Identifying Levers for Mass Market Penetration of Digital Fabrication

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Abstract
The construction industry produces buildings and infrastructure and, hence, satisfies basic needs of modern society. It provides a considerable portion of total value added and worldwide jobs. At the same time, it is responsible for more than 11% of CO2 energy-related carbon dioxide (CO2) emissions worldwide. Digital concrete fabrication is a young, yet already broad research discipline which brings about potential for the necessary reduction of the ecological impact and for further industrialisation of the construction industry, while being compatible with the specific requirements of flexibility and individuality. Still, it has not succeeded to penetrate the mass-market, largely due to lacking competitiveness and compliance with structural integrity requirements. The present contribution comprehensively considers features of conventional construction processes to identify benefits when using digital concrete fabrication. Thereby, it addresses not only a complete substitution of conventional construction methods, but also solutions taking advantages of the synergic combination of traditional and novel technologies. It assesses traditional construction methods (in-situ construction and prefabricated construction) and clusters their features in order to elaborate their strengths and persistent challenges. Following a customised review on the digital fabrication methods, it identifies some new levers and opportunities for mass-market penetration of digital concrete fabrication technologies in structural and civil engineering construction works.

Keywords: digital fabrication, review conventional construction, mass market penetration, concrete structures.

1. Introduction
Buildings and infrastructure are basic needs of modern society. In the UN global status report 2017, Abergel et al. (2017) estimate that by 2060, the building sector floor area will double. In 2016, buildings and the construction of buildings and infrastructure together, including the manufacturing of materials and products, accounted for 36% of global final energy use and 39% of energy-related carbon dioxide (CO2) emissions, while the construction alone represented 11% of CO2 emissions (Abergel et al., 2017). In Switzerland, the total value added of construction industry accounts for 5% of the Swiss total value added providing 8% of Swiss jobs (Swiss Federal Statistical Office, 2020). The contribution of construction industry to the total value added increases to 10% when also considering intermediate inputs mainly procured in Switzerland (KOF Swiss Economic Institute, 2020). Hence, advancement on reinforced concrete is highly relevant for aspects related to both, global economy and ecological sustainability, as it is by far the most used building material today.

On the one hand, existing concrete and reinforcement technologies and approaches for its dimensioning have been optimised for more than a century hand in hand with traditional construction methods. This has led to highly efficient conventional reinforced concrete construction processes. On the other hand, digital fabrication brings about potential for the necessary reduction of the ecological impact and for further industrialisation of the construction industry, while being compatible with the specific requirements of flexibility and individuality. Still, it has not succeeded to penetrate the mass-market, largely due to lacking competitiveness and compliance with structural integrity requirements. The present con-
tribution aims at identifying levers and tangible opportunities of digital fabrication technologies in structural and civil engineering construction works. To this end, it comprehensively assesses the traditional construction methods, clusters their features, and reviews the discipline of digital fabrication. Thereby, it not only addresses a complete substitution of conventional construction methods, but also solutions taking advantages of the synergic combination of traditional and novel technologies.

2. Review of traditional concrete construction methods

From a user perspective, concrete construction works ought to fulfil mainly seven key criteria, basically extending Vitruvius’ famous demands of firmitas, utilitas, and venustas by additional criteria that are equally important today:

- structural safety (firmitas)
- durability
- serviceability (utilitas)
- aesthetics and integration (venustas)
- environmental sustainability
- construction time
- economy

One key decision in every construction work is whether using in-situ or (partially) prefabricated construction. On the one hand, this decision obviously depends on the criteria mentioned above (e.g. architectonic individualism may be a reason for in-situ construction). On the other hand, market specific reasons (tradition and, hence, missing infrastructure for one or the other production method) also play an important role. Either construction method may be characterised by features of production and erection. These features, which may be considered as strengths and challenges, are identified in the following subsections, focusing on building structures.

While the criteria are equally relevant for infrastructure projects (e.g. bridges or retaining walls), a direct comparison is more difficult since the type of structure (e.g. arch bridge or slab deck) and the efficiency of infrastructure projects are highly dependent on regional factors (geology and hydrology, accessibility, availability of material).

In-situ construction

In-situ construction may be used for all members in civil and structural engineering. For in-situ construction, the main steps consist of placing scaffolding and formwork, installing reinforcement, and pouring concrete into the formwork. The members are always produced in their final orientation, e.g. mainly vertical (standing) production of columns and walls while horizontal (lying) production of slabs. When casting walls or columns against inclined surfaces, counteracting formwork may be necessary depending on the inclination of the surface.

Prefabricated construction

Precasting is mainly used for three reasons (the first two according to Gerwick, 1993, the third added by the authors of this paper): the mass-production of industrialised elements as the reason for the most extensive use, the casting of unique and/ or complex units with high demands on form, surface quality and/ or tolerance, and the requirement of (partial) prefabrication due to (temporal or spatial) constraints. The widest applications of precast concrete are according to Gerwick (1993):

- Buildings: floor slabs, roof slabs, wall slabs, piles, columns, façades (complemented by the authors)
- Bridges: piles, girders, deck slabs, superstructure segments, pier segments

Apart from shafts, precast elements (also walls) are preferably cast in horizontal (lying) position, which minimises the necessary formwork area and the effort for compaction. Industrialised prestressed building elements, such as widely used Hollow-Core Slabs or T-girders, are produced on long beds (typically of 100-200 m length), often with extruded / horizontally slipformed concrete (these processes could be seen as precursors of digital concrete fabrication). As soon as the concrete has reached sufficient strength
(after 6-8 hours of curing), the elements are sawn to the desired length, stored and transported to the site. Bridge elements are often made with heavy steel forms suitable for multiple use and are match-cast in order to create accurate, matching surfaces and dimensions.

Aside from precasting complete elements, parts of structural members (e.g. reinforcement, precast parts of elements for composite structures) or formwork may be prefabricated.

2.1. Structural safety of construction works

The structural safety of construction works comprises the resistance to loads at ambient temperature and static conditions as well as in fire or seismic situations. Tensile reinforcement and its activation by bonded concrete are essential for the load carrying behaviour (including load redistribution), ultimate limit state and robustness of reinforced concrete structures, since concrete tensile strength is unreliable. Only with considerable safety margins, concrete tensile strength is used for relevant structural verifications, e.g. for shear in members without transversal reinforcement or deviation forces of bent reinforcement.

2.1.1. In-situ construction

Reinforcement contents and/or cross-sectional dimensions may be optimised as well as sufficient robustness is usually provided thanks to the monolithic connection of structural members creating hyperstatic systems with reinforcement in two directions (even though increased efforts are necessary for continuous reinforcement across construction joints).

Internal stresses due to concrete intrinsic phenomena (shrinkage, creep) and environmental influences (temperature) occur in hyperstatic systems. These internal stresses are very difficult to quantify. By using a minimum amount of ductile reinforcement (allows for application of plasticity theory in design) or strongly over-dimensioning brittle reinforcement (e.g. textile or state-of-the-art fibre reinforcement), they can, however, be ignored in structural ultimate limit state design.

2.1.2. Prefabricated construction

The assembly and its preparation (ensuring plane supports) of precast elements is of great importance for their efficient use and the structural safety (e.g. Hollow-Core Slabs are vulnerable to flexible supports).

Precast elements usually carry loads as one-way systems and, due to transportation limits, over one or maximum two spans. Hence, connection systems (e.g. tying systems) or in-situ toppings and laps are often necessary for providing sufficient strength to horizontal loads (wind and earthquake) and robustness.

2.2. Durability

For providing sufficient durability, a good concrete mix, sufficient concrete cover (against corrosion and for proper compaction with maximum aggregate size), small crack widths, and tight joints are of utmost importance. The required concrete cover imposes a minimum concrete dimension of usually 7–8 cm even with one reinforcement layer only.

2.2.1. In-situ construction

Avoiding joints while creating large monolithic construction works may be of great advantage for durability, e.g. in bridge design (joints often leak, and highly loaded reinforcement in the area of joints is prone to corrosion). However, increased reinforcement contents result from high requirements for small crack widths in monolithic construction works due to internal stresses particularly originating from restrained shrinkage. Furthermore, curing to avoid initial cracking is a challenge for in-situ construction.

2.2.2. Prefabricated construction

Joints are an indispensable prerequisite of prefabricated construction. Their proper and durable tightness is a persisting challenge in civil and structural engineering. At the same time, cracking due to internal
stresses is of lesser importance in precast elements thanks to advanced curing technologies, advanced age of element when installed, and limited element lengths in production.

Prefabricated welded reinforcement is not suitable for structural members subjected to fatigue loading.

2.3. Serviceability of construction works

Serviceability (including the prevention of excessive deflections, isolation to sound, protection from environment, etc.) is the most frequent reason for non-slender building members, especially for members with passive reinforcement (very often applied with in-situ construction). Furthermore, when water tightness is required for underground spaces, increased reinforcement contents result in design of foundation slabs and walls due to crack width limitation (see previous subsection).

2.4. Aesthetics and integration of construction works

The architecture of signature buildings (e.g. museums, churches, or pavilions) or infrastructure works should be examined separately from mass market residential, office, and industrial buildings. The current building stock almost completely consists of rectangular buildings, as summarised by Steadman (2006) based on two exemplary studies\(^1\). Steadman elaborates reasons for vertical and horizontal rectangularity of buildings: Verticality is structurally efficient as typically gravity loads are the dominant action, and horizontal loads are transferred directly to the ground. Furthermore, horizontal flat slabs and straight walls serve to exploit the building space with multiple stories. Of crucial importance for urban areas is that horizontal rectangularity (i.e., in plan) provides unlimited possibilities to divide buildings and rooms and arrange them next to each other.

2.4.1. In-situ construction

In-situ construction facilitates freedom in plan form and, hence, flexibility to adjust to the local environment. For example, the building geometry in plan can be adjusted to non-regular plots. On a smaller scale, e.g. the adjustment of camber for deflections or of slope for surface water runoff, is easily done. However, when casting with countering formwork, entrapped air may be a reason for insufficient surface quality.

When casting slabs in-situ, the vertical space between top and bottom reinforcement is often used for flexibly integrating venting and electric installation, which helps to optimise the overall construction height as well as to avoid visible installation pipes. However, such installations are generally accessible only with great effort after finishing the construction.

2.4.2. Prefabricated construction

Precasting usually allows for increased surface quality which is often asked for in unique and/ or complex units. However, it is less suited for non-regular and variable geometries. For example, a water runoff generally requires extensive formworking.

2.5. Ecological sustainability of construction works

When considering the construction of the structure itself only, the ecological sustainability may be related to energy use of the applied raw material, the static efficiency (representing volume or mass of saved concrete and reinforcement), transport distance, and waste.

\(^1\) Steadman (2006) cites A. F. Bemis, who, in the 1930s, did an exemplary study in Boston, and M. J. T. Krüger, who, in the 1970s, used Ordnance Survey maps from the city of Reading (UK) to study the outlines of the buildings’ perimeters. Bemis found that 83% of the plan shapes were rectangular (remaining 17% being largely attributed to pitched roofs) while Krüger found that 98% of the plan shapes were rectangular.
2.5.1. In-situ construction

Because the in-situ construction process is exposed to the environment, slightly over-strength concrete is typically used. Cast-in-situ walls need a minimum thickness of approximately 20–22 cm (which is mostly more than would be strictly needed for mere static reasons) in order to ensure proper compaction through vibrating needles, which need to enter the space between the reinforcement layers. As cast-in-situ walls, cast-in-situ slabs are often by far not optimised in concrete volume because voids (as e.g. in “bubble deck” systems) are rarely provided. However, reinforcement contents and/or cross-sectional dimensions may be optimised with cast-in-situ solid slabs thanks to hyperstatic systems. Since standard formwork is reused many times, only very low timber waste results for uniform surfaces, possibly with the exception of fitting sizes of slabs in vicinity of columns or of fitting sizes of walls between two adjacent walls.

2.5.2. Prefabricated construction

In precasting, smaller safety margins on the design strength of concrete are allowed by structural codes thanks to better and more controllable casting conditions and, hence, lower scatter. Furthermore, the required tolerances on concrete cover and concrete dimensions in general may be reduced due to good concrete compaction (thanks to lying production and external concrete compaction equipment) and/or controlled casting conditions. This implies lower material consumption with respect to the same member cast in-situ. Products such as Hollow-Core Slabs may be produced with rather large span to depth ratios although they only span one-way thanks to the efficient reduction of self-weight and concrete use (sometimes more than 50%) by voids.

2.6. Construction time efficiency of construction works

The construction time efficiency is mainly important for indirect cost, e.g. by disrupted construction processes, disrupted traffic around construction site, pumping of increased water volumes, etc.

2.6.1. In-situ construction

Placing the formwork, installing reinforcement (if not prefabricated), pouring concrete, and curing while concrete is hardening are generally sequential work steps unless the work on walls or slabs can be carried out in several stages. However, many of these work steps of in-situ construction are standardised and adapted to mass market, such as formwork placement and concrete casting. Rectangular walls are usually formed with standard and reusable formwork elements. Also, the (mostly isolated) process of concreting on site has been optimised with the whole supply chain of preparing and transporting concrete. For example, casting large concrete volumes of 1000 m³/day is done regularly nowadays. Hence, the single work steps can often be carried out rather efficiently.

2.6.2. Prefabricated construction

The assembly of prefabricated members is very fast. For example, the assembly of more than 500 m² Hollow-Core Slabs per day is possible with 3-4 workers (Nordimpianti, 2020). However, in-situ toppings, connections, and/or laps with (possibly) extra formwork interrupt a smooth construction process.

2.7. Cost efficiency of construction works

The cost of construction works is strongly connected to material and labour cost, which both strongly depend on local market and competition.

2.7.1. In-situ construction

Formwork, concrete and reinforcement generally constitute the decisive portion of all costs for the basic structure. Sequential work steps are generally associated with high labour intensity on site.

2.7.2. Prefabricated construction

For production, cost mainly consists of concrete (usually cheaper than on site) and concreting, reinforcement and the preparation of reinforcement cages, a (small portion of) formwork, and the cost for the
plant installation. The preparation of the formwork, of the reinforcement, and casting may be carried out in simultaneous work steps in different positions within a production site resulting in a high degree of industrialisation. Industrialised production of products such as Hollow-Core Slabs is carried out on several beds (up to 200 m length), e.g. efficiently allowing for more than 500 m²/day with four beds (Nor-dimpianti, 2020). Transport distances and the production capacity of the plant are usually weighted against each other (a high production capacity is only reasonable if transport distances are not overly high). The assembly and connections are carried out on site. It should be noted that in-situ toppings for composite action or connecting laps with extra formwork are comparably expensive (Gerwick, 1993).

3. Clustering

In this section, the features, presented in the previous section, are clustered for both studied construction methods, in-situ and prefabricated construction. The clustering is meant to identify opportunities for improvement or exploitation with digital fabrication.

3.1. Traditional in-situ construction

The features attributed above to traditional in-situ construction are:

- **Monolithic construction:**
  - facilitates (i) robust structures and (ii) optimised cross-sectional dimensions for structural resistance by two-way load bearing systems and restraint conditions,
  - requires (i) increased reinforcement contents due to internal stresses and (ii) (sometimes) increased formworking efforts to provide continuous reinforcement across construction joints.

- **Sequential work steps:**
  - facilitate (i) an optimised supply chain to cast large concrete volumes and (ii) the integration of venting and electric installation in slabs (hence, optimisation of the overall construction height),
  - require increased construction time with resulting high labour intensity on site, which may be the reason why members are rarely optimised in terms of concrete use.

- **Majority of work on site:**
  - facilitates (i) freedom of geometry in plan
  - requires (i) over-strength concretes, (ii) the production of members in their final orientation, which may cause entrapped air if the members are not cast in vertical direction, (iii) wall thicknesses often higher than required for mere static reasons in order to provide sufficient compaction, and (iv) efforts for curing to avoid cracking due to the exposure of the fresh concrete to environmental conditions (creating increased internal stresses).

3.2. Traditional prefabricated construction

The features attributed above to traditional prefabricated construction are:

- **Segmented production:**
  - enables concreting in horizontal (lying) position for all building members,
  - requires (i) assembly of elements on site, (ii) connections, (possibly) toppings and laps with extra formwork on site, and (iii) increased efforts to provide watertight construction works.

- **Simultaneous (steady) work steps:**
  - enable (i) fast production and mass-production of industrialised elements and (ii) the optimisation of each work step with the help of elaborate tools and machinery (e.g. facilitates the reduction of concrete volume with the creation of voids as applied for Hollow-Core Slabs).

- **Majority of work in controlled environmental conditions:**
  - facilitates (i) controlled and possibly accelerated curing of concrete, (ii) an increased surface quality, and the reduction of safety margins tolerances in terms of concrete strength and members dimensions, respectively,
  - requires the transportation of elements to the site.
4. Digital concrete fabrication

Digital concrete fabrication is a young, yet already broad research discipline. It may be understood as a discipline in which the fabrication follows directly from the digital model data (Gibson et al., 2015). The technologies of this discipline have the potential of overcoming typical constraints of traditional processes caused by the high impact of labour costs.

4.1. Review

Comprehensive reviews on the current state-of-the-art of digital concrete fabrication have been worked out lately, e.g. by Wangler et al. (2019), who structure the discipline based on a process basis into extrusion, formwork printing, temporary supports, slipforming, and particle bed fusion. All these technologies have the abandonment of traditional formwork in common and are mainly used in prefabricated construction, as many rely on controlled environmental conditions.

Some of these processes’ current characteristics, which serve to identify their challenges to compete with traditional construction methods, are further discussed in the following subsections. It should be noted that this contribution aims at identifying levers of digital fabrication explicitly for mass-market penetration with focus on members with rectangular shapes, as derived in Subsection 2.4. Hence, this discussion (i) is clearly not complete and (ii) is of different focus than other available reviews. Furthermore, it is evident that most of the technologies (and, hence, their challenges) discussed in the following are matters of ongoing research (which indicates that some numbers given may be taken rather as information on the order of magnitude than as absolute values).

4.1.1. Extrusion

Extrusion is typically referred to as 3D concrete printing (3DCP), where a nozzle continuously extrudes sequential layers to produce an element. Layer extrusion as well as sprayed applications (see e.g. Neudecker et al., 2016) are available. Most applications focus on the fabrication of fully prefabricated standing elements (columns, walls, or shafts). Currently, all used extrusion-based applications lack a strategy to implement continuous structural tensile reinforcement across the layers (unless extrusion is used as formwork printing technology or the elements are post-tensioned).

Concrete layer extrusion today is the most used technology for digital concrete fabrication, capturing a wide range of different printing processes (see e.g. Buswell et al., 2018). Buswell et al. (2018) mention current production speeds in the range of 50 mm/s to 500 mm/s (note that a higher production speed leads to comparably lower geometric resolution). The printed filament width typically lies in the range of 30 mm to 50 mm. Usually, a high cement content mortar with maximum aggregate size in the range of 2 mm to 3 mm is applied (Buswell et al., 2018). Most layer extrusion processes produce a somewhat undulated side surface, which is marked from the convex shape of each printed layer. The process of contour crafting includes trellising in order to create smooth surfaces (Khoshnevis, 2004).

The production speed may be transferred into an estimated printable wall surface of 4–20 m²/8 hours (assuming two outside filament-layers and a connecting inner layer), approximately corresponding to the usual working speed of a mason, and a concrete volume needed of about 0.5 m³/8 hours. These numbers are extremely low when compared to the typical construction time efficiency of precasting (see Subsection 2.6), especially as the vertical (standing) production of columns and walls produced by current concrete extrusion processes imposes an extra challenge to compete with conventional prefabrication methods (where walls are mostly cast in lying position, as discussed above).

Sprayed applications currently are faster than concrete layer-extrusion applications with thicker filaments. Fresh state surface post-processing has been explored (e.g. Hack and Kloft, 2020).

4.1.2. Formwork printing

All technologies grouped into the process of formwork printing allow for the integration of reinforcement in all required directions. Evidently, the difficulty of this integration still highly depends on the geometric complexity of the produced structural element.
Cross-sections formed by the process of 3DCP with layered extrusion may be used as lost formwork, which, however, leads to comparably massive volumes due to minimum cover required to activate the reinforcement with bonded concrete.

With the technology Mesh Mould, the robotically produced dense reinforcement mesh is used as a permeable formwork (Hack et al., 2020). Among other challenges for the first real-scale application, the production of the reinforcement mesh was rather time consuming (125 h for a double curved wall of height 2.8 m, length (top) 11.8 m, length (bottom) 11.4 m, and thickness 125 mm) and the surface post-processing required a considerable amount of manual labour, which both may be accelerated in further developments of the technology.

Eggshell describes a technology where a thin thermoplastic shell is printed and used as a formwork for fast-hardening concrete, which is cast in a continuous process (Burger et al., 2020). The speed of this formwork printing as well as of the casting is still very slow (approx. 100 mm² surface per second). However, especially the printing process depends on the used tools and may be further developed.

Pieces created by impregnated particle bed fusion or wax have been used as formwork, which can be used multiple times (reviewed e.g. by Wangler et al., 2019). This way of producing formwork may offer new possibilities in terms of form optimisation, even though in principle it is not different to standard formworking.

4.1.3. Temporary supports

The concept of using flexible formworks (e.g. created by knitted textiles, as developed by Popescu et al., 2018) is mainly attributed to curved concrete elements by Wangler et al. (2019).

4.1.4. Slipforming

Smart dynamic casting as a continuous slipforming process may be used for column-type elements or wall-like structures (applied to thin folded structures) and allows for including standard reinforcement, as summarised by Wangler et al. (2019). Even though some further advancements may be needed, this technology may be close to application in precasting practice.

4.1.5. Particle bed fusion

In particle bed fusion, a binder is used to bind particles, provided in a bed, in order to create elements. The technology, so far, has mainly been used to produce unreinforced elements, which cannot be used for mass-market applications. It will not be further discussed in this context.

4.2. Opportunities

Digital fabrication allows to implement flexibility and individuality into the production of structural concrete elements. It has mainly been used to create topologically optimised structures and/or to introduce innovative architectural elements. Still, the technologies gathered within this framework by the scientific community may also bring about further opportunities which may serve as mass-market related levers. In order to identify these opportunities, the authors suggest, however, to consider the following points:

- Reinforcement should be implemented in an efficient manner when producing complete elements by means of digital fabrication, as pointed out by Asprone et al. (2018) and other authors before.
- Required minimum dimensions (due to requirements in terms of fire, durability, and serviceability including e.g. deflection control, isolation to sound, protection from environment, etc.) should be addressed in research. For example, for reinforced concrete beams or ribs, a minimum concrete cover should be provided for reasons of durability and fire resistance leading.
- "New" features integrated in conventional construction processes should be studied and developed for exploring holistically the opportunities of digital concrete fabrication in mass-market applications. Such features may lie in the use of digital fabrication technologies as support of conventional construction processes. Some of them are being identified and developed within the authors’ research and introduced in the following subsections.
4.2.1. Reduction of minimum reinforcement
Mata-Falcón et al. (2018) introduced the concept of weak interfaces. The concept aims at exploiting the reduced tensile strength of concrete across printed layers, e.g. inherent to 3DCP. Addressing a persistent challenge of in-situ construction, digital fabrication technologies could be used to reduce minimum reinforcement, which is needed due to internal stresses in monolithic structures to (i) avoid brittle failures at cracking or (ii) limit crack width for water tightness or aesthetic reasons. Minimum reinforcement often makes up for more than 50% of the total reinforcement content. The required amount of minimum reinforcement is proportional to the cracking load of the structure, which is directly dependent on the concrete tensile strength.

4.2.2. Production of joints
Addressing a persistent challenge of prefabricated construction, digital fabrication technologies could be used to (i) facilitate the production of fitting dry joints and (ii) to reduce manual labour to create rough surfaces needed for construction joints.

Most technologies developed within the framework of digital fabrication require set-on-demand concrete (see e.g. Reiter et al., 2020). Given the accelerated early setting, fresh-state surface post-processing as applied by Kloft et al. (2019) may be used to produce fitting joints in high accuracy (with the possibility to transfer shear forces) in prefabrication without the need to rely on match-casting. Furthermore, the rough surface characteristic of many digital fabrication technologies may be used without further effort as means to transfer interface shear between prefabricated elements and concrete added in-situ (e.g. a topping).

4.2.3. Advanced formworking
Digital fabrication technologies can be used to introduce new formwork options, for in-situ construction and for prefabricated construction, e.g.:

- The set-on-demand concrete can be used to facilitate the handling of formwork pressure and uplift.
- 3DCP could be used to facilitate the production of construction joints with continuous reinforcement in the horizontal (lying) prefabricated production of structural elements.
- Technologies which introduce flexible temporary supports could be used to facilitate the production of camber or water runoff in prefabricated construction.

Summary
The present contribution comprehensively considers features of conventional construction processes to identify benefits when using digital fabrication. Thereby, the authors not only address a complete substitution of conventional construction methods, but also solutions taking advantage of the synergic combination of traditional and novel technologies. They assess traditional construction methods (in-situ construction and prefabricated construction) and cluster their features in order to elaborate their strengths and persistent challenges. Following a customised review on the digital fabrication methods, they identify some new levers and opportunities for (i) reducing minimum reinforcement, (ii) facilitated production of fitting dry joints and construction joints, as well as (iii) advanced formworking.

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5. References


