FOLDCAST. OPTIMIZING CONCRETE STRUCTURES WITH PAPER FORMWORK

FOLDCAST. OPTIMIZACIÓN DE ESTRUCTURAS DE HORMIGÓN CON ENCOFRADOS DE PAPEL

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Abstract: *Concrete is the most widely used building material worldwide, valued for its availability, strength, durability, and versatility. However, its extensive use makes it one of the largest contributors to CO_2 emissions in the built environment, despite having lower embodied carbon per unit volume than many alternatives. A transition toward more sustainable construction therefore requires reducing material consumption and minimizing waste. Foldcast addresses this challenge by enabling up to 50% material savings in structural elements through the use of low-cost, recyclable paper formwork. This method combines structural optimization strategies with digital fabrication technologies to produce large-scale concrete elements. Two full-scale applications for a ribbed concrete slab and a precast staircase demonstrate the potential of this approach to significantly reduce the carbon footprint of concrete structures while enhancing architectural design flexibility. Furthermore, the affordability and compatibility of paper formwork with conventional construction practices highlight its promise for adoption in the construction industry.*

Key Notes: *Concrete; Sustainability; Formwork; Digital Fabrication; Structural Optimization.*

Resumen: *El hormigón es el material de construcción más utilizado en todo el mundo, valorado por su disponibilidad, resistencia, durabilidad y versatilidad. Sin embargo, su uso extensivo lo convierte en uno de los mayores emisores de CO_2 en el entorno construido, a pesar de tener menos carbono incorporado por unidad de volumen que muchas alternativas. Por lo tanto, una transición hacia una construcción más sostenible requiere reducir el consumo de materiales y minimizar los residuos. Foldcast aborda este desafío permitiendo un ahorro de hasta un 50% de material en elementos estructurales mediante el uso de encofrados de papel reciclable y de bajo coste. Este método combina estrategias de optimización estructural con tecnologías de fabricación digital para producir elementos de hormigón a gran escala. Dos aplicaciones a escala real para una losa de hormigón nervada y una escalera prefabricada demuestran el potencial de este enfoque para reducir significativamente la huella de carbono de las estructuras de hormigón, a la vez que mejora la flexibilidad del diseño arquitectónico. Además, la asequibilidad y la compatibilidad del encofrado de papel con las prácticas de construcción convencionales demuestran su potencial para una adopción generalizada en la industria de la construcción.*

Palabras clave: *Hormigón; Sostenibilidad; Encofrado; Fabricación digital; Optimización estructural.*

INTRODUCTION

In Italy, the 1940s and 1950s were a period of intense structural experimentation, driven by pioneers of Italian engineering such as Pier Luigi Nervi,[1] Aldo Favini,[2] Riccardo Morandi,[3] and Sergio Musmeci.[4] Their work focused on optimizing the use of materials and resources, resulting in innovative concrete structures tailored to specific structural and functional requirements. A notable example is the roof of the Church of San Luca in Via Gattamelata, Rome (1956), designed by Riccardo Morandi, which employs a system of folded forms and diagonal tie rods to minimize slab thickness.[5]

The complex geometries characteristic of optimized structural systems often require highly skilled labour to construct elaborate formwork. In recent decades, however, rising labour costs and the widespread availability of affordable construction materials have reduced the economic appeal of these systems, contributing to their gradual decline.[6]

Today, the climate crisis demands that we look beyond mere cost and speed of execution. It is imperative to rethink construction processes and use resources more efficiently, particularly by reducing greenhouse gas emissions from concrete production. Concrete is by far the world's most widely used building material, with cement manufacturing alone responsible for 8% of global CO_2 emissions.[7] Achieving the climate neutrality targets set by the Paris Agreement for 2050 requires exploring solutions that can significantly reduce concrete consumption in construction. Structural optimization offers a promising response to this challenge, supported by recent advances in digital technologies that can drastically lower the cost and time needed to produce complex formworks.

Foldcast is a research project launched in 2022 by the Fabrication and Material Aware Architecture group at the Academy of Architecture in Mendrisio, Università della Svizzera Italiana (USI).[8] The project deploys digital

FIG. 01

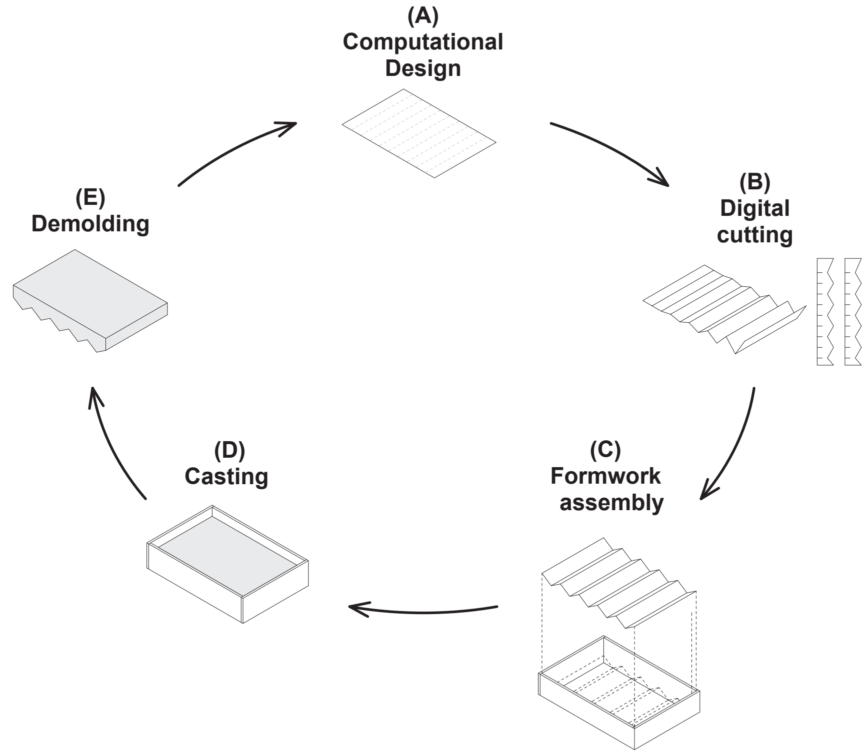

FIG. 02

technologies to produce optimized prefabricated concrete elements using innovative flexible, low-cost, and recyclable paper formwork. This approach demonstrates that it is possible to substantially reduce the environmental footprint of new concrete structures while expanding their design possibilities **(FIG. 01)**.

DIGITAL TECHNOLOGIES FOR RECYCLABLE FORMWORK

Foldcast combines digital design tools with conventional construction methods to create paper formwork. By precisely folding paper and cardboard along predefined patterns, it produces formwork capable of highly complex three-dimensional geometries." The use of digital design and fabrication technologies is central to this approach, allowing a substantial reduction in the time and cost typically associated with producing non-standard formwork. Compared with traditional wood or metal formwork, the paper alternative offers notable advantages in flexibility and sustainability: it is cost-effective, recyclable, lightweight, easy to shape and transport.

The fabrication process begins with the computational design of structurally optimized concrete elements, using advanced software that generates the corresponding folding pattern. This pattern is transferred to a CNC (computer numerical control) cutting and creasing machine,[9] typically used in the packaging industry, which processes sheets of paper and cardboard according to the design. The pre-cut sheets are then manually folded into three-dimensional shapes and positioned within a wooden panel frame. The assembled formwork is compatible with conventional prefabrication processes, incorporating a hydrophobic paper skin and a cardboard substructure that accommodates standard reinforcement and concrete mixes. After curing, the paper skin is removed for recycling, while the cardboard insert can be reused multiple times. Structural elements produced with this method achieve the same load-bearing performance as conventional solutions while requiring 40–50% less concrete **(FIG. 02)**.

The components of typical paper formwork include:

1. a 27 mm-thick wooden frame, composed of multiple elements that can be repeatedly assembled and disassembled to facilitate formwork removal;
2. a 6 mm corrugated cardboard substructure, pre-cut and assembled according to the design to shape and support the concrete element above. As it is not in direct contact with the concrete, the substructure can be reused multiple times or recycled after use;
3. a hydrophobic paper skin, positioned over the substructure. For this experimental series, 0.7 mm-thick silicon-coated paper sheets (70 × 100 cm) were used, resisting the heat and moisture released by fresh concrete. After demoulding, the paper skin could then be easily removed and recycled.

Foldcast technology was developed through extensive preliminary research at the Academy of Architecture in Mendrisio,[10] focusing on the mechanical behaviour of paper materials under the pressure of fresh concrete, while incorporating the knowledge acquired from physical testing into custom-developed software. The two case studies presented in the following sections were conducted in an interdisciplinary setting, bringing together architects, structural engineers, materials scientists, digital fabrication specialists, and industrial partners **(FIG. 03)**.

SUSTAINABILITY AND STRUCTURAL OPTIMIZATION

The Foldcast technology was initially applied to the design and production of a prefabricated ribbed slab system. A distinctive feature of this system is the X-shaped alignment of the ribs, forming an intersecting grid rather than the conventional parallel arrangement. This configuration combines the advantages of both traditional ribbed and waffle slabs while maintaining unidirectional load transfer. The addition of an in-situ cast concrete topping layer enables the transfer of horizontal loads from the slab to the vertical structural elements.

Beyond the well-known benefits of ribbed slabs over solid slabs —such as reduced material use, lower self-weight, and associated environmental gains— the hybrid X-rib configuration ensures a more uniform weight distribution, enhancing load-bearing capacity and increasing stiffness. The complexity and high production costs typically associated with ribbed slabs are effectively addressed with the paper formwork system. This approach streamlines the construction process, lowers formwork production costs, and enables further structural optimization. The slab system was designed in accordance with Swiss building standards SIA 262, [11] for strength class C30/37 and conventional B500B reinforcement.

Two prototypes measuring 200 × 100 cm were produced in collaboration with the industrial partner Müller-Steinag Gruppe[12] at their Müntschemier facility in Switzerland. The formwork was fabricated following the process and composition described in the previous section **(FIG. 04)**.

To further reduce environmental impact, the slabs were cast using a self-compacting concrete mix containing 50% recycled aggregates and reduced cement content, developed in collaboration with the University of Applied Sciences and Arts of Southern Switzerland (SUPSI)[13] and the University of Eastern Switzerland (OST)[14],[15]. After 24 hours, the formwork was dismantled. The wooden frame and cardboard substructure remained intact and were reused to produce a second identical element, while the paper skin was easily detached, recycled, and replaced with a new one **(FIG. 05)**.

The life cycle assessment (LCA)[16] of the elements indicated a 25% reduction in overall environmental impact compared to a conventional 22 cm flat slab produced with standard B500B reinforcement and wooden formwork. The analysis further revealed a 33% decrease in concrete consumption and 18% reduction in reinforcement steel usage, in alignment with Swiss and European targets for reducing embodied carbon in building components.

A subsequent experimental campaign assessed the accuracy and reusability of the paper formwork over 10 consecutive casting cycles of a full-scale concrete

FIGS. 03-04

FIG. 05

FIG. 06

specimen. After each cycle, 3D scanning was used to measure geometric deviations between the produced elements and the design model. The results indicated only slight increases in mean deviation (from +1.4 mm to +1.9 mm) and maximum deviation (from +3.3 mm to +3.8 mm), with all values remaining well within the tolerance range (–5 to +10 mm) indicated in SIA 262. Deviations stabilized after the first few cycles, as the cardboard substructure quickly reached a steady state. Overall, the findings confirm that after 10 uses the paper formwork maintains high geometrical accuracy, suggesting that it could potentially accommodate additional casting cycles before approaching the tolerance threshold (FIG. 06).

VARIATION AND DESIGN FLEXIBILITY

The second case study focused on the design of a staircase composed of prefabricated concrete steps, each featuring wing-shaped extensions on both sides to optimize material use and enhance design flexibility. The steps were manufactured off-site using paper formwork and subsequently assembled directly onto a reinforced concrete beam on site. Each prefabricated step incorporated a cavity on its underside, precisely dimensioned to rest securely on the beam during installation. Inside the cavity, reinforcement bars were arranged to interlock with vertical stirrups extending from the beam. Once the steps were positioned, the cavities were filled with mortar, creating a monolithic connection between the steps and the beam.

The staircase was engineered to transfer external forces applied at the edges of each step toward the centre, where they were redirected through torsion and reaction forces within the filled cavity into the supporting beam. The beam then transferred the accumulated loads from all the steps to the supports. This system eliminates unnecessary material between steps, substantially reducing the volume of concrete typically required in conventional stair construction and resulting in a significantly lighter structure. Details about the design, fabrication, and analysis of the staircase are outlined in a publication by Amicarelli et al.[17]

A prototype staircase was designed, fabricated, and evaluated, consisting of three steps assembled on a cantilever beam with a counterweight base. For the purposes of this experiment, three separate formworks —one for each step— were produced to streamline manufacturing. In serial production, however, the formworks can be reused multiple times, minimizing both material consumption and waste. The formworks were produced according to the previously described fabrication process and completed with corresponding reinforcement cages made from B500B steel bars. Self-compacting concrete with recycled aggregates was mixed and cast using standard procedures. The prefabricated elements were demoulded after 24 hours and cured in a humiditycontrolled chamber for 28 days. Each step, weighing approximately 70 kg, was then transported to the construction site and installed on the cantilever beam, which had been cast in situ using conventional wooden formwork, B500B steel reinforcement, and standard concrete. A concrete base measuring 135 × 91 × 26 cm served as counterweight for the cantilever beam **(FIG. 07-08).**

To verify the load-bearing capacity of the staircase, a structural test was conducted on three steps specifically manufactured for this purpose. The test followed the EN 12390-5:2019 standard, which prescribes the assessment of flexural strength in reinforced concrete elements through four-point bending. The results aligned with the expected performance, confirming the structural adequacy of the steps and their suitability for the intended applications, both for functional performance and ultimate strength.

Finally, life cycle assessment[18] of the prototype indicated a 35% reduction in environmental impact compared with a conventional prefabricated concrete staircase manufactured with standard B500B reinforcement and wooden formwork. This was accompanied by a 50% reduction in concrete use and a 25% reduction in wood for formwork providing a low-impact alternative.

The combination of discretized prefabrication, paper formwork, and on-site assembly is applicable to both new and existing buildings, with potential for projects requiring customized design solutions—such as renovations—due to the reduction in cost and time associated with labour-intensive on-site fabrication **(FIG. 09)**.

BRIDGING RESEARCH AND INDUSTRY

By integrating innovative technologies within conventional construction workflows, Foldcast aims to address the industry's inherent resistance to change through an incremental, non-disruptive way to innovation. This strategy is targeted at facilitating the adoption of advanced construction processes in the built environment and promoting sustainability by reducing material consumption and resource intensity.

Conceived as a research project, Foldcast is now progressing toward industrial application through a dedicated startup[19] focused on the commercialization of optimized precast concrete elements manufactured with paper formwork. The evolving product catalogue includes solutions for slabs, façades, staircases, infill panels, and acoustic barriers, with the objective of improving material efficiency and expanding design possibilities without significantly increasing construction costs. Further applications under development investigate the use of paper formwork for on-site casting, including an upcoming pilot project for a functional concrete slab cast directly at the construction site.

Amid intensifying environmental challenges, the construction sector faces increasing pressure to reduce its ecological impact, an extensive and complex challenge that demands a diverse array of innovative approaches. Scaled implementation of Foldcast has the potential to significantly reduce the carbon footprint of concrete structures, a major contributor to CO_2 emissions in the built environment, while expanding the scope for design flexibility. Supported by bespoke digital tools, architects and engineers can explore a wide spectrum of structural forms that have historically been difficult to conceive and execute, thereby reclaiming a central role in the development of optimized construction systems of high architectural quality.

With the vast amount of buildings and infrastructure to be built in the coming decades, it is both urgent and essential to develop solutions that reduce material use, improve architectural quality, and move the construction industry toward a more sustainable future. **(FIG. 10)**.

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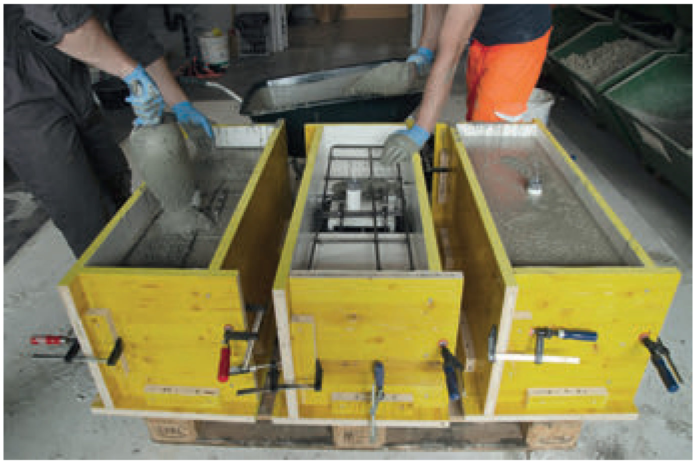

FIGS. 07-09

Fabio Amicarelli

Fabio is an architect, researcher, and entrepreneur passionate about driving innovation in the construction industry and advancing the built environment towards a more sustainable future. In 2024, he co-founded *Foldcast Sagl*, Swiss startup committed to decarbonising construction by developing sustainable concrete building elements produced with innovative paper moulds. Since 2022, he has been pursuing his PhD at the Fabrication and Material Aware Architecture (FMAA) group at the Academy of Architecture in Mendrisio, Università della Svizzera italiana (ARC-USI), where he developed the core technology behind Foldcast. Prior to this, he worked at the Zurich-based architectural firm ROK GmbH, focusing on computational design and digital fabrication.

Ena Lloret-Fritschi

Ena is an architect and Assistant Professor at ARC-USI, where she leads the FMAA research group on digital fabrication methods that reduce material use in architecture. She began her career in leading architectural offices before moving into academia in 2010. As a PhD and later as a postdoctoral researcher at the National Centre of Competence in Research (NCCR) Digital Fabrication at ETH Zurich, she worked at the intersection of building materials science at the Physical Chemistry of Building Materials group (PCBM) and robotic fabrication for architecture at Gramazio Kohler Research (GKR). She has since led multiple industry transfer projects in this field and is also co-founder of Foldcast Sagl.

Figures

FIG. 01. Design variations on 1:10 scaled models made with paper formwork. Source and Author: ©Fabrication & Material Aware Architecture (FMAA), 2024.

FIG. 02. Diagram of Foldcast fabrication process. Source and Author: ©Fabrication & Material Aware Architecture (FMAA), 2023.

FIG. 03. 1:1 scale section of concrete slab element made with paper formwork. Source and Author: ©Fabrication & Material Aware Architecture (FMAA), 2023.

FIG. 04. Paper formwork used for two full-scale concrete slab prototypes. Source and Author: ©Fabrication & Material Aware Architecture (FMAA), 2024.

FIG. 05. Removal of paper formwork on full scale prototype for a precast ribbed slab. Source and Author: ©Fabrication & Material Aware Architecture (FMAA), 2024.

FIG. 06. Render of structurally optimized concrete slab made with Foldcast technology. Source and Author: ©Alessandro Pio Gliaschera, 2024.

FIG. 07. Casting of precast step elements for staircase prototype. Source and Author: ©Fabrication & Material Aware Architecture (FMAA) 2024.

FIG. 08. Assembly of precast step elements for staircase prototype. Source and Author: ©Fabrication & Material Aware Architecture (FMAA), 2024.

FIG. 09. Real-size demonstrator of optimized staircase design. Source and Author: ©Fabrication & Material Aware Architecture (FMAA) 2024.

FIG. 10. Render of structurally optimized staircase design made with Foldcast technology. Source and Author: ©Alessandro Pio Gliaschera, 2025.

Bibliography

- Amicarelli, Fabio, and Ena Lloret-Fritschi. "Optimising Concrete Slabs with Paper Formworks." *Architectural Design (AD), Wiley*, 2024.
- Amicarelli, Fabio, Elia Quadranti, Christian Paglia, et al. "Advancing Precision: Less Concrete, More Innovation in Staircase Design." *Dagmar Reinhardt, Nicolas Rogeau, Christiane M. Herr, Anastasia Globa, Jielin Chen, Taro Narahara (Eds.), ARCHITECTURAL INFORMATICS - Proceedings of the 30th CAADRIA Conference, Tokyo, 22-29 March 2025, Volume 2, Pp. 357–366*, CUMINCAD, 2025. https://papers.cumincad.org/cgi-bin/works/paper/caadria2025_473.
- Flatt, Robert J., Nicolas Roussel, and Christopher R. Cheeseman. "Concrete: An Eco Material That Needs to Be Improved." *Journal of the European Ceramic Society* 32, no. 11 (2012): 2787–98. https://doi.org/10.1016/j.jeurceramsoc.2011.11.012.
- Horat, Alexandra, Fabio Amicarelli, Ena Lloret-Fritschi, Christian Paglia, and Simone Stürwald. "Self-compacting concrete with recycled concrete aggregates." *Concrete Plant Iternational (CPi)*, 2024. https://www.cpi-worldwide.com/us/journals/artikel/72154.
- Lenci, Ruggero. *Studio Passarelli: Cento Anni Cento Progetti*. Electa, 2006.
- Mata-Falcón, Jaime, Patrick Bischof, Tobias Huber, et al. "Digitally Fabricated Ribbed Concrete Floor Slabs: A Sustainable Solution for Construction." *RILEM Technical Letters* 7 (September 2022): 68–78. https://doi.org/10.21809/rilemtechlett.2022.161.

FIG. 10

Notes and bibliographic references

1 Pier Luigi Nervi (1891–1979), Italian engineer and architect, is renowned for his pioneering use of reinforced concrete in innovative structural forms.

2 Aldo Favini (1936–2018) was an Italian structural engineer noted for his expertise in large-span structures and complex concrete works.

3 Riccardo Morandi (1902–1989), Italian civil engineer, is best known for his bridges and experimental use of prestressed concrete.

4 Sergio Musmeci (1926–1981), Italian structural engineer, is recognized for his innovative approach to structural forms and integration of engineering with architecture.

5 Ruggero Lenci, *Studio Passarelli: Cento Anni Cento Progetti* (Electa, 2006).

6 Jaime Mata-Falcón, et al, "Digitally Fabricated Ribbed Concrete Floor Slabs: A Sustainable Solution for Construction," *RILEM Technical Letters* 7 (September 2022): 68–78.

7 Robert J.Flatt, et al, "Concrete: An Eco Material That Needs to Be Improved," *Journal of the European Ceramic Society* 32, no. 11 (2012): 2787–98.

8 https://www.arc.usi.ch/en

9 Zünd G3 3XL-1600 (https://www.zund.com/en)

10 Fabio Amicarelli and Ena Lloret-Fritschi, "Optimising Concrete Slabs with Paper Formworks," *Architectural Design (AD), Wiley*, 2024.

11 Schweizerischer Ingenieur- und Architektenverein (SIA), *prSIA 262:2024-04 – Betonbau (Vernehmlassungsentwurf)*, Zürich: SIA, 2024.

12 https://mueller-steinag.ch/

13 https://www.supsi.ch/en/home

14 https://www.ost.ch/en/

15 Alexandra Horat, et al, "Self-compacting concrete with recycled concrete aggregates," *Concrete Plant Iternational (CPi)*, 2024.

16 LCA calculations were conducted using the Activity Browser software and Ecoinvent database, with datasets selected for the Swiss market. The analysis focused on Stage A (production and construction) in alignment with the Cradle-to-Gate approach.

17 Fabio Amicarelli, et al, "Advancing Precision: Less Concrete, More Innovation in Staircase Design," *Dagmar Reinhardt, Nicolas Rogeau, Christiane M. Herr, Anastasia Globa, Jielin Chen, Taro Narahara (Eds.), ARCHITECTURAL INFORMATICS - Proceedings of the 30th CAADRIA Conference, Tokyo, 22-29 March 2025, Volume 2, Pp. 357–366*, CUMINCAD, 2025.

18 LCA calculations were conducted using the Activity Browser software and Ecoinvent database, with datasets selected for the Swiss market. The analysis focused on Stage A (production and construction) in alignment with the Cradle-to-Gate approach.

19 https://foldcast.com/