This academia-industry collaborative project, Diamanti canopy, demonstrates the design and fabrication of a combined compression and tension funicular canopy with periodic antistatic, diamond surfaces (Fig. 3). The canopy is a part of the European Cultural Centre’s 2024 biennial exhibition, ‘Personal Structures’, in Venice, Italy, at the Giardini della Marinaressa (Fig. 2). Utilising both 3D concrete printing (3DCP) and post-tensioning technologies, the canopy spans 10m and is supported by a cross-laminated timber (CLT) platform (Fig. 4).

The structural form of this composite canopy directly considers both compressive and tensile forces, inherently developed in concrete structural systems, by distributing loads through its unique, minimal-mass geometry. The CLT platform suggests how the combination of a carbon-negative material and concrete can be used in contrast to common construction methods where concrete is typically used as the load-bearing support and wood as the spanning element. Hence, the lightweight design of the Diamanti canopy, spanning over and supported by the CLT platform, showcases the innovative use of these materials, while also satisfying the Venice Port Authority’s installation requirements.

The historical design of ancient masonry structures continues to inspire the use of compression-dominant structures in the Architectural, Engineering, and Construction (AEC) sector because of their ability to perform well and minimise the amount of material, mass, and embodied energy required (López López et al., 2014, and Nuh et al., 2022). While beneficially reducing the overall quantity of material needed for construction, such systems call for extensive external provisions to maintain compression-only load paths requiring, for example, fixed boundary conditions or the inclusion of horizontal tension ties as constraints. Other safety requirements may necessitate the inclusion of additional reinforcement, such as steel fibers, to enhance performance, but can limit the structure’s ability to be recycled.

The exhibited canopy goes beyond compression only by embracing tension as an unavoidable force in systems resilient to different loading scenarios. Hence, a combined form-finding and fabrication approach was developed to achieve the innovative structure with the intention of also minimizing carbon through reduced materials and recyclability. Through the design freedom enabled by the design approach, 3DCP, and the use of post-tensioning, the final design favourably has minimal reinforcement.
while achieving the desired structural performance. Overall, the Diamanti canopy demonstrates how, through the combination of modern technologies and the development of a non-restrictive, comprehensive design approach, new structural forms can be achieved that lead to enhanced sustainable practices.

The geometry-based structural design method of polyhedral graphic statics (PGS) (Akbarzadeh, 2016; Lee, 2018) provided the design freedom to achieve a structure that is capable of dealing with developed compression and tension forces. Polyhedral cells, defined from the resulting structural form, were used to contour periodic anticlastic surfaces, specifically the diamond triply periodic minimal surface (TPMS) geometry to align with the principal stress directions. The diamond TPMS unit’s geometry enhances the structural form’s geometric stiffness and inherently provides the internal conduits for the post-tensioned cables, resulting in a fully integrated material-structural system.

The use of 3D concrete printing allowed for the effective realisation of the innovative structural form, and this otherwise could not be achieved using standard construction techniques. Prefabrication optimisation and construction schemes were developed to address additive manufacturing constraints. To optimise for printability, signed distance function (SDF) (Bernhard et al., 2018; Blinn, 1982; Bernard et al., 2021) combined the funicular form and the TPMS geometry into a smooth, unified model. To print the 10m canopy, the design was divided into segments that ensured preferred structural behaviour and optimisation algorithms were developed to effectively slice the segmented geometry with non-parallel planes perpendicular to the direction of compression force flow. Additional computational algorithms were developed for efficient non-continuous printing to minimise the material dripping and to avoid collision, since the geometry of the segments includes multiple disconnected loops.

The overall design and fabrication approach in this work includes multiple intertwined innovative strategies that result in an extremely efficient structural system utilizing 3D concrete printing and post-tensioning that reduces the construction materials needed compared with conventional structural systems. The prefabrication strategy yields faster section times, reduces soft construction costs, eliminates the need for formwork, allows for recyclability, and minimizes the overall carbon emissions of concrete construction.

Design

A comprehensive computational methodology for form-finding, optimisation, and digital fabrication was developed to design the canopy. The method begins with the generation of a geometric design using PGS, succeeded by the utilisation of volumetric modelling (VM) for structural materialisation. With respect to fabrication, details concerning 3DPCP were considered through the development of print-specific optimisation algorithms. The entire computational method for the canopy is illustrated as a workflow in Fig. 5. While applied here to the canopy, this computational method is general in that the process from design generation to digital fabrication can be employed for a wide range of applications. The specifics of the method are discussed subsequently.

Structural form-finding through polyhedral graphic statics

The structural form-finding process begins with the implementation of graphic statics. Conventional two-dimensional graphic statics establish a reciprocal relationship between form and force. This reciprocity principle allows for the considered forces and form to be altered without violating structural equilibrium, providing design freedom. With stability guaranteed, a range of stable structural forms can be generated considering both tension and compression forces (Fig. 6a). To effectively manage design requirements and material properties for the concrete canopy design, it is beneficial to maintain constant tension forces. In the context of 3D printing,
A surface is defined as anticlastic when the centres of curvatures are located on opposing sides, forming a hyperbolic paraboloid. The intese structure of periodic anticlastic surfaces, their high surface-to-volume ratio, and their property of separating space into two intertwined but disconnected sub-spaces, makes them promising candidates for a variety of applications, including, for example, medical implants, lightweight integral structures, and heat exchangers. While the gyroid surface, discovered by Schoen, is commonly the focus of various applications, the Schwarz-D TPMS, also named “Diamond” by Schoen, is implemented here for the canopy’s design because of its diamond cubic labyrinths. The diamond surface can be approximated by the implicit function:

$$\cos x \cos y \cos z + \sin x \sin y \sin z = 0$$

The surface is the $t$-isosurface of this function, separating spaces in a positive and a negative half-space. Unlike the gyroid, the diamond has several straight lines embedded in its surface that can be separated into three sets (Fig. 7a). A series of transformations are applied to rotate, translate, scale, and mirror the initial unit cell to allow for the visualization generated through PGS. While different alignments can be explored, the continuity of the smooth surface must be guaranteed by enforcing the whiskering to be an integer multiple of $a$ when cells are lined up and morphed into the form diagram, as done with the canopy illustrated in Fig. 5. While the smooth zero mean curvatures of minimal surfaces is beneficial in some applications, it poses some interesting challenges when 3D printed in concrete, engineering, and architecture to name a few.

Concrete materials exhibit anisotropic behaviour, meaning their properties vary depending on the direction of the applied load. The final constant tension force determined in graphic statics can be used as the post-tensioning force for the cables that run through the canopy to ideally produce constant compression. The constant compression force is intended to be developed from post-tensioning the system reduces the risk of localised stress concentrations and delamination of printed layers, the steel post-tensioning strands provide necessary steel reinforcement, allowing for the canopy to deal with tension forces that could be developed from other loading scenarios.

After using two-dimensional graphic statics to determine a geometry capable of dealing with tension and compression forces, PGS is utilized to extend the form and force in the third dimension (Fig. 6). For this project, all the edges defining the two-dimensional force diagram are extruded to two points to establish a new three-dimensional force diagram. The same strategy used in two-dimensional graphic statics to ensure constant tension forces is also applied here. With the form established, segmented cells are defined to be used later for materialization and VM of the anticlastic surfaces.

Embedding periodic anticlastic surfaces

Since first described by Hermann Amandus Schwarz (1843–1922), and later by Edard Rudolf Neovius, Alan Hugh Schoen, and others, periodic anticlastic surfaces, specifically TPMS, are studied in several domains, including mathematics, physics, material science, and architecture. Schoen, and others, periodic anticlastic surfaces are defined to be used later for materialisation and VM of the canopy. Since first described by Hermann Amandus Schwarz (1843–1922), the Schwarz-D TPMS, also named “Diamond” by Schoen, is implemented here for the canopy’s design because of its diamond cubic labyrinths. The diamond surface can be approximated by the implicit function:

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To ensure successful print and assembly modes of the canopy at four different scales, 1:10, 3:10, 1:2 (Fig. 10), and 1:1, were produced. The 1:10 scale model was printed to understand the nuances of the canopy’s structural form. The assembly process was conducted using an upside assembly procedure. As a high-fidelity proof-of-concept, 3m, half-scaled, and full-scaled versions of the canopy were printed using the multi-component, accelerated 3D concrete printing system, to best understand the printing process and the feasibility of assembly (Fig. 12). Overall, this prototyping informed needed printing procedures and assembly schemes on how to best digitally and physically fabricate and construct the full-scale canopy.

Slicing and toolpath generation

Due to the complexity of the canopy’s design and the limitations of the large-scale 3D concrete printer, the slicing and toolpath were adapted to fit this specific process. Non-parallel slicing was used to get the layers perpendicular to the direction of compression forces brought about by self-weight, during printing. To 3D print non-parallel layers, the printing parameters were adapted to keep the layer width constant. Because of the different inclinations of the layers, the resulting layer heights vary throughout the layer around an average value set to 10mm. Varying layer heights combined with a constant printing speed and extrusion rate create variations in the layer width, around an average set to 30mm. To avoid these layer width variations, an adaptation of the printing speed was implemented based on an algorithm that determines the specific layer height on each point of the toolpath. In case the layer height is lower than 10mm, the printing speed is proportionally increased within the G-Code (printing code) to compensate for the layer height variation and keep the layer width of 30mm, and vice versa. One of the limitations when 3D printing is overhang – that is, parts of the print that slope outwards without support. When the overhang is too high, either the contact surface between the layers is too low to enable further layers to be deposited on top, or the material does not support the structure’s self-weight before setting, and parts of the print collapse. Overhangs can be detected during the slicing process by extracting the normal vectors to the mesh model on each face, enabling easier refinement of the shape without creating waste through physical 3D printing trials. Overall, a goal of reducing overhangs below 30° to maximise the success rate of the print was set.

In addition, since the canopy has hollow sections, it could not be printed in one continuous path. Hence, a few layers were printed at once, and then a ‘jump’ was made to print the next group of layers. To avoid material dripping during jumps, the material extrusion was halted; however, prolonged stops can potentially lead to the printer nozzle clogging. To reduce the risk of clogs, which are more likely to occur if the extrusion is stopped for more than 2.5 seconds, the printing path was optimised to ensure jumps would occur outside of the printing area, preventing the dripping of excess material on the 3D-printed element. The convex hull of the toolpath was generated to obtain the contour curve of the element; then, for each jump, the contour was duplicated and moved to the respective
height of the jump. Finally, the contour was split at its closest point with the end of the current layer grouping and the start of the next layer of group. A connecting path was developed using the small scale prototype, whereby the canopy segments were placed on machined foam blocks with casters. Using a rail system, the individual pieces were placed together and post-tensioned (Fig. 12). Additional strategies for manipulating and placing the final canopy for exhibition were implemented.

Closing remarks

The design, fabrication, and exhibition of Dynamic canopy demonstrates how the combination and development of new and existing methods and technologies can lead to high-performing composite structures with reduced material. The comprehensive computational methodology takes full advantage of the geometric capabilities of 3D concrete printing and directly addresses the unavoidable compression and tension forces developed in concrete structures by using post-tensioning. Overall, this project showcases how these technologies can be used for a more sustainable practice where high-performing structural systems can be produced and material recyclability can be achieved, reducing the overall carbon and embodied energy consumption. The authors hope that this collaborative project inspires the AEC sector to implement and further develop the comprehensive design and fabrication workflow, thus expanding its use as a mainstream approach for exploring and producing forms that were previously impossible or uneconomical to build with conventional methods.

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References


