EXEP3D

ABSTRACT

This Deliverable 3.2, prepared under Work Package 3 (*Knowledge Exchange and Innovation Transfer*) of the EXEP3D project.

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DELIVERABLE REPORT

WP3 – D3.2

Report on 3DCP minimum formwork technology

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This project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101158492 — EXEP3D — HORIZON-WIDERA-2023-ACCESS-02.

Delivery Title:	Report on 3DCP minimum formwork technology
Delivery Number:	D3.2
Lead beneficiary:	Eindhoven University of Technology (TU/e)
Type:	Report
Work Package Title:	Knowledge Exchange and Innovation Transfer
Work Package Number:	WP3
Dissemination level:	Public
Due Date:	31 December 2025

Revision History:

Version	Date	Author (Partner)	Remarks
Draft v0.1	22/12/2025	Lauri Hass (TU/e) Karsten Nefs (TU/e)	First draft

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Preface

About the EXEP3D Project and Twinning Partners

The EXEP3D project — Innovation Excellence in Construction Engineering: Novel 3D Concrete Printing Technologies and Sustainable Mixtures — is a Horizon Europe Twinning initiative (Grant Agreement No. 101158492, Call: HORIZON-WIDERA-2023-ACCESS-02-01). The project aims to strengthen scientific excellence, innovation transfer, and research management capacity in the field of construction engineering through focused collaboration on 3D concrete printing (3DCP).

Led by Tallinn University of Applied Sciences (TTK UAS, Estonia) in partnership with Technische Universiteit Eindhoven (TU/e, Netherlands) and Technische Universität Dresden (TUD, Germany), the three-year initiative focuses on enhancing skills, knowledge, and research infrastructure to position TTK as a leading competence centre for 3D concrete printing and printable mixtures in Estonia and Eastern Europe.

The Twinning collaboration combines complementary expertise: TU/e's world-class research and facilities on 3D concrete printing formwork and robotic production, TUD's advanced competence in printable mixtures and digital concrete, and TTK's strong applied research base and industrial outreach in the Estonian construction sector. Together, the partners form a strategic link between widening and advanced countries, accelerating knowledge transfer, strengthening applied research capacity, and promoting innovation in sustainable and automated concrete construction across Europe.

Purpose of this report

Concrete remains one of the most widely used construction materials worldwide due to its availability, durability, and comparatively low specific embodied energy. However, the sheer scale of global concrete production results in a substantial environmental impact. While this impact is commonly attributed to cement manufacture, it is also strongly influenced by how concrete structures are designed and constructed, particularly by the formwork systems into which concrete is cast.

An often under-addressed driver of material inefficiency in concrete construction is formwork. Formwork constitutes the largest single cost component in many concrete structures and can account for a significant share of material use and construction effort. Although standardized formwork systems are economically efficient and robust, they impose strict geometric constraints that frequently lead to oversized, monolithic concrete elements, even where such dimensions are not structurally required. This oversizing propagates through the entire structural system, increasing self-weight, member sizes, and foundation demands, and ultimately amplifying the embodied carbon footprint of the building over its life cycle.

The aim of this report is to provide a structured overview of advanced formwork technologies, with a particular focus on digitally fabricated and additively manufactured systems. Rather than offering an exhaustive historical review, the report treats formwork as a critical design variable that influences geometry, material efficiency, construction stage behaviour, and system-level performance in concrete structures. Special emphasis is placed on 3D-printed formwork, especially concrete-printed formwork, as a case where formwork, structure, and construction process become intrinsically linked.

Within the context of the Twinning project, the report moves beyond cataloguing existing approaches and instead examines functional integration themes, lateral pressure and stability during casting, and design optimisation strategies in order to identify the key technical, conceptual, and regulatory obstacles that currently limit wider adoption. Selected demonstrators are used to highlight both the potential of these systems and the remaining research challenges associated with integrating digitally fabricated formwork into established concrete construction practices.

Structure of the Report

A graphical representation of the overall framework addressed in this report is shown in Figure 1.

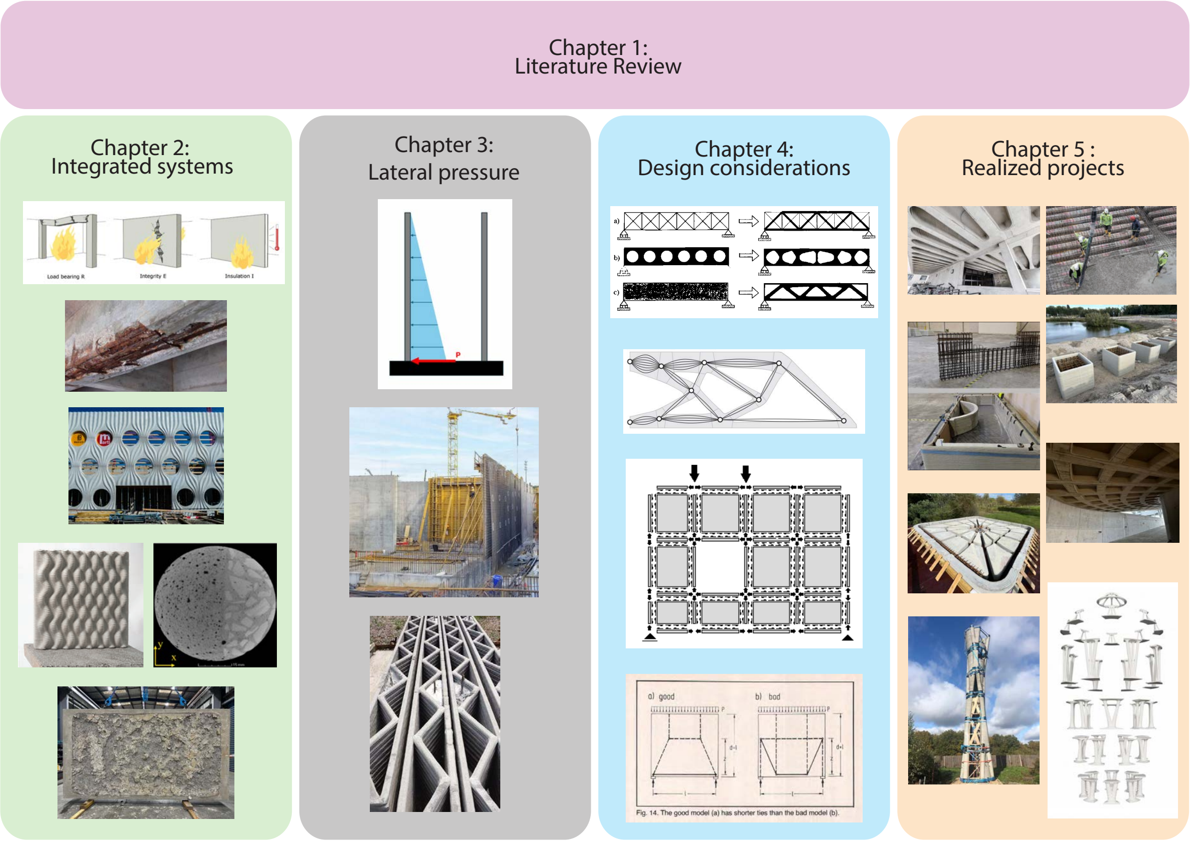


Figure 1: Overview of the minimum formwork report

Declaration on the use of AI-assisted technologies
During the preparation of this work, the authors used ChatGPT and related AI-assisted proofreading tools to improve the readability of the text by correcting grammar and spelling. These tools were employed exclusively to enhance clarity

and linguistic consistency; no new scientific content or data were generated through their use. The authors have carefully reviewed and edited all resulting material and take full responsibility for the integrity, accuracy, and originality of the final text.

Acknowledgements

The authors gratefully acknowledge the financial support of the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101158492 — EXEP3D — HORIZON-WIDERA-2023-ACCESS-02.

Sincere thanks are extended to the academic and administrative staff, researchers, and students of the partner institutions for their active participation in study visits, seminars, and joint research activities that provided the foundation for this material. Their dedication to advancing excellence in construction engineering and digital concrete fabrication has been instrumental in the preparation of this publication. The authors also wish to express their appreciation to the 3D Concrete Printing Group at Eindhoven University of Technology (TU/e)

In addition, the authors gratefully acknowledge the broader 3D printing research community—across academia and industry—whose pioneering studies and practical innovations form the foundation of much of the knowledge referenced throughout this material. Their collective contributions continue to advance the field of digital concrete fabrication and inspire ongoing collaboration and innovation.

Chapter 1

Systematic literature review

1.1 Introduction

The literature review conducted for this report adopts a systematic and forward-looking perspective, with the objective of understanding how digitally fabricated and additively manufactured formwork technologies are reshaping concrete construction. Rather than cataloguing the historical development of formwork systems, the review focuses on state-of-the-art approaches that enable new geometries, construction workflows, and modes of functional integration. Conventional formwork systems are therefore not treated as a primary object of investigation, but only as contextual reference points where necessary to situate recent technological developments.

To achieve this, the study employs a Systematic Literature Review (SLR) methodology, following a predefined protocol to identify, screen, and synthesise relevant academic research. The Scopus database was selected as the primary source of literature due to its broad multidisciplinary coverage of peer-reviewed journals, conference proceedings, and books. An initial search string was developed by combining relevant keywords and synonyms related to digital formwork, additive manufacturing, and integrated concrete systems. This initial search returned more than 3,400 results, necessitating a refinement of the search string, which ultimately yielded 136 relevant publications. The final search string and screening process is presented in Section 1.3 and 1.4.

The adoption of this systematic approach serves to identify key technological developments, representative systems, and recurring challenges that characterise the current state of digitally fabricated formwork. Earlier historical formwork technologies were not systematically reviewed, as older literature is often fragmented, inconsistently indexed, and embedded in non-academic construction handbooks rather than peer-reviewed publications. Consequently, historical context is incorporated selectively through authoritative sources where required, while the primary emphasis remains on contemporary and emerging formwork systems relevant to digital and additive construction.

Based on the outcomes of the literature review, a provisional table of contents was formulated to structure the report. This framework was subsequently used to guide a more detailed investigation of selected topics, informed by the reviewed literature and supplemented with additional relevant research where appropriate.

1.2 Main points of interest

1. Which types of 3D-printed formwork or digitally fabricated molds have been proposed or demonstrated in research and industry?
2. What structural or geometric principles guide minimum-material formwork produced with 3DCP (e.g., shell action, rib optimisation, yield-line logic, staying-in-place logic)?
3. Is there integrated formwork present?
4. What are the reported advantages and limitations of these methods in terms of buildability, stability, material efficiency, and cost?
5. What key challenges remain unsolved and therefore relevant for future optimisation (reinforcement, structural stability, hydrostatic pressure, thin-walled behaviour, digital workflows)?

1.3 Search strategy

To obtain a broad overview of formwork-related research, the search was first carried out in Scopus using a wide query applied to titles, abstracts, and author keywords. The aim of this initial step was to capture the full range of terminology used for formwork, including historical developments and recent digital or automated techniques. The TITLE-ABS-KEY (i.e., title and abstract) field was therefore used in combination with a set of keywords covering traditional formwork systems, materials, and digital fabrication approaches. This broad query returned approximately 3400 documents, confirming that the topic is distributed across multiple domains and that a further narrowing of scope would be required.

To narrow down the search, the same query was restricted to the TITLE field only, so that only papers explicitly referring to these topics in their titles were retained. This significantly reduced the number of results and yielded 136 papers, which formed the basis for the subsequent abstract screening stages.

```
TITLE(
   ("formwork" OR "form work" OR "shuttering")
   AND
   ("concrete" OR "cement" OR "casting")
   AND
   (
     "histor*" OR "evolution" OR "development" OR "traditional"
     OR "timber" OR "steel" OR "modular" OR "reusable"
     OR "climbing formwork" OR "slipform" OR "innovation"
```

```
      OR "technology" OR "automated"
      OR "3D print*" OR "additive manufactur*"
      OR "digital fabrication" OR "robotic construction"
      OR "hybrid formwork" OR "printed concrete"
    )
)
AND PUBYEAR > 1900
```

1.4 Abstract Screening and Refinement

The second stage of the review involved a detailed screening of article abstracts to assess their relevance to the scope of the report. At this stage, the focus shifted toward identifying studies that address formwork materials, fabrication processes, and experimental systems associated with digital and automated production methods. Publications were considered relevant if they provided insight into the design, production, or performance of formwork systems, or if they introduced techniques enabled by automation, robotics, digital fabrication, or additive manufacturing. Abstracts clearly unrelated to concrete casting were excluded, while papers for which relevance remained uncertain were provisionally retained for potential consultation as the report structure evolved.

Abstracts were evaluated against predefined inclusion criteria and scored according to their engagement with one or more core themes: demonstrators and realised projects, design and optimisation strategies, integrated or stay-in-place formwork concepts, and formwork working behaviour and stability during casting. Each publication was assigned a relevance score (0 = irrelevant, 1 = partially relevant, 2 = relevant). This screening process reduced the dataset from 131 to 83 publications selected for full-text review. As not all selected papers addressed every theme, only the aspects directly relevant to the scope of this report were extracted and synthesised.

This screening phase also highlighted an important characteristic of the literature. While many publications used the term formwork in a conventional construction context, similar terminology was frequently applied to unrelated manufacturing processes. Conversely, research on digitally fabricated molds and hybrid printed–cast systems was often indexed under robotics, architectural fabrication, digital construction, or additive manufacturing rather than under traditional formwork classifications. This observation confirmed the necessity of a broad initial search strategy, followed by iterative refinement based on patterns observed in the retrieved literature.

Chapter 2

Integrated systems

2.1 From “lost formwork” to integrated system

In conventional concrete construction, formwork is typically regarded as a temporary construction aid whose sole purpose is to define the geometry of the cast element. Once the concrete has hardened, the formwork is removed or discarded, and its cost and material use are treated as external to the structural performance of the final element. This separation between formwork and structure has historically enabled fast and robust construction processes, but it has also strongly constrained geometric freedom and material efficiency.

In the context of 3D concrete printed formwork (3DPF), this conventional understanding becomes increasingly inadequate. Due to the concrete printing process and the combined effects of geometric interlocking and material bonding between the printed element and the cast concrete, removal of the printed component after casting is, to current knowledge of the authors, not feasible. As a result, 3DPF systems are inherently permanent and cannot be meaningfully evaluated as temporary formwork.

This shift in perspective requires a more fundamental reconsideration of the role of formwork in 3D concrete printed systems. Rather than viewing the printed element as formwork that subsequently becomes integrated into the structure, it is more accurate to interpret the process as the direct fabrication of a structural component that temporarily fulfils the role of formwork during production.

In this interpretation, the printed element is conceived from the outset as a permanent part of the final system. Its ability to act as formwork during casting is therefore not its defining purpose, but one of its transient functions within the construction sequence. This reverses the conventional logic of concrete construction, in which formwork precedes and the structural element follows.

Adopting this viewpoint is particularly relevant in the context of minimum-material concrete design. As elements become thinner, more geometrically complex, and increasingly optimised for material efficiency, the distinction between formwork and structure becomes blurred. The behaviour of the printed element cannot be meaningfully separated from that of the cast concrete, and the system must be understood as a combined entity from the earliest design stages.

2.2 Functional Integration Themes

Having established the necessity of treating 3D concrete printed formwork as an integrated part of the structural system, the following sections examine the implications of this perspective for different performance domains.

For each functional theme, the discussion is structured according to the following logical sequence:

1. **Relevance and state of knowledge:** Identification of why the function is relevant in the context of integrated 3D concrete printed formwork systems, with emphasis on regulatory drivers (where applicable) and on vulnerabilities introduced by minimum-material, geometrically complex concrete elements.
2. **Conceptual potential:** Exploration of what integration could theoretically enable, based on engineering principles and system behaviour, independent of the current availability of validated case studies.
3. **Open challenges:** Identification of unresolved issues, including gaps in understanding, limitations in verification or testing approaches, and constraints imposed by existing regulatory frameworks.

2.2.1 Fire Performance

Relevance and state of knowledge In structural fire design, the required performance of building elements is expressed using the REI classification, which specifies the duration for which an element can fulfil defined functions when exposed to a standard fire curve (e.g. ISO 834, seen on Figure 2.1).

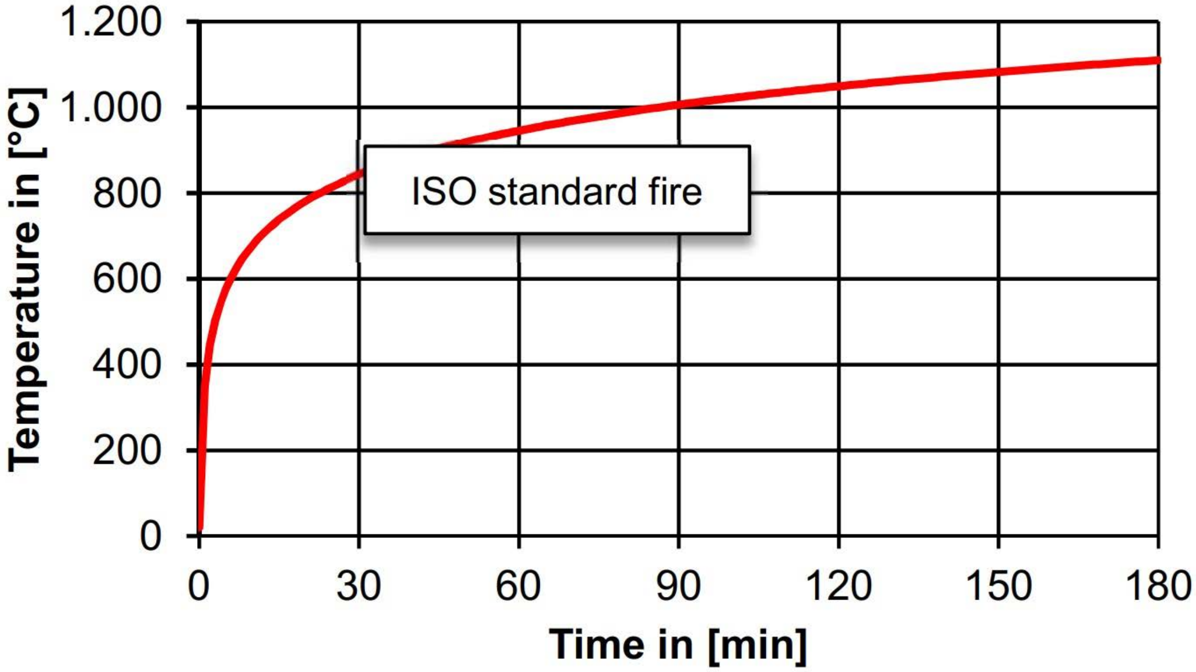


Figure 2.1: ISO 834 standard fire curve

The R criterion, illustrated on Figure 2.2, refers to the ability of a structural element, such as columns, beams, slabs, or load-bearing walls, to maintain its mechanical resistance and global stability under elevated temperatures. Failure of this criterion occurs when the element can no longer sustain the applied design actions during fire exposure. In reinforced and prestressed concrete structures, this performance is governed not only by the residual strength of the concrete but, critically, by the temperature reached in the reinforcement.

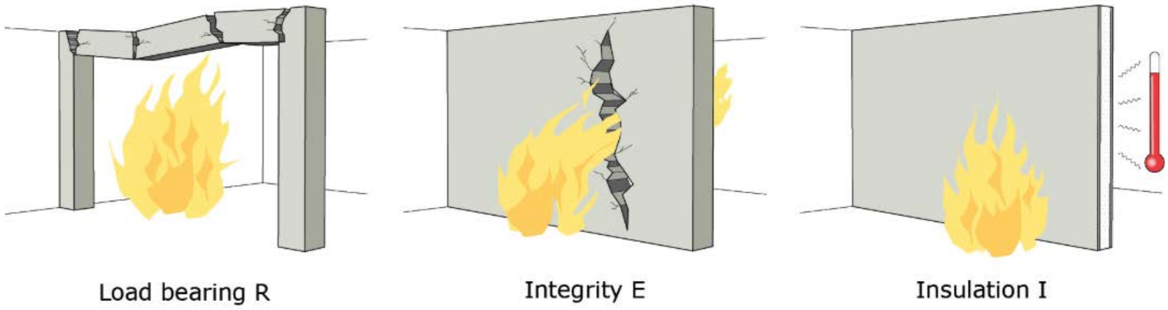


Figure 2.2: Fire-resistance performance criteria according to the REI classification. The criteria comprise R (load-bearing capacity), E (integrity against the passage of flames and hot gases), and I (thermal insulation limiting heat transfer to the unexposed side). These criteria are specified together with a time rating, e.g. REI 60, indicating that the element satisfies all three requirements for 60 minutes under standard fire exposure.

Steel reinforcement exhibits a pronounced reduction in mechanical properties with increasing temperature, and Eurocode fire design provisions define characteristic strength-reduction factors as a function of steel and concrete temperature, shown on Figures 2.3 and Figure 2.4, respectively. For steel, significant strength loss begins already at moderate temperatures: for example, yield strength reductions of approximately 12–15% are reported around 480 °C, followed by a rapid degradation at higher temperatures [1]. Consequently, controlling the thermal exposure of reinforcement is central to achieving the required fire-resistance class.

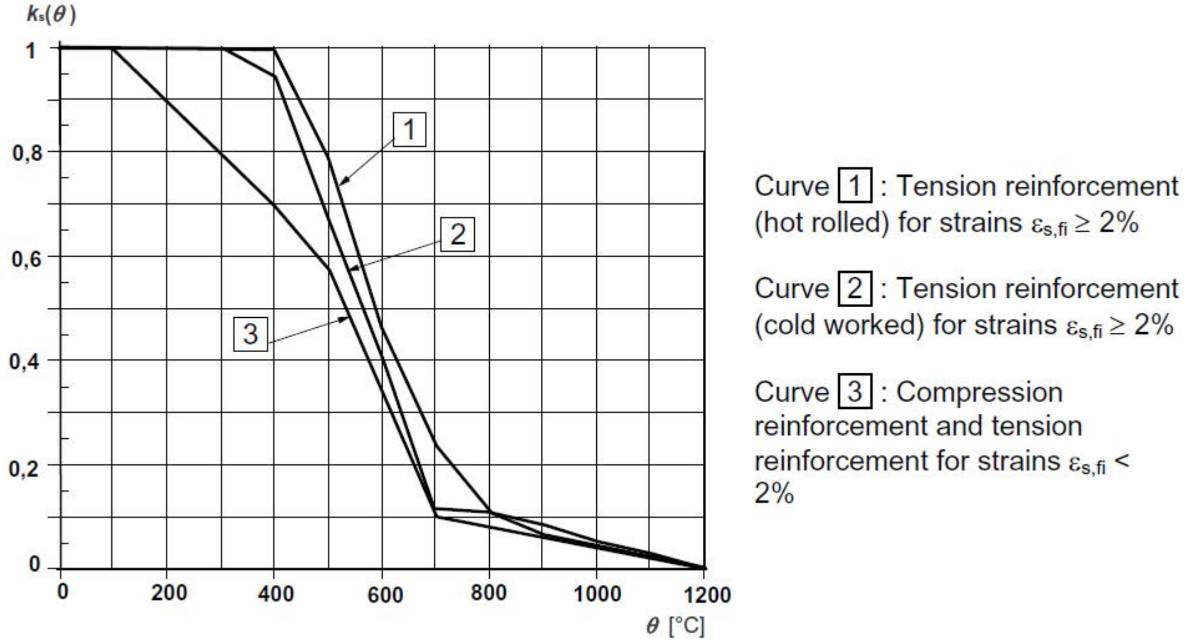


Figure 2.3: Temperature-dependent reduction factor for reinforcing steel strength. Reduction coefficient $k_s(\theta)$ describing the decrease of the characteristic yield strength f_{yk} of tension and compression reinforcement as a function of temperature, distinguishing between hot-rolled and cold-worked reinforcement and strain levels, in accordance with EN 1992-1-2.

This issue is particularly relevant for post-tensioned systems, which are currently among the most prominent reinforcement strategies explored in 3D-printed concrete applications. Prestressing tendons are substantially more sensitive to heat than conventional reinforcement. When insufficiently protected, they may experience significant prestress loss at temperatures above approximately 300 °C. Design standards for prestressed concrete therefore require increased concrete cover or additional thermal protection, recognising that strength loss and stress relaxation in prestressing steel commence at relatively low temperatures, with severe reductions well below 400 °C [2]. This heightened thermal sensitivity underscores the importance of robust fire-protection detailing for any post-tensioned, 3D-printed concrete assembly intended to satisfy structural fire-resistance requirements.

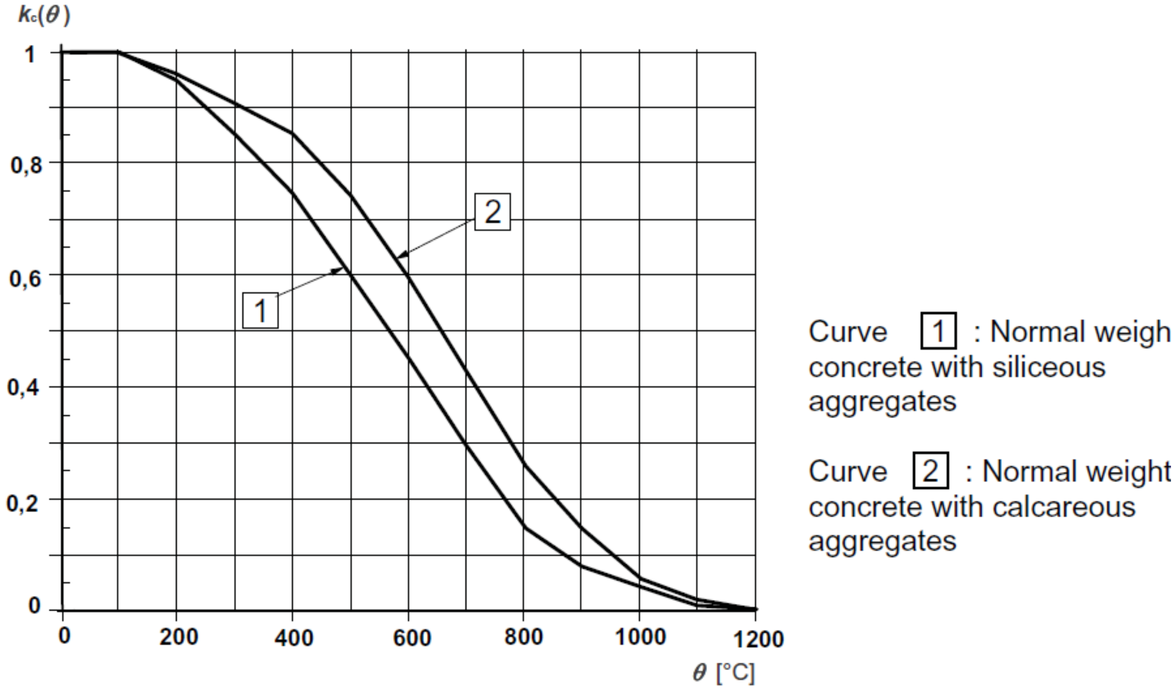
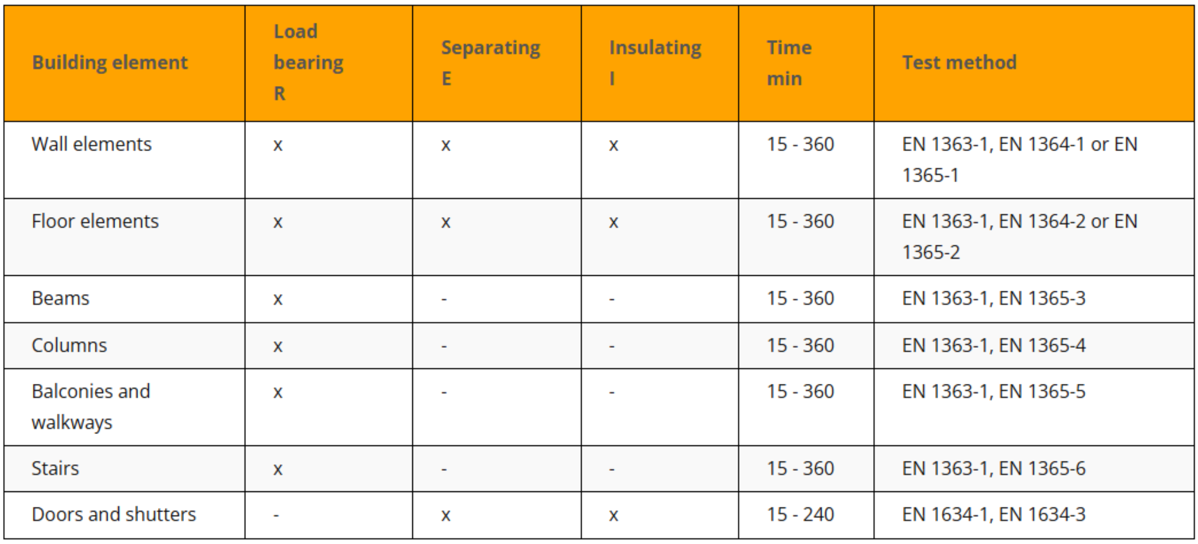


Figure 2.4: Temperature-dependent reduction factor for concrete compressive strength. Reduction coefficient $k_c(\theta)$ describing the decrease of the characteristic compressive strength f_{ck} of normal-weight concrete as a function of temperature, for siliceous and calcareous aggregates, in accordance with EN 1992-1-2.

While E (integrity) and I (insulation) criteria are typically associated with separating elements, they remain relevant where printed formwork or thin concrete shells act as permanent interfaces. Integrity governs the prevention of flame and hot-gas passage through cracks or joints, while insulation limits heat transfer to unexposed surfaces. In hybrid printed–cast systems, degradation of E or I may accelerate heating of the reinforcement, indirectly compromising the R criterion. In accordance with Eurocode the performance criteria and accompanying test methods are shown in Table 2.1.



Building element	Load bearing R	Separating E	Insulating I	Time min	Test method
Wall elements	x	x	x	15 - 360	EN 1363-1, EN 1364-1 or EN 1365-1
Floor elements	x	x	x	15 - 360	EN 1363-1, EN 1364-2 or EN 1365-2
Beams	x	-	-	15 - 360	EN 1363-1, EN 1365-3
Columns	x	-	-	15 - 360	EN 1363-1, EN 1365-4
Balconies and walkways	x	-	-	15 - 360	EN 1363-1, EN 1365-5
Stairs	x	-	-	15 - 360	EN 1363-1, EN 1365-6
Doors and shutters	-	x	x	15 - 240	EN 1634-1, EN 1634-3

Table 2.1: Overview of the applicable R (load-bearing capacity), E (integrity), and I (insulation) performance criteria, associated fire-resistance time ranges (15–360 min), and corresponding standard fire-test methods for different building elements, in accordance with EN 13501-2 and the EN 1363/1364/1365/1634 test series. Taken from [3].

In any case, for reinforced concrete, fire resistance is traditionally fulfilled through sufficient cover thickness. The outer concrete protects the reinforcing bars by delaying heat penetration, and the structural core behind this cover acts as a substantial thermal heat sink, absorbing and distributing heat without significant temperature rise during early fire exposure. The thicker, cooler mass behind the heated face therefore plays a decisive role in slowing reinforcement heating. For optimized structures this is a topic of consideration. For example, as shown in Figure 2.5, the temperature evolution in the three webs is broadly similar. However, higher temperatures are observed at the top of the section (location 1), indicating that a larger proportion of heat is transferred through radiation and convection within the internal voids of the optimised geometry, rather than by conduction through the concrete webs (location 2).

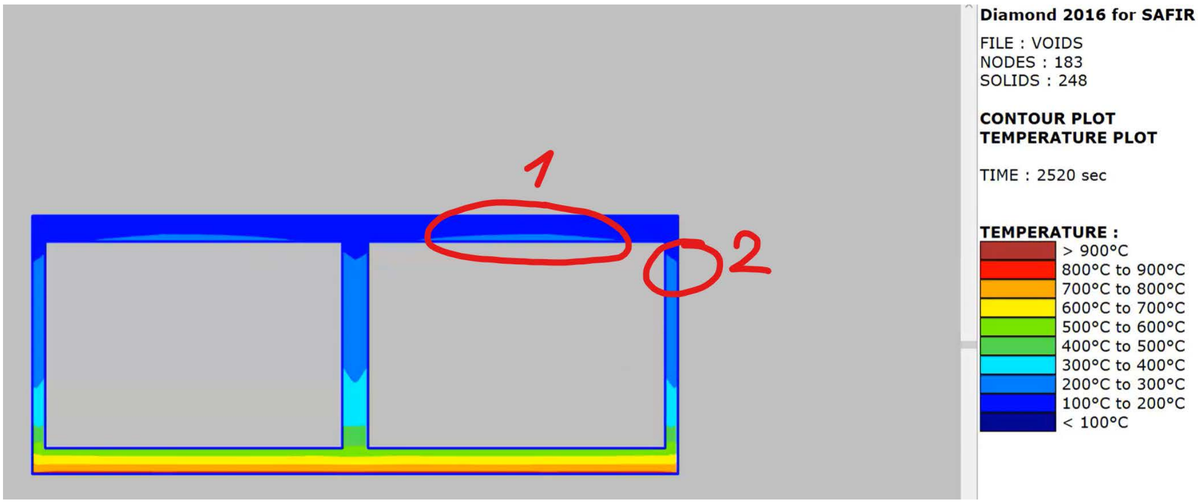


Figure 2.5: Temperature contour plot obtained from SAFIR thermal analysis, illustrating the spatial heat distribution within the cross-section at a simulation time of 2520 s under fire exposure. The colour scale indicates temperature ranges in degrees Celsius, highlighting thermal gradients and heat penetration through the section.

However, fire exposure also creates another vulnerability. Rapid heating generates pore pressure and thermal gradients within concrete, leading to spalling – the sudden loss of surface layers due to vapor pressure buildup and thermal stress. High-performance concretes, particularly those with low permeability and dense microstructures, are more prone to explosive spalling in the first 10–30 minutes of a fire because moisture has fewer escape pathways, illustrated on Figure 2.6.

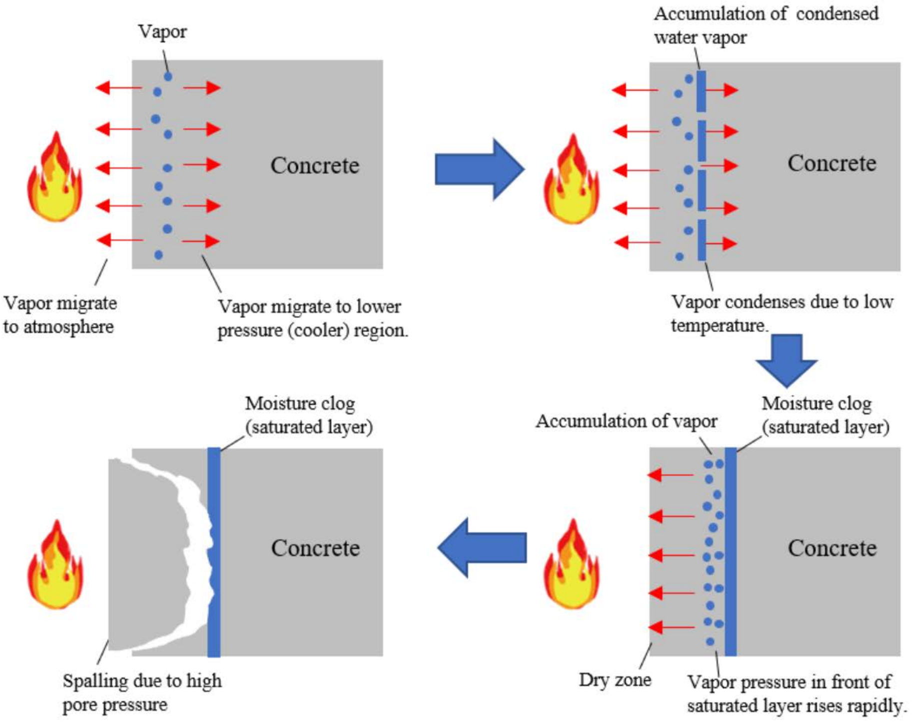


Figure 2.6: Mechanism of pore pressure spalling, adapted from [4].

Experimental fire tests on high-performance concrete (HPC) slabs demonstrate a strong dependence of spalling behaviour on the thickness of applied passive fire protection coatings, as illustrated in Figure 2.7. When exposed to the ISO 834 standard fire curve for 120 minutes, the unprotected slab ($d_p = 0$ mm) exhibited continuous spalling after approximately 17 minutes of fire exposure, rapidly removing the concrete cover and accelerating heat penetration. Introducing a thin protective layer ($d_p = 10$ mm) significantly delayed the onset of damage; however, once critical pore pressure and thermal stresses developed, spalling occurred in an explosive manner after 119 minutes. In contrast, the slab protected with a 20 mm thick coating showed no spalling throughout the entire fire test duration. These results highlight that passive fire protection does not merely delay spalling, but can fundamentally alter its failure mode, and that insufficient coating thickness may shift the response from early continuous spalling to delayed but potentially more severe explosive spalling.

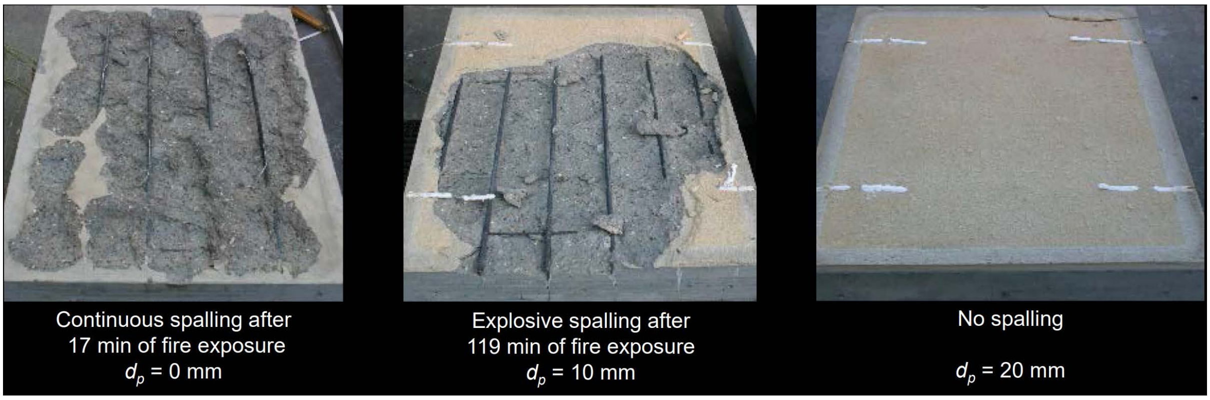


Figure 2.7: Image taken from the *Advanced Structural Concrete* lecture series of ETH Zurich [5], based on experimental fire tests originally reported by Klingsch [6].

A recent full-scale fire test by Guerrieri (Victoria University, Australia) illustrates this vulnerability at structural scale. The test was terminated after only ten minutes due to severe explosive spalling across the heated surface, shown on Figure 2.8. A post-test spatial contour plot of the spalled face revealed highly heterogeneous material loss patterns. Although the specimen was cast concrete, using a mix that was not specified, and not 3D printed, this result reinforces two core points: (i) rapid heating under high mechanical restraint can trigger early catastrophic spalling even in thick sections, and (ii) spalling behaviour is governed by local material and geometric discontinuities. For 3D printed concrete, where layer interfaces form inherent planes of weakness, these observations underline the relevance and urgency of investigating fire response, surface integrity, and thermal protection strategies for printed formwork systems.

Figure 2.8: Spalling in a 4400×2400×400 mm reinforced concrete wall subjected to a high compressive stress was exposed to a modified hydrocarbon fire, measured local losses exceeding 100 mm in depth.

EN 1992-1-2:2027 introduces a strength-class-based distinction for assessing the risk of explosive spalling in concrete elements exposed to fire. For concretes up to strength class C60/75, explicit verification of explosive spalling is not required when tabulated or simplified design methods are applied, provided that no additional risk factors are present. Such risk factors include, among others, high silica-fume content, slender and highly stressed members, or conditions that promote moisture retention. While most printable concrete mixes fall below strength class C60/75, structurally optimised 3D concrete printed elements are typically slender and geometrically refined. As a result, these elements are likely to fall outside the implicit assumptions of the simplified rules and may therefore require explicit verification of explosive spalling. In contrast, for high-strength concretes from C70/85 and above, verification of explosive spalling is mandatory in all cases, regardless of the design approach adopted. This reflects the increased vulnerability of dense, low-permeability concretes to pore-pressure-driven spalling under rapid heating.

Independent of strength class, verification is always required for lightweight aggregate concretes, structures exposed to water-saturated environments, and systems incorporating insulating permanent formwork that restricts moisture dissipation (in addition to the already mentioned slender webs and columns).

3D printed concrete may share some of these characteristics, but its permeability and pore connectivity depend strongly on mix design, printing parameters, and interlayer interfaces, so its spalling behaviour cannot be assumed to follow conventional trends without testing.

Within this regulatory context, the use of a permanent 3D-printed formwork layer that remains bonded to a cast concrete core reflects a shift from purely prescriptive, cover-based fire design rules toward a more performance-oriented interpretation of fire resistance. Rather than being treated solely as nominal concrete cover, the printed layer becomes an integral component of the overall fire-protective system of the member. Its role is twofold:

1. **Thermal function:** The printed layer contributes to delaying heat ingress and increasing the effective thermal mass of the section during the early stages of fire exposure, thereby reducing the heating rate of the structural core and embedded reinforcement.
2. **Mechanical integrity:** The printed layer must maintain its integrity under elevated temperatures by resisting spalling, delamination, or local material loss that could otherwise lead to premature exposure and accelerated heating of the reinforcement.

Unlike monolithically cast concrete, 3D printed concrete is deposited in layers, introducing planar interfaces and directional properties that influence fire performance. Cast concrete is relatively homogeneous; under heat it may crack or spall due to thermal gradients or pore pressure, but deterioration does not typically follow predefined planes of weakness. In contrast, printed elements contain interlayer cold joints and, in hybrid printed–cast sections, interfaces between shell and core. These discontinuities may act as preferential failure paths, promoting delamination or separation when heated.

Experimental evidence supports this behaviour. Cicione *et al.*[7] found that failures in 3D printed specimens exposed to elevated temperatures often initiated at interlayer bonds, shown on Figure 2.9. Similarly, Suphunsaeng *et al.*[8] reported that printed wall interfaces governed thermal degradation and structural response under high heat flux, with the filament surface concentrating thermal stress and accelerating crack development along layer boundaries.

Figure 2.9: Interlayer delamination, after fire testing, taken from [7].

Fire research on 3D concrete printing is still emerging, with layer interfaces playing a dual role: porous seams may facilitate vapour release and reduce explosive spalling, while simultaneously forming weak planes that promote delamination and loss of integrity at elevated temperatures. Anisotropy further complicates fire response, as layer-oriented differences in strength, stiffness, and thermal strain can lead to preferential cracking and heat-induced deterioration along interfaces. Data on load-bearing 3D-printed elements under combined thermal and mechanical loading remain scarce, particularly for hybrid printed–cast systems where additional interfaces and moisture differentials arise. Overall, fire performance in 3DCP is governed less by nominal cover depth than by interface behaviour, anisotropy, geometry, and material selection; while reduced spalling is promising, structural integrity under fire remains a key challenge, highlighting the need for full-scale, performance-based fire testing tailored to printed construction.

Conceptual potential The printed formwork could function as a sacrificial *fire protective shell* that delays heat transfer to the load-bearing core. Under normal conditions this outer layer contributes to strength, durability, or geometry control; under fire it acts as a thermal buffer, absorbing heat and degrading gradually to protect inner concrete and reinforcement. Material design could enhance this effect—for example through heat-resistant mixes. As the outer layer cracks or erodes, it would remove heat from the surface and prolong the time before critical temperatures reach the structural core. This mirrors established strategies such as fireproof claddings or sacrificial mortar layers, but is integrated directly into the printed element. The essential requirement is controlled failure: the layer must remain effective long enough to provide insulation, and its eventual loss should not compromise the stability of the primary structural section.

Geometric freedom in 3D printing enables surface forms that enhance thermal resistance. Corrugated printed shells, for example, lengthen heat-transfer paths and create cooler recesses sheltered from direct flame exposure, while also increasing local stiffness. Targeted thickening can be applied around reinforcement, corners, or edges to delay heating where stresses and thermal demand are highest, even if the overall shell remains thin and material-efficient.

The printed outer layer could be tailored with a high content of polypropylene (PP) fibres to mitigate explosive spalling. As PP fibres melt at relatively low temperature, they create micro-channels that vent moisture and reduce pore pressure during heating [9]. Concentrating these fibres in the outer shell would form a targeted "spalling buffer," protecting the inner concrete. This approach is consistent with Eurocode guidance, which recommends the use of PP fibres to reduce spalling risk in high-strength concrete.

Importantly, 3D concrete printing allows fibre-reinforced mixes to be placed with a degree of preferential orientation arising from the extrusion process. Such directionality may influence vapour transport, crack development, and local permeability under fire exposure, potentially modifying spalling behaviour relative to conventionally cast concrete. However, the extent to which fibre orientation induced by the 3D printing process affects fire performance remains largely unexplored, and its net effect, beneficial or detrimental, has yet to be systematically established.

A further conceptual direction is to design 3D printed formwork for a *predictable* damage mode in fire, allowing the outer printed layer to fail in a controlled manner while preserving the integrity of the structural core. Rather than preventing all damage, the idea is to treat the printed shell as a sacrificial protective layer. For example, deliberate vertical or horizontal weak lines could segment the shell into panels. Under thermal stress, these joints would open in a controlled sequence, reducing the risk of sudden large-scale delamination and exposing the structural core gradually rather than catastrophically.

Alternatively, a light mesh or fibre network could be integrated into the printed cover to retain cracked fragments in place, maintaining partial thermal insulation even after cracking. (Similar mesh concepts have been used to mitigate cover loss and spalling in heavily fire-exposed concrete.) Another speculative option is to incorporate hollow channels or moisture-bearing inclusions in the printed layer to provide short-term evaporative cooling under fire exposure.

These concepts illustrate the *tunable* potential of 3D printed formwork: through local geometry, material differentiation, and embedded features, the printed layer could function as an engineered fire protection system, not merely a construction aid. Implementing such strategies would require targeted testing and validation, but they align with emerging trends toward multi-functional structural materials and systems.

Open challenges A major gap in fire behaviour in printed concrete is the limited experimental data, especially for load-bearing printed elements under simultaneous load and fire, making it difficult to define reliable fire-resistance ratings or satisfy regulatory expectations. This is closely linked to a second challenge: layered, anisotropic behaviour. Interfaces between printed layers influence heat transfer, pore-pressure venting, and failure modes, yet these effects are not captured by current design models or spalling criteria, and modelling tools are not calibrated to represent delamination or interface-driven damage.

In addition, more complex geometries (such as seen on Figure 2.10) now possible introduce another uncertainty. Cavities, ribs, or topology-optimised forms fall outside the scope of standard calculation rules and furnace test setups, complicating verification of insulation and stability criteria. Regulatory frameworks therefore lag behind practice: codes offer no clear guidance on how to treat printed parts, sacrificial layers, or hybrid printed–cast systems within existing fire-design methods, often resulting in conservative or project-specific assessments.

Figure 2.10: Topology optimization of a slab with three supports, taken from [10].

Finally, post-fire inspection and repair are not yet defined for layered systems, particularly where sacrificial behaviour or hidden delamination occurs, and variability in print quality further complicates prediction and assurance of performance. Together, these issues identify a need for systematic testing, model development, and codification to enable confident fire-rated application of 3DCP.

2.2.2 Durability and Environmental Resistance

Relevance and state of knowledge Durability is a key concern for reinforced concrete because environmental deterioration can undermine structural capacity long before the material's theoretical strength is exhausted, Figure 2.11. Codes and engineering practice ensure durability mainly through material quality and cover thickness.

Figure 2.11: Example of durability-related deterioration in reinforced concrete: corrosion of reinforcement leading to cracking and spalling of the concrete cover (taken from Figure 1 in [11]).

Under European exposure classifications (EN 206 and EN 1992-1-1), the main environmental stressors for concrete are (adapted from EN206 with the respective calculation tool [12]):

1. Carbonation: Ingress of CO_2 from the air, which neutralizes concrete alkalinity over time and can lead to corrosion of steel reinforcement. This is critical in many interior or mild exterior exposures (EN 206 classes XC1–XC4) and often governs required cover thickness for a 50+ year service life. Carbonation-induced corrosion is one of the most widespread deterioration causes in European climates.
2. Chloride Ingress: Penetration of chloride ions (from de-icing salts or marine environments) to the reinforcement, causing localized corrosion. This is addressed by classes XD and XS in EN 206. Chloride-induced corrosion can be even more aggressive than carbonation and is considered in design for structures exposed to seawater or road salt.
3. Freeze–Thaw Cycles: Repeated freezing and thawing of pore water can crack concrete and cause surface scaling, especially when the concrete is saturated. EN 206's XF classes cover these environments. In cold, wet climates, freeze–thaw damage is a primary durability limit state for exposed thin elements (e.g. bridge decks, thin walls), unless the concrete is properly air-entrained or protected. Notably, thin-walled concrete members suffer freeze–thaw damage more rapidly due to their quick temperature and moisture exchange with the environment.
4. Sulfate Attack: Exposure to sulfate-bearing soils or water (classes XA in EN 206) can cause chemical deterioration. This tends to be critical in certain foundations, sewage systems, etc. Sulfate attack is typically mitigated by using sulfate-resistant cement and low permeability concrete.

While these are the typical stressors considered, crack control is also a critical determinant of durability in concrete structures. Codes assume that if cracks are kept narrow, they won't significantly compromise durability – e.g., Eurocode states crack widths to be kept between 0.1 mm and 0.4 mm depending on the exposure class. A dense, low-permeability cover (achieved by low w/c ratio, adequate cement, proper curing) and sufficient thickness is expected to sufficiently protect the structural integrity. These rules carry an implicit assumption that the concrete is homogeneous and isotropic, without voids or (layered) interface that could change ingress. Essentially, conventional design presumes a monolithic material where aggressive agents migrate slowly and uniformly from the exterior inward, and that a crack-free (or fine-cracked) cover will protect the steel for the intended service life.

Thus, for optimized (minimal-material) structures, which consist of partly layered components, such produced by 3D-printed concrete systems, where thinner sections and (more) complex geometries reduce the inherent safety buffers against environmental attack, aspects of cracking, ingress need to be taken into consideration. For example, a thin shell or filigree rib has much less moisture storage capacity and thermal inertia than a solid wall. It can saturate quickly and cool or heat rapidly, meaning environmental actions penetrate faster and more deeply, making the concrete more vulnerable e.g. to frost damage or shrinkage gradients. In worst cases it might even mean that the net effect is that durability can become the governing limit state before ultimate strength does (think thin optimized slabs in harsh environments).

In the case of combined cast in printed structures, any degradation of the outer shell directly affects structural performance of the casted part, specifically when it comes to the interface between the printed layers and casted concrete. Printed structures are also notoriously prone to cracking.

In summary, many durability provisions today implicitly expect a relatively chunky, monolithic element (so that cover is reliable, gradients are shallow, and there's some redundancy in thickness). When elements become slender, highly optimized, or layered, these assumptions break down. The result is that designers must reconsider how to ensure longevity – simply applying the same cover thickness or material class may not yield the same life expectancy. For 3D-printed formwork used as a permanent exterior layer, durability performance becomes a primary requirement (on par with structural strength). The printed layer can no longer be thought of as just a cosmetic or temporary element; its ability to withstand carbonation, chlorides, freeze–thaw, etc., without cracking or degradation is crucial to the overall system's safety. This is a significant paradigm shift: rather than adding an arbitrary safety margin of material, one might need to purpose-design the material and geometry of the outer layer for durability.

Conceptual potential Permanent 3D-printed formwork can be deliberately engineered to act as a *durability-enhancing outer skin*, rather than merely replacing conventional cover concrete. Through material differentiation, the printed layer may assume an active protective role within the structural system.

This can be achieved by employing low-permeability concrete mixes for the printed shell, creating a dense outer layer that substantially restricts the ingress of water, chlorides, and aggressive agents. Such a layer effectively functions as an integrated barrier, reducing transport-driven deterioration mechanisms and potentially providing greater chemical resistance than the structural core concrete.

In addition, the inherent surface texture of layered 3D printing can be leveraged to improve the effectiveness of surface-applied hydrophobic treatments or mineral hardeners. Compared to smooth cast surfaces, the printed texture may enhance penetration and mechanical interlock of protective agents, thereby limiting moisture uptake, slowing carbonation, and reducing saturation levels associated with freeze–thaw damage.

The *geometric freedom* afforded by 3D concrete printing enables durability measures that are difficult or impractical to realise with conventional formwork. This freedom can be deliberately exploited to enhance reinforcement protection and reduce corrosion risk through targeted geometric design.

Unlike traditional formwork, where variable cover thickness or locally thickened regions are costly and labour-intensive, printed formwork allows localised optimisation of cover geometry with minimal additional material. Critical zones—such as reinforcement anchorages, lap splices, or tendon end regions—can be provided with increased concrete cover, protective ribs, or shielding features. By concentrating material in durability-critical areas, the printed formwork improves resistance to moisture and chloride ingress without increasing overall section size or self-weight.

Layered deposition also introduces the possibility of crack management through geometry and material interfaces. While interlayer planes are often viewed as a weakness, they may be intentionally utilised to influence crack initiation and propagation. Through geometric tailoring and controlled interface behaviour, cracking could be distributed into multiple fine cracks with reduced spacing and width, limiting the transport of aggressive agents. Smaller, well-distributed cracks reduce permeability and improve long-term durability compared to fewer, wider cracks.

In addition, controlled internal geometries—such as non-continuous cavities, segmented voids, or vented channels—can be designed to disrupt moisture pathways and promote drying. In hollow or infill-printed sections, such features may reduce the risk of sustained internal saturation, which is a key driver of corrosion processes.

Overall, geometry-integrated corrosion protection shifts durability design from uniform, conservative cover prescriptions toward strategic material placement and shape-based control of transport and cracking mechanisms. In this perspective, printed formwork acts not only as a passive protective layer but as an active geometric tool for enhancing the long-term durability of reinforced concrete structures.

Open challenges Accurately predicting durability in 3D printed concrete remains a significant challenge, primarily due to its inherently anisotropic and non-homogeneous transport properties. Standard durability assessments—such as rapid chloride migration and water absorption tests—consistently indicate higher permeability in printed samples compared to cast counterparts. However, translating these short-term laboratory metrics into reliable long-term performance predictions for real structures is still an unresolved task [13].

Traditional durability design methods, particularly those related to crack control, may not be directly applicable to 3D printed systems. New criteria for reinforcement detailing, crack width limitations, and interface behaviour may be necessary to ensure long-term environmental resistance. This need is amplified in systems where the printed shell also functions as permanent formwork: while the internal core is reinforced, the unreinforced, layered shell may act as a plane of weakness from the outset—akin to a network of micro-cracks that predate external loading.

Environmental actions such as freeze–thaw cycles, moisture cycling, and thermal fluctuations present further complications, especially for thin, printed geometries. These elements, with high surface-to-volume ratios and unique surface textures, experience rapid wetting and drying, creating steep gradients and higher deterioration risk. Current laboratory protocols may not fully capture these effects, and more representative test regimes are urgently needed. Consequently, durability design may need to incorporate factors such as geometric complexity, directional exposure, and material anisotropy that are not addressed by existing standards.

In hybrid printed–cast systems, the interface between the shell and the cast core poses a critical durability vulnerability. Differential shrinkage, moisture gradients, and imperfect bonding can introduce hidden delamination or moisture pathways, potentially accelerating deterioration. Without established detailing practices or testing protocols for these interfaces, their long-term integrity remains uncertain—yet their performance may be decisive for the structure as a whole.

Compounding these technical uncertainties is the absence of tailored regulatory guidance. As current codes do not explicitly address 3D printed or hybrid systems, engineers must rely on first principles, bespoke testing, or equivalency demonstrations to meet durability requirements. While organizations such as RILEM are developing frameworks, their codification into building standards is still pending, posing practical implementation challenges.

Finally, the pursuit of durability must be balanced against competing performance requirements. For instance, low permeability is essential for resisting chloride ingress and carbonation—but in fire scenarios, it may increase the risk of explosive spalling by trapping pore pressure. This interplay between environmental and thermal performance highlights the need for multi-functional material strategies and integrated design thinking.

2.2.3 Structural

Relevance and state of knowledge As with several other functional domains discussed in this chapter, the printed formwork is assumed to remain part of the load-bearing system rather than acting as a disposable mold. This shifts the design focus toward the mechanical interaction between the printed shell and the subsequently cast concrete, seen on Figure 2.12. In particular, the bond behaviour at the interface governs force transfer under different load combinations and determines whether composite action can be reliably mobilised. This issue becomes especially critical in optimised systems where primary reinforcement is placed close to the printed formwork, potentially leading to stress concentrations and locally elevated interface demands.

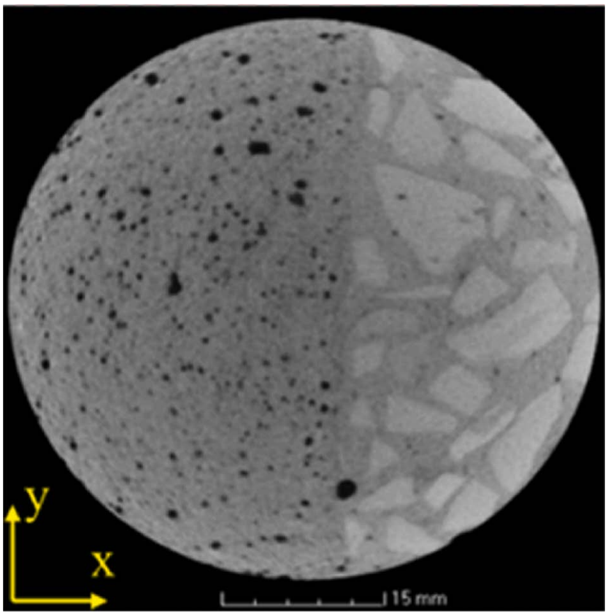


Figure 2.12: CT reconstruction of a cast–printed composite specimen, highlighting the interfacial region between the 3D-printed permanent formwork and the subsequently cast concrete core, taken from [14].

Various strategies have been proposed to enhance this interaction. These include extending reinforcement across the interface (for example by embedding connectors or ties within the printed layers that engage the cast core), as well as tailoring the printed geometry to promote mechanical interlock through surface profiling or intentional roughness at the layer scale. Such approaches echo historical composite construction principles—most notably ancient masonry systems with stiff outer shells and cast cores—but are now reinterpreted through digital fabrication and geometric control.

Experimental studies indicate that the printed concrete shell can already contribute measurable stiffness to the composite member. However, because the printed component is typically thin and materially optimised, it may also introduce new geometric instabilities or sensitivity to local imperfections. As a result, the applicability of existing reinforced concrete design codes to systems incorporating 3D-printed permanent formwork remains uncertain [15]. Current code formulations for strength, crack control, and deflection are based on assumptions of material continuity, whereas 3DPF systems inherently include an interface that may behave as a cold joint governed primarily by shear transfer and friction, and may involve different material strengths and stiffnesses between shell and core. These discrepancies highlight the need for revised modelling assumptions and, potentially, adapted design criteria for reliable structural verification.

Conceptual potential Conceiving the printed formwork as an active structural interface rather than a passive mold opens a range of theoretical possibilities for load-bearing behaviour and structural optimisation. In this view, the printed shell functions as a composite skin surrounding the cast concrete core. Although the printed material itself is typically unreinforced and limited in tensile capacity, its enclosing geometry can contribute indirectly to structural performance by providing confinement, crack restraint, and redistribution of stresses within the core.

Rather than significantly increasing ultimate strength, the primary contribution of the printed shell may lie in controlling damage evolution. By localising, segmenting, or stabilising crack patterns—potentially enhanced through fibre reinforcement within the printed layers—the shell can improve post-cracking behaviour and structural robustness. This role is conceptually analogous to that of fibre-reinforced concrete, where improvements in crack control and toughness are often more significant than gains in peak strength.

Beyond confinement, the geometric freedom afforded by digital fabrication allows the permanent formwork to be shaped deliberately to enhance global and local stability. Features such as ribs, corrugations, or cellular geometries can provide lateral stiffness to otherwise slender members and enable the redirection and spreading of loads in ways that conventional prismatic sections cannot achieve. This enables non-standard cross-sections and internal geometries that more closely follow principal stress trajectories and optimise force flow.

In floor systems, for example, printed ribbed or vaulted formwork could generate shell-like slab behaviour. The resulting surface topography may guide loads from supports to spans along curved, compression-dominated paths—analogous to shallow arch or funicular networks—thereby reducing bending demands relative to flat plate systems. Early research has already demonstrated the feasibility of such concepts through topologically optimised slabs produced using 3D-printed stay-in-place formwork, suggesting substantial untapped potential for material-efficient structural systems.

Open challenges A central challenge for permanent 3D-printed formwork systems is that bond and shear transfer at the interface between printed and cast concrete are not explicitly addressed in standard reinforced concrete design practice, which generally assumes monolithic behaviour. As a result, the mechanical interaction between shell and core remains insufficiently understood and difficult to verify within existing code frameworks.

The cast–printed interface governs whether composite action can be achieved under bending, shear, and combined loading. Key uncertainties remain regarding the effectiveness and reliability of force transmission across this interface. Potential failure mechanisms include relative slip under shear, partial composite action under bending, and local peeling or prying effects if the printed shell tends to separate from the core. The interface is subjected to a combination of adhesion, friction, and normal stresses, all of which may evolve over time due to creep, shrinkage, thermal effects, or cyclic loading. Long-term durability of the bond therefore remains an open question, particularly in thin, optimised shells where stress concentrations are more pronounced.

The layered nature of printed concrete further complicates this behaviour. While surface roughness and intentional geometric interlock at the interface may enhance shear transfer, weak interlayer cohesion within the printed shell itself can introduce predefined planes of weakness that undermine overall composite performance. A recent review identifies mechanical bond behaviour at the cast–printed interface as a "significant obstacle" to the structural integrity of hybrid systems [16]. Ongoing research explores the influence of parameters such as surface topology, printing-to-casting delay, moisture state, and curing conditions, with early findings suggesting that increased internal surface roughness—achieved, for example, through ribbed or grooved geometries—can improve shear interlock and load transfer.

From a design perspective, the absence of validated analytical models poses a major challenge. Engineers cannot directly apply existing reinforced concrete formulas for strength, cracking, or serviceability without assuming full composite action. Instead, current practice relies on bespoke experimental testing or advanced numerical modelling to capture partial interaction and interface failure modes. Developing simplified yet reliable design models that account for non-monolithic behaviour remains an unresolved need.

Finally, permanent 3D-printed formwork introduces new potential failure scenarios that must be explicitly understood to ensure ductile and robust structural response. Questions remain as to whether degradation of the printed shell—through cracking, debonding, or local instability—leads to a gradual redistribution of forces to the core or to abrupt loss of capacity. These risks are compounded by geometric and material variability inherent to off-site or on-site printing processes, where deviations in layer placement, thickness, or alignment may result in locally reduced shell capacity compared to the design intent. Identifying and classifying these failure modes is therefore essential before such systems can be reliably incorporated into structural design practice.

2.2.4 Acoustic Performance

Relevance and state of knowledge In architecture, acoustics is concerned both with limiting noise transmission between different areas of a building (building acoustics) and with shaping how sound behaves inside rooms or outdoor spaces (room acoustics) [17]. The former, building acoustics, is a critical serviceability requirement in residential and mixed-use buildings, governed primarily by regulations on airborne sound insulation, impact sound transmission, and in some cases sound absorption and reverberation control. In the European context, these requirements are typically expressed through indices such as the weighted sound reduction index R_w for airborne sound insulation and the normalized impact sound pressure level $L_{n,w}$, with minimum values prescribed in national building codes derived from EN ISO 717 and EN ISO 16283. Compliance is generally demonstrated at the scale of complete building elements (walls, floors, façades), rather than at the level of material properties alone [18, 17].

The latter, room acoustics, is less strictly regulated. While there are no mandatory codes, planners and designers often follow general recommendations and guidance to ensure adequate sound quality within a space. Relevant references include ISO 23591 for music venues, VDI 2569 for office acoustics, DIN 18041 for room acoustics optimization, and ASR A3.7 regarding workplace noise [17]. Among these, DIN 18041 is frequently highlighted as particularly useful for designing and optimizing the acoustic performance of individual rooms.

In conventional concrete construction, building acoustics performance is largely achieved through mass and separation. Dense, monolithic concrete walls inherently provide high airborne sound insulation due to their surface mass, following the mass law relationship. For floors and partition walls, impact sound is typically mitigated not by the structural concrete itself, but by additional layers—floating screeds, resilient underlays, suspended ceilings, or cavity constructions—that decouple sound transmission paths. As a result, acoustic performance is traditionally addressed through add-on systems rather than through the structural concrete element itself.

Minimum-material concrete design challenges this paradigm. As sections become thinner and more materially efficient, the intrinsic airborne sound insulation of concrete elements decreases, while stiffness-driven vibration transmission becomes more pronounced. Lightweight or optimised concrete elements therefore tend to perform poorly acoustically unless supplemented by secondary layers. This tension between material minimisation and acoustic performance is well documented in lightweight construction systems, but has received limited attention in the context of 3D concrete printing.

Conceptual potential Interpreting 3D-printed formwork as an integrated system component introduces new opportunities for embedding acoustic functionality directly into structural elements, also illustrated on Figure 2.13. Rather than relying exclusively on post-installed acoustic layers, the printed shell can be designed to contribute actively to both building and room acoustics. For instance, modifications to the material composition of the printed element can enhance sound insulation, while geometric adjustments can influence room acoustic behavior.

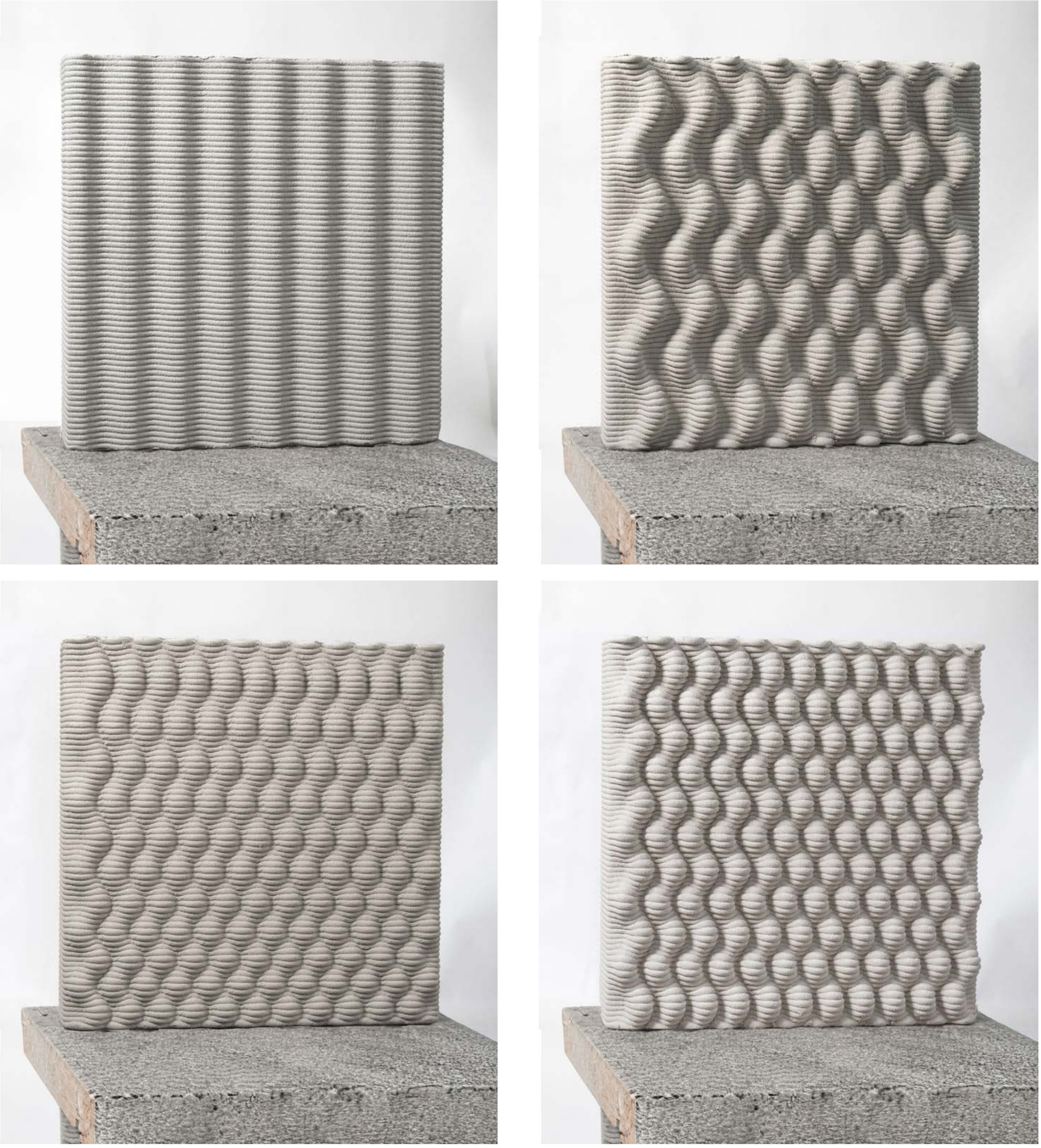


Figure 2.13: Showcasing different printing pattern, focusing acoustic performance, demonstrated by Vertico.

Recent advances in parametric design and numerical simulation enable planners to assess and optimize acoustic performance based on material properties and geometry. Software platforms such as Grasshopper, with plugins like Pachyderm, as well as dedicated acoustic simulation tools including Odeon, CATT-Acoustics, and Treble, facilitate coordinated design and simulation workflows. These tools allow iterative refinement of both form and material, supporting the early integration of acoustic considerations into the architectural design process [17].

Concrete offers specific opportunities for acoustic optimization. Incorporating lightweight aggregates, such as expanded clay or pumice, increases material porosity and improves sound absorption, contributing to reduced sound transmission [17].

Surface texture provides an additional, underexplored avenue for acoustic enhancement in 3D-printed concrete formworks. While previous research has demonstrated the influence of texture in clay prints [17], the layer-wise deposition of printed concrete naturally generates surface roughness. This roughness can enhance scattering and absorption at higher frequencies, particularly in exposed interior applications where control of reverberation is relevant. Although this approach does not directly address inter-dwelling sound insulation, it demonstrates the potential of printed concrete surfaces to combine structural, acoustic, and architectural functions without requiring additional finishes.

Overall, these concepts point toward a shift from acoustic compensation to acoustic integration. Instead of correcting poor acoustic performance caused by material minimisation, the printed formwork could be deliberately shaped and composed to deliver acceptable acoustic behaviour as part of the primary structural system.

Open challenges Despite the conceptual potential of 3D-printed concrete for integrated acoustic functionality, several significant challenges remain. A primary limitation is the lack of validated experimental data on the acoustic performance of 3D-printed concrete elements, particularly in hybrid printed–cast systems. Acoustic behavior is highly sensitive to factors such as boundary conditions, scale, and construction detailing, making it difficult to extrapolate results from small-scale specimens or non-structural panels to full-scale building applications.

Regulatory frameworks present an additional barrier. Current acoustic standards and calculation methods are based on conventional construction typologies, such as solid walls, cavity walls, and floating floors. There is no clear guidance on how to classify or assess monolithic yet internally structured printed elements, nor on how to account for integrated damping or resonant features. As a result, conservative assumptions may reduce the material-efficiency benefits of printed systems by necessitating additional conventional acoustic layers.

From a material perspective, acoustic metamaterials offer intriguing possibilities. These engineered structures manipulate sound through geometry and internal structure rather than material composition, enabling effects such as enhanced absorption, sound redirection, or vibration isolation. While promising in theory, widespread implementation in printed concrete systems remains unlikely in the near term due to practical and manufacturing constraints.

Finally, construction tolerances and print variability introduce further uncertainty. Small deviations in layer bonding, cavity geometry, or surface continuity can have disproportionate effects on acoustic performance, particularly for impact sound. This underscores the importance of quality control, reproducibility, and post-construction verification as critical factors for ensuring reliable acoustic outcomes in printed concrete elements.

2.2.5 Aesthetics

Relevance and state of knowledge Current developments in concrete construction reflect a growing integration of material-efficient design strategies with expressive architectural intentions, positioning aesthetics as an integral component of structural systems, seen on Figure 2.14. 3D printed formwork enables complex geometries and surface details in concrete that were previously impractical, allowing the formwork itself to impart the final architectural finish and texture to structures. Unlike standard flat formwork, which yields plain surfaces requiring cladding or post-processing, digitally fabricated molds can directly create free-form curves, patterns, and even fine ornamentation on concrete surfaces [19]. This has opened up mass-customization in architecture – each concrete element can be unique without extra cost for complexity, achieving bespoke aesthetics (e.g. intricate facades or artistic wall reliefs).

Figure 2.14: Top: Cosmopolitan Vogelweh Elementary School, featuring a textured exposed-concrete foyer wall used as an architectural finish. Bottom: The Swiss Life Arena, one of the largest projects realized with NOEplast. Figure credit: NOE.

Aesthetic integration can transform concrete construction from uniform and utilitarian towards expressive, context-specific design. This is increasingly desirable in modern practice and can even support regulatory goals (for instance, facade shading geometry for energy efficiency).

The feasibility of some such approaches has been demonstrated across research and practice. At ETH Zurich, the Smart Slab in the DFAB House employed 3D-printed sand molds to realize a thin concrete floor with ornamented openings and organic motifs that admit light—forms impractical with conventional formwork. In commercial practice, the One South First tower in New York used large-format printed molds developed with Oak Ridge National Laboratory to produce more than a thousand unique precast façade panels, achieving sharply articulated details and faceted recesses that modulate light while remaining economically viable. Although these examples, seen on Figure 2.15 didn't specifically use 3D concrete printed formworks to achieve aesthetic results, they shown how printed formworks can introduce new visual languages in concrete, from smooth doubly curved surfaces to complex reliefs that were previously cost-prohibitive.

Figure 2.15: Left: Smart Slab in the Dfab House. Right: Domino Sugar site A.

Structures where printed concrete is used as stay-in-place formwork, the aesthetic logic differs from removable molds. In this context, achieving smooth finishes may be more challenging, and the printed shell itself becomes the visible surface. One option here is to post-process the printed surface, for example through milling, seen on Figure 2.16.

Figure 2.16: Structure of a milled surfaced after printing, by Vertico.

Industrial applications—such as the highly articulated columns and components produced by Vertico, seen on Figure 2.17 and 2.13, show how layer control, overhang strategies, and integrated color can yield intricate detailing. Collectively, these developments establish both the relevance and an emerging body of knowledge for the aesthetic role of 3D-printed formwork, particularly as it transitions from removable molds to visible, permanent shells.

Figure 2.17: Different structures showing high detail and coloured layers, as presented on the Vertico website.

Conceptual potential In principle, architects could design concrete elements in a context of high freedom of form – complex organic shapes, biomimicry structures, graded porosities, and high-resolution micro- textures – creating a “new language” of concrete architecture that blends structure and art [19].

As the technology matures, we can envision some developments for information and interaction: for instance, informational surfaces with embossed signage, patterns or even QR codes directly placed into building walls for wayfinding, or pathway cues (e.g. textured pathways) integrated into floors for accessibility. Similarly, formwork-enabled ornamentation could carry cultural or contextual narratives (imagine pillars or panels with locally inspired motifs generated algorithmically and printed on-demand).

Tactile and ergonomic forms are another conceptual avenue – because formwork can be freely shaped, concrete furniture or building elements could be molded to ergonomic profiles (e.g. a 3D-printed formwork for a bench that fits the human body, or handrails and door surrounds contoured for touch comfort). In the long run, such customization might extend to each individual unit in a building, tailoring spaces to their occupants’ needs without cost penalty for uniqueness.

From functional aesthetics, printed formwork could enable multi-performance concrete surfaces. Multiple materials or advanced additives in different zones, allowing, for example, color integration or light-transmitting features in the concrete. Researchers suggest that multi-material 3D printing could layer materials in the formwork to create concrete elements with embedded insulation, conductive or responsive materials, etc., all while preserving a seamless visual design [20].

Open challenges The main challenges remain quitee similar to already discussed aspects, such as code compliance with thin formwork type structures, sensitivity to failure due hydrostatic pressure and the production of custom made reinforcement for these freeform shapes [19]. Because of this, engineers must resort to advanced simulations and sometimes extensive testing, introducing gaps in verification methods.

However, perhaps the main challenge from an aesthetic perspective is the by product of the printing process, the visual look of a layered structure where the lines created between each layer are quite distinct. Some of this can be removed via post-processing, however this is quite a bit of extra work.

Another set of challenges is the practicality and economics of using 3D-printed formworks. Currently, printing large molds or stay-in-place shells can be time-consuming and expensive for one-off elements, and the printed forms can be fragile if they have to lifted and handled. There have been cases of formwork cracking or deforming under the pressure of concrete casting, highlighting the need for robust print materials or external bracing, especially for taller pours.

Chapter 3

Lateral pressure

Hydrostatic pressure induced by fresh concrete is identified as one of the most critical technical challenges for 3D printed formwork systems [19, 21]. Unlike rigid timber or steel formwork, 3D printed polymer- or mineral-based formwork often exhibits lower stiffness and anisotropic material behavior due to the layer-by-layer fabrication process [19]. As a result, formwork deformation, buckling, or rupture may occur if hydrostatic pressure is not adequately managed. Mitigation strategies include controlled casting rates, segmented pouring, geometric stiffening through corrugation or ribbing, and material reinforcement [19]. Accurate prediction of fresh concrete pressure, combined with structural analysis of the printed formwork, is therefore essential to ensure stability during casting while maintaining the design freedom offered by additive manufacturing [19].

3.1 Fundamentals of Fresh Concrete Pressure

3.1.1 Fresh Concrete as a Fluid–Granular Material

Fresh concrete exhibits a complex mechanical behavior that lies between that of a fluid and a granular solid. At early ages and under low shear stresses, it can flow and deform, allowing it to be placed and compacted; however, unlike a Newtonian fluid, fresh concrete consists of a concentrated suspension of solid particles—aggregates and cement grains—within a viscous cement paste. This particulate nature gives rise to internal friction, yield stress, and time-dependent stiffening, which distinguish fresh concrete from an ideal fluid.

From a rheological perspective, fresh concrete is commonly described as a yield-stress material, often approximated by Bingham or Herschel–Bulkley models. Flow occurs only when the applied shear stress exceeds a material-specific yield stress, after which the material deforms with a viscosity-dependent resistance. Simultaneously, thixotropic effects and early hydration processes cause the yield stress to increase over time, even in the absence of external loading. As a result, the material progressively transitions from a fluid-like to a solid-like state.

The interaction between fluid-like behavior and granular skeleton formation has direct implications for pressure development against formwork. While freshly placed concrete may initially exert pressures close to hydrostatic, the formation of interparticle contacts and the development of internal shear resistance reduce the effective lateral pressure with increasing time and depth. This dual fluid–granular behavior provides the physical basis for pressure reduction models used in formwork design, in which casting rate, temperature, and setting time govern the extent to which hydrostatic conditions prevail.

In the context of 3D-printed concrete formwork, this fluid–granular behavior is particularly critical. Printed formworks are often slender and geometrically optimized, making them sensitive to both peak pressure and its temporal evolution. A proper understanding of fresh concrete as a fluid–granular material is therefore essential for accurately assessing formwork loads and for moving beyond conservative hydrostatic assumptions toward more realistic pressure models.

3.1.2 Classical Pressure Models

Full hydrostatic pressure In the most conservative approach to formwork design, fresh concrete is assumed to behave as a homogeneous fluid that exerts a full hydrostatic pressure on the surrounding formwork. Under this assumption, the lateral pressure increases linearly with depth and is independent of time, casting rate, or material setting. The hydrostatic pressure at a given depth is expressed as:

$$P = \rho \cdot g \cdot h \tag{3.1}$$

where P is the hydrostatic pressure acting on the formwork [Pa], ρ is the density of fresh concrete, typically taken as approximately 2400 kg/m^3 [kg/m^3], g is the gravitational acceleration (9.81 m/s^2) [m/s^2], and h is the vertical depth below the concrete surface [m].

This formulation represents an upper-bound loading scenario and is commonly adopted for preliminary design or in situations where the setting behaviour of the concrete is uncertain. In practice, the actual pressure is often lower due to the time-dependent stiffening of concrete, which is addressed through reduced-pressure models discussed in the following section.

Reduced pressure models In practice, the lateral pressure exerted by fresh concrete on formwork is often significantly lower than the full hydrostatic pressure predicted by fluid assumptions. This reduction is primarily attributed to the time-dependent evolution of the mechanical properties of fresh concrete, particularly the increase in yield stress and internal shear resistance due to thixotropy and early hydration. Reduced pressure models aim to capture this behaviour by accounting for the interaction between material setting and construction process parameters, most notably casting rate, temperature, and setting time.

The casting rate governs the duration for which a given layer of concrete remains in a fluid or semi-fluid state. At low casting rates, concrete placed at lower depths has sufficient time to stiffen before additional material is added above, enabling the transfer of vertical loads through internal friction and particle interlock rather than purely through hydrostatic pressure. Conversely, high casting rates limit the development of internal strength, resulting in pressure distributions that approach hydrostatic conditions. Reduced pressure models therefore typically relate the maximum lateral pressure to the rate of placement, often assuming that pressure increases with depth until a limiting value is reached when setting begins to dominate.

Temperature plays a critical role in pressure development through its influence on hydration kinetics. Higher temperatures accelerate cement hydration and thixotropic structuration, leading to a more rapid increase in yield stress and a corresponding reduction in lateral pressure. Lower temperatures delay setting and prolong fluid-like behavior, increasing both the magnitude and duration of pressure acting on the formwork. Many pressure models incorporate temperature either explicitly, through empirically derived correction factors, or implicitly, through its effect on initial and final setting times.

Setting time provides a direct measure of the transition from fluid-dominated to solid-dominated behavior and is often used as a unifying parameter in reduced pressure formulations. Before the onset of initial set, concrete is commonly assumed to behave in a predominantly fluid manner, while after setting, pressure transfer increasingly occurs through frictional and granular mechanisms rather than through hydrostatic action. As a result, pressure models frequently assume that lateral pressure ceases to increase beyond a certain depth or time, leading to a maximum design pressure that is lower than the hydrostatic value.

For formwork design, reduced pressure models are typically expressed as empirical or semi-empirical relationships that define a maximum lateral pressure as a function of casting rate, temperature, and concrete properties. These models form the basis of several design standards and guidelines, providing a more realistic representation of formwork loading while maintaining an appropriate margin of safety. In the context of 3D-printed concrete formwork, where structural capacity and deformation tolerance may be limited, the careful application of reduced pressure models is essential to balance design efficiency with robustness.

Existing standards Several national and international standards provide guidance for estimating lateral pressures exerted by fresh concrete on formwork. These standards are primarily based on empirical observations from conventional cast-in-place concrete construction and incorporate reduced pressure concepts by accounting for time-dependent material behavior and construction parameters.

In American practice, ACI 347 (Guide to Formwork for Concrete) is the principal reference for formwork design [22, 23]. It distinguishes between full hydrostatic pressure and reduced pressure conditions and provides expressions for maximum lateral pressure as a function of casting rate, concrete unit weight, temperature, and setting characteristics. ACI 347 is widely used and forms the basis for many contemporary engineering design approaches, particularly in the context of wall and column formwork.

In Germany, DIN 18218 (Frischbetondruck auf lotrechte Schalungen) specifically addresses the lateral pressure of fresh concrete on vertical formwork [24]. The standard introduces pressure models that explicitly account for casting rate, temperature, and concrete consistency, and defines limiting pressure envelopes rather than assuming a fully hydrostatic distribution. DIN 18218 is notable for its explicit treatment of time-dependent pressure reduction and is often regarded as one of the more detailed national standards on fresh concrete pressure.

At the European level, EN 13670 (Execution of concrete structures) provides general requirements for formwork design and execution, including the need to account for actions imposed by fresh concrete [25]. While EN 13670 does not prescribe explicit pressure calculation models, it establishes performance-based requirements and refers to national standards or project-specific design assumptions for determining lateral pressure. As such, it serves as a framework within which standards such as DIN 18218 or ACI-based methods may be applied.

Although these standards were developed for conventional formwork systems, they are frequently adopted as a starting point for the design and assessment of 3D-printed concrete formwork. However, the unique geometries, reduced stiffness, and material-specific characteristics of additively manufactured formworks highlight the need for careful interpretation of existing provisions and, where necessary, the development of adapted or supplementary design approaches.

3.2 Characteristics of 3D Printed Formwork Systems

Additive manufacturing (AM), and specifically three-dimensional concrete printing (3DCP), is increasingly explored as an alternative to conventional formwork systems in the construction industry [26, 19, 27]. In contrast to subtractive or mould-based fabrication, 3D concrete printing produces geometry by the layer-by-layer deposition of a cementitious material, directly guided by a digital model [28, 19]. This approach enables the creation of geometrically complex and highly customized elements without the need for temporary formwork, thereby reducing material waste, labour intensity, and construction time.

The 3D concrete printed formwork can serve either as a full replacement for traditional formwork or as a hybrid solution. In the former case, structural or semi-structural components are printed directly to their final shape, after which conventionally reinforced concrete is cast into the printed formwork. This casting can occur while the printed concrete is still fresh, relying on its early-age strength and stability to maintain geometry, which requires carefully engineered mixtures with controlled rheology that balance pumpability, extrudability, and buildability. Alternatively, casting can take place once the printed formwork has hardened. In hybrid approaches, 3D printing produces permanent formwork elements within conventional formwork, into which reinforced concrete is cast later. Both methods allow the printed parts to serve as both the geometric mold and a functional part of the final structure, provided sufficient bonding occurs between the printed and cast concrete [19].

The digital nature of 3DCP enables a high degree of design freedom, making it particularly suitable for non-standard, optimized, or topology-driven geometries that would be inefficient or impossible to realize using traditional formwork. Material can be strategically placed only where structurally required, supporting material-efficient design principles. Furthermore, the integration of additive manufacturing with parametric design and robotic fabrication allows for seamless transitions from design to production, reducing errors and increasing precision. However, producing more conventional shapes, such as rectangular shapes with 90-degree angles, is almost impossible. Therefore, it also becomes a more customized process (which can be automated in an integrated parametric workflow) to determine the stability of the formwork during casting.

A critical aspect of 3D concrete printing is the control of dimensional properties, which directly influences the quality, structural performance, and surface finish of printed elements. Printing resolution, typically determined by the nozzle diameter, ranges from 10 mm to 100 mm, with finer nozzles enabling more intricate geometries but slower deposition rates. Layer height, or the vertical thickness of each deposited layer, is generally between 5 mm and 50 mm, balancing buildability with interlayer adhesion. Lower layer heights improve surface smoothness and reduce visible stepping, whereas higher layers accelerate construction but may compromise detail. Interlayer bonding is essential for structural integrity, depending on the time interval between successive layers, concrete rheology, ambient conditions, and printing speed.

Despite its potential, challenges remain, including limitations in reinforcement integration, surface quality, dimensional tolerances (mainly in connections with other elements), and compliance with existing building codes. Nevertheless, ongoing research and pilot projects demonstrate that additive manufacturing offers a promising pathway toward significantly reducing or eliminating temporary formwork in concrete construction and creating more optimised structures in general.

3.3 Mitigation Strategies

Minimum 3D-printed concrete formworks are particularly vulnerable to lateral hydrostatic pressure due to their reduced wall thickness and limited inherent stiffness. To enable safe casting while maintaining material efficiency, a range of mitigation strategies can be employed to reduce, redistribute, or resist these pressures. Rather than relying on a single solution, effective pressure mitigation typically results from a combination of complementary approaches. The following sections, therefore, categorise and discuss mitigation strategies as 'process-based strategies', 'geometric strategies', and 'material or hybrid strategies', highlighting their mechanisms, advantages, and practical implications.

3.3.1 Process-Based Strategies

Controlled casting rates is one of the most effective process-based strategies for limiting hydrostatic pressure on formworks. The lateral pressure exerted by fresh concrete is strongly dependent on the height of fluid concrete at any given time, which is directly influenced by the rate at which concrete is placed. By reducing the casting speed, the lower layers are allowed to gain stiffness through thixotropic build-up and early hydration before additional material is added above. This gradual strength development reduces the effective height at which the concrete acts as a fluid and limits lateral pressure on the formwork. Controlled casting rates are particularly important for slender or thin-walled printed formworks, where small increases in pressure can lead to deformation or failure. In practice, this strategy requires careful coordination between concrete delivery, pumping, and placement. Casting rates may be adjusted based on ambient temperature, concrete mix design, and formwork geometry. While slower casting increases construction time, it significantly improves formwork safety and reliability when minimal material thickness is used.

Segmented or staged pouring reduces lateral pressure by limiting the height of fresh concrete present in the formwork at any given time. Instead of casting the full height in a single continuous operation, the concrete is placed in discrete lifts separated by waiting periods. During these pauses, the previously cast segment undergoes partial setting and structural build-up, enabling it to resist additional loads from subsequent pours. This approach effectively transforms the pressure condition from fully hydrostatic to partially or predominantly solid-like behavior. Staged pouring is especially beneficial for tall elements such as columns, walls, or cores formed using thin 3D-printed shells. The segmentation height and waiting time must be carefully calibrated to ensure sufficient strength gain without creating cold joints or weak interfaces. This strategy can be implemented without altering material properties, making it attractive for on-site applications. However, it requires precise process control and clear definition of allowable time windows between stages.

Casting direction can strongly influence the effective hydrostatic pressure acting on formwork. Rotating or reorienting the element prior to casting can significantly reduce the vertical height of fresh concrete, thereby lowering lateral pressure. For example, casting a column in a tilted or near-horizontal orientation reduces the fluid head compared to a fully vertical cast. This approach was successfully applied in the MAS Stairs project, where elements were rotated to minimize pressure during casting [19]. Casting direction strategies are particularly effective for prefabricated elements, where orientation can be freely adjusted during production. By minimizing the effective height during casting, thinner and less reinforced printed formworks can be used. This method reduces reliance on material strength alone and instead leverages production freedoms during prefabrication. However, it requires careful planning of formwork support, handling, and post-casting rotation.

Counter pressure strategies involve balancing the hydrostatic pressure of fresh concrete with an external material applied to the outside of the formwork [29]. In this approach, the printed formwork is placed within a container, and a counter-pressure material is added externally while concrete is cast internally. The levels of concrete and counter-pressure material are increased simultaneously to ensure pressure equilibrium [19]. Since hydrostatic pressure is proportional to material density, the counter-pressure medium should ideally have a density close to that of the concrete. Typical densities are approximately 2400 kg/m^3 for normal-weight concrete and 1400–1800 kg/m^3 for lightweight concrete [19]. When properly synchronized, this method significantly reduces net lateral pressure on the formwork walls. Counter-pressure techniques enable the use of thin printed formworks that would otherwise fail under full hydrostatic load. However, the method increases process complexity and requires additional containment systems and material handling.

3.3.2 Geometric Strategies

Several geometric strategies can be used to enhance the strength and stiffness of 3D-printed concrete formwork without changing the material composition. These strategies rely on modifying the shape or thickness of the printed elements to improve their ability to resist lateral loads from fresh casted concrete.

Corrugation introduces periodic waves or folds along the wall geometry. This concept is well-known in cardboard structures, where corrugated layers significantly increase bending resistance without adding much additonal material. In 3D concrete printed formwork, similar corrugations can help in bending-related failure mechanisms [30].

Figure 3.1: Left: Corrugated structure of cardboard. Courtesy to [31]. Right: Corrugated wall structures. Courtesy to [32].

Ribbing involves adding discrete stiffening elements at intervals along a wall or panel. Longitudinal or transverse ribs strengthen the formwork in targeted areas, improving bending and shear resistance while minimizing additional material usage. Ribbing is particularly useful in areas of high stress or where the formwork must span longer distances [33, 19].

Local thickening is one of the simplest ways to increase formwork strength [19]. This can be achieved by either increasing the width of individual printed layers or adding more layers to build up the wall thickness. By enlarging the cross-sectional area, the stiffness and load-bearing capacity of the formwork increase, allowing it to better resist bending and tensile forces.

Curvature as stiffening leverages the natural structural benefits of curved geometries. Instead of printing straight walls, introducing slight curvature converts bending stresses into membrane action, significantly increasing resistance to lateral loads. This principle can be observed in traditional masonry, such as curved brick walls in the UK (i.e., Crinkle- crankle wall, see Fig. 3.2), where arches and curved walls provide additional stability without increasing (or even reducing) material usage.

Figure 3.2: Comparison of traditional crinkle- crankle wall (left) and a digitally fabricated wavy 3DCP wall (right). Crinkle- crankle wall: a traditional wavy brick wall design that achieves stability through its serpentine form while using fewer bricks compared to a straight wall. Courtesy to [34]. Wavy 3DCP wall: parametric concrete wall form generated using computational design. Courtesy to [35].

3.3.3 Material and Hybrid Strategies

Concrete rheology plays a central role in determining the magnitude and duration of hydrostatic pressure during casting. By tailoring the mix design to exhibit rapid structural build-up, the concrete transitions more quickly from a fluid to a solid-like state, reducing lateral pressure on the formwork. Thixotropic behavior is particularly beneficial, as the material stiffens at rest but remains pumpable under shear. The use of viscosity-modifying agents, optimized aggregate grading, and controlled water content can significantly reduce pressure development. Rheology control allows higher casting rates or taller pours without increasing formwork stress. However, excessive stiffening may negatively affect surface finish or bonding between layers. Therefore, rheological optimization must balance pressure mitigation with workability and structural performance.

Fiber reinforcement can significantly enhance the structural capacity of minimum 3D-printed concrete formwork subjected to lateral hydrostatic pressure. The inclusion of short fibers, such as glass, basalt, steel (corrosion issues might become a problem), or polymer fibers, improves tensile strength, crack control, and post-cracking ductility of the printed material.

Multi-material printing enables the spatial variation of material properties within a single printed formwork, offering a targeted approach to resisting hydrostatic pressure. By printing stiffer or higher-strength materials in regions subjected to greater lateral loads, such as the lower portions of vertical elements, the formwork can be structurally optimized without uniformly increasing material usage.

Hybrid formwork elements refer to systems in which a 3D-printed formwork is combined with external, non-printed reinforcement to resist lateral hydrostatic pressure during casting. In this approach, the printed formwork defines the geometry and surface quality of the concrete, while additional elements such as straps, clamps, timber battens, or steel frames are applied externally to increase confinement and stiffness. These secondary elements primarily counteract tensile stresses and outward deformation caused by fresh concrete pressure. By providing external restraint, the printed walls are prevented from excessive bending or buckling, even when minimal wall thicknesses are used. This strategy allows the printed formwork to remain material-efficient while relying on conventional construction components for structural support. Hybrid reinforcement can be locally applied in regions of higher pressure, such as near the base of vertical elements, following the hydrostatic pressure gradient. Although this reduces the "fully printed" nature of the system, it significantly increases robustness and safety during casting. As such, hybrid formwork elements provide a practical and scalable solution for on-site applications where strict control of casting pressure is difficult.

Chapter 4

Design Considerations

This chapter focuses on the design considerations for achieving material efficient structures using 3D concrete printed formwork. It is structured into two sections. The first section, Optimization Strategies, explores approaches to reduce material usage, drawing on principles of size, shape, and topology optimization. The second section, Development Steps for 3D-Printed Concrete Formwork, provides a practical guide for the design process, summarizing important steps and linking to previous chapters/sections. Together, these sections offer both theoretical and practical insights into designing optimized 3D concrete printed formwork solutions.

4.1 Optimization strategies

In the context of minimizing concrete/formwork in concrete structures, several optimization strategies can be applied, which can be categorized using for example Bendsøe's and Sigmund's framework of size, shape, and topology optimization, see Fig. 4.1 [36]. Size optimization focuses on adjusting the dimensions of structural elements, such as thicknesses of slabs, beams, and walls, to reduce material usage while maintaining structural performance. Shape optimization involves altering the geometric profile of elements, for instance by introducing tapering, curvatures, or openings, to achieve a more efficient distribution of stresses and minimize ineffective use of concrete. Topology optimization goes a step further by reconfiguring the internal layout or connectivity of a structure, creating voids or redesigning load paths to eliminate redundant material entirely. By integrating these three approaches, designers can achieve significant reductions in formwork and concrete use, leading to lower costs and environmental impact. The strategies can be applied individually or in combination, depending on project requirements and construction constraints. Overall, this framework is used to provide an overview of several optimization strategies to create material-efficient designs in a systematic way.

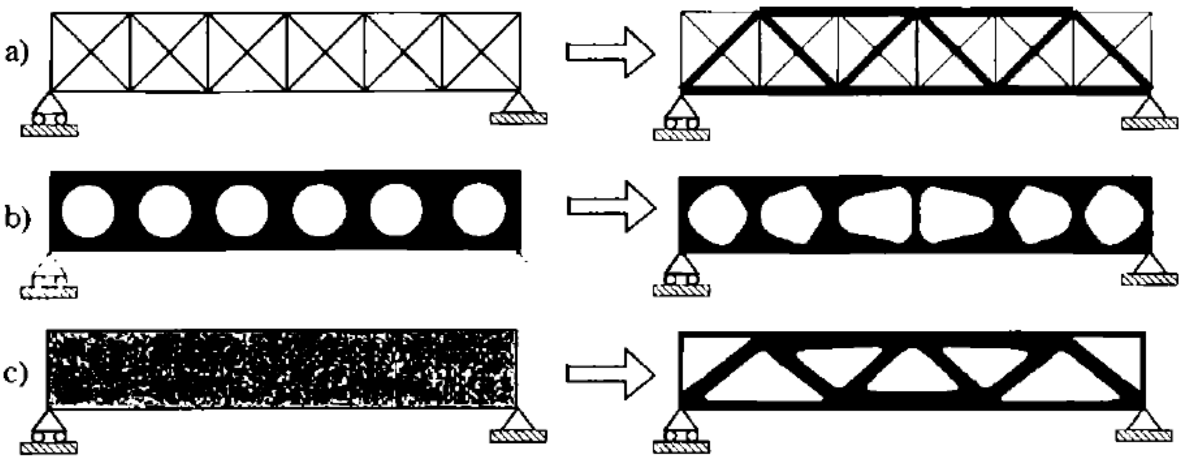


Figure 4.1: Size (a), shape (b), and topology optimization (c). Courtesy to [36].

4.1.1 Size optimization

Size optimization focuses on improving structural efficiency by varying the dimensions of structural elements (such as thickness, cross-sectional area, or rib height) while keeping the overall topology and layout fixed. The objective is to allocate material in proportion to local structural demand, increasing dimensions where stresses are high and reducing them where stresses are low, thereby minimizing material use without compromising performance [36].

4.1.2 Shape optimization

Brute force shape optimization is a method where all possible shape variations within a defined parameter space are systematically generated and evaluated. Each option is tested against objective criteria, such as structural performance or cost. The best-performing shape is selected based purely on comparison of results. While simple and robust, the approach becomes computationally expensive as the number of variables increases.

An example of shape opimization using brute force technique (i.e., evaluating a significant amount of profiles and selecting the best based on certain criteria) can be seen in Fig. 4.2 by Sakha et al. [37], in the paper they show a "bottom-up optimization workflow" that begins with cross-sectional shape optimization followed by spanwise optimization. In the shape optimization phase, they generated a large set of geometrically different ribbed formwork profiles using a custom parametric toolpath generator, varying key parameters such as rib aperture sizes and positions. Each profile was then evaluated using finite element analysis under four- point bending to determine its cracking moment capacity. Candidates were filtered based on cracking resistance and production feasibility. This process narrowed the design space to the most promising profiles for further refinement in the subsequent spanwise optimization stage, which arranges selected cross- sections along the span to balance structural capacity and efficiency. The optimization results from the study can be seen in Fig. 4.3 [37].

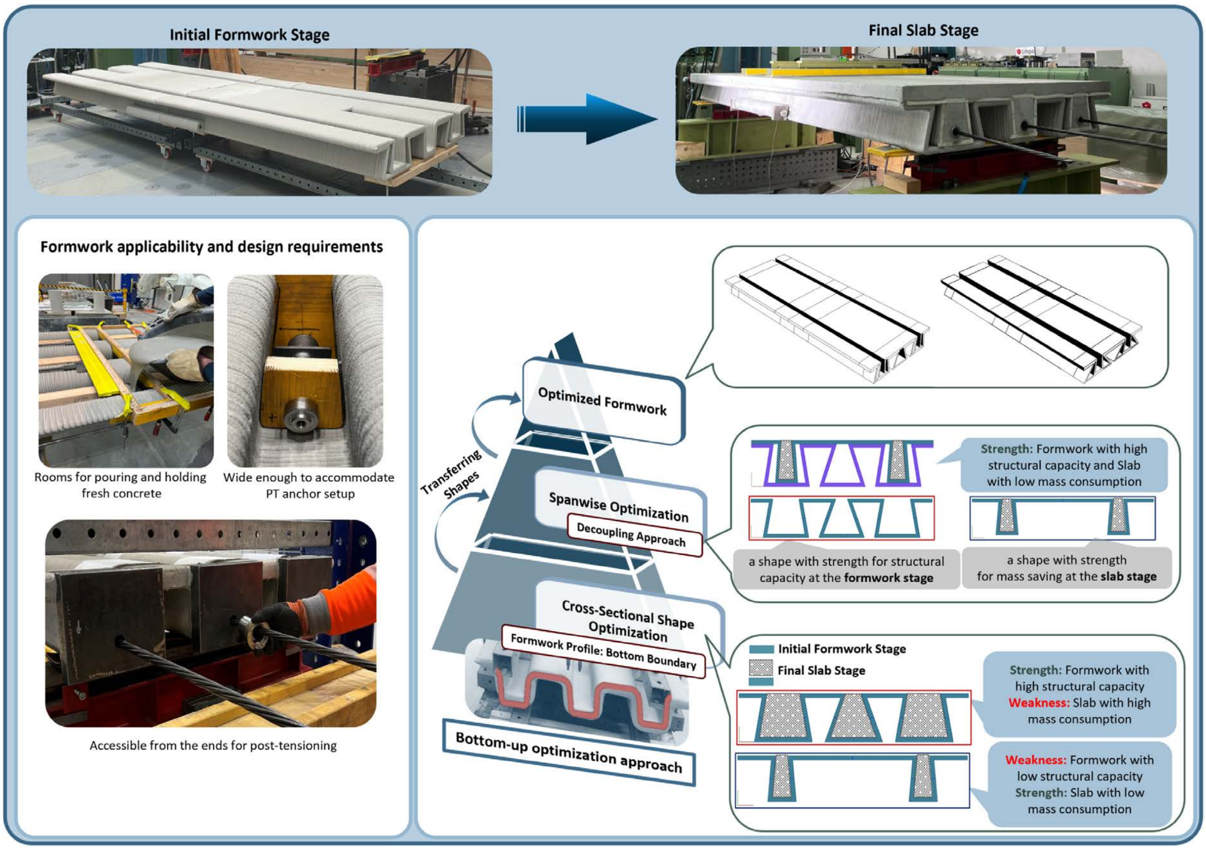
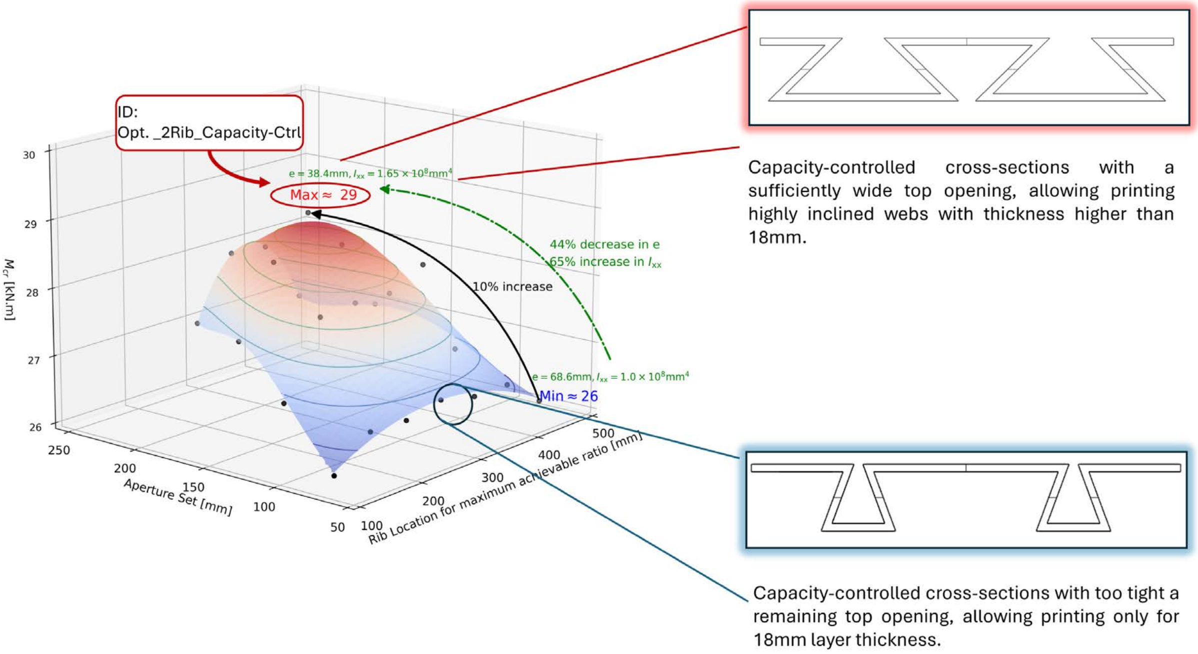


Figure 4.2: Bottom-up optimization workflow for a slab that begins with cross-sectional shape optimization followed by spanwise optimization. Courtesy to [37].



Capacity-controlled cross-sections with a sufficiently wide top opening, allowing printing highly inclined webs with thickness higher than 18mm.

Capacity-controlled cross-sections with too tight a remaining top opening, allowing printing only for 18mm layer thickness.

Figure 4.3: Optimization space. Courtesy to [37].

Principal bending moments Ribbed floor slab systems can be designed by aligning ribs with principal bending moment trajectories rather than following conventional orthogonal layouts, with the aim of placing material only where it is structurally most effective [38, 39]. Using computational analysis, bending moment and stress fields can inform the generation of rib geometries whose orientation, density, and layout adapt to varying loads and boundary conditions. Such stress-aligned configurations generally achieve higher structural efficiency than traditional solid or regularly ribbed slabs, offering comparable stiffness and load-bearing capacity with reduced material usage and self-weight, see Fig. 4.4 [38].

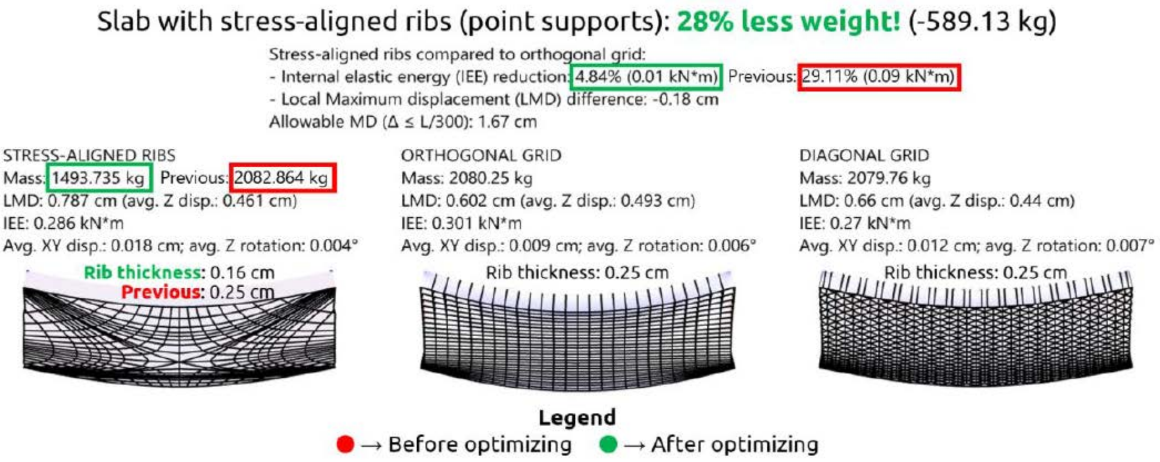


Figure 4.4: Comparison of stress-aligned slabs to orthogonal and diagonal ribs. Courtesy to [38].

The structural behaviour of the system can also be analysed using analytical approaches such as: the **stringer–panel method** [40], **yield line analysis** [41], and **strut-and-tie modelling** [42]. Each method provides insight into different aspects of load transfer and failure mechanisms, enabling the selection of regions with more or less efficient material use, which can lead to shape-optimized structures. The translation of these methods into the final design is not always straightforward and may require additional steps to arrive at a printable solution. A short overview of each method is given below:

Stringer-panel method (SPM) is a lower-bound plastic design approach for reinforced concrete structures in which the internal force flow is idealized by a combination of axial force–carrying stringers and shear-resisting panels [40]. Stringers represent discrete load-carrying paths in tension or compression, while panels transfer shear through distributed stress fields. By enforcing equilibrium and admissible stress states, the method provides a physically interpretable representation of load redistribution, particularly in wall systems. An example analysis of the SPM can be seen in Fig. 4.5.

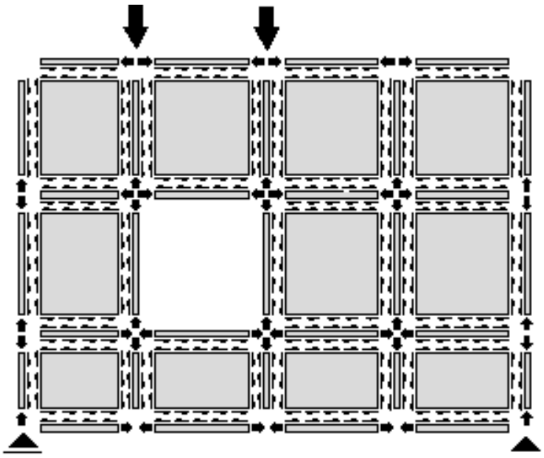


Figure 4.5: Example of the stringer panel method. Courtesy to [40]

Yield line analysis is a plastic analysis method used to estimate the ultimate load capacity of reinforced concrete slabs by assuming the formation of a collapse mechanism composed of yield lines, along which plastic hinges develop. The method is based on the principle of virtual work, equating external work to internal energy dissipation at the yield lines. By focusing on kinematically admissible failure mechanisms, yield line analysis provides an upper-bound estimate of the collapse load and offers valuable insight into governing failure patterns and load redistribution [41].

Strut and tie modeling (STM) is a design approach for reinforced concrete structures in which the internal force flow is idealized as a truss-like system consisting of compression struts, tension ties, and nodal zones (see Fig. 4.6 for one of the original examples [42]). Originally formalized by Schlaich et al. [42], the method provides a rational framework for designing discontinuity regions by explicitly linking structural form to load paths. More recent research, including studies on topology optimization, highlights the conceptual similarity between strut-and-tie models and optimized material layouts, emphasizing STM as a physically interpretable bridge between numerical optimization results and practical, code-compliant concrete design [42, 43].

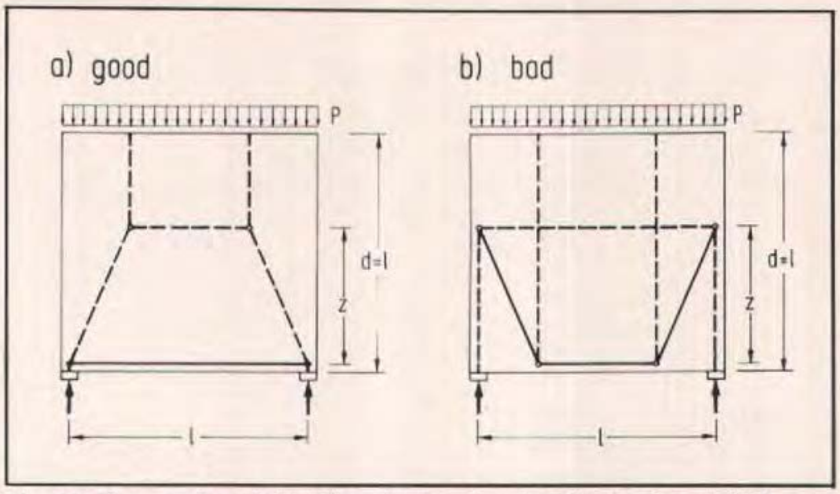


Fig. 14. The good model (a) has shorter ties than the bad model (b).

Figure 4.6: Good (a) and bad (b) strut and tie model. Courtesy to [42].

4.1.3 Topology optimization

Topology optimization is a computational design method that determines the most efficient material distribution within a given design space based on loads, boundary conditions, and performance objectives [36]. It removes unnecessary material to achieve lightweight yet structurally effective geometries. While widely used in engineering design, topology optimization can also be applied to 3D-printed concrete (formwork) designs. However, printing constraints such as minimum thickness, continuity, and overhang limits often need to be integrated into the optimization, along with post-processing strategies, to transform optimized results into printable designs.

Vantyghem et al. [44] created a post-tensioned concrete girder using topology optimization and 3D concrete printing to reduce material use, see Fig. 4.7. The design was refined with finite element analysis, printed in segments, reinforced, and post-tensioned. Experimental testing confirmed its structural performance, showing good agreement with predictions. Their work demonstrates that combining topology optimization with 3D printing can produce efficient concrete structures while highlighting challenges in printing, assembly, and reinforcement integration.

Figure 4.7: Topology optimized 3D concrete printed bridge. Courtesy to [44].

An example of an post optimization strategy to get a printable design can be found in Versteege's master's thesis [45], in which a computational procedure is developed that integrates topology optimization with automated manufacturing for cable reinforced 3D concrete printing, aiming to bridge structural design and fabrication. It begins with a density-based topology optimization tailored to the behavior of extrusion-based 3D printed concrete, producing materially efficient structural layouts. Once an optimized geometry is obtained, the method includes automated print path generation that translates the continuous topology into a printable path within the geometry boundaries, reducing the need for extensive post-processing. The print path algorithm incorporates practical constraints such as continuity (see Fig. 4.8), no self-intersection, and alignment with stress directions to ensure manufacturability. By linking the optimized topology directly to a feasible print route, the workflow moves beyond conceptual optimization toward a design-to-fabrication strategy for 3D concrete printing.

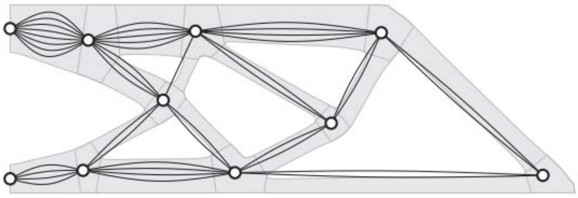


Figure 4.8: Continuous print path generation based on an Eulerian circuit. Courtesy to [45].

Another example of topology optimization, incorporating connectivity into the design process and applied to a chair, is presented by Bi et al. [46]. The chair is split in the middle to make it suitable for 3D printing. Fig. 4.9 in the paper shows the topology- optimized result, and Fig. 4.10 shows the printed chair from that optimized design.

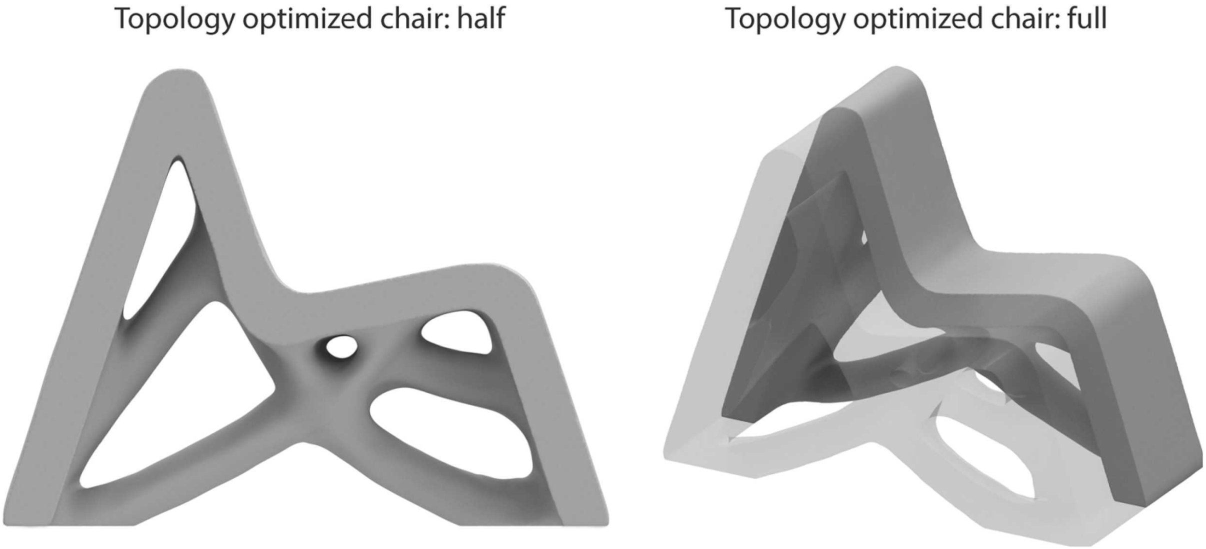
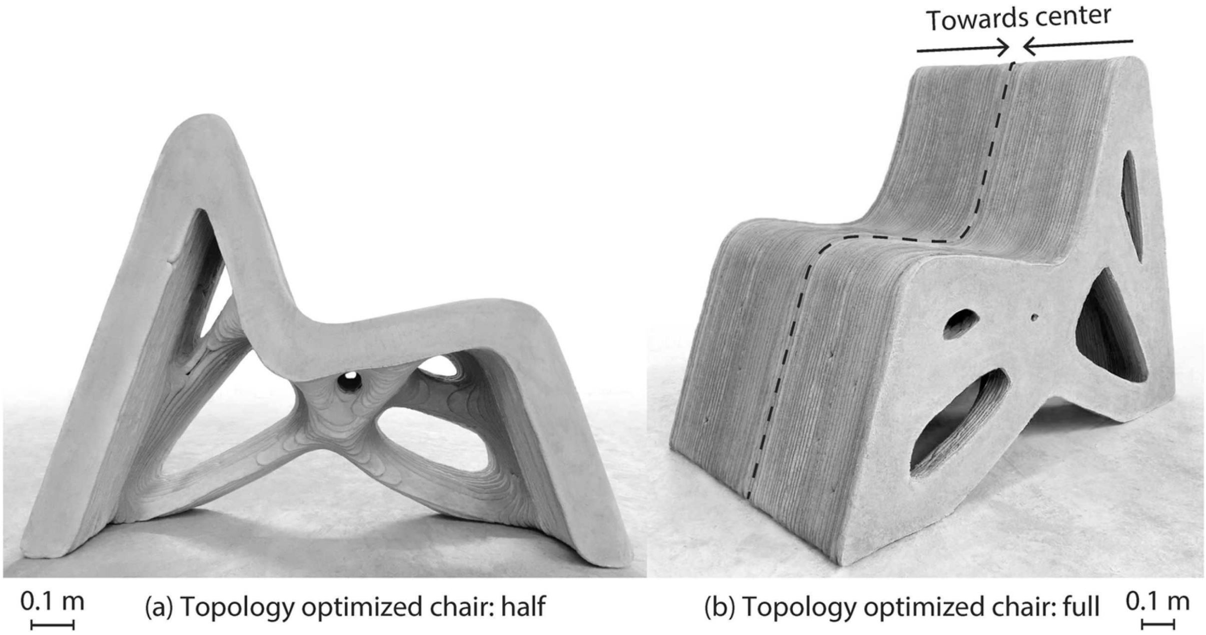


Figure 4.9: Topology optimization result for chair. Courtesy to [46].



(a) Topology optimized chair: half

(b) Topology optimized chair: full

Figure 4.10: 3D concrete printed topology optimized chair. Courtesy to [46].

4.2 Development Steps for 3D-Printed Concrete Formwork

Developing (minimum) 3D-printed concrete formwork requires a systematic approach that integrates material behaviour, geometric design, structural verification, and process planning. While the sequence of steps may vary depending on project requirements, and additional considerations may be necessary for specific applications, the following framework provides an overview of the core stages encountered when designing 3D-printed concrete formwork systems.

4.2.1 Functional Requirements and System Definition

The design process begins by establishing the functional requirements of the formwork within the overall structural system. This includes defining the intended geometry, dimensional tolerances, surface quality requirements, and the role of the formwork in the final structure. A critical early decision concerns whether the formwork will function as fully stay-in-place (permanent formwork), removable formwork, or integrated formwork that contributes to structural performance, durability, fire resistance, or other functional domains.

This initial definition should explicitly address the requirements discussed in Chapter 2, particularly where the printed formwork is expected to provide integrated functionality beyond geometric definition alone. For example, if the formwork must contribute to fire resistance, this requirement directly influences material selection, wall thickness, and geometric detailing. Similarly, if the formwork acts as a protective durability layer, material permeability and interface design become primary concerns.

The functional requirements also determine boundary conditions for subsequent design stages, including exposure classification, required service life, structural load cases, and regulatory compliance pathways.

4.2.2 Material Selection and Characterisation

Once functional requirements are established, the material systems for both the printed formwork and the cast-in-place concrete must be defined. For the printed element, this involves selecting a printable mortar or concrete with known rheological properties. Otherwise, the material should be characterised through standardised testing to establish its mechanical properties, shrinkage behaviour, permeability, and durability indicators.

In parallel, the properties of the concrete used for casting must be specified, including density, workability, setting time, and hydrostatic pressure characteristics. This characterisation forms the basis for predicting the lateral pressure exerted on the formwork during filling, as discussed in Chapter 3.

Where integrated functionality is required, material selection must respond to the specific performance domain. For fire resistance, this may include specification of aggregate type, fibre content (particularly polypropylene fibres for spalling mitigation), or enhanced binder systems. For durability applications, low-permeability mixes or surface densification strategies may be required. For acoustic performance, lightweight aggregates or porosity-enhancing admixtures may be considered.

Material selection should also account for compatibility between the printed and cast materials, particularly with regard to shrinkage differentials, thermal expansion coefficients, and chemical compatibility, all of which influence long-term interface performance.

4.2.3 Casting Approach and Process Definition

At this stage, the production scenario must be determined, specifying whether the formwork will be filled after full hardening, after partial hardening, directly while still fresh, or incrementally during the printing process. This choice fundamentally influences both the available design freedom and the expected failure mechanisms.

Casting after full hardening provides maximum formwork capacity and allows for conventional reinforcement placement and concrete pouring sequences. However, it may result in reduced interface bond strength and therefore limits opportunities for material integration between printed and cast layers.

Casting into partially hardened formwork requires careful control of the formwork's mechanical state and precise timing of the casting operation. This approach can improve interface bonding, but introduces process complexity and requires a reliable prediction of early-age strength development.

Casting while the formwork is still fresh, or layer-by-layer casting during printing, offers the potential for maximum interface integration and composite action, but places severe constraints on formwork geometry, wall thickness, and printing speed. This approach is highly sensitive to lateral pressure and requires robust mitigation strategies as outlined in Section 3.3.

The chosen casting approach should be documented with clear process parameters, including maximum waiting times, minimum strength thresholds (if applicable), and quality control checkpoints.

4.2.4 Load Model and Pressure Prediction

A critical step in formwork design is the establishment of a load model that accurately represents the forces acting on the formwork during casting. As discussed in Section 3.1, the lateral pressure exerted by fresh concrete may range from full hydrostatic pressure to significantly reduced values depending on casting rate, concrete rheology, and setting behaviour.

For conservative design or where material setting behaviour is uncertain, full hydrostatic pressure should be assumed. For more material-efficient designs, reduced pressure models such as those specified in DIN 18218 or derived from empirical models (Gardner, Proske, or similar) may be applied, provided that the assumptions underlying these models are satisfied and process parameters are strictly controlled.

The load model should account for all relevant process parameters, including:

- Casting rate
- Layer thickness (of casted concrete in batches)
- Waiting time between casting stages
- Ambient temperature and concrete temperature
- Concrete density
- Initial and final setting times

In addition to hydrostatic pressure during casting, the formwork may be subjected to significantly different load cases during production (printing and curing), handling and transportation, and in its final in-service state. Each of these load cases should be explicitly considered, checked, and adopted for in the design if needed.

4.2.5 Geometrical Design and Structural Optimization

Based on the predicted loads and functional requirements, the geometry of the formwork is designed. This stage integrates the optimization strategies discussed in Section 4.1, including size optimization (adjustment of wall thickness and cross-sectional dimensions), shape optimization (introduction of corrugations, ribs, curvature, ect.), and topology optimization (reconfiguration of internal layout or void distribution).

The geometric design must assess not only global strength and stiffness, but also local critical zones where stress concentrations, geometric discontinuities, or weak interlayer bonds may govern behaviour. These zones include curves, notches, openings, corners, and regions where reinforcement anchorage or post-tensioning tendons are located.

Depending on the formwork geometry and loading conditions, a range of failure mechanisms may be relevant, including:

- Flexural failure of wall segments under lateral pressure
- Local tensile cracking or punching at supports
- Shear failure along potential slip planes
- Interlayer delamination or bond failure between printed layers
- Buckling or instability of thin-walled regions
- Hydrostatic rupture or bursting at weak sections

Each of these failure modes should be explicitly checked using appropriate analytical models, finite element analysis, or empirical design rules. Where relevant code provisions exist =, these should be applied. Where no guidance is available, conservative assumptions or validation through physical testing may be necessary.

The design should also incorporate the mitigation strategies outlined in Section 3.3, including corrugation, ribbing, local thickening, curvature-induced stiffening, ect. to reduce the effective hydrostatic pressure.

4.2.6 Durability, Fire Safety, and Long-Term Performance

The design must be evaluated in terms of durability and expected service life, following the principles outlined in Section 2.2.2. This includes assessing the quality and long-term stability of interlayer bonding, the permeability and transport properties of the printed material, potential weak planes at layer interfaces, and exposure to environmental actions such as carbonation, chloride ingress, freeze–thaw cycles, or moisture cycling.

Where the formwork is exposed to aggressive environments, additional protective measures may be required, such as surface coatings, densification treatments, increased cover thickness in critical regions, or the use of more closed (less permeable) print structures. The interface between the printed formwork and the cast concrete is a particular vulnerability and should be explicitly considered in durability assessments.

If fire resistance is required, the design must address the performance criteria discussed in Section 2.2.1, including load-bearing capacity (R), integrity (E), and insulation (I). This may involve specification of minimum cover thickness, material composition (e.g., inclusion of polypropylene fibres for spalling mitigation), geometric detailing to protect reinforcement, or the design of the printed layer as a sacrificial fire-protective shell.

For acoustic, aesthetic, or other integrated functions identified in Chapter 2, corresponding verification or design guidance should be followed as applicable.

4.2.7 Validation, Documentation, and Iteration

Once all design stages have been completed, the formwork system should be comprehensively validated against the original functional requirements and applicable design standards. This validation may include analytical verification, numerical simulation, physical testing of representative elements, or combinations thereof.

All assumptions, material properties, load models, failure modes, process parameters, and design decisions should be clearly documented to enable construction execution, quality control, and future assessment or modification. Where novel approaches or untested configurations are employed, documentation should explicitly identify areas of uncertainty and any additional monitoring or verification measures implemented.

Design iteration may be necessary to resolve conflicts between competing requirements, for example, between structural efficiency (minimising material) and durability (requiring adequate cover and section robustness). Such trade-offs should be explicitly considered and resolved based on project-specific priorities and risk assessment.

4.2.8 Summary

The development of 3D-printed concrete formwork is not a linear process but rather an iterative, multi-disciplinary design task that requires integration of material science, structural engineering, process planning, and functional performance assessment. The framework presented here provides a structured approach to this complexity, linking the technical content of previous chapters into a coherent design methodology. Successful implementation depends on careful attention to each stage, rigorous validation, and a willingness to adapt the approach as new challenges or opportunities emerge during the design process.

Chapter 5

Selection of Realised Projects

In this chapter, we present a selection of realized demonstrators and projects that illustrate the current possibilities and applications of 3D concrete printed formwork. For each example, we provide relevant background information to contextualize the design, construction, and technological approach. It should be noted that this selection is by no means exhaustive, but rather highlights a range of notable implementations.

Following this overview of completed projects, the chapter explores ongoing developments in laboratory settings. This includes experimental work and innovative fabrication methods, some of which extend beyond 3D concrete printing. These examples provide insight into emerging techniques, hybrid processes, and new approaches to digital construction that are being investigated in parallel with 3DCP.

5.1 Realised projects

5.1.1 Bended Ribbed Slab

Figure 5.1: Parking garage entrance.

Location: Germany
Formwork material: 3D printed concrete
Integrated functions:
Production strategy: Off-site formwork production, on-site casting and assembly procedure. (See Fig. 5.2).
Optimization approach: Ribbed slab floor oriented along the isostatic bending moment lines.

Figure 5.2: Bauminator bended slab. Taken from [47].

Project description

This project focuses on the development of an optimized ribbed concrete floor slab designed for efficiency, sustainability, and on-site assembly. The slab incorporates 3D-printed concrete voids, strategically placed to reduce material usage while maintaining structural performance. By leveraging additive manufacturing, the design achieves lightweight yet robust floor elements with tailored geometries that would be difficult to produce using traditional methods.

The slabs are prefabricated in modular components and assembled directly on-site, allowing for faster construction times and reduced labor costs. This approach not only minimizes concrete consumption but also enhances the sustainability and adaptability of building floors. The integration of 3D printing with conventional concrete casting demonstrates a hybrid construction method that combines precision, efficiency, and scalability for modern construction projects.

5.1.2 Parking Garage Entrance Nördlingen

Figure 5.3: Parking Garage Entrance Nördlingen. Taken from [48].

Project details

Location: Nördlingen, Germany
Formwork material: 3D printed concrete
Integrated functions: -
Production strategy: Off-site formwork production, on-site casting and assembly procedure (see Figs. 5.4, 5.5).
Optimization approach: Force flow

Figure 5.4: Placement of reinforcement around the lost formwork elements. Taken from [49].

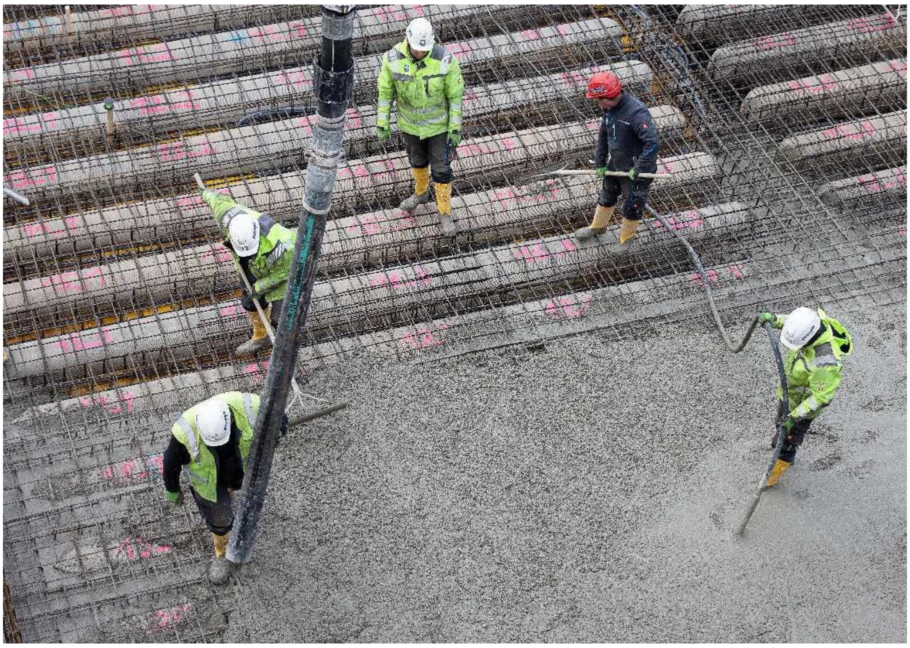


Figure 5.5: Casting of the concrete slab. Taken from [49].

Project description

The Concrete Lightweight Slab Nördlingen (2022) is an innovative reinforced concrete ceiling developed through a collaboration between industry and research. Designed by Lattke Architekten and engineered by EIGNER Bauunternehmung GmbH in cooperation with the Institute of Structural Design at Graz University of Technology, the project demonstrates how material-efficient construction can significantly reduce environmental impact [48].

The slab spans the entrance of an underground parking garage and employs 168 3D-printed concrete segments that act as formwork for 48 optimized void formers. These voids follow the internal force flow of the structure, allowing concrete to be used only where structurally necessary. Combined with a cement-reduced concrete mix, this approach achieves a reduction of approximately 35% in CO_2 equivalents compared to conventional reinforced concrete slabs, while maintaining standard load-bearing capacity and compliance with existing building regulations [48].

5.1.3 Skylight Roof in Lunz am See

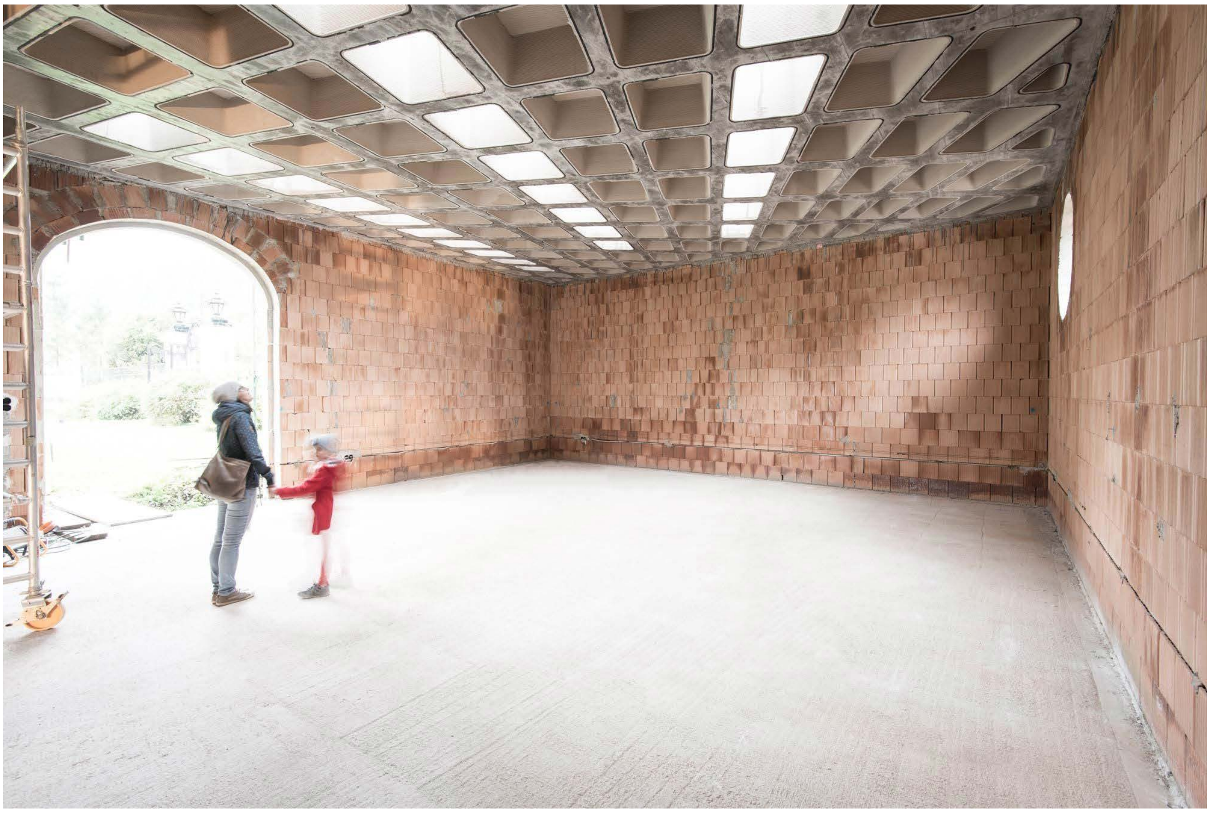


Figure 5.6: Enter Caption. Taken from [50].

Project details

Location: Lunz am See, Austria
Formwork material: 3D printed concrete
Integrated functions: Concrete cover (and sky light/aesthetics)
Production strategy: Off-site formwork production, on-site casting and assembly procedure (see Figs. 5.7, 5.8).
Optimization approach: Force flow

Figure 5.7: On-site assembly. [51].

Figure 5.8: Sky lights are placed in the slab. [51].

Project description

Hansemann et al. [52] developed a digitally integrated design and production method for an optimized reinforced concrete ceiling using 3d concrete printing. A single parametric model formed the basis for the entire workflow, linking slab geometry, rib layout, structural analysis, and reinforcement planning. From this model, the geometry of thin-walled void elements was directly derived and optimized for both material efficiency and stability during casting [52].

The voids function as lost formwork and were designed to withstand self-weight and fresh concrete pressure, with wall thicknesses and corner radii informed by structural simulations. A total of 130 unique void elements were fabricated using robotic 3D concrete printing without the need for conventional moulds. Printing strategies such as cross-ply layering and integrated overhangs were incorporated to improve structural integrity, handling, and on-site placement [52].

Production planning also addressed logistics, with element dimensions adapted to pallet-based transport and digitally organised for correct sequencing on site. The voids were placed on the slab formwork together with reinforcement and cast with in-situ concrete, resulting in a composite slab system that demonstrates the feasibility of a fully parametric, production-oriented construction approach while also contributing to reduced material and CO_2 use [52].

5.1.4 Integrated 3D-Printed Concrete Arch Bridge (China)

Figure 5.9: 3D Concrete printed bridge at the campus of Hebei University of Technology, China. The bridge design is inspired by the Anji Bridge, located in Zhaoxian county (built around 581-618). Taken from [53].

Project details

Location: China (located at the campus of Hebei University of Technology)
Formwork material: 3D printed concrete (containing basalt fibre)
Integrated functions: Structural and durability
Production strategy: Off-site formwork production, on-site casting and assembly procedure. (See Fig. 5.10).
Optimization approach: Compression arch (catenary line). (See Fig. 5.11).

Figure 5.10: Production strategy. Taken from [27].

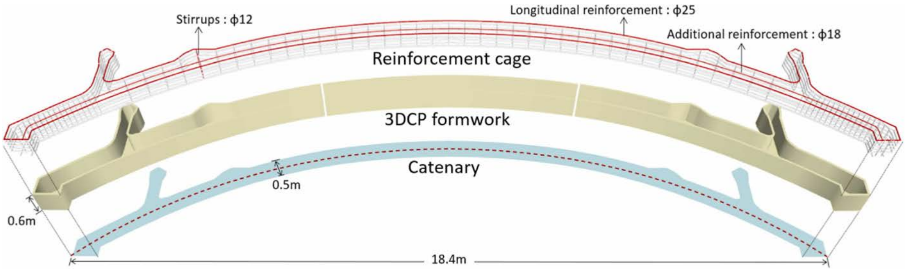


Figure 5.11: Bridge following a catenary line, inspired by the Anji Bridge, located in Zhaoxian county, China. Taken from [27].

Project description

Guan et al. [27] demonstrated the use of 3DCP formwork for a 18 meter spanning bridge at the campus of Hebei University of Technology, China (See Fig. 5.12). The (reinforced) concrete arch bridge demonstrates how 3D printed concrete can be fully integrated as permanent/stay-in-place formwork within a structural system rather than acting as a lost formwork. In the project, the geometry, material development, reinforcement strategy, and construction sequence were co-designed so that the printed shell simultaneously defined the structural form, enabled efficient casting, and contributed to long-term performance. Material characterization showed that the printed concrete met the rheological and mechanical requirements for large-scale formwork, while durability studies explicitly addressed layer-induced anisotropy, acknowledging its implications for carbonation and freeze–thaw resistance. These material-level insights were directly reflected in the structural design and detailing, particularly in thickness, reinforcement placement, and load transfer mechanisms. The printed formwork was designed to work together with the cast-in-place concrete, relying on sufficient interfacial bonding rather than mechanical connectors alone. Full-scale fatigue testing under millions of load cycles demonstrated that the integrated system could sustain realistic service conditions without degradation of structural integrity. Overall, the project illustrates a holistic approach in which 3D printing, material science, and structural engineering are tightly coupled, enabling the formwork to become a functional and durable part of the final bridge structure rather than a 'lost' element.

Figure 5.12: Enter Caption. Taken from [27].

5.1.5 Noise Barrier Foundation Blocks

Figure 5.13: 145 pieces of printed formwork by Saint Gobain Weber Beamix, for the widening of A9 highway. The blocks are the foundation for a noise barrier wall. Taken from [54].

Project details

Location: Highway A9, The Netherlands
Formwork material: 3D printed concrete
Integrated functions: - (Lost/stay-in-place formwork)
Production strategy: Off-site formwork production, on-site casting (see Figs. 5.14, 5.15).
Optimization approach: -

Figure 5.14: Placement of 3D concrete printed foundation block lost/stay-in-place formwork. Taken from [54].

Figure 5.15: Cast foundation blocks. Taken from [54].

Project description

The project employs 145 3D-printed formwork units to form the foundations of the noise barrier walls constructed as part of the A9 highway widening. These formworks are prefabricated off-site and subsequently assembled and cast on-site (see Fig. 5.14) [54].

5.1.6 Mushroom Column–Supported Canopy

Figure 5.16: Mushroom column–supported canopy, made by Riedel Bau Firmengruppe, in collaboration with TU Darmstadt. Taken from [55].

Project details

Location: Schweinfurt, Germany
Formwork material: 3D printed concrete
Integrated functions: -
Production strategy: Off-site formwork production, on-site casting and assembly (see Fig. 5.17).
Optimization approach: Force flow

Figure 5.17: Assembly on-site. Taken from [55].

Figure 5.18: View from below. Taken from [55].

Project description

Researchers at TU Darmstadt developed a full-scale demonstrator for a 3D-printed, topology-optimized concrete slab with a five-meter span, supported by a mushroom-shaped central column. The key innovation lies in the fully additively manufactured formwork, which precisely follows the optimized geometry of ribs, curves, and force paths. Parametric models guided the design, enabling simulations of force flow and material efficiency before printing. The printed formwork was reinforced with steel and cast monolithically on site, producing a structurally sound slab in a single operation. Additive manufacturing allowed geometries that would be difficult or impossible with conventional formwork, particularly for curved and material-efficient shapes. The process also reduced concrete usage and CO_2 emissions by placing material only where structurally necessary. Students were directly involved, designing, simulating, and assembling the formwork at full scale, gaining hands-on experience with modern digital construction techniques. Load tests and material analyses verified the slab's performance and provided data for future research and standards. The project demonstrates how digital design and 3D printing can merge seamlessly with structural concrete construction. Overall, it showcases a pathway toward more efficient, innovative, and sustainable concrete structures [55].

5.1.7 Telecommunication mast

Figure 5.19: XtreeE telecommunication mast. Taken from [56].

Project details

Location: France
Formwork material: 3D printed concrete
Integrated functions: Durability

Production strategy: Off-site formwork production, on-site casting and assembly.
Optimization approach: -

Figure 5.20: XtreeE telecommunication mast project. Taken from [56].

Project description

In the XtreeE telecommunication mast project [56], a 12- metre tall concrete support structure was fabricated by 3D printing concrete formwork segments which were then filled (cast) with conventional concrete to create a solid structural column, which was eventually post-tensioned. Six printed formwork elements were produced and assembled on site, with the printed formwork remaining in place as a protective skin around the cast concrete, see Fig. 5.20. This approach simplified manufacturing, integrated multiple functional features (such as antenna and plant supports) into the geometry, and produced a durable mast capable of resisting earthquake and cyclone loads while being visually adaptable to the landscape.

5.1.8 Nijmegen Bicycle Bridge

Figure 5.21: 3D concrete printed bicycle bridge in Nijmegen. Taken from [57].

Project details

Location: Nijmegen, The Netherlands
Formwork material: 3D printed concrete
Integrated functions: - 'Lost' formwork
Production strategy: Off-site formwork production, on-site casting and assembly procedure.
Optimization approach: Post-tensioned bridge.

Project description

The 3D printed concrete bridge in Nijmegen was designed with a strong emphasis on utilizing the printed material structurally, without relying on traditional casting. The bridge is composed of 3D printed concrete segments that are post-tensioned to form the main span, ensuring that the printed concrete primarily carries compressive loads. The printed cocnrete was only applied as formwork where it was structurally unavoidable or more efficient. Two primary elements were designed as formwork: the beginning and end zones of each bridge segment where the post-tensioning tendons are anchored (see Fig. 5.22), and the columns below each bridge segment (see Fig. 5.23). The begin and end elemetns of each bridge section were casted of-site and later assembled on-site. The collumns below were casted and assembled on-site.

Figure 5.22: Reinforced anchor blocks were cast in 3D-printed formwork, and post-tensioning of tendons.

Figure 5.23: Assembly of printed formwork for bridge columns, with temporary supports, just before casting, courtesy De Gelderlander (Paul Rapp).

5.1.9 Tor Alva

Figure 5.24: Tor Alva. Taken from [58], courtesy to Birdviewpicture / Nova Fundaziun Origen.

Project details

Location: Mulegns, Switzerland
Formwork material: 3D printed concrete
Integrated functions: Aesthetics (see Fig. 5.25), structural.
Production strategy: Off-site formwork production, off-site casting, and on-site assembly procedure.
Optimization approach: Post-tensioned columns that are partially reinforced and cast.

Figure 5.25: Production of one branch, taken from [59]

Project description

Tor Alva is a 30-meter-tall 3D-printed structure composed of 41 elements, each designed to serve both structural and aesthetic functions. Shear capacity is provided by reinforcement placed between the printed layers during the 3D concrete printing process, enabling effective force transfer across the layered material (b in Fig. 5.26). Longitudinal reinforcement is inserted into continuous hollow channels within the printed columns and fixed in place by grouting with cast concrete, creating a fully load-bearing composite element. Finally, unbonded stainless-steel post-tensioning rods running through the column cores clamp the segments together, enhance structural continuity, and limit cracking under service loads. It is the first multi-storey building using load-bearing 3D-printed columns and is designed for circularity, with planned monitoring, disassembly, and reuse at another site [59].

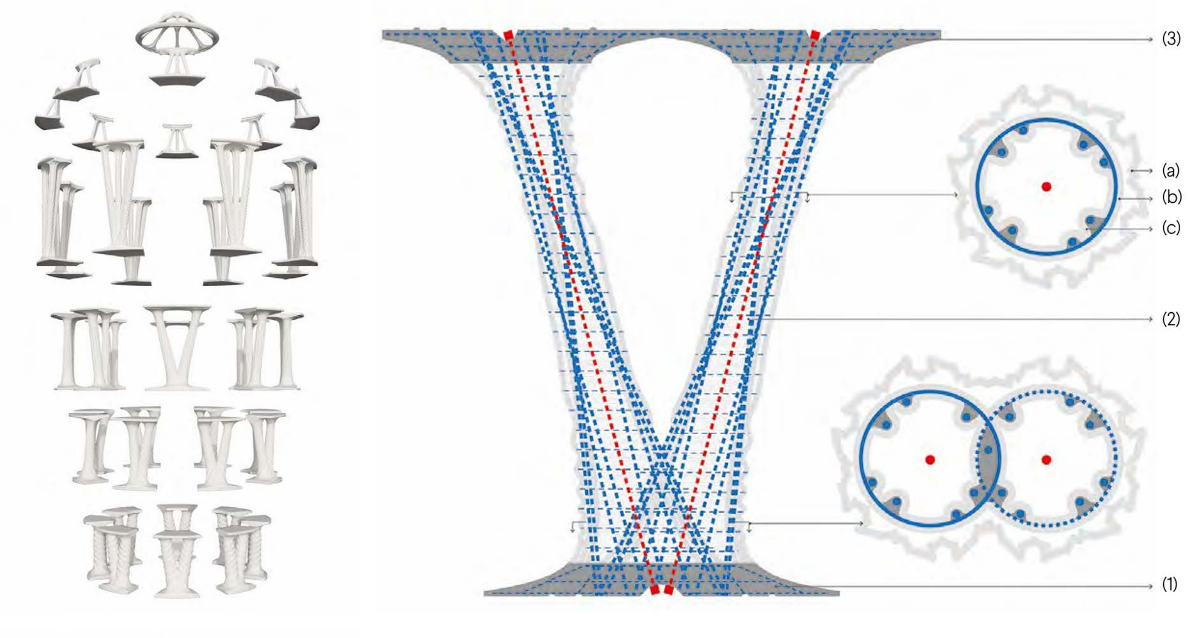


Figure 5.26: Left: Final design of Tor Alva composed of 41 bespoke components assembled using dry shear-keyed connections. Right: Diagram of a branching column component showing its three-part segmentation: (1) precast base segment; (2) load-bearing 3D-printed concrete column with (a) an outer layer providing ornamented texture, (b) a middle layer accommodating shear reinforcement, and (c) an inner layer forming hollow channels for longitudinal reinforcement; and (3) precast capital segment, taken from [59].

5.2 Academic/industry prototypes

5.2.1 Digital nervi

The Digital Nervi demonstrator illustrates the use of 3D-printed concrete as permanent formwork in the realization of lightweight ribbed floor systems [39]. Inspired by isostatic slab principles, the slab geometry was derived through performance-based design to efficiently align material distribution with structural load paths. The optimized rib network was fabricated using large-scale 3D-printed concrete formwork, into which conventional reinforcement and cast concrete were subsequently placed to complete the structural system. The demonstrator validated that complex, non-standard ribbed geometries can be manufactured without traditional temporary formwork while achieving effective composite action between the printed shell and the infill concrete. Structural testing and analysis confirmed that the slab met stiffness and load-bearing requirements with a significant reduction in concrete volume, highlighting the potential of digitally designed, 3D-printed permanent formwork to enable materially efficient and architecturally expressive floor structures [39].

Figure 5.27: Enter Caption. Courtesy to [39].

5.2.2 Fabrication Approaches for Optimized Formwork

Ismail et al. [60] investigated how context-driven formwork design can enable structurally efficient, low-carbon, and scalable concrete construction across diverse economic and material contexts. Rather than treating concrete as a uniform industrial system, the research explores how locally available materials, fabrication methods, and levels of technological access can inform the design of optimized concrete elements. Through a series of lab-based beam prototypes, different formwork strategies are evaluated in terms of geometric freedom, embodied carbon reduction, accessibility, and reusability. Together, these case studies demonstrate how tailored formwork systems can support materially efficient concrete structures while responding to regional constraints in resources, skills, and infrastructure.

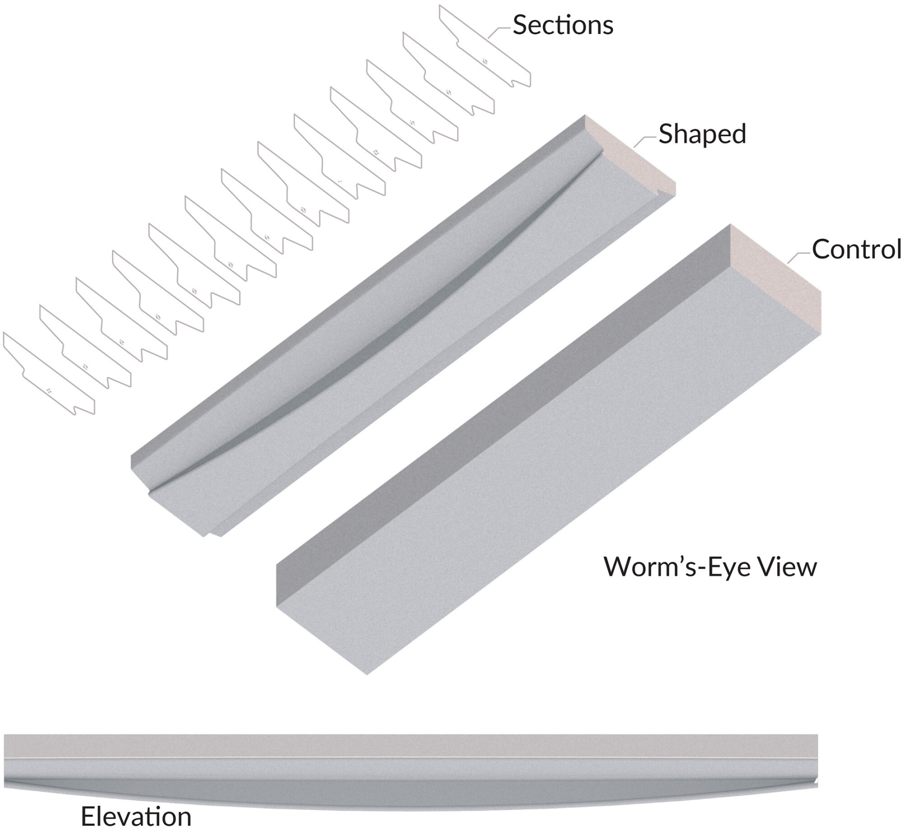


Figure 5.28: Optimised design for a beam loading in bending (designed for clay variant, but similar type of design for bamboo and CNC milled version). Courtesy to [60].

CNC milled expanded polystyrene (XPS) forkwork

Standard XPS insulation sheets were first laminated together with adhesive to create a solid block large enough for the beam geometry. The optimized beam shape was then translated into a digital 3D model and toolpaths were generated for CNC milling. Using a CNC router, material was subtractively removed from the XPS block to produce the variable T-shaped form with smooth single- and double-curved surfaces. The milled XPS pieces were assembled and sealed as needed to act as lightweight, water-resistant concrete formwork, allowing accurate casting of the optimized beam geometry and enabling reuse of the formwork for multiple pours, see Fig. 5.29 [60].

Figure 5.29: CNC milled expanded polystyrene formwork. Taken from [60].

Curved bamboo formwork

A wooden frame defining the beam's shape was first fabricated (CNC-cut), see Fig. 5.30. Small-diameter bamboo strips were soaked in water overnight to increase flexibility, then hand-bent and fixed onto the frame to form the curved geometry. The bamboo itself was not watertight; instead, a thin fabric (cotton jersey) was stretched inside the bamboo to contain the concrete. Reinforcement was placed inside the lined form, after which the concrete was poured, using the flexible bamboo to achieve the optimized curved shape [60].

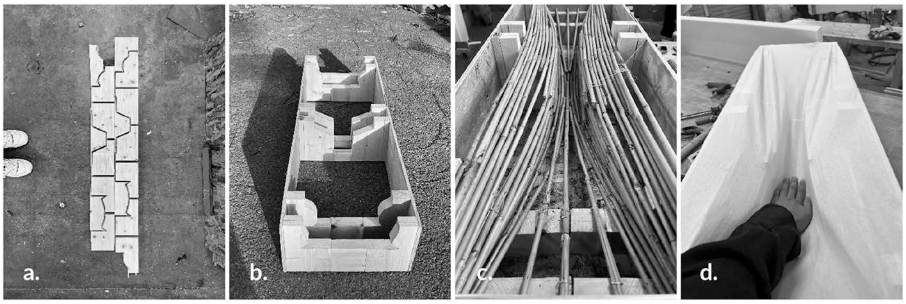


Figure 5.30: Curved bamboo formwork. Taken from [60].

3D printed clay formwork

The beam geometry was first optimized and translated into a CAD model adapted to the limits of clay 3D printing. Test prints were used to determine allowable surface angles, shrinkage, and strength after firing, which informed the final formwork design. The formwork was then divided into printable modules and scaled up to compensate for shrinkage during drying and firing. Each module was fabricated using layer-by-layer clay extrusion with a robotic 3D printer, then dried and lightly bisque-fired for strength. The fired modules (see Fig. 5.31) were assembled on a simple wooden base with end supports, wrapped in a thin plastic sheet to protect the clay from moisture, and used as reusable formwork for casting the concrete beam [60].

Figure 5.31: 3d printed clay formwork. Taken from [60].

5.2.3 Nervi floor printed with clay.

In the study performed by Baritakis et al. [61], a topology-optimised ribbed slab was fabricated using 3D-printed clay bodies as temporary formwork. Two strategies were explored, with the final approach involving individual clay volumes placed inside a wooden mould, enabling the ribs and cast concrete top plate to be poured simultaneously, see Fig. 5.32. The clay was kept moist during the process to prevent

Figure 5.32: Rib slab made with clay formworks. Taken from [61].

shrinkage and deformation, and after the concrete hardened, the clay formwork was easily removed and could be reused. This method allowed the realization of complex, optimized rib geometries while ensuring dimensional accuracy and structural integrity.

5.2.4 Plastic Printed Ribbed Slab

The paper by Burger et al. [62] presents a material- and structurally-optimised ribbed concrete floor slab produced using large-scale 3D-printed plastic formwork. The ribs are placed along principal bending moments trajectories to minimise concrete usage while maintaining stiffness and load-bearing capacity. The 3D-printed formwork serves as a removable mould for casting the slab, enabling a complex optimised geometry. The production steps can be seen in Fig. 5.33.

Figure 5.33: "Fabrication steps of the prototype. (a) 3D Printing bottom 35 mm, (b) placing slab reinforcement, (c) placing rib reinforcement cages, (d) 3D printing cap formwork, (e) 3D printing column-slab transition, (f) casting of rib formwork, (g) demoulding of ribs, (h) cast and demoulded ribs, (i) complete slab prototype after casting of the solid part of the slab" [62]. Taken from [62]

Appendix A

Systematic literature review

Table A.1: Overview of 3D-Printed Concrete Formwork Research

Paper ID	Title	Demonstrators	Optimization Strategy	Integrated Formwork	Formwork Stability	Key Challenges	Relevance
1 [37]	Design optimization and assessment of stay-in-place 3D printed concrete formwork for slabs	1	1	0	0	0	1
2 [63]	Displacement monitoring of modular formwork in sustainable concrete fabrication using 3D laserscanning	0	0	0	1	0	1
3 [26]	Mechanical properties of 3D printed concrete irregular structural formwork: Experimental study and finite element analysis	0	0	0	1	0	1
4 [64]	A Systematic Review on Formwork Pressure Exerted by Self-Compacting Concrete: Parameters, Prediction Models, and Advances in Monitoring Technologies	0	0	0	1	1	1
5	Structural behavior of steel reinforced concrete composite columns with ECC permanent formwork: numerical simulation and parametric study	0	0	0	0	0	0
6	Damage evolution and failure warning in early-age flexible-formwork concrete for underground support	0	0	0	0	0	0
7 [65]	Flexural behavior of stay-in-place load-bearing 3D-printed concrete formwork for ribbed slabs	1	1	1	0	0	1
8 [66]	Feasibility study of 3D-printed rubberized concrete as a permanent formwork: mechanical properties, interlayer interface and durability	0	0	1	0	0	1
9 [15]	Effects of 3D-printed concrete permanent formwork on the flexural behavior of reinforced concrete beams: Experimental and analytical investigations	1	0	0	1	0	1

ID	Title	Dem.	Opt.	Int.	Form.	Key	Rel.
10	Design and construction of high-performance surface textures for precast concrete pavements: A flexible formwork and 3D printing assisted texturing method	0	0	0	0	0	0
11	Proposal for Monitoring Concrete Hardening Process Inside Steel Formwork Using Ultrasound	0	0	0	0	0	0
12	Failure analysis of flexible formwork concrete wall in gob-side entry and its control measures with roof cutting technology	0	0	0	0	0	0
13 [67]	Numerical investigation on shear behaviour of reinforced concrete beam with 3D printed concrete permanent formwork	0	0	1	1	0	1
14 [27]	Material and structural fatigue performance of 18 m-span reinforced arch structure manufactured by 3D printing concrete as permanent formwork	1	0	1	0	0	1
15	Dark discoloration in the lower wall area on exposed concrete surfaces - Interactions between formwork vibrations and concrete technology	0	0	0	0	0	0
16	Using 3D-Printed Formwork to Enable Controlled Crack Creation in Concrete Specimens	0	0	0	0	0	0
17 [68]	3D printed concrete composite slabs fabricated by prestress reinforced permanent formwork: Design, manufacturing, and performance	1	0	0	1	0	1
18	COMPARATIVE ANALYSIS OF QUANTITY TAKE-OFF IN CONCRETE, STEEL BARS AND FORMWORK IN APARTMENT BUILDINGS BASED ON CAD AND BIM METHODOLOGIES	0	0	0	0	0	0
19	Research on Integrated Technology of Overall Aerial Building Formwork Equipment and Concrete Placing-Boom	0	0	0	0	0	0
20 [69]	Load transfer behavior of 3D printed concrete formwork for ribbed slabs under eccentric axial loads	0	0	1	0	0	1
21 [70]	Flexural performance of concrete beams via 3D printing stay-in-place formwork followed by casting of normal concrete	1	0	0	1	0	1

ID	Title	Dem.	Opt.	Int.	Form.	Key	Rel.
22 [71]	Reusable Voxelized Magnetic Formwork: Fabricating complex concrete structures using materialized marching cubes	0	1	0	0	0	1
23 [72]	A Variable Fabric and Wire Formwork System for Complex Concrete Panels: Reusable formwork solution from digital design to fabrication of full-scale prototypes	1	0	0	1	0	1
24 [73]	Analysis and Application of Internally Pulled Steel Truss Prefabricated Concrete Formwork in Bull Leg Structures	1	0	0	0	0	1
25 [74]	Seismic performance of RC column surrounded by 3D printed concrete permanent formwork with short fiber	0	0	0	1	0	1
26 [39]	Digital Nervi: Performance-based design of lightweight isostatic ribbed slab with 3D-printed concrete formwork	1	1	1	1	0	1
27 [75]	Study on the compression performance of 3D printing concrete permanent formwork composite columns	0	0	1	1	0	1
28 [21]	EarthWorks: Zero waste 3D printed earthen formwork for shape-optimized, reinforced concrete construction	0	1	0	0	0	1
29 [76]	An investigation on enhancing the bonding properties of 3D printed concrete permanent formwork and post-casted concrete	0	0	1	1	1	1
30	The simulation analysis method for reinforced concrete tower climbing formwork construction under environmental factors	0	0	0	0	0	0
31 [77]	Additive Manufacturing of TPU and Hybrid TPU-PLA Formwork for Custom Repetitive Precast Concrete	1	1	0	0	0	1
32 [78]	Influence of curing conditions on the shrinkage behavior of three-dimensional printed concrete formwork	0	0	1	1	0	1
33 [79]	Flexural performance tests and numerical analysis of fabricated light-gauge steel reinforced foam concrete filled steel mesh formwork wallboards	0	0	0	0	0	1
34 [80]	Enhancing the flexural performance of concrete beams with 3D-printed UHP-SHCC permanent formwork via graded fiber volume fraction	0	0	1	0	0	1

ID	Title	Dem.	Opt.	Int.	Form.	Key	Rel.
35	Life Cycle Cost and Evaluation of Performance between Steel Formwork and Plastic Formwork in Concrete Structure Building	0	0	0	0	0	0
36 [81]	Seismic performance of Fe-SMA prestressed segmental bridge columns with 3D printed permanent concrete formwork	0	0	0	1	0	1
37 [82]	Numerical simulation analysis on compressive performance of composite columns with 3D printed concrete permanent formwork	0	0	1	1	0	1
38 [83]	Analytical investigation on the structural performance of RC column with 3D-printed concrete permanent formwork	0	0	1	1	0	1
39 [84]	Digital Fabrication of Ribbed Slabs with Post-Tensioned 3D Printed Concrete Formwork	1	0	0	0	0	1
40	Evaluation of bending creep performance of laminated veneer lumber (Lvl) formwork for the design of timber concrete composite (tcc) structures	0	0	0	0	0	0
41 [85]	Axial performances of the steel rebar reinforced column confined by the steel cable reinforced 3D concrete printing permanent formwork	0	0	1	1	0	1
42 [86]	Leveraging clay formwork 3D printing for reinforced concrete construction	0	0	0	1	0	1
43 [60]	Concrete and Development: Context-driven Formwork Design for Scalable, Accessible and Low-carbon Concrete Structures	1	1	0	0	0	1
44 [87]	Structural Behaviours of a Concrete Façade Panel Prototype Facilitated by 3D Printed Formwork	0	0	0	1	0	1
45 [61]	3D-printed Clay Formwork for Topology-Optimized Concrete Elements	1	1	0	1	0	1
46 [88]	THE EFFECT OF PERMEABLE FORMWORK ON THE MECHANICAL PROPERTIES OF STEEL FIBER-REINFORCED CONCRETE	0	0	1	0	0	1
47	Research on axial compression performance of concrete columns with angle steel embedded in BMSCC stay-in-place formwork	0	0	0	0	0	0
48 [89]	Circular, zero waste formwork - Sustainable and reusable systems for complex concrete elements	0	1	0	0	0	1

ID	Title	Dem.	Opt.	Int.	Form.	Key	Rel.
49	Geometry optimization of steel formwork for steel–concrete composite slabs	0	0	0	0	0	0
50 [90]	The Effect of Curing Conditions on the Service Life of 3D Printed Concrete Formwork	0	0	1	1	0	1
51 [91]	Axial compressive behavior and design of semi-precast steel reinforced concrete composite columns with permanent ECC formwork	0	0	1	0	0	1
52 [92]	Shear behaviors of engineered cementitious composites to seawater sea-sand concrete (ECC-to-SSSC) interfaces cast using 3D-printed pre-grooving formwork: Mechanical properties, characterization, and life-cycle assessment	0	0	1	0	0	1
53 [93]	Cyclic behavior of unbonded post-tensioned precast segmental concrete columns fabricated by 3D printed concrete permanent formwork	0	0	1	1	0	1
54 [94]	Influence of SCC rheological properties on evolution of formwork pressure at various casting rates	0	0	0	1	0	1
55	Critical evaluation of cement-coated knitted lost formwork construction technology	0	0	0	0	0	0
56 [95]	3D-printed concrete permanent formwork: Effect of postcast concrete proportion on interface bonding	0	0	1	1	0	1
57 [96]	3D Printed concrete with coarse aggregates: Built-in-Stirrup permanent concrete formwork for reinforced columns	0	0	1	1	0	1
58 [97]	Mineral composites: stay-in-place formwork for concrete using foam 3D printing	0	0	1	1	0	1
59	Research on reasonable width design of flexible formwork concrete wall and tunnel surrounding rock control technology	0	0	0	0	0	0
60	Study on the Bearing Capacity of Steel Formwork Concrete Columns	0	0	0	0	0	0
61	Study on the Technology and Mechanism of Cleaning Architectural Aluminum Formwork for Concrete Pouring by High Energy and High Repetition Frequency Pulsed Laser	0	0	0	0	0	0

ID	Title	Dem.	Opt.	Int.	Form.	Key	Rel.
62 [98]	3D printed concrete as stay-in-place formwork: Mechanics during casting and curing	0	0	1	1	0	1
63 [99]	BioMatters The Robotic 3D-Printed Biodegradable Wood-Based Formwork for Cast-in-Place Concrete Structures	1	0	0	0	0	1
64	Circular Formwork: Recycling of 3D Printed Thermoplastic Formwork for Concrete	0	0	0	0	0	0
65 [100]	Utilizing Textiles as Integrated Formwork for Additive Manufacturing with Concrete	0	0	1	0	0	1
66 [62]	Design and fabrication of optimised ribbed concrete floor slabs using large scale 3D printed formwork	1	1	0	0	0	1
67 [101]	Bending behavior of composite beam with 3D printed concrete permanent formwork	0	0	0	1	0	1
68 [102]	Reusable inflatable formwork for complex shape concrete shells	1	0	0	0	0	1
69	Study on Formwork Erection Technology of Transverse Construction Joints in Cement Stabilized Structural Layer	0	0	0	0	0	0
70	Manufacture and Mechanical Properties of 3D Printing Cement Based Materials For Washable Formwork	0	0	0	0	0	0
71 [29]	Overcoming Environmental Stress Cracking of FDM 3D Printed Formwork for Counter-Pressure Casting of Concrete	0	0	0	1	0	1
72 [19]	3D Printed Formwork for Concrete: State-of-the-Art, Opportunities, Challenges, and Applications	1	0	1	1	1	1
73 [103]	Interfacial bonding properties of 3D printed permanent formwork with the post-casted concrete	0	0	1	1	0	1
74 [104]	Who built the timber formwork for fair-faced reinforced concrete?	0	0	0	0	0	1
75	Development and rationalization of formwork for curved concrete shells in the Japanese construction industry in the 1950s	0	0	0	0	0	0
76	Reusable Augmented Concrete System: Accessible Method for Formwork Manufacturing through Holographic Guidance	0	0	0	0	0	0
77 [105]	Mobile Additive Manufacturing: A Case Study of Clay Formwork for Bespoke in Situ Concrete Construction	1	0	0	0	0	1

ID	Title	Dem.	Opt.	Int.	Form.	Key	Rel.
78 [106]	Towards efficient concrete structures with ultra-thin 3D printed formwork: exploring reinforcement strategies and optimisation	1	1	1	1	0	1
79 [23]	Lateral formwork pressure for self-compacting concrete—a review of prediction models and monitoring technologies	0	0	0	1	0	1
80	Research Progress on Concrete Materials for 3D Printing and 3D Printing Formwork Technology	0	0	0	0	0	0
81 [107]	Structural design, digital fabrication and construction of the cable-net and knitted formwork of the KnitCandela concrete shell	1	0	0	0	0	1
82 [108]	Computational simulation of eccentrically loaded reinforced concrete walls formed with modular thin-walled permanent formwork system	1	0	1	0	0	1
83	Environmental and cost assessment of customized modular wall components production based on an adaptive formwork casting mechanism: An experimental study	0	0	0	0	0	0
84	Analysis of the construction of a reinforced-concrete free-form roof formwork and the development of a unit-construction method	1	0	0	0	0	0
85 [109]	Cocoon: 3D Printed Clay Formwork for Concrete Casting	1	0	0	0	0	1
86	Robotic Pellet Extrusion: 3D Printing and Integral Computational Design: Reinforced Thin Shell System Formwork for Sandwich Concrete Walls	0	0	0	0	0	0
87	Super high steel inclined column formwork support and concrete pouring technology	0	0	0	0	0	0
88	Molding Liquid Stone: A Computational and Experimental Mixed- Method Study of 3D Print Formwork for Interlocking Concrete Modules	1	0	0	0	0	0
89	Min-max: Reusable 3d printed formwork for thin-shell concrete structures: Reusable 3d printed formwork for thin-shell concrete structures	1	0	0	0	0	0
90 [110]	Seismic behavior of composite columns with steel reinforced ECC permanent formwork and infilled concrete	1	0	0	0	0	1

ID	Title	Dem.	Opt.	Int.	Form.	Key	Rel.
91 [111]	Mastering yield stress evolution and formwork friction for smart dynamic casting	0	0	0	1	0	1
92	Automated dimensional quality assessment for formwork and rebar of reinforced concrete components using 3D point cloud data	0	0	0	0	0	0
93 [112]	3D printing of curved concrete surfaces using Adaptable Membrane Formwork	0	0	0	0	0	1
94	A Fuzzy Multi-Criteria Decision Approach to Technology Selection for Concrete Formwork Monitoring	0	0	0	0	0	0
95 [113]	Rapid Composite Formwork: An Automated and Customizable Process for Freeform Concrete Through Computational Design and Robotic Fabrication	1	1	0	0	0	1
96 [62]	Design and Fabrication of a Non-standard, Structural Concrete Column Using Eggshell: Ultra-Thin, 3D Printed Formwork	1	1	1	0	0	1
97 [114]	Sustainable Reinforced Concrete Beams: Mechanical Optimisation and 3D-Printed Formwork	1	1	1	0	0	1
98 [115]	Printed Concrete as Formwork Material: A Preliminary Study	1	1	1	1	0	1
99 [116]	Digital to physical development of a reconfigurable modular formwork for concrete casting and assembling of a shell structure	1	1	0	0	0	1
100 [117]	3D-printed formwork for bespoke concrete stairs from computational design to digital fabrication	1	0	0	0	0	1
101	Response surface optimization of hot□pressing technology for light bamboo-based concrete formwork	0	0	0	0	0	0
102	Studying the Printability of Fresh Concrete for Formwork-Free Concrete Onsite 3D Printing Technology (CONPrint3D)	0	0	0	0	0	0
103 [118]	Automating the Digital Fabrication of Concrete Formwork in Building Projects: Workflow and Case Example	1	0	0	0	0	1
104 [119]	Dissolvable 3DP Formwork Water-Dissolvable 3D Printed Thin-Shell Formwork for Complex Concrete Components	1	0	0	0	0	1
105 [33]	3D-printed formwork for integrated funicular concrete slabs	1	1	1	0	0	1

ID	Title	Dem.	Opt.	Int.	Form.	Key	Rel.
106	Dissolvable 3D Printed Formwork Exploring Additive Manufacturing for Reinforced Concrete	1	0	0	0	0	0
107	BIM for temporary structures: Development of a Revit API plug-in for concrete formwork	0	0	0	0	0	0
108	Evolution of concrete/formwork interface in slipforming process	0	0	0	0	0	0
109	Development of the IoT-based monitoring system for scaffold shoring system of concrete formwork	0	0	0	0	0	0
110	Timber forms Stuttgart 21 - Model-based development and fabrication of a formwork system made of cross laminated timber for the production of reinforced concrete shells; Holzbau-Formen für Stuttgart 21: Modellbasierte Entwicklung und Fertigung eines Schalungssystems aus Brettsperrholz zur Herstellung von Schalentragwerken aus Stahlbeton	1	0	0	0	0	0
111	Automated constructability rating framework for concrete formwork systems using building information modeling	0	0	0	0	0	0
112	Deformation of a 3d printed polyurethane formwork during concrete pouring	0	0	0	0	0	0
113	Deformation of a 3D printed polyurethane formwork during concrete pouring	0	0	0	0	0	0
114 [120]	Large-Scale Additive Manufacturing of Ultra-High-Performance Concrete of Integrated Formwork for Truss-Shaped Pillars	1	1	1	0	0	1
115	A New Robotic Spray Technology for Generative Manufacturing of Complex Concrete Structures Without Formwork	0	0	0	0	0	0
116	Formwork-free, continuous, monolithic construction using concrete 3D printing: Feasibility study; Kontinuierliches, schalungsfreies Bauverfahren durch 3D-Druck mit Beton: Machbarkeitsuntersuchung	0	0	0	0	0	0
117 [121]	Fundamentals of development for adaptive formwork for free formed concrete shells and walls; Grundlagen zur entwicklung adaptiver schalungssysteme für frei geformte betonschalen und wände	1	0	0	0	0	1

ID	Title	Dem.	Opt.	Int.	Form.	Key	Rel.
118 [122]	Development and experimental validation of a lightweight Stay-in-Place composite formwork for concrete beams	1	1	0	0	0	1
119	Research on safety of high formwork supporting system of fastener-style steel pipe in concrete structures	0	0	0	0	0	0
120 [123]	Influence of formwork surface on the orientation of steel fibres within self-compacting concrete and on the mechanical properties of cast structural elements	0	0	1	0	0	1
121	Study on the design mechanism of the new types of suspended formwork supporting system in constructing steel reinforced concrete girder	0	0	0	0	0	0
122	Fibre composites pile rehabilitation and concrete formwork jacket - Concept development and finite element analysis	0	0	0	0	0	0
123 [124]	Formwork with variable geometry for concrete shells production technology	1	1	0	0	0	1
124 [125]	Mechanics analyzing of suspended formwork supporting system and research of decision system in constructing transfer storey structure of steel reinforced concrete	1	0	0	0	0	1
125	Fly ash for concrete for sliding shuttering technology - Special application for a gypsum silo; Flugasche für beton im gleitschalungsbau: Spezielle anwendung für das gipssilo	0	0	0	0	0	0
126	Formwork Innovation: Building an architectural concrete elevator core took comprehensive planning	0	0	0	0	0	0
127 [126]	Development and applications of the intrinsic model for formwork pressure of self-consolidating concrete	0	0	0	1	0	1
128	Reliability assessment of steel scaffold shoring structures for concrete formwork	0	0	0	0	0	0
129 [127]	Robotic Fabrication of Modular Formwork for Non-Standard Concrete Structures	1	1	0	1	0	1
130	History and overview of fabric formwork: Using fabrics for concrete casting	0	0	0	0	0	0

ID	Title	Dem.	Opt.	Int.	Form.	Key	Rel.
131 [128]	Development of Pseudo-ductile permanent formwork for durable concrete structures	1	0	1	0	0	1
132	The effects of various formwork surfaces on the corrosion performance of reinforcing steel in concrete	0	0	0	0	0	0
133 [129]	Combined effect of two sustainable technologies: Self-compacting concrete (SCC) and controlled permeability formwork (CPF)	1	0	1	0	0	1
134	Research on performance of concrete filled steel tube with construction formwork	0	0	0	0	0	0
135 [130]	Development of an explanatory model for concrete formwork labour productivity	0	0	0	0	1	0
136	DEVELOPMENT OF GLASS REINFORCED CEMENT PERMANENT SHUTTERING FOR BRITISH RAIL'S E TYPE BRIDGE DECKS.	0	0	0	0	0	0

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