3D Printing as a Construction Process for Structural Members

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Abstract— In-situ 3d printing is an innovative technology which carries the potential to revolutionise the way construction is being done in India and the world. This paper identifies the techniques used for 3d printing and the sensitivity of the process towards the material being moulded. Few cases of 3d printing have been illustrated as example applications. The paper also explores the advantages, limitations and scope of research in the Indian context.

Key words: 3D Printing, Concrete, Plastics Construction

I. INTRODUCTION TO 3D PRINTING

3d Printing is a manufacturing process whereby objects can be created by layering of thin sections of material on top of each other to produce a finished product. [1] This technology is very well developed with respect to manufacturing components from various kinds of plastics. Other materials with which 3d printing can be done include Metal, Wood/Powder board, concrete, and even chocolate. [2] All 3d printing technologies follow a set of basic principles. The concept of plastic 3d printing is first illustrated.

The process of 3d printing begins from the creation of a STL file (Standard Tessellation Language file). This file is created from a digital model of the object to be printed, typically a CAD file. This cad file is then passed through a software known as a slicer which converts the file into the. STL format. This format can then be interpreted by the 3d printer and used to manufacture the design being produced. This format has now become the standard for most 3d printing products.[3]

A plastic 3d printer consists primarily of a heated nozzle, known as an extrusion head, which moves in 3 dimensions, X, Y and Z. The material used is typically a special type of plastic, known as PLA.[4] This plastic melts easily when exposed to the hot extrusion head. This melted plastic is extruded from the nozzle and allowed to move around the base of the printer via the x and y axes of the printer. After one layer of the material is completed, the head is moved up by one layer width and the process is repeated. This layering of material slowly builds up into a finished product.

One of the primary advantages of 3d printing is that the manufacturing method allows products to be created with high precision without a mould, drastically reducing costs for smaller products or for customised products.[5] 3d Printing has already given rise to many business models of designers either selling designs to be 3d printed by customers on their own or for high precision 3d printers being used to manufacture niche or customised products at far lower costs than otherwise possible with conventional manufacturing. [6]

II. 3D PRINTING TECHNIQUES

There are over 9 different methods of 3d printing used to fabricate components. However, most of these are processes designed specifically for specific materials or are used for only extremely high precision applications such as manufacturing prosthetics or implants or for manufacturing aeronautical grade components.

The first, Extrusion Printing, aka Fused Deposition Modelling is showcased above. As discussed, it consists of a nozzle capable of moving in the x y and z axes. The nozzle maintains a controlled flow of the material being printed. The products is created by the nozzle moving along the x and y axes first, and depositing a layer of material on the printing surface. Then the nozzle is raised by one layer thickness and the process is repeated. For extrusion printing it is important that the material deposited be liquid at the nozzle to enable consistent flow and bonding and set quickly when exiting the nozzle.[5]

With plastic this effect is achieved by using a heated nozzle along with a thin plastic wire known as a Filament. The filament is extruded through the heated nozzle which is calibrated to be at exactly the melting point of the plastic. The plastic sets immediately upon exiting the nozzle and enables the printing of complex shapes.

Similar processes have also been developed for dealing with other materials such as chocolate or?

The advantages of using Extrusion printing are [5]

- No chemical post processing required
- The equipment is less expensive
- The plastics used with powder bed printing tend to be less expensive

However, Extrusion printing does not always give a high quality surface finish, and needs additional sanding and some post processing in some cases.

Different organisations around the world are taking several different approaches to the 3d printing process.

The most basic is the technique adopted by Freeform Construction at the University of Loughborough[7]. A 3 axis gantry similar to that used in Fused Deposition Modelling is used on a larger scale with a relatively larger nozzle and a concrete pump to print either insitu or to pre cast concrete elements. This process has certain predictable constraints. As the work done by Le et all at Loughborough indicates; using concrete with 3d printers leads to new wet properties which must be

Fig. 1: Extrusion Based Plastic 3D printer

The other most common method used for 3d printing is powder bed printing. In powder bed printing, nozzle moves only in 2 axes, x and y. The process involved 2 separate materials, i.e. the powder and the binder. This process is also called 3DP. The process involves sequential layering of a powder base, typically a high quality polycarbonate, followed by a water or polymer based binder. After each layer the base moves one layer thickness lower and another layer of powder is laid down upon the binder. This process is repeated until the entire structure had been created. The excess powder is removed and the surface is finished as needed. Powder bed printing is currently being developed as the base method of manufacturing for prosthetics and implants. [4]

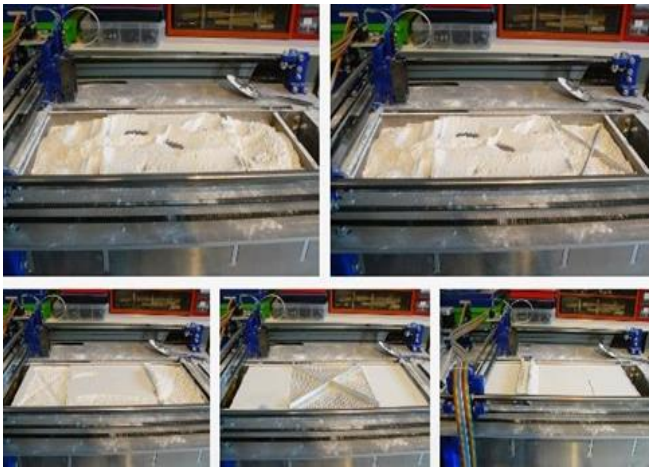

Fig. 2: Powder Bed printing

Other methods of 3d printing include but are not limited to Direct Shall Production, Laminated Object Manufacturing, Stereolithography and Selective Laser Sintering.

III. 3D PRINTING IN CONSTRUCTION

Due to the versatility of the fundamental process of 3D printing, particularly that of extrusion printing, it is possible to adapt it to many materials as long as some of their characteristics accommodate the demands of the process. A prime candidate for this is concrete. taken into account in the mix design process. These are Buildability and Extrudability. [8][9]

Extrudability of the material is important because this process of concreting required a mix design which can be extruded through a 9mm to 30mm thick nozzle and be extruded continuously without any pauses or hiccups. The mix design has to accommodate these constraints. Also, the much higher setting time of concrete means that the printing rate must be calibrated to ensure that no undue deformation takes place of the lower layers due to the additional load while ensuring that the inter layer bonding is not compromised. This is its Buildability and it is related to the quick setting of the concrete upon exiting the nozzle of the printer.[8]

At Loughborough and at other similar organisations around the world, the Buildability and the Extrudability of various mixes are evaluated through careful experimentation. These designs need to be calibrated for variations in climate and material but on the whole give consistent performance and predictable behavior.

Fig. 3: Section Printed by Freeform Construction

A variation of this method is adopted by Behrokh Koshnevis at his organisation, Contour Crafting[10]. Their patented[11] additive manufacturing technology combines the nozzle based extrusion system with a pair of trowels on either side, which give the concrete a smooth surface. The concrete that Contour Crafting works with trades strength for a much quicker setting time and a smoother finish. Evaluations of Contour Crafting seem to suggest that the technology may not be as viable in developing countries as some of its variations.[12]

The other two major organisations working in this are D-space[13] and Emerging objects[2]. Both their methods essentially focus on variations of powder bed printing to print large scale elements.

Emerging Objects is a research organisation based out of the University of California-Berkeley. Their approach essentially inverts the systems used in Freeform Construction and Contour Crafting. Here, the printer puts down layers of extremely fine cement aggregate mix and then layers it with a water admixture based "ink" to facilitate binding[14]. As sequential layers of the material are applied, the mix hardens and the form is built.

Fig. 4: Printing System Used By Dshape

The team at Emerging Objects is collaborating with the creators of D-shape to enable the creation of in-situ concrete printing. D-Shape works with a similar system, however their printing technique uses sand mixed with a metal oxide based catalyst as a substrate and a sea water based binder.[13] This technique enables the creation of precise and large synthetic stone structures. D-shape's methods have been appreciated by several international organisations[15] and they have also been awarded with a patent for their construction techniques. D-Shape is also being funded by the European Space Agency to develop construction techniques which may be used for printing and constructing habitats on the moon using lunar rock.[16]

IV. ADVANTAGES OF 3D PRINTING IN CONSTRUCTION

The use of 3d printing for in-situ construction could lead to a number of innovations and advantages. Particularly it enables significant savings in time and material cost, and savings in labour cost. It also gives a much more consistent quality of product and more options for innovation. By creating these technologies, we enable a number of developments in the construction industry. The advantages in form of mass production and design flexibility are highlighted herein.

A. Mass Production[17]:

This technology carries the potential to enable a new kind of affordable housing option, centred towards incrementally modified structures and sites and services dwelling options. 3d printing does not require any formwork, or large amounts of labour. It is possible to, within a single setting of the equipment and with limited supervision, to construct, on site entire structures at a rate only limited by the strength gain of the material used. One scenario is for slum rehabilitation. Rather than

the current method of reconstruction, which involves displacing the inhabitants for large periods of time, 3d printing enables a new kind of construction.

B. Customisation[18]:

As of now most common methods of working with concrete in construction amount to a version of moulding. With 3D printing it is possible to remove the limitations of formwork and other kinds of casting. It gives architects a greater freedom to design complex forms, by removing the limitations of skilled carpenters. It also simplifies on site execution by reducing the direct labour requirements and giving the engineers more options for service integration and quality control.

C. Quality Control[19]:

Extrusion based 3d printing is not constrained by the limitations of formwork. Particularly, as the printing is always visible it is possible to correct errors as soon as they occur, without needing to undo large amounts of work to correct minor errors. In addition to this as the process is completely mechanised there is no room of human error during construction.

D. Speed[20]:

It is typical for 3d printers to often work for large stretches of time completely unsupervised. Most major companies working with 3d printers often calibrate the systems in the evening, leave them on overnight and return the next day to a finished product. With construction it is similarly possible to have a 3d printer running overnight with only minimal supervision leading to significant savings in time. It is also possible to have multiple printers running in parallel to eliminate equipment constraints.

E. Pre-Casting[19]:

3d Printing has significant applicability in pre cast construction as well. With the advantage of a controlled workshop environment, a printer can completely eliminate moulding material cost from pre cast elements and make it possible for them to be cast much more precisely and much closer to the site itself leading to savings in transportation costs. 3D printing also enables hollow sections which can reduce the dead weight of the sections being cast. With pre cast elements already catering to projects with specialised sections and high unit costs 3d printing is the ideal development for the technologies.

F. Elimination of Formwork[7]:

Formwork represents a significant cost of the construction of any element and also represents the most time consuming activity in construction. By eliminating the time required for shuttering and de-shuttering a structure, 3d printing enables high speed and high quality construction.

V. LIMITATIONS OF 3D PRINTING IN CONSTRUCTION

There are certain problems with current 3d printing technologies which must be addressed during and before wide spread adoption of the technology.

1) Foundations: 3d Printing is not ideal for in-situ casting of foundations and will require either the gantry system to be disassembled prior to backfilling for the plinth or will require the foundations to be constructed by precast elements or by conventional technologies.
2) Shear and Seismic Strength: Printed elements have weaker shear strength along the boundaries between two adjacent layers and elements such as columns become vulnerable to failure along those axes. The structures have also not been evaluated for their response to seismic loads and methods for including reinforcements are not well explored.
3) Spans: To print large spans in-situ printers either need temporary supports or the elements need to be printed off site and then moved into place. This adds a step into the process and required some additional equipment and manpower. Alternatively, curved shapes can be used to give larger spans and better support systems.
4) Implications to labour market: After Agriculture, Construction is the industry which contribute the most to the labour market of India. Adoption of this technology would significantly impact manpower requirements, which would lead to a significant rise in unemployment among the classes typically involved as labourers and workers on site. The increase in mechanisation would impact the overall state of the economy in unpredictable ways, especially when seen in the context of increasing mechanisation in other similar fields such as transportation and manufacturing. However, it will also lead to skilled, green and dignified jobs, offering better work environments.
5) Lack of Standards: Currently 3D printing has only limited standardisation worldwide. While the industry is still developing standards for consumer grade plastic printers, several organisations are developing construction printers of various scales. Standardisation in IS and ASTM codes will become very important within the next decade.
6) Intellectual Property Rights: Many of the technologies being developed right now are currently under patent, with most scheduled to expire around 2030. As these technologies cross over into the public domain, the market shall evolve rapidly to incorporate these into all kinds of construction applications.

VI. 3D PRINTING APPLICATIONS: GLOBAL CASE STUDIES

Some experiments concerning 3d printing using concrete have already been taken up around the world in various regions.

A. NYC Waterfront Construction: 2013[21][15]

As a part of ongoing conservation efforts along the New York city waterfront, the New York City Economic Development Corporation organised a competition focused on encouraging technologies which would be able to make the spaces along the waterfront sustainable in the 21st Century. The results for this competition were announced in 2013. There, the first place prize was allotted to D-Space's 'Digital Concrete' technology.

To quote the NYCEDC's announcement of the winner

D-Shape's 'Digital Concrete' resolves a number of issues regarding the restoration of piers, piles and seawalls that populate New York's waterfront. By 3D scanning, then 3D printing concrete, one combines the best of precast and cast-in-place methods. The advantages of quality control in fabricating off-site yet being able to closely fit the encasements, blocks or extensions to the surface that they are nestled into has a number of advantages, including lower costs, better quality control (thus longer life), lower labour mobilization and quicker delivery and installations. Furthermore, there is a potential opportunity to rejuvenate the waterfront by letting artists leverage the total freedom of design to add an aesthetic touch without a significant added cost. D-shape estimates the potential cost savings to NYC by utilizing its technology across all 565 miles of shoreline to be $2.9 billion.[21]

Essentially, D-shape's proposal is to create 3d scans of the piles which have to be encased for rehabilitation, and then using CAD software, to design customised encasements for each of the piles to be rehabilitated individually to ensure a good seal and a simpler fitting process.

These piles can then be 3d printed on site, with the rebars inserted during the fitting process and then easily jacketed around the piles to be rehabilitated. This process enables the process to be completed much faster, much more safely and with much less skilled labour than conventional rehabilitation methods. As each encasements is custom built to the pile to be rehabilitated, the technology represents a significant saving in cost and time, one the order of 20 to 40%.

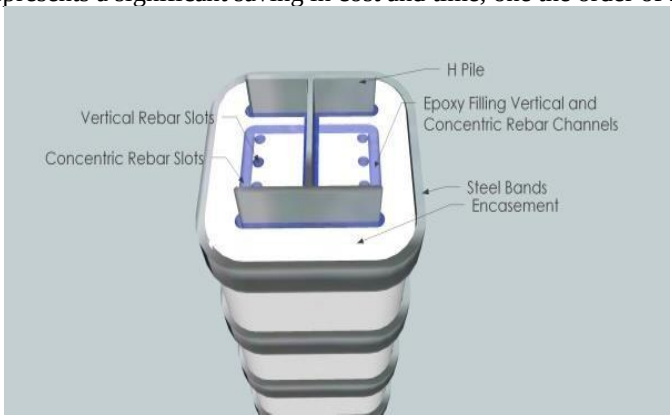

Fig. 5: System proposed by D-shape

B. 3D Printed Hotel Suite in the Philippines[20]

The world's first ever commercial, functional 3d printed structure has been created in the Philippines. The project is a joint venture by Andrey Rudenko- a printing enthusiast from Minnesota, and Lewis Yakich- a material science graduate and real estate investor in the Philippines.

Andrey Rudenko began his career in 3d printing by building a 3d printer in his own garage, as an experiment to see whether the technology was viable. Andrey worked as a contractor in Minnesota and wanted to create a system which would be inexpensive and viable for smaller contractors as a system of construction. This lead to him working out of his garage and developing a custom 3d printer which he later used to 3d print a 160 sq ft two storey castle prototype as a proof of concept. His printer design, which is similar in philosophy to that of free form construction, allows there to be reinforcement and piping integrated easily into the structure while printing is still running or while the printing is paused.

Fig. 6: 3D printed Castle By Rudenko

Fig. 7: 3D Printed Suite in Lewis Grand

The party house constructed for the Lewis Grand Hotel was done in this manner. The 3d printer used entirely local sand and cement as the base for the printing material along with a few admixtures. The local sand consisted of volcanic ash which made the printing process slightly more difficult, however the strength gain from the concrete was excellent.

Their work also found that the hotter climate in the Philippines meant the concrete showed much better strength gain and give ideal performance. The printing of the entire 130sq mt structure took only around 100 hours, including time for the installation of reinforcement wires between the layers and the installation of integrated piping for electrical and water conduits. The fully printed structure was finished and opened for use in December, two months after completion of printing.

Yakich, the owner of the Lewis Grand Hotel, is also interested in using the technology to produce 3d printed private homes and low income housing in association with the government of Philippines. In association with Andrey, they have already been approved as a qualified builder and plan to construct 2000 homes within 2 years.

They estimate the process would lead to a 60% saving in construction costs.

VII. 3D PRINTING: SCOPE FOR RESEARCH IN INDIAN CONTEXT

In-situ 3d printing is a new technology which carries the potential to revolutionise the way construction is being done in India and the world. As of now, little research is being done in the Indian context to make these technologies useful and adaptable to the demands of Indian construction. Due to the different climatic conditions in India, it is important to evaluate the work already being done in other parts of the world to check its applicability. It is also important to look at the technology in the context of construction and design standards in India and evaluate the economic or technical viability of this method of construction. If successful these developments would help promote a new paradigm of construction in India.

The experiments in the Philippines show that the technology is ideal for our climate and context and will give a tremendous opportunity to significantly improve the quality of work done in the Indian construction Industry. Developing indigenous technology is the most effective way to ensure that the industry shall have access to inexpensive equipment.

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