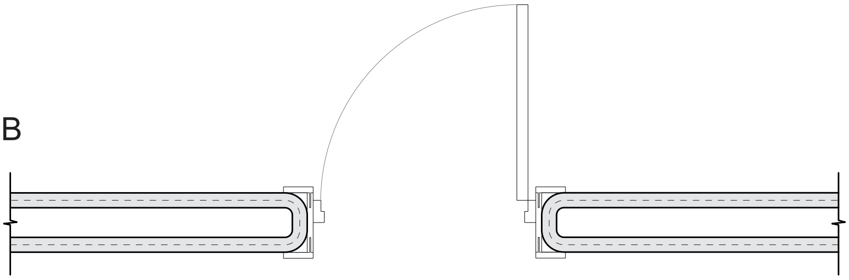
A) The 3D printed wall ends abruptly at the opening edge. This allows for slimmer double walls but will require manual finishing since the edges of these walls will most likely need to be cut even or plastered to allow for a smooth installation of the door.

B) The 3D printed wall is created a 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.

A

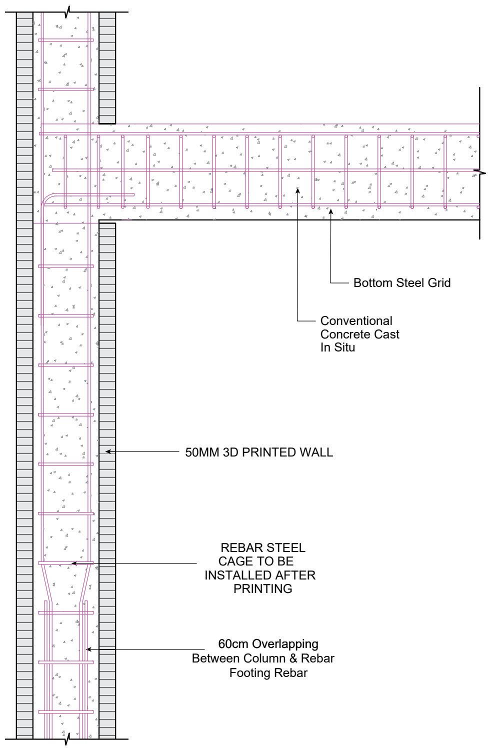


B

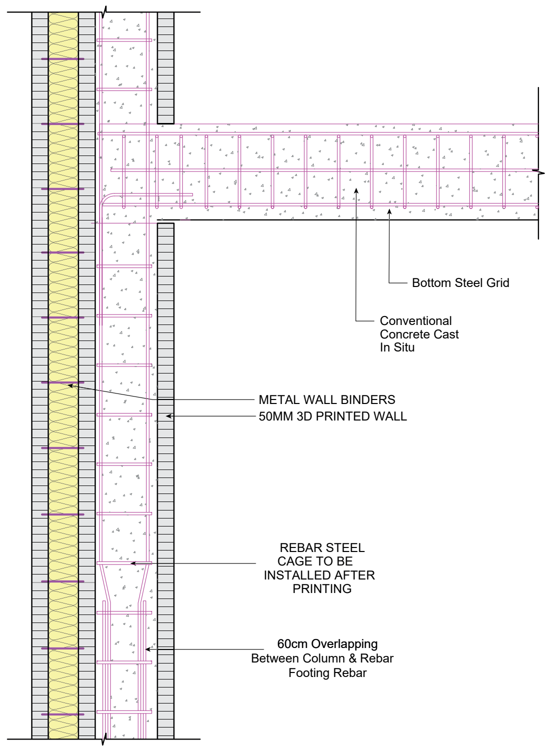


7. Slab

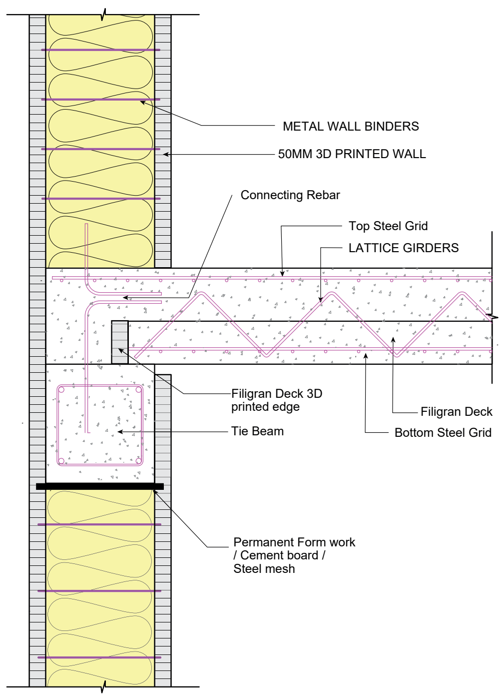
Slabs will be constructed by your local contractor. Different slabs can be used, including:
1. Cast in situ RCC slab (example A + B)
2. Precast slabs (hollow core, double T, etc.) (example C)
3. Filigree slabs (recommended when the shape of the building is complex and can be 3d printed) (example D)
4.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



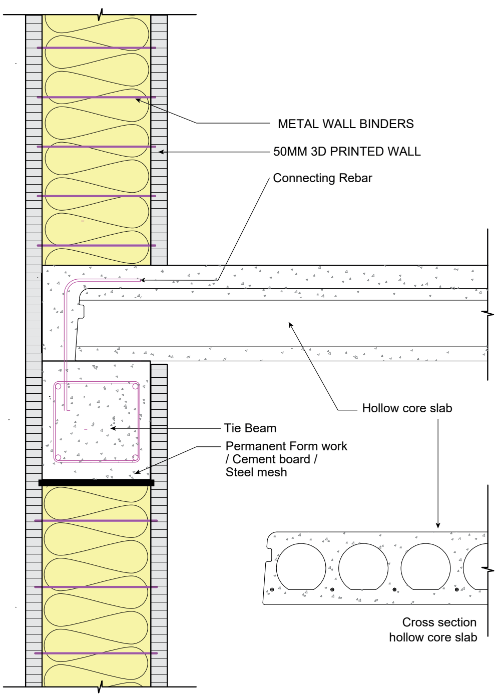
Ⓐ Concrete slab/reinforced column connection



Ⓑ Concrete slab/reinforced column connection with additional insulation



Ⓒ Filigree slab

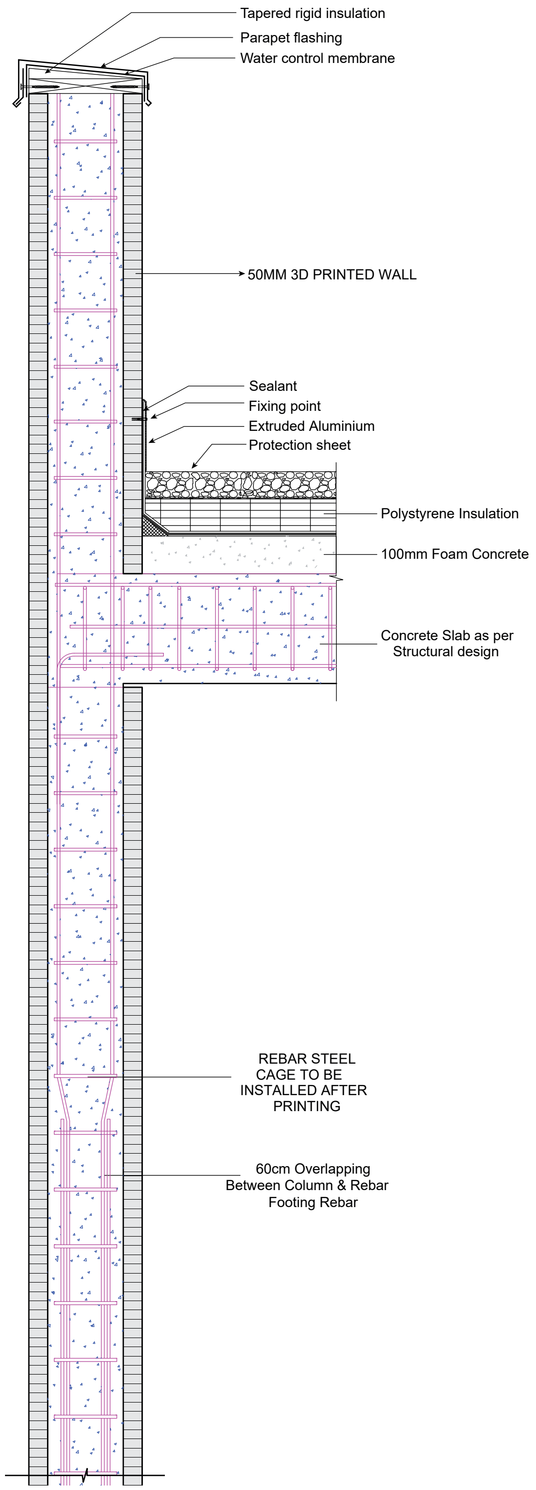


Ⓓ Hollow core slab

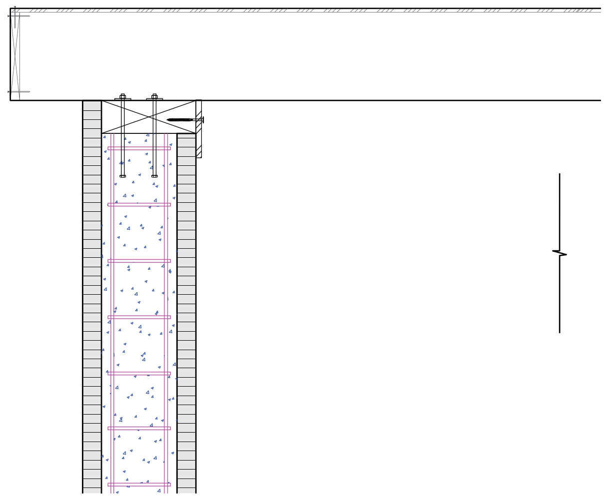
8. Roof

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.

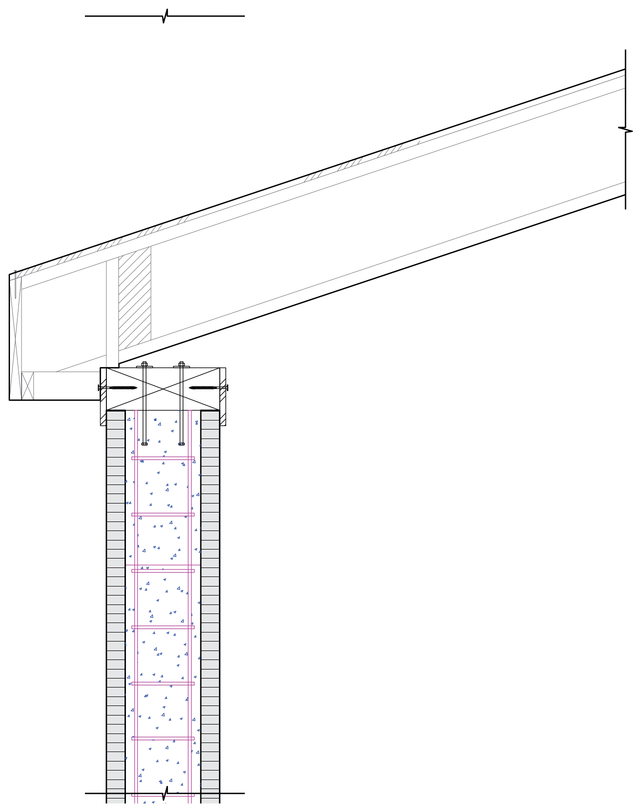
What is shown is the joint connection between the roof and the 3D printed walls underlying the roof.
The type of roof could be a wooden or steel structure or a reinforced concrete structure.



(A) Flat roof with parapet (can vary in height)



(B) Example of roof joint connection for a generic flat roof



(C) Example of roof joint connection for a generic slanted roof

9. 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.

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

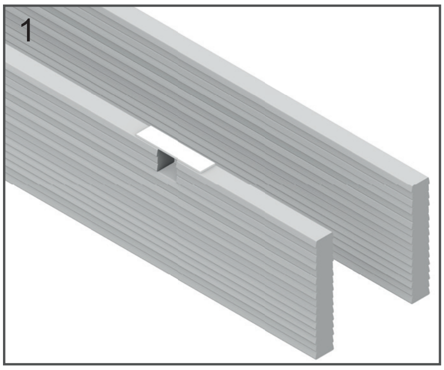


FIg 25. A void for the electrical sockets has been made in the CAD file from which the gcode for the 3D printer is created. At the point where the print reaches the top of the electrical socket, a metal piece is inserted.

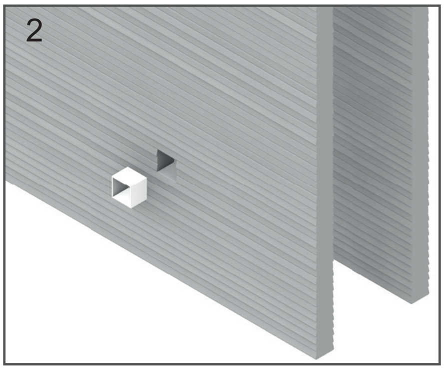


Fig 26. This allows for the rest of the wall to be printed on top, and the socket can then be inserted.

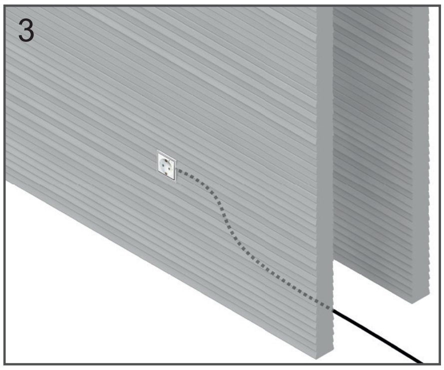


Fig 27. placed in between the walls.

10. 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 out-lets, 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.

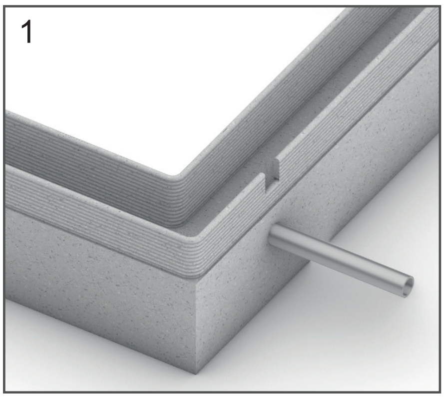


Fig 28. The main water line is placed in the foundation before casting.

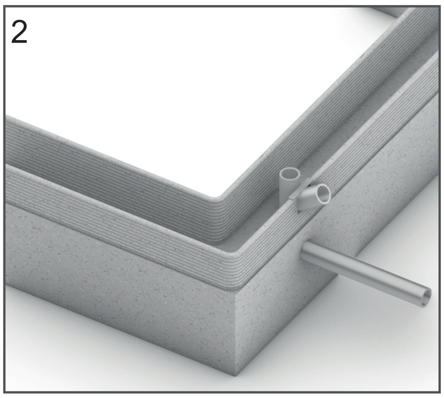


Fig 29. A void for the plumbing voids has been made in the printable file from which the G-code for the 3D printer is created. At the point where the print reaches the top of the void, a metal piece is inserted.

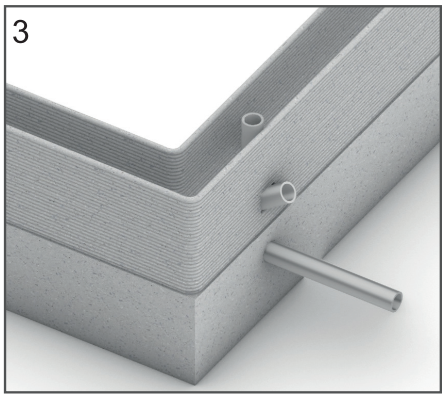


Fig 30. The bifurcated pipes from the primary lines are placed in between the walls.

11. Wall finishing

11.1 Print using the flaps

The nozzle width define the width of a single wall and the nozzle type defines the texture of an untreated 3D printed wall. A Two layered flaps attached to the nozzle can produce more even plane texture (Fig 31). This can minimize the manual labour of finishing after post printing.

Fig 31. Print using two layered flap

Fig 32. Print without flaps

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.

Plaster

Paint

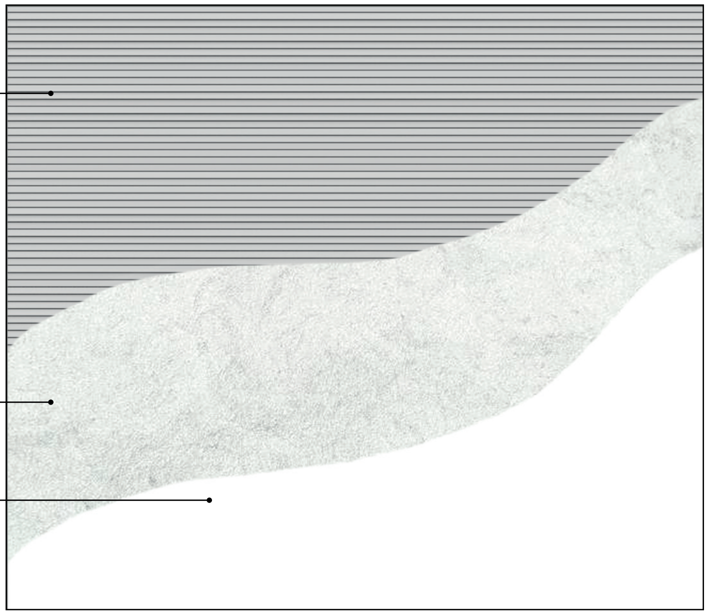


Fig 33. Wall finishes of a 3D printed wall

12. Properties of a 3D printed double wall

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

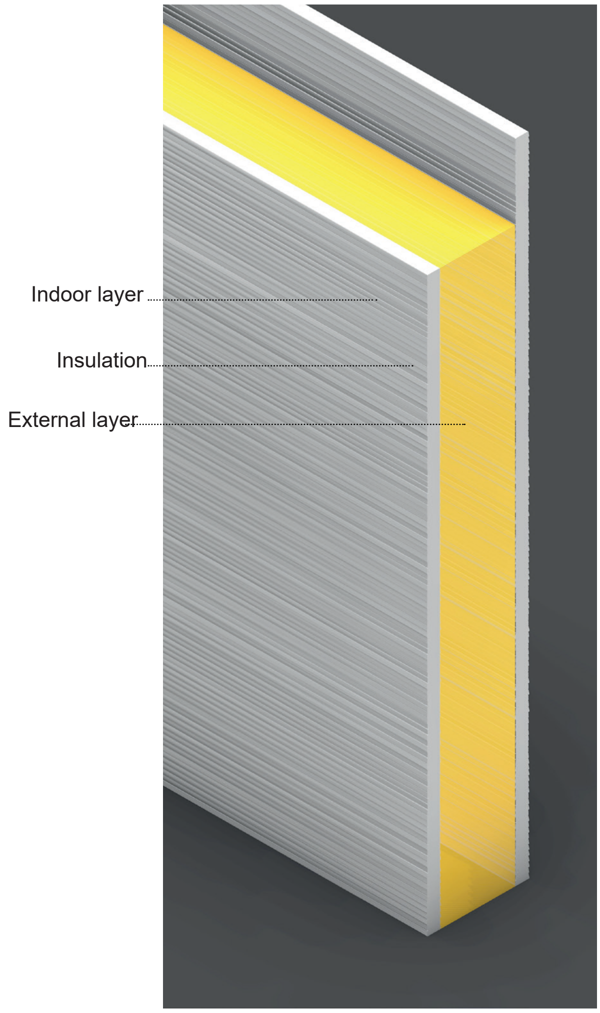
The thermal proprties of a 3D printed wall depends upon:

- Thickness of the individual layers
- Thickness and propreties of the insulation material used
- Density and U-value of the insulation material

Different insulating materials can be used for example:

- Polyurethane foam insulation
- Rockwall
- 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.



	Metric Unit	Imperial Units
Density	2400 kg/m3	137 lbs/ft3
Thermal conductivity (u)	~ 2.4 W/m*K	~ 1.39 BTU/(h*ft*°F)
	For one cm	**For one inch**
Thermal Resistance (r)	~ 0.004 m2*K/W	~ 0.060 h*ft2*°F/BTUT
Thermal Phase Shift	~ 14 minutes	~35 minutes

Table 01. Thermal properties of a 3D primted double wall exulding insultion

12.1 Concrete thickness vs Thermal phase shift

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

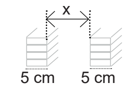
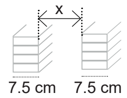
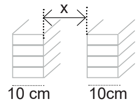
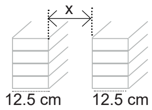
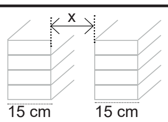
	Total concrete thick-ness	Thermal Resistance		Thermal Phase Shift
	10 cm / ~4 inches	0.04 m2*K/W	0.23 ft2*h?°F/ BTU	2 hours, 20 min
	15 cm / ~6 inches	0.06 m2*K/W	0.35 ft2*h?°F/ BTU	3 hours, 30 min
	20 cm / ~8 inches	0.08 m2*K/W	0.47 ft2*h?°F/ BTU	4 hours, 39 min
	25 cm / ~10 inches	0.10 m2*K/W	0.59 ft2*h?°F/ BTU	5 hours, 49 min
	30 cm / ~12 inches	0.12 m2*K/W	0.71 ft2*h?°F/ BTU	6 hours, 59 min

Table 02. Thickness of the layer vs Thermal phase shift

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 ap-prox. thermal phase shift of 2 - 5 hour without insulation.

12.2 Insulation properties

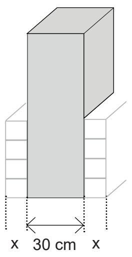
	Insulation type (loose fill)	Blown Cellulose, 30 cm		Mineral Wool, 30 cm	
	Total u-Value	0.14 W/m2*K		0.12 W/m2*K	
	Total r-Value	7.54 m2*K/W	42.8 ft2*h*°F/ BTU	8.61 m2*K/W	48.9 ft2*h*°F/ BTU
	Total Phase Shift	10 hours, 50 minutes		7 hours, 40 minutes	

Table 03. Insulation properties

Note : x is the width of printed layer

Regarding fire safety, Mineral wool is non flammable, cellulose is mixed with fire retardants.
No special precautions are to be taken against fires in the case of loose fill mineral wool.
For loose fill blown cellulose, the firemen will want to remove parts of the insulation to eliminate all embers.

Materials with less u-value, higher density and specific capacity are preferred for a better thermal performance.

The phase shift and thermal resistance can be enhanced by using the right insulation material.

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

13. 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. In order to print an unstable wall, it needs accurate material and controlled environment.

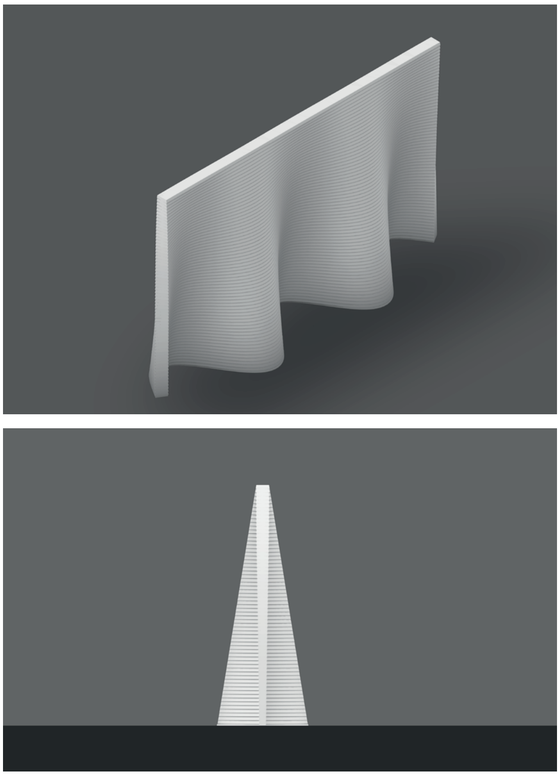


Fig 34. More surface area at the bottom curve - Stable

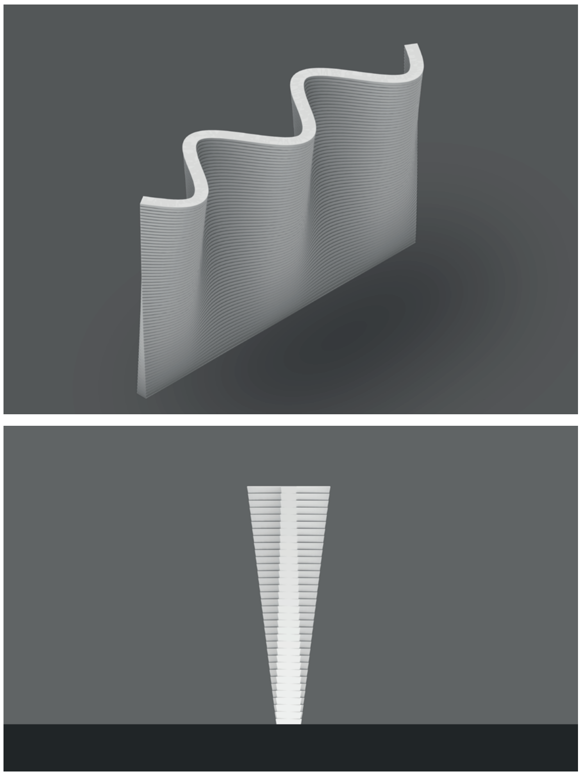
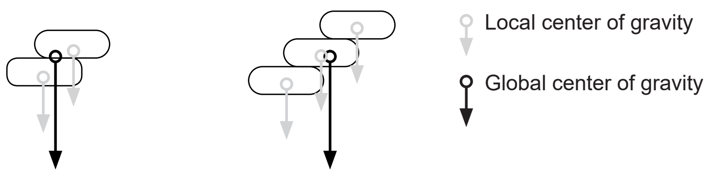


Fig 35. Less surface area at the bottom curve - Less Stable

13.1 Overhangs

The overhang in 3D printing means the extension of projection from the global center of gravity. For printing a successful overhang, the global center 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



Center of gravity per each layer **vs**
Global Center of gravity

13.2 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 intailly and be ready for the next layers.
- **Material properties:** Shorter initial setting time can help printing steeper over hangs
- **Environmental condition**: Controlled environmental conditions could ensure a successful print (Like temperature and humidity).

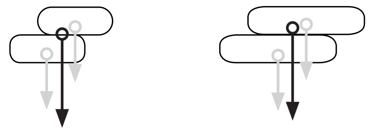
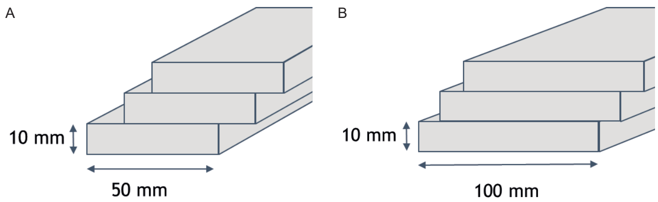


Fig.36 Wider layers provide stability and help printing steep over hangs

Fig.37 shorter layers provide stability and help printing steep over hangs



Normally, overhangs around 10 to 20 degrees are achievable.

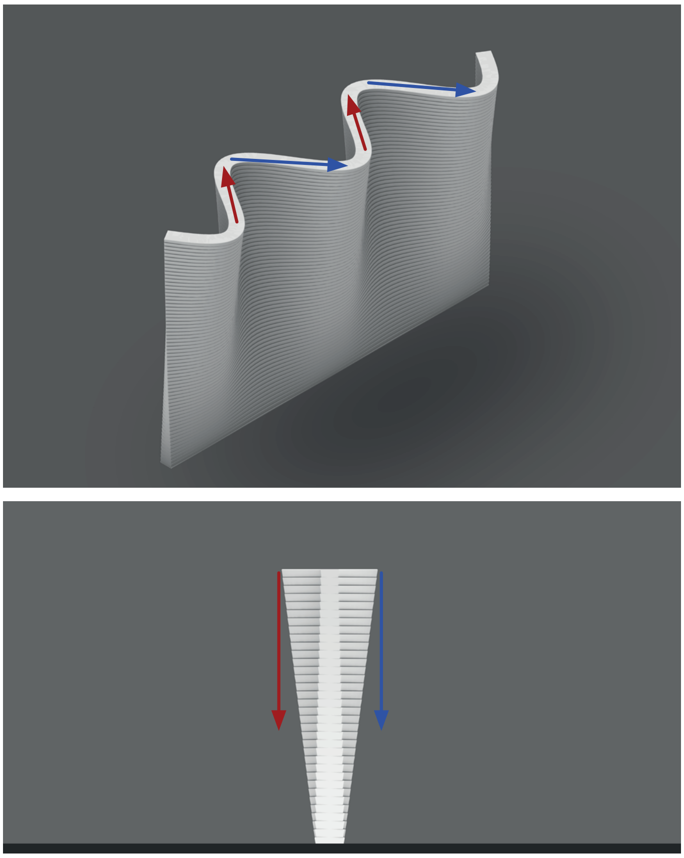


Fig 38. Load distribution diagram for stable overhang. Load is evenly distributed on both sides of support base.

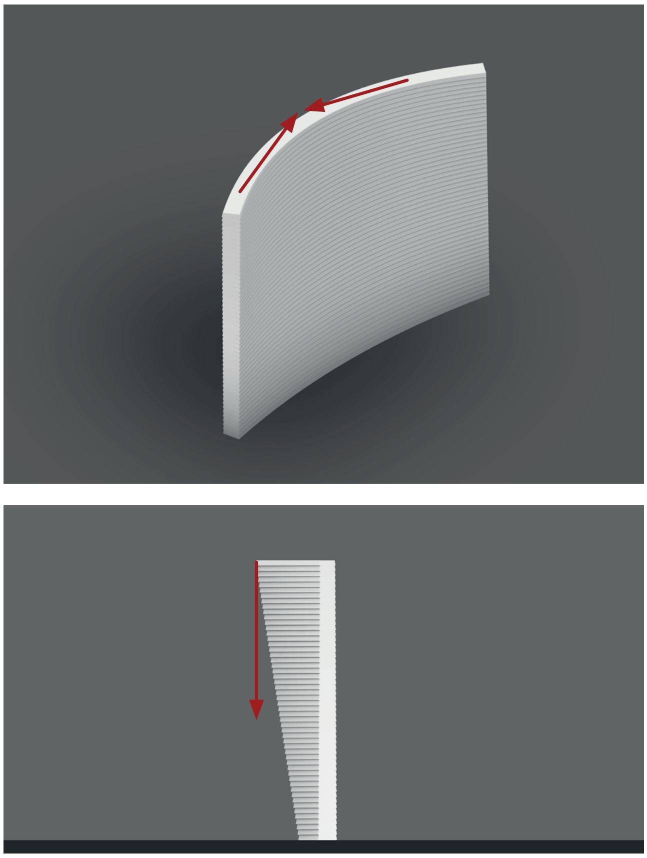


Fig 39. Load distribution diagram for unstable overhang Too large uneven distribution of load will make the model collapse.