# 3D CONCRETE PRINTING IN A CIRCULAR ECONOMY: WHAT WE CAN LEARN FROM A 3DCP SLAB DESIGNED FOR DISSASSEMBLY.

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**Abstract.** This paper investigates how 3D Concrete Printing (3DCP), through the lens of the circular economy and design for disassembly (DfD), could help transition the construction industry to more environmentally sustainable building practices. Through presentation and analysis of a case study design of a 3DCP hybrid slab, we propose how DfD principles can influence the design and construction process of 3DCP architectural elements by looking beyond material optimization and efficiency, to also include circular considerations. The analysis of a case study design finds that it is possible to incorporate DfD principles into 3DCP elements, while still achieving a reduction in overall embodied carbon relative to conventional constructions. Initial experiments on printed connections highlight that further research is required to refine jointing strategies between printed and non-printed elements. This gap is also identified in the tools available for circularity analysis, where it is found that quantitative measures for material circularity needs to be linked to measures for element circularity and disassembly.

**Keywords.** 3D concrete printing, design-for-disassembly, environmental sustainability, hybrid construction, circular design.

## 1. Introduction

Concrete is the most used building material globally. In 2022, it produced an estimated 4.1 billion metric tons of cement, resulting in up to 1.7 bullion metric tons of carbon dioxide (Global Cement Production 2022, n.d.). As the building industry shifts towards less carbon-intensive practices, innovative design and fabrication methods become crucial to help reduce this ubiquitous material's carbon footprint.

3D Concrete Printing (3DCP) has emerged as a promising solution, promoted for its material efficiency in fabrication (Gebhard et al., 2020). However, there is an increasing awareness that material optimization on its own is not enough (Flatt & Wangler, 2022). The environmental sustainability of 3DCP depends on factors beyond material use, including the material recipe, the printed object's role and performance,

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and end-of-life considerations (Heywood & Nicholas, 2023). Therefore, it becomes imperative for designers to integrate circular design principles into the development of 3DCP elements, paving the way for sustainability throughout the lifecycle.

Circular design emerges from the circular economy (CE) concept popularised by the Ellen Macarthur Foundation with their insights into its economic benefits (How to Build a Circular Economy, n.d.). CE proposes a shift in production from “take-make-waste” to more circular ones, keeping energy and materials in use and minimizing waste (Perey et al., 2018). Cheshire et al (2021) interprets these concepts for the built environment, identifying the ‘5 R’s’ of CE in construction: refit, refurbish, reuse, remanufacture and recycle. He discusses the need for a fundamental shift in how we design our buildings to consider the end of life of structures, and extend construction material lifecycles, through a series of design strategies.

One of these strategies is to construct using demountable or disassemblable building components. Often referred to as design-for-disassembly (DfD), this principal requires the construction strategy to be reversable, allowing for the separation and recovery of building components or materials for reuse or recycling.

The key ideas of DfD are that all connections should be mechanical and reversable, all connections should be easily accessible, building elements should be easily separable, and there should be no chemical coatings or adhesives on or between materials or elements (Addis & Schouten, 2004; Cheshire, 2021). Translating these principles into tangible construction practices hinges on the simplicity of jointing and assembly methods. Overly complex connections can make disassembly economically unfeasible, leading to the destructive separation of elements (WellMet 2050, 2010). Additionally, for materials to be readily reusable or recyclable, they too should be easily separable (Roithner et al., 2022).

The size, weight, and accessibility of elements are equally important. In construction, large or heavy elements require custom construction methods and specialist machinery. The assembly sequence should also be considered to ensure the layers are built up to be independent, allowing easy access for maintenance, without affecting the larger building structure (Circular Handbook, 2023).

Incorporating circular design principles into architectural projects in traditional constructions is well underway. The renovation of the Quay Quarter tower in Sydney by 3XN reused 50% of the existing buildings structural elements, using DfD principles to build a flexible floor plan using standard structural profiles, mechanical jointing, and smaller dimensions to make reconfigurable structures (Building a Circular Future, 2016). Henning Larsen also used DfD principals to create a pavilion which could be relocated and reconceived from an exhibition space, to part of a new office (Fritz Hansen Pavillion, 2022). However, while the principles of the CE and DfD have begun to inform the broader context of architectural design, the integration of these principals into 3DCP practices remains nascent.

## 1.1. CIRCULARITY IN 3DCP

Although 3DCP has seen a rapid growth in architecture, to date there are few projects which seek to incorporate circularity principals. Industry application and development is focussed toward monolithic onsite construction, and optimising construction time

(3DCP Group, n.d.; WinSun, n.d.). Current 3DCP applications in architecture predominantly focus on immediate efficiency gains in material use and construction processes, whilst aiming to reduce complex logistics and economic costs. These projects typically follow the conventional practice of embedding or casting steel reinforcement into the printed concrete, which is printed directly onsite. This suggests there is little consideration for the end-of-life recovery of the printed elements or materials.

Recent research is beginning to unfold alternative paradigms. Striatus bridge is a 3DCP DfD bridge, comprising of modular elements which when assembled sit in compression with only friction joints (Bhooshan et al., 2022). By simplifying the construction strategy and eliminating all reinforcement within the 3DCP elements, end of life performance is increased due to the low cost of disassembly and recycling. The circular construction process has been demonstrated through the assembly and disassembly of the bridge at the Venice Biennale. However, the need for complex scaffolding for the construction and deconstruction, and the high impact mortar mixture used still limits the application of this technique in industrial architectural projects.

A more common approach in 3DCP research is design strategies for assembly. Employing offsite, modular fabrication, Wu et al (2022) explore the use of 3DCP to create a bespoke post-tensioned funicular structure. The modular elements allow for easier assembly of a complex structure and take advantage of offsite robotic 3DCP to fabricate complex non-planar geometries. However, steel plates are still embedded and cast into the modular elements, and post tension rods welded into place to ensure structural stability. This irreversibly binds the modules together and makes disassembly or re-use impossible.

A different approach to modular assembly can be seen with US marines 3DCP vehicle hide structure (Camp Pendleton, n.d.). By printing large cross sections of the structure with the 'tilt-up' construction method to aggregate the modules, they reduced the number of lifts needed in the assembly process.

With the emerging importance of material recovery and reuse in architectural design, 3DCP research must embed these considerations if it is to be adopted in a sustainable way. There is potential to both apply existing logics, whilst also developing specific DfD strategies for 3DCP. There is a discernible gap in the research and practical application of 3DCP when it comes to embedding circular design principles, particularly DfD, as a core design driver. This paper aims to bridge this gap by exploring the design and disassembly potential of 3DCP in architectural design, and how a holistic approach to 3DCP can contribute to a more sustainable and circular construction industry.

## 2. Case Study: The 3DCP Hybrid Slab

To investigate how 3DCP could be considered and extended through DfD principles, this paper presents a case study design of a hybrid slab. Based on an ongoing design project for residential terrace housing, the design sought to develop an alternative construction strategy, and investigate how 3DCP could increase the performance, of a slab. Relevant performance and sustainability metrics were derived from desires and regulations relevant to residential terrace housing. These included lower embodied carbon through material optimization, increased material recovery through the embedding of circularity principals, and increased performance through geometric optimization and fire and acoustic considerations.

The design is rooted in vernacular building traditions, seeking to harness digital design tools and the fabrication freedoms of 3DCP to create non-parallel vaulted ceilings (Fig 1). The vaulted form eliminates the need for reinforcement in the printed parts of the slab, both decreasing the upfront environmental impact, and increasing the recyclability of the 3DCP elements.

The vaults are 3DCP. This allows for the exploration of 3DCP and its potential in a DfD design strategy, whilst also creating bespoke, complex geometries. The vaulted geometry enables the use of unreinforced concrete in compression and takes advantage of the materials fire resistance. By wrapping the print paths to protect the timber beams on the sides, only one face of the beams is exposed to fire (Fig 2). This reduces the over dimensioning of the timber beams, optimizing their material use and increasing their overall performance.

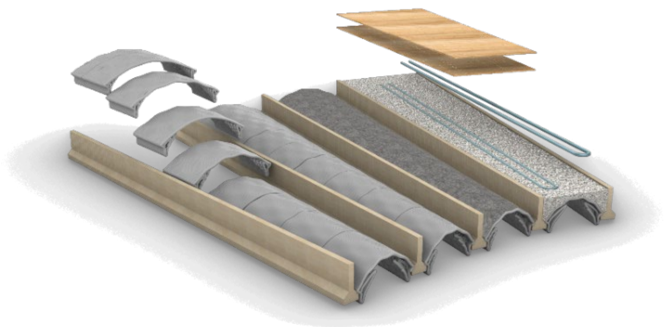

*Figure 1. Exploded Axonometric of the 3dcp hybrid slab, showing assembly of elements*

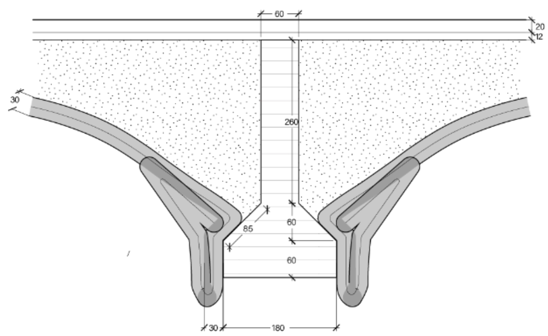


*Figure 2. Detail section of slab design*

The 3DCP vault design seeks enhance the natural acoustic performance of vaulted ceilings, harnessing surface texture of 3DCP to increase acoustic scattering, eliminating the need to install acoustic panels. Due to the fabrication logic of 3DCP, articulations on the print path can also be targeted to specific high-noise locations in the architectural plan.

The 3DCP vaults are assembled from multiple printed modules placed along the length of the beam. These modules sit directly onto a timber beam that transfers the compressive loads from the vaults to the supporting walls. These beams form the main structural component, where the 3DCP vault modules make the shorter span between beams. Each vault is then backfilled with crushed recovered concrete stone to give critical mass, reduce noise transfer by increasing acoustic scattering, and ensure even load transfer on the vault before wooden flooring is installed on top.

The overall construction strategy seeks to combine 3DCP with existing construction techniques. This reduces the need for complex temporary formwork, whilst using DfD principles to allow for fast and low-cost assembly and disassembly.

## 2.1. 3DCP DFD STRATEGIES

The design of the slab seeks to apply DfD strategies in the design of a 3DCP hybrid slab. Specifically, by reducing the amount of different mechanical connections between elements, ensuring easy separability of materials within an element, and considering accessibility and sizing. Whilst some strategies could be directly applied, such as ensuring no chemicals or adhesives are used on or between materials, others needed to be reinvented for 3DCP.

### *2.1.1. Material Strategies*

At the material scale, circularity strategies begin through considering materials and material flows. To ensure the separability and reusability of the printed concrete, the vaults have no reinforcement. This decision requires that the 3DCP material meets a strength class C25/30. This is achieved using a low impact cement with aggregates of 4mm. Through testing, it was found that a 30mm nozzle is the minimum width that can be used without blocking. These two material parameters were then used in the geometric optimization of the vaults. Excluding reinforcement from the printed material also enables a circular waste management strategy, as the design of the hybrid slab directly integrates any production waste into the slab system as a crushed concrete filler, rather than downcycling or landfilling.

### *2.1.2. Element Sizing Strategies*

Weight and size are important considerations in DfD logics. If elements are too large to access and separate, this will reduce the efficiency of disassembly. In the design development of the 3DCP vaulted modules, whilst material optimization ensured lighter modules, the lack of reinforcement also had a logistical limitation, as the assembly process could risk cracking in large, thin shelled forms. The largest module has a weight of 120kg, a maximum width of 1530mm, and a printing height of 700mm. The modules also have simple lifting anchors embedded into the printing paths at the corners to enable easy lifting for assembly and disassembly. The size and weight of the modules reduces the risk of cracking during construction and means a smaller crane can be used for the installation.

The maximum size was also dictated by the fresh state 3DCP material behaviour during printing. The printing strategy for the vaults is to print them vertically. However, when 3DCP, the higher a print goes, the higher the risk of collapse. This materially dictates a vertical limit on the print of each module.

#### *2.1.3. An Integrative Assembly Strategy*

There is no mechanical fixture between vaults and beams, and the jointing between printed modules is also friction based. However, the higher tolerances of 3DCP and the structural design of the vault pose an issue for module-module connections in terms of fire performance. This is resolved by laying a fire-resistant mat over the back of the vaults, to bridge the gap between printed modules.

Each vault is filled with 1.6m3 crushed concrete. This approach allows for underfloor electricity and pipework to be easily installed. OSB timber is then fixed to the top of the beams using a reversable screwed connection. Spanning laterally across the vaults, these plates create an integrated structural system. Because of the discretization of the vaults and crushed concrete between the beams, each vault can be accessed individually. Because the vaults are placed onto the beams, no temporary scaffolding is needed during assembly or disassembly, and they can be accessed individually for repair or disassembly.

### 2.2. ASSESSMENT STRATEGIES

#### *2.2.1. In-use Assessment Tools*

In this case study, selected assessment methods are integrated into the design workflow to iteratively develop the geometry and design strategy. Computational analysis tools were used for initial structural assessment (Preisinger & Heimrath, 2014). These provided feedback on the relationship between material selection, geometry, and structural performance. A basic calculation to check the beam's fire efficiency was used. Assuming a fire charring rate for GLT of 0.7mm/ minute, it was calculated that 42mm would be lost. The beams section has a lower depth of 60mm to deal with deflections. As the beam is only exposed on one side, the calculation suggests the lower part would have a depth of 18mm after 60 minutes of fire exposure. Structural assessments indicated this would be enough to meet structural strength.

#### *2.2.2. Circularity Assessment Tools*

Different methods of measurement are needed to measure different aspects of circular design. In this design, two methods of measurement were used. A custom Life Cycle Assessment (LCA) tool was developed to measure the environmental impact of the entire hybrid slab structure. This tool compared the environmental footprint of 1m² of the hybrid slab with alternative build-ups. The second method uses the concept of Circularity Index as implemented in Rhino Circular (Heisel et al., 2020) to quantify the performance of the design for DfD.

## 3. Application and Results of Circularity Analysis

The hybrid slab was compared to traditional fabrication solutions using both LCA and

Rhino Circular. Figure 3 shows the embodied carbon over the whole lifespan. The calculation follows the Danish standard for LCA and goes beyond them to include further B and C phases. We do this to include broader aspects of use and material recovery. The calculations are modelled using standard Danish construction materials and their associated EPDs. While these calculations are not comprehensive, the hybrid slab has 35kgCO2e/m2, equalling the results of the CLT slab option of 34.5kgco2e/m2

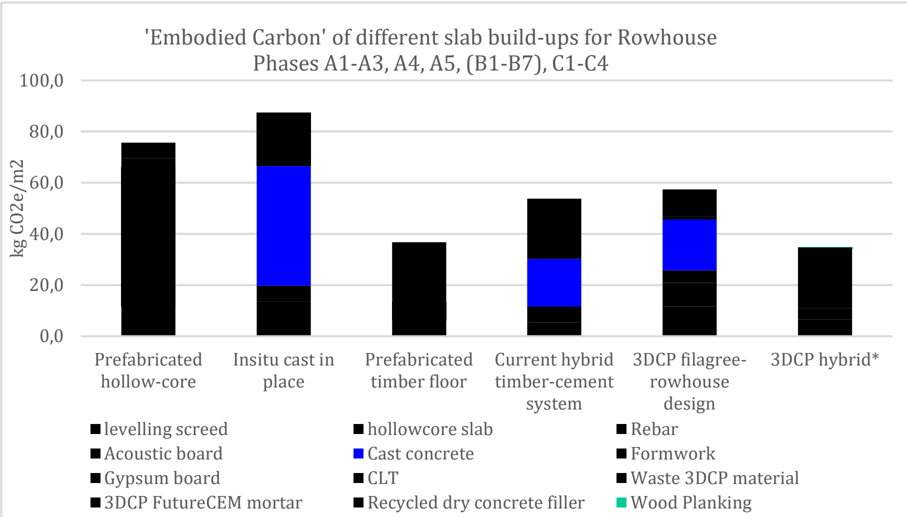


*Figure 3. Embodied carbon of different slab build-ups based on standard Danish construction specifications for a rowhouse typology*

| Type | TOTAL | End of Use | Production | Reused | Recycled | Renewable | Virgin | Reusable | Recyclable | Landfill |
|---|---|---|---|---|---|---|---|---|---|---|
| 3DCP Hybrid | 84,8 | 92,2 | 76,5 | 60,2 | 6 | 10,2 | 23,5 | 75,3 | 20,9 | 3,8 |
| CLT deck | 61,9 | 34,3 | 90,2 | 14,5 | 3,6 | 72,2 | 9,8 | 24,1 | 12,6 | 62,5 |

Table 1. Circularity Index scores for two different slab build-ups as %

LCA does not allow for calculations on DfD. To understand this metric Rhino Circular was used. The underlying data for Rhino Circular comes from a 3D model, and the analysis is performed using the Rhino Circular database, with additional specific data given for the 3DCP material. Table 1 shows the results, comparing the hybrid slab to conventional Danish CLT construction. The 3DCP hybrid scores at 84% circularity, significantly better than the CLT deck. Potential reasons for this include the complete separation of materials within the design, which allows for a far higher rate of material recovery and re-use. Another influential factor relates to the inherent material properties of the concrete, which replace the need for the additional gypsum and acoustic boards required by the CLT.

### 3.1. PROTOTYPING AS A TOOL

Whilst some design decisions are validated through computational tools, many of the unique assembly considerations and material performances can only be tested through physical prototyping. Design considerations are explored using scaled prototyping as quick feedback tool in design development. This increased speed of the process and allowed the development of smaller details. In particular, the joint between vaults and beams, and the start and end print path conditions were explored.

The start and end conditions for material deposition vary significantly. To avoid this, the print path was developed to 'wrap' in on itself, hiding the start and ends. This wrapping created an overlap of the printed paths, thickening the cross section and strengthening the vaults at the critical load point to the beam (Fig 4).

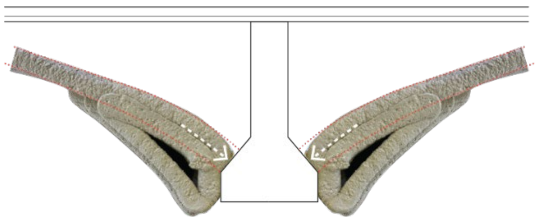

*Figure 4. Diagram showing the wrapping of print paths*

The slabs structural performance relies on the even load transfer at the vault-beam interface. This is a challenge for 3DCP, as the layered deposition of the material results in a textured surface finish and high tolerances compared to cast. To test this, partial prototypes were printed, and their surface tolerance assessed. It was found that the smoothness of the printed surface was not sufficient for an effective load transfer. To address this, a second set of partial prototypes were printed against a formwork located at the vault-beam interface. The partial prototypes were used to verify the connection details that would enable the assembly and disassembly of the hybrid slab system.

## 4. Discussion

The hybrid slab was designed as a case study example to gain an understanding on the potentials of 3DCP in circular design. The aim of the case study was to investigate how 3DCP could be used to develop DfD principles and increase environmental sustainability through three areas: the reduction of embodied carbon, increased material recovery, and increased material and geometric performance.

The analysis of the case study design suggests that designing 3DCP elements with DfD principles offers a promising avenue in the construction industry's transition to more sustainable construction strategies. However, there are also many unresolved challenges. Jointing and assembly strategies between 3DCP elements and to non-printed building components needs further research. The unique fabrication process of 3DCP necessitates innovative jointing techniques to ensure that printed elements can be effectively connected and, importantly, separated for recovery at the end-of-life. The case study presents a specific jointing design for a vaulted slab, but it also highlights the need for a broader range of jointing strategies, particularly in connecting 3DCP modules together.

By optimizing material placement and the adoption of low-impact material recipes, the case study demonstrates a significant reduction in the embodied carbon of printed elements. But material recipes should continue to be developed, not only to reduce upfront carbon emissions, but also to increase printability and explore how they could become part of the circular economy by using recycled waste aggregates and alternatives to Portland cement.

The Circularity evaluations demonstrated the potential of 3DCP in a DfD slab. Whilst the LCA evaluation suggests the hybrid slab is equal in performance to the CLT, the Rhino Circular evaluation showed a significant difference. Currently, each calculation is performed independently of the other, and each requires separate data sources. It is important that both embodied carbon and circularity considerations are embedded into one workflow to allow for faster and more meaningful comparisons in results. Particularly important is understanding circularity and DfD evaluations at an element level, quantifying detailing and jointing. This is currently lacking as most tools focus on the material level of circularity. The relationship between lowering embodied carbon, and increasing circularity is not linear, and focusing design development on one could adversely affect the other. Integrating these considerations into a single calculation could also allow data to be shared between the two, speeding up the analysis process, and allow it to be used earlier in the design process.

## 5. Conclusion

The design of the hybrid slab also raises a critical question, of how do we re-use printed elements? The case study design's floorplan necessitated the use of custom 3DCP geometries, however although the 3DCP vaults can be removed and recovered, they have a bespoke geometry, so at the end of the building's life can only be disassembled to then be downcycled, rather than go to direct re-use. Reversibility is not sufficient to achieve effective circularity. If 3DCP is to contribute towards a circular building economy, the design strategies must consider not only how disassemble the elements are, but also how they might be re-used.

Considering DfD for 3DCP implies a different trajectory to that which has driven current application approaches for 3DCP in AEC, which aim to build entire buildings monolithically and in-situ. It will also necessitate a better understanding of the durability and end of life conditions of 3DCP elements, which are currently still unknown. As a relatively new fabrication process, which uses new kinds of concrete recipe, no long-term studies have been conducted to understand where 3DCP is most applicable in architectural construction. However, by ensuring that the elements themselves are easily separable from each other, and conceptualising 3DCP structures with their end-of-life in mind, not only can the environmental impact of the printed elements be reduced, but it could also contribute towards fostering a more circular construction ecosystem.

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