Will we really live in additively crafted houses, *in future?*
Is this just a hype or does it lack for success only because a common systematic approach of all necessary disciplines is missing?

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The Task

Concrete is the most used construction material in the world. However, concrete application is facing two bottle-necks: The stock of building materials reduces and construction causes about 37% of the global CO_2 footprint. Now, the hope is that applying automated fabrication processes in construction will improve this situation. The idea of an "Automated construction using an Additive Manufacturing (AM) process" is: One can build cheaper, lowers effortful labor work, is more sustainable, more qualified, and even faster in the future. Thereby the aim is to avoid waste by the allocation of material only where it is necessary from structural analysis reasons. Objective is a digitized load path-oriented deposit of a minimum amount of mortar (concrete) probably with reinforcing short fibers in the mixture.
From a technical perspective: Digital Fabrication DF without formwork is a specific aim due to the 20% or even more savings regarding the final structural part cost and this cost increases with the complexity of the required formwork.

The AM Process within all the Manufacturing Processes

There are several manufacturing processes where the AM process is one part of.

1. <u>Subtractive manufacturing process</u> (high waste): geometry to be created is determined by a defined removal of single volumes. Typical representatives of this group of manufacturing processes are machining processes such as turning, drilling or milling. Wooden construction is one example.
2. <u>Formative manufacturing process</u>: production of geometry by forming in compliance with volume consistency. Deep drawing, forging or primary forming (Urformen) of metal semi-finished products are examples for this process.
3. <u>Additive manufacturing process</u>: [VDI 2403], creation of geometry by joining together solid elements (if small, termed "voxels"). Casting of concrete is the most known example.
   This process is of advantage for prototypes and small series. The main feature of all AM processes is low-tool manufacturing. In order to achieve this, the main task in 'AM construction' is Digital Fabrication with cement-based materials. Main characteristic of the AM process is that material is applied layer by layer and thus 3D-parts are built up.

ISO/ASTM 52900 defines AM as "Process of joining materials to make parts from 3D model data, usually layer upon layer". Generally used in AM are building materials such as polymers, metals and aggregated-based ones. The latter applies mortar (concrete) and is the focus here.

Unfortunately, all the AM process types are addressed under the same term '*3D-Printing'* despite of having merely to do with the old term printing. Printing is basically a procedure to apply something by pressure like printing a book page, where at each print a full 2D-cross-section is produced. AM (better AF) is a relative old noun to capture the different AM process types. Why do we need the confusing novel designation '3D-printing' on top? It is extruding. Self-explaining technical terms are a prerequisite for understanding.

For the dimensioning engineer it must be always clear which AM process type is actually used. We clearly speak about casting concrete, shotcrete, placing of reinforcement, laying bricks or mason. So, for instance, we should also find a unique term for the non-accurate one '3D-printing', if we speak about a mortar strand deposit (caterpillar) extrusion. In this context, the term 'strand' (= Strang, 'yarn of limited length') is still practiced and one should not use filament again which in mechanical engineering AM is still the technical term for a continuous plastic thread, despite of the fact that a filament is defined in the fiber-reinforced domain as a thin endless single fiber.

Thankfully, the RILEM Technical Committee 276 classified the AM process types for the layer-wise constructions by names, which pretty well outline the process type:

3a: Particle-bed binding is an AM process in which particles are selectively bound using as binder a bonding agent, includes as sub-classes Binder Jetting, Selective Binder (cement) Activation (analogous to laser sintering of metal powder) and Selective Paste Intrusion

3b: Material extrusion with cementitious and polymer agents includes as sub-class 'mortar strand deposit'

3c: Material jetting. Several nozzles are spraying different material components.

The Main two Layer-wise AM Process Types

Specific for these processes is: *Making a structural part from a 3D digital model by laying down many layers of a material in succession to finally form a 3D-part including cavities.*

Particle-bed binding process, in construction:

Here, at least, the use of the term printing has something to do with the book printing process.

This process belongs to the 3a-subset above, where full (2D) cross-section-wide, relatively thin layers with cavities are built up on another and where the third direction "3D" (see ***Fig.1***) is generated - after consolidation - by lowering the print table (layer thickness less than 1mm through many mm). Or, it is a sum of AM steps with consolidated thin sheets of the full cross section with its cavities. The selective cement activation is one particle bed-based AM technique, in which a dry mixture of sand and cement is spread in thin layers and solidified with water. *Example for a production, at Voxeljet in Friedberg: Automatic production of freely shaped surface formwork applying digital 3D data and using a powder based build material and a usually liquid binder, which acts as an adhesive between the powder layers.*

Mind: Designing a casted concrete part means that the formwork must be designed, too.

The thinner the layer the better the desired smooth surface and the better overhangs can be realized without any support material.

Process steps:

- CAD model of the spatial part (3D)
- Slicing of the part and determination of layer thicknesses
- Powder-based material is placed on the building platform
- Application of a material layer with solidification by the binder
- Repetitions: building platform is lowered due to the layer thicknesses
- Removal of loose powder
- Post-processing of the part's surface.

Mortar strand depositing process:

This process is a material extrusion process and belongs to the 3b-subset above. According to VDI 3405 this process is defined as cold extrusion process, whereby the pasty building material is deposited by strand (caterpillar) via a nozzle. In other words it is an additive fabrication of a building via a deposit of a mortar strand from an extruder head (see ***Fig.2***) using robot-assisted 'injection molding technology. The so-called '3-D printers' (*another artificial name and not extruder as it is standard with polymers*) are equipped with an extrusion-type mortar strand deposition system.

With the 3b process larger structures can be faster fabricated than with the 3a process above.

Shape and size of the strand and the layer-wise deposit process are the essential parameters for the outcome quality of the part. The aim is, beside to obtaining enough load-carrying capacity, to further implement functions of building technology like thermal insulation using glass beads etc. And further, to perform a lightweight and insulation driven use of foam-mortar mixtures, keeping object-oriented sufficient strength. Insulation material or self-compacting concrete may be used to fill the cavities.

Strands with small cross-sections lead to more precision and a less rough surface, whereas a large cross-section increases production speed and enables to use coarser grains. That leads to a reduced amount of cement, less shrinkage and higher compressive strength.

Process steps:

- CAD model of the spatial part
- Performance of slicing and determination of the digitized nozzle path
- Mortar premixes are pumped to the extruder head with its end part, termed nozzle, to form the task-required shape of the strand (elliptical, square etc.)
- The extruder head may have one or more injection nozzles. One may be used for a second material (see 3c). Gradient concrete for compression-tension domains can be produced by extrusion, with and without short fibers.

Fig.1

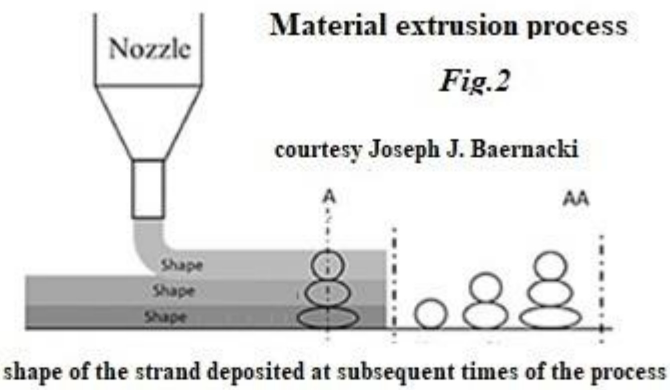

Fig.2

Project Milestone, City of Eindhoven *[Freek Bos, Uni Eindhoven]*

The Topics, Mortar Strand Depositing Process

- Mortar: fine concrete formulation, grain < 4 mm, usually
  - water + cement type + rock grain (fine sand, sand, gravel) +

- additives (flow agents, delayers, superplasticizers + …)
- without or with short fibers (about 6 mm from carbon, glass, basalt, polypropylene)
- water/cement-ratio ≈ 0.3

➢ Reinforcement: continuous fiber, long fiber, short fiber, bar, textile fiber grid etc

➢ Extrusion head guiding robots: single robots, gantry cranes, mobile robot with precise placing of material at site ("AM on wheels"), etc.

The Process Constraints faced in "Mortar Strand Depositing"

1) Recipes for the appropriate mortar mixture, considering processing time (also termed open or setting or pot time) of the deposited strand, essentially depends on the aggregates and the length of the full deposit path
2) The mortar must guarantee pumpability (*transport to extrusion nozzle*), extrudability (*passing through the nozzle*) and buildability (failure). The deposited mortar strand transfers – due to the recipe - with varying times to a solid! Consequently, the early stage rheological properties of the fresh mortar (cement paste) are to characterize, especially the growing yield strength must become larger than the acting compression yield stress to avoid uncontrolled material flow. The fresh cementitious mortar experiences early creep.
3) In the case of a wall the 'mortar strand depositing' process (layered extrusion, material is squeezed out of a nozzle, like contour crafting) the hydrostatic pressure of the drying mortar builds the loading. In consequence some requirements are contradictory: Flowable mortar for pumping and enough stiffness viewing buildability because each mortar layer has to carry the layers above it.
4) The gravitational flow of the deposited strand causes two failure modes to by-pass: Material yielding under compression (addresses pumpability and extrudability) and stability meaning buckling of the multi-layer wall (addresses buildability). Bypassing the 2 failure modes: (1) material failure (material flows away, because the current yield strength is too low for the mass upon). (2) Structural failure (the erected wall loses its stability. *Fig.2* excellently depicts the primary problem. The layers have to bind to on each other to finally form the whole part
5) Rheology-based production process simulation is required – using computational fluid dynamics CFD - in order to finally achieve Buildability and Shape Stability of the freshly manufactured part
6) Extrusion of nozzle near mixed concrete – individually graded in density and in rate of 3D fiber reinforcement. No dispersion of admixture in the nozzle
7) Material characterization, time-dependent properties of the fresh mortar after being deposited and further in the build-up process. Pull-out tests in order to evaluate the bond between concrete and reinforcement
8) Post-processing (rough surface, removal of notches). Notched, rough surface at the touching layer surfaces
9) Quality assurance of mortar, fibers, concrete and fabrication processes
10) Fabrication process with 'real' reinforcement to tackle tension-stressed building elements.

The Challenging Tasks to be solved in Mortar Strand Depositing Process

✓ Successful combination of (a) aimed design, (b) time-dependent and phase-changing material properties (physical-chemical during processing time) and (3) process characteristics

✓ Recipes for the appropriate mortar. Recipe of the mortar with curing procedure (deposit time-dependent, analog polymer matrix)

✓ Moving from only compression load-carrying structures to bending moments carrying ones, with and without short reinforcing fibers, from partly 'just' artwork to load-carrying standard building elements

✓ Introduction of armoring to withstand usual bending of the structural part

✓ Normative Dimensioning

✓ Approval Procedure (ZiE) is necessary as a special load-bearing capability certificate

- ✓ Static & cyclic fatigue due to notched layers and surface
- ✓ Production at the market price level
- ✓ Digital fabrication must focus on the standard building elements in construction.
- ✓ Generation of material testing standards to specify the hardening fresh placed thixotropic mortar with capturing the rheological behavior of the cement paste depending on temperature
- ✓ Adjusting the rheology for good buildability and bond between superimposed strands and mortar with reinforcement
- ✓ Design of the different AM equipment and AM 'printing' (extruding) machines.

The Implementation of Reinforcement in the Mortar Strand Depositing Process

The reinforcement could be integrated during all stages of the AM process and also before as traditionally done: Internally within an AM-formwork (***Fig.3*** *left, rebars and cages*), internally before extrusion of aggregate (***Fig.3*** *center*) and embedded in the strand. Tendons and passive external reinforcement are employed to combine building elements. Further investigated is directly AM-fabricated reinforcement as shown below (***Fig.3*** *right*), however, these Wire and Arc Manufacturing (WAAM)-generated rebars suffers from the process-inherent notches.

In addition there are several possibilities: Short thin steel bars vertical to the layer, randomly distributed short filaments (pumpability reduced) in the mortar strand (rheology must fit), oriented short filaments or steel fibers in the layer plane.

The AM-Future asks for building multi-story houses. Here, in order to resist to the usual bending of the walls vertical reinforcement is the main challenge, post-tensioning by tendons and non-tensioned reinforcement are the tasks. Thereby, the bound of reinforcement to mortar is a further challenge.

Mortar recipe and implementation of the reinforcement remain the crucial tasks for the future.

Fig.3: Reinforcing in AM

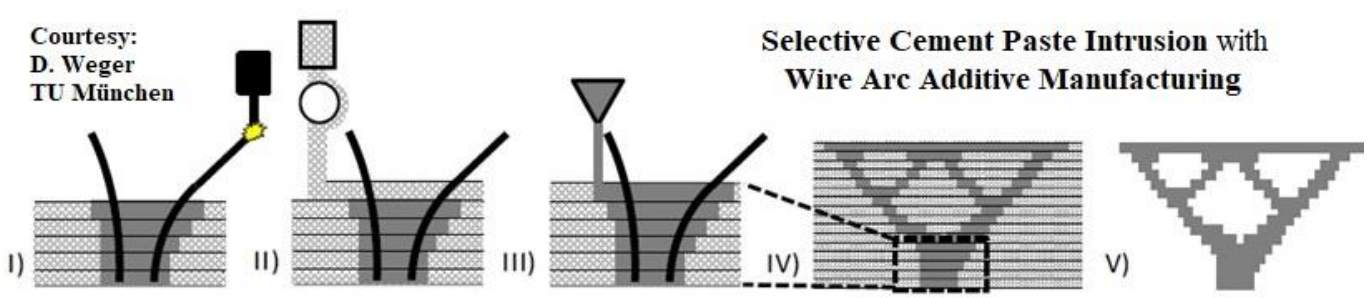

Fig.4: Selective Cement Paste intrusion with WAAM-fabricated rebar

The Process Simulation of the Hardening Mortar Strand and Analysis of the Structural Part

- Designer delivers a CAD model of the structural part
- Check of manufacturability of the provided CAD model, conversion to AM model → adaptation?
- Slicing of the structural part considering layer thickness, mixture recipe, strand geometry etc.
- Production process simulation: Modeling the rheological behavior of the cement paste by an elasto-viscoplastic material model. The extrusion flow and speed of the mortar strand is modelled by a Continuum Fluid Dynamics (CFD) simulation software
- Physics-based simulation of the process by regarding above point, linking all participating 'machines' to avoid collision
- Structural analysis of the fabricated AM part
- Certification process.

Design verification must be demonstrated for the Design Limit States Ultimate (ULS) and Serviceability (SLS). Load-carrying structures are usually too big to test them. Therefore, more or less "Design-by-Analysis only" is practically given and a closed analysis-driven design and verification workflow is required to 'convince' the authorities with a reliable basis for a successful Approval Procedure. In order to achieve this (later) normative material properties play a big role and are to provide with the structural data.

In the Mortar Strand Depositing Process essential for the modelling engineer is, that there are different variants to model: Fully isotropic mortar without any steel- and fiber-reinforcement, reinforcement with polymer strands or stochastically mixed-in short fibers. Production-directed short fiber reinforcements are to be modelled anisotropically etc. Dimensioning here on basis of 'von Mises stresses' is not permitted, anisotropic strength criteria are to employ.

The free-shape possibilities offer to use modern Generic Design methods, where the design space, the loading and the supports must be known, only. Topology optimization is required combining digital fabrication and quality assurance and as well must capture the transient material characteristics and the structure geometry during the construction stages. Buildability then is an essential optimization side constraint.

The Conclusions

The Mortar Strand Depositing process is still a cutting-edge process. Many tasks are to be solved in future as described above. However, there will not come the desired progress viewing the following two citations of present mortar strand depositing manufacturers:

(1) 2019 *statement of an US manufacturer: "We should now also use structural engineers"*! Naturally it cannot be - for instance - a domain of architects and digitizers, alone. It must include other engineers, which is successfully performed by artwork constructions of the ITKE at Stuttgart University or at the ETH Zurich. Then the chance grows for a production of standard multistory houses.

(2) July 2020, statement of a Chinese manufacturer after praising his technology: *"After hardening of the material, the structure proved to be firm enough to turn it over and place it on the side without breaking."* One might this citation interpret: The structure can just carry its self-weight. Where is the necessary bending capacity?

By now, hardly load-carrying constructions - permitting to face the inherent bending - are successfully fabricated, just compression-loaded ones. Hence, ***in the next future we will not live in additively crafted***

multi-story houses. And that will come all the later, the later a systematic approach of all the necessary disciplines is pursued together. Interdisciplinary is mandatory for success.

However, unfortunately not so often, interdisciplinary and Digital Fabrication DF successfully act together: The next two figures show a lightweight 'fiber pavilion'. It is composed of 60 CFRP/GFRP components built by a special automated process using a winding machine which winds endless fiber strands 'around' 3D-fixed nodes. These nodes belong to the pavilion's structural system.

Fig.5: BUGA-Heilbronn. Roving-placing robot machine (left), art-work and load-carrying structure (right) [Knippers, Koslowski ITKE and Menges CD Uni Stuttgart]

The conference Digital Concrete, Zurich 2018, gave first results of the actual AM stage in construction: (1) The world-wide presented AM buildings were basically compression-stressed constructions. (2) To really achieve the promised building time and cost level it will take more time than referenced.

In this context it makes sense to check the status of AM in mechanical engineering stressing a Whitepaper *[In 'Mission Additive' published on "Market research on the state of industrial 3D printing". Vogel, Communications Group]*. The four basic AM objectives there are: (1) Faster Time-to-Market, (2) Optimization of the present product, (3) Shortage of fabrication time, and (4) Reduction of cost.

Some results were:

*Polymeric materials are much more used than metallic materials

*Also here additive processes are still relatively young and testing of the processes is intensively performed

*Metal materials are taken more for novel products aiming at specific improved product properties

*Shortage of fabrication time is essential and intesively used for repair and replacement.

In addition an information w.r.t. construction, where several bridges have been built in the last years:

- The materials used in the different DF processes were polymers (partly short fiber reinforced) and steel
- The author recognized domed (arched) concrte constructions. These are built up by compression loaded elements and not tension load capable ones. External pretension of the elements is a means used. Even the metallic bridges seen are domed. Here, the rough WAAM-surface leads to early fatigue if the elements would be tension stressed

Finally, addressing the mentioned two Bottle-necks:

(1) *The stock of building materials reduces* → The amount of the created construction waste is directly reduced by an AM process and nowadays further indirectly by including in the design the recycling at the end-of-life.

(2) *Construction causes about 37% of the global CO_2 footprint.* The *[World Green Building Council's 2019 Report]* describes actions to revolutionize the buildings and construction sector towards a zero CO_2 footprint future. Buildings and infrastructure around the world account together for 39% of all carbon emissions in the world, with operational emissions from energy used to heat, cool and light buildings. The remaining 11% comes from embodied carbon emissions, that is associated with materials and construction processes throughout the whole building lifecycle. WorldGBC's vision is to reach 40% less embodied carbon emissions. → In future DF (AM) must contribute to this. Of course, no information can be given yet for the future savings.

Note: Additive Fabrication AF would be a better designation than Additive Manufacturing ('handicraft'), which describes the opposite considering the Latin words manus (hand) and facere (to make). However, the still used DF would be the best choice.

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