Fabrication of a Truss-like Beam Casted with 3d Printed Clay Moulds

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Abstract –

The advent of reinforced concrete (RC) at the beginning of the 20th century fostered the industrialisation of construction. Indeed, for the first time machines such as mixers appeared on the worksites. Strangely, RC construction is now probably more artisanal than steel or wood construction. Current technics raise questions about the security of workers, the quality and the control of the work carried out. Automation can, in particular, help tackle these challenges.

In this study, we developed a digital process for the fabrication of truss-like beams. Clay moulds are 3D printed and serve as a formwork for the cavities of the beam. The fabrication of a three-meter-long beam saving 30% of concrete and Eurocode-compliant is thoroughly described in the paper. A detailed evaluation of the process is then provided and future improvements are suggested.

Keywords –

Digital fabrication; Clay printing; Reinforced concrete; Structural optimisation

1 Introduction

Reinforced concrete (RC) is not only a material but also a construction technique and a building system. At the beginning of the 20th century, its rise fostered a paradigm change in the organisation of construction sites. Former highly skilled craftsmen like stonemasons are replaced by a greater but less skilled workforce working in a more industrialised environment [1]. Indeed, for the first time machines such as mixers appeared on the worksites. It is somewhat surprising to note that no major development has been made since then in the way we build with reinforced concrete. In particular, the shapes taken by concrete remain mainly driven by flat wooden or metallic formworks and straight rebars. And, compared to the current standards, RC construction is highly labour-centred. This raises questions in terms of productivity and quality of the work carried out [2][1], as well as in terms of security for workers. Typically, the rebar workers tend to carry heavy loads with poor ergonomics. However, the shift towards a greater automation of tasks is not straightforward. Indeed, as observed by the authors in several factories of rebar cage or RC elements fabrication, there is no numerical continuity between the design offices and the factories. As such, a lot of time is lost due to a lack of efficiency in the management of information between the players at stake, namely the contractors and their subcontractors.

This paper presents an automated process for the fabrication of truss-like beams. By 3D printing clay moulds to form the hollow parts of the beams, one is able to address the challenge of mass customisation and geometric complexity without producing wastes as the clay if fully recyclable [3]. This process is part of a fully digital workflow that allows the efficient transmission of information between the design and the fabrication phases. Section 2 introduces the design of two three-meter-long optimised beams with 30% less concrete than in a traditional prismatic beam. The fabrication of the second prototype is described in Section 3. Eventually, we discuss about potential improvements regarding the fabrication process in Section 4.

2 Structural Design of Optimised Beams

The design of the three-meter-long beam prototypes is based on the struts optimisation approach [4], a Eurocode-based optimisation method [5]. By optimising the height of the concrete struts, the internal shear forces are carried more efficiently from the application points of the loads towards the supports. This methodology leads to the design of unconventional truss-like beams, enabling great concrete savings.

The prototypes presented in this paper were both designed as simply supported beams subjected to a uniform loading including appropriate dead and live loads representing typical office building loading. The geometries of the two prototypes are presented in ‘Figure 1’ and ‘Figure 2’. The main difference is the reduction of the width for manufacturing reasons which are detailed in Section 3.3.

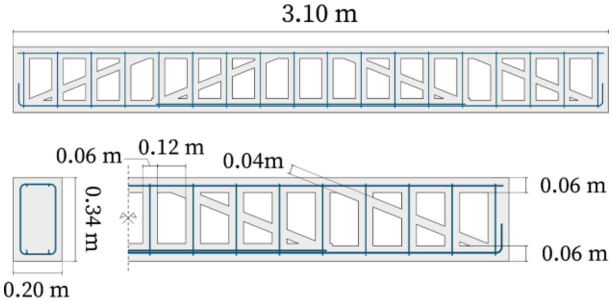

Figure 1. Design of the first prototype. The rebars are represented in blue.

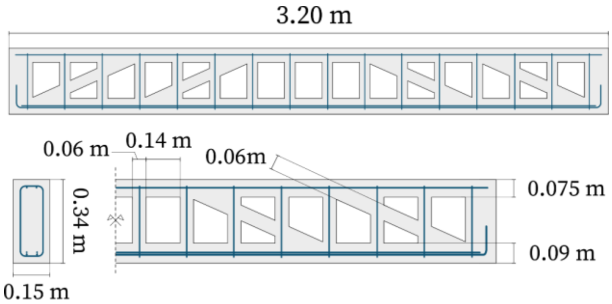

Figure 2. Design of the second prototype. The rebars are represented in blue.

3 Design and Fabrication Workflow

3.1 Computational workflow

Every design and fabrication steps are integrated into a fully automated digital workflow. In this way, the shape complexity and unicity of the cavities of the beams can easily be managed at all point of the process. For instance, the shop drawings as well as the fabrication data, such as the robot's path, are automatically generated. With a view to an industrialisation of the process, it also facilitates the verification steps, reduces the risk for mistakes due to the digitisation of paper plans at the factory, and cuts the time spent in project management. Furthermore, this methodology is necessary to make mass customisation possible so as to fully take advantage of the struts optimisation method. The workflow is presented in 'Figure 3'.

The sizing of the beam elements (struts, ties, rebar cage) is performed with a custom C# library and results in a comprehensive model including key features such as the concrete type and volume, the rebars dimensions, shapes and position as well as geometrical outputs (height and inclination of the struts, width of the ties, concrete covers, etc.). Digital shop drawings are then automatically generated using Grasshopper software.

Although this data could also be leveraged to automate the preparation of the rebar cage and of the formwork, this paper concentrates on the fabrication of the 3D printed moulds.

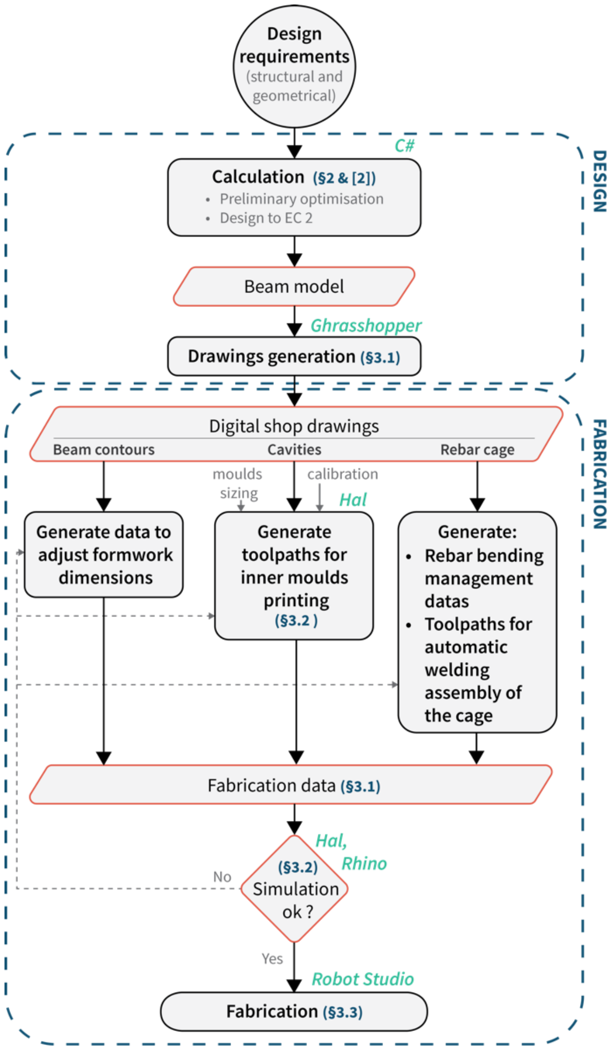

Figure 3. Fabrication-centred computational workflow

3.2 Developments around clay 3D printing

The fabrication of the first prototype, which is presented in 'Figure 4', has already been described in [4]. Key takeaways are that:

- Printing concrete moulds has no environmental interest using the current available technologies as the printing mix is mainly made up of cement.
- Manufacturing tolerances of all parts (formworks, moulds and rebar cage) must be consistent to ensure the insertion of the rebar cage and an even concrete pouring.
- Concrete cannot be vibrated. Indeed, it would displace the moulds which we cannot fix to lost

casing without complicating the demoulding phase.

To address the first shortcoming, a new process for 3D printing clay moulds has been developed. It uses a cartridge-based extruder [6]. The extruder is mounted on a 6-axes industrial robot. A pneumatic jack pushes a piston along a 4-L cartridge containing a clay mix in order to feed a 15 mm nozzle with this mix (‘Figure 5’).

Figure 4. Photo of a three-meter-long optimised beam prototype built with 3D printed concrete moulds.

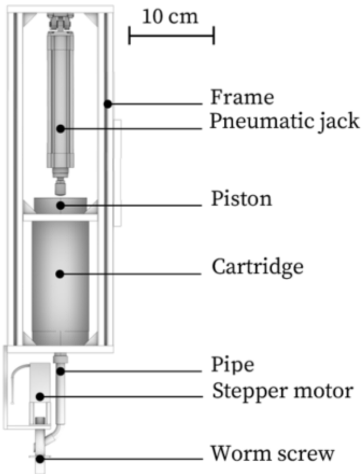

Figure 5. Schematic representation of the cartridge extruder.

The extruded material is a mix between kaolin clay (Speswhite Imerys) and water with a water to clay massic ratio e/k equals to 0.58. With this ratio, the paste remains between the liquid and plastic limits. This is necessary to fulfil the compromise between the printability of the mix and its buildability, i.e. its capacity to support its own weight when extruded into layers.

3.3 Fabrication of the prototype

To assess the feasibility of the process, a second prototype was built following the design presented in ‘Figure 2’.

It is important to note that, to ease the concrete pouring while maintaining an optimal design regarding shear forces, the width of the beam was reduced but the height of the struts was increased. The resisting section is thus kept but its shape is better adapted to the fabrication.

In chronological order, the fabrication includes the following steps:

1. Preparation of the external formwork;
2. Assembly of the rebar cage;
3. Calibration of the robot’s path for printing;
4. Printing of the clay moulds on the lost casing;
5. Filling of the moulds with sand;
6. Insertion of the rebar cage between the formwork and the moulds;
7. Concrete pouring.

The assembly of the rebar cage was done by Sendin in one of their factory. Special care was given to the bending of the rebar, to the spacing between the stirrups as well as to their inclination (perpendicular to the longitudinal rebars).

The robot’s path (generated with Hal software) need to be calibrated to compensate for the non-planarity of the lost casing along the 3.2 m of the beam. This step is necessary to ensure a consistent height for the first layers of the 19 moulds. The moulds are then directly printed on the lost casing. Here, six cartridges were necessary.

Afterwards, the moulds are filled with sand in order to balance the pressure of the concrete at fresh state.

The rebar cage is inserted and finally the concrete is poured. No vibrating was required. In ‘Figure 6’, several photos of the fabrication process are shown.

4 Discussion

4.1 Benefits from a higher fabrication complexity

Table 1’ presents the bill of quantities of both prototypes and ‘Table 2’ some metrics regarding their fabrication.

Table 1. Bill of materials (est.: estimation)

	Pr. 1	Pr. 2
Printed material (kg)	93	44
Poured concrete (m^3)	0.138	0.119
Steel ratio (kg/m^3)	77	156
Poured sand (m^3 - est.)	-	0.029

Table 2. Production data. In red, the number of people required to realise the task. (est.: estimation)

	Pr. 1	Pr. 2
Moulds fabrication (min)	80 (3)	210 (3)
Sand pouring (min)	-	15 (2)
Casting and finishing (min - est.)	120 (1)	25 (2)
Total time (min)	**360**	**710**
Slump flow test (mm)	-	730
Rebar cage assembly tolerance (cm)	2	0.5

Figure 6. Fabrication of the second prototype. From top to bottom: printing of the moulds, insertion of the rebars and filling of the moulds with sand, pouring of the concrete, demoulded beam.

The processing time for the second prototype took twice as much time as the one with concrete moulds. This difference is mainly due to the time taken to prepare the clay moulds. The most time-consuming sub-process for the preparation of the clay moulds was the refilling and reloading of the cartridges whereas the printing time alone was very similar in both case studies. A continuous process avoiding cartridges would decrease highly this time step.

However, several parameters where leveraged to ease the concrete casting by allowing a smoother concrete pouring, especially regarding the coarser aggregates. The better manufacturing tolerance of the cage ensures minimal distances between the rebars and the moulds. The modification of the geometry of the struts also goes in that direction despite a higher steel ratio. This higher ratio is mainly due to the lack of availability of 8 mm diameter rebars in the second case. Lastly, the use of self–compacting concrete (SCC) instead of ordinary concrete, though requiring higher precision in the formulation, makes the pouring easier. To go further, robotic assembly of the rebar cage could also be leveraged to improve even better the precision. Shifting the complexity towards upstream tasks enables to ease the concrete pouring which is necessary to manufacture sound structural elements.

4.2 Complementarity of the formwork and the robot

The setup presented in this paper consists of a fixed wooden formwork and of a 6-axis industrial robot placed on a linear track. 6 axis are not required to print the moulds. Stiffer robots such as gantry robots or SCARA ones would be more relevant in an industrial environment: they are cheaper, more productive, and require less maintenance. Moreover, depending on the context i.e. prefabrication or on-site manufacturing, the moving part might not be the same. In a factory, to enable a continuous process from the preparation of the formwork to the steam-curing of the concrete and the demoulding of the beam, a conveyor is required. As such, a fixed robot should be use. On-site, a robot on a track offers a more compact printing unit. It thus better suits the tight space constraints of worksites in urban areas.

5 Conclusion and perspectives

This paper presented the fabrication of a three-meter-long optimised reinforced concrete beam. This beam, which contains 30% less concrete than a traditional one, displays a truss-like shape. Such beams are generally casted thanks to single-use wooden or polystyrene formworks. Here, the development of a 3D printing process enables the fabrication of fully recyclable clay moulds. This first realisation proved the feasibility of the process and allowed us to identify potential improvements as stated hereinbelow:

1. Clay 3D printing was successfully implemented. As long as no cantilever shapes are required, it is easier to manage than concrete printing as there is no evolution of the material during the process.
2. Clay moulds are not able to withstand the lateral pressure of self-compacting concrete. One solution is to fill them with sand. Another would be to use a mix with a greater yield stress but this might require to use a more powerful pneumatic jack. Work is currently in progress for measuring the yield stress of the paste and characterize its extrudability. Yet another solution would be to print more complex geometries. Typically, topology optimisation could be used to design stiffeners for the moulds. Both these solutions would make the demoulding easier.
3. Introducing more complexity in all the preparatory tasks decrease the complexity of the most important one which is the concrete pouring. The durability of the manufactured elements is thus enhanced.
4. However, it also reduces the range of possibilities in terms of concrete formulations as the beams cannot be vibrated: only SCCs can be used. This requires greater control over the concrete mix preparation.

The automation of the construction industry can help solve some important challenges that it faces. It can improve the security of workers, it can increase the productivity, it can help build optimised structures. But it is important to look back at the evolutions brought by technological improvements. It often causes a polarisation of jobs, some requiring higher skills, some lesser skills. The advent of reinforced concrete construction at the beginning of the 20th century or the current development of prefabrication exemplify this. These aspects must also be studied from a social science perspective.

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References

[1] Simonnet C. Matériau et architecture: le béton armé: origine, invention, esthétique. *Doctoral Dissertation*, EHESS, 1994.

[2] Bock T. The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. *Automation in Construction*, 59, 2015.

[3] Wang S., Huang K., Sodano M., Xu W. and Raspall F. Fabrication of Topology Optimized Concrete Components Utilizing 3D Printed Clay Mould. In *Form and Force: Proceedings of the IASS Annual Symposium 2019 – Structural Membranes 2019*, pages 1224-1230, Barcelona, Spain, 2019.

[4] Maitenaz S., Mesnil R., Onfroy P., Metge N. and Caron J.F. Sustainable Reinforced Concrete Beams: Mechanical Optimisation and 3D-Printed Formwork. In *Second RILEM International Conference on Concrete and Digital Fabrication – Digital Concrete 2020*, pages 1164-1173, Eindhoven, The Netherlands, 2020.

[5] EN 1992-1-1: Eurocode 2 – Design of concrete structures – Part 1-1: General rules and rules for buildings. European committee for standardization, Brussels, 2004.

[6] Archez J., Maitenaz S., Demont L., Charrier M., Mesnil R., Texier-Mandoki N., Bourbon X., Rossignol S., Caron J.F. Strategy to shape, on a half-meter scale, a geopolymer composite structure by additive manufacturing. *Open Ceramics*, 5, 2021.