Abstract

Stress-based Design of Lightweight Horizontal Structures for 3D Concrete Printing
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This research investigates an integrated design-to-fabrication approach that merges robotic extrusion-based 3D Concrete Printing (3DCP) with stress-based computational logics to optimise the carbon efficiency of horizontal reinforced concrete structural elements.

Concrete plays a central role in shaping the built environment worldwide. The concrete and cement industry is responsible for an estimated 7-8% of the total CO_2 emissions worldwide, and it is predicted to only grow along with the growth in population and urbanisation, making it a critical concern in sustainable construction practices.

Horizontal structures, such as beams and slabs, are crucial in supporting vertical loads and ensuring buildings' stability and functionality. These elements account for over 40% of the total concrete volume employed in mid-rise buildings, largely contributing, directly or indirectly, to the carbon emissions generated by construction. Rethinking how we design horizontal structures and optimising the use of materials would provide a direct positive environmental impact.

The advent of digital fabrication tools and computational design methods has unlocked new avenues of research and practice in the search for alternative, structurally- and material-efficient solutions to conventional construction practices. Offering construction flexibility and precise control over the material distribution, 3DCP emerged as a disruptive approach that holds significant potential for architectural innovation and sustainable construction practices. However, a radical shift from conventionally linear design and engineering methods is required to fully unlock such a disruptive fabrication technology.

Encompassing the design, fabrication and structural testing of a series of horizontal structural elements, beams and slabs, this research examines the potential of combining 3DCP with structural optimisation routines in shaping the practice of designing horizontal reinforced concrete structural elements towards more carbon-efficient solutions. A particular focus is placed on developing design-to-fabrication workflows specific to the utilised fabrication technology, seamlessly integrating notions of materiality and fabrication constraints in the design process to minimise translation, post-processing and discretisation operations. This resulted in an approach to digital design that accounts for the trajectory-based extrusion process of 3DCP. Contemporarily, the work integrated methods to integrate Finite Element Analysis (FEA) and the Principal Stresses and Principal Moments fields to optimise the material placement.

This led to the conception of a series of proof-of-concept reinforced concrete beams, namely 3DLightBeam and 3DLightBeam+, characterised by a stress-based porous infill structure with a strength-to-weight ratio of 100% higher compared to non-optimised 3DCP beams. Moreover, the integrated design-to-fabrication approach was implemented to develop a ribbed slab, 3DLightSlab, with toolpath-based stress-optimised ribs' layout. Verified through structural testing and a comparative Life-Cycle Analysis (LCA), the results of this thesis demonstrate that the approach developed for prefabricating carbon-efficient horizontal structural elements using 3DCP is a viable solution with a potentially high impact on the construction industry.

The results of this thesis outline that design, fabrication, simulation and validation are intrinsically intertwined and need to be integrated into a comprehensive, tailored workflow to unlock the full potential of 3DCP for structural applications.