

The Undula facade: design and fabrication of an extrusion-based 3D printed facade informed by global and layer-wise equilibrium

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Abstract

This paper presents the design and fabrication of an extrusion-based 3D-printed cement mortar facade composed of undulating segmented columns that satisfy both global and print-layer-wise equilibrium. Building on previous research, the proposed fabrication-aware design workflow directly integrates structural, material, fabrication, and on-site assembly constraints within a graphic statistics-based form-finding process. Non-planar print path configurations are introduced after subdividing the network to explicitly control local joint geometry and force transmission while maintaining print-layer-wise equilibrium. Comprehensive structural analysis and optimization methods are incorporated to provide structural stability and control throughout fabrication, assembly, and in the final structural state. The cement mortar facade comprises two 12 m-long sections, each composed of 24 columns with heights ranging from 4.60 m to 6.65 m, and 4.50 m to 6.55 m, respectively. To satisfy manufacturing constraints, the columns were subdivided into 240 column drums, each 3D-printed in cement mortar with an accelerator and integrated aramid filament reinforcement. All columns have been assembled through integrated, non-planar dry joints and post-tensioning. The successful formwork-free prefabrication of the columns and the structural integrity of the assembled facade validate the proposed methodology and provide an initial proof of concept for its application in resource-efficient building construction.

Keywords: facade design, self-supporting structures, form-finding, graphic statics, combinatorial equilibrium modeling, additive manufacturing, extrusion-based 3D printing, non-planar 3D printing

1. Introduction

The contemporary construction industry, particularly when compared with other sectors, remains strongly influenced by conventional design workflows and fabrication paradigms, which often lead to process inefficiencies and suboptimal resource utilization [1], [2]. Integrated design approaches that consider architectural intent, structural behavior, and fabrication constraints from the earliest design phases offer significant potential for more efficient and responsible use of material resources. Building on this paradigm, this paper presents the application of a holistic design framework to a segmented, self-supporting facade system tailored for extrusion-based 3D printing. Architectural requirements, structural form-finding and analysis, robotic fabrication constraints, and assembly processes are systematically embedded within an integrated design methodology to address the multifaceted challenges inherent in contemporary construction practices.

1.1. Research context

Extrusion-based 3D printing for robotic fabrication provides an efficient alternative to conventional fabrication methods. Owing to its ability to produce geometrically complex spatial components with high precision and reproducibility, extrusion-based 3D printing enables the direct fabrication of elements generated by structural form-finding [3] processes, which often exhibit intricate doubly curved geometries [4]. Structural components can be fabricated using extrusion-based 3D printing, either directly in situ [5] or via prefabrication [6]. In the latter case, the target geometry is segmented into elements to fulfill manufacturing and transport constraints, and is subsequently assembled on site. Prefabricated extrusion-based 3D printing offers several advantages over in situ fabrication by providing precise control over material deposition and fabrication parameters, and is therefore commonly employed to produce large-scale 3D-printed structures. Projects such as the Baoshan Pedestrian Bridge [6], the Striatum Bridge [7], the FloatArch project [8], Tor Alva [9], and Diamanti [10] demonstrate the feasibility and applicability of extrusion-based 3D printing with cement-based materials.

1.2. Research objective

This study advances the current state of research by applying a previously developed form-finding method for designing structures in print-layer-wise equilibrium [4], [11] to the holistic design of a large-scale facade demonstrator. Structural design, segmentation, fabrication, and assembly are integrated as explicit parameters within a unified, iterative computational framework. The approach leverages advanced graphic-statics-based form-finding [12] alongside comprehensive structural analysis, enabling direct, simultaneous control over multiple design states while ensuring strict compliance with the constraints required for successful formwork-free 3D printing. A detailed description of the utilized method is presented in the following section (Section 2), where it is directly applied to the design space of the facade project.

2. Computational design approach

The method employed in this study (Figure 1) builds upon previously investigated approaches [4], [11] and is implemented as a computational design tool using Grasshopper and custom Python components within Rhinoceros 3D [13]. The process is initiated by defining the design objectives through direct manipulation of predefined design parameters for each column, such as the nodal coordinates of the first print layer, the cross-section profile defined by a seam trail, and the total number of print layers. Based on these initial design decisions, a global structural network is iteratively form-found (Section 2.1). Subsequently, a global structural analysis using the *Finite Element Method* (FEM) is performed, and the dimensions of the individual structural segments are optimized through an iterative adjustment of the design parameters. Once the global optimization loop has converged, each form-found column is partitioned into individual column drums to satisfy constraints on the maximum allowable dimensions imposed by assembly and fabrication processes. Each drum is individually form-found while satisfying equilibrium without additional support in both the final and all intermediate layer-wise fabrication states (Section 2.2). A print layer-wise FEM analysis is conducted to optimize the drums for the geometric

formation of specified dry joints. Finally, a comprehensive structural FEM analysis is implemented (Section 2.3) to validate the resulting design. If all constraints are satisfied, the individual column drums proceed to fabrication. Otherwise, the design parameters are revised, and the entire design loop is repeated (Figure 1).

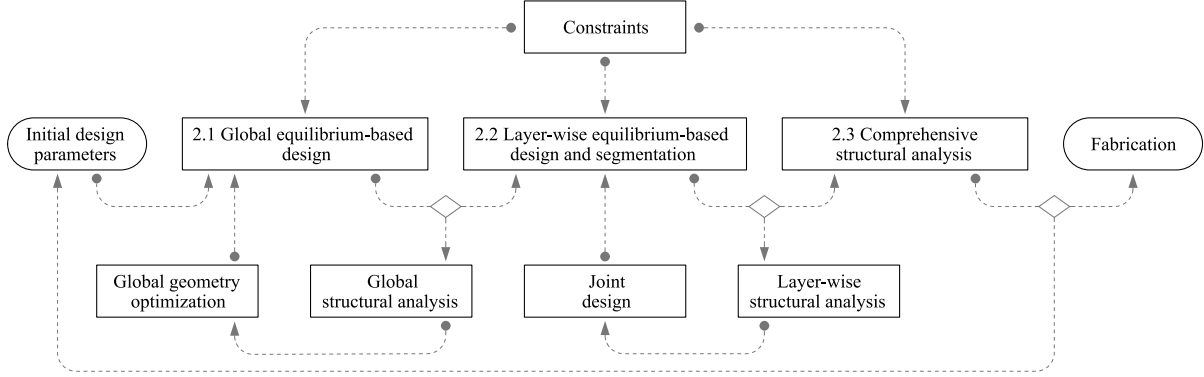


Figure 1: Holistic computational design workflow: Initial design parameters define a global structural network, which is iteratively optimized through global structural analysis. The column is then segmented and form-found at the segment level while satisfying equilibrium in all fabrication stages, and validated through layer-wise structural analysis. A comprehensive structural analysis is implemented for final validation prior to fabrication.

2.1. Global equilibrium-based design

Global and layer-wise equilibrium is achieved using an extended version of the *Combinatorial Equilibrium Modeling* (CEM) form-finding method [4], [14]. CEM represents structural equilibrium through a topological diagram T , its corresponding form diagram F , and its force diagram F^* (Figure 2). Equilibrium is computed sequentially along trail elements T_{ij} that define directed load paths from origin nodes $V_{o,i}$ to support nodes $V_{s,i}$. Trail elements T_{ij} are controlled by their assigned lengths and by the combinatorial state of tension or compression, while deviation elements D_{ij} interconnect vertices V_i and are defined by prescribed force magnitudes. Loads $q_{E,i}$ are applied as nodal force vectors. Once the user defines the spatial coordinates of the origin nodes $V_{o,i}$ and the metric inputs for T_{ij} and D_{ij} , equilibrium is computed iteratively from $V_{o,i}$ toward $V_{s,i}$, yielding F and F^* , which together represent a network in equilibrium within the infinite design space of T (Figure 2).

Using the CEM method, the 48 individual columns of the facade are initially globally form-found as vertical cylinders (Figure 2e). The dimensions of each column are governed by fabrication and assembly constraints that impose upper limits on the allowable column size [4]. The cylindrical columns are constructed by positioning radial $V_{o,i}$ and connecting the origin nodes with a series of T_{ij} , forming what is referred to as a trail. Self-weight is applied as a point load at every V_i to the network. Additionally, internal post-tensioning is modeled as point loads applied to $V_{o,i}$. To introduce undulations within individual columns in the facade, rings of deviation elements D_{ij} are inserted between V_i at consistent topological distances (Figure 2d). The magnitude of each deviation ring is controlled by a function that defines the direction of the initial trail, termed the seam trail T_{0ij} , on a nodal basis. To reduce column depth while maintaining a constant width, $V_{o,i}$ were arranged along an elliptical layout, establishing an initial global configuration for the facade design (Figure 2c). Each facade column cross-section profile is primarily defined by its minimum and maximum diameters and by a continuous, repetitive geometric transition based on a cosine function defined using a specific target seam trail (Figure 2c). The maximum diameter of 45 cm results from the center-to-center distance between neighboring columns, while the minimum diameters are not governed by direct geometric constraints. To balance load transfer through the facade, the minimum diameters vary along the structure and are optimized by adjusting the target seam trail T_{0ij} to achieve a similar stress level in each minimum section (Figure 2a, b). The form adaptation accounts for the height and position of each column and is evaluated under the structure's self-weight and a post-tensioning force of 10 kN.

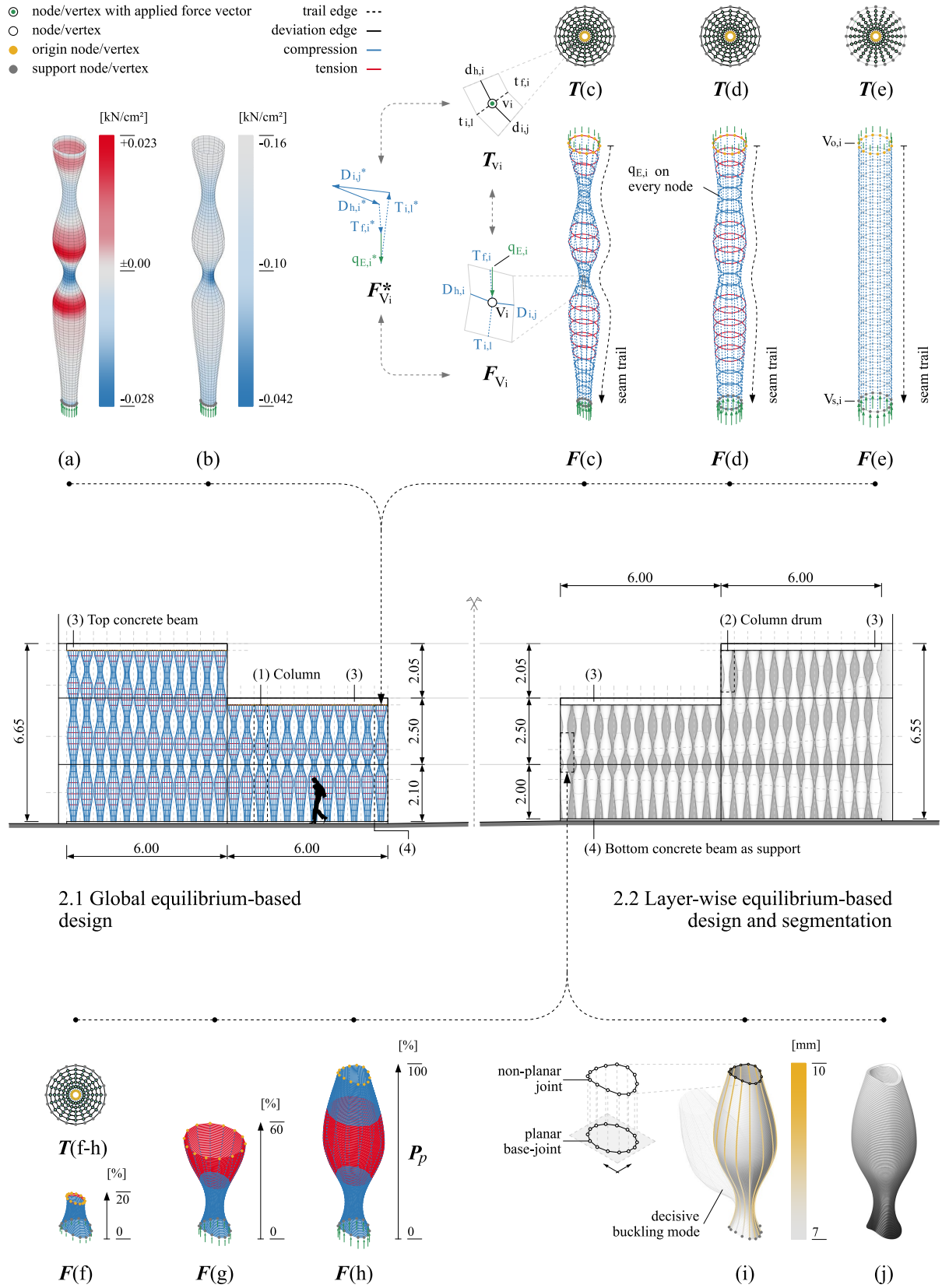


Figure 2: Global and layer-wise structural form-finding; (a) first principal stresses of a single column; (b) second principal stress of a single column; (c) final global form-finding of a single column with elliptical cross-section; (d) opening and undulation of an initial form-found cylinder; (e) initial global form-finding of a cylindrical column; (f-h) print layer-wise form-finding of an individual column drum; (i) buckling and layer-overhang analysis of a single column drum; (j) volumetric representation of the print path of one column drum. The facade is composed of discrete columns (1), each subdivided into individual column drums (2). The columns are capped by a top concrete beam (3) and supported at their base by a bottom concrete support beam (4).

2.2. Layer-wise equilibrium-based design and segmentation

Based on the global form-found geometry, a segmentation pattern is defined to divide the form-found columns into column drums to be individually fabricated. To ensure stability after assembly, adjacent segmentation interfaces are vertically offset, preventing the formation of extended slip directions (Figure 2). Furthermore, the segmentation interfaces are positioned in regions of reduced hoop forces, corresponding to low principal stress σ_1 values within the transition zone between tension and compression [4]. In the first step, the segmentation interfaces are defined as planes oriented along the direction σ_1 , resulting in planar joint interfaces that follow the principal stress trajectories. In the second step, these planar joints are transformed into periodic segmentation interfaces defined by a cosine function (Figure 2i). The resulting smooth, wave-like profile increases the effective contact area and enhances mechanical interlocking, thereby improving shear transfer between segments while avoiding sharp discontinuities that could compromise print quality or disrupt continuous toolpaths. The subsequent step involves integrating the segmentation strategy into an existing layer-wise form-finding framework, based on the CEM method [4], [14], that guarantees equilibrium during the fabrication process, where each addition of a fully closed print layer represents an intermediate state of equilibrium. To make these states constructively solvable, equilibrium is enforced under a sequence of constraints that progressively reduce the degrees of freedom of the thrust network. First, the geometric layout is constrained so that equilibrium conditions lie on a plane for each trail, forming offset polygons in the horizontal plane **(a)**. Second, the seam trail defined within the global form-finding step is implemented to control the shape of the network **(b)**. Finally, self-weight nodal loads are adjusted to match equilibrium conditions **(c)**. In this work, we use an index $i = u + vn_u$ to identify a node in a grid, where $u \in [0, n_u)$ represents the within-layer index, and $v \in [0, n_v)$ the layer index.

(a) Planar equilibrium (Figure 3a): Each trail is constrained to lie on a plane containing a vertical axis. This restriction reduces the nodal equilibrium problem from three dimensions to two. The two deviation forces applied at a node define a resultant that must lie in the plane of the corresponding trail (1). Under this condition, the incoming force can be resolved uniquely into the deviation resultant and the outgoing trail force (2). In practice, this condition is enforced by requiring the horizontal projections of deviation and trail elements to remain parallel across layers, forming offsets of a strictly convex polygon:

$$D_{i,i-1}^* + D_{i,i+1}^* = R_i^* \quad (1)$$

$$q_{E,i}^* + T_{i,i-n_u}^* = -T_{i,i+n_u}^* - R_i^* \quad (2)$$

(b) Shape control through the seam trail (Figure 3b): A nodal target direction is introduced with the seam trail. For every node within this trail, with a grid coordinate $u = 0$, planar equilibrium at initial and final states are handled explicitly via a linear system, while keeping element orientation constant:

$$-R_i^{*(initial)} - T_{i,i+n_u}^{*(initial)} = -\lambda_i^{R(initial)} \hat{R}_i^* - \lambda_{i,i+n_u}^{T(initial)} \hat{T}_{i,i+n_u}^* = q_{E,i}^* \quad (3)$$

$$-R_i^{*(final)} - T_{i,i+n_u}^{*(final)} = -\lambda_i^{R(final)} \hat{R}_i^* - \lambda_{i,i+n_u}^{T(final)} \hat{T}_{i,i+n_u}^* = q_{E,i}^* + T_{i,i-n_u}^{*(final)} \quad (4)$$

The system of equations (3,4) solve for the force magnitudes $\lambda_i^R, \lambda_{i,i+n_u}^T$, which are applied in predetermined directions $\hat{R}_i^*, \hat{T}_{i,i+n_u}^*$. Considering the equilibrium of the deviation forces on the horizontal plane, the initial and final deviation forces across the layer result from $R_i^{*(initial)}, R_i^{*(final)}$.

(c) Adjustment of self-weight (Figure 3c): For the nodes that are not in the seam trail $u \neq 0$, the self-weight $q_{E,i}^*$ is adjusted to match the formulated initial and final equilibrium states. Initial and final deviation forces and incoming trail forces are provided, enabling the resolved self-weight $\lambda_i^q \hat{q}_{E,i}^*$ and the outgoing trail element forces with magnitudes $\lambda_{i,i+n_u}^{T(initial)}, \lambda_{i,i+n_u}^{T(final)}$ and direction $\hat{T}_{i,i+n_u}^*$:

$$-q_{E,i}^* - T_{i,i+n_u}^{*(initial)} = -\lambda_i^q \hat{q}_{E,i}^* - \lambda_{i,i+n_u}^{T(initial)} \hat{T}_{i,i+n_u}^* = R_i^{*(initial)} \quad (5)$$

$$-q_{E,i}^* - T_{i,i+n_u}^{*(final)} = -\lambda_i^q \hat{q}_{E,i}^* - \lambda_{i,i+n_u}^{T(final)} \hat{T}_{i,i+n_u}^* = R_i^{*(final)} + T_{i,i-n_u}^{*(final)} \quad (6)$$

As a result of these constructive rules, all intermediate and final equilibrium states are satisfied exactly, and the form-finding problem reduces to a set of design variables without redundancy: a seam trail, the location of the origin nodes, and the loads applied to them. This reduction is nontrivial, as the number of equilibrium conditions scales quadratically with the number of layers, whereas the number of CEM variables scales linearly with it.

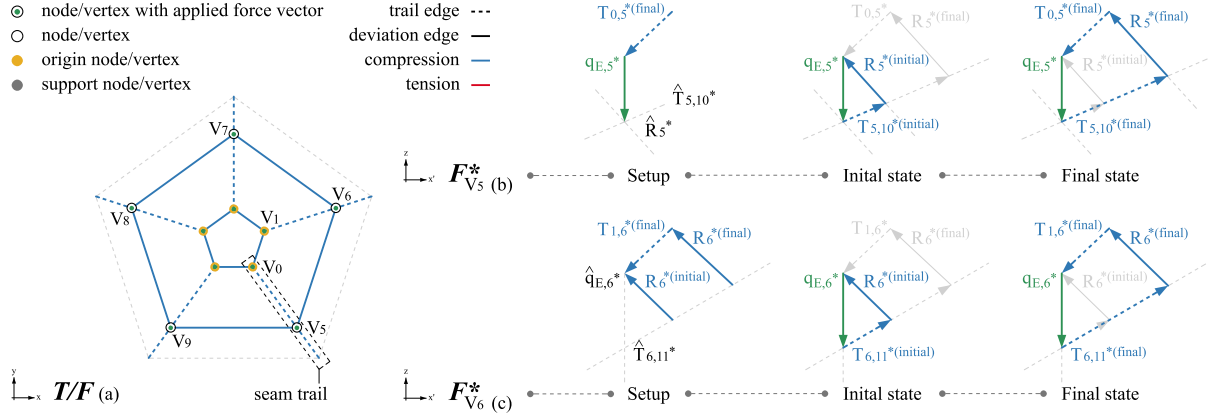


Figure 3: Constraints to fulfill layer-wise equilibrium; (a) trails lie on a plane; (b) internal forces are determined to match a target seam curve; (c) forces are adjusted in the remaining nodes of a layer.

The seam trail and origin nodes are provided from the design specification. The remaining degrees of freedom are exploited to design interlocking interfaces between column drums. The configuration of self-weight loads in the origin nodes is determined to match the target cosine curve at the supports. This inverse problem is solved using gradient-based optimization [15], with the deviation between target and form-found coordinates used as the objective function, and gradients approximated using finite differences. To improve robustness, layers are activated incrementally during the optimization, first matching a planar support interface and subsequently morphing it into the final interlocking configuration. As a reference for runtime, an evaluation of a design with 191 layers and 2674 nodes can be performed in 63 ms per global solve on a standard desktop CPU. Across the full project, 2,147,602 layer-equilibrium states were satisfied, with a maximum *Root Mean Squared Error* (RMSE) of 0.25 mm on the target interlocking curve.

Based on the final form-found column drum, both a robotic print path $\mathbf{P}$ and a volumetric print path $\mathbf{P}^*$ for geometry preview (Figure 2j) are directly derived from the form diagram $\mathbf{F}$. Furthermore, layer-wise analyses of strength-based failure, buckling, and layer overhang [4] are performed on the individual column drums to ensure successful formwork-free fabrication (Figure 2i). Using the proposed design approach (Figure 1), a final design comprising 48 columns (Figure 2(1)), with heights ranging from 4.60 m to 6.65 m, and 4.50 m to 6.55 m, and a total of 240 individual column drums (Figure 2(2)) was form-found using global (Section 2.1) and layer-wise (Section 2.2) form-finding.

2.3. Comprehensive structural analysis

After the final facade geometry is defined (Figure 2), a comprehensive structural analysis is performed for verification. The FEM model explicitly represents the segmented configuration, joint geometries, local detailing, and the experimentally determined material properties of the additively manufactured components [16]. The thin-walled facade columns are discretized using two-dimensional shell elements with an average element edge length of 30 mm. Local mesh refinement is introduced along the segmentation interfaces, which are modeled as linear spring-hinge connections to capture the governing load-transfer mechanisms and the stiffness discontinuities resulting from the fabrication and assembly strategy. The joint model incorporates translational stiffness in the local x-, y-, and z-directions and

rotational stiffness about the local y-axis. A geometrically non-linear analysis is performed to evaluate the structural response and verify compliance with the *Serviceability Limit State* (SLS) and *Ultimate Limit State* (ULS) requirements in accordance with Eurocode. The analysis considers self-weight, post-tensioning, horizontal wind loading, and temperature-induced actions. Global response measures, including load-bearing capacity and overall deformation, are evaluated alongside local effects at the segment interfaces, where stress concentrations and relative displacements govern structural performance. A primary objective of the analysis is to determine the minimum post-tensioning force required to maintain structural integrity and ensure stability under horizontal wind loading for both ULS and SLS while accounting for seasonal temperature variations. Particular attention is given to the local stress distribution across the dry joints. Joint deformation may produce localized stress concentrations and non-uniform contact pressure, resulting in local cracking, crushing, or other damage mechanisms that impair the intended load-transfer behavior. To account for these effects and the uncertainties associated with the numerical modeling, a conservative design approach is adopted by limiting the maximum compressive stress to 75% of the experimentally determined compressive strength (or corresponding design strength). This additional safety margin reduces the risk of local joint failure and ensures reliable structural performance. A detailed description of the FEM modeling strategy, joint formulation, material models, and numerical validation will be presented in a follow-up publication.

3. Implementation and results

The column drums were fabricated individually using extrusion-based 3D printing (Section 3.1). After curing, the column drums were assembled directly on site (Section 3.2), resulting in the final facade demonstrator (Figure 6). The demonstrator is positioned in front of a newly constructed storage hall at the 3D-printing company UniQum GmbH at Gessenschwandt 61, 4882 Oberwang, Austria.

3.1. Component fabrication

Each of the 240 individual column drums is fabricated by the industry partner UniQum GmbH (Figure 4). The fabrication setup uses an ABB six-axis robotic arm equipped with a Baumit end effector. Baumit PrintCret 230, a cementitious mortar, was used as the printing material. To achieve rapid setting, an accelerator was mixed with the mortar at the end effector, forming a two-component system. An aramid cord was embedded along the print path, thereby enabling the rings to carry tensile forces [4]. When required, an additional support base was printed for drums with non-planar supports. A grease layer separated the printed support and the final column drum to prevent bonding between adjacent layers. Following successful fabrication, the column drums were post-processed using an angle grinder, hydrophobized, and stored under controlled conditions for curing before assembly.

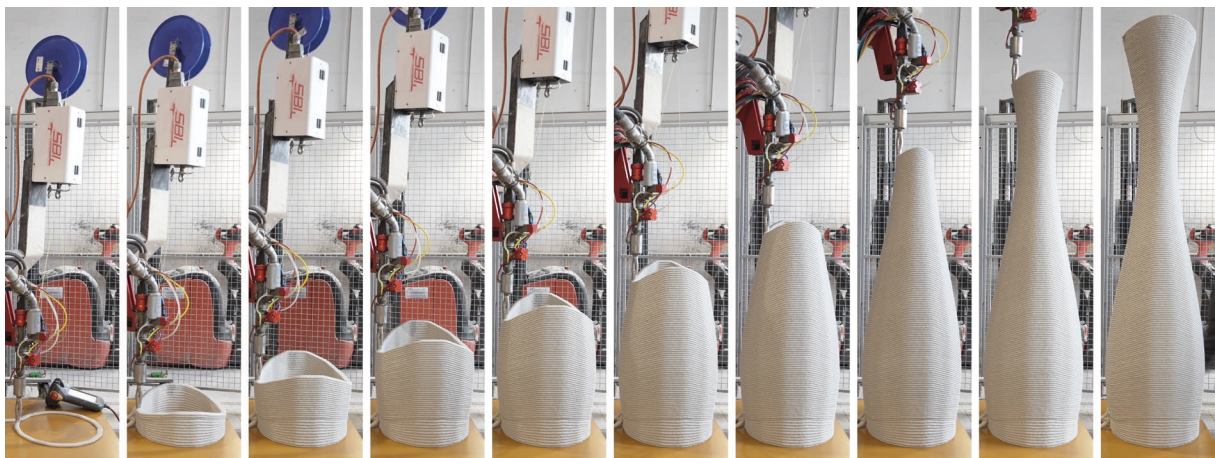


Figure 4: Component fabrication. When the column drum has a non-planar support base, the drums are fabricated on a 3D-printed support structure. A grease layer is applied between the printed support and the final drum to prevent bonding between adjacent layers.

3.2. On-site assembly

After a 30-day drying period, the 240 column drums (Figure 2(2)) were assembled on site (Figure 5). The individual drums have been delivered to the construction site on pallets and assembled sequentially. Each column drum was lifted into position by crane using a specially manufactured bracket (Figure 5a-c). After the individual column drums had been lifted, the support base was easily removed using a hammer (Figure 5a). A milled wooden stencil was used to position the first drums of each column. After precise alignment (Figure 5b-d), every column drum was locally secured to the wall behind with a stainless-steel anchor (Figure 5e). This procedure enabled installation without the need for formwork or auxiliary supporting structures. Steel threaded rods, which were screwed into anchor rails embedded in the concrete foundation (Figure 2(4)), were extended incrementally as the column drums were added, allowing the post-tensioning of each column (Figure 5f). The individual drums were connected using dry joints, without adhesives, allowing direct disassembly and potential reuse of the entire structural system. The high precision of the 3D-printed segments, together with the selected assembly process, enabled rapid installation, allowing both facade sections to be fully erected within 10 days.

Once the individual column drums were fully assembled, two reinforced concrete beams (Figure 2(3)), constituting the upper closure of the facade, were positioned using a crane and secured with steel anchors. These beams serve multiple structural functions: they interconnect the individual columns, provide a rigid connection between the columns and the supporting back wall, and facilitate the application of internal post-tensioning. Post-tensioning is applied by tightening nuts against steel plates mounted on the steel threaded rods above the beams. After successful on-site assembly, the facade serves as a permanent self-supporting structure, with vegetation growing behind it (Figure 6).

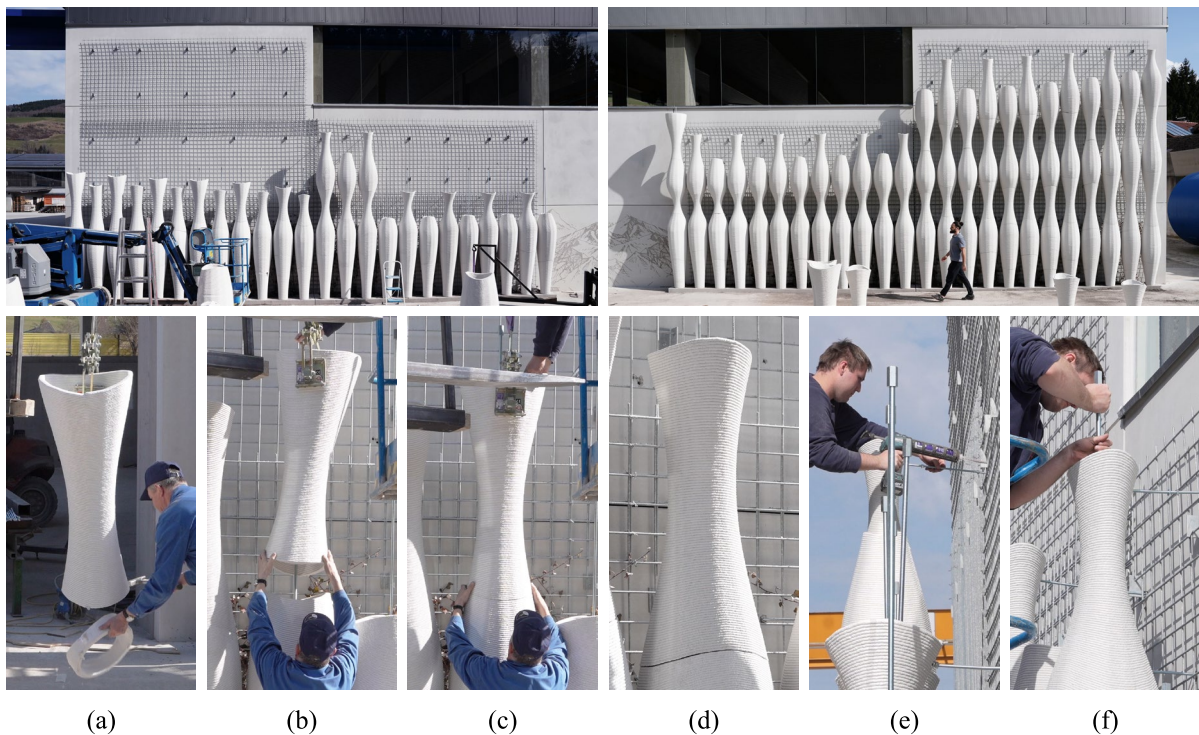


Figure 5: On-site assembly process of the individual 240 column drums; Top: Facade sections during assembly; (a) removing the support base; (b - d) placing the individual column drums using a specially manufactured bracket; (e) securing the column drum with a stainless steel anchor; (f) extending the steel threaded rods.

4. Conclusion and outlook

This paper presented the successful realization of a 3D-printed cement mortar facade (Figure 6) composed of 240 individual drums forming 48 undulating columns across two facade sections (Figure 2). Each section spans 12 m in length and reaches heights of 6.65 m and 6.55 m. Columns were subdivided into discrete drums, featuring non-planar dry joints and localized post-tensioning to enable formwork-free prefabrication and reliable structural performance. The project builds on a previously developed extended Combinatorial Equilibrium Modeling (CEM) framework, combined with fabrication-aware design strategies [4], [11]. It ensures both global and layer-wise equilibrium while systematically incorporating structural, material, fabrication, and assembly constraints. The two facade sections (Figure 6) demonstrate the complete workflow from digital design to on-site assembly, validating the feasibility of serial production, robotic fabrication, and the precise installation of complex geometries. The successful project confirms the method's ability to control structural behavior throughout fabrication and installation, providing strong evidence of its potential for resource-efficient construction. Future work should address long-term monitoring, such as detailed scans, measurements, and 1:1 load tests with joint analysis to further verify structural performance. Further research shall explore the application of this method in full-scale building projects and its extension beyond current limitations, broadening architectural and structural possibilities. In addition to the stringent geometric constraints inherent to the presented form-finding method, an optimization-based approach can be employed to achieve layer-by-layer equilibrium, thereby substantially enhancing design flexibility.

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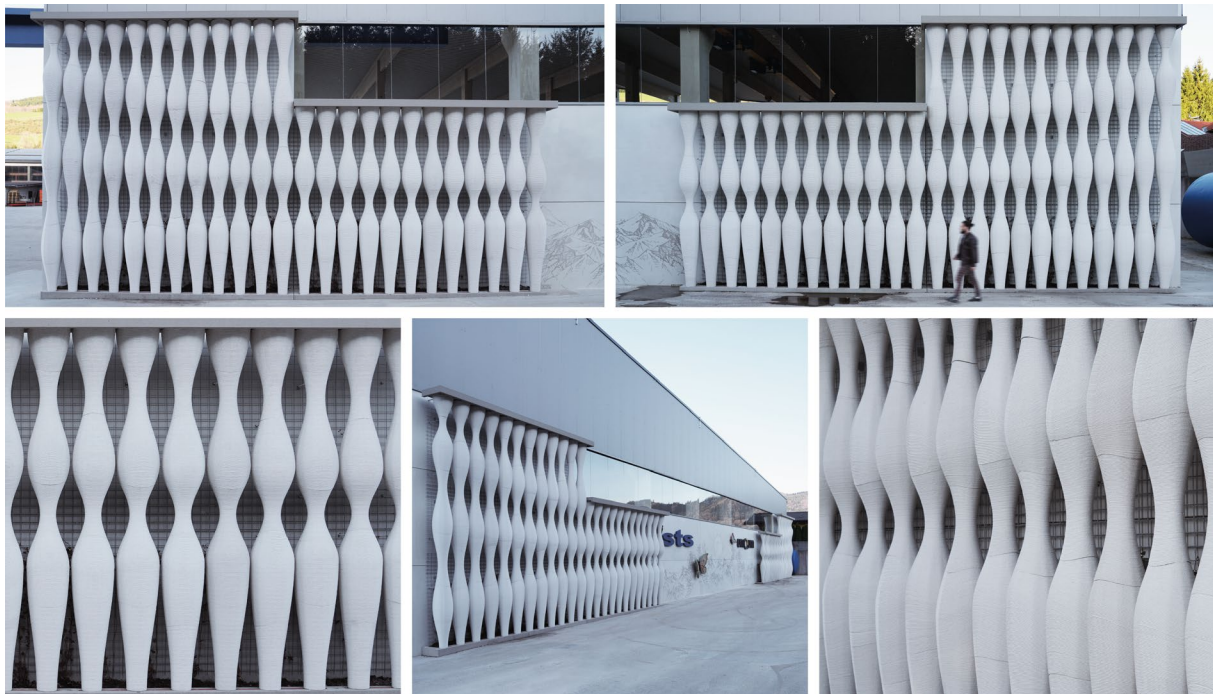


Figure 6: Final facade design. The facade consists of 240 individual drums, forming 48 columns within two facade sections. Each section is 12 m long, with a height ranging from 4.60 m to 6.65 m, and 4.50 m to 6.55 m. The facade was erected on the premises of UniQum GmbH at Gessenschwandt 61, 4882 Oberwang, Austria.

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