Admixtures And Special Concretes

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Lecture -73

Special concretes - Concrete for 3D printing - Developments, advantages, case study

3D Printing process- Steps Involved:

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Hello all, we were talking about 3D printing and the differences between additive and subtractive manufacturing and what are the steps involved in the overall process of 3D printing. So, the 3D model is broken down into two-dimensional layers which are then subjected to the printing operation by the printer and post processing involves curing because we need to ensure that concrete gains sufficient strength and if there is any surface finishing required after placement or after printing the material it has to be properly finished on the surface.

Major developments in extrusion 3D Printing:

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So, as far as concrete 3D printing is concerned the journey is about 20 years old now. So, if somebody tells you that it is something brand new do not believe them it has been happening for 20 years. So, at Loughborough University, you see the structure here (Refer to the top-right picture), this was done in 2003. In the early 2000s they had already started the work with 3D printing of concrete.

In 2003 they made that structure and it is still displayed also during the last 3D printing conference in June 2022 we had a large group of visitors to look at it. At the University of Southern California and Los Angeles, Vero Koshnevis who is a prof there, started a company called Contour Crafting Corporation that is essentially based on 3D but contour crafting simply implies that post printing, they also have a finishing tool that gives the necessary surface finish. At around the same time, a lot of work was already going on at ETH Zurich which then started propagating this idea of smart dynamic casting. This is an interesting concept here (refer to the left picture in the slide) the idea is instead of printing concrete layer by layer without formwork you have dynamically changing formwork and that is what is being done here in this picture.

This is the formwork which is hydraulically controlled to change its shape as the concrete is being poured. So, you have a certain shape in the beginning you pour the concrete, the concrete gains a significant bit of strength or rather self-standing ability, should not say strength it is more yield stress or structural build-up is sufficient that this formwork can then move up and change its shape. So, you can see this column is getting an intricate structure because the formwork itself is changing shape. This is called smart dynamic casting. So, this is not layer-by-layer deposition of concrete but it is the shift in the formwork.

Now you can imagine this as being a higher level of slip-form casting. What happens in slip form? You have a formwork, you pour the concrete and then you slowly slip it up, and then you pour more concrete slowly slip it up. The idea is to increase productivity but of course, you are not dealing with changing shapes there. The shape is constant or at least the shape like a cooling tower that is typically run a thermal power plant using slip-form construction. There the shape has a well-defined curvature which changes the time with respect to the location in the height.

But here you have a constantly changing shape and that is made possible via control of the formwork. Then, at ETH they looked at something called mesh mould casting (refer to the bottom right picture in the slide). So, you have a 3D printer that unfurls the mesh and then you do shot-creating to ensure that the concrete can go around the mesh. So, this is again a form of digital construction. You do not need too much manual intervention in this case.

Around this time Chinese companies came forward and took it to the next dimension in terms of the type of productivity and the extent of projects that they could run with it. It was simply incomparable like Winsun in China did a lot of work and then there are several companies around the world like Apis Cor, Cybe, and COBOD which have done several projects in 3D printing across the world.

Advantages of Additive Manufacturing Techniques:

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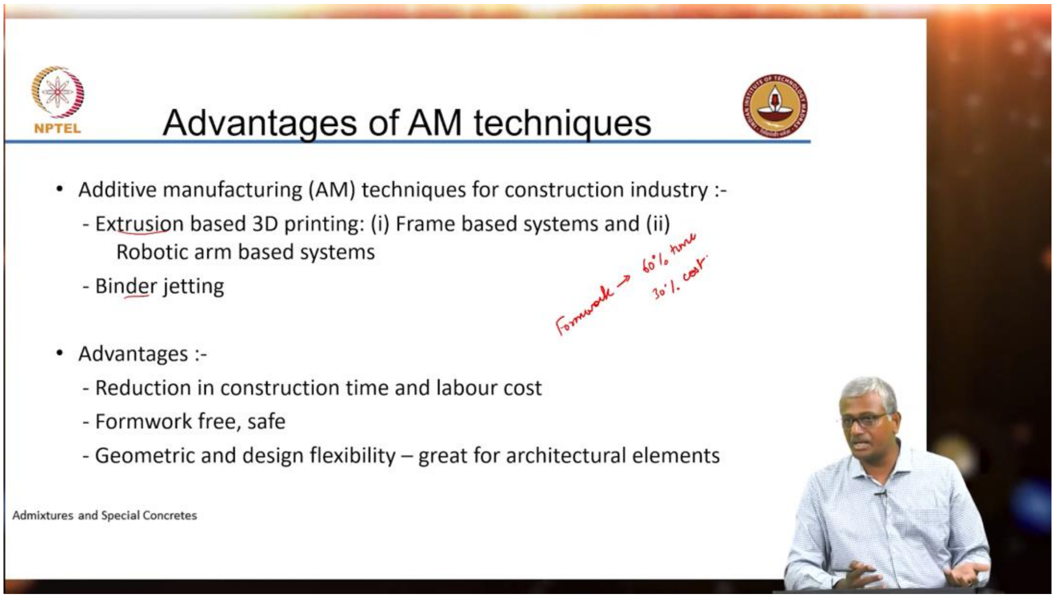

Why are we interested in additive manufacturing techniques in construction? Of course, if you look at the type of systems that are involved which we already discussed previously - extrusion-based 3D printing and binder jetting are the two types of 3D printing that can be done for cement-based materials of a concrete. With extrusion-based printing, you can have a frame-based system like I told you earlier about, the gantry-based frame or the delta frame. Those are frame-based systems in which the frame is bigger than the structure that is being built.

So, you have your 3D printer on a frame and your entire area of building is within that frame. Instead of that if you have a robotic arm, you place the robotic arm in the center of the room and construct it all around you. So, there you have much greater flexibility in the way that the construction can be taken out. So those are ways of doing extrusion-based 3D printing. That is what we will talk about primarily in this chapter.

Binder jetting is again I will talk in detail later. It is essentially where the binder which is water or cement paste, in our case mostly we will choose water is jetted onto a surface that has cement and sand, and water is put only in those locations where the cement needs to react with it to harden the structure and you slowly build the structure layer upon layer. I will show you some examples later. The primary advantage is that you have a reduction in construction time and labor costs. Now you may imagine this to be a reality as far as Western countries are concerned where labor is quite expensive.

In India when labor is available for much cheaper than mechanization why would this be useful? This can be useful in locations where labor is not easy to get and secondly, much of the type of construction that we expect to do with 3D printing may deal with structures that skilled labor is needed to do. So skilled labor is not very easily available, as you all know on our construction sites and the labor workforce keeps changing because of that something as complicated as doing nonrectilinear shapes, which are typically popular with 3D printing, you cannot imagine with conventional construction. So even in locations where labor is not that much of an expense we still can get a lot more with 3D printing. The other aspect is its formwork free. It's formwork free which means you are saving the time and cost it takes to put a formwork.

Any idea on how much time or cost is spent? Time involves of putting up the formwork and removing it. About 60% of construction time and about 30%, really less than 30% let us say 30% cost. So concrete construction involves formwork placement and removal which takes 60% of the time of the overall construction and 30% of the cost. So if you can save on formwork and not use formwork at all then obviously you have a major advantage there. The other primary selling point as far as 3D printing is concerned is the design and geometry flexibility that you have.

You do not necessarily have to constrain yourself with rectangular or square shapes. You can now look at more architecturally pleasing features that need specialist concrete to be poured which cannot be easily done with formwork because if you have a constantly changing shape you have to keep adapting the formwork to that shape and that is not possible beyond a certain extent. So, then your construction starts getting uneconomical if you have to create formwork for new shapes each time.

Extrusion based 3D Printing:

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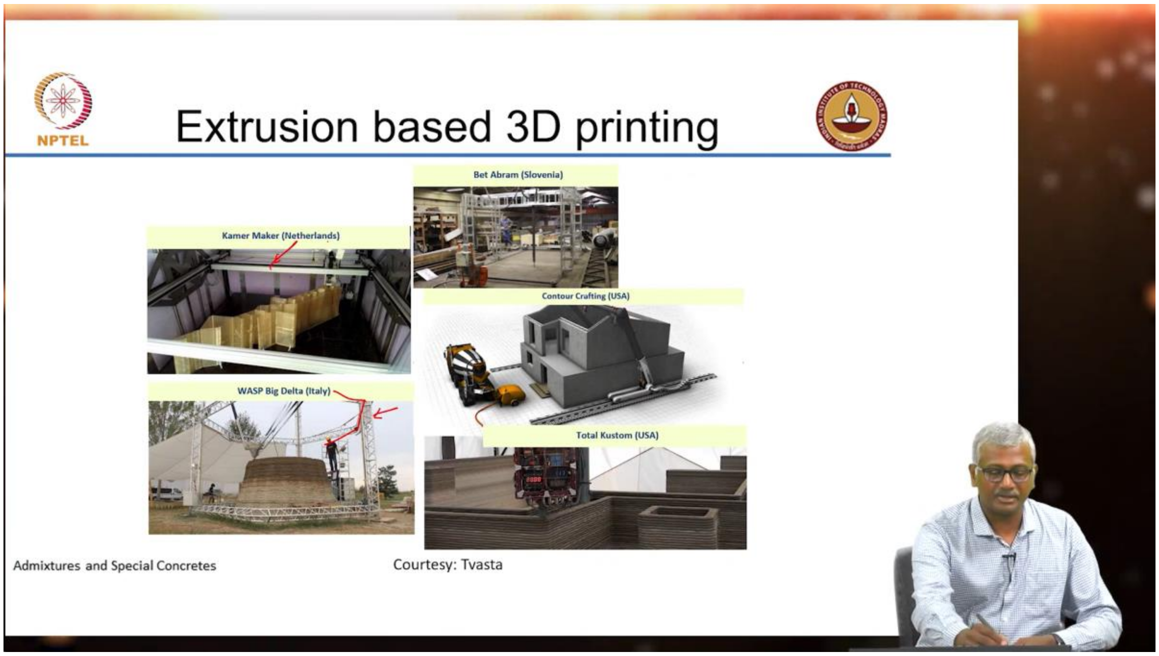

So again, some examples as I said contour crafting, then you have, this is the delta printer (refer to the bottom-left picture in the slide). It is also a frame-based printer but the overall coordinate system is more like 3 axis coordinate system.

So, with 3 different axes instead of a rectilinear XYZ coordinate system, now you have a 120-degree coordinate system. This is a typical gantry system (Refer to the top-left picture in the slide). You have the overall frame and then you have the gantry portal which moves on the frame and carries along with it the nozzle.

Construction of a 3D printed building in Shanghai:

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So, this is an example from the construction of a 3D-printed building in Shanghai. You can see that the construction elements that is the 3D-printed walls are being prefabricated in a factory.

This is the frame (refer to the top-left picture in the first slide) and this is the nozzle (Refer to the top-left picture in the second slide) depositing the concrete in a layer-by-layer fashion and it is depositing concrete in such a way that you have a periphery that is filled up and the interior part is filled up with the rib that is to increase the extent of stiffness that you can get from the system. The finished components after the printing have been done the components are kept aside and then they are expected to be cured until sufficient strength has been achieved. You can see that all these components have cavities where you can have reinforcement and these cavities can also serve as points where the reinforcement will join the elements vertically. If you stack one element on top of the other and have a constant continuous reinforcement running through this then you can have a good degree of joining also between the two systems. After the completion of curing, you do transportation to the site and there the segments are assembled.

Now this operation looks very much like a precast operation. There is no difference here except for the fact that the production of the elements did not involve any formwork. Everything else is just the same.

Binder Jetting:

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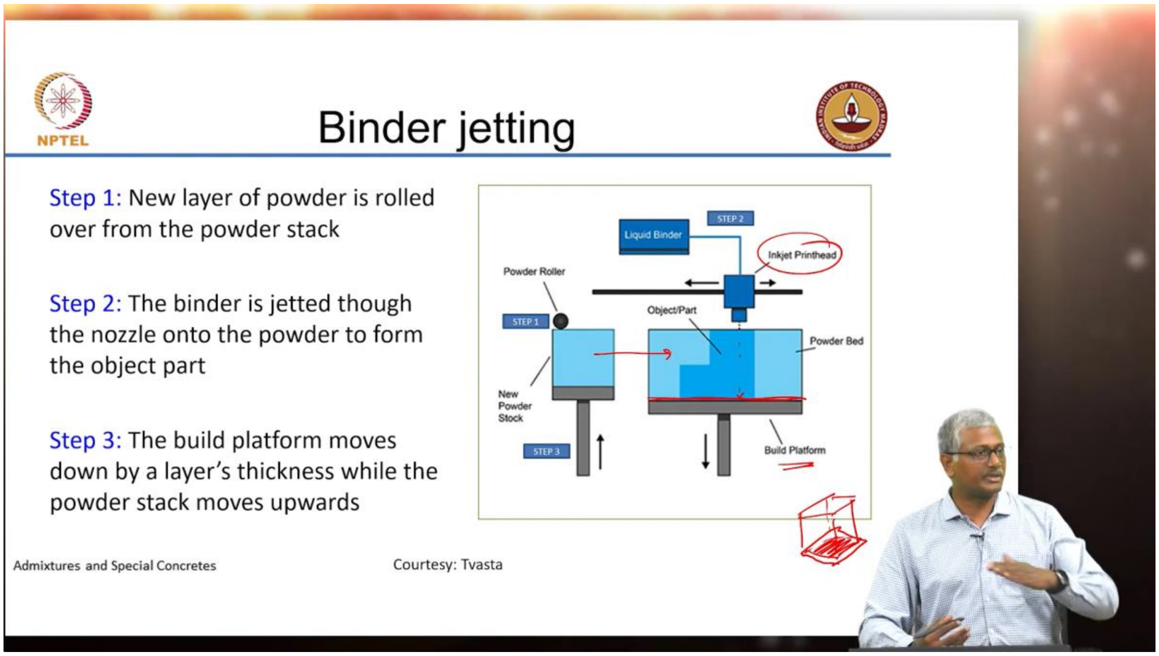

Now binder jetting as I said is a slightly different process.

Here you are trying to spray the ink on a bed which consists of your cementing material. So, ink here is just water. So, you take a mixture of cement and sand in the ratio that you desire to make your concrete mix. You lay it on this build platform. You lay one layer of the cement and sand combination.

Not too thick but at the same time not too thin. You put one layer. When you have the print head it sprays the water. It just jets the water onto the top of the cement and sand layer and it jets the water only where you need the specific shape. Suppose you want to make a box. You want to make a box shape. So, you first put one layer of the cement and sand at the bottom of the box and then you simply spray the water only at the periphery. You only spray the water at the periphery so that the inner portions of the cement do not have a chance to react with water. Then continuously you do this by putting the next set of powder onto the build platform. You transfer one more layer of powder onto the build platform.

Spray the water again in the required shape. Then get the next layer, the next layer, and so on. So, what will happen is you will have a layer-by-layer build-up where the water is simply interacting with cement only where the shape needs to be defined. And at the end of the entire process, it will take some time to harden obviously. Cement will take some time to react and harden.

You wait until that time and then what you need to do is remove all the excess material that is dry which has not reacted and then you will get your shape. You may want to also do some curing, if necessary, after the shape has been extracted. So, in this way, you are depositing the powder that is cement and sand mixture layer by layer onto the build platform and then you simply keep spraying the water wherever you desire.

Binder Jetting based structures:

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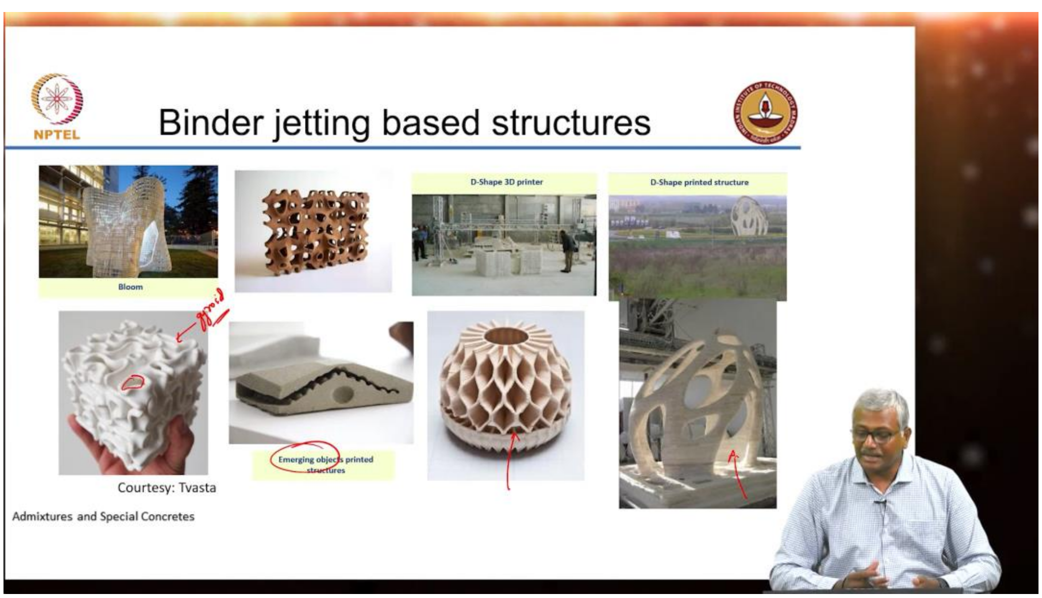

Now using this you can create such intricate shapes. You can see the kind of shapes that are created here. Look at this shape here it is called a gyroid (refer to the bottom-left picture in the slide). So here again the shapes involve several of these vesicles and cavities which are inbuilt in the structure. If you must extrude a material to take that shape it is going to be extremely difficult. So, in such instances, you must use something like binder jetting. So, this (Refer to the second picture in the bottom row from left) is from a company called Emerging Objects and they have done a great job in printing different types of structures.

Here this is the D-shaped 3D printer (Refer to the third picture in the top row from left) and you can see the kind of elements (Refer to the third picture in the bottom row from left) that have been created using this kind of printer. And if you look at this structure (Refer to bottom-right picture in the slide) here getting that kind of a system out of a typical extrusion-based print is going to be extremely difficult. So, you must do some binder jetting there to get that shape realized.

Reference to videos:

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Now I am not going to show you videos of course you can get tons and tons of videos from YouTube on 3D printing. Now every day some new videos are added and a lot of discussion forums are also in place that talk about is 3D printing sustainable, whether is it a good solution for regular construction all those kinds of things are very nicely debated.

I do not think I can even match that level of presentation here. So, I will leave this to you to watch. I will go more toward the scientific end of things which describes how the materials are designed.

3D Printing for houses:

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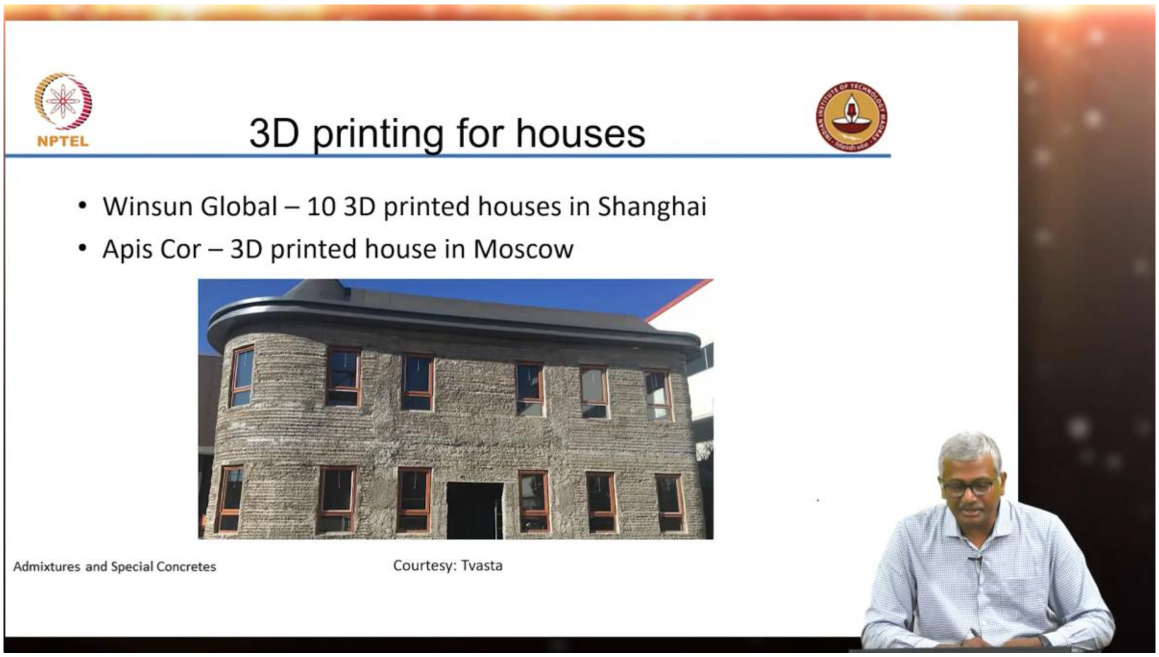

But before that some examples of 3D printing for houses. Winsun is a Chinese company that has printed 10 3D printed houses in Shanghai.

Apis Cor did this house in Moscow. You can see it is a ground plus one storey house. So, they had a slab in between which is cast in situ. The walls were all done with 3D printing.

3D Printing of architectural elements and furniture:

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This is just a park bench (refer to the bottom-right picture in the slide), a furniture element that is quite easy. You can see the layers are in this direction which means the printing would have happened like that and then you just tilt it to the side and keep it on the ground.

This is a bus shelter (Refer to the bottom-left picture in the slide). Again, you can see layers are in this direction. So, printing would have happened in this direction and then you just tilt it up to make the bus shelter. This is a bridge (Refer to the top picture in the slide) that was 3D printed in Madrid and it is a very interesting example. Of course, it is a pedestrian bridge. It is not a highway bridge but still, it is a good example of how you can build intricate designs into a 3D-printed structure.

Printer for production of house elements:

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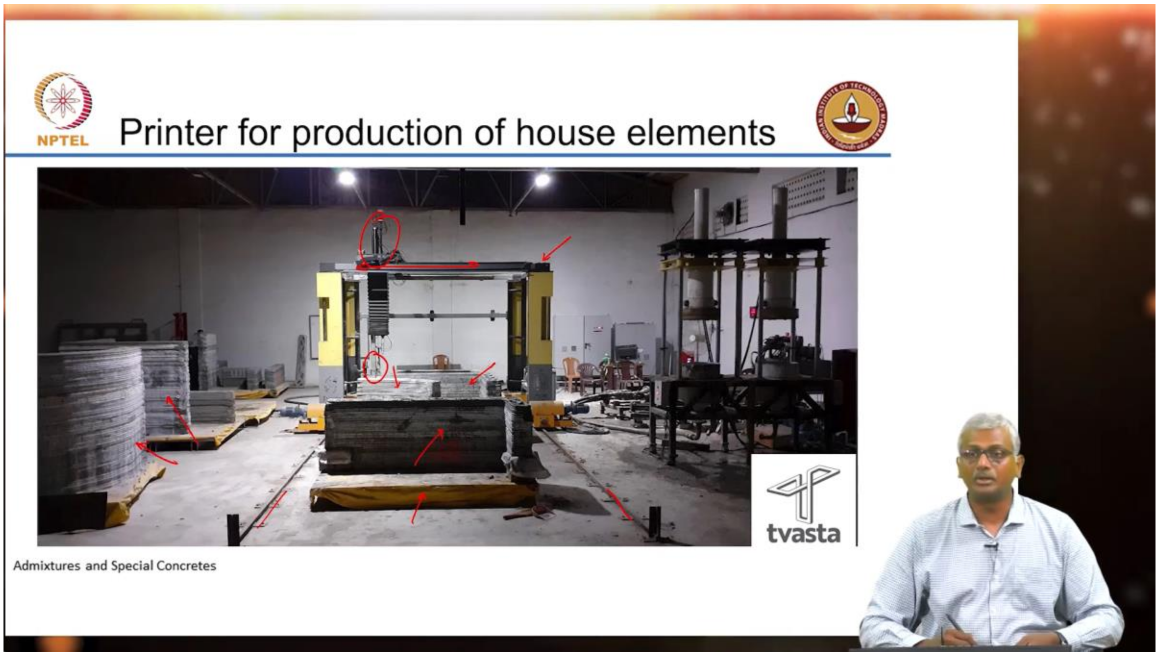

Now I will give you some examples of the work that has been executed in India by Tvasta. We had of course several stages in which we did the work. I will bring some examples of that later also. But just to show you the printer that was used for the construction of the house, this is the printer.

It is a gantry-based system. As you can see this is the moving head which can move along the gantry in this direction and the entire portal can move and then you have the nozzle at the bottom which is doing the printing. So here the entire printer was put on rails. So, the printer could be moved in one direction. Of course, you can make it infinitely long if you have the space but here you had space to put 3 print beds. Like this, there were 2 other beds on which printing could be done which indicates that multiple elements can be printed at the same time without waiting for one element to get hardened.

You can go on to the next bed and print the next element and so on. So here you can see that this element is getting printed on the first bed. 2 elements are getting printed on the second bed and similarly, there is one more element on the back. 3 beds were there. So, all these elements are printed and then stacked, and cured inside the factory, brought to the site, and then assembled.

3D Printed house at IIT Madras:

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These were assembled here. I do not know how many of you have been to this house. Has anybody seen the house? Just outside the cricket stadium, Chemplast ground. So, in this house of course you would not see the layers anymore because everything is plastered and painted but some segments are left open. So, you can see here clearly the distinction between the layers. This is the first layer; this is the second layer and that is the third layer on top.

So, there was a height limitation in the print. We could only go up to a height of 1.5 meters. So, 3 layers, each one of them, at least the main layers being 1.4 meters tall were printed at the same time and these were then stacked using mortar joints. You can see the mortar joint and then also connected with reinforcement that went right through the cavities.

If you look at the cross-section of these walls, it had the peripheral concrete and then there was a rib running through like that. So, there were gaps that could then be inserted with the reinforcement and then the reinforcement was grouted in place that help the connection between the different members. Not all the gaps were grouted, only a few, wherever reinforcement was desired were grouted. And you can see interestingly there is also a masonry wall segment that seems to be coming here that happened because this was the first time that such a large structure was being done here and because of the misalignment. So, this is the 3D-printed element that was supposed to have come right on top of this segment of the wall but there were a lot of misalignments.

So, to cover up for that mistake, we had to add this layer of masonry wall in front. So, such interesting innovations were also done on-site but that was only because we did not get a perfect geometric conformity in matching the different elements. This is also like precast operations. In precast operations also when you do match curing or match casting, every segment must be properly numbered because that is exactly the same location it will come on-site also. If you make a mistake in that, then you do not get that fixing, you do not get the perfect match between the elements that have been cast, and if you bring it to the site and you have to do some jugaad to get it sorted out.

So here this is an example, classic example of jugaad. You can also see that the lintel elements were prefabricated reinforced concrete lintel elements. They were not 3D printed, they were just beams that were precast and brought to place and simply kept, and of course, these are the stubs that are there to define the plaster thickness that needs to be applied. Now because of these geometric errors that were there in the overall construction process, the thickness of the plaster layer that needed to be put varied significantly. What is typically the thickness of plaster that is put on walls? What should be the thickness? Around 12 mm is desired.

In this case, the geometry was so different in some locations that they even put nearly 80 to 100 millimeters of plaster. So, what will happen when you put so much plaster? Of course, it is porous but the problem is it starts cracking. Shrinkage cracks would be high in the plaster and you can see when you go to the house there, the front curved portion on the right which is directly subjected to sunlight, a lot of shrinkage cracks have come in the plaster. It is looking bad but we have not done anything to repair it yet. That is essentially the cracks that are there in the plaster.

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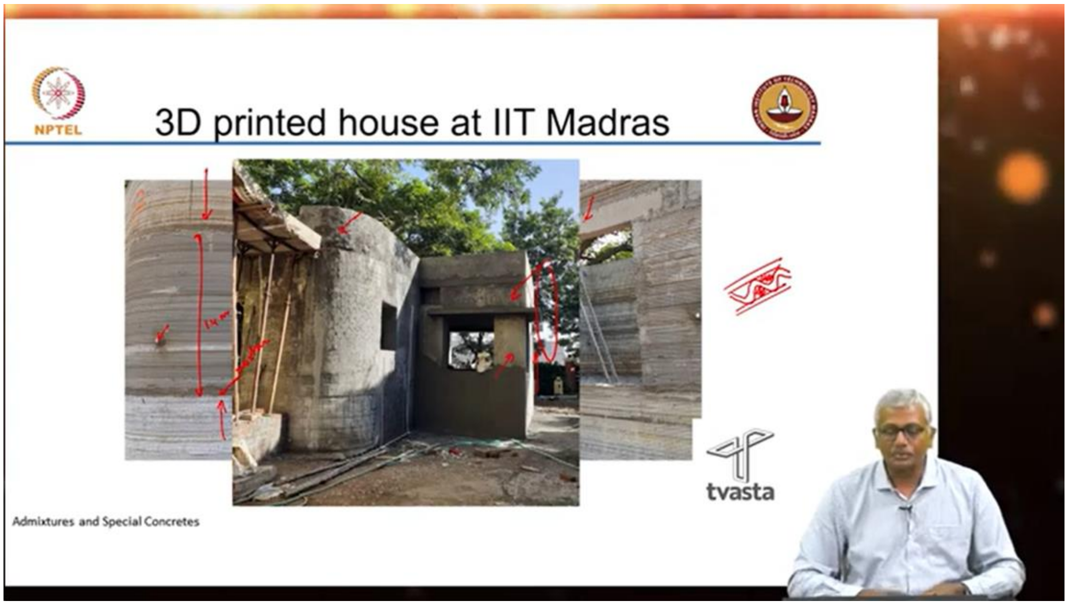

So, as you can see this is the plastering that was done on top. There were some segments which are left open to show the clear 3D-printed texture. On the other side of the building also there are few.

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And this is the overall 3D-printed house. The top slab was cast in situ. So once the walls were built up to the top slab level, roof slab level, there was formwork, shuttering was raised from inside, supported from inside, and then a proper regular reinforced concrete roof was done.

This portico also is cast in situ. It was not done by 3D printing and these 2 columns too. They were cast in situ columns. So overall this entire project right from starting with the foundation, the foundation was a strip foundation just a reinforced concrete strip under the walls, and right from that point onwards till the completion it took about 21 days from start to finish. Now these 21 days do not include the time it was spent for the printing of the elements in the factory. The printed elements were brought to the site after the foundation was ready and everything and from the start of the foundation till the end of the entire finishing it took 21 days.

The printing would have added perhaps another 7 to 14 days followed by subsequent curing of 7 to 14 days also. So, you must account for that also. If you do proper project management you can also ensure that you create enough elements, cure them and your entire site operations can get completed within 7 to 10 days. So, it is possible to do this house entirely within 1 week if you have the printed elements ready.

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So, you can see the house on the day of the inauguration. Of course, there were no cracks at that point of time. This is the wall which is where the exterior has been shown very clearly to show the layered structure. You can see one more location where this has been done and even on the inside some parts of the wall are left open for people to appreciate the 3D-printed textures. We initially wanted only that same texture throughout the building but since it was the first time this house was being built people decided that it should look like a normal house so that people appreciate it as a regular house and then only some segments are 3D printed, they can appreciate the texture better inside.

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Again, just another view, and all the planters that are outside are also 3D printed.

And you can see outside our gate also there are 3D printed planters one of which broke. I do not know whether it broke, it broke I mean many people are sitting on it also and some vehicles may have also banged into it. It is not going to be sufficient because there is no reinforcement in that. It is just a planter with some soil inside and I think many of the others have also cracked and I think the soil pressure has started getting onto it now.

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During this time, they also got another project from St. Gobain of course these were COVID days this structure came up in October 2020 that is when it was completed but formally inaugurated only in April 2021.