D-SHAPE - REPORT

Made by the pioneer Enrico Dini, the D-Shape powder bed technology is responsible for the first 3D Printed bridge in the world (Spain) and offers true 3D possibilities suitable for very complex constructions, but unlikely to be competitive for traditional simpler constructions.

Company: Monolite UK (Dinitech SpA)
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1. Technology overview

D-Shape is a well-known name, and certainly one of the first known technologies that focused on 3D construction printing. The printer uses a binder jetting technology (described further below), and is currently the single available company providing printers of this type. Using a large gantry structure to move, the printer creates an alternative type of concrete by selectively applying a liquid binder on top of layers of powder material consisting of a cement-sand blend. Where the binder is applied, the powder material solidifies, while the remaining unbound material remains as a support for the solidified parts.

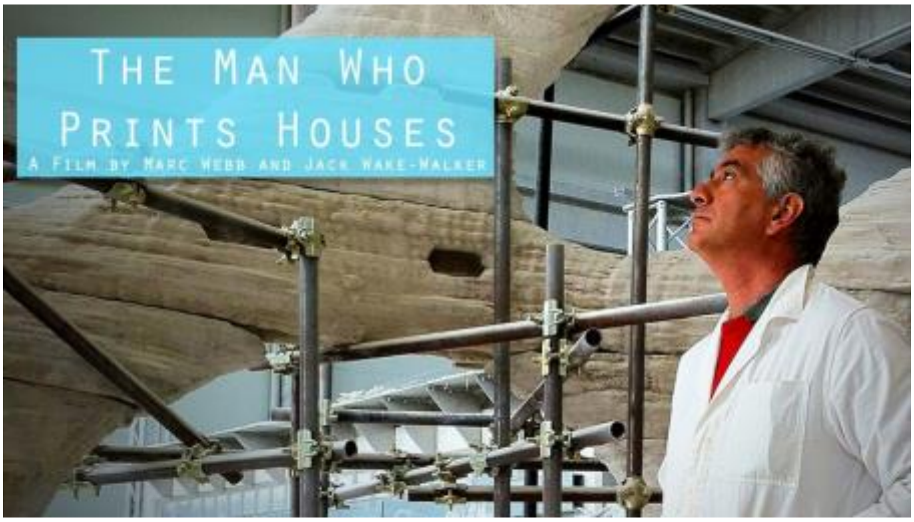
The printer allows to print 3D models directly from file into concrete-like shapes with a high degree of form freedom. These shapes are not only extremely difficult or even impossible to obtain with any other traditional construction technology, but are very often a great challenge also for other types of 3D Printing technologies. On the other hand, directly printing buildings with this technology is very slow due to the need for removal of large quantities of support material. The technology is therefore well suited for the production of unique pieces and parts, whereas it is deemed less suitable for direct fabrication of conventional buildings. The D-Shape 3D printer is probably best suited for off-site prefabrication of various highly complex construction elements.

The D-Shape printing technology (a printed layer)

2. Company and development

2.1 Company´s history and overview

The company’s first attempts with an epoxy resin based 3D printer go back in 2006, while the first version of the current magnesia cement based system were invented in 2008. The technology quickly gained large media attention, and firmly established itself as one of the first construction scale printers in the world. All the D-Shape machines were invented by its chairman, Enrico Dini, who is also the owner of its patents, with the help of his brother Riccardo Dini. The two have been running the Dinitech company ever since, and have participated in many different projects across the globe, along with strong names in the architectural world and construction industry such as Foster+Partners or the Royal BAM Group. The D-Shape technology has also recently been used to print the first 3D Printed bridge in the world in Madrid, Spain, in collaboration with Acciona and the Institute of Advanced Architecture of Catalonia (IAAC). The D-Shape printer remains the only binder jetting technology on the construction-scale market. It has gained considerable media attention throughout the years, that includes a dedicated documentary, several articles, TV-reportages, TED-talks, conferences etc.



The cover of the documentary about D-Shape and Enrico Dini

2.2 Company size and number of employees

The current number of employees and the sheer size of the company are not clear at this stage, but it is still quite small (less than 10 employees). Several experts have been cited as collaborating on various projects with D-Shape.

2.3 Targeted market

The company aims at selling printer units and offering technical support and maintenance of the machines. The company has also recently partnered with a printing service facility called Desamanera in Rovigo, Italy, which aims at printing custom sculptures and furniture on demand (D-Shape is the provider of the printer).

2.4 Past, current & future projects

There are numerous projects where the D-Shape printing technology is involved. These include:

- First 3D Printed bridge in the world in Madrid, Spain (in collaboration with Acciona and Institute of Advanced Architecture of Catalonia (IAAC)

- A 3D Printed reconstruction Palmyra's Arch of Triumph replica erected in central London, under the initiative of the Institute of Digital Archaeology and UNESCO.
- A research study for 3d-printed lunar bases, in association with Foster+Partners and the European Space Agency.
- Landscape House, a museum shaped like a Mobius stripe, made of 3d-printed formwork blocks (in collaboration with Universe Architecture and the Royal BAM Group)
- The Leaf, a conceptual project for revitalizing desert areas through the construction of large 3d-printed shading structures
- Villa Rocca, a villa made of 3d-printed formwork components, planned in Sardinia, Italy
- An artificial 3d-printed coral reefs project, aimed at restoring coral barriers around the world
- Many other minor projects, including sculptures, coffee tables, furniture etc.

Components of the 3D Printed (and CNC milled) Palmyra's Arch replica being assembled in London

First 3D Printed bridge in the world located in Madrid, Spain

A section of the wall for the lunar base project

A rendering of the Landscape House project

A printed table with organic shapes and voids

Additional printed furniture with organic shapes

Replicas of archeological statues made with the D-Shape printer

2.5 Development stage of printers

D-Shape has currently four or more operational machines, which participate in the various projects. Each new machine has been slightly modified compared to the previous one, in order to improve the efficiency and solve some smaller issues that have been learned on the previous models. The machines are used as working products, even though they are still partially in a prototype phase. No official sales of printers have been publicly known up to date. The company has used the printers to print several prototypes and sculptures, both for its own projects and tests, as well as other clients.

2.6 Development stage of printed materials and largest print to date

Currently there is a good degree of knowledge on the material, as it has been partially tested on several occasions. The material is showing promising results for construction use, both structural and non-structural. But further in depth research would be necessary to allow for a more reliable use within the industry.

The technology is capable of printing on an area of 6m x 6m, with a theoretical maximum height of 6m. However, these dimensions can theoretically be easily extended, by enlarging the frame of the structure. This has already been conceptualized by the company, with a goal to create a printer that can be enlarged in a modular way up to 24 meters in each dimension or more, to allow the direct printing of whole buildings. The largest object delivered in a single printing session up to now is a small conceptual house of a 4m x 2,4m footprint. While the size of the prints is still limited, larger buildings and structures have been planned and can be printed in components, and then be glued together afterwards with a mortar based on the same type of cement. An example of this is the first 3D Printed bridge in Madrid, Spain, which has been printed in sections. Same goes for the planned Villa Rocca project.

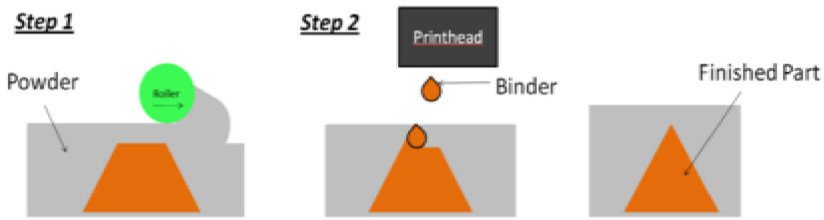
Largest printed object in a single print session up to date

Components or test prints for Villa Rocca, a large organic villa project, to be used as stay-in-place formwork

3. Technology

3.1 Additive manufacturing technology

The D-Shape printing process is effectively an up-scaled ***binder jetting (bj)*** process, where a binder is selectively deposited on each layer of powder material. The powder material in this case is consisting of sand and magnesia-based cement, which are mixed together into a dry powder, before being fed to the 3d printer and spread into layers. The jetted (or sprayed) binder material is a saline water solution, which is deposited on each layer of dry powder material, similar to ink on paper in a traditional desktop inkjet printer. When deposited, the binding material travels through the powder layer, reaching the layer below. The process is repeated for each layer, until reaching the end of the structure. The sum of all layers is a volume of unbound powder material that contains the solidified/printed part inside.



Binder jetting process

3.2 Printing procedure

The printing procedure starts with the 3D model being sliced into layers according to the desired thickness, within the machine range (5-10mm layers). Each layer is then translated into the instruction code for the movement of the material deposition heads, and the printing process can start. The first layer of dry-mixed sand and magnesia cement is deposited on a flat surface, and leveled according to the selected layer thickness. A layer of binder is deposited on top of a layer of dry-mix powder, exactly where the printed object should be created, according to the specific instructions dictated by the software. As soon as the binder is in contact with the powder, it starts the hardening process, which will eventually solidify the material. The binder is deposited only on the areas of the powder layer that should contain the printed object, while no binder is applied to the rest of the powder bed, which remains unbound, and acts only as a support for the following layer that is coming on top. The process is repeated until all the layers of the print have been made. The object is then left to cure, ready to be taken out the next day.

A layer being printed (dark gray areas indicate the deposited binder)

3.3 Form freedom

Since the powder material of each layer acts as a support for the next one across the whole area, this process allows having a full three-dimensional printing freedom (full 3D freedom). This includes structures that are encapsulated or linked to each other, with some design consideration regarding the removal of the supporting powder material afterwards.

An intricate shape with linked rings, made possible because of the use of binder jetting technology

An intricate shape with complex voids

3.4 Fabrication location and approach

The printer requires a firm support for its structure to be erected. Since the printer levels its own material prior to the actual printing procedure, it allows a certain level of uneven terrain. However, a relatively flat surface is desired, especially if the printed object needs to be structurally connected to the surface. Additionally, the support needs to withstand the large weight of the layers of sand

The printing process is most likely to be performed in off-site environments (off-site prefabrication), or with some temporary protection on site (on-site prefabrication), since most of the material must remain unbound during the whole process. It must be protected from wind, rain, moisture, and other elements. The technology is therefore best suited for indoor production of components that can be assembled on site afterwards.

The D-Shape printer in outdoor conditions

Since the whole print volume gets filled during the printing process, the D-Shape technology operates at the best efficiency when most of the volume is filled with printed objects. This is rarely the case with direct printing of full-scale buildings, which are mostly made of empty space. It is therefore best to slice the print into components that will be assembled afterwards, and place them as close together inside the printing volume. The pieces can be easily glued together by a layer of mortar made of the same material. This fabrication approach not only reduces the amount of unbound material that needs to be cleaned afterwards, but also increases the printing speed by using a higher portion of the print volume.

3.5 Additional procedures and considerations

3.5.1 Object extraction / Cleaning

Once the print has successfully hardened, it is necessary to extract it out of the powder support. This cleaning operation requires a lot of time, depending mostly on the complexity of the shape and the quantity of unbound powder materiall surrounding the object. It can often prove difficult or even impossible to reach and clean some areas, so this step has to be taken into consideration when designing the object, in order to facilitate the extraction. Furthermore, some prints can prove fragile, and their extraction process can induce cracks or broken parts. The cleaning process is very often facilitated by the use of a vacuum cleaner.

Additionally, parts of the unbound powder bed can accidentally get hardened, either through spillage or when excessive moisture is trapped in the print volume. Clusters of partially hardened material are often found inside the powder bed or attached to the printed object. They require tools and some force to be removed, which complicates further the cleaning process. However, most of the powder bed material proves reusable after the cleaning.

Removing of the powder bed from the printed object

4. Printer

There are several machines that have been built under the D-Shape name, all of which are working prototypes. Each new version has seen some improvements or adjustments, trying to solve or mitigate some issues that have been discovered along the way. However, the basic functioning principle has essentially stayed the same. The first version of the printer is described below, with additional explanations for the newer versions where they are necessary.

4.1 Movement

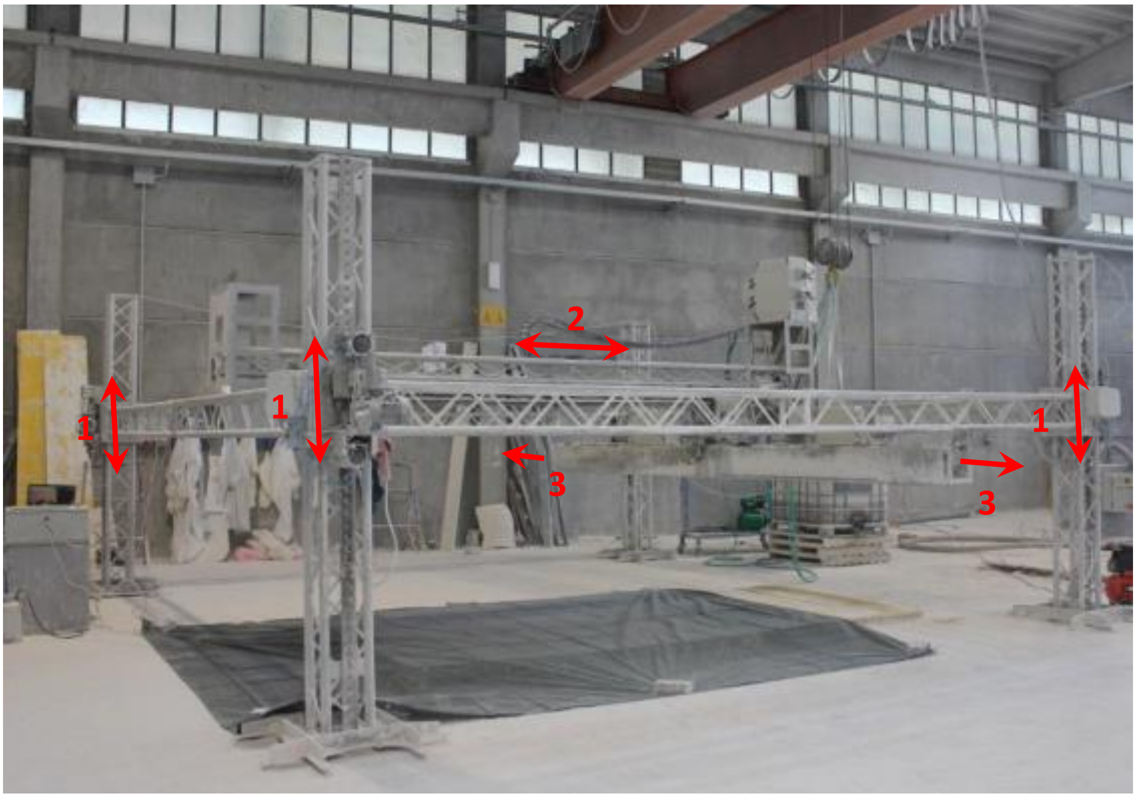
The D-Shape printer is a Cartesian gantry system forming a large 3 meter high box with a 5m x 5m printable area. The printer is made of a large 6m x 6m square structure that is mounted on top of four 3 meter long columns. Each columns is equipped with an electromotor, allowing the system to move up and down its vertical axis. The columns can be extended to 6m, if it is necessary to increase the height of the printer.

Across the middle of the large square structure lies a 6m long double beam. This double beam is equipped with another electromotor that carries along its length a 6m large array of nozzles, which sits perpendicular to the beam itself and selectively drops the binder where necessary. The whole printable area is therefore covered by a single movement of this long row of nozzles, running up and down along the middle beam, and swiping the whole surface of the square printable area. Since the nozzles are spaced apart 20mm between them, it is not possible to cover the space between two nozzles in a single swipe. Therefore an additional electromotor is mounted on top of the nozzle array, which allows offsetting the nozzles with each new swiping. This way, all the surface is covered with a few swipes of the nozzles, each offset from the previous one.

This swiping motion, resembling a traditional desktop scanning device, is also used to level each layer of powder material. When the powder is dropped on the printer bed, a longitudinal trowel spreads it across the surface of the last printable layer. This trowel is located behind the nozzle array system, on its back side. The printer can therefore deposit the binder when moving in one direction, and level the powder bed when moving backwards. Once the powder bed is leveled, the next level of binder can be deposited on the newly created flat surface.

There are a few differences on some of the newer versions, which are worth mentioning:

- On newer versions of the printer side panels have been added. These panels are self-elevating and follow each new layer of the printer, creating a rising box around the printable area. Their main purpose is to contain the powder bed material, which would otherwise create a slope on the edges. They are also being used as the supporting frame for the swiping motion instead of the middle beam.
- In same cases the troweling mechanism is mounted on a separate beam, so the two motions are controlled by a different set of electromotors and are independent from each other.
- In newers versions there are two motors controlling the swiping, one on each end of the beam. This is probably to increase the strength and firmness of the beam in order to increase the precision and reduce the stresses on the machine.



Movements of the machine in all the possible directions:
-vertical movement along the 4 columns (1)
- horizontal movement along the middle beam (2)
- offset motion of the nozzle array (3)

4.2 Material (Binder) deposition system

The deposition system is made of a series of nozzles placed in a straight line (array) along a 6m long beam, which swipes across the whole print area. There is a pressurized feeding tank shaped like a tube and attached to the beam. Each nozzle is connected to this longitudinal feeding tank through a small hose, on the end of which is a valve that controls the opening and closing of each nozzle.

Underside view of the nozzle array

The valves are electronically switched on and off during the swiping movement, following a specific sequence for each printed layer. The nozzles are spaced 20mm apart, while each one covers a 5mm thick print line. It is therefore necessary to perform four swipes for a full print of each layer, with each layer offset by 5mm from the previous one.

This component has essentially stayed the same on all versions of the printer.

4.3 Material feeding

The D-Shape technology is of the binder jetting type, which means it has two components that need to be delivered to the printer: the liquid and the dry powder mix.

The liquid component sits in a large container next to the printer. A pump is continuously delivering the liquid through a hose into the pressurized feeding tank which is connected to the nozzles and moves together with them (described above). The pump in the container is creating the necessary pressure in the feeding tank, so that the liquid can be released when the nozzles are open.

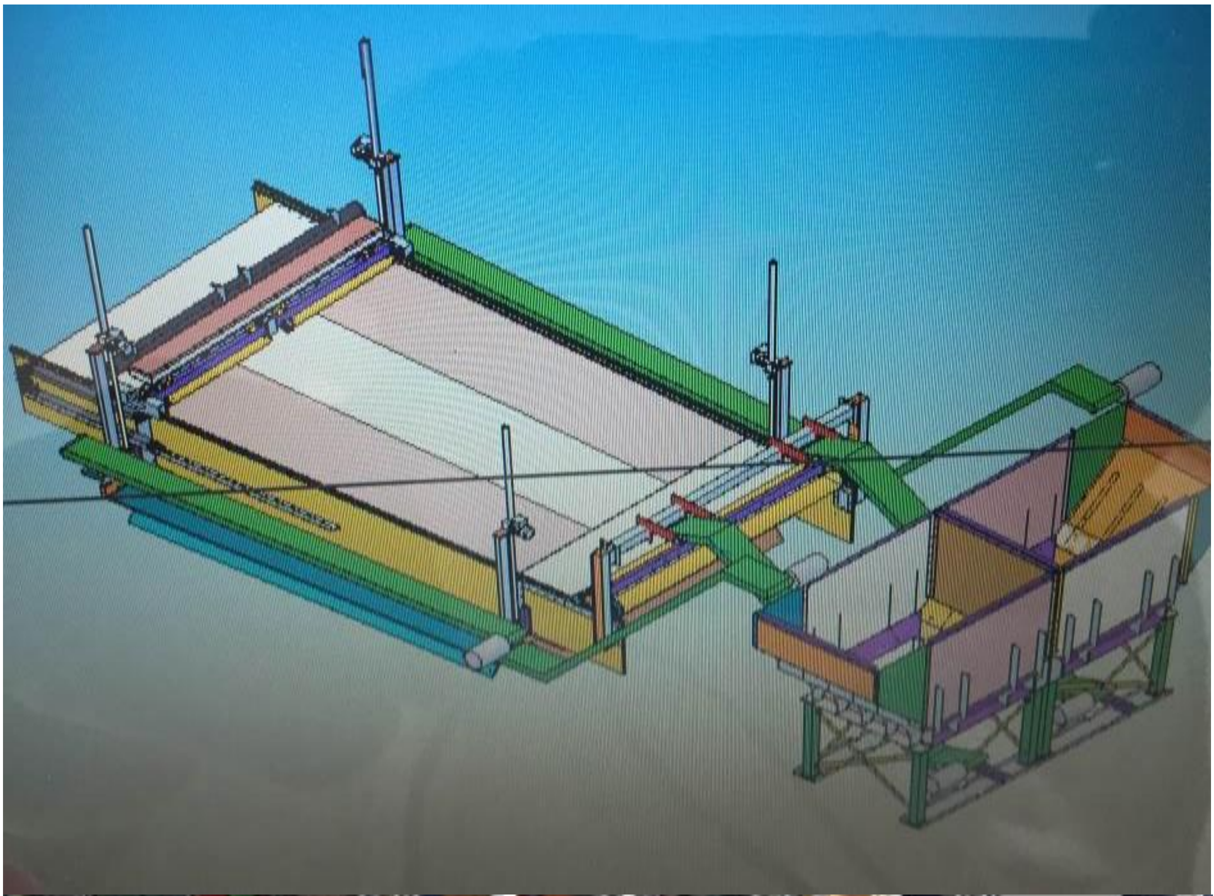
Feeding tank for the liquid component (with the feeding hose on the right)

The deposition of the powder component is done manually on the first version of the printer through the use of a suspended skip filled with the dry mixed material, from which the material is dropped. In the following versions a sand feeder is added. The sand feeder is sitting on one edge of the printer. The approximate quantity of powder component necessary for one layer is dropped on the surface of the previous layer, and then spread and leveled. The leveling is then done by the swiping motion of the longitudinal trowel that is placed behind the nozzle array.

The sand feeder has been changed several times, mostly simplified to reduce issues and jams, but the main function of dropping the material close to one edge has stayed the same. On some versions, a conveyor belt has been added on the sides of the printable area in order to collect the excess material and bring it back to the feeder, where it can be dropped again and used for the next layer.

Sand feeder mounted on top of the printer gantry (2nd generation printer)

Sand leveling procedure using the trowel



One of the latest versions of the machine, with self-elevating side panels and new sand feeder

4.4 Printer electronics and software

The printer is operated through a set of programmable logic controllers, connected via Profibus communication protocol to a desktop computer, located next to the printer.

Programmable logic controllers mounted on top of the printer

The computer is equipped with proprietary software that slices the models into layers, and then each layer into droplets of material. Additional proprietary software is used for communicating with the printer machine itself.

Computer with dedicated software for controlling the machine

4.5 Printer speed

The speed of the D-Shape printer is mostly determined by two factors: the deposition of the dry material (powder bed), and the swiping motion of the nozzle array that delivers the liquid component (binder).

The deposition of the dry mix is manual in the first version of the printer, which can be cumbersome and slow down the process from time to time. It is mostly influenced by the operator. Newer version of the printer have a sand feeder, which needs to be refilled every few layers. In either case, the material can be prepared or refilled while the printer is spraying the binder from the previous layers. This way, the loss of time is reduced. Once the material is dropped on the surface, the printer will then quickly spread it autonomously.

The delivery of the liquid material from the nozzles is instantaneous, but the swiping motion is kept slow, in order to avoid dropping the binder in the wrong spot, too soon or too late. Also, the spacing of the nozzles requires 4 consecutive swipes to complete a full layer, which could be reduced by placing four offset rows of nozzles, instead of one.

The current speed of the system is 6min/layer, which includes all the procedures and difficulties described above. When considering the whole printable area of 5m x 5m and a 10mm tick layer, the printer can theoretically still reach as high as 2,5m^3/hour speeds of deposited material. However, this includes also the unbound material. The percentage of actual solidified material depends on how the prints are distributed inside the printer volume. Therefore, it is realistic to consider the actual speed reduced at least by 50% (down to an actual speed of 1,2m^3/hour).

There is certainly room for great improvement in each of the bottlenecks of the printer, which could bring the speeds up in the future. But one of the prevailing factors for this additive manufacturing technology remains the maximum usage of the printer space (reducing the unused/unbound material to the minimum). This can be done by using specific software that optimizes the distribution of the printed parts within the volume.

4.6 Printer accuracy

The accuracy of the D-Shape printer is much harder to control, since it is highly influenced by the spreading of the binder through the powder mix. This spread is determined by many factors, such as the size of particles contained in the powder, and the quantity and properties of the liquid binder traveling through it. It is possible to optimize and predict this behavior by studying it more in depth, to further optimize the accuracy. Currently the printer can provide an accuracy of 10-20mm.

4.7 Printer operation, handling and assembly

Theoretically, a single operator can operate the whole printing procedure. One must first deposit the powder bed material, and then initiate the printing procedure on the computer. The process is repeated for each layer. This excludes the dry-mixing procedure, which can be performed before, but requires a separate machine. Both the mixing of dry material and the feeding can be fully automated with industrial machinery. These machines are readily available on the market, and include conveyor belts, feeding tanks etc.

The extraction and cleaning of the specimens is usually done by a team of 3-4 people, given its particularly time-consuming nature. It can be facilitated with the use of vacuum cleaners, but it remains a very manual procedure.

There is currently no official information on the time required to assemble or remove the printer on site.

4.8 Printer specifications (1st generation)

Printer size (assembled): 6m x 6m x 3m (Width x Length x Height)

Printer size (stored): Not available

Print volume: 5m x 5m x 2,5m
(Note: the required powder bed area grows with each new layer)

Theoretical printing speed: 6 min/layer (or 2,5m^3/hour at 10mm layers)

Actual printing speed: 1,2 m^3/hour at 10mm layers (with approx. 50% of space used)

Layer thickness: 5-10mm

Accuracy: 10-20mm

Deposition head: Nozzle array (300 nozzles)

Structure: Aluminum gantry

Movement: 6 electromotors (4 vertical, 1 horizontal, 1 small for lateral offsetting)

Shape freedom: Full 3D

Weight (w/o sand feeder): 1.300 Kg

Total weight: 5.000 Kg

Energy consumption (w/o sand feeder): 2kW

Total Energy consumption: 40kW

Required personnel: 1-2 persons

Price per unit: 250.000 € (1st generation printer)

5. Material

5.1 Material overview

The D-Shape binder jetting process creates a material that is essentially concrete, which is made by mixing three components: sand as the aggregate, cement as the binder, and water as the catalyst. The only two substantial differences are the way this material is made, and the type of cement that is used.

Instead of mixing all the materials into a workable paste, as would be done for a regular concrete, the material is made by separately mixing the powder components (sand and cement), and then adding the liquid component on top. Each layer of powder material is followed by a layer of liquid component, stacking them like a cake. With this process the components of the concrete bond in a completely different way. This creates a layered concrete with very different characteristics than regular mixed concrete. Mixing the material will always result in a more even distribution, which will bring to better mechanical properties and fewer weak points.

Any type of concrete can be used with the D-Shape printer, including traditional Portland cement, which reacts with plain water during the curing process. The D-Shape technology uses mainly magnesia-based concrete, which is based on an alternative type of cement with unique properties. However, the company has also experimented with regular Portland cement recently, and plans to use it more extensively.

5.2 Material possibilities

The D-Shape binder jetting introduced a whole new range of possibilities for experimenting with concrete materials within construction. Various components can be added either to the liquid or the powder component, and create a variety of completely new layered materials.

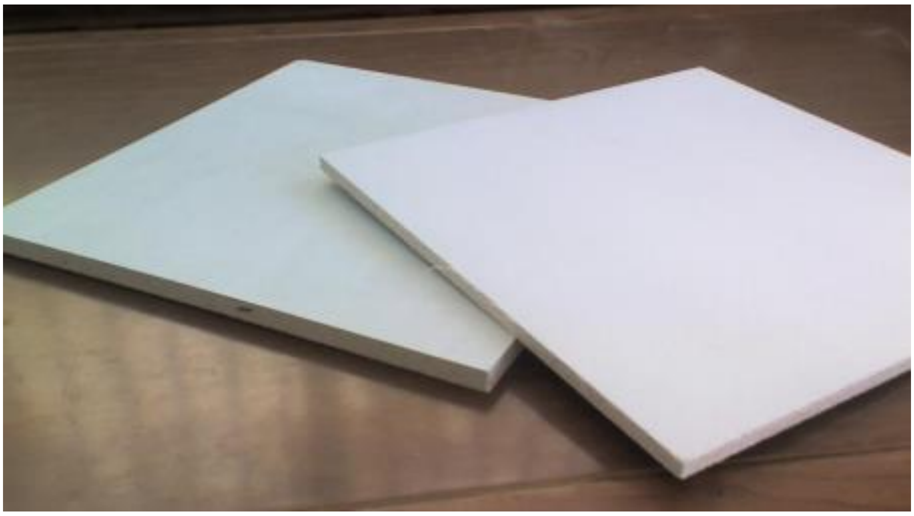
The D-Shape printer is currently suited for using only one liquid component at a time, since it has a single feeding tank for it. However, it is possible to prepare different dry powder mix for each layer. This way it is possible to design layered objects with different characteristics (different aggregates) on each new layer.

5.3 Regular magnesia concrete properties

Magnesia (or magnesium oxychloride) cement creates concretes with far superior mechanical properties when compared to traditional Portland cement. They can easily reach a compressive strength of 80 Mpa, compared to a 30-50 MPa range for Portland cement concrete. Magnesia concrete is praised for: curing without water, high fire resistance, thermo-insulating properties, good resistance to abrasion, high strength values after a short curing time, ability to absorb damage, insect mitigation etc. It is also praised for very good bonding properties with a wide range of materials, including organic aggregates, such as saw dust.

Construction use of magnesia concrete is limited, due to a number of crucial drawbacks. It presents poor water resistance, with heavy strength losses after prolonged water exposure. Furthermore, it is prone to shrinking, expansion, cracking and warping, with highly unpredictable buckling behavior. It is also highly corrosive towards traditional reinforcement steel. For creating a magnesia reinforced concrete other types of reinforcement need to be used, such as fiberglass etc., which increases the costs drastically.

The most common industrial applications for magnesia concrete are fireproofing, sound-proofing, and thermo-insulating magnesia boards. It is often found in drywalls, and suspended ceilings and floors, as a substitute to gypsum.



Magnesia concrete boards

5.3.1 Curing process / Chemical reaction

Magnesia concrete is created when Magnesium Oxide (MgO) in powder form is mixed with Magnesium chloride in water solution ($MgCl^2$*$(H2O)_n$). The dominant curing reaction in the process is:

$$5MgO + 1MgCl_2 + 13H_2O \rightarrow 5Mg(OH)_2 \cdot 8H_20$$

The curing emits a high amount of thermal energy and starts immediately. The material hardens very fast, usually in less than 15 hours. The sand is pre-mixed to Magnesium Oxide (MgO) in powder form and used as aggregate. The sand does not participate in the hardening process, but gives hardness and strength to final material.

5.3.2 Raw materials

Magnesium Oxide

Magnesium Oxide (MgO) or magnesia is a readily available material at industrial scale. It can be found in food, feed, paint, ceramic and many other industries. The chemical has the appearance of white powder. It is known in construction as component of magnesia cements. The material is also very environmentally friendly. Prices for construction grade magnesia range from 150 to 400 USD per metric ton.

Magnesium Oxide in powder form

Magnesium chloride solution

Magnesium chloride ($MgCl_2(H2O)_n$) is a salt, highly soluble in water, and readily available on the market. It can be obtained from seawater and salt lake brine. It is also extracted from mineral sea beds. It is commonly used for dust control, soil stabilization, wind erosion mitigation, ice control, fertilizers, wastewater treatment, feed supplement, paper, fireproofing agents, fire extinguishers, cements, refrigeration etc. Prices range from 50 to 100 USD per metric ton.

Magnesium chloride salts (dry form)

5.4 3D Printed magnesia concrete properties

3d-printed magnesia concrete has a rugged and layered appearance. The surface of the material is often ribbed due inaccurate spreading of the binder inside the powder bed. These inaccuracies depend on the way the binder spreads through the powder bed, and are quite hard to predict. Printed objects have a scattered distribution of both vertical and horizontal protrusions. There is also a clear presence of voids and pores. The horizontal variations in color tones clearly indicate the orientation of the layers.

A print-out showing the rugged appearance of the material

A cut-out showing the color variation of the layers

Some testing has been performed to the D-Shape 3D-printed magnesia concrete, which has predictably lower strength values than its mixed counterpart. Compression strength values reached an average of 49 MPa when loaded orthogonally to the layers of the material. When loaded parallel to its layers the material reaches an average of 59 MPa. This indicates a slight difference in strength in the two directions (also known as anisotropy). Flexural strength reaches average values of 9 MPa, while the elastic modulus reaches 25 GPa. Porosity levels (through water absorption) average 5,6%, which is probably why the material is also 20% lighter than normal concrete (the weight is roughly 20 kN/m^3).

The material proves suitable for construction, and can compete with traditional concrete. However, additional tests and studies need to be performed to consolidate these findings, and be able to use the material as a load carrying structure. There is also a lot of room for optimizing the printed material even further.

A speciment tested under compression load

5.5 Material pre- or post-treatment

No material pre-treatment or post-treatment is required for the process. However, if the powder material is reused, it must be sieved first, to remove larger agglomerates of bound material that could compromise the print. It is also possible to impregnate or cover the material afterwards (post-treatment), in order to achieve particular finishes or additional resistance to external factors, such as water ingress, thermal cracking etc.

6. Useful links and sources

D-Shape/Monolite UK web page:
http://d-shape.com/

Dinitech SpA web page:
http://www.dinitech.it/

D-Shape Enterprises global web page:
https://dshape.wordpress.com/

3DPrinted bridge in Madrid, Spain:
http://www.archdaily.com/804596/worlds-first-3d-printed-bridge-opens-in-spain
https://iaac.net/research-projects/large-scale-3d-printing/3d-printed-bridge/